

# Essays on the Role of Emerging Economies in International Climate Policy

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# Chapter I

## Introduction

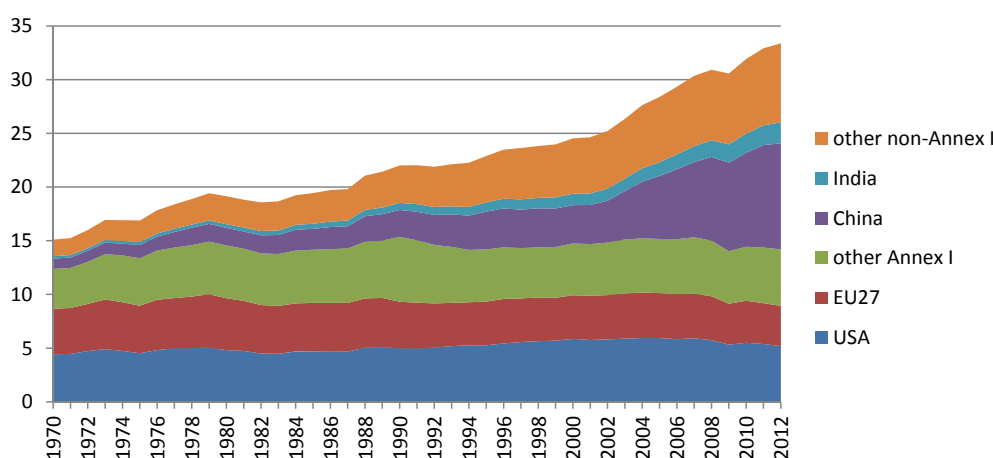
Climate change is one of the most pressing environmental problems, leading to rising temperatures and increased probabilities in the occurrence of extreme events (IPCC, 2007). This in turn induces economic cost from reduced productivity in certain sectors and regions or damages like flooding, respectively. The main driver for anthropogenic climate change is the emission of greenhouse gases (GHG). Among all GHGs, carbon dioxide (CO<sub>2</sub>), associated mainly with burning fossil fuels, accounts for the largest share. Yet the global economy in its current form still heavily depends on this energy input, leading to an unsustainable level of global CO<sub>2</sub> emissions. Mitigation of CO<sub>2</sub> to keep global warming within a manageable range, e.g. 2 degrees Celsius, would however require deep cuts in emissions. While costly, it is suggested that the cost of limiting climate change by reducing emissions outweighs the cost from climate change impacts (IPCC, 2007; Stern, 2007). This is also reflected in international agreements, e.g. in the Copenhagen Accord, which makes mention of the target to limit warming to 2 degrees Celsius.

As CO<sub>2</sub> is a global pollutant (i.e. it does not matter where it is emitted), a global solution would be preferable. Incentives for individual countries to participate in global regimes are however limited because they do not reap the full benefits of their efforts. Instead, each country would usually be better off to free ride because engaging in climate policy induces a risk that a loss of competitiveness occurs or the mitigation actions are offset by “carbon leakage”. Emissions of CO<sub>2</sub> are therefore a prime example for an economic externality. The nature of CO<sub>2</sub> as an externality limits the scope for unilateral solutions. Furthermore, to have an effect on the climate system, a global policy would be needed, or at least a policy that includes control of a large share of global emissions.

Between 1970 and 2010, global CO<sub>2</sub> emissions have doubled (see Figure 1). While at the beginning of that time frame the vast majority of CO<sub>2</sub> was emitted by developed countries, much of the additional growth in recent years came from emerging economies. In particular, the rise of the Chinese economy has led to a growth in global emissions and China has replaced the USA as largest emitter. While under the Kyoto protocol emissions in most developed economies are regulated, emissions in developing countries are not. It is expected that without climate change policies, the growth of emissions in emerging economies such as India and China will continue and render ambitious climate policy infeasible (Blanford et al., 2009). Therefore the future emission developments in these countries are crucial to limit global warming.

In India and China, CO<sub>2</sub> emissions have grown along with economic development, yet emissions are still relatively low in terms of per capita emissions (at least for India) and these countries have contributed relatively little to the current stock of CO<sub>2</sub> in the atmosphere. While that will change at least for China in the coming decades, in climate negotiations India and China have argued that they are not (yet) responsible for emission reductions or able to pay for mitigation measures. Finding

**Figure 1:** CO<sub>2</sub> emissions from combustion and fossil fuels and cement production. Own representation based on Olivier et al. (2013).



ways to integrate these countries into global climate policy is however crucial to avoid dangerous climate change as delaying action is most likely to further increase global abatement costs (Clarke et al., 2009).

This dissertation analyzes current proposals of integrating China and India into a global climate policy regime both qualitatively and quantitatively. Consequences of different scenarios are explored with the help of a computable general equilibrium (CGE) model. The model is used to assess economic consequences of entering a global climate policy regime. Global policies, however, have repercussions in today's globalized economy: Fossil fuel markets would be heavily influenced as climate policy would make the use of fossil fuels expensive and thus unattractive. A global emission trading would ensure efficiency in abatement, however it is also a potential source of repercussions. Some chapters of this dissertation deal with these repercussions. Chapter IV analyzes the effect of international transfers and the fossil fuel markets, Chapter V focusses on the transmission of a technology shock, and Chapter VI takes a closer look at misusing climate policy as a means to exploit the international connectedness in trade. A CGE model is a useful tool this analysis, since it explicitly takes these repercussions into account.

While it is important to balance an economic development objective with the impacts of climate policies in developing or emerging countries, it is important to keep in mind that emission reductions in developing countries are often cheaper than in more advanced economies. Technologies used in developing countries are further away from the technology frontier, thus giving an opportunity for exploiting "low hanging fruits" by transferring technology already commonly used in more advanced countries. Currently this is already done in the Clean Development Mechanism (CDM), but could be further institutionalized in a future climate regime that includes developing countries.

This dissertation aims at analyzing policies or policy proposals on the global level as well as for India and China, in particular. Each of the individual chapters discusses a specific aspect or a specific policy that is either already in place or proposed.

Chapter II sets the stage by presenting a literature overview of regime proposals and how they would affect China and India. These proposed regimes obtained from the literature are based on different equity criteria. Under a global emission trading scheme, these equity principles could serve as guidelines of how to allocate emission rights between countries. This chapter focusses on the emissions rights allocated to India and China under different regime types as well as under varying parameters such as the ambition of global emission reduction. This chapter also analyzes the resulting economic consequences under the different emission allocations for China and India.

Chapter II argues that the “Common but Differentiated Convergence” (CDC) (Höhne et al., 2006) regime might be an acceptable compromise for both developing and developed countries as several equity principles are combined in this regime. Chapter III analyzes this regime’s economic and energy system consequences for China and India. Since China has not only higher per capita CO<sub>2</sub> emissions, but also is more advanced in terms of development, China and India would be affected quite differently from the CDC proposal. While India would have surplus emission rights that it could sell on the international carbon market to offset domestic cost from abatement, this would not necessarily be the case for China. The analysis is built on a comparison of model results from different models. The purpose of such model comparison is twofold: On the one hand, such a comparison can deliver more robust results, but on the other hand, it can also serve to detect the source of differences between models. This model comparison includes both single country and global models as well as CGE and energy system models.

Chapter IV refines the analysis of Chapter III by taking a closer look on India. Compared to the previous chapter, two crucial repercussions and their role for a closer model coupling are discussed in a more in-depth analysis. Earlier literature already identified repercussions through international fossil fuel markets (Böhringer and Rutherford, 2002), and emission trading markets (McKibbin et al., 1999b,a). Besides the impact of these repercussions, we also analyze how different (domestic) allocation schemes affect different household classes. As poverty is of utmost concern to Indian policy makers, we focus especially on poor households. The analysis carried out in this chapter indicates that international repercussions have indeed an impact that should not be overlooked when analyzed in a single country model. There are also important distributional issues that might be missed in a global model which depicts a country in a more aggregated way. Furthermore, as different household groups behave differently, changes to the domestic allocation of revenues from emission pricing can have a feedback on the macro level.

Chapter V takes into account that abatement costs are uncertain. Affordable mitigation is expected to rely on low carbon technologies like renewable energy or carbon capture and storage (CCS). Both technologies are expected to further reduce their deployment cost in the future, making large scale deployment more economical. While there are many sources of uncertainty in the economic analysis of climate change (e.g. uncertainty in the climate system or uncertainty about the correctness of the economic model), this chapter focusses on uncertainty in these key abatement technologies. A simple theoretical model shows that both the nature of the shock (renewable energy vs. CCS) as well as the policy instrument under which a shock occurs (quantity vs. price based) can influence who gains from a shock and who is worse off from lower abatement costs. Simulation with a more complex CGE model indeed confirms that there are cases where lower (total) abatement costs can lead to higher cost for some regions.

Although it is necessary to include Chinese and Indian emissions in a long term climate regime to achieve the required emission reductions, it is questionable whether developing countries are willing to enter a regime on a short term basis as this could potentially harm their economic development. Staying outside a regime, however, influences also the cost of emission reductions in other regions which are willing to go ahead with unilateral emission reductions. A main concern is that production and thus emissions are (in part) relocated to countries without a climate legislation, thus undermining the reduction effort. To counter these concerns, border carbon adjustments (BCA) are proposed. These measures would make imports from a region without a carbon price subject to a tariff which would be based on the carbon content embodied in the traded goods. While BCAs are effective in reducing leakage (Böhringer et al., 2012), there remain issues on practicability (Weitzel and Peterson, 2012) and economic incentives. Chapter VI analyzes the incentives for introducing BCA in regions with emission reduction policies and how this affects other regions’ incentives to also engage in

emission reductions. Although BCAs do provide a measure to reduce leakage and therefore have an environmental effect, BCAs, nevertheless, are also an intervention into international trade which potentially could be abused. The chapter finds that BCAs could be misused as substitute for optimal tariffs at the expense of countries outside a coalition.

As Chapter VI finds that there is an incentive to overstate emissions embodied in trade. China could be negatively affected in particular because the trade of goods from China to developed countries in Europe and North America is relatively carbon intensive. Yet there are some uncertainties in the carbon content embodied in trade. Chapter VII compares different input-output models to quantify emissions embodied in exports. A considerable share of Chinese exports can be characterized as processing trade, with little value and emissions added (Koopman et al., 2012). Furthermore, export production is predominantly located in the coastal provinces which are producing more (energy) efficiently compared to the average of China. By taking these features into account, the carbon content of exports can be different than in a standard model, particularly on a sectoral level.

While the previous chapters focussed on the analysis of potential future climate regimes, India and China can already utilize their low cost abatement potential within the under the Clean Development Mechanism (CDM) implemented under the Kyoto protocol. The CDM allows developed countries who have committed to emission reduction to carry out part of these emission reductions in developing countries where abatement is cheaper. Besides this efficiency argument, it is hoped that the CDM can also bring along more advanced technologies to developing countries. Chapter VIII analyses whether this hope was fulfilled for CDM projects in China. The econometric analysis based on CDM projects initiated until 2010 shows determinants of international technology transfer. Whereas there are clear differences between technologies applied in the individual projects, there are also various effects from different types of available knowledge. We also look at spillover effects from early CDM projects on subsequent projects.

This dissertation thus provides an analysis of existing and proposed international climate policy measures. It helps to understand the role of emerging economies in current climate negotiations, but also suggest ways of engaging them in a global climate policy architecture.

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## Chapter II

# Emission allowances and mitigation costs of China and India resulting from different effort-sharing approaches<sup>\*†</sup>

*To meet ambitious global climate targets, mitigation effort in China and India is necessary. This paper presents an analysis of the scientific literature on how effort-sharing approaches affect emission allowances and abatement costs of China and India. We find that reductions for both China and India differ greatly in time, across- and within approaches and between concentration stabilisation targets. For China, allocated emission allowances in 2020 are substantially below baseline projections. Moreover, they may be below 2005 emission levels, particularly for low concentration targets (below 490 ppm CO<sub>2</sub>-eq). Effort-sharing approaches based on allocating reduction targets lead to relatively lower reductions for China than approaches that are based on allocating emission allowances. For 2050, emission allowances for China are 50–80% below 2005 levels for low concentration targets with minor differences between approaches. Still, mitigation costs of China (including emissions trading) remain mostly below global average. According to literature, Chinese emission allowances peak before 2025–2030 for low concentration targets. India’s emission allowances show high increases compared to 2005 levels. If emission trading is allowed, financial revenues from selling credits might compensate mitigation costs in most approaches, even for low concentration targets. India’s emission allowances peak around 2030–2040 for all concentration targets.*

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<sup>\*</sup>This chapter is published as van Ruijven, B. J., Weitzel, M., den Elzen, M. G. J., Hof, A. F., van Vuuren, D. P., Peterson, S., and Narita, D. (2012). Emission allowances and mitigation costs of China and India resulting from different effort-sharing approaches, *Energy Policy*, 46:116–134.

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## 1 Introduction

With the approaching expiration of the first commitment period of the Kyoto protocol in 2012, there is a need for a new international climate policy regime for allocating future commitments across all countries. The contours of such a regime are still very uncertain, but the United Nations (UN) climate negotiations in Durban (2011) made a first start by the established a new body to negotiate a global agreement that would cover all countries by 2015.

Following the Copenhagen (2009) climate negotiations, 42 industrialised countries submitted quantified economy-wide emission targets for 2020. In addition, 43 developing countries submitted so-called nationally appropriate mitigation actions (NAMAs) for inclusion in the Appendices to the 2009 Copenhagen Accord. All these reduction proposals were later “anchored” in the Cancún (2010) Agreements. Several studies assessed these national greenhouse gas emission reduction proposals for 2020 (den Elzen et al., 2010, 2011; Rogelj et al., 2010), and concluded that they are not sufficient to meet the ambitious target to limit global mean temperature increase to less than two degrees from pre-industrial levels, a climate target that is also mentioned in the Copenhagen Accord (UNFCCC, 2009) and Cancún Agreements (UNFCCC, 2010).

The mitigation effort of China and India are increasingly important for meeting ambitious climate targets, as their rapid economic growth leads to an increasing share in the world’s greenhouse gas emissions. Substantial delay in the mitigation of their emissions would bring such targets out of reach. In fact, emissions from developing countries alone will soon exceed the global emission trajectory for reaching a low concentration target (Blanford et al., 2009; Clarke et al., 2009; Metz et al., 2002). However, as income levels in both China and India are still much lower than that of industrialised countries and both countries have historically contributed less to current greenhouse gas concentrations, they are not eager to take on (ambitious) emission reduction targets. This position is consistent with Article 3.1 of the UNFCCC (1992) that indicates that countries have a “common but differentiated responsibility” to contribute to future reductions.

There are many different possible views on which allocation of emission reduction targets reflects a fair “common but differentiated responsibility” (den Elzen and Höhne, 2008, 2010; Rose et al., 1998). Consistent with these views, there are many different post-Kyoto effort-sharing approaches or post-2012 regimes to allocate future reductions to the various regions, each with different participation levels, timing of reductions, as well as stringency and type of commitments, varying from voluntary action to absolute reduction commitments (see an overview of proposals in e.g. Bodansky, 2004; Gupta et al., 2007; Kameyama, 2004; Philibert, 2005). The IPCC’s Fourth Assessment Report (AR4) (Gupta et al., 2007) summarised how emission reductions would be allocated to developed and developing countries according to various proposals by assessing model studies on this subject. It indicated that for meeting low stabilisation targets, developed countries as a group would need to reduce their emissions within a range of 25–40% below 1990 levels by 2020, as long as emissions in developing countries deviate substantially from their baseline emission levels. Den Elzen and Höhne (2008, 2010) elaborated further on this issue and concluded that 25–40% reduction below 1990 levels in 2020 for developed countries, combined with a 15–30% reduction below baseline for the developing countries, is needed to meet a 450 parts per million (ppm) CO<sub>2</sub>-eq stabilisation target. The reduction percentages for individual countries vary among different regimes and parameter settings and may be outside this range. For higher stabilisation levels, reductions would have to occur only at a later date. These differences in reductions have obviously major consequences for the economic impacts for developing countries in joining a regime (Gupta et al., 2007). Hof et al. (2009) have evaluated the impact of different regimes on regional mitigation targets and costs for large world regions.

The aim of this paper is to present a detailed overview of how different regimes may affect China and India. The focus is on emission allowances over time, the peaking year before which emission allowances start declining, and the costs or economic impact. Compared to the above-mentioned studies, this paper includes more studies and discusses the results vis-à-vis current policy initiatives and scientific literature in India and China. The information might be important to assess how different view points on different policy regimes might be combined with the observation that an early contribution of China and India is necessary to meet ambitious climate targets.

The paper is structured as follows. Section 2 describes the regimes and Section 3 the methodological aspects related to comparing the results of different studies. Section 4 discusses the findings and plausibility of regimes with respect to reductions, peaking of allowances and mitigation costs. Recently published literature from Indian and Chinese authors is discussed in Section 5. Finally, Section 6 concludes and discusses some of the caveats of this study.

## 2 Description of regimes

### 2.1 Definition of climate regime

The term climate mitigation regime (or climate change agreement) is defined here as a set of rules that specify international commitments between countries to reduce greenhouse gas emissions. A regime can be characterised by a *certain goal*, a set of rules that determine *participation* and a *defined form of action* (Gupta et al., 2007).

For many climate regimes, the *goal* is to avoid dangerous climate change, most often specified top-down as a long-term greenhouse gas concentration target or corresponding global emission target, after which certain rules for allocating emission allowances or reduction requirements are applied. By contrast, in a bottom-up approach the emission allowances are put forward by regions without a predefined global reduction effort or global emission cap. The climate change problem can be defined as a property-sharing issue, in which case emission rights are allocated (*resource sharing*). In a *burden sharing* approach, the differentiation of commitments focuses on allocating reduction efforts. An important difference between these approaches is that with resource sharing surpluses in emission allowances (i.e. emission allowances are projected above baseline emission levels) are possible, while with burden sharing this is not the case.

The *participation level* relates to the number of countries that actively participate in the prescribed actions. A distinction can be made between immediate, full participation regimes and gradual participation regimes. In the first group, all countries join a grand scheme of emission allocation, while in the second group participation of a country depends on certain participation thresholds. These thresholds can be indicators for equity principles, like responsibility and capability. Immediate, full participation ensures that global abatement costs are minimised as marginal abatement costs are equalised (if emissions trading is allowed). The motivation for gradual participation regimes is that countries should only join in international climate policy once their economic status reaches a certain level. This not only ensures that there will be less economic burden for poorer countries, but also that participating countries have sufficient institutional capacity to ensure a functioning international carbon market.

The *prescribed actions* vary widely. Many regimes include explicit binding emission reductions, but other regimes are more flexible, as they include relative or dynamic targets or non-binding targets.

## 2.2 Classification of climate regimes

Regimes can be classified according to the equity principle on which they are based. These principles refer to general concepts of distributive justice or fairness. Clearly, since no globally shared interpretation of equity exists, regimes are based on many different principles, and hence, many attempts of classification have been made as well (see e.g. Ringius et al., 2002; Rose et al., 1998). Den Elzen et al. (2003) distinguish four main types of equity principles:

1. *Egalitarian*: i.e. all human beings have equal rights in the ‘use’ of the atmosphere.
2. *Sovereignty and acquired rights*: all countries have a right to use the atmosphere, and current emissions constitute a ‘status quo right’.
3. *Responsibility/polluter pays*: the greater the contribution to the problem, the greater the share of the user in the mitigation or economic burden.
4. *Capability*: the greater the capacity to act or ability to pay, the greater the share in the mitigation or economic burden.

Classifying the different regimes for comparison can also be done by their characteristics: the ambition level, the participation level or the form of prescribed actions. We here build upon the categorisation of climate regimes put forward in Hof et al. (2009), grouping regimes on the basis of participation level. The first group consists of regimes in which all countries are fully included with absolute emission targets from the start (immediate, full participation). The second group consists of regimes in which gradually more countries are included, based on a predefined criterion or a combination of criteria (gradual participation). The third group consist of regimes in which only part of the world is included. As most often these regimes exclude India and China, this group of fragmented regimes is not included in this study. Within each of these groups, one can distinguish regimes that use a global emission gap and those that do not use such a cap.

## 2.3 Description of included regimes

This paper focuses on regimes that play a major role in scientific literature, and regimes that are oriented at developing countries. We therefore excluded regimes of which only very few studies were available, like Multicriteria (MCC) (Vaillancourt et al., 2008; Vaillancourt and Waaub, 2006), Global Compromise (GC) Müller et al. (2009), Horizontal/Vertical Equity Rose et al. (1998), Emission Intensity (EI) (Blanchard, 2002) and Ability to Pay (AtP) (Böhringer and Löschel, 2005; Jacoby et al., 2008). Table 1 shows an overview of the regimes that are included in this paper, as well as the abbreviations that will be used throughout this study. A more elaborate selection of regimes is analysed in van Ruijven et al. (2010). We did not include regimes on cumulative per capita approaches (such as Ding et al., 2009; Messner et al., 2010) in the comparison of regimes, due to a lack of comparable information in these studies. However, we discuss these approaches in Section 5.1 on Chinese literature.

### 2.3.1 Immediate, full participation regimes

In the Contraction and Convergence (C&C) regime (Meyer, 2000), all countries participate with quantified emission targets. In a first step, countries agree on a path of future global emissions that leads to an agreed long-term stabilisation level for greenhouse gas concentrations (‘Contraction’). In a second step, the targets for individual countries are set so that per capita emissions converge from the current level of the country to a level equal for all countries within a convergence period

**Table 1:** Overview and brief description of regimes included in this study

<b>Name</b>	<b>Abbreviation</b>	<b>Short description</b>
<b>Immediate, full participation</b>		
<i>Regimes with a global emission cap</i>		
Contraction & convergence	C&C	Emission targets based on a convergence of per capita emission levels under a contraction of the global emission level
Grandfathering	GF	Distribute emission allowances in proportion to current emissions
Equal per capita allocation	EqPC	Distribute emission allowances in proportion to population
Historical responsibility <sup>a</sup>	HR	Distribute emission allowances in proportion to the contribution of climate change over a certain period of time
<i>Regimes without a global emission cap</i>		
Triptych	TY	National emission targets based on sectoral considerations
Carbon tax	Tax	All countries agree to a common, international carbon tax
<b>Gradual participation</b>		
<i>Regimes with a global emission cap</i>		
Common but differentiated convergence	CDC	All countries' per capita emissions converge, but the convergence is differentiated in time
Income Distribution	ID	Distribute emission allowances in proportion to the share of rich or poor people in a country, with a participation threshold
Multi-stage	MS	Countries participate at different stages and with stage-specific types of targets
<i>Regimes without a global emission cap</i>		
South-North Dialogue	S-N	Countries participate in the system at different stages and with stage-specific types of targets

<sup>a</sup> The historical responsibility approach is placed under full participation, but there are also some applications of this approach with a participation threshold that could be placed under gradual participation.

(‘Convergence’). The convergence is calculated in a way that resulting global emissions follow the agreed global emission path. This regime is based on both the sovereignty and egalitarian equity principles, as first allowances are based on current emission levels but in time, equal emissions per capita is the dominant factor on which allowances are based. As the problem definition is based on resource sharing, some developing countries could be allocated more (surplus) emission allowances than their expected baseline emissions.

In a Grandfathering regime (GF), emission allowances are allocated on the basis of present day emissions and the relative share of allocations between countries remains constant. This regime is a direct outcome of the sovereignty principle. In theory, allocation of surpluses is possible, in particular for developed countries with declining baseline emission levels.

Equal per capita allocation of emission allowances (EqPC) is based solely on the egalitarian equity principle. An immediate start of allocating emission rights according to this approach implies that countries currently below global average emissions per capita would gain large excess emission rights. For countries with relatively high per capita emissions, on the other hand, very stringent targets would result. This allocation would therefore result in emission allowances being traded from developing to developed countries on a very large scale.

Historical responsibility (HR) regimes are based on the equity principle of responsibility and the

polluter pays principle. Historical responsibility is also often referred to as the Brazilian Proposal, since Brazil proposed in 1997 HR as a method to differentiate emission reduction targets between Annex I (developed) countries for the Kyoto Protocol (UNFCCC, 1997). The proposal suggested that reductions towards an overall emission ceiling were to be shared among individual countries proportional to their relative share of responsibility for climate change. This could be estimated based on their contribution to the increase of average global surface temperature over a certain period of time (den Elzen et al., 2005a). This requires a complex analysis to attribute countries' contributions to temperature change based on historical emissions (see e.g. Höhne et al., 2010). In general, HR implies that countries with a longer process of industrialisation and thus a longer record of greenhouse gas emissions will have a greater share of responsibility for emission reductions than countries, which industrialised later. If emissions from land-use change and forestry are taken into account, also some developing countries would have a high responsibility (see, e.g. Baumert et al., 2005; den Elzen et al., 2005a; Höhne et al., 2010; UNFCCC, 1997). This regime differs from the previous ones in that the problem definition is based on burden sharing instead of resource sharing.

The Triptych (TY) (Groenenberg et al., 2004) approach is a bottom-up sectoral approach to distribute emission reductions among countries. It originally covered three sectors (the heavy industry sector, the power sector and the domestic sector) and was later extended to include also process emissions from industry, agriculture, waste and land-use change and forestry. Emissions of the sectors are treated differently: For the power and industry sector, a growth in the physical production is assumed together with an improvement in production efficiency. For the domestic sector, convergence of per-capita emissions is assumed. For the remaining sectors similar rules are applied. The allowances of the sectors are added up to a national allowance for each country (i.e., no sectoral targets are set to allow countries the flexibility to pursue any cost-effective emission reduction strategy).

Finally, one of the most straightforward proposals for future climate policy is a global uniform carbon tax (Tax) (Nordhaus, 2006, 2010). This approach leads to the global equalisation of marginal abatement costs. Hence, a cost efficient reduction of emissions is ensured even without emissions trading. Most proposed taxes increase progressively over time, in order to reduce emissions in a cost-effective way. A carbon tax regime has the advantage of a relatively high certainty on costs, but has relatively low certainty on the amount of emission reduction. An important disadvantage is that given the relative importance of the energy sector at low levels of development costs might be higher in developing countries. There are methods to deal with this, but at the costs of the simplicity of the approach.

### **2.3.2 Gradual participation regimes**

The Common but Differentiated Convergence (CDC) regime (Höhne et al., 2005, 2006) is an alternative, staged implementation of per capita convergence regimes. In this approach, developed countries' per capita emission allowances converge within a certain time period (e.g. from 2010 to 2050) to an equal level for all countries. Individual developing countries' per capita emissions also converge within 40 years to the same level but convergence starts from the date when their per capita emissions reach a certain percentage threshold of the (gradually declining) global average. Developing countries that do not pass this percentage threshold do not have binding emission reduction requirements. Either they take part in the clean development mechanism (CDM) or they voluntarily take on "positively binding" emission reduction targets. The CDC approach aims at equal per capita allowances in the long run. However, many developing countries have more time to develop without emission reduction requirements. Developing country participation is conditional to reductions

made in developed countries through the gradually declining world average threshold.

Two proposed regimes allocate emission allowances on the basis of income distribution within countries (ID) (Baer et al., 2008; Chakravarty et al., 2009), which can be seen as an advanced variation on the principle of Ability to Pay. The proposals for income distribution regimes are framed in two different ways. First, the approach of Greenhouse Development Rights (GDR) (Baer et al., 2008) starts from the point that poor people (in developing countries) have a need for further development. In this approach, emission allowances are allocated on the basis of both responsibility and capability, with the latter being represented by a country's population share below a global poverty line. The second approach, by Chakravarty et al. (2009), starts from the opposite direction, as it allocates emission reductions according to "high emitting individuals" in a country. Population above a certain income threshold is a dominant parameter in this equation.

In the Multi-stage regime (MS) (Berk and den Elzen, 2001; den Elzen et al., 2006), countries follow consecutive stages with different commitments. For instance, the first stage could involve no commitments, the second stage could involve emission intensity targets and the third stage could involve absolute emission reduction targets (e.g. based on per capita convergence). Graduation of countries to the next stage can, for instance, be dependent on income levels (GDP per capita), average per capita emissions relative to the global average or a combination of these two. The Multi-stage approach is rather flexible as the number of stages, the targets in the different stages and the graduation criteria can vary between studies. Model outcomes critically depend on the time when large countries such as China and India enter the system.

The South-North Dialogue proposal (S-N) (den Elzen et al., 2007; Ott et al., 2004) can be seen as a developing country alternative to the Multi-stage regime. This approach includes differentiated obligations for different classes of developing countries. In this proposal, developing countries are divided in newly industrialised countries, rapidly industrialising developing countries, least developed countries and "other" developing countries. All these groups have different emission reduction objectives. Least developed countries and other developing countries have no reduction targets, rapidly industrialising developing countries have absolute emission limitations if funding is provided by developed countries and newly industrialised countries have absolute emission limitation or reduction targets.

## **3 Methodology**

### **3.1 Studies included in the assessment**

We collected data from many different studies to assess the different regimes (see Table 2). We assessed baseline emissions, emission allowances, emissions under climate policy, costs or economic impact and the peaking year of emission allowances. Moreover, global indicators on economic impacts and direct costs were collected. Comparing these indicators between regimes and studies is not an easy task. There are a number of reasons for this: (i) there is a bias in literature towards certain regimes, (ii) studies use different regional definitions, (iii) different timescales are used in studies, (iv) different measurements for reduction are used to assess emission allowances and (v) different measurements for costs are used.

#### **3.1.1 Literature bias**

While some regimes are analysed in many studies (such as C&C or MS), analysis of other regimes is scarce (e.g. S-N or Tax). This bias in literature towards certain regimes complicates the comparison



**Table 2:** Overview of studies and regimes analysed in this report

Studies	Allocation schemes	Concentration target
Baer et al. (2008)	ID	400 ppm CO <sub>2</sub> e
Berk and den Elzen (2001)	C&C, HR, MS	450 ppm CO <sub>2</sub>
Blanchard (2002)	C&C, EI, HR	550 ppm CO <sub>2</sub>
Bode (2004)	HR	450 ppm CO <sub>2</sub>
Boeters et al. (2007)	MS	450 ppm CO <sub>2</sub> e
Böhringer and Helm (2008)	C&C, EqPC	550 ppm CO <sub>2</sub> e
Böhringer and Löschel (2005)	AtP, GF	550 ppm CO <sub>2</sub> e
Böhringer and Welsch (2004)	C&C	550 ppm CO <sub>2</sub> e
Böhringer and Welsch (2006)	C&C, EqPC, GF	550 ppm CO <sub>2</sub> e
Chakravarty et al. (2009)	ID	400 ppm CO <sub>2</sub>
Criqui et al. (2003)	C&C, MS	550, 650 ppm CO <sub>2</sub> e
den Elzen and Lucas (2005)	AtP, C&C, EI, GF, HR, MS, TY, CSE, MC, GC	550, 650 ppm CO <sub>2</sub> e
den Elzen and Meinshausen (2006)	C&C, MS	400, 450, 500, 550 ppm CO <sub>2</sub> e
den Elzen et al. (2005b)	C&C, HR, MS	550, 650 ppm CO <sub>2</sub> e
den Elzen et al. (2007)	S-N	400, 450, 500, 550 ppm CO <sub>2</sub> e
den Elzen et al. (2008a)	TY	450 ppm CO <sub>2</sub> e
den Elzen et al. (2008b)	C&C, MS	450, 550 ppm CO <sub>2</sub> e
Ekholm et al. (2010)	C&C, MS, TY	450, 550 ppm CO <sub>2</sub> e
Groenenberg et al. (2004)	TY	450 ppm CO <sub>2</sub>
Hof and den Elzen (2010)	C&C, MS, CDC	550, 620 ppm CO <sub>2</sub> e
Hof and den Elzen (2010)	TY	500 ppm CO <sub>2</sub> e
Höhne and Moltmann (2008)	C&C, ID, MS, CDC	450, 550 ppm CO <sub>2</sub> e
Höhne and Moltmann (2009)	ID, MS, CDC	80% below 1990 levels by 2050
Höhne et al. (2005)	C&C, MS, CDC, TY	400, 450, 550 ppm CO <sub>2</sub> e
Höhne et al. (2006)	C&C, CDC	550, 650 ppm CO <sub>2</sub> e
Höhne et al. (2007)	C&C, EI, MS, CDC, TY	450, 550 ppm CO <sub>2</sub> e
Jacoby et al. (2008)	AtP, EqPC, GF	450 ppm CO <sub>2</sub> e
Knopf et al. (2009)	C&C, HR	450 ppm CO <sub>2</sub> e
Kuntzi-Reunanen and Luukkanen (2006)	C&C	400 ppm CO <sub>2</sub>
Leimbach et al. (2010)	C&C, EI, MS	415 ppm CO <sub>2</sub>
Leimbach (2003)	C&C	450 ppm CO <sub>2</sub>
McKibbin and Wilcoxon (2009)	EqPC, GF	550 ppm CO <sub>2</sub> e
Nordhaus (2006, 2010)	Tax	430, 500 CO <sub>2</sub>
Persson et al. (2006)	C&C, EqPC	450 ppm CO <sub>2</sub>
Peterson and Klepper (2007)	C&C, GF, Tax	550 ppm CO <sub>2</sub> e
Rose et al. (1998)	EqPC, GF, MC, Hor, Vert	20% below 1990 from 2010 onwards
van Vuuren et al. (2009)	Tax	450 CO <sub>2</sub> e
WBGU (2003)	C&C	400, 450 ppm CO <sub>2</sub>

of different regimes: what seems a difference between regimes might well be a difference between studies or models. On the other hand, for widely analysed regimes it is possible to study the impact of different regime parameters, such as the stringency of the goal or convergence year. A similar problem comes from overrepresentation of certain models in published literature, especially the FAIR model (den Elzen and Lucas, 2005) and the EVOC model (Höhne et al., 2003).<sup>1</sup>

### **3.1.2 Regional definitions**

Differences in regional definition are another issue for comparison between studies. Not all studies in literature report regional emissions and reduction targets for India and China explicitly. Some studies (e.g. Bollen et al., 2004; Manne et al., 1995) do not disaggregate Asia into smaller regions and are therefore not included in this study. If results are reported for regions where China or India is the dominant country (e.g. East Asia and South Asia), we included results of these studies in our assessment. In these cases, it should be noted that the absolute figures for baseline emissions and allowance are biased upward.

### **3.1.3 Timescales**

The time resolution across studies did not always match – in general we aimed to get data for 2020, 2030 and 2050, but some studies only had model evaluations in other years. In these cases, the results were compared with nearest year to 2020, 2030 or 2050.

### **3.1.4 Emission measurement**

Emissions are reported as either CO<sub>2</sub> only or as CO<sub>2</sub>-equivalent (Kyoto gases), and studies report different sources (energy, industry, land-use). For comparison, we therefore expressed all emission (allowance) reductions relative to baseline and to the 2005 emission level, corrected for the regional definition and greenhouse gases included in the study. It should be noted that the observed 2005 emission level that we used might deviate considerably from the numbers actually used in the study (in case 2005 emissions were still unknown). In these cases, the results may be inconsistent with the reductions compared to baseline of the study. For example, older studies tend to have lower baseline projections for China, and their 2020 projection might actually be equal to the observed 2005 values. Such studies could have 2020 allowances equal to 2005 emissions, but with no reduction below baseline. This would probably not have been the result if they used a more recent, higher, baseline projection. There is, however, no way how this can be solved.

### **3.1.5 Cost measurement**

Studies report very different cost measurements. The type of cost measurement is generally related to the type of model that is used in the study. Usually, general equilibrium models measure costs as losses of GDP, consumption or welfare compared to a baseline scenario without emission mitigation. Partial equilibrium models (mostly energy system models) measure costs as direct abatement costs, usually expressed as percentage of GDP. Costs even may include climate change damages or benefits of mitigating climate change (in our analysis only Nordhaus, 2010). Other differences in cost measurement are cumulative costs vs. costs in a particular year and discounted costs or not. Finally,

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<sup>1</sup>In general, much of the literature comes from the European research institutes. This also has a historical reason, as the EU adopted in 1996 the 2 degree climate target. This led to many burden-sharing studies from the EU, to analyse the countries' emission implications to meet this climate target. In addition, the issue of internal burden-sharing to allocate the overall EU reduction target across the EU Member states, already before the Kyoto Protocol, has triggered many burden-sharing studies as well.

**Table 3:** Key data of the economy, energy use and CO<sub>2</sub> emissions of India and China in 2005 compared to global levels (World Bank, 2009).

	China	India	Global
Population (billion persons)	1.30	1.09	6.46
GDP, MER (billion US \$ <sub>2000</sub> /yr)	1893	645	36610
GDP per capita, MER (US \$ <sub>2000</sub> /yr)	1452	589	5665
GDP, PPP (billion int \$ <sub>2005</sub> /yr)	5314	2445	56667
GDP per capita, PPP (int \$ <sub>2005</sub> /yr)	4076	2233	8769
Poverty (% population below 1.25 \$ <sub>PPP</sub> /day)	15.9	41.6	
Poverty (% population below 2 \$ <sub>PPP</sub> /day)	36.3	75.6	
Energy use (MTOE <sup>a</sup> /yr)	1700	538	11253
Energy use per capita (GJ/capita/yr)	54.8	20.7	72.9
CO <sub>2</sub> emissions (GtCO <sub>2</sub> /yr)	5.5	1.4	29.2
CO <sub>2</sub> emission intensity (kg CO <sub>2</sub> /US \$ <sub>2000</sub> )	2.9	2.2	0.8
CO <sub>2</sub> emissions per capita (tCO <sub>2</sub> /capita/yr)	4.3	1.3	4.5

<sup>a</sup> Million tons of oil equivalent

for some studies numbers had to be estimated by reading graphs, which obviously leads to some imprecision. Obviously, the absolute values of these different metrics cannot be directly compared. Therefore, we have instead focussed on the relative costs of regions compared to the global average costs as presented in the studies, irrespective of which measurement is used. We classified those after (but slightly different than) Hof et al. (2009) as: (1) 'no cost or gains', (2) 'costs lower than half of global average', (3) 'costs between half global average and global average', (4) 'costs above global average'. Earlier, van Vuuren et al. (2009) showed that the relative costs of different metrics reasonably correlate.

### 3.2 Current situation in India and China

Table 3 presents some major statistics on India and China in 2005 to provide some context to the discussions below (World Bank, 2009). Both countries have a large population, with a 20% and 17% share of the global population for China and India, respectively. China produces 5% of global GDP calculated in market-exchange rates (MER) (9% in purchasing power parity, PPP), while India produces 2% of global GDP in MER (4% in PPP). GDP per capita is well below the global average in both countries, with the Indian per capita GDP in fact being much lower than the Chinese. This difference is also reflected in the poverty situation of both countries. In India, more than 75% of population lives below 2 \$<sub>PPP</sub>/day, and almost 42% at less than 1.25 \$<sub>PPP</sub>/day. In China, these numbers are 36.3% and 15.9% of population below 2 and 1.25 \$<sub>PPP</sub>/day, respectively. China's economy is also more important globally in terms of energy use and CO<sub>2</sub> emissions, with resp. 15% and 19% of the global energy use and CO<sub>2</sub> emissions. In fact, per capita emissions of China approach the global average. The Indian economy has a share of nearly 5% in both energy use and CO<sub>2</sub> emissions.

### 3.3 Baseline scenarios

An important factor determining the outcomes of studies on future climate regimes are the assumed developments of population, income, technology, energy use and resulting emissions. Especially the relative growth of various regions plays an important role. However, most of the studies that focus on effort sharing only provide data on emissions, not on the other factors. Interestingly, many studies have baseline estimates for 2020 for China and India that are below their actual emissions in 2005. This is mostly explained by the accelerated growth after 2000, which has not been factored in by models which are calibrated on data collected prior to the period of high income and emissions growth. This unexpected growth is also reflected in the IEA forecasts for 2020 of different years. In

2004, the IEA projected the Chinese emissions for 2020 to be 5700 MtCO<sub>2</sub>; the latest projection is in fact 9990 MtCO<sub>2</sub> (see also Blanford et al., 2009, for the need to update emission projections for China). The rapid Chinese growth does have implications for emission reduction projections. While Chinese emissions have been growing rapidly, this has been partly on the basis of exports (Pan et al., 2008). In other regions other trends can be noticed, the implications of these changes for mitigation regimes are discussed in Section 4.

India's emissions are at a lower level than China, but the projected growth of emissions in India is generally faster than in China. In contrast to China, most studies further assume that the growth rate remains high for a longer period and may even increase, and also population projections are very different.<sup>2</sup> For India, the difference between CO<sub>2</sub> and total greenhouse gas emissions is an important one as the contribution of non-CO<sub>2</sub> greenhouse gases emissions are about the same as CO<sub>2</sub> emissions. This is mainly caused by a large contribution of methane from agriculture and livestock (Garg et al., 2004).

## 4 Results

This section discusses and compares the above presented regimes and proposals for India and China with respect to three main aspects: the reduction below baseline, the timing of peaking in emission allowances and the economic impacts and costs. Finally, we discuss some other relevant issues, like baseline uncertainty and timing of emission reduction.

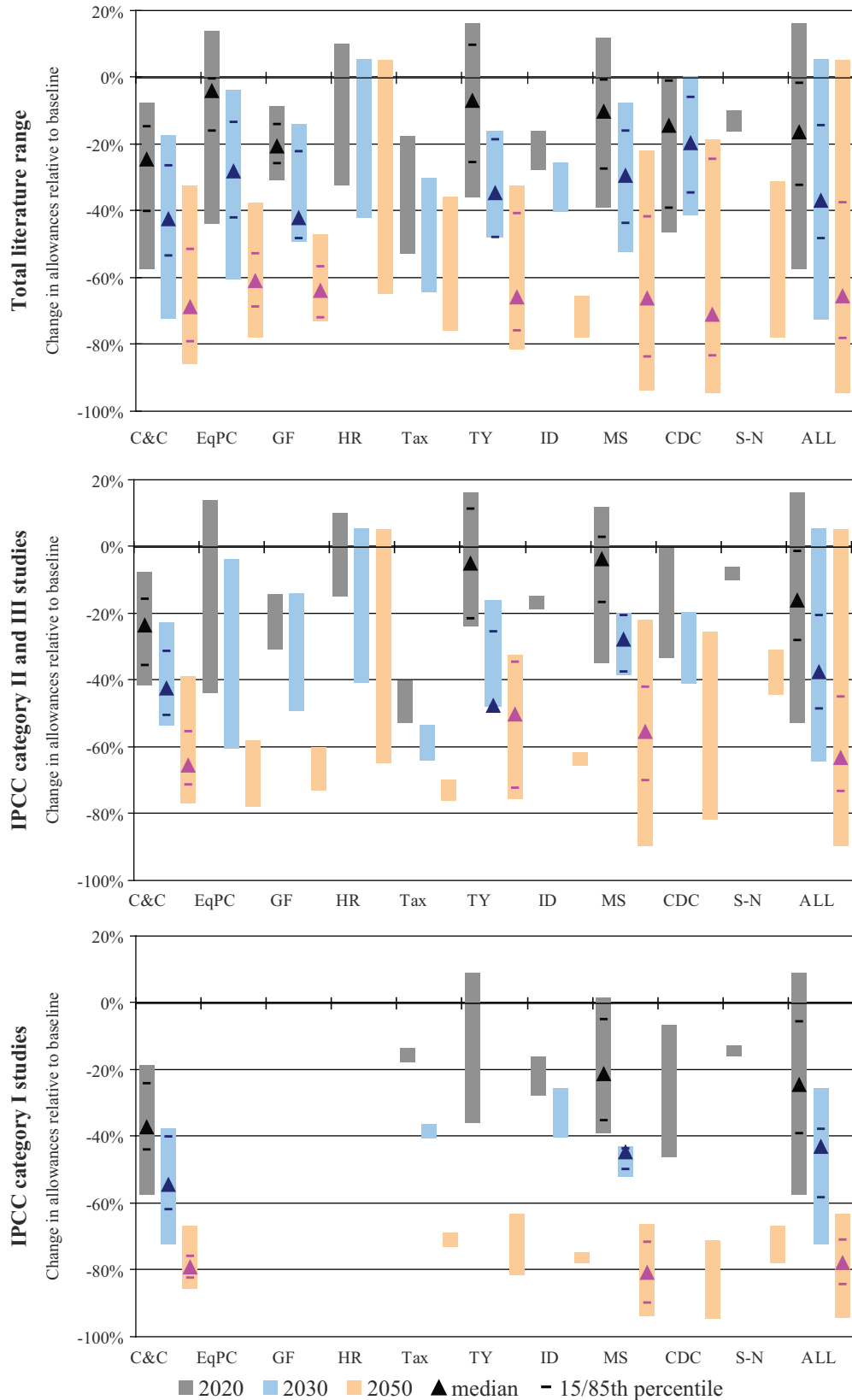
### 4.1 Emission (allowance) reduction targets

The ranges of emission reduction targets (in terms of allowances) for China and India for the climate policy regimes are shown in Figures 1–4. Figure 1 and Figure 3 show the change in emission allowances relative to baseline. In these graphs, a value of zero indicates that allowances are equal to baseline emissions, positive values represent a surplus of emission allowances and negative values an emission reduction requirement. Figure 2 and Figure 4 show emission allowances relative to the observed 2005 emissions, corrected for the regional definition and greenhouse gases included in the study. In these graphs, the value zero indicates that allowances are equal to 2005 emissions and positive and negative values represent emissions above or below 2005 values, respectively.

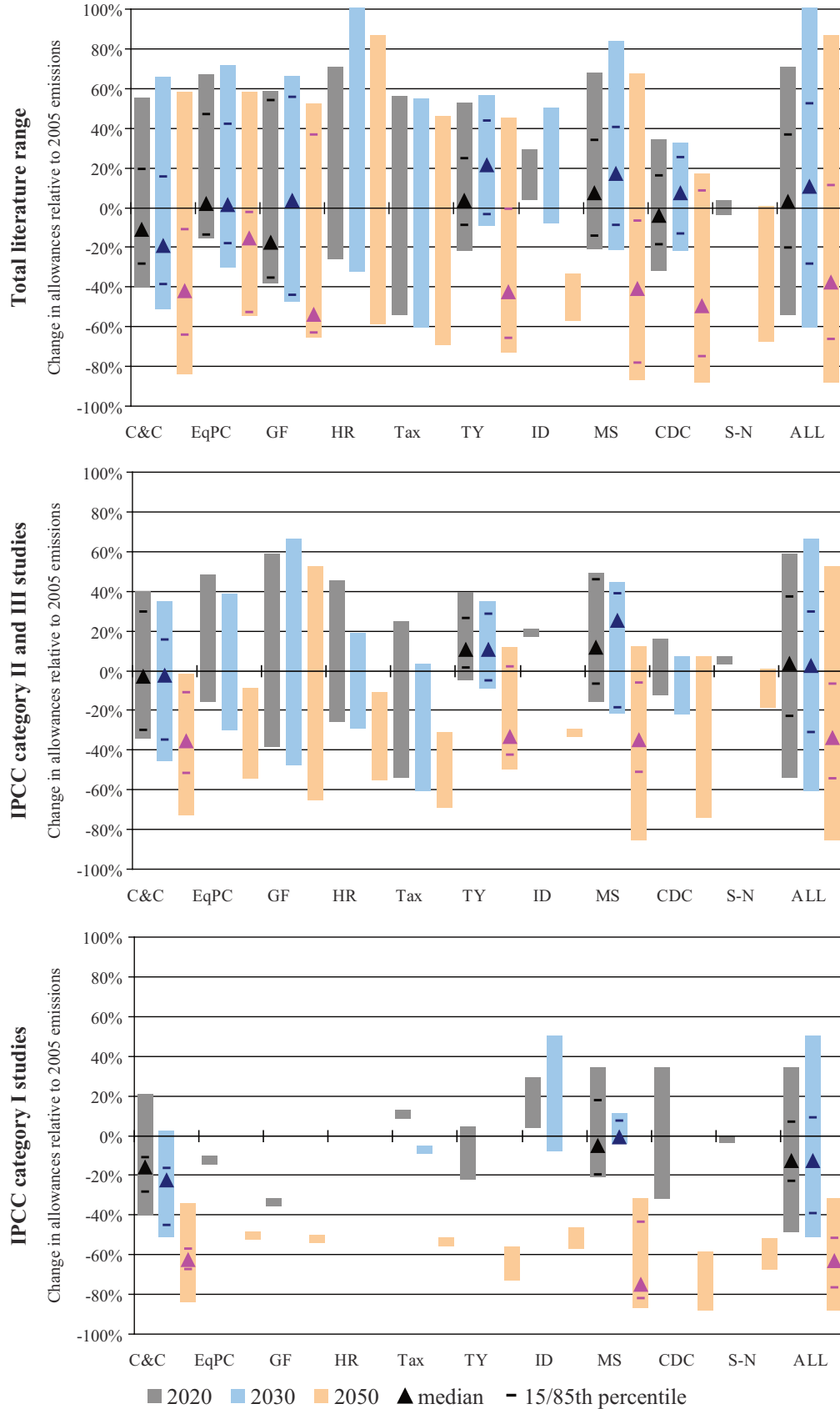
In each figure, the coloured areas reflect the total range, within which we have indicated the median value and the 15<sup>th</sup> and 85<sup>th</sup> percentile of the results of the studies. The latter is mainly to indicate whether wide ranges are caused by outliers, or whether there is wide variation across the total literature. We only applied the statistical analysis (median, 15<sup>th</sup>–85<sup>th</sup> percentile range) if at least 8 analyses were available. Each figure contains three graphs: the upper graph reflects the total range of literature analysed in this study, and the middle and lower graphs only include studies with a certain stabilisation target, as categorised by the IPCC (Metz et al., 2007). Category I contains scenarios aiming for radiative forcing of less than 3 W/m<sup>2</sup>, or a CO<sub>2</sub>-equivalent concentration below 490 ppm CO<sub>2</sub>-eq and categories II and III aim for 3–4 W/m<sup>2</sup> or 490–590 ppm CO<sub>2</sub>-eq. We clustered categories II and III because very few studies contain category II targets.

<sup>2</sup>Interestingly, older studies such as Berk and den Elzen (2001); Blanchard (2002) and Rose et al. (1998) are at the upper range of the estimates for India, but the lower end for China. This can be seen as an indicator that China exceeded the growth expectations while India remained short of them.

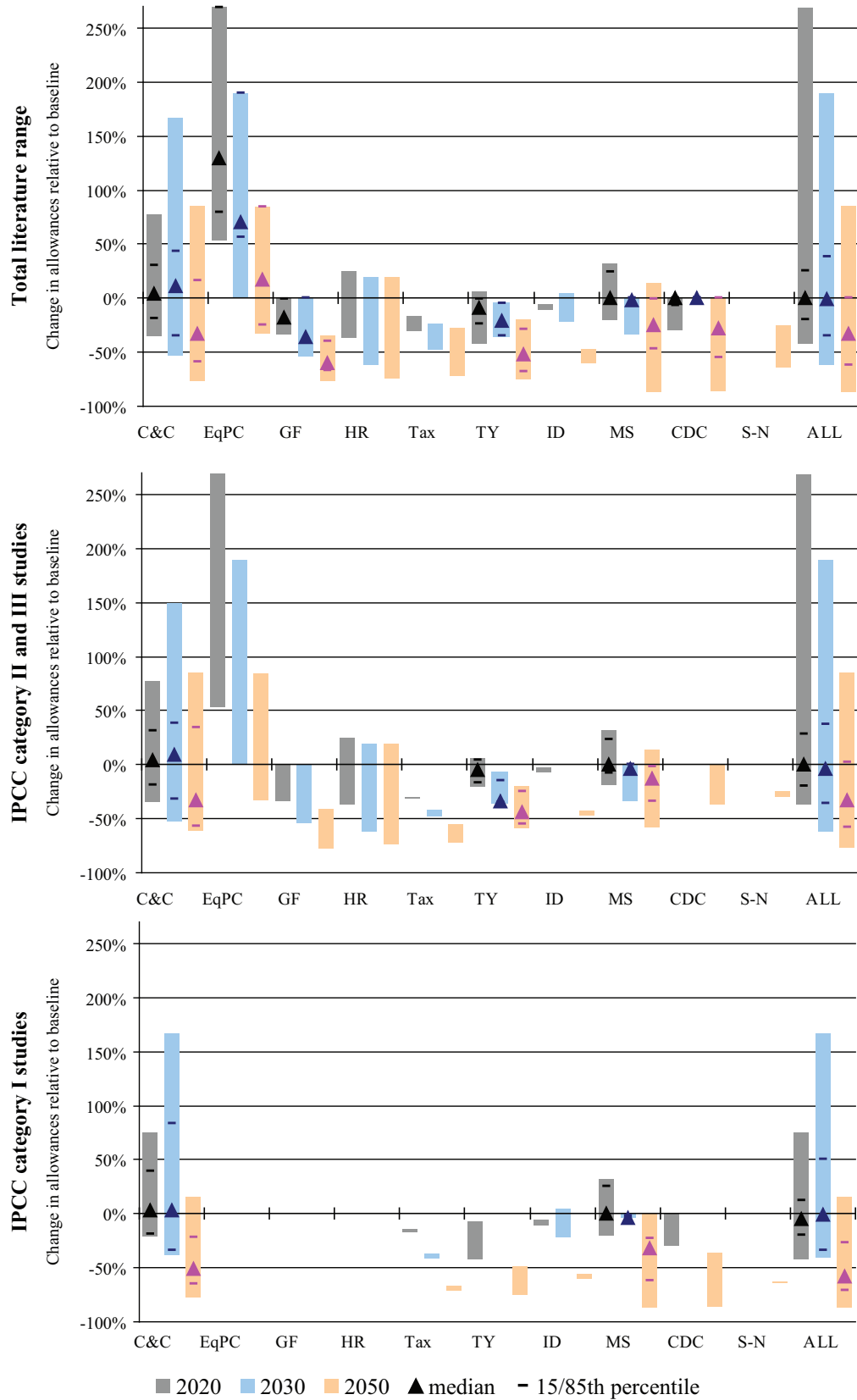
**Figure 1:** Emission allowances relative to baseline for China for several regimes for the total range of reviewed literature, IPCC category I and II&III studies. Statistical indicators are only shown if more than eight studies were involved.



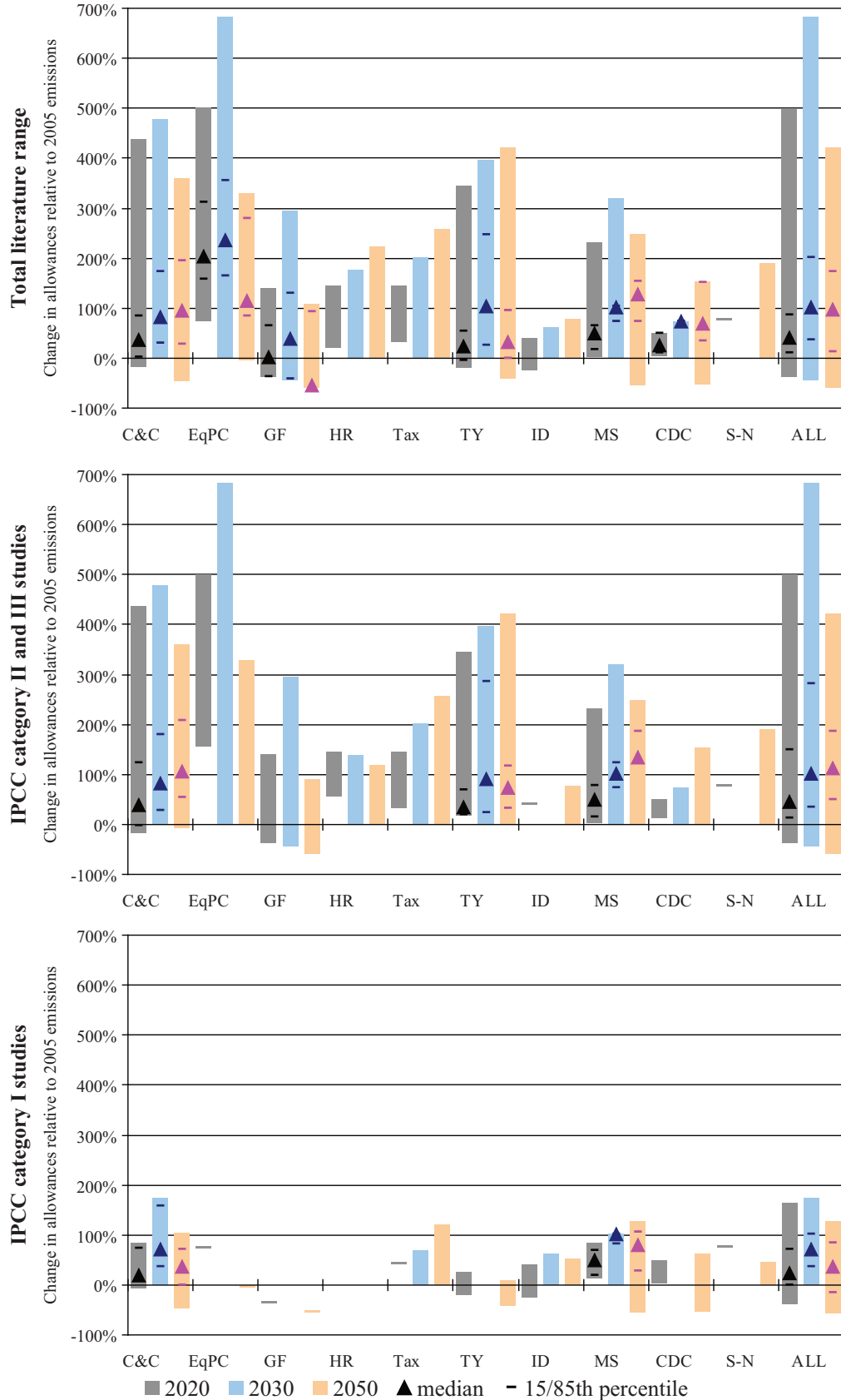
**Figure 2:** Emission allowances relative to observed 2005 emissions for China for several regimes for the total range of reviewed literature, IPCC category I and II&III studies. Statistical indicators are only shown if more than eight studies were involved. Note that we related allowances to historically observed 2005 emissions. The individual studies (may) use different levels of 2005 emissions, and hence, lead to different results.



**Figure 3:** Emission allowances relative to baseline for India for several regimes for the total range of reviewed literature, IPCC category I and II&III studies. Statistical indicators are only shown if more than 8 studies were involved.



**Figure 4:** Emission allowances relative to 2005 emission levels for India for several regimes for the total range of reviewed literature, IPCC category I and II&III studies. Statistical indicators are only shown if more than 8 studies were involved. Note that we related allowances to historically observed 2005 emissions. The individual studies (may) use different levels of 2005 emissions, and hence, lead to different results.





#### 4.1.1 Results for China

Generally, across all regimes and stabilisation levels, the figures show a fairly diverse picture for China. In 2020, allowances of the 15<sup>th</sup> and 85<sup>th</sup> percentile of all literature are between zero and 35% below baseline, or +40 to –20% compared to the observed 2005 level. For IPCC category II&III scenarios, the reduction over all regimes is zero to 30% below baseline (or +40 to –20% on 2005 levels), and for IPCC category I scenarios it is 5 to 40% below baseline (or +5 to –20% compared to 2005). For 2050, the 15<sup>th</sup> and 85<sup>th</sup> percentile of all literature is between about 40 and 80% below baseline or +12 to –66% compared to 2005 emissions. The stringent climate target scenarios are on the low side, with 70–80% reduction below baseline (or 50–80% below 2005). It should be noted that here our earlier remark on the impact of fast emission growth in China in the early 2000s may play a role; current studies might yield different results (see Section 4.4).

It is important to note that low stabilisation scenarios have only been evaluated in the literature for a small selection of studies and regimes. Still, all regimes show for 2050 a reduction of 70–80% below baseline for China in order to reach low stabilisation levels (or 60% below 2005). For the 2020–2030 period, there are very relevant differences between regimes for low stabilisation levels. For instance, the resource sharing approaches (i.e. C&C, Grandfathering, or Equal PC) would involve significant reductions for China – while the burden sharing approaches (i.e. Multi-stage, Income Distribution and a global carbon tax) would require lower reductions. This is because China’s per capita emissions are very close to the world average (see Section 3.2), leaving little flexibility in resource sharing approaches. Burden sharing approaches have generally more flexibility to account for China’s particular situation.

As can be expected, the category II&III climate targets require less stringent targets for China. The broader ranges for these targets can be explained by the fact that more studies have evaluated regimes for these targets. Nevertheless, also here, the difference between the regimes is mainly relevant for the shorter term. By 2050, reductions vary between 40–80% below baseline in all regimes. Regimes with the lowest reduction effort for China in the short term seem to be HR, MS, CDC, S-N and TY. GF, C&C and Tax require generally high emission reductions in the short term. The suggestion in Figures 1 and 2 that a Tax regime leads to less emission reduction for China under low stabilisation scenarios, than under the IPCC category II&III studies seems not to be robust (and is a consequence of the limited amount of studies in this category).

#### 4.1.2 Results for India

For India, in 2020, emission reduction requirements of the 15<sup>th</sup> and 85<sup>th</sup> percentile of all literature are between +25 and –20% of the baseline, or between +10 and +90% compared to 2005. For IPCC category II&III scenarios, the reduction over all regimes is +30 to –20% of the baseline (or 30 to 150% above 2005 levels), and for IPCC category I scenarios it is +13 to –20% of the baseline (or zero to 70% above 2005 levels). For 2050, the 15<sup>th</sup> and 85<sup>th</sup> percentile of all literature is between zero and 60% below baseline or 18–185% above 2005 emissions. The range for the stringent climate target scenarios is 30–70% reduction below baseline (or +84 to –15% on 2005 levels).

The results also show that many regimes lead to surplus emission allowances for India. Because India has a smaller share in global emissions than China, and its per capita emissions are also much lower than those of China, there is generally more flexibility in reaching low stabilisation levels. This leads to a much wider range of results across regimes and even within regimes. For instance, for C&C allowances range from a surplus of 50% to 50% reduction below baseline in 2050. For the low stabilisation scenarios, C&C also shows surpluses in 2020. The CDC, S-N, Income Distribution and Triptych approaches instead show small reductions. Grandfathering requires clearly most reductions

for India (see category I), as it is the only regime with allowances below the 2005 level in 2020. In the category II and III scenarios, C&C and EqPC allow considerable surpluses, whereas Grandfathering requires most efforts here as well. The gradual participation regimes seem for India on the middle of the road, not allowing as much surpluses as EqPC, but not requiring fierce reductions either.

## 4.2 Emission allowance peaking

Closely connected to the issue of the emission reduction requirements for China and India is the question on when emissions should peak in these countries. This issue has been discussed for the global emissions path in order to reach low carbon goals or when the need for emission reduction in developing and developed countries is compared (see, e.g. Fisher et al., 2007).<sup>3</sup> On country level, less information has been published, but still the issue plays an important role in discussions. In the run-up to COP 15 in Copenhagen, Chinese officials announced that its domestic emissions could peak in 2050, making this figure subject to political discussion.<sup>4</sup> In the follow-up, several Chinese think tanks have presented studies indicating that an earlier peak between 2020 and 2040 would be feasible with the necessary policies (CAS, 2009; ERI, 2009). India has not (yet) discussed peaking of emissions.

It should be noted that we focus here on emission allowance peaking, rather than emissions peaking. Most regimes allow emission trading, differentiating emissions from allowances.

The peaking year of emission allowances depends strongly on the regime. As shown in Section 3, a C&C regime generally leads to emission allowances below baseline levels for China, but could lead to emission allowances higher than projected baseline emissions for India. This could lead to a peak in emission allowances for India in the convergence year and for China soon after their participation in 2020, if the convergence level in per capita emissions is chosen sufficiently low. Because both economies are growing fast but have contributed relatively little to global emissions in the past, HR regimes would start with high emissions allocations but these would decline over time, as their share in global emissions increase fast after 2005 (also due to declining shares of the developed countries).

Figure 5 and Figure 6 show an overview of the peaking years for allowances in the studies that are included in this report.<sup>5</sup> Most studies find that in China, allowances peak before 2025, while in low stabilisation scenarios this is even before 2020. For India, in low stabilisation scenarios the average peak in allowances is around 2030–2045 and for higher concentration targets even later. Again, it should be noted that the peaking year for allowances might differ from the peaking year in domestic emissions. This is clearly the case for EqPC regimes, where allowances peak directly at the beginning of the regime, though at levels far above baseline emissions.

## 4.3 Economic impact & costs

Table 4 shows the costs for China for several regimes relative to the global average costs as share of GDP. It shows the percentages of studies that find 1) ‘no cost or gains’, 2) ‘costs lower than half of global average’, 3) ‘costs between half global average and global average’, 4) ‘costs above global average’.

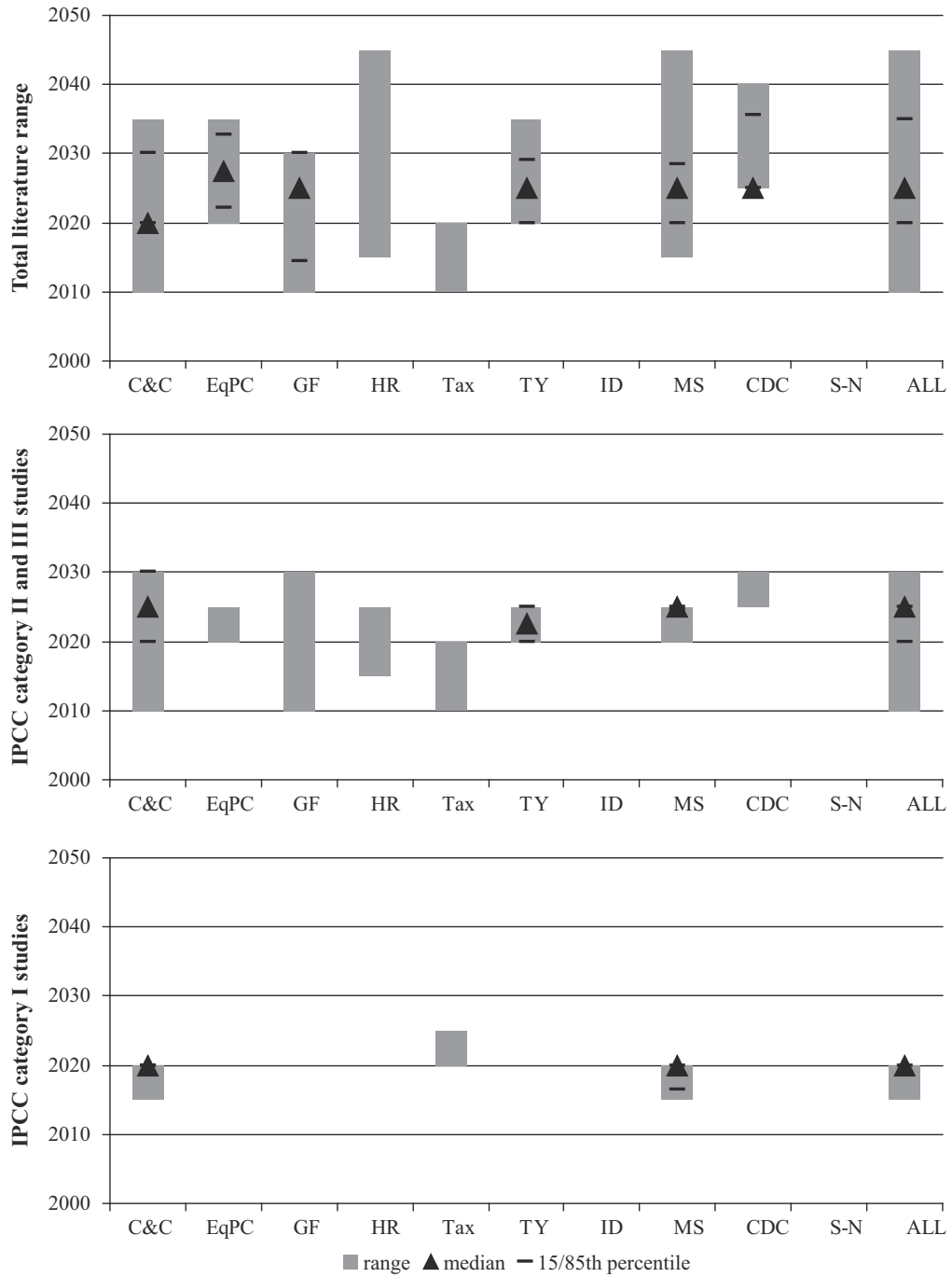
It is clear that economic impacts and costs for China vary widely among different regimes, but also across studies and measurements. The costs strongly depend on the amount of allowances that

<sup>3</sup>Much of this discussion comes from the timing of emission reductions and the trade off between an early start with higher abatement costs in the near future and delayed action which would call for more mitigation effort at a later phase. The parameter of the peak year could hence be seen as a simple indicator on when emission reductions should take place.

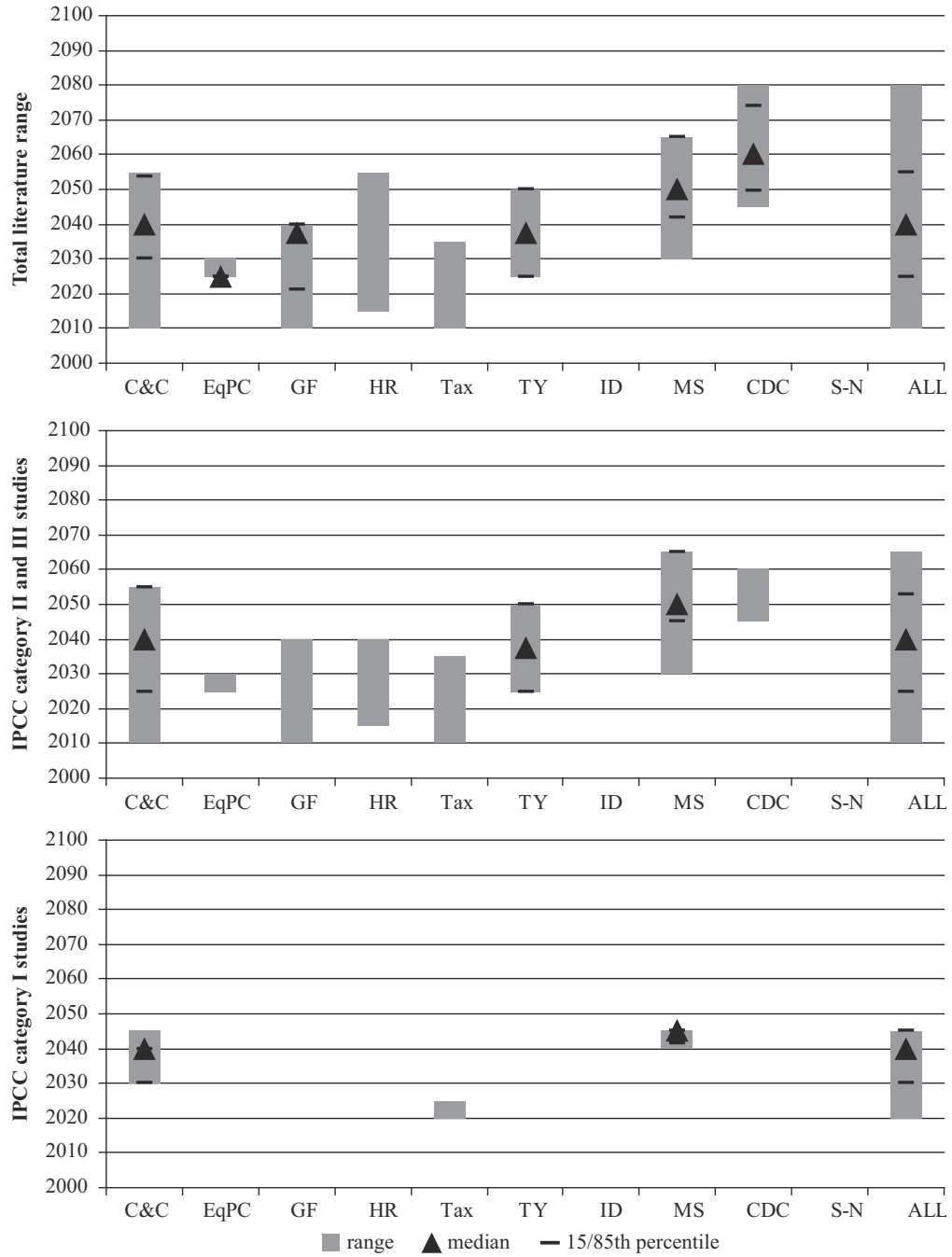
<sup>4</sup>See e.g. <http://www.reuters.com/article/idUSTRE57E0BA20090815>.

<sup>5</sup>The peaking year cannot be derived for all studies, which is clearly limiting the number of studies included in this part of the analysis.

**Figure 5:** Overview of allowance peaking years for China in several regimes for the total range of reviewed literature, IPCC category I and II&III studies. Statistical indicators are only shown if more than eight studies were involved.



**Figure 6:** Overview of allowance peaking years for India in several regimes for the total range of reviewed literature, IPCC category I and II&III studies. Statistical indicators are only shown if more than eight studies were involved.





**Table 5:** Indian costs relative to global average costs. The cost categories are no costs or gains (0), costs lower than half of global average (1), costs below global average (2), costs above global average (3).

Regimes	Total literature range				IPCC category II + III studies				IPCC category I studies					
	relative cost category				relative cost category				relative cost category					
	0	1	2	3	0	1	2	3	0	1	2	3	studies	
<b>2020</b>														
C&C	89%	11%	0%	0%	18	90%	10%	0%	0%	10	83%	17%	0%	6
EqPC	75%	0%	25%	0%	4	100%	0%	0%	0%	2	100%	0%	0%	1
GF	33%	0%	0%	67%	6	25%	0%	0%	75%	4	0%	0%	100%	1
HR	100%	0%	0%	0%	2	100%	0%	0%	0%	1	0%	0%	0%	0
ID	0%	0%	50%	50%	4	0%	0%	50%	50%	2	0%	0%	100%	1
MS	100%	0%	0%	0%	9	100%	0%	0%	0%	4	100%	0%	0%	4
Tax	0%	100%	0%	0%	1	0%	0%	0%	0%	0	0%	100%	0%	1
TY	100%	0%	0%	0%	20	100%	0%	0%	0%	10	100%	0%	0%	8
All	81%	5%	5%	9%	64	82%	3%	3%	12%	33	82%	9%	0%	22
<b>2030</b>														
C&C	92%	8%	0%	0%	12	86%	14%	0%	0%	7	100%	0%	0%	2
EqPC	100%	0%	0%	0%	3	100%	0%	0%	0%	2	0%	0%	0%	0
GF	50%	0%	0%	50%	4	33%	0%	0%	67%	3	0%	0%	0%	0
HR	100%	0%	0%	0%	3	100%	0%	0%	0%	1	0%	0%	0%	0
ID	0%	25%	25%	50%	4	0%	0%	50%	50%	2	0%	0%	100%	1
MS	100%	0%	0%	0%	1	0%	0%	0%	0%	0	0%	0%	0%	0
Tax	0%	0%	0%	0%	0	0%	0%	0%	0%	0	0%	0%	0%	0
TY	100%	0%	0%	0%	9	100%	0%	0%	0%	5	100%	0%	0%	2
All	81%	6%	3%	11%	36	75%	5%	5%	15%	20	80%	0%	0%	5
<b>2050</b>														
C&C	88%	8%	0%	4%	25	81%	13%	0%	6%	16	100%	0%	0%	7
EqPC	100%	0%	0%	0%	6	100%	0%	0%	0%	4	100%	0%	0%	1
GF	17%	0%	17%	67%	6	25%	0%	0%	75%	4	0%	0%	100%	1
HR	100%	0%	0%	0%	2	100%	0%	0%	0%	1	0%	0%	0%	0
ID	25%	0%	0%	75%	4	0%	0%	0%	100%	2	0%	0%	100%	1
MS	89%	11%	0%	0%	9	100%	0%	0%	0%	4	100%	0%	0%	4
Tax	0%	0%	0%	0%	0	0%	0%	0%	0%	0	0%	0%	0%	0
TY	100%	0%	0%	0%	19	100%	0%	0%	0%	10	100%	0%	0%	7
All	83%	4%	1%	11%	71	80%	5%	0%	15%	41	90%	0%	0%	21

can be traded internationally. Regimes with a (temporary) surplus of allowances obviously lead to gains (e.g. EqPC or Multi-stage) whereas others require domestic mitigation effort in the short term (e.g. C&C and Grandfathering). A similar pattern can be found in the sub-graphs for low stabilisation scenarios and category II&III scenarios, although the amount of studies for individual regimes is too limited for valid conclusions. Overall, economic impacts and costs for China are far below the global average in the short term, but approach the global average towards 2050. This pattern holds for the lower stabilisation scenarios as well. Other analyses, that looked towards the whole period 2000–2100, report higher costs for China, which can probably be explained from increasing costs in the second half of the century (Edenhofer et al., 2010).

For India, almost all studies and regimes show economic gains (Table 5). However, grandfathering and a global carbon tax are relatively costly regimes for India. Equal per capita would bring along the highest gains; Multi-stage, C&C, and Historical responsibility would also be economically attractive for India, although the range of the gains in relation to international costs has a significant spread. It is thus important for India that future climate policy is based on a *grand scheme* with global emission trading, in which potential gains can be realised. If future climate policy continues along the line of voluntary pledges, as happened in Copenhagen, it is hard to generate and monetise surplus emission allowances.

#### 4.4 China's recent emission growth and timing of reductions

The huge uncertainty in the baseline scenario leads to a large variation in the emission reduction requirements. Especially for China, the growth of emissions in recent years was faster than anticipated. The baseline projections of many studies for 2020 published before 2005 are actually below or only slightly above emission data from recent years. Therefore, we analyse a subset of studies with high baselines for China. High baselines were defined as those with emissions in 2020 being at least 30% higher than the observed 2005 values. This is roughly the baseline projection from recent Chinese national studies (ERI, 2009; UNDP, 2010).

Figure 7 compares the emission reductions of the high baseline studies with the total range of studies, expressed relative to 2005 or compared to baseline. Not surprisingly, in absolute terms the high baseline studies generally involve only the higher side of the total range. This is in line with the observation that Chinese growth has led to lower emission projections for developed countries, and hence, a larger share of future emissions can be allocated to China. Compared to baseline, mitigation efforts in the high-baseline group are slightly higher than the total literature. This is most clearly shown for the regimes with many studies (C&C and MS).

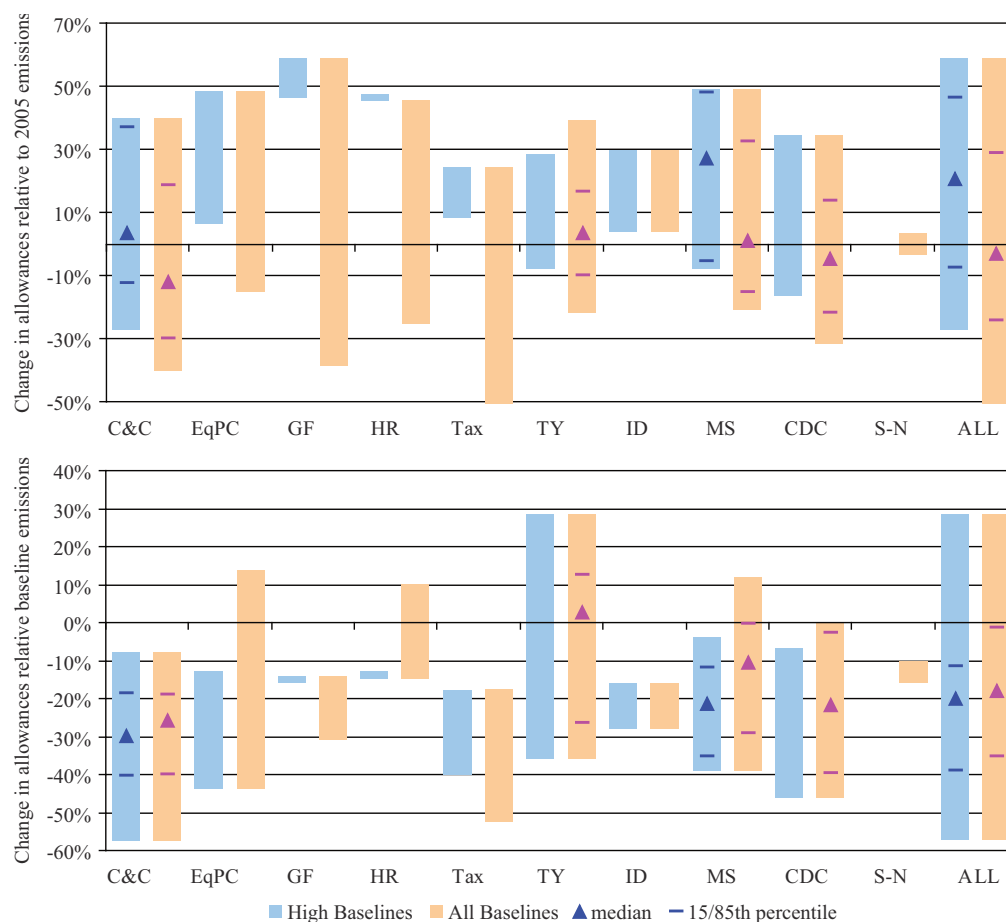
Generally, one can conclude that analysis of regimes on the basis of higher baselines of China, allow for more emissions in absolute terms, but involve similar efforts compared to the baseline, as the total range of studies.

## 5 Recent literature from China and India

### 5.1 Chinese proposals and considerations

As part of the Copenhagen accord, China submitted a mitigation action plan to the UNFCCC. This plan consists of reducing CO<sub>2</sub> emissions per unit of GDP by 40–45% by 2020 compared to 2005, increasing non-fossil fuels in primary energy consumption to around 15% and increasing forest coverage by 40 million ha and forest stock volume by 1.3 billion m<sup>3</sup> relative to 2005 levels (as analysed by e.g., den Elzen et al., 2011; Rogelj et al., 2010; UNEP, 2011; Zhang, 2011a).

**Figure 7:** Emission allowances of China compared to 2005 levels and compared to baseline for 2020 under different reduction regimes in IPCC category I, II and III scenarios, for all studies and a selection of studies with high baselines (emissions in 2020 at least 30% above observed 2005 levels). Statistical indicators are only shown if more than eight studies were involved.



Recently, two climate policy scenarios for China have been published. ERI (2009) explored the possibilities for low-carbon development in China under two scenarios: low-carbon and enhanced low carbon development. Both scenarios include a reduction of about 20% below baseline in 2020, increasing to 31% and 60% in 2050. The emission control and emission abatement scenarios of the UNDP (2010) China Human Development Report are slightly more ambitious, with 28% reduction below baseline in 2020 and resp. 41% and 66% in 2050. In the latter case, the underlying modelling study from Renmin University foresees rather fierce macro economic impacts, reaching up to 10% reduction of GDP compared to baseline.

Recent literature on effort-sharing regimes from Chinese authors focuses mainly on historical responsibility. While the Brazilian proposal is based on historical responsibility of countries, Chinese considerations focus on the concept of cumulative emissions per capita. Hu et al. (2009) determined the historical emissions of greenhouse gases in terms of cumulative per capita emissions since pre-industrial levels. They find that China's contribution to climate change in terms of cumulative per capita emissions is about 50% below the global average, whereas the historical responsibility of China in national terms is above the global average of countries.

Several studies have put forward proposals for burden sharing regimes on the basis of cumulative per capita emissions. The Project Team of the Development Research Centre of the State Council (2009) developed a theoretical framework for National Emission Accounts that distinguishes between historical emissions and future emissions under a future climate regime. Ding et al. (2009,



2010) published an analysis for China under a cumulative per capita regime using multiple emission scenarios, which are all considerably higher than the allowances in the studies with low stabilisation levels analysed above. They conclude that regimes that aim at convergence of annual per capita emissions are more attractive for industrialised countries than cumulative per capita regimes. The publications on cumulative per capita approaches did not contain enough information to include them quantitatively in this analysis.

He et al. (2009) propose an allocation scheme, in which developing countries gain room for development by allowing the per capita emission allowances of non-Annex 1 countries to exceed per capita allowances of industrialized countries for some time, after which both levels converge to a sustainable emission level. The peaking level of per capita allowances decreases over time, argued for by technology development and global emission cap that becomes more stringent over time. This regime is comparable to the Common but Differentiated Convergence approach (Höhne et al., 2006).

Other authors discuss the current position of China in the climate debate and propose ways forward. Zhang (2010) highlights several reasons for China's currently fast growing CO<sub>2</sub> emissions and why these cannot be reduced in the short term. For instance, there is a large difference between central and local governments, and local governments have to be convinced of the urgency of GHG emission mitigation. As a way forward, Zhang proposes to set longer term targets for 2030, since 2020 is becoming increasingly short term. For long-term Chinese climate policy, Zhang (2011b) proposes to peak Chinese emissions in 2030. He regards 2020 not realistic, due to grace periods, implementation time of treaties and the fact that CCS has to be available before China can reduce its (coal-based) CO<sub>2</sub> emissions. A proposed roadmap towards 2030 includes first intensity targets (45–50% reduction in 2020 on 2005 levels), a target below baseline for 2025 and an absolute emission cap for 2030.

## 5.2 Indian proposals and considerations

As part of the Copenhagen accord, the mitigation action plan of India for 2020 pledges to reduce CO<sub>2</sub> emissions per unit of GDP by 20–25% compared to 2005.

Recently, two studies on climate policy scenarios for India have been published. Shukla et al. (2008) explored a low-carbon scenario and a sustainable society scenario for India. The low-carbon scenario reduces 8% below baseline in 2020 and 80% in 2050. The sustainable society scenario outlines an early shift to broader sustainable development policies, leading to 20% reduction below baseline in 2020 and 62% in 2050. TERI (2008) present a set of three mitigation scenarios: the Evolution, Resolution and Ambition scenarios. This study includes a particularly high baseline scenario, projecting a doubling of CO<sub>2</sub> emissions in 2021, compared to 2011, and a fivefold increase in 2031. The mitigation scenarios show reductions of 13–27% below baseline in 2020 and resp. 36%, 63% and 75% below baseline in 2050.

Recent Indian literature on climate policy is rather broadly and qualitatively oriented. Two main themes dominate the discussion: 1) Equity principles and grand designs of future climate policy, and 2) the implementation of voluntary Sustainable Development policies and measures as developing countries' contribution to climate policies. The discussions on equity are generally forward looking, combined with proposals for the design of future climate policies. In that respect, equal per capita allocation is generally more dominant than Historical responsibility (Pandey, 2004; Sanwal, 2009; Shukla, 2005). Both Pandey (2004) and Sanwal (2009) argue that equal per capita allocation should be the basis of future climate regimes. They both also favour to broaden the scope of climate policies from a focus on reduction targets alone to sustainable development in general or a globally shared vision on the future sustainable global economy. This broadening of the debate is

supported by Hourcade et al. (2008), who propose a fairly detailed but flexible approach for future climate policy. This proposal includes mainly a global carbon market to induce mitigation measures and non-binding quotas for developing countries, combined with sectoral targets and clean development mechanisms. Shukla (2005) discusses the role of both justice (equity principles) and efficiency (economic optimal solutions) in future climate regimes. He favours two proposals for future climate policy. The first is an adjusted, more equitable, implementation of Contraction and Convergence, in which per capita emissions of developing countries temporarily exceed those of industrialised countries. This is comparable to the Chinese two-convergence approach or the CDC approach (see He et al., 2009) or the CDC approach (Höhne et al., 2006). The second issue is the implementation of voluntary Sustainable Development policies and measures (SD-PAMS) as option for developing countries to contribute meaningful to climate policies in the short term (Bhandari, 2006; Srivastava, 2006). Examples of such measures are the Brazilian PRO-ALCOOL biofuel programme and the Chinese and Indian national policies on renewable energy and energy efficiency (Halsnæs and Shukla, 2008). Halsnæs and Shukla (2008) further discuss required policy mechanisms to successfully implement SD-PAMS. They argue in favour of a broad Sustainable Development – Climate Finance Mechanism (SDCFM) that finances broad measures (such as infrastructures) that contribute to low-carbon development and whose carbon evaluation can be ex-ante (based on baseline development, as the CDM) or ex-post (based on actual reductions in the past 5-10 years). Further, programs for technology development and transition and technology standards are important pre-requirements for successful implementation of SD-PAMS. Finally, Sudhakara Reddy and Assenza (2009a,b) argue that many benefits of broad sustainable development policies are not quantified and measured in current practice (such as health benefits) and therefore are not included when evaluating policies.

### **5.3 Main differences between the Chinese/Indian position and international studies**

We first compare the national studies on climate policy scenarios for China and India with international studies with respect to mitigation levels. For China, expressed in terms of reductions below baseline, the national scenarios are on the short term comparable to low-stabilisation scenarios of regimes with relatively high allowances for China (Multi-Stage or CDC). However, as reductions do not carry on towards 2050, the national literature is in total most comparable to international literature on less stringent scenarios (IPCC II/III category) with Contraction and Convergence approaches. Expressed in absolute terms (on observed 2005 emission levels), the national studies are roughly comparable to international less stringent scenarios with Multi-Stage or Triptych approaches, though with a much higher emission level on the short term.

The national scenarios for India are comparable to international low-stabilisation scenarios, in terms of reductions below baseline. However, expressed in absolute emission levels, only the lowest national scenarios would match with IPCC category I studies, the others would be in line with less stringent stabilisation scenarios. Given the wide ranges in results for India, it is hardly possible to compare the national scenarios to different effort-sharing approaches.

When comparing the national literature on effort-sharing approaches with international studies, it can be seen that the Historical Responsibility approaches, as interpreted by Chinese researchers in terms of historical emissions per capita, are hardly analysed in an international context. Other approaches that appear in the Indian and Chinese literature do often have an international equivalent, like common-but-differentiated convergence or Multi-Stage approaches. The approaches that are based on sustainable development measures are less-committal, and therefore appear hard to quantify in an international context.

## 6 Conclusion and discussion

Based on a comparison of the scientific literature on climate policy regimes, with respect to allowances, peaking year and economic impact or costs, we conclude that the allocation of emission allowances to both China and India are more sensitive to the global emission target than to the allocation regime, especially for low concentration targets. As both countries have expressed their support for the 2°C target, this implies that ambitious emission reductions will have to be achieved in both China and India.

Furthermore, the allocation of emission allowances to both China and India differs greatly, not only across regimes, but also within regimes, especially in the short term. This can largely be explained by methodological issues such as model structure differences, assumptions on baseline developments and parameter assumptions within the regimes. Studies show especially a wide variation in baseline emission developments for China, leading to large uncertainties in the results.

Notwithstanding the large differences between and within regimes, all studies show deep cuts in allowances for China in the long term. Towards 2020 and 2030, studies of Multi-stage, CDC, Triptych and Historical Responsibility show the highest emission allowances and lowest costs or economic impact. Studies of Grandfathering and C&C show large reductions in allowances for China. By 2050, however, studies of low stabilisation scenarios (IPCC category I) show that Chinese emission allowances reduce to 50–80% below 2005 levels, irrespective of the regime.

The economic impact or costs for China remain below the global average in most analysed studies and regimes. While literature shows that China is likely to face costs in many regimes, it also shows that there are initial revenues from selling allowances in several regimes and that domestic mitigation costs can be dampened by buying emission allowances in the long run. Therefore, the upper range of literature projects costs to increase to about the global average at maximum.

In the literature on climate policy regimes, Chinese emission allowances peak relatively early, before 2025–2030. Especially in low stabilisation scenarios, the median of the studies is observed around 2020–2025, which is soon, given the currently high growth rates of the Chinese economy and emissions.

The literature shows that emission allowances for India increase considerably relative to 2005 – and are even above baseline emissions in a number of studies and regimes. EqPC and Multi-stage allow for small surpluses of allowances, whereas CDC and S-N require minor reductions compared to baseline. Grandfathering and a global carbon tax (without trade) show the largest reduction of allowances (or emissions, in case of global carbon tax).

Studies show that India can expect to gain, or to incur only low costs, from climate policy. Net revenues can be explained by revenues from selling carbon credits being larger than mitigation costs. Therefore, climate mitigation seems beneficial for India, except in regimes that lead to a reduction in allowances in the short-term, like Grandfathering and a global carbon tax.

In the literature on low stabilisation scenarios, Indian emission allowances peak towards mid-century. In most low stabilisation scenarios, emission allowances for India peak around 2030–2045.

These results imply that the inclusion of the 2 degree climate target in the Cancún Agreements (UNFCCC, 2010) has consequences for emission peaking and allowances in the short term, especially for China. Another implication is that policy regimes in which emissions are allocated to countries based on meeting the two degree climate target may be more attractive to both China (at least on the short term) and India, compared to the current muddling through approach since the Copenhagen Accord – provided that these countries are allowed to sell emission credits to developed countries.

It should be noted that there are many uncertainties in this analysis. These firstly relate to tech-

nical uncertainties in the underlying studies, for instance with respect to baseline assumptions and methodology. Secondly, the methodology that was applied in this report involves uncertainties, of which the most important are the following. First, there is a bias in literature towards certain regimes, which complicates the comparison of different regimes: what seems a difference between regimes might well be a difference between studies or models. Second, there is a geographical bias of underlying analyses. Most studies that were reviewed in this report contain global analyses of climate policy regimes. Unfortunately, these studies are mainly carried out by scholars and institutes from industrialised countries; global analyses from Indian and Chinese sources (that are published in English) are rare. There might be a (perceived) bias in the literature to under-represent the values of developing countries with respect to “common but differentiated responsibility”. Third, and more methodological, are the different measurements for costs. Studies report very different cost measurements, ranging from direct costs to changes in GDP and welfare. When comparing the regimes, we have focussed on the relative costs of regions compared to the global average costs as presented by the studies. A final issue is the recent high growth of economy and emissions in China. Observed emissions and baseline emission projections for China have been growing rapidly over the last few years. Therefore, the conclusions with respect to reduction targets and allowance peaking in this paper might deviate from studies that would be performed with present day information and current future projections. In general, it might be assumed that such studies would allow more emission space for China and later peaking of allowances.

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## Chapter III

# Multi-model comparison of the economic and energy implications for China and India in an international climate regime<sup>\*†</sup>

*This paper presents a modeling comparison on how stabilization of global climate change at about 2°C above the pre-industrial level could affect economic and energy systems development in China and India. Seven General Equilibrium (CGE) and energy system models on either the global or national scale are soft-linked and harmonized with respect to population and economic assumptions. We simulate a climate regime, based on long-term convergence of per capita carbon dioxide (CO<sub>2</sub>) emissions, starting from the emission pledges presented in the Copenhagen Accord to the United Nations Framework Convention on Climate Change and allowing full emissions trading between countries. Under the climate regime, Indian emission allowances are allowed to grow more than the Chinese allowances, due to the per capita convergence rule and the higher population growth in India. Economic and energy implications not only differ among the two countries, but also across model types. 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. The reduction in carbon intensity is mostly achieved through deployment of carbon capture and storage, renewable energy sources and nuclear energy. The economic impacts are generally higher in China than in India, due to higher 2010–2050 cumulative abatement in China and the fact that India can offset more of its abatement cost through international emission trading.*

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# 1 Introduction

In the Copenhagen Accord (UNFCCC, 2009) and the Cancún Agreements (UNFCCC, 2010) under the United Nations Framework Convention on Climate Change (UNFCCC), countries worldwide agreed on limiting global average temperature increase to maximum 2°C above the pre-industrial level. In order to reach this political target of staying below 2°C above the pre-industrial level with a probability of more than 50% global greenhouse gas emissions need 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., 2011). However, the greater share of future emissions is expected to come from developing countries. In fact, emissions from developing countries alone will soon exceed the global emission trajectory for reaching the 2°C target (Clarke et al., 2009; Metz et al., 2002; Blanford 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 is essential.

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 the carbon dioxide (CO<sub>2</sub>) emissions from combustion of fossil fuels (International Energy Agency, 2011). 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, while China's average per capita CO<sub>2</sub> emissions have reached almost similar levels as those of the EU (Olivier et al., 2013). Already, China and India have pledged emission intensity targets (i.e., reduction in emissions per unit of GDP) as part of the Cancún Agreements.<sup>1</sup> While the aggregated pledges for all countries are able to reduce global emissions compared to baseline development, after 2020 deeper cuts beyond these pledges are required in order to achieve the 2°C target.

Deep global emission cuts will however come at economic costs. There are many proposals discussed in literature that address how the global emission space, compatible with the 2°C target, could be shared between different countries or regions, and the related costs and macro-economic implications. These effort sharing or emission allocation proposals have 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 different proposals, and many papers discuss how China and India would be affected (see Chapter II and references therein).

The overall objective of this study is to develop an integrated modelling framework that enables policy and scenario analyses on how China and India can be affected by international climate policies. Specifically, we apply the framework to analyze the consequences for China and India of a climate policy scenario aiming at achieving the 2°C target, using an effort sharing approach that aims for long-term convergence of per capita emission levels and staged participation of developing countries. The analysis focuses on (1) the impact on their energy systems; and (2) the direct mitigation costs and welfare implications.

We analyze these issues in a multi-model comparison approach involving seven models in a single framework. The modeling framework harmonizes and soft-links national and global as well as CGE and energy system models. It aims to yield a more consistent global and national perspective compared to the existing literature. Most past assessments of climate policy impacts in India or China have either been carried out in national models only (e.g. Shukla and Chaturvedi 2012; Shukla 1996; Fisher-Vanden et al. 1997 for India; and ERI 2009 for China), or within global models (e.g.

<sup>1</sup>In general as part of the Cancún Agreements, 42 developed countries (including the 27 EU Member States) have submitted quantified economy-wide emission reduction targets for 2020, and 48 developing countries submitted so-called nationally appropriate mitigation action plans reaching until 2020.

Edenhofer et al., 2010; Luderer et al., 2012; van Vuuren et al., 2003). There is also broad literature on model comparison studies (e.g. Clarke et al., 2009; Edenhofer et al., 2010), including the Energy Modeling Forum (EMF) and – more closely related to the context of this paper – the Asian Model Exercise (AME) (Calvin et al., 2012). Compared to the AME we make use of a smaller number of models; however, we provide greater consistency by harmonizing and soft-linking the models.

## 2 Modeling framework

### 2.1 Description of the models

Central to the modeling framework is the climate policy model FAIR (Framework to Assess International Regimes for the differentiation of commitments). It is used to construct the long-term global greenhouse gas emission pathway consistent with the 2°C target and to derive regional emission targets by applying specific effort sharing approaches. 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 CGE models. While the global models can capture international linkages and feedbacks, the national models account better for country specific details and can therefore analyze the national impacts of international climate policies 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 service demand and shifts in trade. Central features of the models are presented in Table 1. For specific assumptions of each model we refer to Sections 2.1.1 and 2.1.2 and papers covering the details of each model. For more details on the DART model and modifications made to the model for this study, see Appendix A.

The FAIR model links long-term climate targets and global emission reduction objectives with regional emissions allowances and abatement costs (den Elzen and Lucas, 2005; den Elzen et al., 2008). It includes the models FAIR–SiMcaP (Simple Model for Climate Policy assessment) (den Elzen et al., 2007) and the MAGICC 6 (Model for the Assessment of Greenhouse Gas Induced Climate Change) climate model (Meinshausen et al., 2011) to construct long-term cost effective global greenhouse emission pathways, consistent with long-term climate targets. Furthermore, the model includes an emission allocation model that calculates regional emission allowances for a wide range of effort sharing and emission allocation proposals (den Elzen and Lucas, 2005). Finally, the FAIR model also include a cost model that uses a least-cost approach involving regional Marginal Abatement Cost (MAC) curves to determine regional mitigation costs, allowing offsetting mechanisms such as international emission trading. The MAC curves consider abatement of all major emission sources, including abatement of energy- and industry-related greenhouse gases emissions (based on the TIMER (The IMAGE Energy Regional model) energy model (see Section 2.1.1)), land-use CO<sub>2</sub> emissions (based on the IMAGE model (Bouwman et al., 2006), and emissions of non-CO<sub>2</sub> greenhouse gases (Lucas et al., 2007)). The MAC curves account for technology change, including technology inertia and removal of implementation barriers.

#### 2.1.1 Energy systems models

Three energy system models are used, which take into consideration the 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

**Table 1:** Overview of the key characteristics of the seven models included in the applied model framework.

	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
Global or national coverage	Global (26 regions)	Global (26 regions)	Global (13 regions)	China	China	India	India
Household groups	NA	10 (urban and rural quintiles)	1 representative agent per region	2 (urban and rural)	2 (urban and rural)	9	1
Sectors	NA	5	12	24	5 sectors; 32 sub-sectors	18	5 Sectors; 46 end-use sectors
Energy resources technologies	NA	Coal, oil, natural gas, modern biofuels, traditional bio-fuels, nuclear, solar, wind and hydro power	Coal, natural gas, oil, bio-energy, wind, solar and hydro power	Coal, natural gas, oil, bio-energy, nuclear, wind, solar and hydro power	Coal, natural gas, oil, bio-energy, nuclear, wind/solar and hydro power	Coal, natural gas, oil, bio-energy, nuclear, wind/solar and hydro power	Coal, natural gas, oil, bio-energy, nuclear, solar, wind and hydro power
Technology dynamics	Based on MAC curves from TIMER and other models	Capital stocks, penetration rate and learning by doing	Capital stocks, learning by doing, and autonomous energy efficiency improvements	Capital stocks, and autonomous energy improvements	Capital stocks, penetration rate constraints	Capital stocks, energy efficiency improvement, total factor productivity and efficiency improvements	Capital stocks, penetration rate constraints, and energy infrastructure improvements
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	Not explicitly modeled	Electricity, modern biomass, hydrogen
Demand side measures <sup>a</sup>	Included in MAC	End use efficiency and conservation measures	End use efficiency and conservation measures	End use efficiency and conservation measures	End use efficiency measures	End use efficiency and conservation measures	End use efficiency measures

<sup>a</sup>End use efficiency refers to technological measures that can be used to increase energy efficiency, while conservation measures refer to measures representing changes in energy service demand, e.g. price responsive service demand.

are linked together by energy (and/or material) flows. TIMER<sup>2</sup> 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). China MARKAL (Chen, 2005; Chen et al., 2010, 2007) and MARKAL-India (Shukla, 1997; Shukla et al., 2008) are national energy system optimization models based on the MARKAL (MARKet ALlocation) modeling system (Fishbone and Abilock, 1981).

All three models account for energy-related CO<sub>2</sub> emissions from fossil fuels, while TIMER accounts for energy and industry related emissions of all greenhouse gases included in the Kyoto Protocol under the UNFCCC. The models include most primary energy resources and energy conversion technologies (and their costs and conversion efficiencies), including fossil fuels, biomass, nuclear power and several renewable energy resources/technologies (solar photovoltaics (PV), wind and hydro power). A carbon tax can be used to induce a response such as increased use of low or zero-carbon technologies, energy efficiency improvements 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 fossil fuel prices and fuel preferences. These two factors drive multinomial 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 determined by resource depletion (fossil and renewable energy resources) and technology development. Technology development is determined by endogenous learning curves and exogenous assumptions. The MARKAL models are dynamic linear programming energy system optimization models, encompassing extraction, transformation and end-use of energy. They are driven by a set of demands for energy services and their 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 of resources. The optimizing feature ensures that the models compute 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 CGE models are used in this model exercise, describing the behavior of economic agents and their interactions in the macroeconomic system. DART (Dynamic Applied Regional Trade Model) 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 (China Energy and Environmental Policy Analysis) describes the Chinese economy (Liang et al., 2007; Liang and Wei, 2012), based on input-output data of the (National Bureau of Statistics of China, 2009).

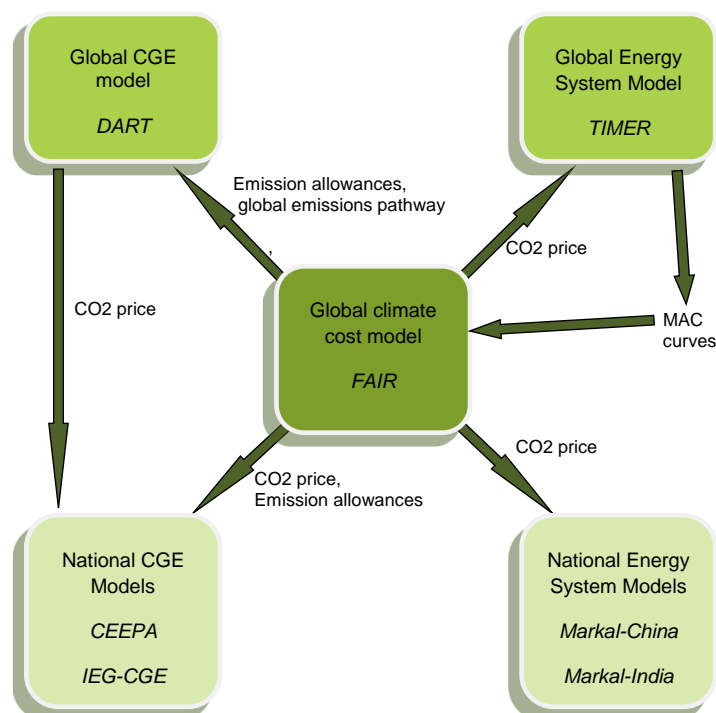
IEG-CGE (Institute of Economic Growth-CGE) describes the Indian economy (Pradhan and Ghosh, 2012b,a) and is based on a social accounting matrix (Ojha et al., 2009; Pradhan et al., 2006). The single country models capture characteristics of the labor and energy markets of the respective countries. For international trade, all models assume imperfect substitution between imported and domestically produced goods (Armington, 1969).

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.

<sup>2</sup>TIMER is part of the IMAGE integrated assessment model (Bouwman et al., 2006), but is here used as a stand-alone energy model.



**Figure 1:** The figure shows a schematic overview of how the seven models are soft-linked in the applied model framework, and how outputs from some of the models are used as input to other models.



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 9 household groups (based on socioeconomic characteristics), enterprises, and government. DART and IEG-CGE model consumption as a linear expenditure system.

All models account for energy related CO<sub>2</sub> emissions from combustion of fossil fuels. All models have introduced electricity generation technologies with low or zero CO<sub>2</sub> emissions. In the DART model, making use of information provided by the TIMER model, the electricity sector was split into conventional generation and new generation technologies from four renewable energy sources; additionally electricity generation from gas and coal generation with CCS is introduced as a latent technology.<sup>3</sup> Different electricity generation technologies are assumed to be perfect substitutes, each technology has a convex cost function and exhibits learning-by-doing, i.e., the cost of the technology decreases as the cumulative use of it increases. 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 any of the three CGE models, although implicit efficiency improvements in the transport sector are considered.

## 2.2 Description of the model framework

In order to exploit the advantages of all seven models and compare the results from the different 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 the model framework, the FAIR model provides a bridge function, see Figure 1.

<sup>3</sup>A detailed description of modifications to the DART model can be found in the Appendix.

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<sub>2</sub>-equivalent emissions.<sup>4</sup>
3. DART determines the globally uniform carbon price and climate policy cost based on the global energy related CO<sub>2</sub> 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 climate policy cost.
5. The national MARKAL models use the emission allowances and carbon price from FAIR to determine changes to energy system and climate policy cost.
6. TIMER uses the emission allowances from FAIR to determine changes to the energy system.

The reason for letting the national CGE models using CO<sub>2</sub> prices from DART and the national MARKAL model using CO<sub>2</sub> prices from FAIR (based on MAC-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. As will be seen in the results (Figure 3) letting the different models using different prices will not have any major impact on the result since the prices are very similar in DART and FAIR up to 2045. However, the CGE models (MARKAL models) would render too little (much) abatement in 2050 if they were using the FAIR (DART) prices in 2050.

### 3 Basic modeling and scenario assumptions

#### 3.1 Baseline assumptions and model harmonization

The models are harmonized with respect to discount rate, population growth, Gross Domestic Product (GDP) growth and fossil fuel prices. The discount rate is set at 5% as in the Global Energy Assessment (GEA, 2012). Table 3 summarizes the key baseline assumptions for population and GDP. The population projection is in line with the medium variant of United Nations World Population Prospects (UNDESA, 2011), with the global population projected to increase to about 9.1 billion people in 2050. The GDP growth rates are based on the reference scenario of the OECD Environmental Outlook, with the global economy projected to grow with a factor of about 4 (OECD, 2012). Finally, developments in international fossil fuel prices towards 2035 are taken from the current policy scenario of the World Energy Outlook 2010 (International Energy Agency, 2010). Prices are kept constant after 2035.

#### 3.2 Global emission pathway

We constructed a global emission pathway that aims for a total radiative forcing of 2.9 W/m<sup>2</sup> 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 emission pledges for 2020 presented in the Copenhagen Accord to the UNFCCC (den

<sup>4</sup>All greenhouse gas emissions refer to all emissions relevant under the Kyoto Protocol (Annex A) including the land-use related CO<sub>2</sub> emissions, i.e., the global warming potential-weighted sum of six Kyoto greenhouse gas emissions (CO<sub>2</sub>-equivalent emissions) pathway, a globally uniform carbon price and regional emission allowances based on the energy related CO<sub>2</sub> part of the pathway and an effort sharing approach. Climate policy cost is also determined by FAIR.

**Table 3:** Assumptions on population and GDP per capita that are harmonized among the models and used in the baseline scenarios.

	Year	World	India	China
Population (million people)	2010	6927	1214	1388
	2020	7691	1367	1467
	2050	9154	1614	1454
GDP per Capita (MER <sup>a</sup> , USD <sub>2005</sub> /yr)	2010	7268	965	3278
	2020	9375	1975	7186
	2050	19836	9944	22841

<sup>a</sup> Market Exchange Rate.

Elzen et al., 2011).<sup>5</sup> Between 2020 and 2025 global emissions gradually decline, while between 2025 and 2050 a constant reduction rate is assumed. For details see Lucas et al. (2013). Only the energy-related CO<sub>2</sub> emissions from the CO<sub>2</sub>-equivalent pathway are used (see Figure 2). Figure 3 presents the global CO<sub>2</sub> price 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 which to 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 that per capita emission allowances of all countries converge, but that developing countries start their convergence trajectory only after reaching a certain threshold, e.g. per capita emissions or income. A similar differentiated convergence approach is discussed by He et al. (2009).

Important parameters for the CDC approach are the long-term per capita emission targets 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 based on 2009 Gross National Income (GNI) per capita (World Bank, 2011), including developed countries, Advanced Developing Countries (ADC) and Other Developing Countries (ODC). Countries that according to their GNI per capita are high and upper middle income countries, and that are not already classified as developed countries, are classified as ADCs, and countries that according to their GNI per capita are low and lower middle income countries are classified as ODCs. After implementing their more ambitious Copenhagen pledges in 2020 (den Elzen et al., 2011), the developed countries and the ADCs start converging instantly, China and India start in 2025 and 2030, respectively, and the remaining ODCs start in 2035.<sup>6</sup> Between 2020 and the start of convergence countries follow their baseline trend.<sup>7</sup> Developed countries converge in 2040, while all other countries take 30 years for convergence. All countries converge to a target level of 1.7 tCO<sub>2</sub>/capita, consistent with the global CO<sub>2</sub> emissions pathway.<sup>8</sup>

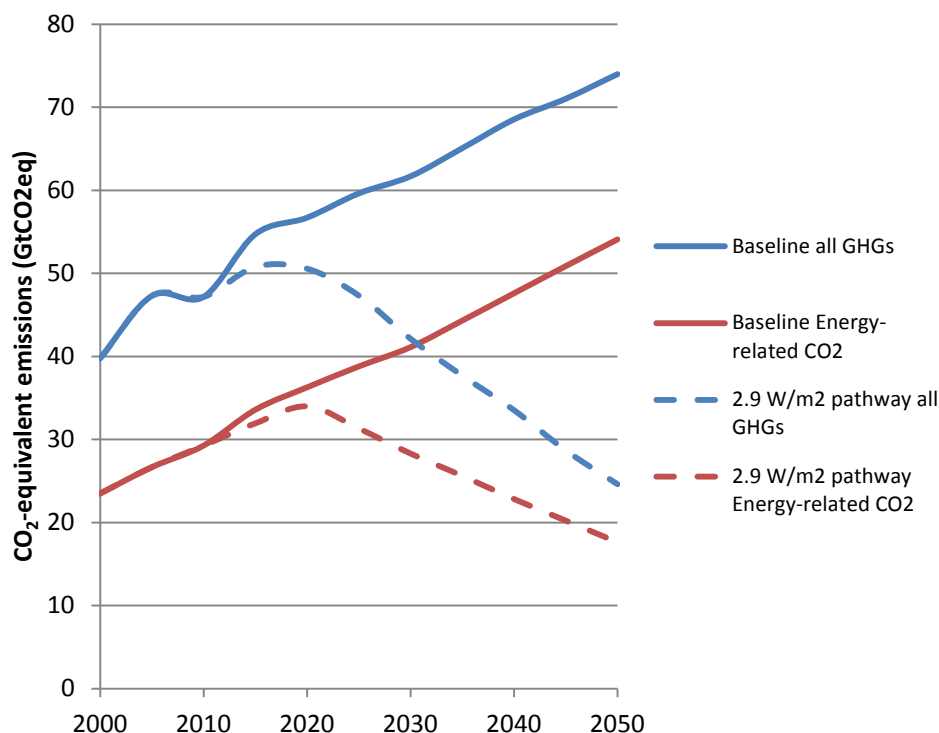
<sup>5</sup>The emission resulting from pledges for the developing countries – including China and India – has been revised in this study due to a different baseline assumptions (OECD, 2012), but keeping the same reduction below baseline from den Elzen et al. (2011).

<sup>6</sup>According to the World Bank data, China and India are both classified as ODCs. As China's per capita income in 2009 is almost reaching the upper-middle income threshold, it starts converging earlier than the other ODCs, but later than the ADCs. India also starts converging earlier than the other ODCs, but later than China.

<sup>7</sup>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.

<sup>8</sup>Convergence to 1.7 tCO<sub>2</sub>/capita is consistent with the lower bound of IPCCs 2.5–3.0 W/m<sup>2</sup> category of 80–95% reduction in 2050 for the group of aggregated developed countries (IPCC, 2007).

**Figure 2:** The figure shows, based on results from global climate policy model FAIR, global CO<sub>2</sub>-equivalent emissions (all greenhouse gases as included in the Kyoto protocol under UNFCCC) and energy-related CO<sub>2</sub> emissions, for the baseline scenario and the 2.9 W/m<sup>2</sup> pathway.



## 4 CO<sub>2</sub> emissions, emission allowances and global carbon taxes

### 4.1 Global results

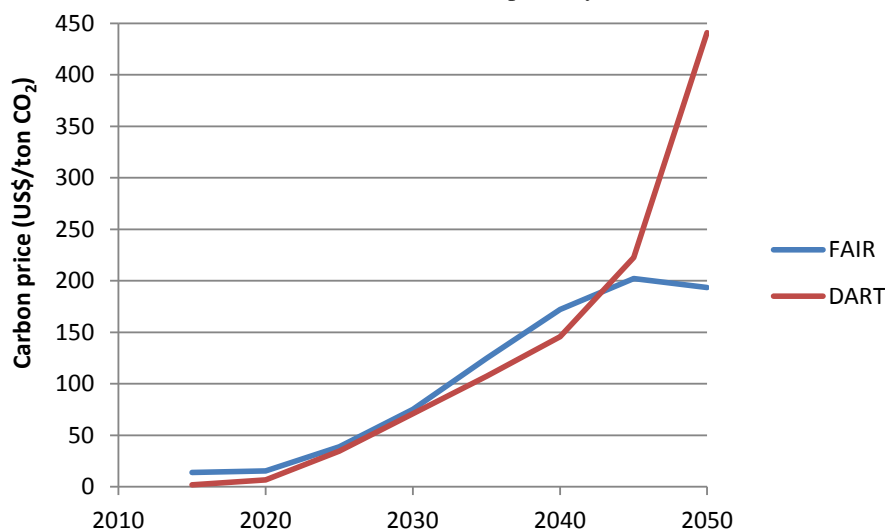
The global greenhouse gas emissions, including all greenhouse gases and land use related emissions included in the Kyoto Protocol under the UNFCCC, and the corresponding energy related CO<sub>2</sub> emissions generated by FAIR, are shown in Figure 2. Without any mitigation policies, global greenhouse gas emissions and energy related CO<sub>2</sub> emissions continue to increase towards 2050. The dotted lines in Figure 2 represent the 2.9 W/m<sup>2</sup> stabilization emissions pathway described in section 3.2.3.2. While global greenhouse gas emissions peak before 2020, energy-related CO<sub>2</sub> emission peak slightly later as reductions of non-CO<sub>2</sub> emissions are more cost-effective in the short-term than reductions of energy-related CO<sub>2</sub> emissions (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<sub>2</sub> emissions, respectively, by 2050.

In DART and FAIR the transition from the baseline emissions to the 2.9 W/m<sup>2</sup> pathway is achieved via a uniform carbon price on CO<sub>2</sub> emissions (see Figure 3). These prices are very similar up to 2045, beyond that the price in DART rises further, as mitigation options in DART are limited after certain abatement levels, while FAIR allows for more radical technology changes that become especially available in the long run due to technological change.

### 4.2 Results for China

In the baseline scenario (without any international climate policies) CO<sub>2</sub> emissions for China continue to increase in all models (Figure 4 left panel). 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

**Figure 3:** The figure shows carbon prices (in 2005 US\$ value) compatible with the global emissions pathway from the global climate policy model FAIR and the CGE model DART to achieve the transition from the baseline emissions to the 2.9 W/m<sup>2</sup> pathway.

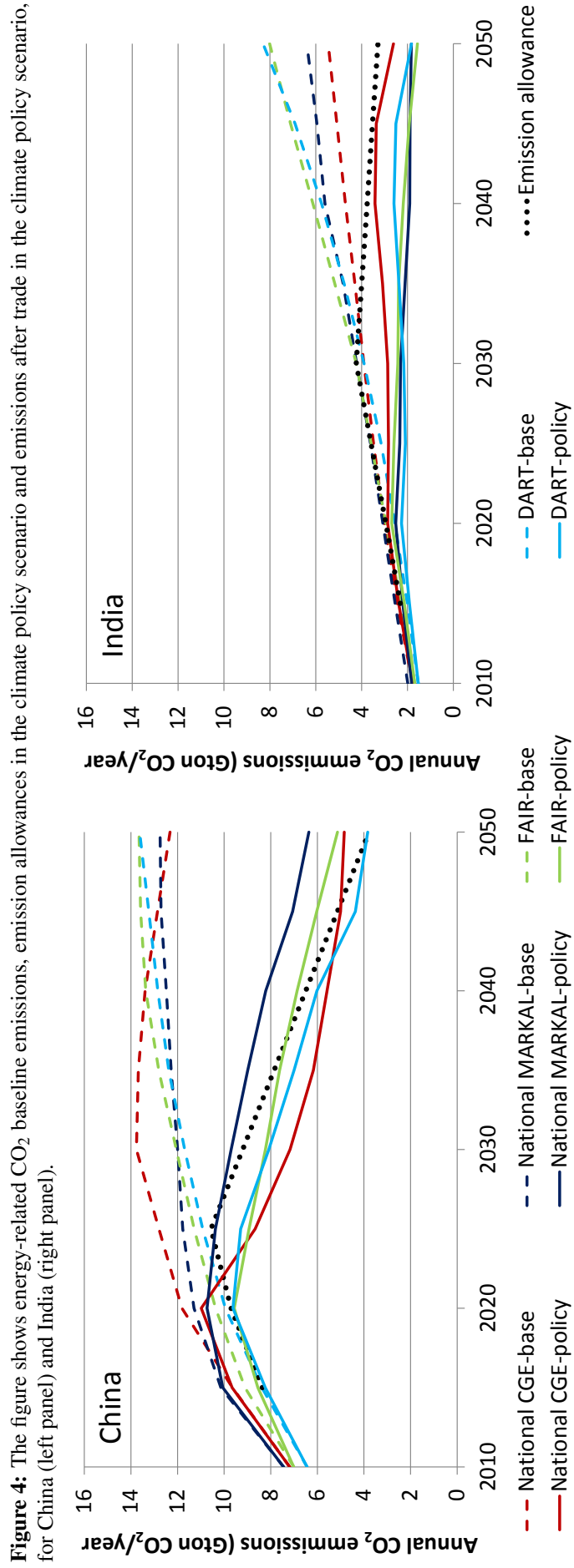


emissions were not harmonized among the models, there is a spread already in 2010.<sup>9</sup> Interestingly, national models show considerably higher emissions in 2030 compared to the global models. This implies that meeting the emission pledges for 2020 presented in the Copenhagen Accord to the UN-FCCC is much more challenging under these assumptions than in the global models. It should also be noted that China MARKAL considers 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 other models also consider decoupling between energy demand and GDP, but do not consider explicit policies. 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.

### 4.3 Results for India

In the baseline scenario CO<sub>2</sub> emissions in India continue to increase over the coming decades in all models (Figure 4 right panel). The 2020 Copenhagen Accord 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 other models also do consider decoupling between energy demand and GDP, but do not consider explicit policies. IEG-CGE stands out here with the highest decoupling assumptions. 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 period between 2020 and 2050. This implies that India is a net seller of credits on the international carbon market.

<sup>9</sup>This is because models have different calibration years (2004–2007) and are calibrated to different data sources.



## 5 Energy system change and climate policy costs

### 5.1 Changes in fuel mix

#### 5.1.1 China

Figure 5 presents the Chinese primary energy supply generated by the models in the baseline and the climate policy scenario.<sup>10</sup> 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, with 43–56 exajoules (EJ) in the baseline scenario. Between 2020 and 2050 primary energy supply grows on average at a lower annual rate, with an additional 20–56 EJ in the baseline scenario. 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 fossil fuels due to resource scarcity. This, together with the Armington assumption of imperfect substitution between domestic and imported fuels, implies that domestic energy price increases and energy demand decreases.

In all models, coal remains the most important fuel in the baseline scenario; in 2050 it still contributes with about 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 the energy supply in the models grows with 34–55 EJ between 2010 and 2020. Beyond 2020 the models indicate only a weak growth or even a decline in energy supply. Actually, a reduction of energy use stands out as a key mitigation option, especially in the CGE models (Figure 5; see also Figure 7 for a decomposition analysis of abatement activities). 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 (China MARKAL and TIMER).

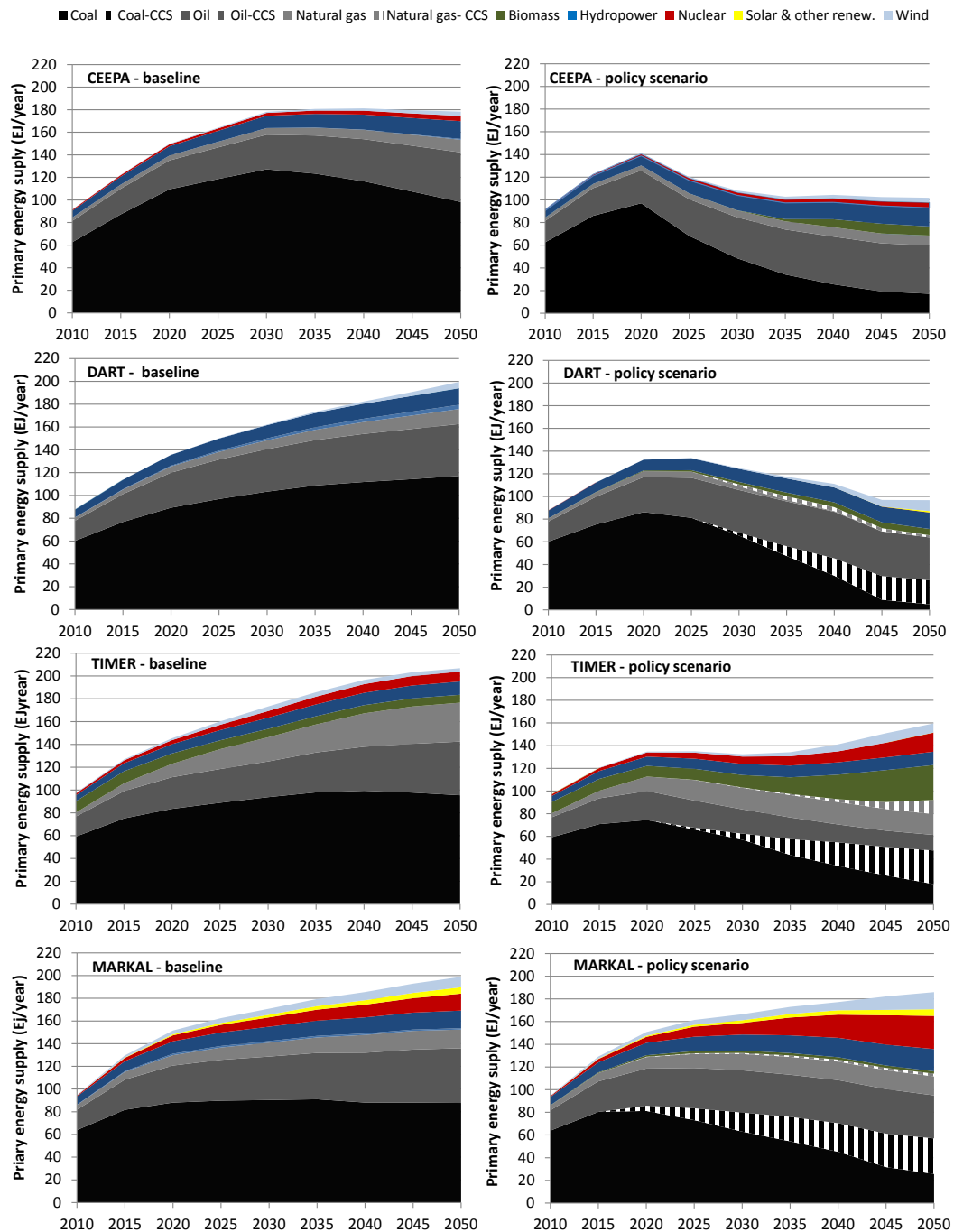
A large difference across models is the degree to which technologies with low or zero CO<sub>2</sub> emissions are deployed. The energy system models show higher shares of technologies with low or zero CO<sub>2</sub> emissions than the CGE models, especially in the policy scenarios. In the energy system models, high carbon prices imply that the system starts investing mainly in technologies with low or zero CO<sub>2</sub> emissions. It also means that less energy efficiency improvements are required to achieve the same level of emission reduction as compared to 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.

#### 5.1.2 India

The primary energy supply scenarios for India diverge in the different models (Figure 6). Quite a large range of different energy demand levels are projected already for 2020: the lowest demand amount to 20 EJ in IEG-CGE while the highest amount to 50 EJ in MARKAL-India. However, one reason is that IEG-CGE does not include traditional biofuels, but more importantly, IEG-CGE shows a very high decoupling between energy and economic growth.

<sup>10</sup>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, 2012).

**Figure 5:** The figure shows the results on primary energy supply in China for the baseline scenario and the climate policy scenario from the different models.

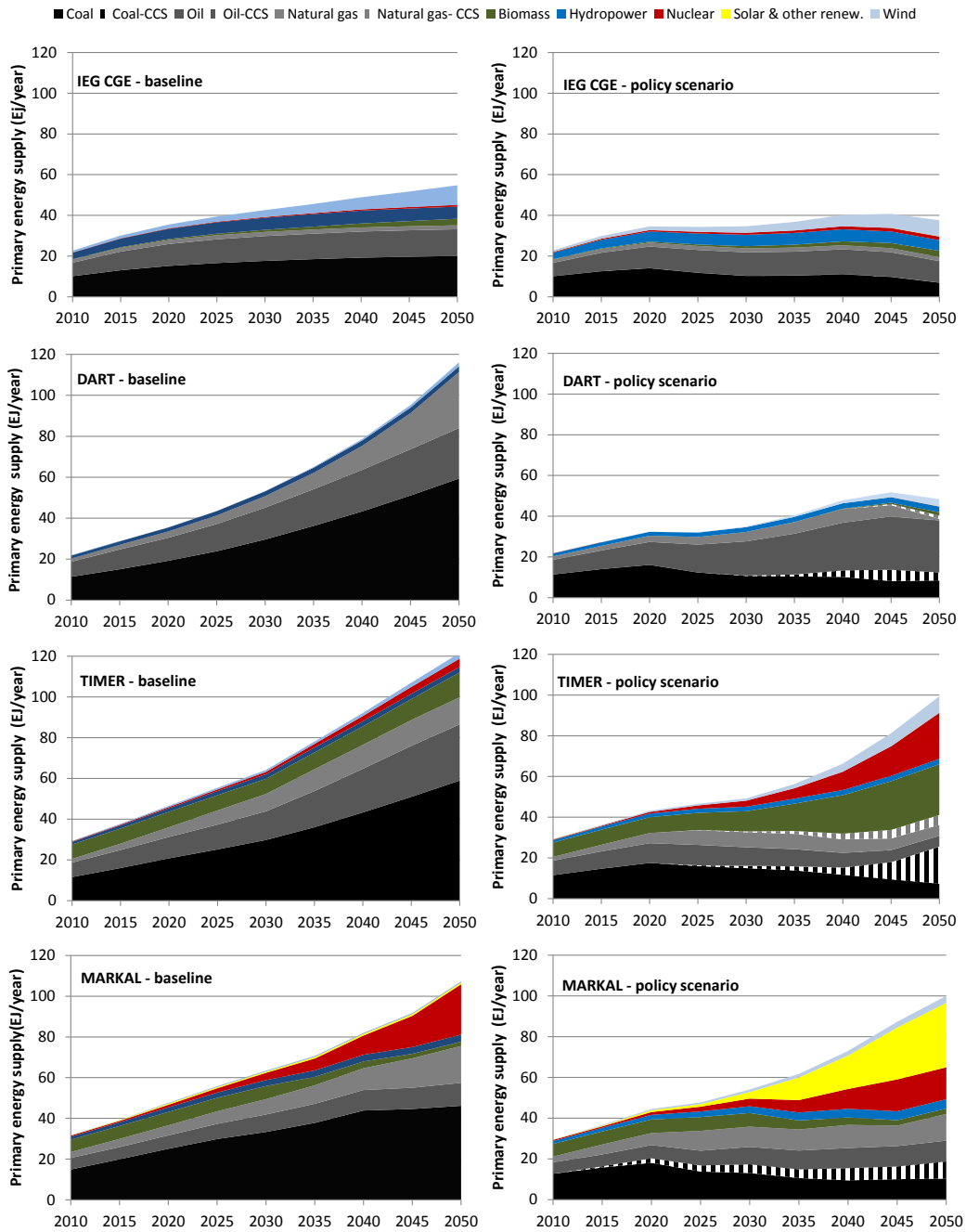


Similar as for China, it is projected that coal remains the most important fuel in the baseline scenario, followed by oil. In DART and TIMER, natural gas increases most rapidly. While natural gas also increases fast in MARKAL-India, it is outrun by nuclear power by 2050. This is attributed to the positive policy outlook towards building nuclear power capacity in the country, which is explicitly taken into account in MARKAL-India. This is not accounted for in IEG-CGE, DART and TIMER.

Again, the CGE models project a much larger role for reduction in energy consumption as an abatement option compared to the energy system models. Other important abatement options are CCS (all models except IEG-CGE), increased use of biomass (primarily in TIMER) and other re-



**Figure 6:** The figure shows results on primary energy supply in India for the baseline scenario and the climate policy scenario from the different models.



newable energy resources (mainly being different forms of solar energy in MARKAL-India; particularly PV). Similar to the results for China, the abatement in the energy system models depends to a stronger degree on biomass and other renewable energy sources than in the CGE models.

## 5.2 Decomposition of abatement

To visualize key differences in abatement strategies across the models we undertake a decomposition analysis using the Kaya identity (Kaya, 1990):

$$E_{CO_2} = GDP \times ei \times ci \quad (1)$$

where  $E_{CO_2}$  is annual CO<sub>2</sub> emissions,  $GDP$  the annual Gross Domestic Product,  $ei$  annual average energy intensity (i.e., unit primary energy per unit GDP) and  $ci$  annual average carbon intensity (i.e., unit CO<sub>2</sub> emissions per unit primary energy). Based on additive decomposition techniques we analyze the contribution of  $GDP$ ,  $ei$  and  $ci$  changes to total cumulative emissions reductions (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 7 left panel). The total level of abatement in China is smaller in the energy systems models compared to the CGE models (see Figures 5 and 7 left panel).

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. Yet, 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 the energy intensity contribution to emissions reductions in the models where CCS expands significantly underestimate actual energy end use efficiency improvements. In addition, in China MARKAL, energy conservation and efficiency improvements are considered in the baseline scenario leaving a smaller room for further efficiency improvements in the climate policy scenarios compared to other models which do not consider this in the baseline. Finally, since by construction China MARKAL is a technology focused model it does not consider the option for changes in energy services demand changes when relative prices change. However, 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 energy sources, nuclear power and CCS is considerably more important than energy efficiency measures for reducing emissions. These results are in line with the fact that renewable energy sources, nuclear power and CCS (and thus reductions in the carbon intensity) play a more important role in energy system models than in CGE models in general, and in particular in China MARKAL as seen in Figure 5.

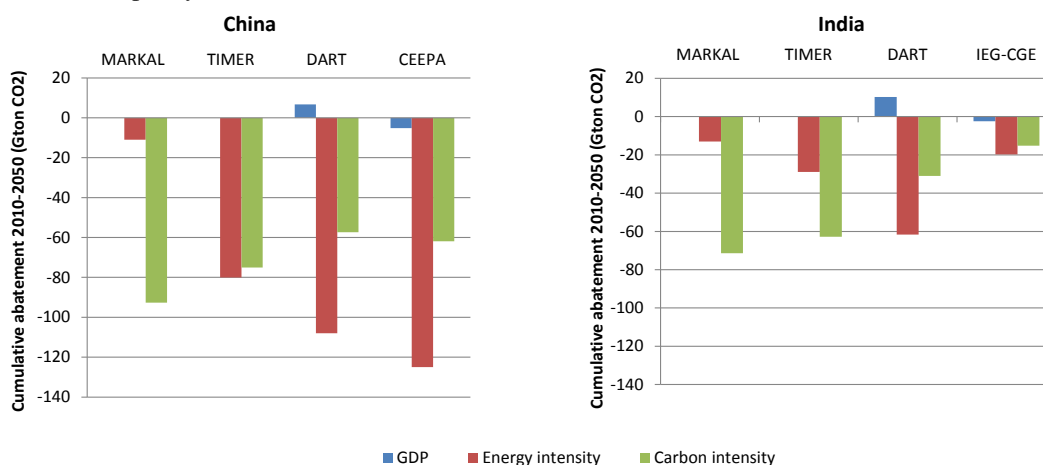
In the two CGE models GDP is affected by climate policies. CEEPA shows a loss in GDP in the climate policy scenarios as compared to the baseline scenario and for this reason the reduction in GDP contributes to further emission reduction. DART shows an increase in GDP as a result of climate policy, partly due to emissions trading, and partly due to a decline in fossil fuel prices. 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.

### 5.2.2 India

Similar to the models results for China, abatement in India occurs differently in the different models (Figure 7 right panel). 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,<sup>11</sup> and that reducing emissions in this model is relatively costly.

<sup>11</sup> Although baseline emissions in IEG-CGE are very close to the projections of the National Council of Applied Economic Research until 2030 (GOI, 2009).

**Figure 7:** The figure shows results on primary energy supply in India for the baseline scenario and the climate policy scenario from the different models.



Also, similar to the case for China, both CGE models (DART and IEG-CGE) mainly abate through a decrease in energy intensity (see Figure 7). This fact indicates, again, that efficiency improvements and structural changes within the economy are central for abatement in these models. On the other hand, 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.<sup>12</sup> A reduction in carbon intensity can be achieved via the use of CCS and renewable energy sources, and a switch from carbon intensive coal to less carbon intensive natural gas. In MARKAL-India virtually all abatement occurs through decreased carbon intensity. The reasons why MARKAL-India is showing only a small reduction in energy intensity in comparison to the other three models are 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 increases in GDP that follows from climate policies contribute to increasing emissions. As in the case of China the overall contribution of GDP to total cumulative abatement is relatively small.

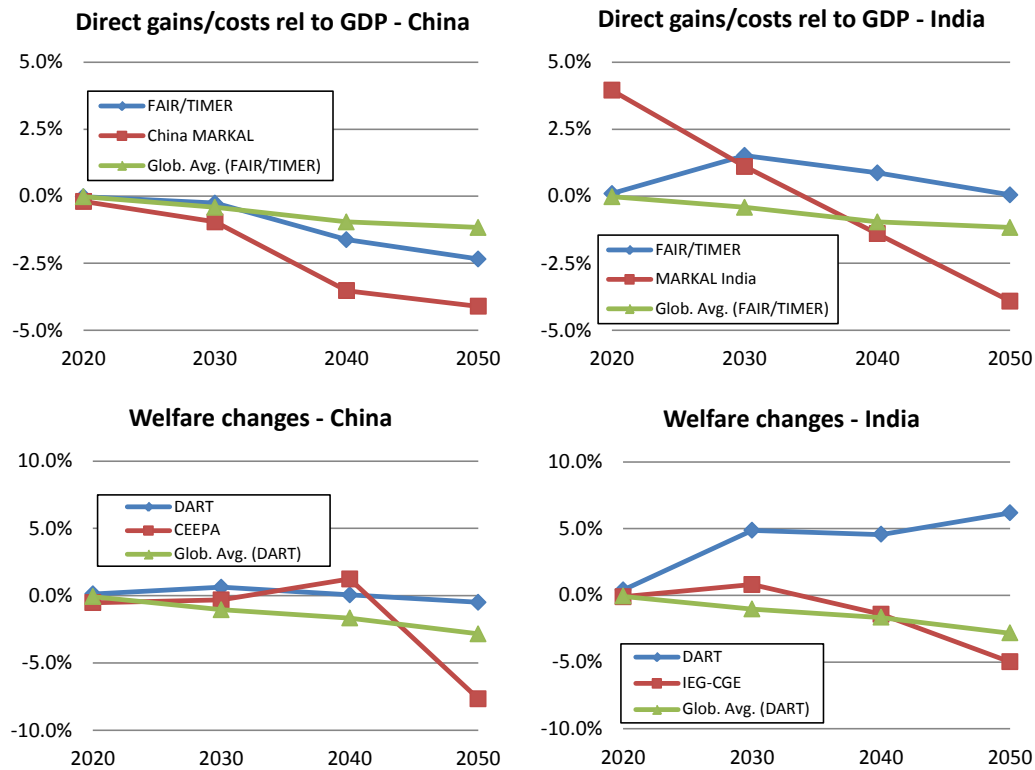
### 5.3 Direct and macro-economic costs of climate policy

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 are therefore not directly comparable between the two model classes. 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 capture overall structural changes and economy wide effects.

The economic impacts of the climate policy scenario for China and India are depicted in Figure 8. The figures also show the global average effects from FAIR and DART to put regional effects into

<sup>12</sup>This is different from the situation in China where a slower increase in energy demand limits the transition from the existing fossil capital to low carbon technologies in TIMER – see also van Ruijven et al. (2012).

**Figure 8:** The figure shows the economic impacts of climate policy in China (left) and India (right) estimated by the different models. For FAIR and MARKAL gains or costs are reported as abatement cost relative to GDP (top), while for the CGE models welfare changes (Hicks equivalent variation) are reported (bottom).



perspective (for the economic burden of India and China relative to the global average (Hof et al., 2009, see also Chapter II).

### 5.3.1 China

In general, costs are increasing over time although 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 the end of the time horizon.

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 China MARKAL captures this effect. Further, China is a net seller of credits up to 2050 in DART, while in CEEPA and FAIR, China is a seller until 2020, but becomes a net buyer afterwards (see Figure 4). In China MARKAL, China is a net buyer of credits over the whole time period considered.

### 5.3.2 India

As expected, the climate policy scenario also affects India differently in the different models (Figure 8 right). The global models, DART and FAIR, show an economic gain from international climate policies throughout the simulation period. The key reason is that the Indian emissions calculated by

the models are substantially lower than the allocated emission allowances, see Figure 4. As a consequence, India can, in the models, sell allowances on the international allowance market and generate revenues that are large enough to offset increased investment costs in energy efficient technologies and technologies with low or zero CO<sub>2</sub> emissions. This is different from the model results for China, where the possibility to sell on the international market is much smaller (see Figure 4). In addition, the Indian economy is smaller than the Chinese and for this reason an equal net export of carbon allowances in absolute terms has a larger impact on India in relative terms. 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 exported allowances.

For the DART results it is again important that international fuel prices decline in the policy scenario compared to the baseline scenario causing benefits to 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 IEG-CGE, capital inflows (from selling allowances) lead to an appreciation of the Indian currency which lowers international competitiveness.<sup>13</sup> 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 methodology. The perfect foresight assumption implies that the knowledge of future high CO<sub>2</sub> prices causes investments and national fuel prices to decline early on in the model leading to an initial gain from climate policies. Later, costly investments in abatement technologies are needed and the benefit of climate policies found at earlier decades turns to a loss.

## 6 Sensitivity analysis

Model results are sensitive to a broad range of assumptions. Here, we discuss the economic implications of an alternative GDP growth path, the timing of global emission reductions and two alternative effort sharing approaches. Global studies have in the past underestimated the economic growth in the emerging economies in Asia, particularly in China (see Chapter II). To address its impact, the models are run with a higher GDP growth scenario for China and India, while the rest of the world still follows our reference growth rate.<sup>14</sup> With respect to the timing of global emission reduction, in our climate policy case countries implement their high Copenhagen Accord pledge in 2020, after which global emissions gradually decrease. In the existing literature, most studies have used cost optimal pathways, with global 2020 reductions generally being larger, while the mid- and long-term reductions can be slightly lower compared to our climate policy case (den Elzen et al., 2011). Therefore, for comparison, we also run our models with a cost optimal pathway, resulting in global early action (van Vliet et al., 2012). See also Lucas et al. (2013) for a discussion of energy system implications for the different assumptions on abatement timing. Finally, as national costs are highly dependent on how the global emission reductions are shared among countries, we assess the impacts of two alternative effort sharing approaches: a global uniform carbon tax approach and a delayed participation CDC approach. In the delayed participation CDC approach, China and India start converging 5 years later than in the base case.<sup>15</sup> Table 4 shows the economic impacts of these

<sup>13</sup>Chapter IV analyzes the effects of international fuel price and exchange rate repercussions on India in more detail. Further information (e.g. world market prices for fossil fuel) is passed on from DART to IEG-CGE.

<sup>14</sup>For China, the national projection is based on Goldman Sachs (2010); International Energy Agency (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.

<sup>15</sup>To stay within the global emission pathway, developed countries have to reduce more and converge to a target level of 0.6 tCO<sub>2</sub>/cap – instead of 1.7 tCO<sub>2</sub>/cap in the base case, while the developing countries still converge to a target level of 1.7 tCO<sub>2</sub>/cap. The global emission pathway is the same as in the reference climate policy case.

**Table 4:** Economic implications of alternative assumptions on economic growth, timing of global emission reductions and the effort-sharing approach, measured as 2010–2050 NPV. Positive numbers represent net gains and negative numbers net costs.

		Reference case	Higher GDP growth	Global early action	Global uniform carbon tax	Delayed participation CDC
China	DART	0.2%	−0.2%	−0.2%	−0.4%	1.3%
	CEEPA	−0.4%	−2.4%	−3.0%	−9.7%	3.6%
	FAIR	−0.7%	−1.0%	−0.6%	−0.7%	−0.3%
	China–MARKAL	−1.7%	−2.9%	−1.2%	−1.0%	−1.1%
India	DART	4.0%	3.9%	3.0%	−0.2%	5.7%
	IEG–CGE	−1.1%	−1.6%	−1.7%	−2.0%	0.0%
	FAIR	0.7%	0.7%	0.1%	−1.1%	1.5%
	MARKAL–India	1.7%	−2.4%	−1.0%	−0.2%	2.5%

alternative assumptions per region and model, using the 2010–2050 Net Present Value (NPV) of welfare impacts for the CGE models and direct abatement cost, including emissions trading, relative to GDP for the energy systems models.

The economic impacts are generally larger for the two alternative effort sharing approaches, especially the global uniform carbon tax, compared to the alternative assumptions for economic growth and the global emission pathway. Higher economic growth and a global uniform carbon tax increase total climate policy costs for China and India, while delayed participation CDC results in lower climate policy costs for both countries. The impacts of global early action, i.e., higher global 2020 abatement, differ per country and model.

While the baseline emissions increase much more under the higher economic growth scenario, the emission allowances remain moreover the same, thus resulting in higher climate policy costs, especially for China. Since India remains a net seller of credits it continues to benefit from higher carbon prices. In sum, these two contradicting effects lead to only a small impact in both DART and FAIR, while in MARKAL-India, gains from emissions trading cannot offset the large increase in mitigation costs.

Global early action has a mixed impact on climate policy costs in the two countries and differs across models. For China, climate policy costs decrease in the energy system models and increase in the CGE models. The differences in results can at least in part be explained by the more detailed description of the capital stock turn-over in energy systems models. 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 demand growth 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., 2012). Hence, a less rapid emission reduction rate would be beneficial for Chinas in these models. In India, climate policy costs increase in all models, i.e., benefits either drop or costs increase. The increased costs due to a higher reduction objective in 2020 are not fully compensated through higher gains from selling allowances at higher carbon prices.

In both countries and all models delayed participation CDC results in reduced climate policy costs, while a global uniform carbon tax increases climate policy costs. This result is driven by the capital inflow from emissions trading, which is especially large for delayed participation CDC. Only China MARKAL shows decreasing climate policy costs under a global uniform carbon tax. Here, China is a net buyer of emissions credits in the whole 2010–2050 period in this model, while in all

other models China becomes a net buyer only beyond 2035 (see Figure 4).

## 7 Discussion

In the prevailing literature, estimates on energy system and cost impacts of different climate regimes are often not directly comparable and differences in result are not always easy to explain (see Chapter II). We find in our analysis that models with a similar structure (CGE vs. energy system) lead to comparable results. Thus, differences in model results can be explained in part by the use of a CGE or an energy system model.<sup>16</sup>

In our analysis not all CGE models include technologies with low or zero CO<sub>2</sub> emissions to the same extent as the energy system models (see Table 1) and thus react differently to climate policies. As a consequence the energy system models have more options for meeting the 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 7). In the CGE models abatement primarily takes place via energy intensity reductions since these models offer more options for reducing energy demand and/or changing the structural composition of the production in the economy leading to production of less energy intensive goods.

Concerning cost estimates, CGE models take into account different kinds of repercussions on markets that the energy system models do not consider. Still the estimates on the cost of climate policies are comparable across the models. An important difference between the national CGE models and the global CGE model is that the global model takes into account repercussion on international fossil fuel markets. This has an important impact on the cost estimates, and results in lower overall costs for climate policies in India and China. Furthermore, impacts on the exchange rate following capital transfers from emission trading have a key impact on the effect climate policies has on welfare measures in the Indian CGE model. For both mechanisms see also Chapter IV.

Finally, the models used in this paper are intentionally representing a strong simplification of the real world. This is important so as to make an interpretation of the results possible and since modeling of social-technical systems are utterly complicated. The key outcome from modelling exercises such as this one is not the exact numbers generated by the models, but rather the insights obtained. The key decision criteria used here is cost-effectiveness, i.e., social goals (such as climate targets) should be met at the lowest possible cost given various assumptions. Given this modeling approach the results presented in this paper represent future scenarios that are internally consistent in each model given the assumption at hand. Public opinion on technologies such as nuclear power and CCS may constrain or even inhibit large-scale expansion of such technologies. In our analysis we have intentionally left such issues aside and leave the implications of such issues to the user of the model results.

## 8 Conclusions

This paper presents an overview of an international modeling comparison project, which focuses on how achieving the 2°C target could affect economic and energy systems development in China and India. The analysis concludes that independent of models structure significant reductions are required in both China and India, implying huge changes in their energy systems.

In the main climate policy case (the common-but-differentiated convergence effort sharing approach), Indian emission allowances are allowed to grow more than the Chinese emission allowances,

<sup>16</sup>See for example Hourcade et al. (2006) and van Vuuren et al. (2009) for further discussions on these types of models.

due to the per capita convergence rule and the higher population growth in India. In 2010, China's CO<sub>2</sub> emissions are almost three times higher than the Indian emissions, while in the baseline and policy scenarios in 2050 the CO<sub>2</sub> 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.

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. Energy efficiency improvements are more important in the CGE models, while improvements in the carbon intensity, primarily through expansion of CCS and renewable energy sources, are more important for the energy system models. With respect to the carbon intensity improvements, CCS is more important in China, while renewable energy sources (including biomass) are more important in India.

The negative economic impacts of international climate policy are generally larger in China than in India, and India can even gain economically. The reason for this is that India has a larger potential of selling reductions on the international carbon market generating revenues. In general, the model result show that 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 appreciation resulting from a net capital inflow from international carbon trading and timing of emission reductions.

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## A Including renewable electricity generation and CCS into the DART model

### A.1 Introduction and Background

The DART model (Klepper et al., 2003)<sup>17</sup> is a global computable general equilibrium (CGE) model, with the aim to provide macroeconomic and welfare effects of climate policy in different scenarios. In previous versions, renewable energy was not explicitly modeled. This is problematic with regard to the analysis of long term scenarios that are likely to include strong changes in the electricity sector and prevents the analysis of renewable targets.

The DART model previously has mostly been used for a limited time horizon, e.g. until 2020 or 2030. For the near future, an implicit inclusion of renewable energy in electricity generation was a sufficient representation of the energy sector, as over the relatively short period of time there would only be limited change in the energy mix. Furthermore, in the base year, renewable energy production is already included implicitly in the calibration for the traditional electricity sector. The CES-production technology allowed for some substitution in the production structure away from fossil fuels towards capital and labor. This could be interpreted as a shift towards more capital intensive renewable or nuclear energy generation, however the technologies were not explicitly modeled as there was only a single electricity sector.

Similarly, the missing option to include carbon capture and storage (CCS) into the DART model was negligible, as widespread use will be unlikely to happen in the near future for technological reasons.

For longer term projections<sup>18</sup>, however, inclusion of renewable energy generation and CCS provide a better picture of mitigation scenarios. First of all, including more detailed technologies options provides more information on abatement strategies in different regions. Secondly, the inclusion of additional abatement options lowers the cost of mitigation scenarios relative to a scenario where the options are excluded from. Hourcade et al. (2006) argue that in conventional top-down models substitution would be relatively costly and limited by elasticities estimated from observations where these technologies were not present. Inclusion of these options therefore flattens the marginal abatement curve. Without these modifications, relatively high carbon prices are necessary to reach a stringent target as abatement is carried out only through substitution of fuels, substitution to more capital and labor intensive production relative to energy intensive production, and a reduction of energy demand or a shift towards less energy intensive products. The nature of CES production function prevents a complete decarbonization of the electricity sector and leads to increasingly costly abatement.

The inclusion of more detailed energy generation technologies into top-down models has been carried out by several models (see e.g. Böhringer (1998) or McFarland et al. (2004) and Hourcade et al. (2006) for a recent overview). Böhringer and Rutherford (2008) distinguish between linking independent bottom-up and top-down models, implementing features of one type into the other type of models, and integrated hybrid modelling, i.e. directly combining bottom-up and top-down information. Boeters and Koornneef (2010) model supply curves for different renewable technologies and integrate them into a CGE model.

The appendix is structured as followed: The next section briefly describes the DART model, the sections thereafter provide more detailed information on how renewable energy and CCS were integrated into the DART model, and the last section presents some illustrative runs.

<sup>17</sup>See also [http://www.ifw-kiel.de/academy/data-bases/dart\\_e/dart-en](http://www.ifw-kiel.de/academy/data-bases/dart_e/dart-en) for applications.

<sup>18</sup>Within the POEM project however, DART will need to analyze scenarios until 2050.

**Table A.1:** Regions and sectors of DART

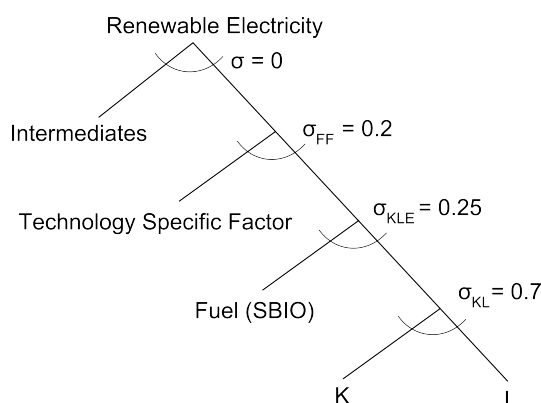
Countries and regions			
WEU	Western Europe	CPA	China, Hong-Kong
EEU	Eastern Europe	IND	India
USA	United States of America	LAM	Latin America
JPN	Japan	PAS	Pacific Asia
CAN	Canada	MEA	Middle East and Norther Africa
ANZ	Australia, New Zealand	AFR	Sub-Saharan Africa
FSU	Former Soviet Union		
Production Sectors/Commodities			
<b>Energy Sectors</b>		<b>Non-Energy Sectors</b>	
COL	Coal	AGR	Agricultural Prod.
CRU	Crude Oil	ETS	Energy Intensive Production
GAS	Natural Gas	OTH	Other Manufactures & Services
OIL	Refined Oil Products	CRP	Chemical Products
ELY	Electricity	MOB	Mobility
		OLI	Other light industries
		OHI	Other heavy industries
		SVCS	Services
Renewable and advanced electricity technologies			
WIN	Wind	SOL	Solar
HYD	Hydro	SBIO	Solid Biomass
GASCCS	Advanced Gas with CCS	COLCCS	Advanced Coal with CCS

## A.2 The DART model

The DART (Dynamic Applied Regional Trade) Model is a multi-region, multi-sector recursive dynamic CGE-model of the world economy. The economy in each region is modeled as a competitive economy with flexible prices and market clearing. There exist three types of agents: a representative consumer, a representative producer in each sector, and regional governments. All regions are connected through bilateral trade flows. The DART-model has a recursive-dynamic structure solving for a sequence of static one-period equilibria. The major exogenous drivers are the rate of productivity growth, the savings rate, the rate of change of the population, and the change in human capital. The model horizon goes until the year 2050. The model is calibrated to the GTAP7 database that represents production and trade data for 2004. The elasticities of substitution for the energy goods coal, gas, and crude oil are calibrated in such a way as to reproduce the emission projections of the the International Energy Agency 2009; 2010. For a more detailed description of the DART model, see Klepper et al. (2003) and the descriptions in Chapters VI.<sup>19</sup>

For the simulation of Post-Kyoto emission reduction scenarios, DART is calibrated to an aggregation of 13 regions and 12 sectors, which are shown in Table 1. The electricity sector is split into several sub-sectors, which produce electricity at perfect substitutability. Besides the traditional electricity sector which includes fossil fuel (and nuclear) generation, there are four renewable energy sectors (wind, solar, hydro, and solid biomass) as well as advanced generation from gas and coal with CCS.

<sup>19</sup>The only real change to the model described in Klepper et al. (2003) is that we introduced an LES consumption function, replacing the former Cobb-Douglas consumption function.

**Figure A.1:** Production structure of renewable electricity.

### A.3 Modeling of renewable energies in the DART model

In the current set-up of DART several renewable electricity technologies are modeled: Wind, solar, hydro, and solid biomass. These technologies provide electricity that is a perfect substitute to (traditional) fossil fuel electricity, albeit at a higher cost.<sup>20</sup>

For this version, the elasticity between capital and labor has been reduced to 0.7, and the elasticity of the KL bundle with energy to form the KLE bundle has been increased to 0.7 except in the electricity sector, where it has been decreased to 0.25. Modeling the electricity sector with a CES production function with high substitution possibilities could result in thermodynamically infeasible input combinations (McFarland et al., 2004).<sup>21</sup> The adjusted values better reflect estimations of electricity use in the future compared to projections of the World Energy Outlook or the TIMER model. Furthermore, the parameters also are better matched with empirical evidence (van der Werf, 2008).

The basic modeling approach is to split the electricity sector into renewable electricity sub-sectors and a remaining traditional electricity sector.

To achieve some market penetration as well as to avoid “flip-flop” adjustments due to the fact that electricity from different generation sectors is a perfect substitute, a fixed resource is introduced as production factor. An intuition behind this technology specific factor can both be seen in a capacity constrained in actual resources (e.g. suitable land) or knowledge needed as input. The modeling approach does herein follow the EPPA model (Paltsev et al., 2005). This is also familiar to the production of fossil fuels in DART where a fixed resource enters the production function. In any given year, there are hence decreasing returns to scale in the renewable energy sectors as the fixed factor is becoming scarcer and substitution away from the fixed factor requires additional other inputs. For a graphical representation of the production function, see figure A.1.

In the short run, subsidies are needed to have some renewable energy generation, in the absence of such a support, the renewable energy sectors would not be active because there exists a cheaper way to produce electricity. The initial subsidy rates are calculated such that the share of renewable energy production in the base year is reached. While the tax or subsidy rate for the conventional

<sup>20</sup>This does not regard a limitation for intermittent electricity from solar and wind, another modeling approach would hence be to consider intermittent electricity as imperfect substitute (Paltsev et al., 2005); such an approach prevents a very high share of intermittent energy. Yet another approach is to explicitly include backup capacities to allow for intermittent energy to become better substitute for conventional electricity (Morris et al., 2010). There is also no distinction in load characteristics of the different generation technologies as in McFarland et al. (2009).

<sup>21</sup>If the electricity sector is understood as a broad combination of generation technologies, this might be less important, as a substitution away from fossil fuel input could be interpreted as a switch to more capital and labor intensive renewable technologies. If the electricity sector is however reduced to traditional thermal generation from fossil fuel this assumption might be less sensible.



electricity sector is fixed, the subsidy rates to achieve a given level of renewable energy production are calculated endogenously such as to reach a given level of renewable electricity generation (see section A.3.2). The tax rate  $\tau$  of the conventional electricity sector is calculated such that the value of the output matches the value of the output of the sector, i.e. the value of the sum of all input costs faced by the producer match the electricity generation valued at the average cost of electricity:

$$\tau_r = 1 - \frac{(1/(1 - Share_r^{non-renewable}) * Input_r^{non-renewable})}{Y_r}$$

Here  $Y_r$  refers to the output value of the complete electricity sector.<sup>22</sup>

In the long run, renewable energy technology improves its relative position to traditional energy via cost reduction through learning, a rising availability of the fixed factor, and increasing fossil fuel prices.<sup>23</sup> In the baseline scenario, wind energy becomes competitive and does not need the subsidy thereafter, however, solar energy remains to be subsidized throughout the whole period.

### A.3.1 Translating the bottom-up information into DART

Data for cost shares, penetration levels and price mark-ups is taken from the global energy model TIMER (de Vries et al., 2001).<sup>24</sup> The bottom-up model TIMER uses cost data for various generation technologies in different world regions. With an underlying learning assumption, cost parameters change over time and react to installed capacities (learning-by-doing) and carbon prices. Specifically we use information of the ‘‘Electric Power Generation’’ sub-model of TIMER that simulates investment decisions based on electricity demand and relative generation costs which are mainly driven by fuel and carbon prices.

The approach to match the bottom-up data with the data from GTAP is broadly following Sue Wing (2008), interpreting O&M as labor cost and capital cost as capital input. All cost inputs (labor, capital and fuel) are broken down per unit of electricity generated.

In the approach chosen here, output and inputs of various factors were calculated independently. The output of the complete electricity sector in GTAP was split according to the shares of generation of the respective technologies taken from the TIMER model for the year 2004.<sup>25</sup> For the factor input of capital and labor, the total input of these factors in the GTAP data was divided into the different generation technologies. The parameter of the allocation share was calculated from data taken from the TIMER model: Capital or labor input to each generation technology was divided by the total capital or labor input of all generation technologies. Fossil fuel input was completely allocated to generation of the conventional sector.

Intermediate inputs to the electricity sector are taken to be the same for all generation technologies and are hence distributed according to the generation share. These inputs could be thought of as inputs to transmission and distribution (T&D) and would hence be equal across all generation technologies per unit of electricity generated.<sup>26</sup> Intermediate inputs also include electricity, this could be thought of as transmission losses which are proportional to the unit of electricity generated.

<sup>22</sup>This sets the tax rate to achieve zero-profits, as manipulating yields  $(1 - \tau_r) * (1 - Share_r^{non-renewable}) * Y_r = Input_r^{non-renewable}$ . The output value for non-renewable electricity corrected by the tax hence equals the value of the inputs.

<sup>23</sup>Fossil fuel prices are rising over time in the DART model with increasing demand. In scenarios with climate policy, the fuel price that the electricity sector is facing is even higher.

<sup>24</sup>See also [http://www.pbl.nl/en/themasites/image/model\\_details/energy\\_supply\\_demand/index.html](http://www.pbl.nl/en/themasites/image/model_details/energy_supply_demand/index.html), and [http://www.pbl.nl/en/themasites/image/model\\_details/energy\\_supply\\_demand/Mainassumptions.html](http://www.pbl.nl/en/themasites/image/model_details/energy_supply_demand/Mainassumptions.html) for updates and additional data sources.

<sup>25</sup>The base year share in of wind energy in Africa and the former Soviet Union as well as the share for solar energy in Africa was revised upwards from the original TIMER data. Otherwise increases of predicted generation would be very large and cause problems with convergence in the DART model.

<sup>26</sup>This is similar to Sue Wing (2008) where each input was in part allocated to generation, overhead and T&D.

For solid biomass, the amount of fuel (i.e. agricultural) input in region  $r$  was calculated given the capital and labor inputs:

$$Input_{AGR,SBIO}^r = (Input_{CAP,SBIO}^r + Input_{LAB,SBIO}^r) * \frac{Share_{FUEL,SBIO}^r}{Share_{LAB,SBIO}^r + Share_{CAP,SBIO}^r}$$

where *Input* refers to the total dollar value of the respective factor input and *Share* to the share in levelized cost of electricity (without transmission and distribution). The amount of agricultural input assigned to solid biomass exceeded the total agricultural input into energy generation reported of the GTAP data in many regions. Hence, in this case, the initial production is not in an equilibrium and needs to be rebalanced.

This approach of calculating the input shares and relating them to the output of each sector already includes a region and technology specific mark-up. This markup differs from the mark-up that would be calculated purely from the TIMER model because the ratio of the factor inputs into the electricity sector in GTAP differs from the ratios in the TIMER model, and there are intermediate inputs that are equal for all generation technologies. Nonetheless, the differences in the levelized cost of electricity of the TIMER model are well reflected in the DART model.

As there were substantial reductions in the levelized cost of renewable energy to be observed in the previous decades, learning-by-doing has been implemented in the development of inputs relative to outputs. This was done by multiplying the inputs to generate one unit of renewable electricity by a learning factor  $\gamma < 1$ , thus reducing the cost relative to conventional generation technologies.<sup>27</sup> The parameter reflects the learning rate, i.e. the cost adjustment resulting from a duplication of deployment of the technology (Yelle, 1979).

$$\gamma^r = \left( \frac{\sum_r Y_r^t}{\sum_r Y_r^{2005}} \right)^{\frac{\log(\text{Learning rate})}{\log(2)}}$$

The values for the learning rate comparable to the TIMER and have been set to 0.925 for wind, 0.825 for solar, and 0.95 for solid biomass.

### A.3.2 Fixed resource and calibration

A fixed resource is included in the production of renewable energy. This prevents flip-flop changes in the generation structure as the different generation technologies are modeled as perfect substitutes and capital is perfectly mobile. Furthermore, the calibration prevents shares from intermittent renewable energy that are not possible to sustain without additional backup or storage capacities. Alternatively higher costs for additional deployment could be viewed as measures, to increase the grid or have backup capacities, although this is not explicitly modelled.

A support policy (i.e. subsidies) ensures that there is a minimum level of each renewable activity, even if it would not be cost efficient. The subsidy rates are calculated endogenously as to meet a given level of renewable energy generation.<sup>28</sup> First, the level of the activity is not allowed to fall short of unity, i.e. there is at least the level of production that was present in the base year. Furthermore, the level of renewable energy of a given technology  $Y_{tech}$  is increasing with an increase in the electricity

<sup>27</sup>Learning does not apply for intermediate inputs as these are thought to the constant per unit of electricity generated as described above.

<sup>28</sup>This is not a renewable energy target in the sense of the European directive on renewable energy, since the level of renewable energy is not a percentage share and not dependent on total generation but rather dependent on the generation in the base year and the price development of electricity.

price  $P_{ELY}^r$ , but inversely to the price mark-up relative to the average cost of generation:<sup>29</sup>

$$Y_{tech}^{r,t} = 1 + \frac{P_{ELY}^{r,t} - P_{ELY}^{r,2005}}{1 + \text{mark up}_{tech}}$$

The subsidy rates decline over time depending on the competitiveness of the various technologies which is governed by the price of elasticity and the cost of generation which is subject to learning-by-doing.

The fixed resource in the production function is dependent on the current deployment of the technology and calibrated to match the projections in 2050 of the TIMER model for the various technologies. The functional form for the development of the fixed factor  $FF$  is similar to McFarland et al. (2004):

$$FF = 0.1 * Y_{tech}^{\lambda} K$$

where  $Y$  is the output level (output relative to the base year output),  $\lambda$  is a parameter smaller than unity and  $K$  is the capital to be used as input in the renewable technology in the reference year. Hence in the base year, when  $Y$  is equal to unity, 10% of the capital are a technology specific factor.<sup>30</sup> This means this production factor grows with the capacity in the region (“local learning”) but as a rate slower than the capacity.  $\lambda$  is calibrated such that the level of the respective renewable activities are matching the level in the TIMER model.<sup>31</sup>

As in the TIMER model, the development for hydro energy is taken to be exogenously. It could be argued that deployment of (large scale) hydro power does not only take into account economic cost benefit analysis in the presence of climate change, but also political factors. To replicate the TIMER growth path of hydro energy in DART, the activity level to be met is implemented as an additional constraint; it is met by endogenously choosing the relevant tax or subsidy rate for hydro energy.

#### A.4 Modeling of CCS in the DART model

The inclusion of advanced coal and gas technologies with capability of capturing and storing CO<sub>2</sub> closely follows the approach of the EPPA model (McFarland et al., 2004, 2009; Paltsev et al., 2010). The general approach is to add two additional sectors (gas and coal with CCS) into DART that are initially not active in the base year and are activated once their ability to generate zero-profits (as opposed to negative profits) is ensured. In mixed complementary problems, as DART is formulated, this method of including additional technologies that are not active in the base year is relatively simple (see Böhringer (1998) for a more theoretical discussion).<sup>32</sup>

Whereas for renewable energy the electricity sector was split into subsectors, here cost shares are assigned based on data from Paltsev et al. (2010) as the technologies are not present in the base year. The cost shares are reported in table A.1, the remainder to unity are intermediate inputs. The cost mark-up for the various regions is taken from the TIMER model.<sup>33</sup>

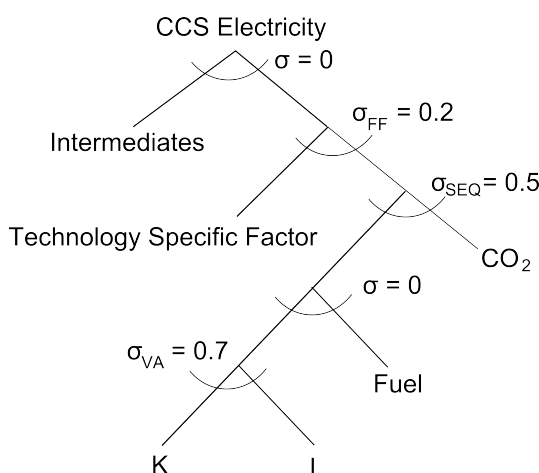
<sup>29</sup>Expensive technologies such as solar hence react less sensitive to a change in the Armington price of electricity in comparison to wind energy which is closer to being competitive in the market.

<sup>30</sup>This is deducted from the capital input  $K$  in figure A.1. The capital stock of the economy is reduced by the amount of the fixed resource to avoid double counting, although the impact would be negligible as the fixed resource is tiny in comparison to the capital endowment of a region.

<sup>31</sup>For solid biomass, the calibration does not work in all cases, as input from agriculture was too costly and hence did not become competitive in some countries in the baseline scenario. With sufficiently stringent climate policy scenarios, however, a higher level of the solid biomass activity can be observed in all regions.

<sup>32</sup>Additionally, CCS technologies are constrained to become active only for a carbon price above US\$<sub>2004</sub> 30 and only after the year 2020.

<sup>33</sup>The mark-up levels for coal are: CAN 1.53, USA 1.68, LAM 1.53, MEA 1.40, AFR 1.92, WEU 1.45, EEU 1.56, FSU 1.63, IND 1.97, CPA 1.95, PAS 1.58, JPN 1.30, ANZ 1.78. For advanced gas with CCS the mark-up was taken from Paltsev et al. (2010) and set to 1.57 for all regions.

**Figure A.2:** Production structure of renewable electricity.**Table A.1:** Input shares for CCS electricity.

Input	CCSCOL	CCSGAS
CAP	0.610	0.318
LAB	0.095	0.052
FUEL	0.105	0.432

The production function of the CCS sectors is modeled as shown in figure A.2. As for renewable resources, there are intermediate inputs which are constant per unit of electricity generated and a sector specific factor. The elasticities of the generation and sequestration process follow Paltsev et al. (2005).<sup>34</sup>

In contrast to the conventional sector, there is no carbon price for the fuel input to be paid based on its carbon content. CO<sub>2</sub> emissions however are not completely abated with CCS, roughly 85 to 90% of CO<sub>2</sub> emissions can be avoided (Hendriks et al., 2004). The CES nesting however allows for the possibility to improve capture rates at the cost of a lower plant efficiency, i.e. an increase in capital, labor and fuel can improve the capture and hence reduce residual emissions. The calibration chosen for DART is such that 90% of the emissions are captured, i.e. for 10% of the fuel input a carbon permit is needed or the carbon tax has to be paid. The CO<sub>2</sub> content of the respective fuel is used to calculate the carbon permits needed as input. An increase in capture rates can thus be observed when input prices are reduced relative to the carbon permit price.

Similar to the renewable energy sectors, there is also a sector specific factor. Its growth initially is 2.5% annually, when CCS electricity is deployed, the fixed factor growth is dependent on the level of the activity, as in the case for renewable energy. The level of the fixed factor however is only 5% of capital input. Hence, the fixed factor endowment can be calculated  $FF = 0.05 * Y_{tech}^{\lambda} * K$ , where  $K$  is the capital input and  $Y_{tech}$  the level of the activity. It is made sure that  $FF$  does not fall below the level of the last year in which growth was determined by the percentage growth rate.  $\lambda$  is calibrated such that the share of CCS electricity in total electricity in 2050 matches the results from TIMER in a scenario with a carbon tax of \$50 from 2010 onwards. The parameter values for different regions fall in the range of 0.8 to 0.9 which is used by McFarland et al. (2004). Initially the endowment in the base year is set such that it would suffice to produce 1% of electricity with CCS in the initial calibration.

<sup>34</sup>Different to the EPPA model, the generation and sequestration process have been collapsed into a single process, and the transmission and distribution part are not modelled with capital and labor but rather include other intermediate inputs.

Figure A.3: Marginal abatement curves.

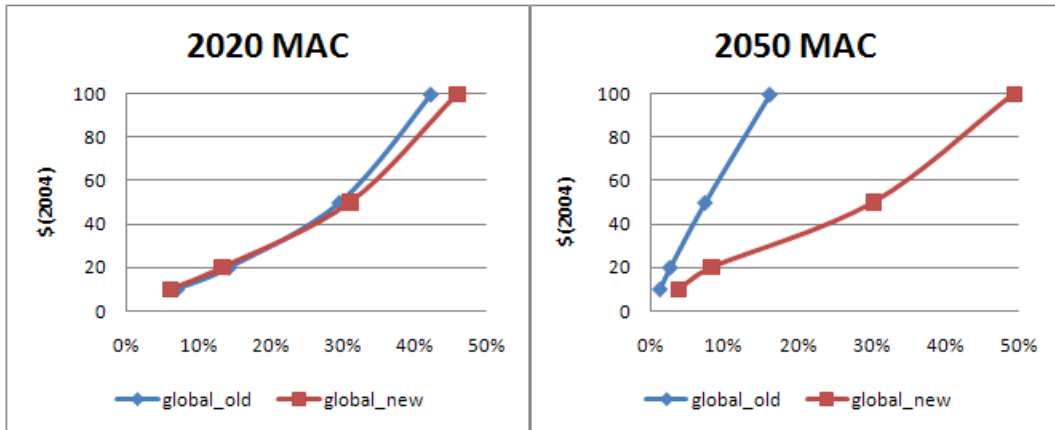
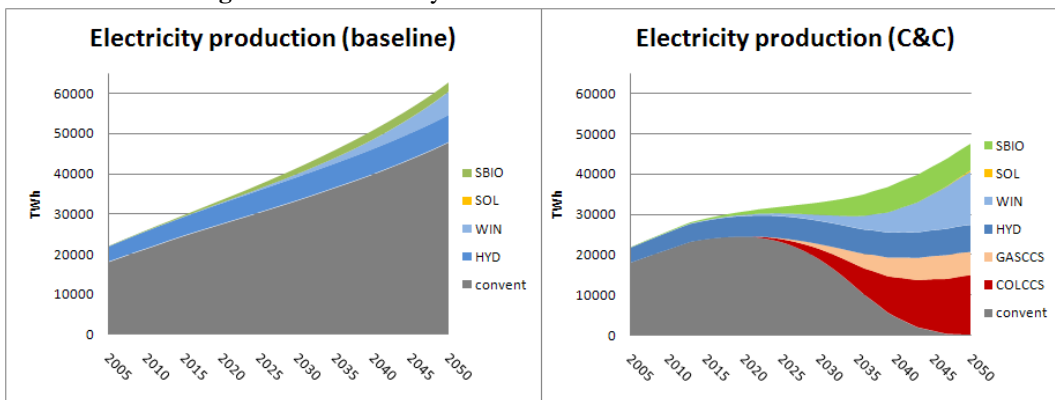


Figure A.4: Electricity mix under baseline and C&C scenarios.



### A.5 Some illustrative runs with DART

Renewable energy technologies and CCS provide for new abatement options in the DART model. This reduces marginal abatement costs compared to the previous version, especially in the long run.

In some simple runs with the updated version of the DART model, the shift in the MAC curves can be seen in figure A.3.<sup>35</sup> For 2020 the changes are relatively little, as CCS is not an option and renewables are still relatively costly. For higher carbon prices and for the more distant future (year 2050) however, the inclusion of CCS and renewable energy has a considerable effect by shifting the global MAC curves outward, hence reducing the carbon price necessary to reach a given percentage reduction.

Simulating a simple policy regime such as the Contraction and Convergence (Meyer, 2000) regime to reach a 40% reduction of global emissions in 2050 relative to 1990 with global carbon trade, the necessary carbon price almost halves to ca. \$US<sub>2004</sub> 650 compared to the previous version of DART. Figure A.4 shows the electricity mix under the baseline scenario and the C&C regime. In this graph the interaction of the features of the top-down and the bottom-up can be obvious: The top-down part determines the demand for electricity, which is reduced under the policy scenario, the bottom-up information provide information on the shift in generation to more renewable electricity and the deployment of CCS technology. With a carbon price of ca. \$US<sub>2004</sub> 650, the electricity sector becomes (almost) decarbonized by 2050, this shows that abatement in the energy sector is cheaper compared to other sectors.

There remain several shortcomings and limitations in this version. In the classification of Hour-

<sup>35</sup>Note that the changes are not only due to the inclusion of renewable energy and CCS, but also stem from changes parameter values for elasticities as described in the text.

cade et al. (2006), DART would remain a top-down model, but there are now some elements from bottom-up models included. In some assumptions, the current implementation of renewables and CCS remains “ad hoc”, however, some additional features of the electricity sector now provide more detailed information on abatement options, albeit naturally much less than a more detailed bottom-up model. A difference to bottom-up models is also the treatment of capital, which is fixed in a bottom-up model, but flexible in DART. With the fixed factor which evolves over time based on the previous deployment of advanced generation technologies, however, some features of time dependence are now present in the current model.

## Chapter IV

# Effects of international climate policy for India: Evidence from a national and global CGE model<sup>\*†</sup>

*In order to significantly reduce global carbon emissions, it is necessary to control CO<sub>2</sub> emissions also in fast growing emerging economies such as India. The question is how the Indian economy would be affected by including the country into an international climate regime. In this analysis we soft-link a global and a single-country computable general equilibrium model to be able to capture distributional issues as well as international repercussions. We analyze different options of transferring revenues from domestic carbon taxes and international transfers to different household types and the effects of different assumptions on exchange rates on transfer payments. Our results show (i) that welfare effects can differ significantly for different household types which is generally ignored in analyses with global models and (ii) that these effects are significantly influenced by international price repercussions and by accounting for transfers from international permit sales which is generally ignored in single-country models.*

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<sup>\*</sup>This chapter is accepted and forthcoming as Weitzel, M., Ghosh, J., Peterson, S., and Pradhan, B. K. (2014). Effects of international climate policy for India: Evidence from a national and global CGE model. *Environment and Development Economics*. ©Cambridge University Press, reproduced with permission.

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## 1 Introduction

While India is still a developing country, carbon emission reductions in this country are needed in order to achieve ambitious global climate targets. Furthermore, realizing the relatively cheap abatement options in India helps to minimize global mitigation costs. In 2008, India ranked third in terms of absolute emissions after China and the US (if Europe is not taken as one entity) (World Bank, 2012). If the current rapid economic growth in India continues, emissions will rise further in the next decades unless climate policy counteracts this trend.

That India is still a developing country is reflected in its per capita income of only US\$ 1410 and 32.8% of the population living on less than \$<sub>PPP</sub> 1.25 per day in 2010; per capita emissions of 1.5t CO<sub>2</sub> in 2008 are only one third of world average (World Bank, 2012). Not surprisingly, India's primary goal is to develop its economy and to reduce poverty. Yet, in the Copenhagen Accord India pledged to reduce its carbon intensity, i.e. emissions per unit of GDP, by 20 to 25 % in 2020 relative to 2005. This reduction is voluntary and not legally binding (GOI, 2010a). It is also at least questionable if this pledge is binding economically. Several projections expect that the targeted carbon intensity will be reached without new policy measures (den Elzen et al., 2010; Tavoni, 2010; GOI, 2011). In addition to this internationally visible pledge on the aggregate level, India also aims at implementing more specific measures, stated e.g. in the Jawaharlal Nehru National Solar Mission which targets 20 GW of solar electricity generation capacity by 2022 (GOI, 2010b).

Since mitigation efforts are costly and could conflict with the need to develop, most *global* climate regime proposals include measures to at least partly compensate India for their mitigation costs. In particular, many emission trading proposals include surplus allowances that India can sell on an international carbon market (see e.g. Chapter II). Assessments of costs that India would face under such global climate change regime are mostly carried out with the help of global models and indicate that India would either gain or face only little economic cost when joining an international regime (see Chapter II for an overview). Global models are useful because climate change is a global problem and only global models can analyze where abatement is most efficient. However, global models typically only represent the Indian economy in a highly aggregated way and furthermore often reduce cost estimates for India to a single aggregate figure such as impact on GDP or welfare. There is for example no information on distributional or regional impacts of climate policy.

In addition to global models, single country models are used to assess the effects of climate policy measures for India. Many of these assessments are carried out with energy system models which have a particular focus on the energy system (see e.g. Shukla and Dhar, 2011). The models do not only include various renewable energy technologies, but a portfolio of specific policies such as urban planning and transport infrastructure (Shukla et al., 2008). Computable general equilibrium (CGE) models in contrast are able to include economy wide repercussions resulting from climate policy. Early applications include Fisher-Vanden et al. (1997) who compare the cost of stabilizing Indian emissions unilaterally with the costs in a global regime and Bussolo and O'Connor (2001) who apply a single country model for India to assess impacts of climate policy on four different Indian regions, taking into account ancillary benefits of CO<sub>2</sub> reduction. Besides disaggregated sub-regions single country CGE models can include different household types. This allows determining distributional effects of climate change policies. Energy policies in India have a history of containing goals of social policies (e.g. subsidized fuels), albeit they are not always successful in fulfilling these goals (Rao, 2012). Yet, distributional impacts of any carbon abatement policy for India would be under scrutiny, especially with respect to impacts on the poorest.

Distributional effects of climate mitigation policies such as carbon taxes have been in the focus before. Boccanfuso et al. (2011) present an overview of intra-country distributional impacts. Most



of the studies are focused on industrialized countries but there is no consensus on whether the overall effects are regressive (e.g. Jorgenson et al., 2011) or progressive (e.g. Rausch et al., 2010; Oladosu and Rose, 2007). There are fewer studies for developing countries. For Indonesia, Yusuf and Resosudarmo (2007) find carbon taxes to be progressive for rural households but neutral to progressive for urban households. For China, Boyce et al. (2005) find that carbon taxes would be progressive, while Liang and Wei (2012) argue that carbon taxes would widen the rural-urban income gap without transfers targeted to rural households. For the Philippines, Corong (2008) finds that higher skilled workers have higher welfare gains when carbon tax revenues are used to reduce income taxes. In general, the progressivity of a carbon tax is determined by the design of revenue recycling, the carbon intensity of consumption patterns of different households, and changes in the demand for factor endowments of different households. For India, two papers analyze the impact of climate policy on poverty. Murthy et al. (2007) find that a decrease in per capita income leads to an increase in poverty. Ojha (2009) finds an increase of poverty which cannot be eliminated but significantly reduced if tax revenue is recycled as transfers to poor household groups.

In single country CGE models, India is usually modeled as a small open economy, i.e. it is implicitly assumed that national climate policy is carried out in the absence of climate policy abroad and has no effect on world markets. Global models however are able to simulate international carbon markets and repercussions on international energy markets. In this paper we want to bring together both types of models to overcome the shortcomings of the existing analyses which are either very aggregated or ignore international repercussions. We do so by soft-linking the multi-region CGE model DART to a one-country CGE model for India, in order to take advantage of the specific capabilities of both types of models. In particular, we analyze on the one side the distribution and allocation effects of international climate policy regimes for India in more detail, while on the other side we account for two important implications of a global regime, namely the impact of international transfer payments and price repercussions on international markets.

As mentioned above, financial transfers are seen as means to compensate for mitigation costs. In some cases these financial flows can be substantial and can influence exchange rates and thus competitiveness of countries. This issue was first debated between Keynes and Ohlin in 1929, but has also been applied to climate change regimes (McKibbin et al., 1999b,a). The multi-regional, perfect foresight model of McKibbin et al. includes a rather sophisticated representation of international financial flows based on returns to investment and trade in carbon permits. While there is no explicit modeling of exchange rates in DART, the national model captures some of the exchange rate movements.

Concerning price repercussions on international markets, ambitious climate policy has the effect that carbon intensive products become (relatively) more expensive, and that fossil fuels are demanded less. Countries that are net importers of fossil fuels – such as India – can thus benefit from lower energy prices (net of carbon prices) through improved terms of trade. CGE models are able to capture these repercussions as the interplay between markets is taken into account. This fuel price effect is acknowledged in global models (e.g. Böhringer and Rutherford, 2002) but to our knowledge not in any national model study for India. In our analysis we pass on variations in international fuel prices that show up in the global model to the national model so that the impact of changes in terms of trade is accounted for. At the same time, the national model shows which types of agents in the economy profit from this effect.

Since a considerable share of the population in India still lives below the poverty line, the impact on poor household groups is of particular importance. We thus focus on distributional impacts of climate policy and analyze how carbon pricing, (international) transfer payments and international price repercussions affect different household groups. Compared to earlier studies mentioned

above, we extend the simulation horizon to 2050 and incorporate current climate policy (Copenhagen pledges) into the analysis. By using harmonized models, there is greater consistency when feeding global data such as prices for CO<sub>2</sub> or energy into the national model. With such a soft-link of the two models we aim in particular to shed light on the following research questions: How do additional insights from a national model change when taking into account that the rest of the world is also engaging in climate change and causing changes on international markets? How robust are the results from the national model when changing the outside world? How does the more detailed analysis of the national model compare to the international broad picture?

The paper is structured as follows: Sections 2 and 3 describe the models and the policy scenarios, respectively. Focusing on distributive effects for different household types as mentioned above, Section 4 presents and discusses the simulation results. Section 5 concludes.

## 2 Model description

In this study, two computable general equilibrium (CGE) models are used. While DART is a multi-regional model of the entire world economy, IEG-CGE is a national model of the Indian economy. Both models are multi-sectoral, recursive-dynamic models solving for a sequence of static one-period equilibria for future time periods. The time horizon of this study is 2050.

DART is based on the GTAP 7 data set (Narayanan and Walmsley, 2008) with the base year 2004, aggregated to 12 sectors and 13 regions including India (see Weitzel et al., 2012). Based on bottom-up information, the electricity sector is split into conventional generation and new generation technologies from four renewable sources (wind, solar, biomass, and hydro); additionally electricity generation with carbon capture and storage (CCS) from gas and coal is introduced as a latent technology (see appendix of Chapter III). Electricity from different generation technologies are assumed to be perfect substitutes, each technology has a convex cost function and exhibits learning.

IEG-CGE (Pradhan and Ghosh, 2012b,a) consists of 18 sectors rather similar to the DART sectors (see appendix A). The main data source is a social accounting matrix (SAM) for India (for 2003-04) developed by Ojha et al. (2009) that includes a decomposition of the electricity sector into three separate sub-sectors (hydro, nuclear and non-hydro). For this study the non-hydro sector was further disaggregated into thermal and wind/solar electricity and, in addition, a sector that uses CCS technology (coal) to produce electricity was created. The CCS technology sector is similar to the thermal electricity sector, but is less efficient and produces emission free coal based electricity.

Producer behavior in both models is derived from cost minimization for a given output or equivalently profit maximization. All industry sectors are assumed to operate in perfectly competitive markets and at constant returns to scale. Multi-level nested separable constant elasticity of substitution (CES) function describes the technological possibilities (see Figure A.1 in the appendix for the nesting structure). Primary factors include labor and capital and in DART also land. Factor markets are assumed to be perfectly competitive and there is full employment of all factors which are sectorally mobile, but in DART regionally immobile.

Households maximize utility subject to income and prices, and household demand is modeled through the Linear Expenditure System (LES) that first satisfies basic needs. The remaining consumption good is a composite of an energy aggregate and a non-energy aggregate. Household income comprises factor income and transfers from the government and the rest of the world. Households also save a fixed part of their incomes and pay taxes to the government. While in DART there is one representative agent in each region, households in IEG-CGE are classified into nine categories:

**Table 1:** Economic indicators for the different household groups in the base year (2004)

Household group	Per capita income (US <sub>2004</sub> )	Share of labor income <sup>a</sup> (percent)	Share of capital income <sup>a</sup> (percent)	Share of total income (percent)	Share of total population <sup>b</sup> (percent)
Rural non-agricultural self-employed (RH1)	467	8.3	8.6	8.4	10
Rural agricultural labor (RH2)*	213	15.9	0.1	9.1	23
Rural other labor (RH3)*	313	5.0	0.4	3.0	5
Rural agricultural self-employed (RH4)	462	14.0	34.2	22.6	27
Rural other households (RH5)	616	3.5	12.6	7.4	7
Urban self-employed (UH1)	643	10.1	13.8	11.7	11
Urban salaried (UH2)	1118	36.3	3.0	22.1	11
Urban casual labor (UH3)*	466	5.5	1.0	3.6	4
Urban other households (UH4)	1002	1.3	4.5	2.7	2
All	512	100.0	78.2 <sup>c</sup>	90.7	100

Calculations from SAM; households marked with an asterisk are considered as poor in this study; <sup>a</sup> household factor income shares based on Pradhan and Roy (2003); <sup>b</sup> population shares from Sundaram and Tendulkar (2003); <sup>c</sup> remaining capital income goes to public and private enterprises, government, and rest of the world; exchange rate assumed to be 44 rupees per dollar

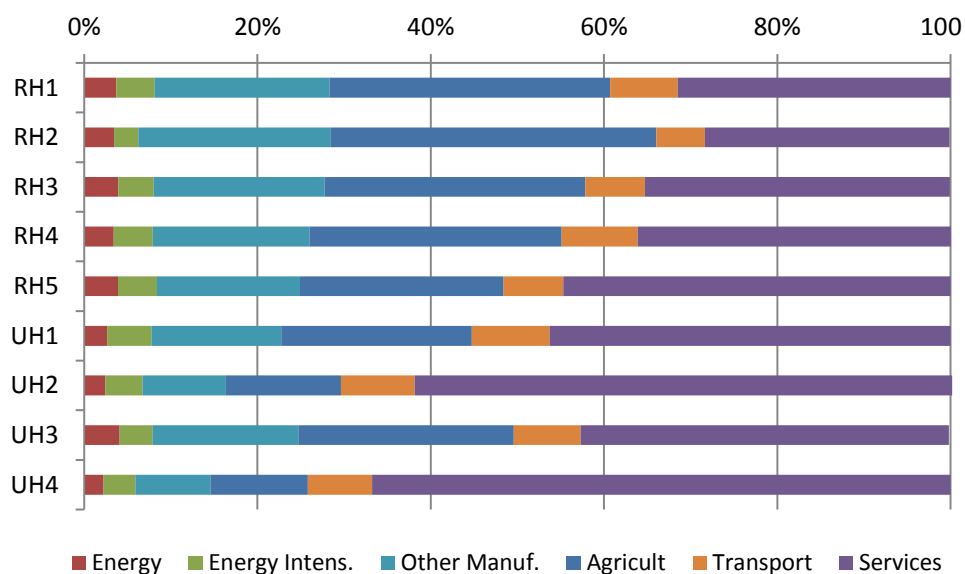
five of them are rural and four of them are urban (see Table 1).<sup>1</sup> We consider three labor households types (two rural and one urban) as poor, these households with a low per capita income are characterized by a lack of income derived from capital. Richer households have a higher expenditure share for services; the share of energy expenditure is slightly higher for poor households (Figure 1). This difference in preferences is captured in the calibration of the LES. When households become richer, the share of services in their expenditure increases.

Both models follow an investment-driven closure, i.e. aggregate investment is fixed. In DART only households save at a fixed exogenous rate. In IEG-CGE aggregate savings is the sum of household, government, corporate and foreign savings and adjusts to satisfy the saving-investment balance. Foreign savings is assumed to be fixed while the real exchange rate is flexible. Government expenditure for consumption of goods and services, transfers to households and enterprises as well as subsidies rates are fixed. Government savings is residually determined.

In DART, all regions are linked by bidirectional trade flows of all commodities except the investment good and in both models domestic and foreign commodities are imperfect (Armington) substitutes. They are also distinguished by the country of origin in DART. There is no direct balance of trade constraint, only at the global level trade has to be balanced.

In DART, the major exogenous, regionally different driving factors of the model dynamics are population growth, labor productivity growth, human capital growth and capital accumulation. Rather similar, IEG-CGE assumes exogenously determined growth in total factor productivity (TFP), labor force, government consumption expenditure and aggregate investment. In both models, capital accumulation is driven by exogenous depreciation and savings rates. In order to capture future in-

<sup>1</sup> Even though households are categorized by occupation, their labor endowment can be used in any sector. This allows for change in the economic structure on the production side.

**Figure 1:** Expenditure shares for different household types in the base year.

creases in energy efficiency, an energy efficiency growth rate is assumed. In DART, the autonomous energy efficiency improvement is 1% per year, for the electricity sector 0.1%; in IEG-CGE it is 1.5%.

In both models GDP growth is calibrated according to the OECD Environmental Outlook (OECD, 2012) by adjusting factor productivities. In DART, CO<sub>2</sub> emissions of the baseline scenario (see Section 3.1) are calibrated by adjusting the elasticities of fossil fuel supply to match global CO<sub>2</sub> emissions. In IEG-CGE, exogenous drivers for CO<sub>2</sub> emissions are world market prices of fossil fuels and energy efficiency improvement (see Chapter III).

### 3 Scenarios

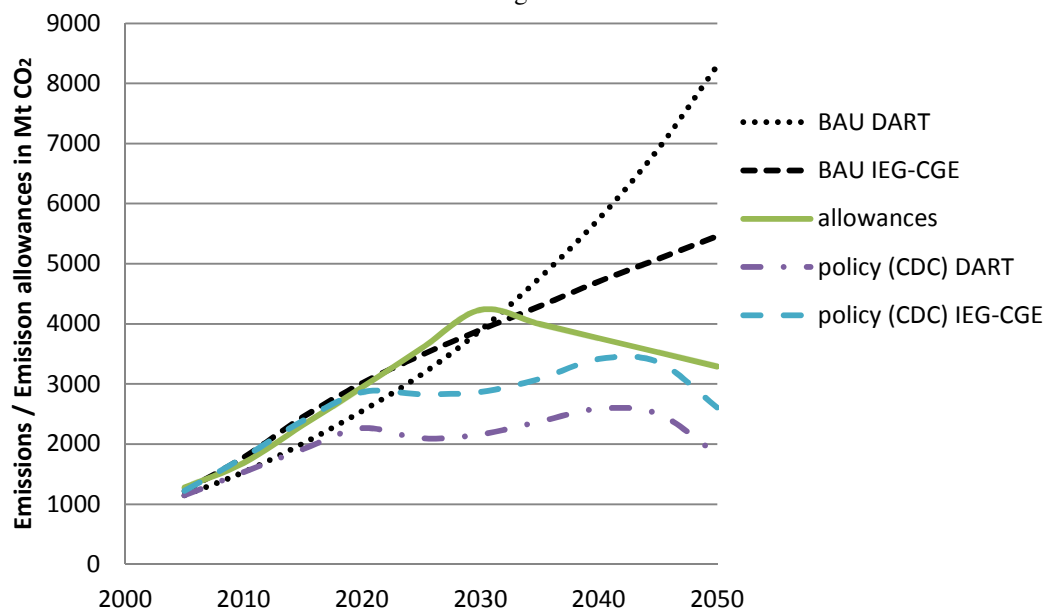
#### 3.1 Baseline scenario [BAU]

The models were harmonized with respect to GDP and population (i.e. labor force) projections. The GDP path follows the reference scenario of the OECD Environmental Outlook (OECD, 2012). The population projections are based on the medium variant of UN World Population Prospects (UNDESA, 2011). Globally, the population is projected to increase to 9.5 billion people in 2050, with 1.6 billion in India. Energy use and therefore CO<sub>2</sub> emissions differ between the models (see also Chapter III for a more detailed comparison on energy use). In DART, global emissions reach 54 Gt CO<sub>2</sub>, with India contributing 8.3 Gt. In IEG-CGE, baseline emissions are only 5.5 Gt in 2050. As Figure 2 shows, emissions in IEG-CGE are growing slightly faster than in DART in the near future, while emission projections in DART are higher after 2030. Both models project little change in the carbon intensity in the baseline; a higher improvement in the energy intensity in IEG-CGE explains the difference in CO<sub>2</sub> emissions.

#### 3.2 Climate policy scenarios

It is not possible to implement a dynamically efficient climate policy in a recursive-dynamic model. In our analysis, we follow a “standards and prices approach” (Baumol and Oates, 1971), i.e. take an exogenous emission path and determine minimal economic cost to achieve this path. The emission

**Figure 2:** Indian emissions under the [BAU] and policy scenarios in DART and IEG-CGE. Emissions allowances for international emission trading are also shown.



path incorporates the Copenhagen pledges until 2020. After 2020, it is derived from intertemporal optimization with the target to avoid a global temperature rise of more than two degrees compared to pre-industrial times with 50% probability (see Chapter III for a detailed discussion of the pathway). In the basic climate policy scenario global energy related emissions peak in 2020 at a level of 34 Gt CO<sub>2</sub> and are subsequently reduced to 17.6 Gt in 2050. Compared to baseline emissions, this is a reduction of 67%, or 17% below 1990 emissions. A global harmonization of marginal abatement cost is reached via global emission trading. We hold global emissions constant in all policy scenarios, i.e. there are no efficiency gains or losses from changing the temporal emission dynamics dimension between scenarios in order to avoid confounding welfare effects.

To derive a first best policy outcome, a forward-looking model would be necessary. Babiker et al. (2009) compare a recursive-dynamic to a forward-looking model and conclude that while forward-looking dynamics have preferable theoretic properties, the simulation differences in the energy sector were relatively small. Macroeconomic costs were lower in the forward-looking model because of consumption smoothing. However, the forward-looking dynamics forced the modelers to simplify the technological detail of the respective model in order to reduce complexity and to achieve computational feasibility. In this paper, our aim is not to find the cost minimal pathway for emission reductions, but we are interested in the differences between several scenarios that all incorporate the Copenhagen pledges. These pledges are not dynamically efficient because they were set politically. For our purpose a recursive-dynamic model is therefore justified.

For India, CO<sub>2</sub> emission reductions in the policy scenarios are determined endogenously: In the global model DART they are the result of equalizing marginal abatement costs globally. In the national model, CO<sub>2</sub> prices are taken from DART and imposed as a domestic carbon tax. For the simplest scenario, this is the only information passed on from the global to the national model. Fisher-Vanden et al. (1997) and Shukla et al. (2008) also use this methodology, however our study is potentially more consistent because the global and the national model are harmonized to some degree. Due to differences in abatement potential and costs in the two models, the policy pathways turn out to be somewhat different. Both models stay near the baseline close to 2020, followed by a longer stabilizing period. After 2020, effort has to be increased in order to reach the overall reduction target. This leads to a higher global CO<sub>2</sub> price which also slows Indian CO<sub>2</sub> emissions. Emissions

**Table 2:** Surplus allowances, CO<sub>2</sub> prices and resulting international transfer revenues in the policy scenario.

year	surplus allowances		CO <sub>2</sub> price (US\$/tCO <sub>2</sub> )	International transfer revenues			
	(Mt CO <sub>2</sub> )			billion US\$		% of baseline GDP	
	DART	IEG		DART	IEG	DART	IEG
2015	401.4	-73.3	1.9	0.8	-0.1	0.1%	0.0%
2020	680.0	81.5	6.8	4.6	0.6	0.2%	0.0%
2030	2071.4	1366.6	71.1	144.4	95.3	3.2%	2.1%
2040	1173.6	346.4	145.7	166.8	49.2	2.0%	0.6%
2050	1461.9	681.2	440.8	567.3	264.4	4.7%	2.2%

in both models peak in the 2040s and decline towards 2050. For both models, abatement potential becomes increasingly scarce, especially after 2040, which leads to high CO<sub>2</sub> prices of 441 US \$<sub>2004</sub> in 2050, compared to 146 US \$<sub>2004</sub> in 2040 (see Table 2 or Chapter III for the whole path). Compared to the baseline, both models show improvement in both carbon and energy intensity.

### 3.2.1 Revenue allocation

It is important how revenues from domestic carbon taxes are used because they can potentially bring along a double dividend.<sup>2</sup> There is also a discussion of an additional third dividend in terms of reduced poverty (see e.g. van Heerden et al., 2006, who also briefly review the relevant literature). We distinguish between three different uses of revenue:

- [all] Revenues are transferred to all household groups based on their population share. This is closest to the assumption of the DART model where one representative agent is receiving all revenues. This scenario is equivalent to an equal per capita allocation of emission rights for all Indian households.
- [poor] Revenues are transferred only to the poor household groups based on the respective population shares of RH2, RH3, and UH3.
- [gov] Instead of making lump sum payments to households, the revenues are used for government investments. This leads to crowding-out and lower savings from other agents.

### 3.2.2 International transfers

To account for the different development status of countries, many regime proposals include a transfer of funds. We model a common-but-differentiated-convergence (CDC) regime (Höhne et al., 2006) that allows emissions of developing countries to peak later than emissions of developed countries. We assume that all countries first fulfill their (high) Copenhagen pledges and subsequently Annex I countries converge to 1.7 t CO<sub>2</sub> per capita in 2040, while other countries start their 30 year convergence period between 2020 and 2035 (see Chapter III for the detailed assumptions). In this regime, India enters in 2030 and converges in 2060. India's allowances peak at 4.23 Gt in 2030, and amount to 3.29 Gt in 2050 (see also Figure 2).

Under the CDC regime India sells emission allowances on the international carbon market. In the Indian model, international carbon trade is not modeled directly. In addition to the domestic

<sup>2</sup>If revenues from environmental taxes are used to lower other distorting taxes, this potentially yields not only a first, environmental dividend but also a second, economic dividend in terms of more employment or GDP.

carbon tax (with the carbon prices from DART), capital flows from international carbon trade are calculated from the difference of (exogenous) allowances with (endogenous) actual emissions in the Indian model, multiplied with the (exogenous) carbon price.<sup>3</sup> The revenues from international carbon trading are allocated in the same way as the revenues from domestic carbon tax (see Section 3.2.1). The magnitude of financial flows is rising over time, due to the rising CO<sub>2</sub> price (see Table 2). When the revenue is expressed as a ratio of GDP, a drop around 2040 is visible due to lower surplus emissions in that year. Generally, the DART model projects a higher amount of permits sold on the international carbon market than IEG-CGE, hence capital flows are higher. However, each model is internally consistent and the price of carbon is equal in both models.

Because DART is based on data in real values, there is no exchange rate. Allowances are allocated to the representative agent (RA) in the respective regions. Changing the allocation of allowances implies a transfer of income from one region to another. Compared to a scenario where the globally efficient reductions are reached via a harmonized global carbon tax so that there are no financial transfers, the RA in India is enjoying a larger endowment of allowances in the CDC scenario which increases national income. This leads in turn to demand changes in India, which are partly fulfilled by domestic production and partly by imports. This means that consumption as well as relative prices rise and therefore Indian trade is affected in DART, but not because there is a change in the exchange rate but through the income transfer as such. In IEG-CGE, in all scenarios with capital inflows, demand is increased for the same reasons as explained above. In addition, in IEG-CGE the exchange rate decreases, i.e. the rupee appreciates, as a result to the capital inflow. This leads to higher imports and lower exports.

In order to assess how insights from a national model change when taking into account that the rest of the world is also engaging in climate policy and causing changes on international markets, we run a set of scenarios with IEG-CGE based on the carbon prices of DART. The scenarios differ in the dimension of the (real) amount of transfers and the usage of carbon revenue. The (real) amount of capital inflow is varied both by different modeling and policy assumptions focusing on commonly made proposals:

- [noTr] No international transfers are assumed. This scenario is similar to a globally harmonized carbon tax regime with no compensation payments. The tax rate for the domestic CO<sub>2</sub> price in India is taken from the DART model.
- [Tr-Rup] Transfers take place and are based on the allowances that India is able to sell on the international carbon market under the CDC regime. Here we denominate the transfers in rupees, i.e. fix the exchange rate for the carbon price at the base year. This excludes the effect of the Indian appreciation, i.e. the exchange rate changes are as in the [noTr] scenario in which the exchange rate reacts only to a change in the demand and production structure.
- [Tr-\$] Recognizing that transfer payments will not be carried out in rupees and can potentially shock the exchange rate, we denominate the carbon price in US\$. Due to the appreciation in response to the capital inflow, the exchange rate appreciates and the real transfer payments are smaller than in [Tr-Rup].

### 3.2.3 Repercussions in international markets

IEG-CGE is a small open economy model, with the underlying assumption that India and the rest of the world do not affect each other through price changes. In the climate policy scenario, there are hence no international repercussions in IEG-CGE. In DART, the main repercussions are twofold: On

<sup>3</sup>This approach is similar to Fisher-Vanden et al. (1997) and Ojha (2009), although they use different international regimes.

the one hand, climate policy is carried out globally, hence global world market prices (especially for fossil fuels) change because of the carbon price and a reduced demand for fossil fuels. On the other hand, the Indian economy is affected by the climate policy which is reflected in changing demand patterns, leading to different import and export prices for other goods as well. The latter effect is smaller in terms of price changes and is thus neglected in this study.

In terms of modeling, we pass on relative price changes due to international climate policy from DART to IEG-CGE for each simulation year. In DART, export prices for India result from a transformation function where producers produce for the domestic and the world market. For imports a nested Armington function is used in DART. In the first stage, a composite of goods from different regions is aggregated which in a second step is combined with domestic varieties. We pass on the price of this first step composite to IEG-CGE. The prices are expressed relative to an Indian price index which is used as numéraire in the Indian model. Again, we harmonize prices; quantities in trade volumes are not harmonized and can differ between the two models.

We differentiate between three scenarios with different extend of passing on price information from DART:

- [P-exo] Exogenous world market prices are assumed for IEG-CGE, which are not changed between the baseline and the policy scenario. This scenario is standard for most single country analyses, but fails to account for repercussions on international markets.
- [P-fuel] Relative changes in fossil fuel world market prices due to climate policy are passed on from the DART model, i.e. are different between baseline and policy scenario.
- [P-all] Relative world market prices changes for all sectors due to climate policy are passed on from the DART model. This also accounts for interconnections through intermediate markets. Since sectoral aggregation differs slightly between the two models, the price changes were mapped to different sectors where appropriate.

With the help of these scenarios we can analyze the distributional impact of international price repercussions, i.e. the impact on different household groups and put it in relation to the overall impacts of climate mitigation. In combination with the variations concerning capital inflows, we can also derive interactions between price effects and transfer payments.

## 4 Simulation results

Soft-linking DART to IEG-CGE generally affects all model outcomes of IEG-CGE. For example, CO<sub>2</sub> emissions and production of energy intensive goods rise when lower fossil fuel prices resulting from international climate policy are passed on from DART to CGE-IEG. All sectoral production as well as export and import levels react to the relative changes in input prices. While we discuss some of the relevant reactions in IEG-CGE, as for example the changes in sectoral production levels resulting from different assumptions on the allocation of transfers, our focus is on welfare and income gap changes for the different household groups in order to assess how different groups are affected by international climate policy. All results are taken from the national CGE model if not stated otherwise. We also briefly discuss overall welfare changes in IEG-CGE and DART.

### 4.1 Effects of revenue allocation

The welfare impacts of our basic climate policy scenario implemented via a (domestic) carbon tax are comparable to previous estimations of single-country CGE models. In our first analysis, we vary



the recipients of the tax revenue and there are no international transfers. The resulting welfare losses for different household types relative to the [BAU] scenario without climate policy are shown in Figure 3.<sup>4</sup> Not surprisingly, the decision of how to use the revenue of a carbon tax is crucial for how the households' welfare is affected. The top part of Figure 3 shows welfare losses for a domestic carbon tax with lump-sum payments of the tax revenue to [all] households which is equivalent to equal per capita emission rights. In this case poor households as defined above (RH2, RH3, and UH3) can gain substantially. Despite the fact that tax revenue remains below 5% of GDP in 2050, gains for the "poor" RH2 group can reach almost 20%. The per capita transfer payments are higher for poorer households relative to their consumption expenditure. Furthermore, the LES consumption framework assumes a higher share of subsistence consumption for poorer households. Equal income per capita gains thus lead to higher welfare changes for poor households. On the contrary, richer households are negatively affected. The overall more pronounced effects towards 2050 are due to the high CO<sub>2</sub> tax and the lack of abatement possibilities in the models (see also Chapter III). In this scenario per capita income of poor households reaches 63% of rich households' per capita income in 2050 (compared to only 40% in 2005 or 54% in the [BAU] scenario in 2050). The reduction of the income gap occurs within groups, i.e. poor urban (rural) households reduce the gap to rich urban (rural) households. This holds especially for poor rural households who are the households with the lowest per capita income. However, the relative income difference between urban and rural households increases over time both in the [BAU] and the policy scenario.

If tax revenue is exclusively re-distributed to the three [poor] household groups, these effects are reinforced. Compared to the other richer households groups, urban salaried households (UH2) are relatively unaffected. Welfare gains for poor rural households reach about 70% in 2050. Towards the middle of the century, per capita income of rural poor households reaches the level of other rural households.

The picture becomes rather different when government uses the tax revenue for investment ([gov]). Now the effects are rather similar across household types, though poor households as well as UH2 are affected slightly more adversely than other household classes. The main explanation is that richer households are saving less due to crowding-out and consume more instead. Furthermore, urban households spend a higher share of their income on less carbon intensive services for which the average carbon tax rate is lower. Because savings rates of richer households are higher, GDP growth is slightly higher than in scenarios with more redistribution and thus the total (weighted) welfare losses are smallest in this this scenario. In short, we find that while distributing tax revenue to households is progressive, using tax revenue for government investment is regressive. At the same time, using the revenue for investment decreases overall costs of climate policy.

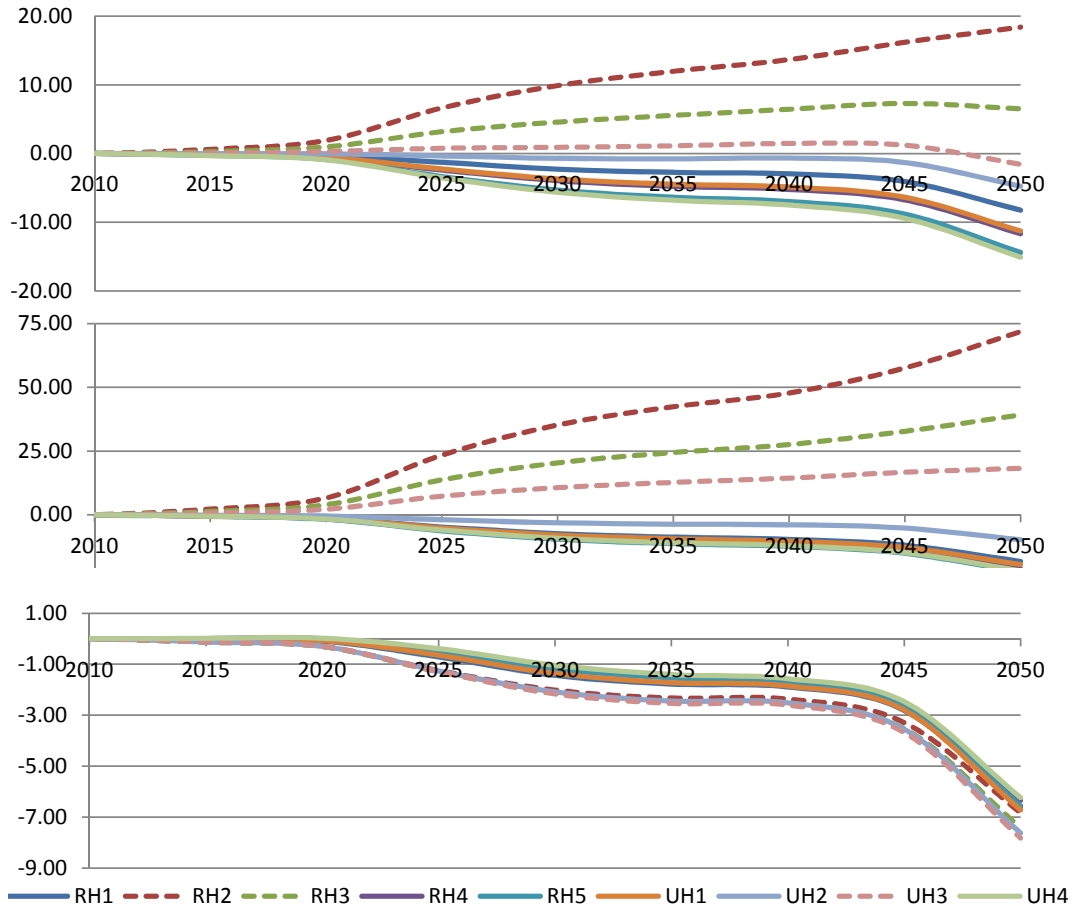
## 4.2 Effects of international transfers

In a second step, we add international financial transfers to the model. This reflects an international regime (CDC) in which India is able to sell allowances on an international carbon market. For the start we assume that the revenues from selling allowances are paid in lump sum fashion to the households in addition to the tax payments and that transfers are in US-\$ ([Tr-\$]). In Figure 4, we isolate the effect of additional revenue of international transfers, i.e. we are analyzing welfare changes relative to the respective [noTr] scenario. The N-shape of the figures can be explained by the variation of revenues relative to GDP over time as shown in Table 2.

When the international transfer payments are distributed on a per capita basis to [all] households,

<sup>4</sup>Note that the models only include welfare effects from mitigation and do not include benefits or damages from avoided climate change. This allows consistent analysis of welfare changes between policy scenarios because emissions are the same, but needs to be taken into account for interpretation of welfare losses relative to [BAU].

**Figure 3:** Welfare impact (% Hicks EV) for different households of domestic climate policy compared to the [BAU] scenario. The top panel shows welfare impacts of scenario where revenues flow to [all] households, in the middle revenues go to [poor] households exclusively and at bottom revenues are used for investments by the government [gov]. Poor households marked with dotted lines.

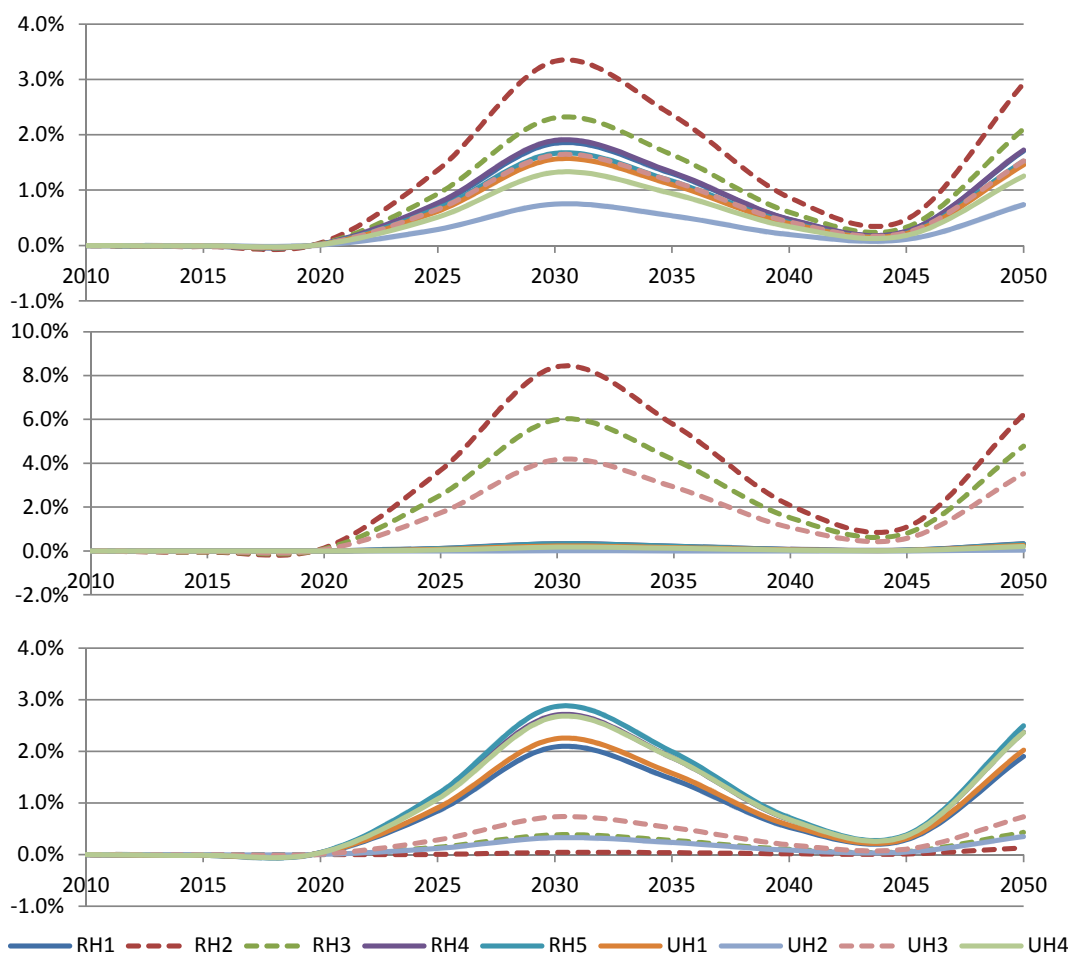


poorer households gain more than richer households for the reason explained in Section 4.1. The total welfare gains for poorer households from climate policy get stronger, while richer households can only partly offset their welfare losses from the scenario without international transfers. This effect is even stronger when transfer payments are restricted to the [poor] household groups.

When transfer payments are used for government investments ([gov]), poor households profit less from the transfers than rich households, similar to the case when the tax revenue was used for government investments. Household groups with the highest gains from the capital inflow are in this case richer household types (except UH2). Transfers are able to fully offset the losses from CO<sub>2</sub> emission reductions shown in Figure 3 until the 2030s. Poorer households gain relatively little from the transfers under this scheme. The findings are broadly consistent with Ojha (2009) who finds that without targeted transfers of revenues to the poor poverty increases. As carbon taxes and thus transfer payments in Ojha (2009) are lower than in this study, the transfer schemes are not sufficient to fully compensate poor households.

Compared to Figure 3, which shows impacts of different allocations for domestic carbon tax revenue, the effect from the additional transfers from carbon trading seems rather small. The magnitude of transfer payments reaches about a quarter of the domestic tax revenue. However, the welfare changes induced by the transfer payments are substantially smaller than a quarter of initial gains.

**Figure 4:** Welfare improvement of different households due to international financial transfers [Tr-\$] relative to respective [noTr] scenario under different allocation schemes: [All] households (top), [poor] households (middle) and government [gov] (bottom).



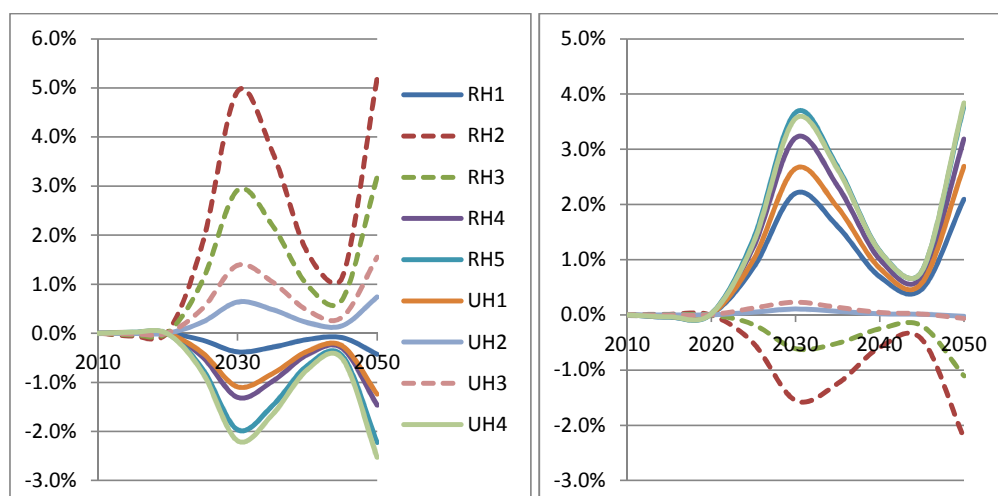
This is due to the fact that international transfer payments are paid in foreign currency. Inflow of foreign currency leads to an adjustment of the exchange rate in IEG-CGE which significantly reduces the gains from the transfer payments.

To decompose the total effect shown in Figure 4 into a transfer effect and an exchange rate effect, we first compare the welfare changes between a scenario without transfers ([noTr]) and a scenario with payments in rupees calculated based on an exogenous exchange rate ([Tr-Rup]) to single out the transfer effect. We then compare the scenario with payments in rupees ([Tr-Rup]) and in US dollars ([Tr-\$]), respectively to derive the pure exchange rate effect.

Figure 5 plots the transfer and exchange rate effects for the case where revenues are paid lump-sum to all households on a per capita basis. For poor households, the transfer effect is larger than the total effect (cf. Figure 4 above). Surprisingly, the transfer effect for richer households is negative despite that all households receive some funds, although for richer households the transfer relative to their expenditure is smaller than for poorer households. The negative welfare effect for the richer households is caused by detrimental price changes as there is a shift towards labor intensive production which leads to decreasing non-labor income.

The exchange rate effect leads to an additional appreciation and is counteracting the transfer effects. Here, richer households gain while poorer households are experiencing welfare losses. This is due to the fact that richer households consume more goods from sectors that have a higher share

**Figure 5:** Decomposition of the total effect of international payments. Welfare changes of transfer payments (to [all] households, cf. Figure 4, top panel) decomposed into pure transfer effect (left) and an exchange rate effect (right).



of imports and poorer households work in sectors with higher export shares. In the absence of an exchange rate adjustment (i.e. when transfer payments are in rupees), the additional demand from transfer receipts leads to quantity changes, while when the transfer payments are denominated in foreign currency, part of the demand shock is absorbed in exchange rate adjustments. The total effect as shown in Figure 4 above is smaller than the pure transfer effect, as exchange rate adjustments reduce the transfer effect for the (poorer) households.

### 4.3 Effects of repercussions in international markets

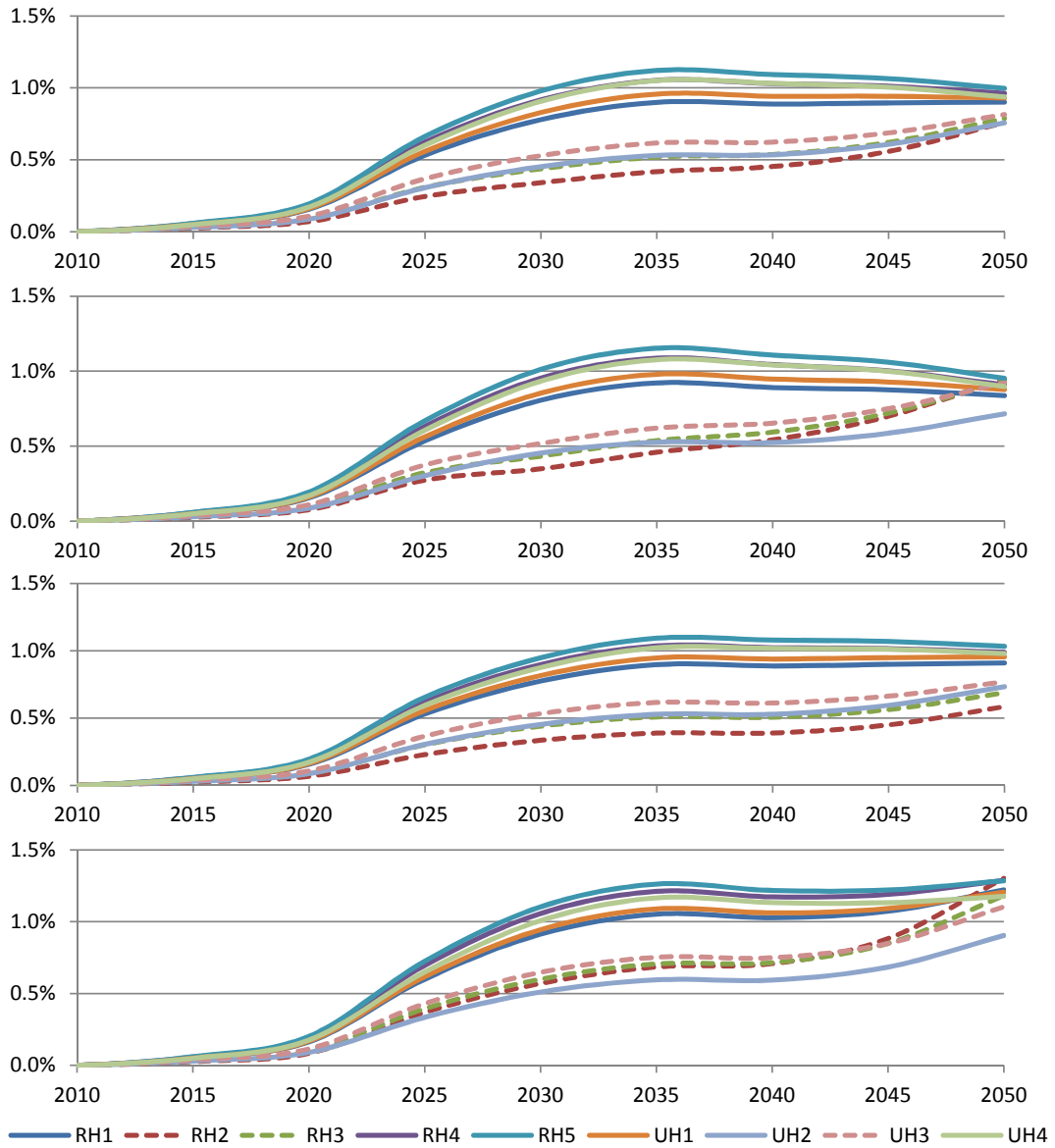
International repercussions of global mitigation policies are also transmitted via price changes on international markets. In particular, fossil fuel demand and therefore also fossil fuel prices net of carbon costs decline under a CO<sub>2</sub> cap. Single country models do not include export and import price changes and therefore lack some important consequences of international climate policy. For DART it is not possible to exclude the price effect<sup>5</sup>, but the price effect can be separated in the national model. We can also determine the relative importance of fuel prices which show the strongest reaction in the policy scenario compared to the baseline and the price changes of other sectors which stand for the larger share of import and export values. In DART, compared to the [BAU] scenario import prices for India in 2050 are reduced by 64% for coal, 56% for crude oil, 52% for refined oil and 38% for gas, respectively. Price changes of other sectors remain in the range of  $\pm 10\%$ .

Figure 6 presents the welfare changes induced by price changes in global fossil fuel markets for different transfer scenarios. For adjustments in fossil fuel prices only [P-fuel], all households improve their welfare because India is a fossil fuel (net) importer. The income gap between rich and poor households is almost unaffected, yet richer households have relatively higher welfare gains in 2030. Lower fuel prices do not only bring along welfare gains for households with fuel intensive consumption, but also import intensive consumption in general as the balance of payments constraint is relaxed. This is comparable to the exchange rate effect described in Section 4.2 which benefits the richer households.

The gains from fossil fuel price repercussions differ however for different distributions of tax

<sup>5</sup>Veenendaal et al. (2011) adjust natural resources endowments of countries with the aim to hold energy prices fixed in a climate policy scenario in order to estimate leakage effects. Such adjustments create endowment effects which affect welfare, so that welfare comparison is not feasible with this approach.

**Figure 6:** Welfare changes induced by price changes in global fossil fuel under different transfer scenarios. The four parts (top to bottom) show the impact from switching from [P- ex] to [P-fuel] with international transfers [Tr-\$] to [all] households, [poor] households and [gov] and without internal transfers [Tr-no] (revenues from domestic tax allocated to [all] households).



revenues and international transfers. When revenues are distributed to [all] households or used for investments by the government ([gov]), rich households have larger welfare gains than poorer households. When allocating revenues only to [poor] households, at least in the long run the poor household have similar gains as richer households because incomes of poorer households rise due to the transfers and thus consumption patterns change towards those of richer households. International price repercussions thus benefit the poor households more in scenarios in which they already have a higher income.

Without international transfers the gains from decreased fossil fuel prices are stronger than with international transfers; this holds especially for poorer households. International transfers lead to an appreciation (see Section 4.2) which already reduces the cost of (fossil fuel) imports. The reduced world market price due to international climate policy thus has a smaller (additional) impact in the presence of international transfers.

**Table 3:** Accumulated and discounted welfare changes relative to [BAU] for poor households vs. overall welfare in IEG-CGE.

Fuel price adjustments	International transfers (in US\$)	Poor households' welfare changes <sup>a</sup> when revenues are allocated to:			Overall welfare changes (in %) when revenues are allocated to:		
		poor	all	gov	poor	all	gov
No	No	+	+	–	–5.1	–3.4	–2.4
No	Yes	+	+	–	–4.5	–2.6	–1.6
Yes	No	+	+	–	–4.3	–2.5	–1.7
Yes	Yes	+	+	–	–3.9	–1.9	–0.9

<sup>a</sup> A “+” indicates that all poor household groups both gain relative to the [BAU] and that the income gap decreases while a “–” refers to the opposite.

Despite the fact that the trade volume of non-fossil fuel sectors is large for India, price changes in the remaining sectors have only a small impact. Welfare changes between [P-fuel] and [P-all] remain below 0.15% throughout the whole modeling period and there is no clear pattern which household type benefits most.<sup>6</sup> This is because that the transfer payments lead to higher incomes for the poor households which shift the consumption patterns towards some goods that can now be imported cheaper.

#### 4.4 Overall welfare effects

Table 3 shows under which scenarios poor households do not lose relative to the [BAU]. This depends less on international transfers or taking into account international price repercussions but rather on the distribution of revenues. The decline in the income gap between richer and poorer households comes however at the cost of a lower GDP growth rate leading to higher overall welfare losses.

Table 4 provides more detailed information on the welfare changes for different scenarios and household types. This reconfirms that different households which have different types of factor income and different consumption preferences can be affected very differently from the climate policy induced price changes and transfers. Only when revenues are used for investment purposes welfare losses are relatively equal between households even though this policy is slightly regressive. International transfers make this pattern even more pronounced, however they play a smaller role compared to the distribution of the domestic carbon tax revenue.

Fossil fuel price repercussions of international markets decrease the adverse welfare effects as expected, since India as a net energy importer benefits from lower fossil fuel prices. Price changes in other sectors have virtually no additional welfare effect. The welfare gains of price changes are larger under a scenario without transfers since as discussed above, the exchange rate appreciation caused by transfer payments reduces the benefits of the fuel price effect.

Table 4 also contains welfare changes in DART for two scenarios (with and without international transfers). The most comparable scenarios in IEG-CGE contain transfers to all households and price repercussions in all sectors. Welfare losses in DART are smaller compared to IEG-CGE. With transfers Indian welfare even increases in DART. Different underlying economic structures and different assumptions about elasticities imply cheaper abatement options in DART than in IEG-CGE. As a consequence, the gains from international transfers are larger in DART because of the larger amount of surplus emissions in DART (cf. Table 2). Different assumptions on the exchange rate adjustment also contribute the differences, as in IEG-CGE international transfers lead to an appreciation with reduced the welfare gains.

<sup>6</sup>Only in the scenario in which the [poor] only are receiving transfer payments, they benefit from the price effect in the remaining sectors (but still only up to 0.3%)

**Table 4:** Changes in accumulated and discounted welfare in selected scenarios.

Model	Intl.		Welfare changes relative to [BAU]												
	transfer	Revenue allocation	Intl. prices	RH1	RH2*	RH3*	RH4	RH5	UH1	UH2	UH3*	UH4	overall		
IEG-CGE	no	all	exo	-3.4	12.1	5.4	-5.6	-7.3	-5.3	-1.3	0.7	-7.8	-3.4		
IEG-CGE	no	poor	exo	-9.7	43.8	25.0	-11.7	-12.4	-10.5	-4.3	12.8	-12.3	-5.1		
IEG-CGE	no	gov	exo	-2.4	-2.7	-3.0	-2.2	-2.3	-2.4	-3.0	-3.1	-2.1	-2.4		
IEG-CGE	US\$	all	exo	-2.6	13.8	6.5	-4.8	-6.6	-4.6	-0.9	1.5	-7.3	-2.6		
IEG-CGE	US\$	poor	exo	-9.6	49.0	28.4	-11.6	-12.3	-10.4	-4.3	14.9	-12.2	-4.5		
IEG-CGE	US\$	gov	exo	-1.5	-2.7	-2.8	-1.0	-1.0	-1.4	-2.9	-2.8	-1.0	-1.6		
IEG-CGE	no	all	fuel	-2.5	12.9	6.1	-4.6	-6.3	-4.4	-0.7	1.4	-6.9	-2.5		
IEG-CGE	no	all	all	-2.5	12.9	6.1	-4.6	-6.3	-4.4	-0.7	1.4	-6.9	-2.5		
IEG-CGE	US\$	all	all	-1.8	14.4	7.1	-3.9	-5.7	-3.8	-0.4	2.1	-6.4	-1.9		
DART	no	RA	all										-0.2		
DART	yes	RA	all										4.3		

“Overall” refers to a weighted average (weight by household consumption expenditure) for IEG-CGE and of the representative agent (RA) for DART. Household types marked with an asterisk are considered as poor.

## 5 Conclusion

For ambitious global climate policies, it is necessary to include India into a global climate regime. There is however a fear that this comes at a cost of lower economic growth and that especially poor households would suffer from carbon pricing. Traditional impact analysis of climate mitigation in India has been carried out with single country models which lack international repercussions or with global models which represent the Indian economy in a highly aggregated manner. This paper shows that both classes of models miss important features for the Indian economy. Soft-linking these two model types can give a more detailed and accurate view for India. The soft-link here is established by harmonizing the models with respect to GDP and population and by passing on price information.

In the global model with only one representative agent distributional effects are missing. For India, such effects are crucial for policy makers when assessing the impacts of climate mitigation policy. As the national model shows, welfare effects can differ significantly for different household types so that average welfare numbers are of little use. In addition, redistribution of revenue from a carbon tax and international transfers to poorer households – which cannot be captured in the global model – does benefit the poorer households but comes at the cost of overall higher GDP and welfare losses. The analysis also shows that accounting for the international transfers often ignored in national models indeed reduces negative welfare effects for India. Income distribution is furthermore affected by international price repercussions which are also normally not accounted for in national models. By passing on price changes from the global to the national model we can show that poor household groups benefit least from lower international fossil fuel prices and also have higher welfare losses when revenues are used for investments which is most efficient in terms of GDP or overall welfare losses. This does not mean that revenues need to be allocated to poor households exclusively; we show that transfers to all households on a per capita basis already make poor households better off than the baseline and reduce the income gap between rich and poor households. Generally, accounting for international price repercussions has significant implications for the outcome of the national model.

We also see that the rather small negative or even positive welfare effects of international climate policy have to be treated with care. Even though the differences in our model analyses partly stem from different implicit abatement costs, neglecting exchange rate adjustments and overall welfare effects of different revenue recycling could lead to overly optimistic results in the global model.

While the model soft-linking allows a more detailed view on distributional effects of international climate policy in India and allows identification of the relative importance of the different channels, the overall consistency of the two models is clearly limited and our scenarios are necessarily highly stylized. E.g. other use of the revenues such as financing clean energy or other “green technologies” would be possible but cannot be analyzed in our modeling framework. Against the backdrop of urbanization and industrialization, the household types will probably not correspond to the initial occupation categories in the long run. If interpreted in a more general way as household types of different income levels (derived from different endowment ratios) and different consumption preferences, the results give still give an indication of how rich and poor households are affected under different policy options.

Furthermore, a more complete coupling which could include a further harmonization of the baseline scenarios and potentially also feedbacks from the Indian model to the global model is challenging for two independently developed models with their own focusses and underlying assumptions. Only a fully integrated model, which could be achieved by splitting the input data of the global model for India, would lead to entire consistency. Such a model would however require significant data work. Even though this was beyond the scope of this paper, our results show that it might be



worth the effort.

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## A Model Details

**Table A.1:** Regional and sectoral aggregation of the DART model

Regions		Sectors	
WEU	Western Europe	Energy Sectors	
EEU	Eastern Europe	COL	Coal
USA	United States of America	CRU	Crude Oil
CAN	Canada	GAS	Natural Gas
ANZ	Australia and New Zealand	OIL	Refined Oil and Coal Products
JPN	Japan	ELE	Electricity <sup>a</sup>
FSU	Former Soviet Union	Other Sectors	
CPA	China, Hong Kong	AGR	Agriculture
IND	India	ETS	Energy Intensive Production
LAM	Latin America	CRP	Chemical Products
PAS	Pacific Asia	OLI	Other Light Industry
MEA	Middle East and Northern Africa	OHI	Other Heavy Industry
AFR	Sub-Saharan Africa	MOB	Mobility
		SVCS	Services

<sup>a</sup> The electricity sector is split into conventional generation and renewable electricity generation in the following forms as perfect substitutes: Wind, solar, hydro, and biomass. Generation from coal and gas with CCS is implemented as latent technology. For details for the treatment of the electricity sector, see appendix of Chapter III.

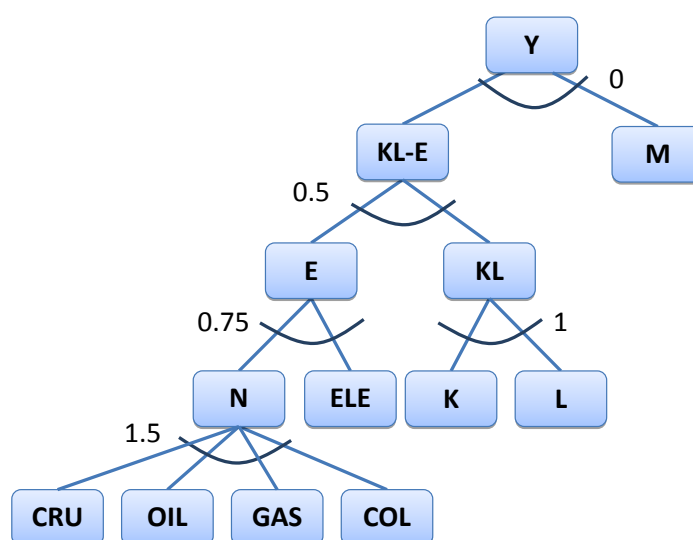
**Table A.2:** Sectoral aggregation of IEG-CGE

Energy Sectors	Other Sectors
Coal	Agriculture
Oil	Manufacturing 1 (Food and Beverages, Textiles, Wood, Minerals)
Gas	Manufacturing 2 (Paper, Fertilizers, Cement, Iron and Steel, Aluminum, Chemicals)
Oil products	Manufacturing 3 (Plant and Machinery)
Thermal electricity	Construction
CCS electricity	Road Transport
Hydro electricity	Other Transport (Rail/Sea/Air)
Nuclear electricity	Other Services
Wind/solar electricity	
Biomass electricity	

**Table A.3:** Sectoral mapping for DART and IEG-CGE used for international price adjustments

Sectors in DART	Sectors in IEG
OLI	Manufacturing 1
ETS, CRP	Manufacturing 2
OHI	Manufacturing 3
SVCS	Construction, Other Services
MOB	Road Transport, Other Transport

Note: Agriculture and energy sectors (coal, oil, gas, oil products, electricity) are the same in both models. For price comparisons in sectors where one sector of the DART model corresponds to two sectors of IEG-CGE, the price is used for both IEG-CGE sectors. In the case of the ETS and CRP sectors in DART which correspond only to one sector of IEG-CGE, a weighted average based on import/export volumes is calculated.

**Figure A.1:** Production structure

The main CES production structure and substitution elasticities for each sector and region in the DART model.  $Y$  = output,  $K$  = capital,  $L$  = labor,  $E$  = energy,  $M$  = other intermediates,  $N$  = non-electricity. Fossil fuel inputs (crude oil, refined oil, natural gas and coal) are associated with  $\text{CO}_2$  emissions in fixed proportions. For the production of refined oil, inputs of crude oil and coal are treated as intermediates  $M$  at the top nest (Leontief), no direct carbon emissions are associated with the use of this energy feedstock. The remaining fossil fuels (crude oil, natural gas and coal) use a fixed resource at the top nest. The elasticity between the fixed resource and the remainder of the production function is scaled to achieve a given global supply taken from OECD (2012). Production structure in IEG-CGE follows the same nesting, however elasticity values may differ. In IEG-CGE renewable and non-renewable electricity generation are assumed to be imperfect substitutes. The electricity sector in IEG-CGE therefore contains a more complex sub-nesting.

## Chapter V

# Worse off from reduced cost? The role of policy design under uncertain technological advancement<sup>\*†</sup>

*A simple model is used to illustrate the effects of a reduction in (marginal) abatement cost in a two-country setting. It can be shown that a country experiencing a cost reduction can actually be worse off. This holds true for a variety of quantity and price based emission policies. The most important channel is that a country with lower abatement costs engages in additional abatement effort for which it is not compensated. Under a quantity based policy with a given allocation, a seller of permits can also be negatively affected from a lower carbon price. We also argue that abatement cost shocks to renewable energy and carbon capture and storage (CCS) are different in terms of their effects on international energy markets. A shock to renewable energy reduces fossil fuel rents benefiting energy importers, while the opposite holds for a shock to CCS. The channels obtained in the theoretical model can be confirmed in a more complex global computable general equilibrium model. Some regions are indeed worse off from a shock that lowers their abatement costs.*

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<sup>\*</sup>This chapter is available as Weitzel, M. (2014). Worse off from reduced cost? The role of policy design under uncertain technological advancement. Kiel Working Paper No. 1926.

<sup>†</sup>I am deeply indebted to Sonja Peterson for very helpful comments. I would like to thank Thill Requate for fruitful discussions and Michael Rose for his research assistance. Funding by the German Federal Ministry of Education and Research (reference 01LA1127C) is acknowledged.

# 1 Introduction

In order to avoid dangerous climate change, deep and costly cuts in CO<sub>2</sub> emissions on a global scale are unavoidable. Cost for emission reductions are determined by the underlying demand factors such as population and economic growth and supply factors such as efficiency improvements (IPCC, 2007). Since these underlying factors are not deterministic, therefore also the resulting emissions or costs of emission abatement are uncertain. An unanticipated shock to these demand or supply factors can move abatement costs away from their expected value.

It is obvious that macroeconomic shocks affect the cost of reducing emissions to a given level. A lower growth rate leads to less aggregate demand for fossil fuels and thus less abatement effort to reach a certain emission level. The recent financial crisis can serve of an example of how an economic slowdown can also lead to a drop in CO<sub>2</sub> emissions. In Europe, part of the decline in prices for CO<sub>2</sub> can be explained by lower demand for fossil fuel (Ellerman et al., 2014). On the other hand, more rapid economic growth can accelerate emissions. Following China's entry into the WTO and the subsequent export driven growth, emissions in China exceeded projections (Blanford et al., 2009, see also Chapter III).

Another source for uncertainty of abatement costs lies in the uncertainty of technological advancement and thus the cost development of low carbon energy sources. The availability of cheap renewable energy options or carbon capture and storage (CCS) makes abatement more affordable. Many of the cost estimates and scenarios for possible future energy systems rely on assumptions of technological development in key technologies, which today still play only a minor role or are at their infancy. But it is uncertain whether these technologies can live up to the expectations placed on them. Most prominently, various renewable energy technologies and CCS play a crucial role in many future low carbon scenarios. In general, economic costs estimates of future emission reductions are quite sensitive to changes in the underlying assumptions on inclusion of key technologies like CCS or renewables, especially for scenarios aiming at very low emission levels. For example, economic costs for mitigation can be substantially higher when CCS is limited or not available (Edenhofer et al., 2010; Luderer et al., 2012; Kriegler et al., 2014). The (policy driven) fast expansion of renewables in Europe has also demonstrated that the availability of renewable energy can lead to lower carbon prices. The result from this overlapping regulation is a decline in emission prices and a thus a reduction in the cost of emission abatement within the emission trading scheme (ETS) (Böhringer et al., 2009).<sup>1</sup> In this paper we focus on the effects of shocks to cost of key abatement technologies, more specifically their future cost.

These examples of shocks obviously have a strong direct impact on the country where they originate, yet in today's interconnected world shocks will also affect other countries indirectly.<sup>2</sup> One important transmission channel is changes in international energy prices. A lower demand for energy in response to a shock would lead to lower energy prices and thus affect exporters and importers of fossil fuels. With respect to this transmission channel, shocks to renewable energy and CCS are likely to be different because a positive shock to renewable energy will lower the demand for fossil fuel while this is not necessary the case for CCS (Kalkuhl et al., 2014). Important questions related to the nature of shocks therefore are: How do different types of technology shocks affects other countries? What are the different channels for transmission? What is the role of positive correlation between shocks in different countries?

<sup>1</sup>The total welfare cost increases because renewable energy requirements constitute an additional constraint in the cost minimizing problem; however the emission reduction within the ETS only is reduced.

<sup>2</sup>Shocks to cost of key abatement technologies are likely to be positively correlated so that all countries will enjoy a cost reduction. However, the benefit will be higher in countries that can make better use of the technology, e.g. because of geographical features.

The different transmission mechanisms can be influenced by the instrument choice to regulate emissions. McKibbin et al. (2008) have demonstrated that unexpected macroeconomic shocks in one country always have some, yet different, feedback effects on other countries under a price based and a quantity based emission control policy, respectively. While a carbon tax as an instrument has no repercussion on interlinked emission trading schemes, effects on other markets such as international fossil fuel markets might be more pronounced compared to an ETS system. These feedback effects on the fossil fuel market are acknowledged in the literature (Böhringer and Rutherford, 2002; Klepper and Peterson, 2006), yet have not explicitly been analyzed with respect to the choice of policy instrument under (technological) uncertainty.

While it seems to be straightforward that countries would benefit from reduced abatement costs caused by lower costs for the deployment of renewable energy or CCS technologies, this might in fact depend on the policy instrument. It is even possible that under certain circumstances lower abatement cost can lead to higher total cost. Under a price based system with a fixed carbon price, lower than expected abatement cost would translate into additional (costly) abatement effort. A negative effect could also happen under an emission trading scheme. Suppose that in an emission trading scheme a country is a net seller of permits. Then lower marginal abatement costs reduce the carbon price and hence the value of the permits it can sell – the overall effect of a seemingly positive shock could well turn out to be negative. Questions in the realm of policy design can thus be formulated as follows: How can the choice of policy instruments influence international transmission of a technology shock? Can policy design lead to additional cost as a result to lower abatement costs? How should this be taken into account when designing policies?

These considerations are further developed with a simple theoretical model in Section 2. To better understand whether these results also apply in a more realistic setting, a computable general equilibrium (CGE) model is used to assess the impacts of a technology shock under different policy instruments in Section 3. This allows to tackle questions like: Do these theoretical arguments also carry over to a more complex model? What is the relative importance of the different channels? Section 4 finally discusses implications and concludes.

## 2 Simple theoretical model

### 2.1 Repercussions under different policy instruments

In this section, a simple two country model is used to illustrate the effects of different policy instruments on the distribution of abatement costs. For simplicity, quadratic marginal abatement costs (MAC) are assumed, as there is some evidence for this form (Klepper and Peterson, 2006; Klepper, 2011). Marginal abatement costs in countries  $i = 1, 2$  depend on the level of abatement  $a_i$ . Without loss of generality, they can be described

$$MAC_1(\phi, a_1) = \frac{\beta}{\phi} a_1^2; \quad \phi, \beta, a_1 > 0 \quad (1)$$

and

$$MAC_2(a_2) = a_2^2; \quad a_2 > 0. \quad (2)$$

where  $\beta$  represents a parameter in order to allow for different MACs in different countries and  $\phi$  is a parameter representing a technology shock.  $\phi$  is anticipated to be equal to one and an unexpected technology shock  $\phi > 1$  shifts the  $MAC_1$  downward.<sup>3</sup> The efficient level of abatement to achieve a

<sup>3</sup>In this section we only analyze the impacts of a shock that leads to lower abatement costs in an abatement technology.



given abatement target<sup>4</sup>  $\bar{a}$  can be found by minimizing total abatement costs

$$\mathcal{L} = \int_0^{a_1} MAC_1(\phi, x_1) dx_1 + \int_0^{a_2} MAC_2(x_2) dx_2 + \lambda \left( \bar{a} - \sum_i a_i \right). \quad (3)$$

The first order conditions show that the efficient solution is characterized by equalization of marginal abatement cost at  $\lambda$

$$\lambda = \frac{\beta}{\phi} a_1^2 = a_2^2. \quad (4)$$

The individual quantities of abatement consequently depend on the technology parameters  $\beta$  and  $\phi$ , such that the country with cheaper abatement options carries out more abatement

$$a_2 = \sqrt{\frac{\beta}{\phi}} a_1. \quad (5)$$

When emissions are controlled by either a tax or an emission trading scheme, in expectations (i.e. when  $\phi = 1$ ) a price based instrument and a quantity based instrument are equivalent. In both cases, emissions are reduced when the MAC is below the price of a carbon tax or carbon permits, respectively.

### 2.1.1 Tax

Under a tax scenario, the carbon price is held constant at  $\bar{\lambda}$  regardless of any deviation from  $\phi = 1$ . Abatement is carried out as long as the marginal abatement costs are below the tax rate. Tax revenues are assumed to be returned lump sum and are thus discarded from the analysis. When there is a shock to marginal abatement costs (i.e.  $\phi$  increases), cost for each unit of abatement is lowered. At the same time, however, the amount of abatement is increased because now a larger quantity of abatement can be carried for a cost below  $\bar{\lambda}$ . Taking the integral of marginal abatement costs from equation (1) yields total abatement cost  $C$  for the quadratic case, which depend on the technology shock and the level of abatement

$$C_1 = \frac{1}{3} \frac{\beta}{\phi} a_1^3. \quad (6)$$

The level of abatement  $a_1$  will adjust such that the new marginal cost is equal to the (unchanged) tax rate. From equation (4), it can be calculated as

$$a_1 = \sqrt{\bar{\lambda} \frac{\phi}{\beta}}. \quad (7)$$

When there is a shock to abatement costs (i.e.  $\phi > 1$ ), abatement and abatement costs for country 2 are not affected by the shock. The cost for country 1 is influenced by two opposing factors

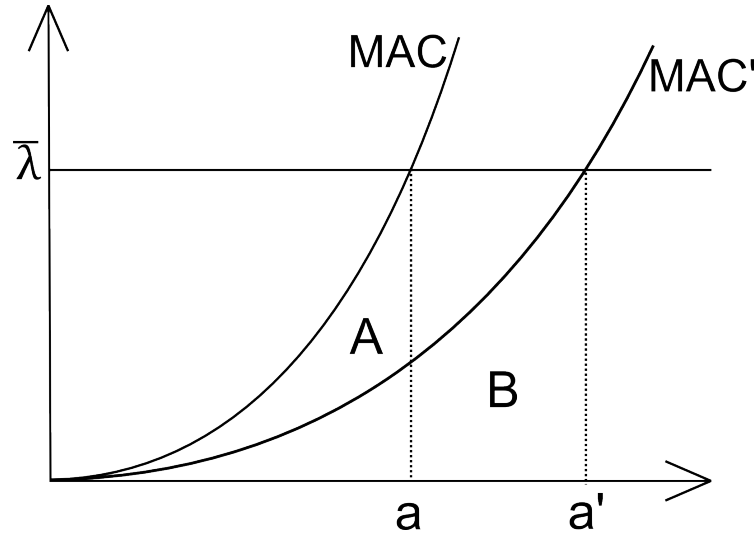
$$\frac{\partial C_1}{\partial \phi} = \underbrace{-\frac{1}{3} \frac{\beta}{\phi^2} a_1^3}_{<0} + \underbrace{\frac{1}{3} \frac{\beta}{\phi} \frac{\partial a_1^3}{\partial \phi}}_{>0}. \quad (8)$$

The first term reflects lower cost from abatement that would have been carried out also in the absence of a shock, the second term reflects changes in the quantity of abatement which is adjusted

The results however can easily be carried over to the case when costs of abatement technologies are higher than expected.

<sup>4</sup>Note that this model does not explicitly include marginal damages and we assume here an exogenous target for emissions. A comparison of marginal damages and marginal abatement cost would however be required to find the optimal policy instrument under uncertainty (Weitzman, 1974). The aim of the paper is not to determine an optimal policy, but rather to stress the characteristics of policy instruments under abatement cost uncertainty.

**Figure 1:** Change in abatement cost due to a technology shock under an emission tax policy.



according to equation (7). As there is one positive and one negative term, a technology shock can thus lead to cases where a country which experiences a shock to lower MACs has to bear higher abatement costs. For the case of quadratic marginal abatement cost curves a technology shock always increase total abatement costs.<sup>5</sup> Figure 1 shows the opposing effects of equation (8) graphically. The area under the MAC curve represent abatement costs. The technology shock shifts the MAC downward to MAC'. Total cost is reduced by *A*, yet additional abatement leads to an increase of cost by *B*.

Note that the additional cost from additional abatement might bring along some gain due to avoided damage. Here we focus however on the distributional effects and show that a technology shock under a tax regime can increase the cost of the country which experiences this shock.<sup>6</sup>

### 2.1.2 Tax with constant global emissions

Under a tax policy lower marginal abatement cost lead to increased global abatement and thus increased global abatement cost. Is the adverse effect to country 1 only due to the fact that the global abatement level rises? To check for this, we can fix the global level of abatement and endogenize the price of abatement, such that global emissions are equal with and without a technological shock. This affects the choice of optimal emission levels both in the country directly affected by the shock and the other country influenced only indirectly through reactions in the carbon price.<sup>7</sup>

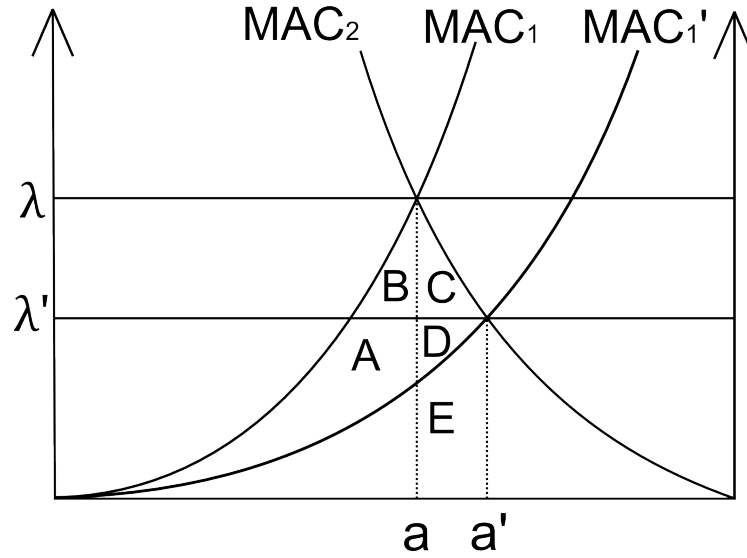
Rather than assuming a fixed level of emissions, it is more straightforward to follow the model from above and keep the model in units of abatement. Plugging in (4) into the cost expression from (6), cost can be expressed as  $1/3\lambda a_i$ . Total cost depends on the carbon price and the quantity of abatement. Note, however, that in contrast to the case above,  $\lambda$  is not fixed but reacts to a technology shock. Differentiating cost with respect to  $\phi$ , there are again two opposing effects for country 1.

<sup>5</sup>Plugging the expression for  $a_1$  from equation (7) into (6) and differentiating with respect to  $\phi$  yields  $\frac{1}{6} \frac{\bar{\lambda}^{\frac{3}{2}}}{\sqrt{\beta\phi}}$  which is larger than zero, indicating rising costs for the quadratic case. For other convex functions it is a priori not clear which of the two effect dominates. For a function which is relatively flat at first and then quickly turns steeper area *A* might exceed area *B* in Figure 1.

<sup>6</sup>This result is comparable to Peterson and Klepper (2007), who state that under a globally harmonized carbon tax countries with lower marginal abatement costs will face higher total abatement costs.

<sup>7</sup>This setting would be equivalent to an auctioning of permits by a global agency which then redistributed revenues lump-sum to those countries which have bought the permits.

**Figure 2:** Change in abatement cost due to a technology shock under a tax policy with fixed global emissions.



$$\frac{\partial C_1}{\partial \phi} = \underbrace{\frac{1}{3} \frac{\partial \lambda}{\partial \phi} a_1}_{<0} + \underbrace{\frac{1}{3} \lambda \frac{\partial a_1}{\partial \phi}}_{>0} \quad (9)$$

The two opposing terms and their interpretation is similar to that of the terms in equation (8). The first term is negative because the same overall abatement  $\bar{a}$  can now be carried out at a lower cost. The sign of the second term follows from equation (5) and the fact that total abatement is unchanged. A higher  $\phi$  leads to more abatement from country 1 and less abatement from country 2. It is therefore not clear how the total cost of country 1 reacts and it again is possible that lower abatement cost due to a technological change lead to higher total abatement cost. Cost of country 2 on the other hand will decline unambiguously.

$$\frac{\partial C_2}{\partial \phi} = \underbrace{\frac{1}{3} \frac{\partial \lambda}{\partial \phi} a_2}_{<0} + \underbrace{\frac{1}{3} \lambda \frac{\partial a_2}{\partial \phi}}_{<0} \quad (10)$$

Figure 2 shows this graphically. The length of the abscissa corresponds to the total abatement requirement  $\bar{a}$ . The MAC for country 1 is shown from left to right, while the MAC from country 2 is shown from right to left. The equilibrium would be at carbon price  $\lambda$  and the abatement set  $a$  with  $a_1$  and  $a_2$ . A shift to  $MAC'$  changes both the carbon price (to  $\lambda'$ ) and the abatement set (to  $a'$ ). Country 1 enjoys lower abatement cost  $A$  and  $B$ , but additional abatement cost  $E$ . Country 2 can reduce its abatement and thus abatement cost by  $C$ ,  $D$ , and  $E$ . Country 1 can still experience a loss (when  $E$  exceeds  $A$  and  $B$ ), however, this is smaller than the loss under the tax case. This is because the level of total abatement remains unchanged after a shock.

Under this setting, total abatement cost declines by  $A$ ,  $B$ ,  $C$ , and  $D$ , but it depends on the relative slope of  $MAC_1$  and  $MAC_2$  how the gain is shared between countries 1 and 2. When  $MAC_2$  is steep compared to  $MAC_1$ ,  $a'$  is relatively close to  $a$  and the additional abatement by country 1 relatively small.

### 2.1.3 Permits with given allocation

Certainty about global emissions can also be achieved with an emission trading system. There are many possible ways of allocating emissions rights to different countries. The allocation schemes in possible future global emission trading system is often proposed to incorporate various equity principles (see also Chapters II and III). For example in the largest existing emission trading scheme of the European Union (EU ETS), emission allowances are in part distributed to countries based on these principles. While most allowances are distributed to member states based on past emission levels, 10% of allowances are based on per capita income and benefit poorer member states (EU, 2009, Article 17). These countries can thus benefit from selling the emission allowances on the European carbon market.

In the theoretical model, costs for country  $i$  under an emission trading system with some allocation rule can be written as

$$C_i = \frac{1}{3}\lambda a_i + \lambda(\hat{a}_i - a_i). \quad (11)$$

$\hat{a}_i$  is the amount of permits allocated to country  $i$  (and  $\sum_i \hat{a}_i = \bar{a}$ ), the difference between allocated and actual abatement has to be bought or sold at the market price  $\lambda$ . Differentiating with respect to  $\phi$ , we find that a shock influences costs via several channels

$$\frac{\partial C_i}{\partial \phi} = \frac{1}{3} \frac{\partial \lambda}{\partial \phi} a_i + \frac{1}{3} \lambda \frac{\partial a_i}{\partial \phi} + \frac{\partial \lambda}{\partial \phi} (\hat{a}_i - a_i) - \lambda \frac{\partial a_i}{\partial \phi}. \quad (12)$$

The first two terms are identical to the case where global emissions are held constant under a tax scheme and refer to actual abatement cost. The last two terms are new and stem from effects from emission trading. The third term describes the change in the value of transfers due to a change in the carbon price. As the price declines, a permit buyer benefits from this effect while a permit seller now sells its surplus permits at a lower price. The last effect finally describes the changes in the trading positions. As there is a shift in relative abatement, country 1 can benefit from generating new abatement to reduce the need to buy permits when it is a permit buyer or to generate additional permits when it is a permit seller.<sup>8</sup>

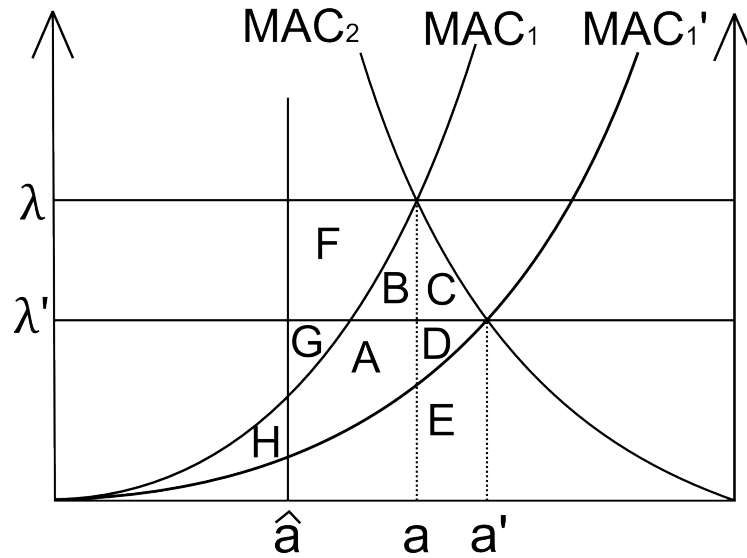
Compared to the case with a tax with constant global emissions, it is less likely that country 1 is worse off due to the shock because it can benefit from the additional low cost abatement potential by either decreasing the amount of permits it needs to buy when it is a buyer of permits<sup>9</sup> or it can sell additional permits when it is a seller of permits. However, in the later case, there is the possibility that this gain is outweighed by the loss from a lower carbon price at which it can sell permits.

This is illustrated by Figure 3. The figure is similar to Figure 2, but in addition  $\hat{a}$  shows the set of abatement allocation. In the figure, the allocation set  $\hat{a}$  is chosen such that country 1 is a seller of permits. In the situation without a shock and the abatement combination  $a$ , country 1 would sell  $a_1 - \hat{a}_1$  permits as it does more abatement than it would be required to. The permits are sold at  $\lambda$ . Since abatement costs are lower or equal to  $\lambda$  it gains  $F + G$  from this trade. With a technology shock, the equilibrium shifts to  $\lambda'$  and  $a'$ . Abatement costs are reduced by  $A$ ,  $B$ , and  $H$  and increased by  $E$  as in the case with a tax with constant global emissions. As country 1 can now only ask for  $\lambda'$ , the gains from carbon trade are reduced by  $B$  and  $F$  due to the lower carbon price and are increased by  $A$  and  $D$ . The net gain for country 1 is thus  $H + A + D - F$ . If the price drop is large and country 1 is a seller of many permits, then it can loose from the technology shock. For country 2, the gains are

<sup>8</sup>There are of also cases where country 1 could switch from a buyer to a seller. This is not visible in equation (12) as this is only the marginal effect, but could be easily shown in a variation for Figure 3.

<sup>9</sup>In this case it will gain unambiguously because also the cost for the remaining permits it needs to buy declines.

**Figure 3:** Change in abatement cost due to a technology shock under an quantity policy with a given allocation.



*B* and *F* due to the lower carbon price and *C* due to a shift in abatement.<sup>10</sup>

Compared to the tax scheme with constant global emissions, gains are larger for the country 1, because it can use the increase in low cost abatement potential by selling emission allowances to the other country. The other country also gains from this trade because it now pays a permit price that is lower than its own abatement costs – gains for country 2 are however smaller than in the case of a tax with constant global emissions. Yet, it is not automatic that a lower abatement cost will lead to lower abatement costs for both countries, because of repercussions in the existing price for carbon and its impact to the value of emission trading.

#### 2.1.4 Correlated shocks

Key abatement technologies are expected to be used in many regions. A shock to the cost of these technologies can therefore be expected to affect not only one country, but both countries. This leads to shocks which are positively correlated across countries but have varying impacts in the different countries.

In the case of taxes, abatement costs for a given country only depend on the impact of the shock on own cost and on the quantity of own abatement (see equation (8)). There are no spillovers from the policy instrument. With correlated shocks both countries benefit from lower cost for abatement that they would have carried out even without the shock but both countries also engage in costly additional abatement effort. Overall effects should be stronger in the country affected stronger by the shock.

For quantity based policies however, the optimal abatement level in both regions adjusts to a shock. Let us first think of two extreme cases. When country 2 is not affected at all, the results from above hold. When country 2 is affected equally strong from the shock as country 1, both MACs would shift downward by the same amount. There is hence no shift in abatement, i.e.  $\partial a_i / \partial \phi = 0$  and hence there would be no additional cost (in equations (9) and (10) the second term would vanish). Both countries would gain from lower cost to reach abatement levels  $a_i$ . Compared to a situation with only one country being subject to a shock, the downward shift in  $\lambda$  would be increased when the shock affects both countries. This means that in the case with fixed allocation the adverse effect

<sup>10</sup>For the interval between  $a_2$  and  $a'_2$  country 2 now prefers to buy additional permits, which is cheaper than own abatement.

for permit sellers is increased.

When the shock affects country 2 not as much as country 1, all channels found in the theoretical model would still be present but weaker than when the shock only affects country 1. The only effect that would be reinforced is the change in value of emission trading (the third term in equation (12)).

To summarize, the theoretical model shows that is possible under all policy settings that a country loses from lower MAC. This is because a shock not only leads to lower cost for existing abatement but also leads to additional abatement. The likelihood for or the extend of a loss depends on how policies adjust the burden sharing in response to a shock. Under a tax system, there is no adjustment and costly additional abatement is not compensated for. This holds to some extent even if the tax rate is endogenized and global emissions are held constant. However, in this case the quantity of additional abatement is limited and thus additional cost is lower than under a pure tax policy. Under an emission trading scheme, the adverse effects are further reduced because additional abatement effort generates emission permits and thus a full compensation. Under a system with emission trading with a given allocation there is however the chance of loss through another channel: Countries which are sellers of emission permits are affected negatively as prices for permits fall due to a shock.

## 2.2 Repercussions on international fossil fuel price markets

Marginal abatement costs not only depend on the direct emission reductions but are also determined by other factors. One important determinant is the demand for and trade in fossil fuels (Peterson and Klepper, 2007; Morris et al., 2012). Price changes on international fossil fuel markets can significantly impact welfare in fossil fuel importing and exporting countries (Böhringer and Rutherford, 2002, see also Chapter IV). The rents that fossil fuel exporters gain from importers are affected by the price and CGE analysis has shown that MAC shift upwards or downwards when other countries engage in abatement activities (Peterson and Klepper, 2007; Morris et al., 2012).

Shocks to abatement options have the potential to affect demand for fossil energy and thus the rents that resource owners can receive. However, the mechanism of a shock's influence of resource rent can be different under the type of shock and the policy instrument in place. The nature of renewable energy and CCS as abatement technologies is very different in its impact on resource rents (Kalkuhl et al., 2014). Whereas renewable energy can serve as a substitute to fossil fuels and thus reduce the scarcity rents, CCS can make fossil fuel more valuable in a setting of restrictive climate policy because fossil fuels can still be used. In general, a shock to CCS can be expected to benefit for resource owners, while the opposite holds for a shock to renewable energy.

How a shock to different abatement technologies impacts fossil fuel importers and exporters also depends on the policy instrument in place. In an emission trading system, the emission quantity is fixed and as there is a close relationship between carbon emissions and fossil fuel use. A binding emission constraint should therefore not change the quantity of fossil fuel used in the economy.<sup>11</sup> A shock to CCS technology however changes this fixed relationship between fossil fuel use and emissions: For the same amount of emissions a higher amount of energy from fossil fuels can be used, leading to a gain for the owners of the resource. When an easier substitution towards renewable energy is possible due to a shock to renewable energy, however, the demand for and thus the resource rent of fossil fuel declines. This can even be the case under a fixed emission cap and a fixed amount of fossil fuel that can be used because the value of the fuel and thus the rent that the resource owner can extract is reduced.

Under a tax system, the quantity of abatement is endogenous and increases in response to the

<sup>11</sup> As different fossil fuels have different emission factors, this is not a fixed relationship. For this part, we assume only one fossil fuel which has a fixed proportion to emissions.

**Table 1:** Impacts on rents and (global) quantities of fossil fuels as response to shock in abatement costs to renewables and CCS

Policy instrument	Impacts on	Lower abatement costs in:	
		Renewables	CCS
Quantity based	Rent per unit of fossil fuel	Decrease	Increase
	Quantity of fossil fuel	Unchanged	Increase
Price based	Rent per unit of fossil fuel	Decrease	Ambiguous
	Quantity of fossil fuel	Decrease	Ambiguous

shock. A shock to renewable energy leads to a lower demand in fossil fuels as they can be better used as a substitute for fossil fuels. In addition to this effect which is similar to the situation under a quantity based system, total abatement will increase (see Section 2.1.1) and thus reduce also the quantity of fossil fuels. A shock towards lower cost for CCS has an ambiguous effect. On the one hand, fossil fuel now has a higher value because it can be better used (as in the case of a quantity based instrument), but on the other hand, the overall level of abatement is higher and lower emissions could mean a lower quantity of fossil fuels that is used. As these effects are influencing demand in opposing directions, a numerical simulation can provide an indication about the relative size of the effects.

Table 1 summarizes the impacts of the different shocks to rents from fossil fuels and to quantity demanded globally under different policy instruments. To summarize, a shock towards lower cost of CCS seems better for resource owners compared to a shock in renewable energy costs. Resource owners are also better off in a quantity based system compared to a price based system.

### 3 Simulation Results

To illustrate the results from the theoretical model, we use the CGE model DART to run climate policy scenarios with shocks to the cost of abatement technologies. The CGE model captures repercussions both on energy and emission trading markets and can thus provide guidance on the question whether the adverse effects derived in the theoretical model also hold in a more complex setting. The model can also give an indication on the relative importance of transmission channels.

#### 3.1 Model and Scenarios

The DART model is a multi-sector, multi-regional recursive dynamic computable equilibrium (CGE) model (Klepper et al., 2003, see also appendices of Chapters III and VI). It is calibrated to the GTAP 8 dataset (Narayanan et al., 2012) and aggregated to 12 sectors and 13 regions (see Appendix A). In each region, a representative agent maximizes utility from consumption. Consumption preferences are modeled as linear expenditure system (LES). Income of the representative agent is derived from factor income from labor, capital and land as well as income from tax revenues. The model horizon is 2050.

The model was extended to include different electricity generation technologies which are assumed to be perfect substitutes (see appendix of Chapter III). Renewable electricity and CCS in the electricity sector are modeled based on cost data from the TIMER model (de Vries et al., 2001) and recent literature surveys for solar energy (Renz, 2012) and CCS (Lämmle, 2012). These generation technologies require a technology specific factor as input, its fixed supply for a given year leads to

an upward sloping supply curve. Costs for these technologies are reduced over the simulation period through learning-by-doing. This is implemented in DART by using different vintages of capital, learning only applies to new capital vintages, to correctly model investment decisions based on the current productivity in a given technology.

As long as costs for renewable electricity exceed costs of conventional electricity generation, subsidies are paid to producers. Subsidies are determined endogenously in the model to achieve at least the deployment level of the current policy scenario in the World Energy Outlook (International Energy Agency, 2013). This ensures also some learning in the baseline scenario as the level of renewable energy is increasing.<sup>12</sup>

The different technology shocks for renewable electricity and CCS are modeled as follows: For renewable energy, current costs are relatively certain, yet the cost development in the future is uncertain. The technology shock is therefore modeled as a deviation from the expected learning rate, i.e. the rate at which costs are reduced when output doubles. Per design, this effect becomes more visible in the long run. Higher learning reduces the cost of deployment and thus eases switching to low carbon generation technologies. For CCS, the main source of cost uncertainty is not the change of costs, but the general markup of commercially viable CCS compared to the respective conventional generation technologies. The technology shock therefore is modeled as a lower than expected markup.

For the shock in renewable energy, only the learning rates for solar and wind are adjusted, as the largest growth is expected in these technologies in climate policy scenarios (International Energy Agency, 2013). In the shock scenario, the learning rate for wind increases from 15% without a shock to 18.7% and the rate for solar increases from 19% to 22.8%. This is the about the 99% percentile value obtained from a literature review (Renz, 2012). For CCS, the cost markups differ for the model regions and are obtained from a Monte Carlo analysis based on several technological and economic aspects (Lämmle, 2012). For CCS, in the shock scenario we apply the 99th percentile of the probabilistic markup, the average of markup is reduced from 1.74 to 1.51 for coal and from 1.42 to 1.31 for gas in the shock scenarios.<sup>13</sup>

As there is a global market for these technologies, it is likely that lower costs can be applied in all regions. We therefore model shocks affecting all regions, yet the shocks have still different impacts in different regions. This is due to the fact that countries are not equally well suited for the technologies.<sup>14</sup>

The scenarios run here are designed to illustrate the theoretical model. We here analyze a time horizon until 2050 because the abatement technologies under scrutiny will only become relevant when there are sufficiently high carbon prices and learning does not matter much in short run.

The climate policy scenario follows an emission path leading to radiative forcing of 2.9 W/m<sup>2</sup> and a 50% probability to limit climate change to 2 degrees (see Chapter III) when abatement costs are at their expected level. Without a technology shock, a tax is equivalent to an emission trading system (without transfers).

In line with the theoretical model presented, scenarios are designed here that vary along two dimensions. This first dimension is the nature of shocks (renewable energy or CCS), the second dimension is the policy instrument regulating CO<sub>2</sub> emissions. There are several different options:

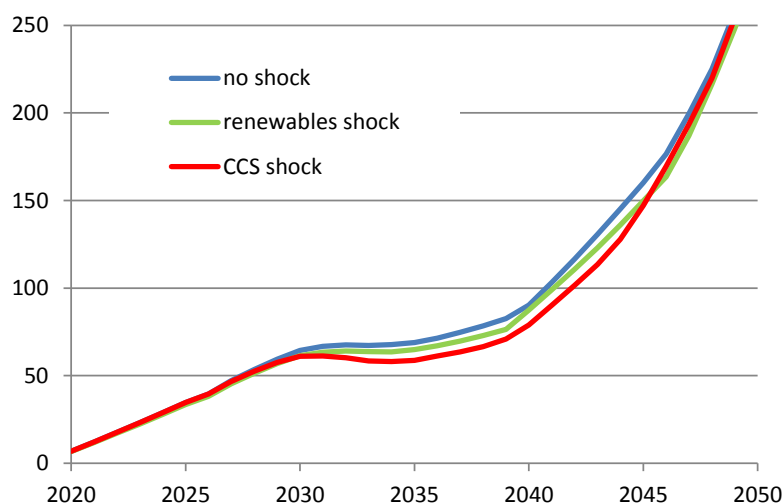
- Quantity based emission trading system with fixed allocations: The emission rights are distributed to and subsequently auctioned by the individual regions. There are two sub-scenarios:

<sup>12</sup>The scenario is not designed to find an optimal policy to exploit learning-by-doing. We are rather interested in the changes of cost induced by a certain shock.

<sup>13</sup>The markups here are simple unweighted averages of the model regions.

<sup>14</sup>The conditions of using a renewable resource are clearly different in different countries. For example, lower cost of solar energy has much less value for Russia than to the Middle East region.



**Figure 4:** Global marginal abatement cost under different shocks in the “ntr” scenario.

In the first sub-scenario, emission allocation to regions is such that in expectation (i.e. when  $\phi = 1$ ) there are no transfers (ntr) through emission trading, i.e. without a shock each region receives as much permits as it has emissions. Under a technology shock, however, countries affected by the shock and carry out more abatement can sell emission permits on an international carbon market. In terms of Figure 3, this means that  $\hat{a} = a$ . A second sub-scenario explicitly includes a combination of various equity principles incorporated in the allocation of emission rights. We here use the “Common but Differentiated Convergence” (CDC) regime which prescribes industrialized countries to start with convergence of per-capita emissions in 2020 while developing countries start to converge later (Höhne et al., 2006, see Chapter III for detailed assumptions). This yields an allocation which leads to transfer payments to compensate poor countries with low per capita emission levels. In terms of Figure 3, this means that  $\hat{a} \neq a$ .

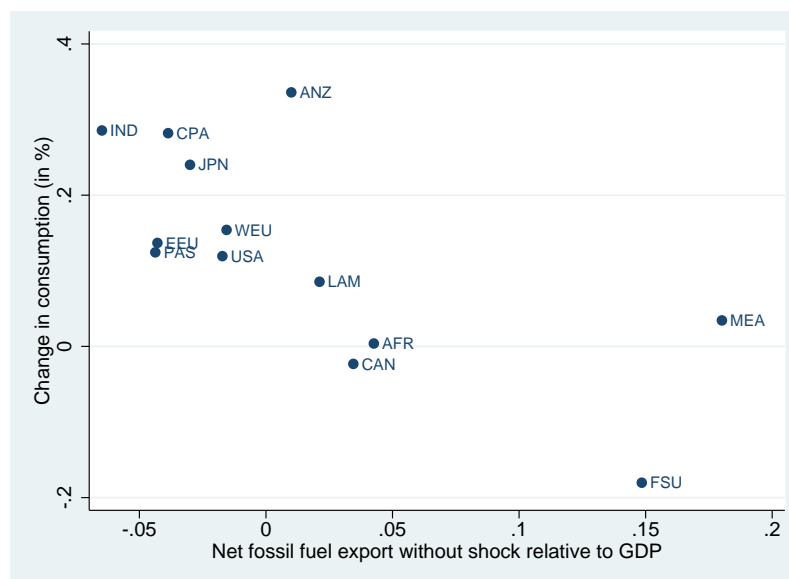
- Price based, globally harmonized tax rate: Instead of emissions, the carbon price is held constant. The carbon price is determined such that without a technology shock emissions are the same as in “ntr”. Under a technology shock, the price is unchanged, but the level of abatement adjusts.
- A tax with globally constant emissions (tax\*): Global emissions are the same as in the quantity based regime, yet they are achieved via a price based policy. In this scenario global emissions are constant, and the carbon price endogenous.

Note that “ntr”, “tax” and “tax\*” yield the same results when there is no unexpected shock. All quantity based scenarios (“ntr”, “CDC” and “tax\*”) lead to the same global emissions with and without technology shocks. In the tax case the carbon price is the same both with and without a shock but the level of emissions can adjust. In order to illustrate the role of shocks under different policies, each of the two shock types (renewables and CCS) is combined with each policy instrument in one scenario.

### 3.2 Findings

Comparing the global marginal abatement costs with and without shocks, it appears that the largest differences occur between 2030 and 2040 (Figure 4). This is the result of two factors. First, as

**Figure 5:** Relation of changes in consumption due to a technology shock in renewable energy and net energy trade (under no shock situation, relative to GDP) under a price based policy.



explained above, the shocks as implemented in the model are less important for the short run development, hence there is less variation before these years as less costly abatement options are used (e.g. energy efficiency or fuel switch). Second, the electricity sector still offers potential for decarbonization in this period and marginal abatement costs are in a range where cost differences of renewable energy or CCS can play a role. After 2040–2045, abatement becomes increasingly costly and there is little potential left for renewables or CCS (see also Chapter III). For this reason, results are presented first by showing simple scatterplots for the year 2035 to understand the general relationship between fossil fuel trade and the impact of a technology shock. Furthermore, simple regressions are used to show the differences between policies, as this allows taking into account several observation years and adding more factors compared to only one factor in the scatterplots. We here use changes in the level of consumption as dependent variable.<sup>15</sup>

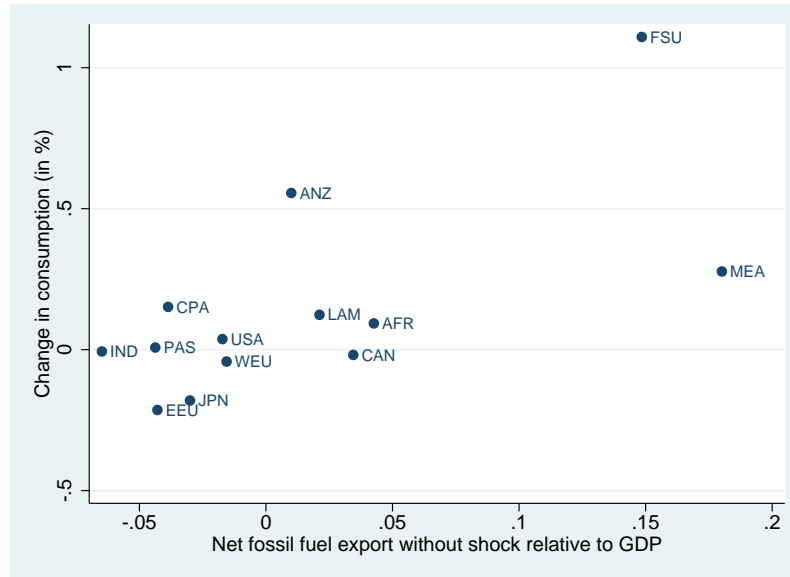
As discussed in Section 2.2, it can be expected that the different types of shocks affect fossil fuel markets differently. For the shock in renewable energy sources, substitution away from fossil fuels becomes more affordable and demand for fossil fuel declines which results in lower world market prices. This benefits (net) importers of fossil fuels. This can best be observed under a tax instrument where the reaction on the world market can be expected to be largest. Figure 5 clearly shows the changes in consumption<sup>16</sup> are negatively correlated to net exports of fossil fuels. Fossil fuel exports (prior to the shock) are set in relation to GDP of the respective region to indicate the importance of the region's economy on fuel exports. This indicates that under a shock towards lower cost in renewable electricity, net exporters of fossil fuels are having much smaller consumption gains than net importers or they even face losses. This pattern is best visible under tax scenario because not only the price but also the quantity of fossil fuel use is affected (see Table 1).

For a shock to CCS, there is a positive trend between the status of being a fossil fuel exporter and consumption change due to a shock (Figure 6). When CCS becomes more affordable, resource owners can benefit from the higher demand of fossil fuels. This holds for all policies with fixed emissions, while there is no clear trend under the tax scenario.

<sup>15</sup>The LES demand system differentiates between basic demand which is not generating utility and other consumption. The consumption level here only refers to the latter.

<sup>16</sup>Changes in consumption are relative to consumption in the same climate policy scenario without the technology shock.

**Figure 6:** Relation of changes in consumption due to a technology shock in CCS and net energy trade (under no shock situation, relative to GDP) under a quantity based “ntr” policy.



The impact of different shocks for energy exporters and importers can easily be read off from Figures 5 and 6, however, determining the effect of different policies is more complex because it is difficult to attribute the differences to the different channels. Furthermore, the correlation of shocks should be taken into account: all countries are affected by shocks, however, not in the same magnitude. A closer analysis thus needs to take into account how the different regions are affected by the shocks. This analysis is carried out with the help of simple regressions based on the result variables taken from the the CGE model. In other words, we regress the consumption changes that the CGE model projects for a technological change on several other variables also taken from the model simulations. The other variables are chosen such that they represent the different channels obtained in the theoretical model. While performing regression analysis on the model outcomes is not very common in the CGE literature, this procedure can help to determine factors that drive results a CGE model (see Dixon and Rimmer, 2013, for more information and applications of this method). Identification depends on variation between different regions and years in the CGE model.<sup>17</sup> The method has the advantage of including more dependent variables identified in the theoretical model in Section 2 in the analysis, thus enabling a comparison of how policies affect consumption while controlling for repercussions from the fossil fuel market and the different impact of shocks. The main benefit is not to generate significant results, but rather to use the coefficients for a decomposition of total consumption changes. This allows identifying more and less important channels.

Table 2 shows the regressions for a shock to renewable energy.<sup>18</sup> The direct effects of the shock are captured in two variables. Lower technology costs lead to a higher share in renewable energy in the electricity mix (“change in renewables”) and lower cost for existing renewable energy (captured in “pre-shock level of renewables”). The latter is a benefit especially to those countries which have a large share of renewables already in place without a shock. It captures the first term in equations (8), (9) and (12). The former variable should reflect the cost from a additional abatement as captured in the second term of equations (8), (9) and (12) and would be expected to be negative. For all climate policies, there a is significant positive coefficient for both variables. The positive effect also from

<sup>17</sup>We here use “observations” for the years 2030 to 2039 as in these years the technology shock is most important, see Figure 4.

<sup>18</sup>All variables referring to levels are in per cent and variables referring to changes are expressed in percentage points, see also Appendix B for more details on the variables.

**Table 2:** Different channels influencing consumption change due to a shock in renewable energy.

	no policy	ntr	CDC	Tax*	Tax
Change in renewables	0.056***	0.035***	0.034***	0.032***	0.022***
Pre-shock level of renewables	0.000	0.004***	0.005***	0.004***	0.003***
Pre-shock net fossil fuel exports	-0.010***	-0.002	-0.001*	-0.001	-0.012***
Change in emissions	0.051***	0.023***	0.026***	0.035***	0.014***
Pre-shock surplus			-0.003***		
Constant	0.000	0.000	0.000	0.000	0.000
Adjusted R <sup>2</sup>	0.765	0.641	0.709	0.521	0.708

Notes: \*\*\*/\*\*/\* significant at 1%/5%/10%. Each regression has 130 observations (10 years  $\times$  13 regions). Variables are described in Appendix B.

deployment of additional renewable energy is likely due to a positive learning externality. The shock for renewables is related to the learning rate and as all countries increase their renewable deployment, the global learning progress is increased. This overcompensates countries for the cost of renewable energy deployment. Under all quantity based regimes, the size of the coefficients related to the direct shock impact is very similar. In the tax case it is still positive, yet much smaller than under a quantity based regime.

Energy exporters are only little affected adversely from the shock under all quantity based policies. Under these policies total emissions which is closely related to total (fossil) energy use is not affected. Energy prices and thus unit rents decline only slightly.<sup>19</sup> This is however very different in the tax scenario, because of increased abatement supply of fossil fuel is reduced, harming energy exporters. Table 2 also contains regressions on how a shock affects consumption in the absence of climate policy (column “no policy”). In this case the effect on fossil fuels has a similar magnitude as under a tax policy because there is no binding cap and fossil fuel rents and quantity demanded decline as response to a shock.

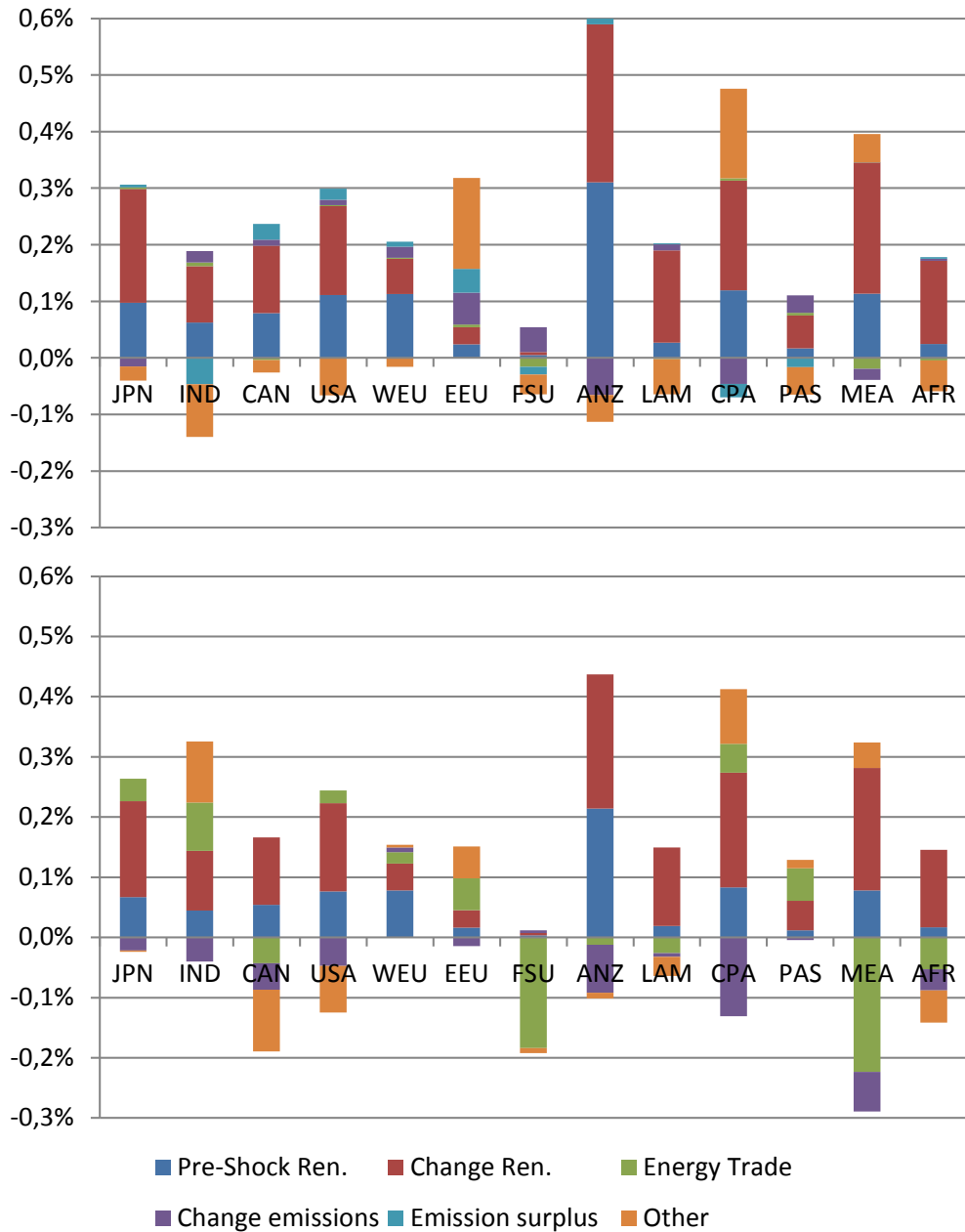
The change of emissions can be seen as an indicator for the gains of countries less affected by the shock. As demonstrated in Section 2.1, countries not directly affected by the shock can benefit from lower abatement levels (and thus higher emissions). In line with the theoretical model, the coefficient is highest under the Tax\* scenario because a country not (or less) affected by the shock can reduce its abatement efforts without having to compensate other countries. Under quantity based instruments with fixed allocation, the gain for countries not subject to a shock is smaller (as expected) and is even smaller for the pure price based instrument (theory suggests no effects).

For the CDC regime which is designed such that it includes transfers to poorer countries, there is a negative effect of pre-shock permit surpluses. As expected, the value of the surpluses declines with a lower carbon price and hence the value of emission permits that these countries can sell on the international market.

The coefficients from the regression can now be used to show importance of the different channels by evaluating the results for given the dependent variables for a certain year and policy scenario. Figure 7 shows the impact evaluated at variables for the observation of year 2035 for the different regions under the CDC and the tax scenarios (figures for the other policies can be found in Figure C.1 in Appendix C). This indicates the relative importance of the transmission channels. It can be seen that the direct effects of the shock are largest and other factors play a less important role. For India, which has a significant surplus of emission allowances that it can sell, the effect of value decline of surplus emissions is as important as other channels. For industrialized countries who gain via this channel, the effect is of minor importance.

<sup>19</sup>The coefficients are small and significant at the 10% level only in the case of the “ntr” scenario.

**Figure 7:** Decomposition of consumption changes due to shock in renewable energy in different regions in 2035 under a CDC (top) and a tax (bottom) policy. Calculations based on regressions from Table 2 (for the figure, regressions without a constant were used), “other” refers to residual effects.



**Table 3:** Different channels influencing consumption change due to a shock in CCS.

	ntr	CDC	Tax*	Tax
Change in CCS	−0.062***	−0.059***	−0.060***	−0.044***
Pre-shock level of CCS	0.008***	0.008***	0.008***	0.006***
Pre-shock net coal exports	0.418***	0.467***	0.389***	0.311***
Pre-shock net gas exports	0.125***	0.127***	0.125***	0.098***
Pre-shock net oil exports	−0.000	0.002	0.002	−0.018***
Change in emissions	−0.045***	−0.059***	−0.023***	−0.016***
Pre-shock surplus		−0.005***		
Constant	0.002***	0.002***	0.002***	0.001***
Adjusted R <sup>2</sup>	0.785	0.862	0.763	0.631

Notes: \*\*\*/\*\*/\* significant at 1%/5%/10%. Each regression has 130 observations (10 years × 13 regions). Variables are described in Appendix B.

When comparing the CDC scenario with the tax scenario, it is obvious that the energy trade channel is more important in the tax scenario. As emissions are no longer fixed and the tax scheme induces additional abatement, net exporters lose and net importers gain. This leads to a net loss for Russia (FSU) which benefits little from the shock but at the same time loses through reduced fossil fuel rents. When the direct effects are compared, they are smaller in the tax scenario than in the CDC scenario. This is due to the additional cost of additional abatement measures that the technology shock brings along.

Table 3 presents the results of the simple regressions for a shock to CCS. Different from the shock in renewables and more in line with the theoretical model, the direct shock always contains a positive and a negative part. The negative part is associated with the deployment of additional CCS which per se is a cost at first. The positive part refers to lower cost for CCS that would have also been deployed without the shock. Again, the shock coefficients are similar for all quantity based scenarios while they are lower for the price based tax scenario.

The energy channel is more complex in the case of CCS as there is a higher demand for coal and gas (because they can be used in combination with CCS), but a lower demand for oil. This is reflected in the analysis by splitting fossil fuel trade into its components. This confirms that different energy carriers have different effects for net exporters: only coal and gas exporters can benefit, while there is a small loss for oil exporters. Similar as in the case for fossil fuel trade under a shock for renewables, the adverse effect of oil trade is most visible in the tax scenario.

The change in emissions due to the shock is more difficult to interpret than in the case for renewables. This is because lower cost for CCS changes the stable relation between emissions and abatement. In fact, under a tax policy emission even increase slightly despite additional CCS deployment. Under the emission trading with fixed allocation, additional emissions require to buy additional permits and are hence more costly than in the case of Tax or Tax\*.<sup>20</sup> The coefficient for the surplus of emission rights prior to the shock is negative as in the case of a shock to renewable energy cost; again, it is only a minor factor.

Figure 8 shows the impacts of a shock to CCS for different regions in 2035. For different countries, different effects dominate. Australia (ANZ) gains from its coal trade, while other countries gain from reduced cost of CCS which they would have built also in the absence of a shock. There is also a larger difference between benefits from existing CCS and cost from additional CCS deployment. Russia (FSU), for example, is having a relatively high share of CCS already in the baseline

<sup>20</sup>Both in the case of Tax and Tax\*, revenues are returned lump sum, while in the case of a fixed allocation there is a transfer to other countries.

leaving less room to increase the share of electricity with CCS.

Compared to a shock to renewables which has a larger positive direct impact, the shock to CCS leaves several countries worse off – even though they all also are facing lower CCS costs.<sup>21</sup> The losses are usually caused by a combination of additional cost from additional abatement and increased cost from energy imports. Note that total direct effects of the shock can be negative. This holds from some regions under the quantity based policies and for almost all regions under the tax policy.

The decomposition based on regression analysis confirms the transmission channels identified in the theoretical model. All coefficients have the anticipated sign, with one exception being the positive effect of additional renewable deployment after a shock. This confirms that a shock reducing abatement cost not only brings along benefits but can also lead to additional costs from additional abatement effort. Different policies and different shock types influence the importance of different transmission channels. In general, the tax regime is most adverse because additional abatement in response to a shock is not compensated for. At the same time, a tax regime does not fix global emissions and thus fossil fuel exporters are more affected than in quantity based regimes. Under a shock to CCS, energy exporters can gain while the opposite holds for a shock to renewable energy. Under a shock to CCS, for some regions the direct effect from a shock can be negative. This can be reinforced if negative effects from a shock coincide with additional cost from international energy trade. The more complex CGE model thus confirms the theoretic model also in this respect.

## 4 Conclusions

The model simulations have confirmed the channels identified in the theoretical model. This indicates that it is not necessarily the case that a country or a region gains when its marginal abatement costs are reduced. The main channels for this are repercussions on fossil fuel markets and policies that do not fully compensate for the utilization of reduced cost abatement potential. The latter channel is more pronounced in more flexible policies (tax or tax with constant global emissions), i.e. under policies that do not fix emissions allocation but instead a carbon price or a global cap.

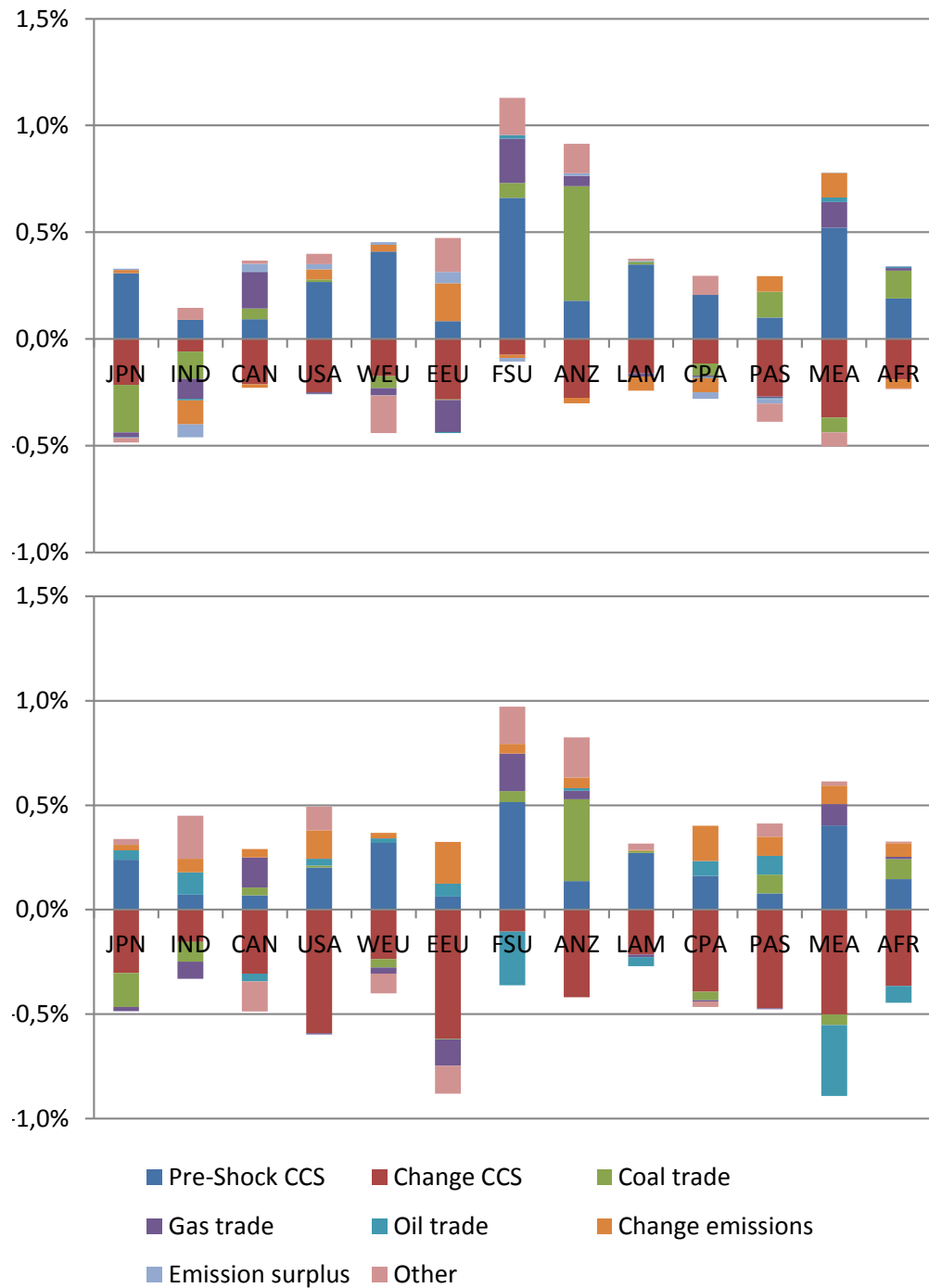
Could policies which limit reaping the benefits from lower abatement costs pose a problem? If the country were to be seen as a single actor this might in fact reduce the incentive to innovate. This result is contrary to the seminal paper of Milliman and Prince (1989). The reason for this is the different level of analysis. For an individual firm the incentives might be different compared to a (large) country. One important difference in our setting is that payments for taxes or carbon permit revenues are returned lump-sum to the country, such that paying a tax might be better than engaging in real effort to abate emissions.<sup>22</sup>

While it could be seen that in more flexible systems without fixed allowances a country might not benefit from the reduced cost of its abatement potential, this could also be interpreted as an insurance against higher abatement costs. This paper has looked at a shock towards lower abatement costs, yet the opposite results would hold for a shock towards more costly abatement. In this case, a system without fixed allowances would spread the additional cost of an shock and reduce the direct impact of countries experiencing the shock. There could thus be a tradeoff in policy design between incentivizing innovations and insuring against higher abatement costs.

<sup>21</sup> Under the Tax\* and ntr schemes, Japan, Canada, Europe (WEU and EEU), and Pacific Asia are worse off. Under CDC, only India and Japan are worse off while in the tax scenario all countries but India, Russia (FSU), Australia (ANZ) and Latin America are worse off.

<sup>22</sup> If payment of taxes and revenue allocation were decoupled, then this effect would no longer hold. This would however require an international mechanism for distribution of revenues and would create international transfers. Proponents of a regime with a coordinated tax rate claim that the very absence of international transfers increases the chances for implementation.

**Figure 8:** Decomposition of consumption changes due to shock in CCS in different regions in 2035 under a CDC (top) and a tax (bottom) policy. Calculations based on regressions from Table 3 (for the figure, regressions without a constant were used), “other” refers to residual effects.





The results are based on analysis of large countries which can influence global fuel or emission trading markets. In this model, countries do not act strategically. If they were using several instruments in their favor, it can be shown that for large countries a subsidy for renewable energy benefits countries that are importers of emission permits (Eichner and Pethig, 2014). The channel is the price drop in emission permits and the reduced import demand. These channels can also be identified in the model applied here.

The scenario design in this study might be unrealistic in the sense that it fixes policy for several decades. Yet, this is not completely unrealistic, as for example the EU is currently discussing their emissions path until 2030. Along this way however, there might not only be technology shocks but also unexpected macroeconomic shocks. The effect from the stylized technology shocks presented here were relatively small compared overall changes in consumption between now and the year under consideration (2035) and also compared to the primary impacts of climate policy at least in some countries. The overall abatement costs are more sensitive in changes to the overall regime type (see e.g. Chapter II) and a country's status on the fossil fuel markets (exporters vs. importers). Yet, the analysis might also shed some light on the consequences of macroeconomic shocks when these shocks lead to changes in abatement costs. It might therefore be worthwhile to explicitly model such shocks to see whether emission policies can act as economic stabilizers.

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## A Regions and sectors in the DART model

**Table A.1:** Regions and sectors of DART

Countries and regions			
WEU	Western Europe	CPA	China, Hong-Kong
EEU	Eastern Europe	IND	India
USA	United States of America	LAM	Latin America
JPN	Japan	PAS	Pacific Asia
CAN	Canada	MEA	Middle East and Norther Africa
ANZ	Australia, New Zealand	AFR	Sub-Saharan Africa
FSU	Former Soviet Union		
Production Sectors/Commodities			
<b>Energy Sectors</b>		<b>Non-Energy Sectors</b>	
COL	Coal	AGR	Agricultural Prod.
CRU	Crude Oil	ETS	Energy Intensive Production
GAS	Natural Gas	OTH	Other Manufactures & Services
OIL	Refined Oil Products	CRP	Chemical Products
ELY	Electricity	MOB	Mobility
		OLI	Other light industries
		OHI	Other heavy industries
		SVCS	Services
Renewable and advanced electricity technologies			
WIN	Wind	SOL	Solar
HYD	Hydro	SBIO	Solid Biomass
GASCCS	Advanced Gas with CCS	COLCCS	Advanced Coal with CCS

Note: See also the appendix of Chapter III for more information on the modelling approach to include different electricity generation technologies in DART. Different to Chapter III information from Renz (2012) for solar and from Lämmle (2012) for CCS is used.

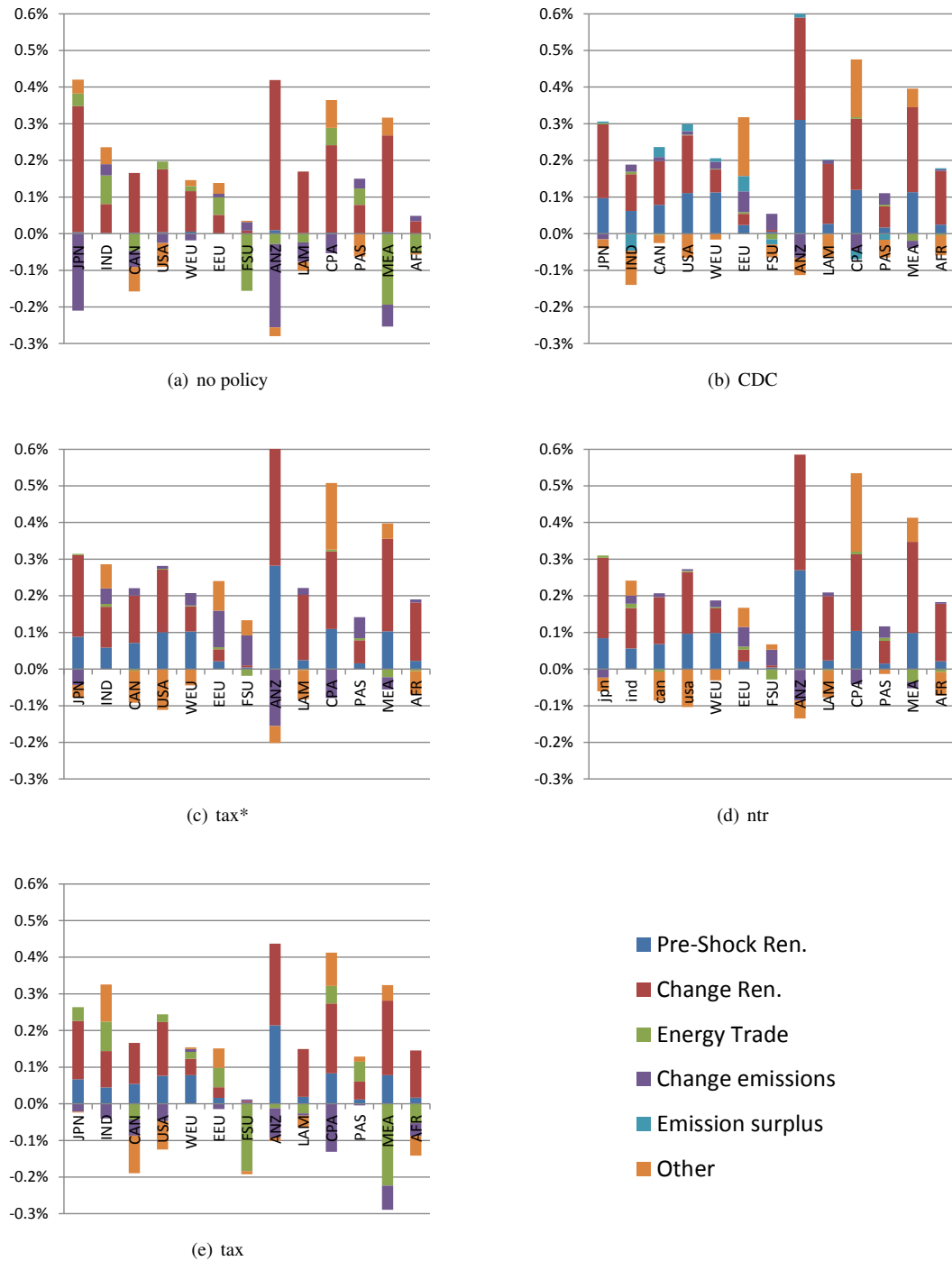
## B Variables used in regression analysis

**Table B.2:** Variables used in regression analysis

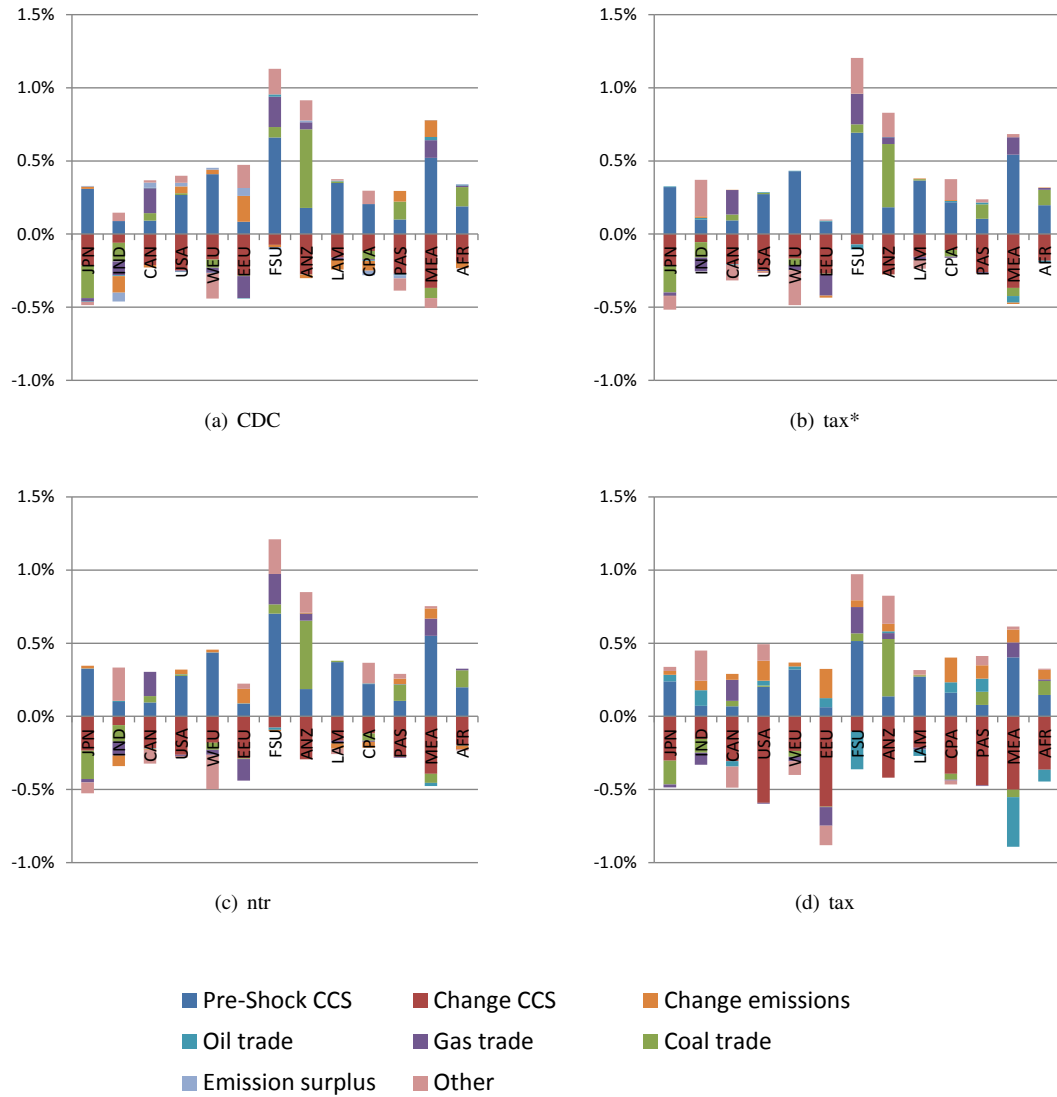
Variable name	Description
Change in renewables	Change in the share of solar and wind in the electricity mix in percentage points (relative to the scenario without a shock)
Change in CCS	Change in the share of CCS in the electricity mix in percentage points (relative to the scenario without a shock)
Pre-shock level of renewables	Share of solar and wind in the electricity mix in percent in the scenario without a shock
Pre-shock level of CCS	Share of CCS in the electricity mix in percent in the scenario without a shock
Pre-shock net fossil fuel exports	Value of net fossil fuel export without shock relative to GDP
Pre-shock net coal exports	Value of net coal export without shock relative to GDP
Pre-shock net gas exports	Value of net natural gas export without shock relative to GDP
Pre-shock net oil exports	Value of net export of crude oil and oil products without shock relative to GDP
Change in emissions	Change in emissions in percent (relative to the scenario without a shock)
Pre-shock surplus	Value of emission allowances sold on the international carbon market relative to GDP in the scenario without a shock

## C Decomposition of consumption changes

**Figure C.1:** Decomposition of consumption changes due to shock in renewable energy technologies in different regions in 2035 for different policies. Calculations for the year 2035 based on regressions from Table 2, “other” refers to residual effects.



**Figure C.2:** Decomposition of consumption changes due to shock in CCS in different regions in 2035 for different policies. Calculations for the year 2035 based on regressions from Table 3, “other” refers to residual effects.



## Chapter VI

# Fair, Optimal or Detrimental? Environmental vs. Strategic Use of Border Carbon Adjustment<sup>\*†</sup>

*We carry out a detailed sensitivity analysis of border carbon adjustment (rates) by applying a global Computable General Equilibrium (CGE) GTAP7-based model. We find different incentives for the regions in the climate coalition to raise carbon-based border tax rates (BTAX) above the standard rate that mimics an equalisation of carbon prices across regions. Herein, the strategic use of BTAX (the manipulation of the terms of trade) is stronger for all coalition regions than the environmental use (the reduction of carbon emissions abroad). Higher BTAX can reduce carbon leakage but with a declining marginal effect. Furthermore, we find different incentives for regions outside the coalition to oppose high BTAX rates: Russia and the other energy exporters would oppose it, while the Low-Income Countries would not because of benefits from the trade diversion effect. Thus, BTAX encourages the former to join the coalition, while compensating transfers are necessary to encourage the other (developing) countries including China and India.*

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<sup>\*</sup>This chapter is published as Weitzel, M., Hübler, M., and Peterson, S. (2012). Fair, optimal or detrimental? Environmental vs. strategic use of border carbon adjustment. *Energy Economics*. 34(S2): S198–S207.

<sup>†</sup>We are grateful to Christoph Böhringer, Edward Balistreri and Thomas Rutherford for organising the model comparison exercise and editing the special issue. Participants in the workshops leading up to the special issue provided helpful suggestions. We would like to thank two anonymous referees for their valuable comments and suggestions.

## 1 Introduction

Economic theory on trade and the environment, in particular the seminal work by Markusen (1975) has derived an optimal tariff that encompasses two terms: a term (a) that influences the terms of trade in Home's favour (given monopolistic power on international markets) and a term (b) that internalises the negative environmental externality caused by Foreign's export production. In the context of climate policy, Hoel (1996) shows that a carbon tax should not be differentiated across sectors if import and export tariffs are available for all traded goods. Such tariffs, also known as border tax adjustment, have recently created a controversy regarding their feasibility for reducing negative competitiveness effects of unilateral climate policy through carbon leakage – that is the relocation of carbon intensive industries to regions without climate policies - and for reducing carbon emissions in general.

Herein, term (a) creates an incentive for policy makers to set a carbon-based tariff higher than the environmentally optimal term (b) in order to influence the terms of trade in their favour. This is especially true in a situation of uncertainty about the true carbon intensities of traded commodities (based on directly created emissions or a full life cycle analysis<sup>1</sup> or the practical assumption that Foreign's emission intensities are equal to Home's emission intensities). Accordingly, there are incentives for policy makers to deviate from the standard carbon tariff rate. This deviation might harm other countries and might be in conflict with WTO legislation (cf. Bhagwati and Mavroidis, 2007). Due to the uncertainty about the true carbon intensities of products imported from different regions, this deviation can easily occur by chance. Therein, small deviations might or might not have significant effects on Home's and Foreign's welfare and global emissions. These considerations complicate the practical implementation of border tax adjustment policies. Therefore, it appears highly policy relevant to assess how important such effects are. A complex multi-region, multi-sector CGE (Computable General Equilibrium) model using real-world data and capturing relevant intersectoral and international feedback effects is an appropriate instrument to do so. In a related work with a different setting, in which Home aims to minimise the costs of unilaterally reaching a given emission target with sectorally differentiated carbon prices and accounting for leakage effects to Foreign, Böhringer et al. (2010b) show that the environmental term (b) is of less importance than the strategic terms of trade effect (a). From a methodological point of view they show that the strategic terms of trade effect can be switched off by compensating Foreign through lump-sum transfers such that its welfare remains at the level without climate policy in Home. Unfortunately, this approach does not carry over to the setting with border carbon adjustment where Foreign's welfare is not only affected by changes in the terms of trade, but also by the border tax Foreign has to pay. Also, in Böhringer et al. overall efficiency of abatement in Home and maximising Home's welfare go hand in hand since emission taxes apply to Home sectors only. This is different in a setting with border carbon adjustment. Overall cost efficiency is nevertheless a relevant issue also under border carbon adjustment. Against this background, our first set of research questions can be formulated as: How sensitive is regional welfare with respect to changes in carbon tariffs? How important is the strategic term (a) relative to the environmental term (b)? Are there different incentives for economies within a climate coalition to impose border tariffs that deviate from the standard rate against certain economies outside the coalition? Which countries or world regions will significantly gain or lose?

Concerning term (b) the problem is that it is difficult to assess climate damages and thus the external costs of carbon. Moreover, the value of term (b) depends on the market power of Home that imposes it: Having more market power, Home can induce higher emission reductions in For-

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<sup>1</sup>Cf. Peters et al. (2011).



eign; thus a higher tariff rate can be optimal from an environmental point of view. In reality, it is overall difficult to determine how high the optimal carbon-based tariff is. Theoretically, it can even be shown in a  $2 \times 2$  general equilibrium trade model that term (b) can become negative if Foreign's export sector is less carbon intensive than Foreign's non-export sector (Jakob et al., 2011, based on Markusen, 1975) and that an optimal border adjustment is a net import tariff set below the standard Pigouvian rate (Yonezawa et al., 2011). The reason is that border tax adjustment might shift production from exports towards (on average) more carbon intensive non-export production. And in general, in a second best world of existing taxes, tariffs and subsidies, the additional effect of border tax adjustment on top of these is ambiguous. The standard carbon-based tariff rate sets the tariff rate such that the tax bill on imports from Foreign to Home is equal to the tax bill that exporters would have to pay in Foreign if the same carbon price as in Home existed in Foreign. Thus, the standard rate need not reduce global emissions in a (socially) optimal way and the effects of border carbon adjustment on global emissions are not clear-cut. Moreover, policy makers mainly fear that firms will relocate production to regions without a carbon price, which is the "relocation channel" of carbon leakage. Previous model simulations (e.g. Böhringer et al., 2010a), on the contrary, indicate that the reduction in global fossil fuel prices due to climate policy-induced demand reductions, i.e. the "fossil fuel price channel" is clearly the dominant channel. In this sense, our second set of research questions can be phrased as: How sensitive are regional and global emissions with respect to changes in carbon tariffs? How will carbon leakage change when the tariff rate deviates from the standard rate? Is it realistic that very high tariffs can increase carbon leakage? Is the relocation channel or the fossil fuel price channel dominant?

Furthermore, Lessmann et al. (2009) show that under certain conditions, tariffs can encourage non-coalition countries to join a climate coalition as long as the tariff rate is small relative to the Armington elasticity. They show that global welfare rises in the coalition size. In this sense, border carbon adjustment could be a feasible instrument to achieve a large climate coalition. Herein, a third leakage channel occurs, the "free-rider channel". This means a larger climate coalition increases the incentive to leave the coalition and to free-ride on the reduction efforts of the coalition. In the context of carbon-based border measures, a larger coalition can reduce emissions at a lower carbon price, which in turn reduces the carbon-based border measure rates. Thus, the "punishment" for being outside the coalition via border measures decreases and raises free-rider incentives. But again, it is an open question whether these effects are significant. A multi-region, multi-sector CGE model can help assess how this mechanism works, how strong it is and what it implies.<sup>2</sup> Moreover, the linkage of climate policy to trade policy will likely result in trade creation and trade diversion effects (Viner, 1961) between coalition and non-coalition countries. This leads to our third set of research questions: Do carbon-based tariffs indeed give incentives for a larger climate coalition? Is such a coalition stable or is the free-rider channel dominant? How high are the tariff rates that are necessary to induce certain countries (such as China) to join the climate coalition or to achieve a global coalition? Is it better for the coalition to use border measures or (financial) transfers to encourage non-coalition members to join? How pronounced are the trade creation and diversion effects?

To address these questions, we apply a version of the CGE model DART and focus our analysis on the year 2020. Our analysis is closely related to the literature that examines border carbon adjustment in numerical models for climate policy analysis such as Babiker and Rutherford (2005) and Böhringer et al. (2010a). This literature often finds a limited potential of border tax adjustment

<sup>2</sup>Finus (2008) concludes in his overview article focusing on CGE modeling that there are plenty of opportunities for studying the prospects of cooperation "but also a serious need to improve and further develop current models in order to provide policy guidance..."

to reduce carbon leakage. It is furthermore related to the original theoretical literature on border tax adjustment regarding value added taxes such as Meade (1974) and Grossman (1980). They show that a uniform sales tax for all goods is non-distorting and trade-neutral under border tax adjustment of imports and exports. However, this does not hold under border carbon adjustment because tax rates differ depending on the carbon content of goods.

Our analysis is also related to the literature on optimal tariffs: Hamilton and Whalley (1983) find that existing tariffs are at “some distance from optimal tariffs” and that there is a high potential for trade wars. Herein, they point out that import price elasticities are crucial parameters for such calculations. Summarising the literature, Mayer (1984) concludes that “political decisions on tariff rates are reflections of the selfish economic interests of voters, lobbying groups, politicians, or other decision makers in trade policy matters”. Gros (1987) shows (based on Krugman, 1980) that the optimal tariff in form of a uniform ad valorem tax is an increasing function of the economy size and of product differentiation. Kennan and Riezman (1988) build on the common view that particularly large economies can manipulate the terms of trade in their favour, while retaliation would make all countries worse off. The authors show that substantially large economies can win despite retaliation. Kennan and Riezman (1990) examine custom unions<sup>3</sup> that are similar to climate coalitions in our context: Custom unions can improve the welfare of their members charging optimal tariffs compared with free trade. According to the authors, the move from Nash equilibrium to free trade improves global resource allocation, while this is not necessarily the case when moving from free trade to a custom union. Yilmaz (1999) shows that results from a CGE analysis of export taxes differ from those in a partial equilibrium analysis. He finds a higher welfare improvement via Nash revenue maximising taxes than via Nash optimum taxes. Finally, Broda et al. (2008) state that “countries set import tariffs nine percentage points higher on inelastically supplied imports relative to those supplied elastically” exploiting their power on international markets. Despite the long history of theoretical work on optimal tariffs accompanied by statistical estimates, the role of optimal tariffs in an applied CGE framework appears to be not yet fully researched – in particular regarding the current climate policy debate.

Against this backdrop, our paper proceeds as follows: Section 2 describes the CGE model DART and the scenarios under scrutiny. Section 3 addresses our first set of research questions regarding welfare effects. Section 4 addresses our second set of research questions regarding global emissions and leakage. Section 5 addresses our third set of research questions regarding climate coalition formation and trade effects. Section 6 concludes.

## 2 Model and Scenarios

The DART (dynamic applied regional trade) model version used in this exercise is a multi-region, multi-sector recursive dynamic CGE model of the world economy.<sup>4</sup> DART is implemented in MPSGE (Mathematical Programming System for General Equilibrium Analysis; Rutherford 1999), a subsystem of GAMS (General Algebraic Modeling System; Brooke et al. 2010), using PATH (Dirkse and Ferris, 1995) for solving the MCP (mixed complementarity problem). This version of DART is calibrated to an aggregation of 9 regions:

**USA – United States, RUS – Russia, EUR – EU27 and EFTA , RA1 – Other Annex I except Russia, EEX – Energy Exporting Countries except Mexico, CHN – China, IND – India, MIC**

<sup>3</sup>The theory of custom unions goes back to Viner (1961) He shows that a custom union has a trade creation (replacement of domestic production by imports from within the customs union) and a trade diversion effect (replacement of imports from outside by imports from inside the union).

<sup>4</sup>For more details see [http://www.ifw-kiel.de/academy/data-bases/dart\\_e/a-short-description-of-dart/view?set\\_language=en](http://www.ifw-kiel.de/academy/data-bases/dart_e/a-short-description-of-dart/view?set_language=en)

– **Other Middle-Income countries, LIC – Other Low-Income Countries.**

It distinguishes 9 sectors:

**OIL – Refined oil products, COL – Coal, GAS – Natural Gas, CRU – Crude Oil, ELE – Electricity, CRP – Chemical Products, TRN – Transport Services, EIT – Emission Intensive Trade Goods, AOG – All Other Goods.**

The model distinguishes four production factors: labour, capital and land and natural resources (fossil fuels). In order to analyse climate policies, CO<sub>2</sub> emissions are calculated based on the carbon contents of the fossil fuels coal, gas and oil burned in final or intermediate production or consumption.

We assume perfect commodity and factor markets. In each region, there is one representative consumer who incorporates private and public consumption, and one representative producer for each sector. Producer behaviour is derived from cost minimisation for a given output. The final consumer receives all income generated by providing primary factors for production. A fixed share of income is saved, while the remaining income is used for purchasing commodities. Herein, the linear expenditure system (LES) first satisfies basic demand. The remaining consumption good is a composite of an energy aggregate and a non-energy aggregate.

Labour and capital are homogenous goods, mobile across industries within regions, but immobile across regions. All regions are linked by bidirectional trade flows of all commodities except the investment good. Domestic and foreign commodities are imperfect (Armington) substitutes distinguished by the country of origin. The trade balance of each country is kept constant relative to total (private plus government) consumption.

The DART model is recursive-dynamic. It solves for a sequence of static one-period equilibria for future time periods. The major exogenous, regionally different driving factors of the model dynamics are population growth, labour productivity growth, human capital growth and capital accumulation. Population growth rates and labour participation rates are taken from the PHOENIX model (Hilderink, 2000) and are in line with recent OECD projections. Growth rates of human capital are taken from Hall and Jones (1999). Capital accumulation is driven by an exogenous depreciation and savings rates. The time horizon of this exercise is 2020.

The static part of the DART-Model is calibrated to the GTAP 7 database (Narayanan and Walmsley, 2008) for the benchmark year 2004. For the dynamic calibration we match GDP growth and CO<sub>2</sub> emissions of the business as usual (BAU) scenario to the OECD Environmental Outlook (OECD, 2012) by adjusting total factor productivity growth to approximately match the GDP growth and the elasticities of fossil fuel supply to match global CO<sub>2</sub> emissions. This leads to an average per capita growth rate between 7% in CHN and 1.5 to 1.8% in coalition countries (Europe, USA and Annex I countries except Russia). Global energy-related CO<sub>2</sub> emissions reach 34.5Gt in 2020 with 13.4Gt stemming from the coalition countries, followed by China that contributes 9.6Gt. In all regions, the output of the energy sector grows more slowly than the output of the other production sectors. Only in CHN and IND the emissions and trade-intensive sectors (EIT, CPR) grow noticeably faster than other sectors (AOG).

In the **business as usual (BAU) scenario**, no climate policy is assumed. The **reference scenario (REF)** assumes emission reductions in a coalition consisting of Europe, the USA and Annex 1 countries except Russia (EUR, RA1, USA). The level of global emissions in 2020 in REF (and all following scenarios that include climate policy) is fixed at BAU emissions in 2020 of the non-coalition countries plus 80% of 2005 coalition emissions. Globally, this leads to a 10.3% emission reduction in 2020 relative to BAU. The reductions are reached via an endogenous uniform carbon tax in all coalition countries that ensures the targeted global emission level. Since there is carbon leakage to non-coalition countries, the coalition in general ends up reducing more than 20% in 2020.

**Table 1:** Pre-existing tariff rates, carbon tariff rates, and export rebate rates for 2020 in percent

Non-coal. region	Sector	Pre-existing import and export tariffs for imports into			Standard BTAX rate for imports into			Carbon export rebate for exports from		
		USA	EUR	RA1	USA	EUR	RA1	USA	EUR	RA1
CHN	OIL	0.5	0.0	1.3	3.0	3.0	3.0	1.6	0.6	0.8
IND	OIL	1.3	0.0	2.7	0.4	0.4	0.4	1.6	0.6	0.8
RUS	OIL	20.5	22.0	20.4	2.4	2.4	2.4	1.6	0.6	0.8
EEX	OIL	1.2	0.4	2.4	5.4	5.4	5.4	1.6	0.6	0.8
MIC	OIL	1.5	1.8	2.4	1.0	1.0	1.0	1.6	0.6	0.8
LIC	OIL	1.9	11.1	7.0	1.7	1.7	1.7	1.6	0.6	0.8
All	OIL	2.3	7.5	1.8	3.1	3.4	3.7	1.6	0.6	0.8
CHN	CRP	3.0	3.5	1.3	5.5	5.5	5.5	1.5	0.6	1.1
IND	CRP	1.8	0.7	2.1	8.0	8.0	8.0	1.5	0.6	1.1
RUS	CRP	5.1	6.7	7.7	18.5	18.5	18.5	1.5	0.6	1.1
EEX	CRP	1.4	1.1	1.6	7.7	7.7	7.7	1.5	0.6	1.1
MIC	CRP	1.4	1.5	2.0	3.2	3.2	3.2	1.5	0.6	1.1
LIC	CRP	1.6	1.7	5.9	13.3	13.3	13.3	1.5	0.6	1.1
All	CRP	0.1	0.3	0.3	5.2	5.8	5.6	1.5	0.6	1.1
CHN	EIT	3.4	2.7	0.9	10.9	10.9	10.9	2.5	1.4	1.7
IND	EIT	0.3	0.4	1.7	14.8	14.8	14.8	2.5	1.4	1.7
RUS	EIT	6.5	7.0	9.5	12.5	12.5	12.5	2.5	1.4	1.7
EEX	EIT	1.5	1.0	1.2	11.5	11.5	11.5	2.5	1.4	1.7
MIC	EIT	0.6	0.7	1.0	5.6	5.6	5.6	2.5	1.4	1.7
LIC	EIT	1.8	0.8	2.3	15.1	15.1	15.1	2.5	1.4	1.7
All	EIT	0.7	1.4	1.0	8.4	9.5	9.4	2.5	1.4	1.7
CHN	all <sup>a</sup>	6.8	4.6	4.1	0.6	0.5	0.7	0.3	0.1	0.3
IND	all <sup>a</sup>	5.5	2.8	3.3	1.4	0.9	1.2	0.3	0.2	0.6
RUS	all <sup>a</sup>	9.9	24.5	24.3	5.9	3.0	3.7	0.1	0.1	0.3
EEX	all <sup>a</sup>	1.2	2.1	1.1	0.6	0.8	1.0	0.2	0.1	0.3
MIC	all <sup>a</sup>	1.4	3.8	2.8	0.5	0.5	0.7	0.4	0.2	0.3
LIC	all <sup>a</sup>	6.4	2.7	3.4	0.2	0.7	0.6	0.2	0.1	0.3
all	all <sup>a</sup>	4.2	5.0	4.2	0.6	0.7	0.9	0.3	0.1	0.3

<sup>a</sup>Trade-flow-weighted average tax rate for the total trade between non-coalition and coalition countries.

Climate policy starts in 2010 and emission reductions in the coalition countries are implemented as linear reductions until 2020.

In order to cope with the negative effects of unilateral policies, coalition members impose **border tax adjustments (BTAX)** to the emission and trade intensive sectors (OIL, CRP, EIT). We apply full border tax adjustment such that coalition exporters receive rebates for what they paid for using carbon inputs, besides levying border taxes on imports based on the carbon content of the imported goods. In the central BTAX scenario, we apply the carbon tax in the coalition countries as the standard BTAX rate reflecting the carbon content of trade based on direct emissions and emissions caused by electricity generation Böhringer et al. (for a discussion on alternative calculations see 2012b). This has the aim to fully level the carbon playing field on international markets and could thus be seen as a kind of “fair” rate. The tax revenues are in a lump-sum fashion transferred to the representative consumer of the importing country who also pays for the export rebate in a lump-sum fashion.

Since, as described above, global emissions are held constant in all climate policy scenarios, global and regional climate change damages (not represented in the model) stay constant and do not influence the welfare analysis.

Table 1 presents the border measure rates for 2020 as well as pre-existing (combined ad valorem

export and import) tariff rates in percent showing that there are large differences in the overall importance of the border measures and also their importance relative to pre-existing trade measures. The differences will determine the resulting welfare effects analysed in Section 3. According to the table, carbon-based BTAX rates for imports from non-coalition to coalition countries in 2020 range from 0.4 to 18.5 %. For the EIT sector, tariff rates are higher than for OIL and CRP (except for Russia where CRP is highest); between 10.9% for India and 15.1% for LIC goods. EIT goods from MIC are less carbon intensive and therefore taxed lower. Export rebates are much lower than import tariff rates and amount to 0.6 to 2.5%. The reason is that the export rebates are determined based on the emission intensities of developed coalition countries inside the climate coalition which are lower than those of developing countries outside the coalition. This explains why export rebates have only a small additional impact compared to import tariffs. In order to assess the overall importance of the border carbon measures, we calculate the trade-flows-weighted average tariff rate for total trade between non-coalition and coalition countries (lines “all”) in 2020. This yields an average tariff rate of only 0.6% for imports to Europe, 0.7% for imports to RA1, and 0.9% for imports to USA. Exports from RUS into the coalition are subject to a considerably higher average carbon tax rate, as the share of goods subject to border measures is high. Concerning the pre-existing tariffs, Table 1 shows that these are particularly high in Russia and here especially in the oil sector (mainly export levies).

As discussed above, there are presumably incentives to deviate from the standard rate. In our model analysis, we therefore multiply the border measure rate in the time period 2010 to 2020 with a constant factor that we vary in a sensitivity analysis. Two special cases are worth mentioning: If the multiplier is zero, no border measures will be imposed as in scenario REF. If the multiplier is set to unity, the standard rate, i.e. the equalisation of carbon prices for coalition imports and coalition production, will be reached.

Furthermore, to analyse the incentives of border measures to join a global coalition, we run one additional climate policy scenario, where the same global emissions as in the other climate policy scenarios are reached via a globally uniform carbon tax.

### 3 Welfare Effects

This section examines the sensitivity of regional welfare with respect to changes in carbon tariffs, the importance of the strategic relative to the environmental part of the tariff and the incentives for different regions to deviate from the standard border tax rate.

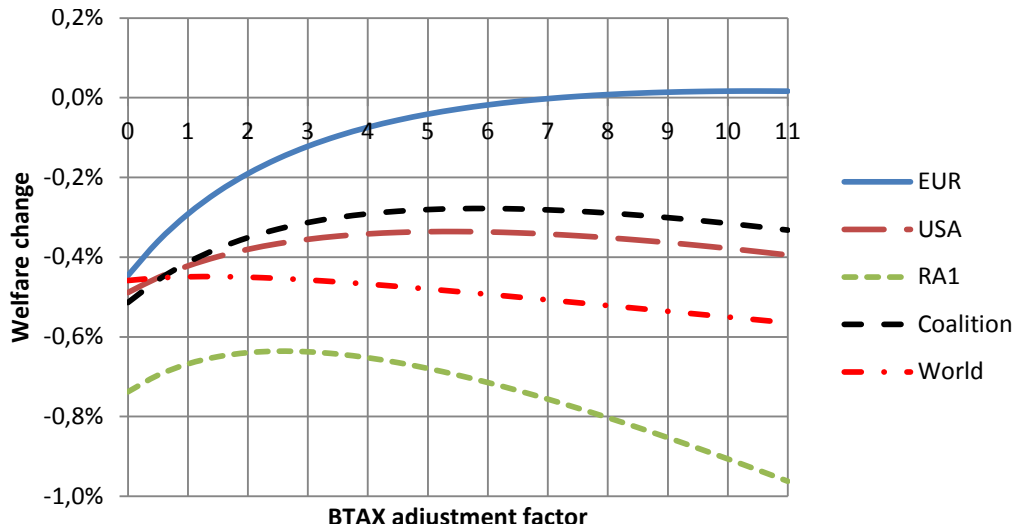
Figure 1 plots first of all the change in coalition welfare in the presence of border tax adjustment at different rates relative to the business as usual (BAU). Welfare effects are measured as percentage changes in accumulated, discounted welfare effects based on the relative Hicks equivalent variation relative to the BAU scenario.<sup>5</sup> Obviously, a typical “optimal tariff picture” emerges for the coalition countries: Higher border measure rates improve the terms of trade (TOT)<sup>6</sup> of the coalition since it decreases import prices and increases export prices. E.g. when doubling the standard rate (factor 2 instead of 1) the TOT increase by 0.1% for EUR and by 0.2% for the USA and RA1. This translates into welfare changes as well, but after a certain point higher rates reduce welfare.<sup>7</sup> As expected, all coalition regions have an incentive to set the border measure rate above the standard rate. The extent to which regional decision makers would augment existing tariff (and export subsidy) rates differs across regions, though. Europe (EUR) has a high potential for benefitting from increased tariff rates.

<sup>5</sup>Accumulated over the time frame 2004 to 2020 with yearly time steps and discounted at a rate of 2% per year.

<sup>6</sup>The terms of trade are computed in form of a Laspeyres price index for exports divided by imports.

<sup>7</sup>This outcome becomes intuitive when thinking of a monopolist who raises the price of his product to the optimal level above the competitive level. If he has at the same time market power on factor markets, he will reduce the price of the inputs he uses below the competitive level.

**Figure 1:** Change in coalition and global welfare (accumulated and discounted from 2004 to 2020) under border carbon adjustment at different rates represented by a BTAX adjustment factor (a multiplier of the standard BTAX rate) relative to BAU.

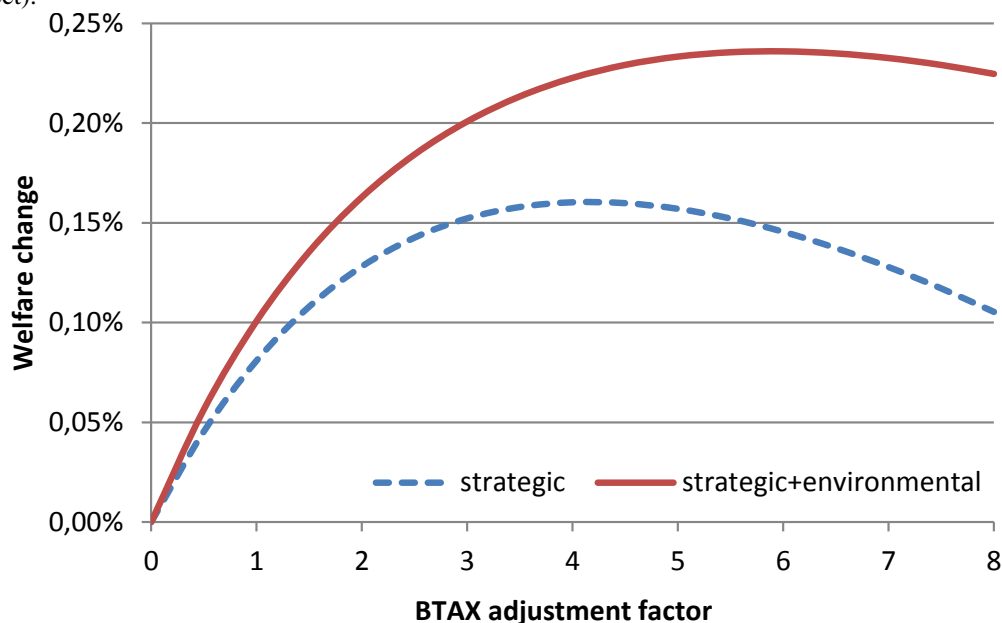


The maximum for EUR lies at a multiplier of 10.7. The USA's potential is somewhat lower than the average potential of the coalition with a maximum around the factor 5.6. For the other Annex I countries (without Russia) the maximum is only at a factor of about 2.9. The welfare of the entire coalition is maximised around the factor 6.2. Differences in the optimal level of border measures stem from different trade and production structures of the coalition members, differences in the level of border tariffs resulting from different carbon intensities and differences in pre-existing tariff rates. If a coalition country has for example a high share of carbon-intensive imports or a high share of OIL, CRP or EIT products from carbon-intensive countries, this will result in high tariffs, but also in high welfare costs as the consumer has to substitute imports by other goods. The carbon tariff as a value share over total imports from non-coalition countries is highest in RA1 (0.9%), and lower in EUR (0.7%) and the USA (0.6%). At the same time, export rebate rates are higher in RA1 and the USA (0.3% of export value for exports to non-coalition) and lower in EUR (0.1%) when applying an equal multiplier for all regions in the coalition. Pre-existing tariff rates and trade costs are slightly lower for the USA compared to EUR and RA1. As a consequence, the same BTAX rate implies a higher relative rise in overall tariffs in the USA than in EUR and RA1 and has thus stronger effects.

We discussed the distinction between the strategic part of border measures and the environmental part in the Introduction. In our analysis, the strategic term is represented by changes in the terms of trade. In our model that does not include climate damages, the question is how to interpret and identify the environmental term. Existing approaches, as e.g. in Böhringer et al. (2010b) that was discussed in the introduction, do not carry over to our setting where in particular overall efficiency of abatement and maximisation of coalition welfare do not go hand in hand. Overall cost efficiency that is underlying the environmental term in Böhringer et al. is nevertheless a relevant issue in our analysis. It can be deduced in our case from looking at global welfare across different adjustment rates (also shown in Figure 1).<sup>8</sup> The level of the adjustment factor that minimises global abatement costs and that is efficient from an environmental point of view is 1.3 which is considerably lower than the levels that maximise the welfare level of the individual coalition countries or the coalition as a whole. Under this interpretation of the environmental motive, it is thus mainly the strategic motive that drives the optimal adjustment factors to levels much higher than 1.3. Compared to BAU,

<sup>8</sup>Global welfare is calculated as the income weighted sum of individual regions welfare changes.

**Figure 2:** Change in coalition welfare between the scenario allowing global emissions to change (strategic effect) and the scenario keeping global emissions constant (strategic + environmental effect).

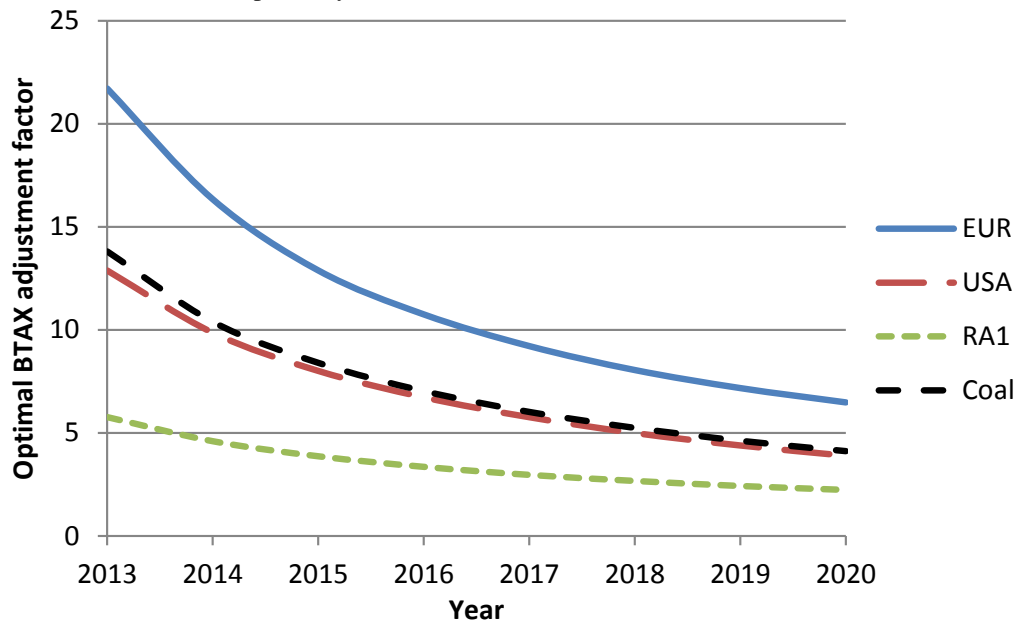


climate policy without border measures reduces global welfare by 0.5%. This does not take reduced climate change damages into account. Border measures can reduce the global welfare loss to 0.4% at the best because the inefficient distribution of abatement is reduced by broadening the base for the carbon tax (see Böhringer et al., 2012a).

Another way to identify the environmental motive in our setting is that the coalition suffers negative welfare effects from emission leakage that requires it to abate more to keep global emissions constant. Border carbon adjustment thus increases coalition welfare by reducing leakage and requiring lower emission reductions in the coalition countries to reach the same global target (see Section 4). In order to separate the strategic effect, we run an additional scenario where we fix emission reductions of the coalition and allow global emissions to change. In such a scenario, welfare changes in the coalition countries only stem from the strategic effect while the environmental effect through reductions in carbon leakage as we explained it above is completely ignored and switched off.

Figure 2 plots the welfare change of the coalition relative to climate policy without border adjustments. When determining the welfare maximising border measure as above, the coalition makes use of a strategic effect improving its terms of trade and an environmental effect. The latter stems from the fact that border measures reduce leakage, thus making the reduction target of the coalition less strict when global emissions are held constant. This effect will be switched off when coalition reductions are fixed to their level in REF. Figure 2 shows that for low adjustment rates the strategic effect dominates. At the standard border measure rate it accounts for 80% of the total effect. For the individual regions, the strategic effect is most important for EUR, where the 88% of the total effect are due to the strategic part. For the USA and RA1 the decomposition attributes 72% and 62% of the total effect to the strategic effect, respectively. It turns out that only at very high border measure rates the environmental effect becomes dominant. Current climate policy usually formulates fixed reduction targets, independent of leakage to non-coalition countries, which neglects the environmental effect. For such policies, the welfare maximising border measures are closer to the standard rate, albeit still higher. With the strategic effect only, coalition welfare is maximised at 4.2 times the standard rate and for the individual regions EUR, USA, and RA1 at 7.7, 3.8, and 1.9 times the standard rate, respectively.

**Figure 3:** The BTAX adjustment factor measured relative to the standard BTAX rate that maximises Home's welfare in the respective years.



Another indicator for the environmental benefit of border measures is the CO<sub>2</sub> price in the coalition. It depends on different border measure rates and drops from about 75 to about 66 2004-US-\$ when raising the border measure rate from 0 (REF) to a factor of 8. This happens because the global emissions are held constant: The coalition can afford smaller emission reductions when carbon leakage to non-coalition regions decreases. If not global emissions, but the emission reductions of the coalition are held constant, the price effect reverses. Increasing the border measure multiplier from 0 to 8 leads to an increase of the CO<sub>2</sub> price from 75 to 80 2004-US-\$.

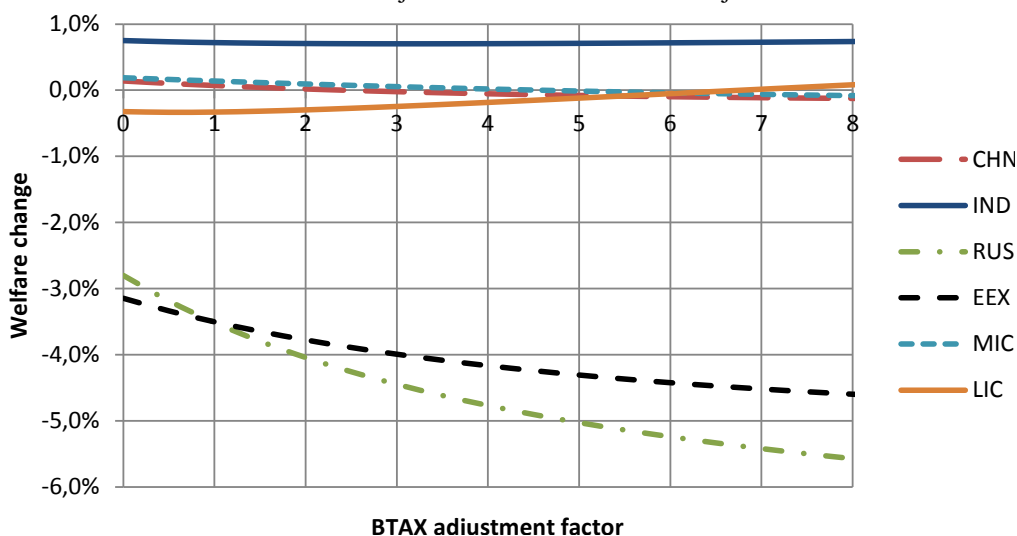
Note that for more stringent climate targets of the coalition, Figures 1 and 2 remain similar in their shape; however, the welfare maximising BTAX multiplier would be lower. The intuition behind this is that the welfare optimising tariff is largely determined by pre-existing tariffs and the economic structure of the coalition regions which remain similar between scenarios. More stringent climate policy with a higher CO<sub>2</sub> price therefore leads to a lower multiplier and reduces the incentive to deviate from the “fair” rate.

Figure 3 plots the optimal adjustment factor, this means it plots only the adjustment factor given by the maximum point in Figure 1, now plotted for different years. Obviously the optimal adjustment factor declines over time for each region. This happens because the carbon price rises over time within the coalition, which results in a rising standard rate of the border measure. Therefore, the strategic part that we identified as the dominant term is reduced in order to keep the export and import prices at the optimal level for the Home region. Nevertheless, the optimal rate is still well above the standard rate in 2020 for all regions.

Figure 4 shows the change in non-coalition welfare in the presence of border measures at different rates relative to BAU (like Figure 1 for the coalition). It is obvious that the welfare change without border measures (factor 0, REF) is larger than the changes due to higher or lower border measures. The driving factor for the difference across regions is the so-called “fossil fuel price effect”. Climate policy implies a reduced demand for fossil energy and thus also reduced fossil fuel prices net of carbon costs. This is in tendency welfare enhancing for major energy importing countries (like CHN, IND) and welfare reducing for major energy exporters (RUS, EEX). For different levels of border measures, the welfare effect reaches a minimum within the range of tariff rates under



**Figure 4:** Change in non-coalition welfare (accumulated and discounted from 2004 to 2020) between a scenario with border carbon adjustment at different BTAX adjustment factors and BAU.



examination in the upper graphs (IND, CHN, MIC and LIC) wherein the welfare effects are relatively small, though. Russia (RUS), where energy exports are a major share of GDP and exports are subject to relatively high border measures (see Table 1), is hit hardest by border carbon adjustment, followed by the other Energy Exporting Countries (EEX). The Low-Income Countries (LIC) lose to a smaller extent, but they gain at high border measure rates. In these countries, exports from sectors subject to border measures only account for a quarter of imports in the same sectors, i.e. the LIC benefit from export rebates but are hurt relatively little by increased import tariffs of the coalition. Furthermore, LIC's ratio of trade with non-coalition members versus trade with coalition members is higher than in other regions. Trade within the group of non-coalition members increases, and the terms of trade improve in LIC's favour. The Middle-Income Countries (MIC) lose to a small extent at high rates. All rates appear slightly beneficial for China (CHN) and significantly beneficial for India (IND).

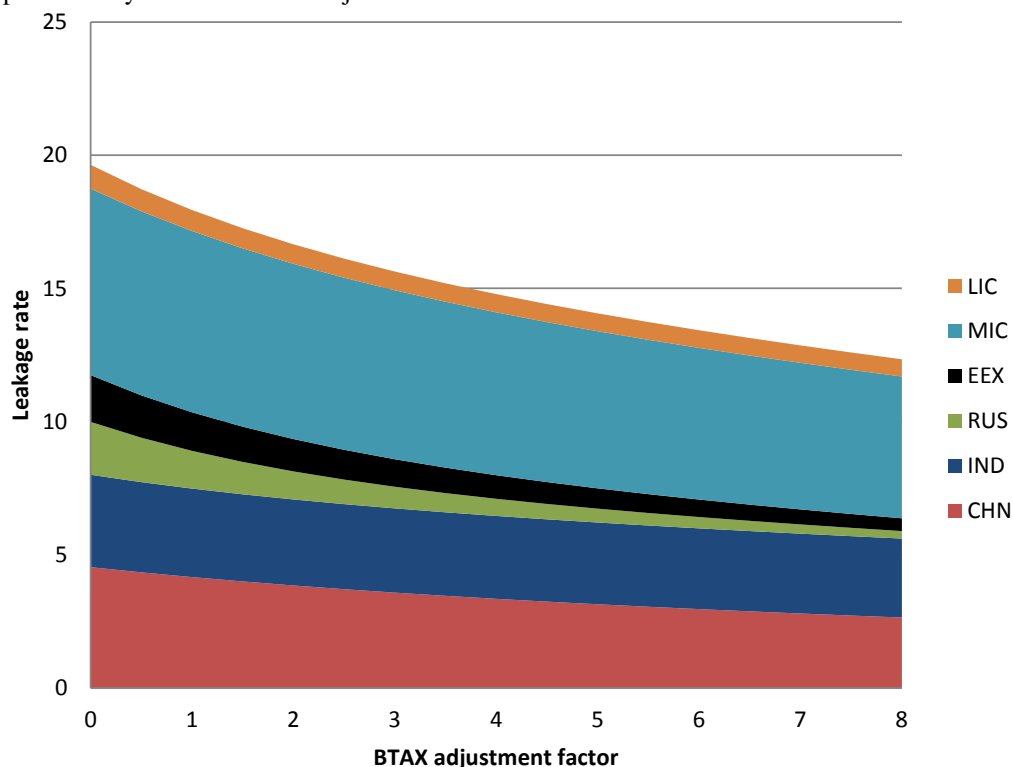
## 4 Carbon Leakage

Carbon-based border measures are supposed to reduce carbon leakage to regions without a carbon price.<sup>9</sup> Therefore, this section examines the sensitivity of regional and global emissions and carbon leakage with respect to changes in the carbon tariff rates. Since we keep global emissions constant in our scenarios, a reduction in leakage abroad allows for a more generous emissions target at home. In this way we capture the environmental benefit of border measures for the home region.

Figure 5 shows the global leakage rate including all non-coalition countries at the uppermost line. The coloured parts below the upper line illustrate to what extent specific regions contribute to *global* leakage. The global leakage rate is 19.6% without border measures, 17.9% for the standard border measure rate and 13.3% for eight times the standard rate. Accordingly, increased border measure rates have the potential to reduce total leakage by almost 8% when setting the rate to eight times the standard rate. Herein, the curve flattens at higher rates. This means, the (marginal) potential for reducing leakage declines at higher rates. The Middle-Income Countries (MIC), China (CHN) and India (IND) contribute most due to their size. The Low-Income Countries (LIC), Russia (RUS) and the Energy Exporting Countries (EEX) contribute to a small extent. We find no evidence for

<sup>9</sup>The leakage rate is defined as the increase in emissions in the regions without an emission cap (CHN, IND, RUS, EEX, MIC, LIC) divided by the decrease in emissions in the coalition (EUR, USA, RA1).

**Figure 5:** Regional carbon leakage rates depending on the strength of border carbon adjustment represented by different BTAX adjustment factors.



increased leakage due to border measures. This is in line with our finding that the environmental effect is always positive for the range of border measures we examine (see Section 3). Besides the magnitude of leakage from different regions, the reaction of leakage rates to higher border measures is also important. While leakage to energy exporters (RUS, EEX) is reduced significantly with higher border measures, leakage to IND, MIC and LIC is more robust. This shows that leakage to these regions is mainly determined by the original climate policy while BTAX has only a small effect. The effect of BTAX on leakage to CHN is somewhat higher, probably because on the one hand China is a fossil fuel importer, but on the other hand higher border measures also reduce production relocation to China.

To better understand the channels of leakage we also undertake additional runs where the fossil fuel (coal, gas and crude oil) prices are held constant at their BAU levels by adjusting the endowments of the fossil fuel resources in all model regions. In these runs, the fossil fuel price channel of carbon leakage is not present. We find that although the overall leakage rate is significantly reduced (from around 20% in the case of no border carbon adjustment and flexible fuel prices to around 1%), border carbon adjustment still reduces carbon leakage compared to a scenario without border carbon adjustment. The percentage point reduction in leakage due to border measures actually remains almost the same (around two percentage points at the standard rate). This shows that the fossil fuel price channel is the dominant leakage channel of the original climate policy and that this channel can hardly be rendered ineffective via border measures.

## 5 Stability of the Climate Coalition

This section explores to what extent border measures can help create a larger climate policy coalition. It also explores the role of trade creation and diversion effects between coalition and non-coalition regions.

We basically compare the situation of a grand coalition, this means a global climate policy coalition including all countries (regions), to the situation of the small coalition (consisting of USA, EUR and RA1) and the non-coalition (consisting of CHN, IND, MIC, LIC, EEX and RUS) that we have considered throughout the paper. In each case, the respective coalition has implemented a uniform carbon price across all regions and sectors in the coalition in order to reach the same global environmental outcome as in REF. Table 2 summarises our coalition stability analysis. The left bloc deals with the grand coalition without compensation transfers. The left column reports the regional welfare changes (accumulated and discounted year by year from 2004 to 2020) between being in the grand coalition and being in the non-coalition facing border carbon adjustment imposed by the coalition (at the standard rate). As expected, the world as a whole benefits from the formation of a grand coalition compared to the previous small coalition with border measures. This shows that super-additivity holds, i.e. total coalition welfare increases in the coalition size. Among the non-coalition regions, China (CHN), India (IND), the Middle-Income Countries (MIC), and Low-Income Countries (LIC) are worse off and would thus prefer being in the non-coalition. Energy Exporters (EEX) and Russia (RUS) would clearly prefer joining a global coalition instead of being outside the coalition – even without border carbon adjustments, represented by an adjustment factor of zero in the second column of Table 2. This is due to the following reasoning: The grand coalition abates a higher share of emissions from coal compared to a sub-global climate coalition. This leads to a higher share of oil in the global fuel mix in the grand coalition scenario and EEX and RUS therefore profit from higher oil prices and resource rents. This applies to the standard border measure rate. Higher border measure rates increase the cost of not joining the coalition though. However, they turn out to be only effective in incentivising CHN and MIC to join the grand coalition and only at very high BTAX rates of six to ten times the standard rate as shown in the second column.<sup>10</sup> LIC and IND, on the contrary, will never prefer being in the grand coalition within the scope of our feasible parameter space, even not at very high BTAX rates.

Instead of threatening non-coalition countries through border measures, *compensation transfers* can create an incentive to join the grand coalition. We thus run a scenario where – everything else equal – we achieve global cost effectiveness via full international carbon trading and allocate “surplus allowances” to certain regions such that they become indifferent between being in the grand coalition and being in the non-coalition together with the other non-coalition regions and facing border carbon adjustment. This situation is shown in the middle bloc of Table 2. The fourth column of Table 2 lists the additionally allocated surplus allowances in Mt CO<sub>2</sub> per year.<sup>11</sup> Multiplying the volume of surplus allowances by the carbon price and discounting at 2% yields the monetary value of the transfer in 2010 which is shown in the sixth column of Table 2. For simplicity we assume that the volume of allowances that the original coalition regions USA, EUR and RA1 transfer is equally distributed across them. It is an endogenous model result though that the resulting welfare changes for these regions relative to the BTAX scenario with the standard rate are also equal. As can be seen from the table, EUR, USA, and RA1 are still better off in the global coalition with compensation transfers than in the small coalition with border carbon adjustment.

In addition to this exercise where compensation assures indifference between the grand coalition and the small coalition with BTAX, we examine compensation transfers that achieve indifference between being in the grand coalition and being in the non-coalition without border carbon adjustment. The latter scenario is REF. The resulting transfers are reported in parentheses in the middle bloc of

<sup>10</sup>In this exercise, we raise the BTAX rate that all non-coalition countries face and find that at an adjustment factor of 6.6 MIC is indifferent between being in the grand coalition and being in the non-coalition, while at an adjustment factor of 10.0 CHN is indifferent between these situations. Herein, the non-coalition encompasses the same members as before.

<sup>11</sup>For simplicity we keep surplus allowances in each simulation step constant over the whole reduction period 2010 to 2020.

**Table 2:** Incentives to join the climate coalition: The left bloc compares the grand climate coalition consisting of all regions to the small coalition that consists per assumption of USA, EUR and RA1, while the other regions form the non-coalition. Therein, higher BTAX rates (expressed by a higher adjustment factor) make single regions indifferent between being in the grand coalition and being in the non-coalition. The middle bloc shows the situation where the grand coalition entrants are equally off as being in the non-coalition due to compensation transfers. The right bloc shows the situation where regions' incentives to free-ride as singletons (rather than jointly being in the non-coalition) are compensated additionally to the previous compensation.

Region	Grand coalition		Grand coalition with compensation via emissions allowances							
	Comparison to small coalition & non-coalition facing BTAX		Grand coalition members equally off as in non-coalition facing BTAX (not facing BTAX under REF)				Grand coalition member equally off as singleton facing BTAX			
	Welfare change rel. to BTAX in %	BTAX factor to making region join	Welfare change rel. to BTAX in %	Surplus allowances <sup>a</sup> in Mt CO <sub>2</sub> p.a.	Cumulative value <sup>b</sup> in US-\$	Incentive to become singleton	in bill.	to be- come single- ton	Addit. allow- ances Mt CO <sub>2</sub> p.a.	Addit. cumul. value in bill. US-\$
CHN	-0.2	10.0	0.0	810 (1076)	48.0 (63.7)	yes	172	10.2		
IND	-0.8	/ <sup>c</sup>	0.0	770 (798)	45.6 (47.3)	no	0	0.0		
MIC	-0.2	6.6	0.0	482 (603)	28.5 (35.7)	yes	38	2.3		
LIC	-0.2	/ <sup>c</sup>	0.0	77 (79)	4.6 (4.7)	yes	36	2.1		
EEX	1.9	0	1.9	0 (0)	0.0 (0.0)	yes	165	9.8		
RUS	2.3	0	2.3	0 (0)	0.0 (0.0)	no	0	0.0		
USA	0.4	-	0.3	-713 (-852)	-42.0 (50.5)	-	-137	-8.1		
EUR	0.4	-	0.3	-713 (-852)	-42.0 (50.5)	-	-137	-8.1		
RA1	0.6	-	0.3	-713 (-852)	-42.0 (50.5)	-	-137	-8.1		
World	0.3	-	0.3	0 (0)	0.0 (0.0)	-	0	0.0		

<sup>a</sup>Calculated as the difference between the allowance allocated to this region under the emission trading scenario and the emissions in the uniform tax scenario.

<sup>b</sup>Value of the transfer in 2010 calculated by multiplying the surplus allowances in Mt CO<sub>2</sub> by the carbon price and discounting at 2%.

<sup>c</sup>Within the range of feasible BTAX rates under scrutiny, we find no BTAX rates that make IND and LIC being equally off in the coalition and in the non-coalition facing BTAX.

Table 2. The difference between the compensation transfers in these two cases reveals how valuable a credible threat of border carbon adjustment is for the original coalition regions: The underlying reasoning is that non-coalition members presumably have lower welfare when facing BTAX than when not facing BTAX. The welfare difference between the grand coalition and the BTAX case is thus expected to be smaller than between the grand coalition and the REF case. This results in smaller compensation transfers when border carbon adjustment exists as a credible policy instrument. And indeed, we find that the compensation transfers with respect to the BTAX scenario are substantially lower than with respect to the REF scenario (values in parentheses). The reduction in compensation payments for each coalition member due to BTAX amounts to (a discounted value of) 8.5 billion 2004-US-\$. This reduction can largely be attributed to lower surplus allowances for China which receives 25% fewer surplus allowances, and for MIC which receives 20% fewer surplus allowances.

Once a grand coalition has been formed, there can still be an incentive for single regions to leave the grand coalition and free-ride as singletons (rather than being in a non-coalition together with other regions as examined before). Hence, we also test whether the global grand coalition is stable

in terms of internal stability. For this purpose, we compute the welfare change between being in the grand coalition and being the only region outside for each region except the core regions USA, EUR and RA1.<sup>12</sup> We assume that when a country leaves the coalition, it will face border carbon adjustment at the standard rate imposed by all regions within the coalition and will not receive any compensation payments anymore. A priori, it is not clear whether border measures are still a useful threat: On the one hand, all other regions are members of the coalition and impose border measures. On the other hand, the CO<sub>2</sub> price and therefore also the standard border measure rate are much lower than in a smaller coalition because the given global emission reduction can be achieved more efficiently. Indeed, our results indicate an incentive for CHN, MIC, LIC and EEX to be a single non-coalition region. For EEX this is somewhat surprising since EEX seems averse to border measures in our previous analysis (see Section 3). EEX will obviously be affected differently in the case of low border measures imposed by all other regions than in the case of high border measures imposed by EUR, USA and RA1 only.

A stable grand coalition can still be achieved by granting additional allowances as a “stability premium” for *all* potentially deviating regions at the same time, paid by the core regions, EUR, USA and RA1.<sup>13</sup> This compensation scheme is shown in the right bloc of Table 2. The stability premium increases the costs of compensation payments by 19% compared to the previous compensation scheme.

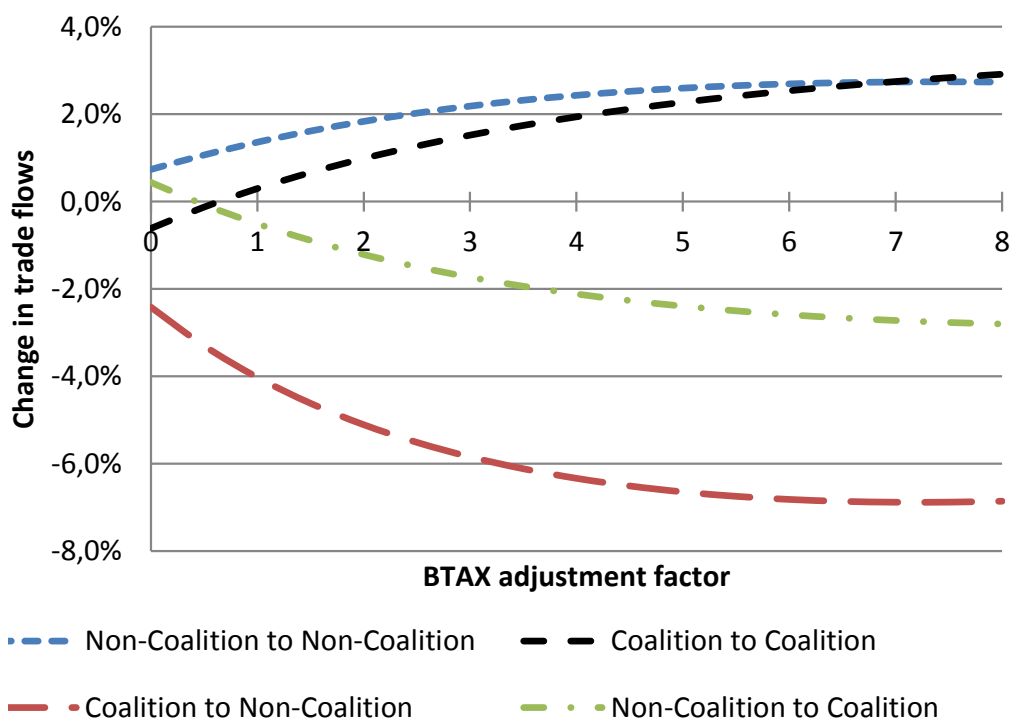
Looking at the core coalition countries (EUR, USA and RA1) under different BTAX rates, only EUR would be better off with a small coalition and a BTAX rate of more than 4.6 the standard rate compared to a global regime with a uniform global carbon price and no border adjustments. The USA and RA1 are always better off in a global coalition. Yet, when shifting the burden sharing of compensation payments towards RA1 and USA, it is possible to reach an outcome in which all coalition countries would prefer a global coalition.

Let us now look at trade between the standard small coalition (EUR, USA and RA1) and the non-coalition. Figure 6 illustrates *trade creation and diversion* effects between the coalition and the non-coalition in 2020. Real trade flows into and out of the coalition regions are computed as the sum of imports into the coalition and export values, respectively. The figure illustrates the typical trade diversion effect of custom unions: Trade increases within the coalition and within the non-coalition; but trade decreases between the two groups. Compared to the situation without border measures, imports into the coalition are reduced and thus replaced by domestic production. Furthermore, since the coalition as an aggregate cannot (substantially) change its trade deficit with the non-coalition countries by assumption, a lower import value leads to a lower export value in spite of tax rebates on coalition exports. Since the average import tariff rates of the coalition are higher than the export rebate rates (see Table 1), the import changes drive the export changes in the coalition countries. Coalition exports in the sectors subject to border measures however increase with higher export rebate rates. Without border measures they drop by 6.6% relative to BAU. Introducing border measures now has two effects: First, there is a shift from exporting to supplying to the domestic market because import tariffs reduce supply from abroad. Second, the opposite shift occurs due to the export rebates. At the standard level of border measures the former outweighs the latter and exports are reduced by 8.0% below BAU or 1.5% below REF. Further increases in the border measure rate then lead to an increase in exports, however still below the BAU level when applying eight times

<sup>12</sup>It would also be beneficial for EUR, USA, and RA1 to drop out of the coalition. However, our initial policy assumption is that this small coalition has to reduce global emissions by a given amount based on the assumption that the industrialised (Annex-I) regions are the front-runners of climate policy. Allowing one of these regions to drop out would not be consistent with this assumption.

<sup>13</sup>Again, the caveat described in footnote 12 applies, as it would be beneficial for EUR, the USA and RA1 to drop out of the grand coalition.

**Figure 6:** Regional carbon leakage rates depending on the strength of border carbon adjustment represented by different BTAX adjustment factors.



the standard rate. Coalition imports in these sectors react more sharply to border measures. Without border measures, imports increase by 7.4% above BAU due to production relocation. At the standard rate, the import level is already reduced by 11.8% below BAU. The level is below BAU because production outside the coalition is more carbon intensive compared to production in the coalition, which leads to higher relative prices for imported goods when the carbon price is taken into account. When further increasing the border measure rate to 8 times the standard rate, coalition imports in the affected sectors will be reduced by up to 70%.

## 6 Conclusion

Our global CGE analysis reveals different incentives for the regions in the climate coalition – USA, Europe, and the other Annex-I countries – to raise carbon-based border tax rates above the standard rate that mimics an equalisation of carbon prices across regions. We find the strongest incentives for Europe and still a significant incentive for the USA. We also find that the strategic use of border measures (the manipulation of the terms of trade) is stronger for all coalition regions than the environmental use (the reduction of carbon emissions abroad). According to our results, there is a risk that policy makers misuse border measures for strategic reasons in the presence of market power on international markets – but there is an upper limit on increasing tariffs. With rising carbon prices over time, the welfare-optimising tariff approaches the standard rate based on the carbon content of trade. Not exploiting the environmental effect further lowers the incentive to apply higher than standard rates. However, for all coalition regions there remains an incentive to set border measures in excess of the standard rate in 2020. With respect to the WTO legislation, our results support the view that if border measures are employed, they are to be limited to levels justified by the environmental benefits.

Furthermore, the sensitivity of non-coalition countries' welfare to increasing border tax rates

above the standard rate appears diverse: Russia and the other energy exporters lose strongly, while China, India and the Middle- and Low-Income Countries are hardly affected. The Low-Income Countries might even slightly gain from the resulting trade diversion effect: Trade decreases between the groups of coalition and non-coalition countries, but it increases within each group. As a consequence, the Low-Income Countries can benefit from increased trade with other non-coalition countries. According to these results, some countries like Russia and other energy exporters might strongly oppose the introduction of border measures, arguing that the misuse would be harmful. Other countries like developing countries would hardly exert this argument.

Our results also confirm in accordance with the literature that carbon-based border measures have a significant but limited potential for reducing carbon leakage. Higher border tax rates are able to reduce leakage, but the marginal leakage reduction declines with higher border tax rates. Furthermore, we do not find evidence that border measures would increase carbon leakage, although that is theoretically possible. Finally, we confirm that the fossil fuel price channel of leakage (through climate policy induced changes in fossil fuel prices) is far more important than the relocation channel.

Finally, carbon-based border measures can encourage certain regions like Russia and other energy exporters to join a climate coalition. Border measure rates much higher than the standard rate can make China and the Middle-Income Countries indifferent between being within the global coalition and facing border measures outside the coalition. International compensating transfers, in form of additional emission allowances, for instance, appear to be a more efficient instrument (regarding coalition welfare) to create a stable global (grand) coalition than border measures.

Overall, our paper confirms previous findings that there are clear incentives for countries outside inside sub-global coalitions that undertaking climate policy to implement border measures. Mainly for strategic reasons this increases their welfare. Yet, border measures are not a good substitute for an efficient global carbon policy with a uniform global carbon price. They do not provide strong incentives to participate in a global climate regime for all regions either. This is especially true for India and the least developed countries.

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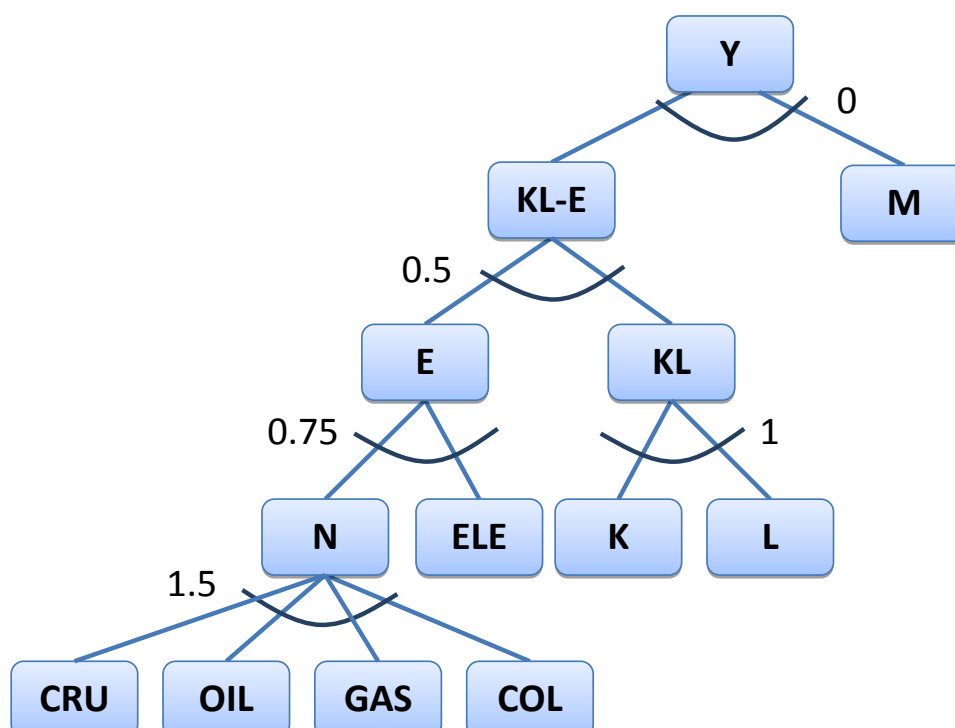


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## A Appendix

### A.1 Production structure

**Figure A.1:** The main CES production structure and substitution elasticities for each sector and region.  $Y$  = output,  $K$  = capital,  $L$  = labour,  $E$  = energy,  $M$  = intermediates,  $N$  = non-electricity. Fossil fuel inputs (crude oil, refined oil, natural gas and coal) are associated with  $\text{CO}_2$  emissions in fixed proportions. For the production of refined oil, input of crude oil and coal are treated as intermediates  $M$  at the top nest (Leontief), no direct carbon emissions are associated with the use of this energy feedstock. The remaining fossil fuels (crude oil, natural gas and coal) use a fixed resource at the top nest. The elasticity between the fixed resource and the remainder of the production function is scaled to achieve a given global supply taken from OECD (2012).



### A.2 Key model equations

This section lists the key model equations, i.e. it describes the model in a stylised way that highlights the principal structure. The model equations are written as a mixed complementarity problem (MCP) for each region  $r$  and each period  $t$ . An MCP consists of zero-profit and market clearance conditions and a consumer's budget condition. The model equations are implicitly programmed under GAMS/MSPGE.  $p$  denotes a price,  $X$  denotes a pecuniary quantity.  $i$  or  $j$  denote a sector described.  $f$  denotes a production factor such as capital  $K$  and labour  $L$  and in case of fossil fuel extraction also natural fossil resources.  $\theta_{f,i}^G$  represents a set of taxes and subsidy rates on output and inputs.  $M$  indicates an Armington (intermediate) good.  $C$  is  $\text{CO}_2$  associated with fossil fuel inputs in fixed proportion.  $\pi$  denotes profits,  $CES$  a constant elasticity of substitution function, and  $LTF$  a Leontief function.

### A.2.1 Zero-profit conditions

(Z1) Goods  $Y$  production (in sectors  $i$ ) as shown in detail in Figure A1.

$$\pi_i^Y = p_i^Y - CES_i^Y (p_f^F, p_j^M, p^C | \theta_{f,i}^G) \leq 0 \quad \forall (r, t)$$

(Z2) Armington aggregation  $M$ , combining imports from foreign regions  $s$ , associated with a price for transportation  $p_{s,r,i}^T$  in a first step (M1) and then forming an aggregate with domestic goods (M2):

$$\pi_i^M = p_i^M - CES_i^{M2} \{ p_i^Y, CES_i^{M1} | [LTF (p_{s,i}^Y, p_{s,r,i}^T) | \theta_{f,i}^G] \} \leq 0 \quad \forall (r, t)$$

(Z3) Utility  $U$  generation of the representative consumer in each region  $r$  combines an energy with a non-energy input bundle:

$$\pi^U = p^U - CES^U | (p_i^Y) \leq 0 \quad \forall (r, t)$$

### A.2.2 Market clearance conditions

(M1) Goods markets (domestic inputs, Armington imports and domestic consumption):

$$\sum_j \frac{\partial \pi_j^Y}{\partial p_i^Y} X_j^Y + \sum_s \frac{\partial \pi_{s,i}^M}{\partial p_i^Y} X_{s,i}^M + \frac{\partial \pi^U}{\partial p_i^Y} X^U \leq X_i^Y \quad \forall (r, t)$$

(M2) Armington goods  $M$  markets:

$$\sum_j \frac{\partial \pi_j^Y}{\partial p_i^M} Y_j \leq X_i^M \quad \forall (r, t)$$

(M3) Factor  $F$  markets (given regional factor endowments):

$$\sum_i \frac{\partial \pi_i^Y}{\partial p_f^F} Y_i \leq \bar{X}_f^F \quad \forall (r, t)$$

### A.2.3 Budget condition

(B1) Consumers' purchases and investments  $I$  must not exceed their factor income (including natural fossil resources) plus revenues from selling CO<sub>2</sub> allowances  $C$  plus tax minus subsidy  $Q$  revenues as a function of given tax and subsidy rates, plus net financial inflows from abroad  $D$  less the expenditure on subsistence consumption  $S$  (Linear Expenditure System):

$$\sum_i p_i^Y X_i^Y + p^I X^I \leq \sum_f p_f^F \bar{X}_f^F + p^C \bar{X}^C + X^G (\theta_{f,i}^G) + p^D X^D - \sum_i p_i^Y \bar{X}_i^{Y,S} \quad \forall (r, t)$$

## Chapter VII

# Emissions embodied in Chinese exports taking into account the special export structure of China<sup>\*†</sup>

*Quantification of CO<sub>2</sub> emissions embodied in China's trade is important for an informed debate on whom to blame for the recent rise in Chinese emissions or the calculation of border carbon adjustments. Applying input output (IO) techniques, we calculate these emissions in (1) a standard model, (2) a regionally disaggregated model, taking into account that export production is concentrated in more advanced and more emission efficient provinces and (3) in a model with export processing, taking into account that almost half of the Chinese exports rely on a large share of imported intermediates and little domestic value and emissions added. We compare year 2007 emissions embodied in Chinese exports in a unified framework. We also report emissions embodied in Chinese imports used for intermediate production of exports by combining calculations for China with data from global IO models. We find that both a model with 30 provinces (1730 Mt CO<sub>2</sub>) and a model accounting for export processing (1630 Mt) yield lower Chinese emissions embodied in exports compared to the standard model (1782 Mt). In the regional model, emissions are even lower (1522 Mt), if interprovincial trade is not taken into account.*

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## 1 Introduction

China has become the world's largest emitter of CO<sub>2</sub> in 2006, and in 2012 Chinese emissions already accounted for 29% of global emissions (Olivier et al., 2013). A substantial share of these emissions is associated with the production of export goods, because for a large economy China has a very high export share in GDP. Both the absolute number of CO<sub>2</sub> emissions embodied in Chinese exports as well as the share of emissions associated with export production in total Chinese emissions has risen over time (Weber et al., 2008; Peters et al., 2011; Zhang, 2012), driven by a growth rate of trade that exceeds overall GDP growth rates (Wei et al., 2011).

The quantification of emissions embodied in Chinese exports is partly rooted in a discussion on who is responsible for the rise in Chinese emissions (Pan et al., 2008). From the Chinese perspective, these emissions could be attributed to foreign consumption and thus are not (exclusively) subject to the Chinese responsibility. From a developed country's different perspective, these emissions can however also be viewed as leakage arising from emission constraints. Countermeasures for leakage such as border carbon adjustments could therefore target these emissions embodied in trade. A calculation of the emissions at stake could thus inform this political discussion.

The emissions embodied in China's exports are subject to several input-output (IO) analyses of a single country (e.g. Su and Ang, 2010; Weber et al., 2008; Zhang, 2012), of bilateral trade flows (e.g. Guo et al., 2010), or of multiple regions (MRIO) (e.g. Atkinson et al., 2011; Peters et al., 2011; Davis et al., 2011). Previous studies often assume that the structure of the export production and production for domestic use is identical. In reality however, Chinese exports are produced mainly in energy and emission efficient coastal provinces and a sizable fraction comes from "export processing" where little value and energy is added in China.

China is very diverse regionally, both in terms of income and efficiency in production, but also in terms of the share of exports in GDP. Exports are regionally concentrated in the more advanced provinces. The coastal provinces of Jiangsu, Guangdong, Shanghai, and Zhejiang alone contributed 69% of Chinese exports in 2007 (National Bureau of Statistics of China, 2009b). To determine the emissions embodied in exports, the economic structure of these provinces is important. Emission intensity (emissions per unit of value added) in these provinces is lower than the average for China. Recent studies calculating emissions embodied in Chinese exports based on a regionally disaggregated IO model find indeed lower emissions compared to a standard model (Su and Ang, 2010; Guo et al., 2012). Interprovincial trade plays however an important role in China, and provinces with a high share of export production are net receivers of emissions embodied in domestic trade (Feng et al., 2013; Guo et al., 2012). In this study we therefore want to analyze how export concentration in carbon efficient provinces on the one hand and interprovincial trade on the other hand offset each other.

At the same time, about half of the export production is carried out under "export processing" provisions, i.e. provisions that stipulate production in "customs special supervision zones" where imported intermediate inputs enjoy a preferential treatment. Export processing is thus characterized by a high share of imported intermediates and a low share of Chinese value added (Koopman et al., 2008). Recent studies find that emission intensities especially in the export processing sectors are much lower than if average domestic production technology is assumed (Ma, 2012; Dietzenbacher et al., 2012; Su et al., 2013).

In this study we extend the standard IO model to calculate emissions embodied in exports by relaxing the assumption of homogenous production functions for all output in a given sector. We model export sectors differently and compare this to the standard calculation of emissions embodied in trade in two ways: First a spatial disaggregation and second a special treatment of the export

processing sector. For the spatial disaggregated model, we specifically discuss the role of emissions embodied in interprovincial trade. For a consistent comparison, we carry out our analysis in a unified mathematical framework and balance disaggregated IO tables in a way that a re-aggregation would yield the national IO table. Furthermore, we base all our calculations on 2007 IO tables and thus provide an update of previous studies that compare regionally disaggregated models or models with export processing.

China is not only characterized by a high share of exports in GDP, but also by a high share of imports in GDP. Consequently, emissions embodied in imports which are used as intermediate inputs in the production of export goods are not negligible. Previous studies often used Chinese domestic technology assumption to calculate these emissions. Emission intensities of Chinese imports are however lower than of its own production. Differences in efficiency between countries were usually corrected for only in simplified ways if at all. To improve the depiction of these emissions, we combine our analysis of Chinese IO models with data derived from a global MRIO model based on GTAP data (Narayanan et al., 2012).

Our main aim in the comparison of the three IO models is to determine the magnitude of differences in the estimates for emissions embodied in Chinese exports and Chinese domestic final use. If there is only little change in the more complex models relative to the simpler national model, then a national model can be seen as a justified approximation in future applications. However, the more detailed models can also provide valuable insights to better understand where (in what provinces) and how (export processing vs. normal exports) emissions embodied in exports are originated. This can provide guidance to design emission reduction policies.

The article is structured as follows: Sections 2 – 4 present an IO model in a standard way, with spatial disaggregation, and a separate export processing sector, respectively. Section 5 presents and compares results from the different models. Section 6 concludes.

## 2 Standard input-output approach to calculate emissions embodied in exports

In the standard input-output model, total output  $X$  is the sum of intermediate production  $Z$  and final demand  $Y$

$$X = Z + Y = AX + Y = (I - A)^{-1}Y \quad (1)$$

with the production coefficient matrix  $A = \frac{Z}{diag(X)}$  and the Leontief inverse  $(I - A)^{-1}$  indicating total production requirements for one unit of final output.<sup>1</sup> To obtain CO<sub>2</sub> emissions  $c$  associated with the final use of  $Y$ , the production requirements to produce  $Y$  have to be multiplied with the environmental coefficient vector  $F$  with elements  $f_i = c_i/x_i$ , with  $c_i$  being the total direct emissions of production  $x_i$  in each sector  $i$ .

$$c = F'(I - A)^{-1}Y. \quad (2)$$

The final demand vector  $Y$  consists of domestic demand and exports  $E$ . Accordingly, the emissions associated with the production of export demand are then

$$c^E = F'(I - A)^{-1}E. \quad (3)$$

Chinese input output tables assume competitive import assumption, i.e. the technology matrix  $A$  consists of both domestically produced and imported intermediate inputs  $A = A^D + A^M$ . By replacing

<sup>1</sup>Matrices and vectors are denoted by capital letters, while scalars such as elements of matrices are denoted with lower case.

$A$  with  $A^D + A^M$ , Su and Ang (2013, Appendix A) show that emissions in export can be re-written as

$$c^E = F'(1 - A^D)^{-1}E + F'(I - A)^{-1}A^M(1 - A^D)^{-1}E. \quad (4)$$

The first term gives domestic emissions in exports while the second term describes the emissions embodied in imported intermediate inputs required for export production. Replacing the total emission intensity for imported goods  $F'(I - A)^{-1}$  with  $F^{M'}$ , domestic and imported emissions embodied in exports can be denoted by

$$c^{D,E} = F'(I - A^D)^{-1}E \quad (5)$$

and

$$c^{M,E} = F^{M'}A^M(I - A^D)^{-1}E. \quad (6)$$

This allows also for calculation of emissions associated with Chinese domestic final use by subtracting emissions embodied in exports from total (direct, energy related) emissions in China  $c_{prod} = \sum_i c_i$  and adding emissions embodied in total imports  $c^M = F^{M'}M$ . This leads to consumption based rather than production accounting of Chinese emissions:

$$c_{cons}^D = c_{prod} + c^M - (c^{D,E} + c^{M,E}) \quad (7)$$

### 3 Embodied emissions in exports with spatial disaggregation

For the spatial disaggregation we use the same concept as above, however now matrix  $A^D$  and vectors  $F$  and  $E$  have different dimensions. While the dimensions in the standard model were determined by the numbers of sectors, the regionally disaggregated model now has the dimensions of the number of sectors  $n$  times the number of regions  $m$ . We construct a multiregional IO matrix:

$$A^{D*} = \begin{pmatrix} A_1^D & 0 & \cdots & 0 \\ 0 & A_2^D & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & A_m^D \end{pmatrix}$$

where  $A_k^D$  is the  $n \times n$  use matrix of the  $k^{th}$  province. To obtain  $A^{D*}$ , we split total regional inflows provided in the data into imports from abroad and inflows from other provinces using an entropy method (Robinson et al., 2001) and then remove imports from foreign as in the section above to obtain  $A_k^D$ .

If  $A^{D*}$  was directly used in the IO analysis, all domestic intermediate inputs are originating in the region. To incorporate interprovincial trade flow, we pre-multiply  $A^{D*}$  with a transfer matrix  $T$ . This Chenery-Moses transfer matrix  $T$  is structured as follows

$$T = \begin{pmatrix} T_{1,1} & T_{1,2} & \cdots & T_{1,m} \\ T_{2,1} & T_{2,2} & \cdots & T_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ T_{m,1} & T_{m,2} & \cdots & T_{m,m} \end{pmatrix}$$

The diagonal submatrix  $T_{r,s}$  contains elements  $t_{i,r,s}$  stating the share of good  $i$  traded from region  $r$  to region  $s$  in total use of good  $i$  in region  $s$ . For the special case where  $T$  is the identity matrix, there is no interprovincial trade.

The equations for calculating Chinese (domestic) emissions and imported emissions embodied in exports are

$$c^{D,E} = F'(I - TA^{D*})^{-1}E \quad (8)$$

and

$$c^{M,E} = F^{M'}A^M(I - TA^{D*})^{-1}E. \quad (9)$$

The vector  $F^{M'}$  is an  $m$  times stacked vector  $F^{M'}$  from equation (6) above, i.e. import emission intensities are not differentiated by destination province. The national emission intensity vector  $F'$  is calculated with provincial energy data, however scaled such that the sum is equal to the sum of national emissions.

## 4 Emissions embodied in trade with disaggregated export processing sector

An alternative method to improve the representation of the exports is the introduction of export processing sectors. As the spatial disaggregation method, this approach also splits the national IO table based on additional information. Here, this additional information comes from Chinese customs data and allows for better representation of imports and domestic intermediates (and value added) in export production. The split of the underlying national IO table was first proposed by Koopman et al. (2008) to determine the Chinese domestic value added share of Chinese exports and adapted to environmental IO modeling by Ma (2012), Dietzenbacher et al. (2012) and Su et al. (2013).

The intuition is to split the input-output table into (a) "normal" production sectors  $N$  for regular production to fulfill Chinese demand for domestic products  $Y^D$  and foreign demand for non-processing exports  $E^N$  and (b) into sectors  $P$  for processing exports  $E^P$ . These export processing sectors are not producing any output that is used as intermediate input or domestic final consumption, however, goods produced in the regular production sector  $N$  can be used as intermediate input in the export processing sector ( $A^{NP}$ ). The model from equation (1) is therefore more complex:

$$\begin{bmatrix} X - E^P \\ E^P \end{bmatrix} = \begin{bmatrix} A^{NN} & A^{NP} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} X - E^P \\ E^P \end{bmatrix} + \begin{bmatrix} Y^D + E^N \\ E^P \end{bmatrix} \quad (10)$$

where  $A^{NN}$  are intermediates both produced and used in  $N$ . Solving the model for the output vector yields

$$\begin{aligned} \begin{bmatrix} X - E^P \\ E^P \end{bmatrix} &= \begin{bmatrix} I - A^{NN} & -A^{NP} \\ 0 & I \end{bmatrix}^{-1} \begin{bmatrix} Y^D + E^N \\ E^P \end{bmatrix} \\ &= \begin{bmatrix} (I - A^{NN})^{-1} & (I - A^{NN})^{-1}A^{NP} \\ 0 & I \end{bmatrix} \begin{bmatrix} Y^D + E^N \\ E^P \end{bmatrix} \end{aligned} \quad (11)$$

and the production requirements for the normal sector

$$X - E^P = (I - A^{NN})^{-1}(Y^D + E^N) + (I - A^{NN})^{-1}A^{NP}E^P. \quad (12)$$

Pre-multiplying with the environmental intensity vector  $F^N$ , dropping the domestic demand  $Y^D$  and adding direct emissions from the export processing sector ( $F^{P'}E^P$ ) yields an equation similar to



equation (3) which states the Chinese emissions associated with the production of exports.<sup>2</sup>

$$c^{D,E} = F^{N'}(I - A^{NN})^{-1}E^N + F^{N'}(I - A^{NN})^{-1}A^{NP}E^P + F^{P'}E^P. \quad (13)$$

The first term provides the emissions associated with domestic emissions from the regular (export) production sector. The second term provides indirect emissions of the export processing sectors, associated with domestic intermediates that enter the export processing sector. The third term finally provides direct emissions in the export processing sector.

In order to calculate the emissions embodied in exports associated with imports to China, we use the fact that all imports not for final consumption have to enter intermediate production either in the regular domestic sector or in the export processing sector:

$$M - Y^M = A^{MN}(X - E^P) + A^{MP}E^P \quad (14)$$

Replacing  $X - E^P$  with the expression from (12) and again dropping domestic demand, we can calculate the import requirements for export production:

$$M^E = A^{MN}[(I - A^{NN})^{-1}E^N + (I - A^{NN})^{-1}A^{NP}E^P] + A^{MP}E^P \quad (15)$$

By pre-multiplying the environmental intensity vector of the imported goods  $F^{M'}$ , we can now calculate the emissions associated with imported intermediates that are embodied in Chinese exports.

$$c^{M,E} = F^{M'}A^{MN}(I - A^{NN})^{-1}E^N + F^{M'}A^{MN}(I - A^{NN})^{-1}A^{NP}E^P + F^{M'}A^{MP}E^P \quad (16)$$

The first term describes emissions associated with exports from the normal production sector while the second and third term describe the indirect and direct emissions from imports in the export processing sector, respectively.<sup>3</sup>

## 5 Results

We now fill the theoretical models with data from the Chinese IO tables for 2007. For models which relax the assumption of homogeneity in the domestic and export sectors, we augment the data from the IO table with additional information taken from provincial IO tables, energy consumption data and information on international and interprovincial trade for the regionally disaggregated model flows or with customs data for export processing trade model, respectively. All disaggregated models are calibrated such that a re-aggregation would result in the national IO table. Appendices A – C describe the steps taken for the different models in more detail.

In all models, total direct emissions (including residential use) are 5767 Mt. CO<sub>2</sub>. Emissions embodied in imports are 301 Mt. The emissions embodied in imports are much lower than comparable studies because the emission intensity is not calculated assuming Chinese production technology, but by using the emission intensity obtained from a MRIO model based on the GTAP dataset.

Table 1 reports emissions embodied in exports and imports as well as emissions associated with Chinese final use. In the standard IO model based on the national IO table, domestic emissions embodied in exports amount to 1782 Mt CO<sub>2</sub>, i.e. about 31% of domestic emissions result from

<sup>2</sup>Note that there are two intensity vectors  $F^N$  and  $F^P$ . Direct emissions in  $P$  stem from use of energy goods as intermediates.

<sup>3</sup>Direct here refers to imported intermediates that are directly used in the export processing sector, while indirect refers to imported intermediates that are required for the production of domestic intermediates which then enter the export processing sector.

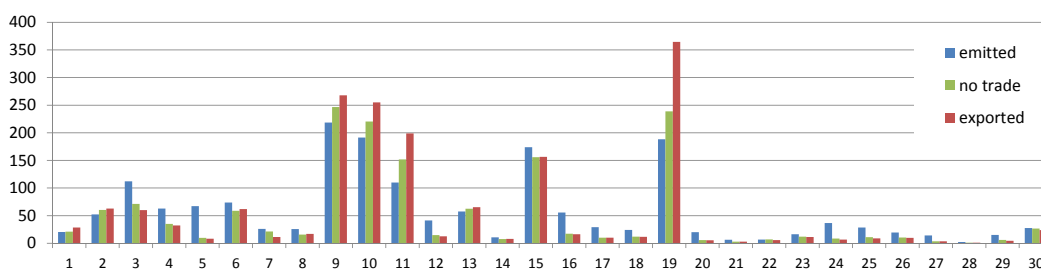
**Table 1:** Emissions embodied in Chinese trade and consumption (in Mt. CO<sub>2</sub>). Summations might differ due to rounding.

IO Model	Chinese (domestic) emissions embodied in exports (A)	Emissions from imported intermediated embodied in exports (B)	Total emissions embodied in exports (C=A+B)	Domestic emissions for domestic final demand (D)	Emissions embodied in imports not used for export production (E)	Total emissions from domestic final demand (F=D+E)
Standard	1782	97	1879	3985	205	4190
Regional Disaggregation (no interprovincial trade)	1525	105	1631	4242	196	4437
Regional Disaggregation (with interprovincial trade)	1732	96	1828	4035	206	4240
Export Processing (normal+ processing)	1264+366 =1630	34+119 =153	1298+485 =1783	4137	149	4286

the production of export goods. In addition, 97 Mt of the emissions embodied in imports are re-exported. This is also about one third of all emissions embodied in imports. China therefore is a net exporter of 1674 Mt CO<sub>2</sub>. The similar share is due to the assumption of proportionality of imports in all use categories. Adding imported emissions to and subtracting exported emissions from the direct production emissions yields emissions embodied in Chinese final use. These emissions amount to 4190 Mt.

In the regional model without interregional trade, emissions embodied in exports are 248 Mt. lower than in the national model. This model takes into account that export production is concentrated in coastal provinces of China which are producing with lower emission intensity. Emissions associated with imported goods for export production in contrast are slightly higher than in the national model because the export intensive provinces are also the provinces with a higher import share. Compared to the national model, domestic emissions embodied in exports are 14% lower, but domestic emissions embodied in final use are 6% higher.

Taking into account interprovincial trade, much of this difference between the regional and the national models disappears. Export intensive provinces are importing a considerable share of intermediate goods from other provinces. Since these provinces are less emission intensive, total emission intensity in exporting provinces increases. Overall there is a convergence of emission intensities between provinces. As for the national model, there is a proportionality assumption, hence for each province the share of imported good use as intermediate goods is equal to the share in other final demand.

**Figure 1:** Domestic emissions embodied in exports by province (in Mt CO<sub>2</sub>). Province names in Appendix D.

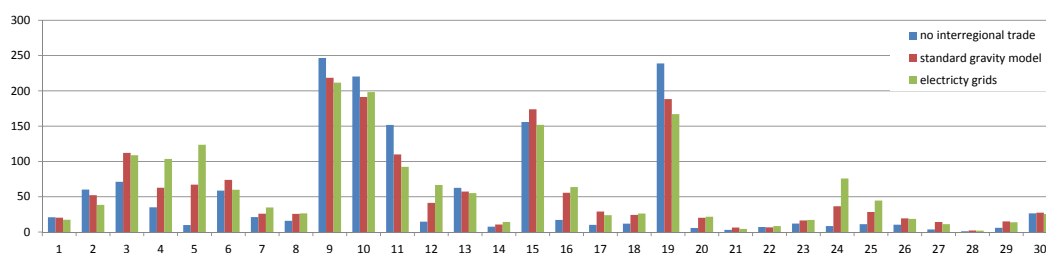
Taking a closer look at the regional model, we can analyze emissions in the different provinces. Figure 1 shows domestic emissions embodied in exports by province. Emissions are attributed either to where they are added in the production chain (i.e. the location in which the emissions were released into the atmosphere, blue bars) or to where the final export good is produced (red bars). In the scenario without interprovincial trade (green bars), both calculations yield the same provincial emissions.<sup>4</sup> It can be seen that the top exporting provinces Shanghai (province 9), Jiangsu (10), Zhejiang (11), and Guangdong (19) account for the most emissions embodied in exports.<sup>5</sup> The western provinces (20 through 30) on the other hand contribute relatively little Chinese emissions in exports. There are however substantial differences between scenarios. When emissions are accounted for where the final export product is assembled, these emissions are highest for the top exporters, because all emissions along the value chain are accounted for in the final production step. If emissions are however accounted at the stage where they are released into the atmosphere, the picture changes and the emissions released in the top exporting provinces are lower. On the other hand, provinces which provide energy intensive intermediates (such as electricity, steel etc.) now account for higher emissions embodied in exports. This is very obvious for Inner Mongolia (5) which has very little exports, but some of its energy intensive production ends up in exports. Emissions embodied in exports in the scenario without interprovincial trade usually lie between other two reported emissions in the scenario with trade. Shandong (15), which also ranks among the provinces with the highest emissions in exports, does not show this variation between the different accounting methods. For Shandong emissions are relatively constant because its emission intensity is higher than the other top exporting provinces and there is less (net) inflow of intermediate inputs for export production.

The interregional trade matrix  $T$  is based on a simple gravity model. Due to a lack of accurate data, in this model we do not differentiate between sectors initializing trade flows in the calibration (see Appendix B). As this is a bold assumption, we run two robustness checks. First, we remove the assumption that trade depends on the distance in service sectors (sectors 28–42) and use only province GDP as a predictor for trade flows. With this specification, trade coefficients  $t_{i,r,s}$  in the respective sectors change, however the impacts on carbon emissions on exports are virtually unchanged (total emissions embodied in exports increase to 1733 Mt). This is because services embody very little carbon added and the traded share of some service sectors is relatively low – therefore it does not matter where these service inputs were produced. Second, we replace the estimation of trade flows for electricity and set up the trade matrix  $T$  in a way that electricity within an electricity grid and not within a province is a homogenous good (see Appendix B for details on the calculation

<sup>4</sup>Note that while the sums of the first two calculations are identical (blue and red bars), the sum of the model without interprovincial trade is lower (green bars, cf. also Table 1).

<sup>5</sup>While Shanghai is exporting a lot, there might be some statistical problems when exports are accounted for Shanghai because they are shipped from Shanghai, although production might not necessarily be located in Shanghai. The data used accounts for differences in production and export location but this might be difficult to distinguish, especially when in addition there are company headquarters also located in Shanghai.

**Figure 2:** Domestic emissions embodied in the regionally disaggregated model without interprovincial trade, with the standard interprovincial trade formulation, and with interprovincial trade creating average emission intensity for of electricity on the level of grids instead of provinces. Province names in Appendix D.



of  $T$ ).<sup>6</sup> Instead of 30 provinces, there are 7 regional grids and each province in a given grid now uses electricity with the average emissions intensity of the respective grid. This leads to more pronounced changes shown in Figure 2. This is not surprising since electricity is an important channel of emissions embodied in interprovincial trade (Lindner et al., 2013). Total emissions embodied in exports increase to 1827 Mt CO<sub>2</sub>, even exceeding the value from the standard model. The additional emissions stem from provinces which have a carbon intensive electricity sector and are located in the same grid as exporting provinces, e.g. Shanxi (4), Inner Mongolia (5), Anhui (12), or Guizhou (24). This estimation might however overstate emissions embodied in exports because trade flows in electricity might be exaggerated (see Appendix B). The choice of the interregional trade matrix can therefore crucially influence the estimate of emissions embodied in exports. It also confirms Su and Ang (2010) that spatial aggregation towards fewer regions increases the share of emissions embodied in exports. A reason is that more emission intensive provinces are put into an aggregate with exporting provinces and hence the average emission intensity of exports rises.

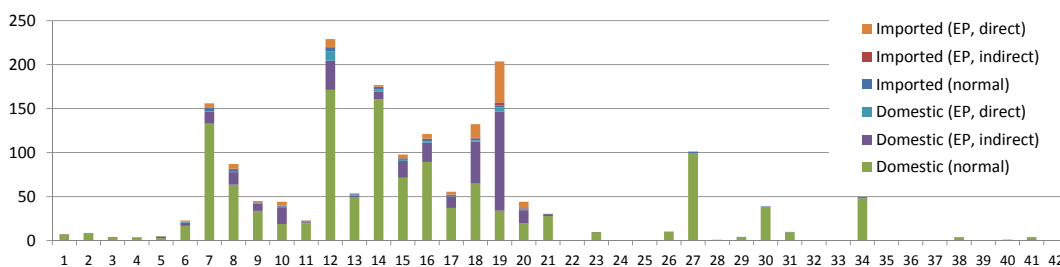
Turning to the model with a separate export processing sector, emissions embodied in exports again are lower than in the national model. With 1783 Mt, total emissions embodied in exports are also below the regionally disaggregated model with interprovincial trade. The share of imports that is used as input in the export processing sector is higher than in the other models, resulting in higher emissions embodied in imports for export production (153 Mt). Although the export processing sector accounts for 42% of the export value, it contributes only 22% of domestic emissions in all exports. Because imports are used as intermediate inputs for export processing in a higher proportion, there are fewer imports used as intermediates in the domestic sector. This results in higher emission intensities in the domestic sector and exports from the normal sector embody 1264 Mt. CO<sub>2</sub>. As emissions embodied in exports are lower than in the national and the regionally disaggregated model with interprovincial trade, emissions embodied in Chinese final consumption are consequently higher.

The emissions embodied in exports can be decomposed (cf. equations (13) and (16)). Figure 3 presents this decomposition for the different sectors. The direct emissions added in export processing are very small (34 Mt) and the majority of emissions embodied in exports from the processing sector comes from intermediates produced in the domestic sector. In electronics sector (sector 19), 89% of exports stem from the processing sector. Because the export processing sector is using many imports, emissions embodied in imports are relatively high in this sector and consequently domestic emissions are relatively low.

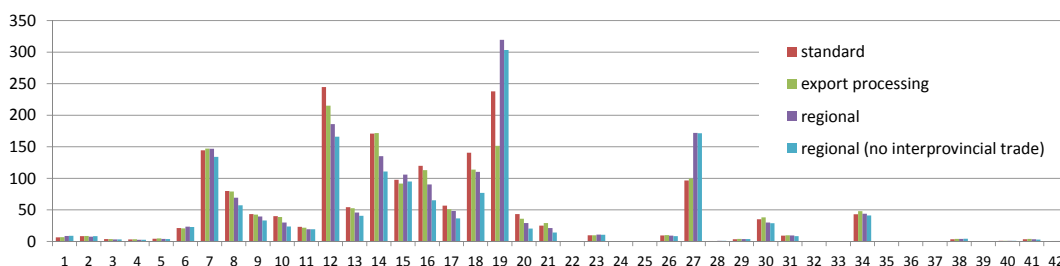
Comparing sectoral emissions in the different models gives an indication in which sectors the differences between the model versions arise. Figure 4 shows that there is no clear ranking between

<sup>6</sup>Due to the fact that it is an island, Hainan constitutes the only grid where grid and province coincide and there are no trade flows to other grids.

**Figure 3:** Emissions embodied in exports by sector and channel taking into account export processing (in Mt CO<sub>2</sub>). Sector codes in Appendix E.



**Figure 4:** Domestic emissions embodied in exports by sector in different IO models (in Mt CO<sub>2</sub>). Sector codes in Appendix E.



the sectors across different IO models. Compared to the national model, the regionally disaggregated model indicates lower emissions embodied in sectors chemicals (12), metals (14), machinery (16), and electric equipment and machinery (18), but higher emissions in sectors 19 and 27. The higher emissions in the transport sector (27) are due to a concentration of export activity in this sector in Shanghai. Because Shanghai has a higher emission intensity compared to the national average, emissions in this sector are high. For the electronics sector (19), which also has a higher amount of embodied emissions, it is more difficult to find a driver as export production is more spread between different provinces. The export processing model has lower emissions in sectors with a high share of export processing, e.g. chemicals (12), electric equipment and machinery (18) and electronics (19). In these sectors there is little value and energy added, hence emissions embodied in exports are lower. Even if the emissions embodied in imported intermediates are taken into account (cf. Figure 3), the total emissions embodied in the electronics (19) sector are still lower than the (domestic) emissions calculated in other models. The national and in this sector especially the regional model disregards therefore the high export processing share in the electronics sector – instead export production is assumed in relatively emission intensive provinces.

Compared to previous literature, our results for the emissions embodied in exports in the standard model are in line with other estimates. Several recent studies report emissions embodied in Chinese trade for 2007: Zhang (2012) and Yan and Yang (2010) report 1751 Mt and 1725 Mt, respectively. This is very close to our estimate of 1782 Mt.<sup>7</sup> Chen and Zhang (2010) report 2021 Mt, their estimate also includes industrial process emissions, while the other studies (including ours) only report energy-related CO<sub>2</sub> emissions. Estimates of imported emissions vary much stronger depending on the assumption of Chinese or foreign technology.

When we compare the results from the regional model to estimates in the literature, we can provide a direct comparison with Su and Ang (2010) who compare a regionally disaggregated model with a national model. For the year 1997, they find that 16.4% of domestic emissions are embodied

<sup>7</sup>Wei et al. (2011) report 2814 Mt. The deviation might be due to their use of only 3 emission factors for solid, liquid and gaseous fuels. The share of emissions embodied in exports (34.8% of domestic emissions) is however relatively close to ours (32.3%).

in exports, lower than the 19.0% estimated in a national model. Our drop in emissions embodied in exports when moving from the national to the regionally disaggregated model is smaller (30.8% to 30.0%). The overall increase in the percentage values compared to 1997 shows the growing importance of trade in China. The reduction in the difference between the estimates in the different models might be due to increased interprovincial trade (Feng et al., 2013), with a higher share of energy embodied in exports now originating from non-coastal provinces compared to 1997. Guo et al. (2012) find 688 Mt or 20.3% of domestic emissions embodied in exports for 2002.<sup>8</sup> The regionally disaggregated model of Feng et al. (2013) is closest to ours, but they focus more on domestic flows of embodied CO<sub>2</sub> and do not report emissions embodied in exports. Yet they confirm our finding that emissions originating in non-coastal provinces play a substantial role for the emissions embodied in export production.

For the model with special treatment of export processing, we provide an update to studies using data for 1997 (Su et al., 2013) or 2002 (Dietzenbacher et al., 2012). Su et al. (2013) estimate 12.6% of domestic emissions embodied in exports (thereof 1.5 percentage points in export processing), lower than the 18.4% in a standard model. Dietzenbacher et al. (2012) also report 12.6% of domestic emissions embodied in exports (thereof 2.1 percentage points in export processing), lower than the 20.3% in a standard model. Our estimate of domestic emissions embodied in exports in the model with export processing is 28.3%, thereof 6.3 percentage points in export processing. These figures are higher and can be explained by the strong increase in trade volumes both inside and outside the export processing regime between 2002 and 2007 (see also Su et al., 2013). Note that there was a change in the methodology of the Chinese IO table and the 2007 version subtracts goods that are imported as intermediate inputs for the exporting processing sector from the data. In our export processing model we correct this by re-adding these goods (see also Appendix C). The smaller difference between the standard model and the export processing sector in this study compared to earlier studies might therefore also be driven by this improvement of the underlying data for the standard model. However, the difference between the export processing and the standard model remains. This is because the main driver for the difference is not reflected in the standard IO model, as the specific production structure of the export processing sector (imported vs. domestically produced intermediates) is not taken into account.

## 6 Conclusions

We provide IO analysis of emissions embodied in Chinese exports. Relaxing the assumption of homogenous production in export and domestic sectors, we find that

- a standard model is likely to overestimate Chinese domestic emissions embodied in exports, because this does not take into account that a large share of exports is processing trade with little emissions added and that many exports are produced in provinces with lower than average emission intensity.
- for a regional model, interprovincial trade flows matter: They (partly) offset the lower emission intensity of export intensive provinces because export intensive provinces use energy intensive intermediates produced in more emission intensive provinces. This also shifts the regional distribution of emissions added to exports away from the coastal provinces. This effect is particularly strong when electricity use is based on the average emission intensity of

<sup>8</sup>Guo et al. (2012) however use a model that uses the domestic production assumption and then calculate emissions embodied in trade between provinces instead of a MRIO with  $TA^D$ . Their findings are therefore more comparable to the model without interprovincial trade.

regional grids.

- for a model with export processing, a larger share of emissions embodied in exports is from imported intermediates and domestically added intermediates are thus lower. This leads to lower domestic emissions embodied in exports.
- emissions embodied in imports are relatively low when emission intensities from a global MRIO model are used. The share of imported emissions that are re-exported is different in the different IO models. While a standard and a regional model assume proportional use of imports in total use, the model with export processing takes into account that imports are used for export processing and a higher share of (energy intensive) imports is used for the production of export goods.

The findings are policy relevant both on a macro and on a sectoral level. On the macro level, lower emissions embodied in exports (compared to standard estimates) translate into higher emissions of final use in China. This informs the discussion on the responsibility of Chinese emissions. On the sectoral level, emission embodied in certain sectors and therefore emission intensity of exports depend on the model chosen. This is crucial when considering policy effects of border carbon adjustments. When targeting international leakage concerns, it has to be taken into account that export processing might lead to much lower than average emission intensities.

Our results can also inform analysis on the current Chinese policy of introducing six pilot emission trading systems mostly in economically more advanced provinces and cities (National Development and Reform Commission, 2012). Both the regionally disaggregated model and the model with export processing provide valuable information on where emissions embodied in exports originate and thus how they might be affected by the policies. The regional disaggregation shows that the majority of emissions originate in coastal provinces, but a substantial share of emissions is embodied in exports initially comes from burning coal in non-coastal provinces. The model with export processing shows that emissions are mostly from non-processing exports. Export processing zones lie predominantly in the coastal areas, and are thus more likely to be included in an emission trading scheme. A binding emission trading systems in advanced regions will therefore not do much to curb emissions embodied in exports, despite the fact that many goods are exported from the pilot regions. Furthermore, the importance of interprovincial trade indicates that carbon leakage to non-regulated provinces could take place, offsetting part of the reduction efforts.

Rather than specifically reducing emissions of exports production and also given the high interprovincial trade we suggest a comprehensive approach for future Chinese policy. Such a broader approach could continue to strive for reduction of the share of coal in the energy mix or for an increase in R&D investment in energy saving and emission reducing technologies. As our results show, emissions embodied in exports are not specially a phenomenon of coastal regions. The Chinese government could thus also promote industrial transfer among regions to achieve emission intensity reductions in the non-coastal provinces. This would also take into account equity considerations between regions and act as a means to realize balanced development. The planned future expansion of the regional coverage of the emission trading schemes can be an adequate policy to reduce emissions at low costs and prevent leakage between provinces.

Our main aim in this study is to identify differences between more complex IO models and a standard model for China. While our results are of relevance both at the aggregate as well as the disaggregated level, future work could lead to an even better understanding of the observed results. A decomposition analysis of changes between years would be fruitful for understanding the drivers of emission growth and provide better targeted policy recommendations, especially as the differences

in the regionally disaggregated models and in the model with export processing are relative large compared to the existing literature estimates for 2002.

Further limitations of the study rest in the uncertainty of the underlying data, e.g. inconsistencies between the national and the regional IO tables or energy data (see also Guan et al., 2012). This requires balancing the IO tables to match the national values and potentially adds noise to the data. In this study we can also only compare the results of the regional and the export processing model. Since export processing is however concentrated in provinces with lower emission intensity, it can be expected that taking into account both features in the same model would influence our model results. A model taking into account both features is however beyond the scope of this paper.

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## A Standard (national) input output model

For the standard estimation we use the 2007 IO table for China (National Bureau of Statistics of China, 2009b), and energy information provided by the energy yearbook (National Bureau of Statistics of China, 2009a). Since energy use is grouped only into 7 sectors, the energy use is split according to the share of corresponding intermediate energy inputs in the various sub-sectors.

The calculation of  $A^D$  is made using a proportional assumption which implies the use ratio of domestic and imported goods is equal for intermediate and final use:  $A^D = SA$ . The elements of the diagonal matrix  $S$  contain the sectoral import shares  $s_i = m_i / (x_i + m_i - e_i)$ , calculated as the share of imports  $m_i$  over total demand less exports  $e_i$ . This assumes that imports are used in same proportion in each sector and final demand (Weber et al., 2008).

We follow Guan et al. (2012) in the calculation of emissions (excluding process emissions) and estimate national emissions to be 5767 Mt CO<sub>2</sub>. Emissions are very similar to Guan et al. (2012), but lower than most studies conducted with the 2007 IO table reviewed in Su and Ang (2013). A difference is that the energy data is taken from a different source. The reason is that the energy source needs to allow for disaggregation on the spatial level, i.e. energy information for the province level needs to be compatible with the source used for the national IO analysis. Energy use is attributed to the different sectors proportionally according to the energy value input share of the respective sector in the IO table.

For the calculation of emission intensity of imports  $F^M$  we employ a global MRIO model based on the GTAP 8 dataset which provides CO<sub>2</sub> emissions and input-output data for 129 regions and 57 sectors for the year 2007 (Narayanan et al., 2012). The 57 sectors are mapped to the the 42 sectors of the Chinese IO table. The calculation of the  $i^{th}$  element of  $F^M$  is a weighted sum of emission intensities of China's imports in sector  $i$  from all trade partners. We use this average sectoral numbers since we do not have information of how the use of imports in China differs by their origin. This yields lower emission intensities for imports compared to Chinese production intensities  $F$ .

## B Spatial disaggregation

For the spatially disaggregated input output models, we augment the data from the IO table with additional information taken from provincial IO tables (National Bureau of Statistics of China, 2011), provincial energy flow data (National Bureau of Statistics of China, 2009a) and information on interprovincial trade.

The regional IO tables are scaled and re-balanced to match the national table by applying the cross-entropy method:

$$\begin{aligned} \min \sum_{r,i,j} x_{r,i,j} \ln \frac{x_{r,i,j}}{x_{r,i,j}^0} + \sum_{r,i} va_{r,i} \ln \frac{va_{r,i}}{va_{r,i}^0} + \sum_{r,i} y_{r,i} \ln \frac{y_{r,i}}{y_{r,i}^0} \\ \text{s.t. } \sum_r x_{r,i,j} = \bar{x}_{i,j} \\ \sum_r va_{r,i} = \bar{va}_i \\ \sum_r y_{r,j} = \bar{y}_j \\ \sum_i x_{r,i,j} + va_{r,j} = y_{r,j} \end{aligned}$$

Intermediate inputs  $x_{r,i,j}$ , value added  $va_{r,i}$ , and output  $y_{r,i}$  in each sector are matched to the

respecting national total (marked with bar). Values marked <sup>0</sup> indicate initial values taken from the regional IO tables.

Energy use taken from regional energy balance tables is also adjusted to sum up to the national values. Initial calibration is based on the adjustment for regional IO coefficients. For example, if the intermediate input of coal in one sector was reduced by 20%, the initial value for coal use in that sector is the value taken from the energy data reduced by 20%.

We also balance regional imports from abroad to match national imports by applying cross-entropy method:

$$\begin{aligned} \min \sum_{i,r} m_{i,r} \ln \frac{m_{i,r}}{m_{i,r}^0} \\ \text{s.t. } \sum_r m_{i,r} &= \bar{m}_i \\ \sum_i m_{i,r} &= \bar{m}_r \end{aligned}$$

The values for sectoral imports  $\bar{m}_i$  are taken from the national IO table, the value for regional imports  $\bar{m}_r$  are taken from National Bureau of Statistics of China (2009b, Table 17-12). Since the two values are different, we scale the regional imports such that  $\sum_r \bar{m}_r = \bar{M}$  holds. The initial values of  $m_{i,r}^0$  are based on total inflows into a province (including domestic inflows from other provinces), scaled such that they sum up to the total imports.

Provincial imports  $m_{i,r}$  are bound upwards by the minimum of total use and total inflows into a province. For sectors where this renders the problem infeasible, only total use is used as an upper bound.

Entropy estimation of the interregional trade flow matrix  $T$  is based on regional inflow and outflow data from IO tables and gravity estimation using freight data from railway transport for average transport between 2006 and 2008 (China Transportation & Communications Press, 2009). The average 2006-2008 is used to avoid outliers. Independent variables in the gravity estimations used to predict trade flows are the log of distance between the provincial capitals of the trade pair, the log of GDP of the importing and exporting province, and dummies to indicate whether the trade flows are between neighbor provinces or whether municipalities (Beijing, Tianjin, Shanghai, Chongqing) are either the importer or exporter. The predicted trade flows are scaled to match the trade flow in a given sector and used as initial value  $t_{r,s}^0$  in the estimation of trade matrix  $T$  for the initial calibration.

Trade flows are calculated sectorwise, such that trade flows  $t_{r,s}$  from region  $r$  to  $s$  match inflows  $a_s$  and outflows  $b_r$  in a given province.<sup>9</sup>  $a$  and  $b$  are taken from the regional IO tables. Imports to abroad and exports from abroad are deducted from the flows and the values are scaled so that total inflows equal total outflows.

$$\begin{aligned} \min \sum_{r,s} t_{r,s} \ln \frac{t_{r,s}}{t_{r,s}^0} \\ \text{s.t. } \sum_r t_{r,s} &= a_s \\ \sum_s t_{r,s} &= b_r \end{aligned}$$

The interprovincial trade matrix  $T$  is then calculated by dividing trade flows  $t_{r,s}$  by total use of the destination province. The main diagonal of  $T$  is set such that the column sums equal one.

For the alternative specifications of  $T$  with regard to the service sectors and the electricity sectors two different methods have been applied. To relax the assumption of trade being distance dependent

<sup>9</sup>We drop the sectoral subscript  $i$  as the optimization problem is solved for each sector independently.

in the service sector, for these sectors the initial value of  $t_{r,s}^0$  were replaced with predicted trade flows only based on GDP and not of distance between provinces. For the alternative specification of the electricity sector, trade coefficients  $t_{r,s}$  for the electricity sector were replaced by calculations on observed electricity use and production obtained from NDRC (2009). The basic idea is that the use of electricity in a given province is associated with the the average emission intensity of the grid and not the province. For example, in 2007 Beijing produced 8.6% of electricity in the Huabei grid, therefore each of the province in that grid now is assumed to satisfy 8.6% of its electricity use with electricity from Beijing. The trade coefficient  $t_{r,s}$  for  $r = \text{Beijing}$  and provinces  $s$  that belong to the Huabei grid would therefore be set to 0.086. This might however overstate electricity trade as this formulation would indicate that only 8.6% of electricity use in Beijing are actually produced in Beijing. Flows between grids are taken into account, this is however only of minor importance.

## C Disaggregation of export processing sector

For the IO model with a disaggregated export sector, we use customs data for export processing trade (taken from Koopman et al., 2008). The data provides information on the share of exports in a sector produced under the export processing regime. Furthermore, the shares for specific use of imports (intermediate input in either the normal domestic or the export processing sector, or in other categories of final demand) are reported. These shares are used to split sectoral imports of the national IO table into imports for final use, imports for use as intermediates in the normal sector  $m_i^N$  and the export processing sector  $m_i^P$ . We split exports into  $e_i^N$  and  $e_i^P$  accordingly.

The initial values of  $Z^0$  are calculated by first attributing the intermediate inputs of the national table  $\bar{Z}$  into a normal and export processing sector based on the shares of in total output. Denoting the set of sector types  $N, P$  with  $\tau$  and the set of the origin of inputs  $D, M$  by  $\sigma$ , we have

$$\begin{aligned} z_{i,j}^{P*} &= \frac{e_j^P}{\bar{z}_{i,j} x_j} \\ z_{i,j}^{N*} &= \frac{x_j - e_j^P}{\bar{z}_{i,j} x_j} \\ z_{i,j}^{M,\tau^0} &= m_i^\tau \frac{Z_{i,j}^{\tau*}}{\sum_j z_{i,j}^{\tau*}} \\ z_{i,j}^D &= \bar{z}_{i,j} - \sum_\tau z_{i,j}^{M,\tau^0} \\ z_{i,j}^{D,P^0} &= z_{i,j}^D \frac{e_{p,j}}{x_j} \\ z_{i,j}^{D,N^0} &= z_{i,j}^D \frac{x_j - e_j^P}{x_j} \end{aligned}$$

We then re-balance the elements the disaggregated IO table, such that its values match their equivalents from national input output table:

$$\begin{aligned} \min \sum_{\sigma,\tau,i,j} z_{i,j}^{\sigma,\tau} \ln \frac{z_{i,j}^{\sigma,\tau}}{z_{i,j}^{\sigma,\tau^0}} + \sum_{\tau,j} va_j^\tau \ln \frac{va_j^\tau}{va_j^{\tau^0}} \\ \text{s.t.} \sum_{\tau,j} z_{i,j}^{D,\tau} + e_i^N + y_i^D = x_i - e_i^P \end{aligned}$$

$$\sum_{\tau,j} z_{i,j}^{M,\tau} = m_i^{\tau}$$

$$\sum_{\sigma,i} z_{i,j}^{\sigma,N} + va_j^N = x_j - e_j^P$$

$$\sum_{\sigma,i} z_{i,j}^{\sigma,P} + va_j^P = e_j^P$$

$$\sum_{\sigma,\tau} z_{i,j}^{\sigma,\tau} = \bar{z}_{i,j}$$

$$\sum_{\tau} va_i^{\tau} = \bar{va}_i$$

The coefficients matrices  $A^{NN}$ ,  $A^{NP}$ ,  $A^{MN}$ , and  $A^{MP}$  are then obtained by dividing the respective  $Z$  matrices by output of  $N$  or  $P$ , respectively.

## D Provinces of China

**Table D.1:** Provinces of mainland China. Tibet is not included due to a lack of data.

1 Beijing	11 Zhejiang	21 Hainan
2 Tianjin	12 Anhui	22 Chongqing
3 Hebei	13 Fujian	23 Sichuan
4 Shanxi	14 Jiangxi	24 Guizhou
5 Inner Mongolia	15 Shandong	25 Yunnan
6 Liaoning	16 Henan	26 Shaanxi
7 Jilin	17 Hubei	27 Gansu
8 Heilongjiang	18 Hunan	28 Qinghai
9 Shanghai	19 Guangdong	29 Ningxia
10 Jiangsu	20 Guangxi	30 Xinjiang

## E Sectors

**Table E.1:** Sectors in the Chinese IO table.

1 Agriculture, Forestry, Animal Husbandry & Fishery	22 Scrap and Waste
2 Mining and Washing of Coal	23 Production and Supply of Electric Power and Heat Power
3 Extraction of Petroleum and Natural Gas	24 Production and Distribution of Gas
4 Mining of Metal Ores	25 Production and Distribution of Water
5 Mining and Processing of Nonmetal Ores and Other Ores	26 Construction
6 Manufacture of Foods and Tobacco	27 Traffic, Transport and Storage
7 Manufacture of Textiles	28 Post
8 Manufacture of Textile Wearing Apparel, Footwear, Caps, Leather, Fur, Feather (Down) and its products	29 Information Transmission, Computer Services and Software
9 Processing of Timbers and Manufacture of Furniture	30 Wholesale and Trade
10 Papermaking, Printing and Manufacture of Articles for Culture, Education and Sports Activities	31 Hotels and Catering Services
11 Processing of Petroleum, Coking, Processing of Nuclear Fuel	32 Financial Intermediation
12 Chemical Industry	33 Real Estate
13 Manufacture of Nonmetallic Mineral Products	34 Leasing and Business Services
14 Smelting and Rolling of Metals	35 Research and Experimental Development
15 Manufacture of Metal Products	36 Comprehensive Technical Services
16 Manufacture of General Purpose and Special Purpose Machinery	37 Management of Water Conservancy, Environment and Public Facilities
17 Manufacture of Transport Equipment	38 Services to Households and Other Services
18 Manufacture of Electrical Machinery and Equipment	39 Education
19 Manufacture of Communication Equipment, Computer and other Electronic Equipment	40 Health, Social Security and Social Welfare
20 Manufacture of Measuring Instrument and Machinery for Cultural Activity & Office Work	41 Culture, Sports and Entertainment
21 Manufacture of Artwork, Other Manufacture	42 Public Management and Social Organization

## Chapter VIII

# Determinants of Technology Transfer through CDM: The Case of China<sup>\*†</sup>

*Technology transfer (TT) is not mandatory for Clean Development Mechanism (CDM) projects, yet proponents of CDM argue that TT in CDM can bring new technologies to developing countries and thus not only reduce emissions but also foster development. We review the quantitative literature on determinants of TT in CDM and estimate determinants for CDM projects in China. China is by far the largest host country of CDM projects and it is therefore crucial to understand the factors that drive TT there. We focus on heterogeneity within a single country and results thus can be linked to specific policies of the country for better interpretation. Our probit estimations confirm results of international cross-country studies, indicating that larger projects and more advanced technologies are more likely to involve TT. In addition, we find evidence that agglomeration effects are more pronounced on the province level rather than larger regions. We also find a positive effect of FDI on TT and a complementary role of academic R&D engagement to TT.*

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<sup>\*</sup>This chapter is available as Weitzel, M., Liu, W.-H., Vaona, A. (2013). Determinants of Technology Transfer through CDM: the Case of China. Kiel Working Paper No. 1889, Kiel Institute for the World Economy.

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## 1 Introduction

The main aim of the Clean Development Mechanism (CDM), introduced by the Kyoto protocol, is decreasing CO<sub>2</sub> emissions in developing countries, at the same time giving buyers in developed countries more flexibility in achieving reduction requirements. Although there is no explicit objective of transferring knowledge, technology and equipment to developing countries, it is hoped that CDM can bring them advanced low carbon technologies, by connecting partners from developing and developed countries. In addition, revenues from selling carbon credits might finance more advanced technologies that would not have been viable without this revenue stream. CDM thus reduces barriers especially with respect to finance costly foreign technology (Schneider et al., 2008).

While technology transfer (TT) in CDM projects is not well defined in international legal documents (Das, 2011), there has emerged a literature trying to find determinants of this phenomenon (see Section 2). Previous studies are mainly based on international cross-sectional datasets, i.e., they try to explain the heterogeneity between countries, thus potentially neglecting heterogeneity within countries.

The CDM has led to 7127 registered projects (as of July 30, 2013). These projects have led to the issuance of 1353 million certified emission reductions (CER), i.e., they have avoided the equivalent of 1353 Mt of CO<sub>2</sub> emissions. The projects are however distributed very unequally, with China and India hosting 52% and 19% of all registered CDM projects, respectively. Cross-country estimates are therefore to a large extent driven by these two countries, whose specificities are however customarily controlled by simple dummies though. As a consequence there is generally no in-depth interpretation of these country specific effects.

Providing this interpretation for China is all the more important given that the Chinese government has adopted national legislation to facilitate TT in CDM projects.<sup>1</sup> It is stated there that, “CDM project activities should promote the transfer of environmentally sound technology to China” (Article 10). This, however, does not mean that TT is a necessary condition for project approval and there are no direct incentives for TT. At the same time, other restrictions potentially harm the willingness of foreign firms towards TT. For example, foreign partners are eligible to conduct CDM projects in China, however the project owner can only be a Chinese (majority) owned entity (Article 11). Other legislation requires certain shares of local content in renewable energy technologies. Schroeder (2009) therefore concludes that initial hopes of Chinese project owners for TT were not entirely met.

As far as China is concerned, it is very diverse and CDM projects are carried out both in rather developed coastal regions and western regions, the latter have a per capita GDP only half that of coastal provinces. Yet, most existing international studies often do not take into account this regional heterogeneity. This paper tries to fill this gap, taking a closer look at China. On the footsteps of cross-country studies, we aim at investigating whether the determining factors they highlighted – such as different levels of development of technological capacity – also hold at a regional level. This extends recent studies on TT in Chinese CDM projects which either had a different focus or relatively few controls. In particular, we measure the agglomeration effects of existing CDM projects along different spatial scales and introduce a more detailed analysis on the role of R&D expenditures.

To sum up, our paper provides a more detailed view on the drivers of TT through CDM in China, which hosts more than half of all CDM projects worldwide. We do not only investigate whether the determinants found to be important in an international context also hold for China at a sub-national level. This paper additionally analyzes agglomeration effects on TT through co-locating with similar CDM projects using different geographic contexts and explores the role of R&D from

<sup>1</sup><http://cdm-en.ccchina.gov.cn/Detail.aspx?newsId=5628&TId=37>.



different innovators on TT. In this way, our paper both complements existing international studies and it also extends recent papers concerning Chinese projects (Luo and Ye, 2011; Marconi and Sanna-Randaccio, 2012; Zheng and Zhang, 2012).

The remainder of the paper is structured as follows. Section 2 provides an overview of the relevant literature. Section 3 describes the data and estimation strategy. Section 4 discusses our econometric results. Section 5 concludes.

## 2 Relation to the existing literature

There exist several quantitative studies on TT of CDM projects. In principle, all studies made use of information published in the official project design document (PDD) describing the project. This method is not perfect because the information on TT in PDDs is not standardized. However, follow-up surveys indicate that PDDs predict TT sufficiently well (Murphy et al., forthcoming). Criteria to measure TT differed slightly between studies. Most studies searched the PDDs for indications of involvement of foreign partners or suppliers. Das (2011) however differentiated between simple technology imports and “superior” TT, the latter one specifically adjusting a technology for the host country or the CDM project. Schmid (2012) analyzed different forms of TT by differentiating between transfer in equipment, knowledge, or both.

Econometric (either probit or logit) estimation was usually carried out to investigate the relevance of different factors in fostering TT of CDM projects. Most studies regressed the observed flow of TT on project and host country specific characteristics. While the former included truly project specific characteristics (such as the project’s abatement potential, its technology, and starting year), the latter gave information on characteristics of the host country. Earlier studies simply used host country dummies, while many later studies replaced these host country fixed effects by variables identical to all or several projects in a given host country (e.g. GDP or tariff rates). Some studies UNFCCC (2010); Haites et al. (2012) used country fixed effects in a first stage estimation and subsequently added a second estimation which regressed country characteristics on predicted TT probabilities from the first stage (including country dummies).

Table 1 presents determinants found to be significant in previous studies. In general, studies found that larger projects are more likely to involve TT, whereas either small-scale ones or those without a foreign partner (“unilateral”) are less likely to involve TT. As a consequence, projects which either require more capital or are more complex due to their size are more likely to involve TT.

International cross-section estimations with country dummies did not find a consistent coefficient for China. As many of China’s initial projects included TT, the coefficient was positive in Haites et al. (2006), but negative (yet not always significant) in later studies (UNFCCC, 2010; Seres et al., 2009). Some studies also analyzed the effects of different roles that CER buyers and project consultants can fill. TT is more likely in projects where PDD consultants are more closely connected to the project (e.g. through ownership of the project) and less likely when CER buyers are coming from financial institutions and thus have less direct interest in the technology used.

**Table 1:** Overview of determinants of TT in CDM projects in the quantitative literature

Study	Observations <sup>a</sup>	Determinants of TT <sup>b</sup>	Further controls	Remarks
		+		
de Coninck et al. (2007)	63 (reg)	No regression analysis		Technology types, estimation of capital flows and investment costs
Haïtes et al. (2006)	854 (all)	China dummy, Size	Technology and country dummies	
Dechezleprêtre et al. (2008)	644 (reg)	Size, GDP growth, Project firm is subsidiary of firm from Annex I country <sup>d</sup> , Trade, (Technological capability)	GDP per capita, Population, Technology and country dummies	Technological capability weakly positive, inter-acts positively for energy/chemicals projects and negatively with agricultural projects
Dechezleprêtre et al. (2009)	644 (reg)	Size, Project firm is subsidiary of firm from Annex I country, Trade, GDP growth, Tech. capability	GDP per capita, Population, Carbon intensity, Technology and country dummies	China dummy negative, TT in China driven mainly by high growth and technological capability
Seres et al. (2009)	3296 (all)	Size	Technology and country dummies	Analyze origin of TT and credit buyers

UNFCCC (2010)	4974 (all)	Size, (business climate)	(Unilateral), Small scale, dummy). 2 <sup>nd</sup> stage: (Exports), development tance, Population, rates, Knowledge stock, Democracy index, Renewable energy share	Similar, (China GDP, FDI, Fixed capital formation, Imports	Technology, country, and year effects. 2 <sup>nd</sup> stage: per capita GDP, FDI, Fixed capital formation, Imports	Two stage estimations for country effects: Predicted TT probability based on estimations with country dummies regressed on country characteristics in a 2 <sup>nd</sup> stage. Further estimations with a subset of countries to identify specific barriers
Das (2011)	1000 (reg)	No regression analysis				More narrow definition of TT, Involvement of international consultant improves likelihood of TT
Luo and Ye (2011)	889 (reg)	EU emission allowance price, Consultant is carbon trader or from research institute, Developed regions dummy	(Price of certified emission reduction (CER)), (Buyer is financial institute)	Size, Similar	Only Chinese projects, focus on buyer/consultants, no controls for industries, instead of year dummies the average annual price of EU emission allowances or the price for CERs was included	
Marconi and Randaccio (2012)	715 (reg)	Size, Investment/CER, Project owner is consultant, Credit buyer is large consultant	Northwest China dummy, Similar projects for wind	Technology and region dummies, Similar, Chinese PDD consultant, Size of PDD consultant	Only Chinese non-hydro projects, analysis of technology providers and CER buyers, similar projects positive but significant only when controlling for interaction with technologies, declining trend over time (increasingly negative year effects)	
Schmid (2012)	3296 (all)	Size, (Business climate), (duration), (Unilateral)	(Similar projects), MFN tariff rates on environmental goods, (R&D), (GDP)	Technology and country dummies	Analysis of different TT types; education, unilateral and R&D only significant in specification without technology and country dummies	

Murphy et al. (forthcoming)	3530 (all)	Size, Imports, FDI, Tariff rates, Abatement Transferred technology <sup>f</sup> , 2 <sup>nd</sup> stage: Official development assistance, Knowledge stock	Similar projects, scale, Capital formation, Abatement potential, Technology base. 2 <sup>nd</sup> stage: Population, Share of renewables	Technology and country dummies	Two stage estimations for country effects, year dummies show declining effect over time, China dummy in first stage positive but not significant, some variables switch sign in one and two stage estimation (per capita GDP)
Zheng and Zhang (2012)	1509 (reg)	GDP, Size	(Patent stock), Similar projects	Technology dummies, Internal rate of return	Only Chinese projects

<sup>a</sup> Observations refers to number of projects, and all/reg. refer to all projects in the pipeline or only registered projects, respectively.

<sup>b</sup> Drivers do not include specific technologies, but technologies are often controlled for. The symbol “+” indicates that regressors have a statistically significant positive effect on TT, while “-” a statistically significant negative effect on TT. Determinants shown in parenthesis are not robust in the estimations.

<sup>c</sup> “Unilateral” denotes projects that started without a foreign partner.

<sup>d</sup> “Annex I countries” refers to countries with binding emission targets as listed in Annex I of the Kyoto protocol.

<sup>e</sup> “Similar” refers to the number of projects in the same country/region and the same technology.

<sup>f</sup> “Transferred technology” refers to the number of applications by foreign patent holders relating to the technology used by the CDM project.

Unlike all other quantitative studies mentioned above which measured determinants for TT in CDM, Haščić and Johnstone (2011) focused on the effect of CDM (among other channels) on bilateral TT in the wind energy sector.<sup>2</sup> They found that wind energy patents first registered in Annex I countries are more likely to be also registered in countries with more wind energy CDM projects. For China, this effect is larger than for other important CDM host countries. They also found a negative stock effect, i.e., with more CERs already issued, the propensity to transfer wind energy patents to CDM host countries declines.

Three studies analyzed CDM projects in China only (Luo and Ye, 2011; Marconi and Sanna-Randaccio, 2012; Zheng and Zhang, 2012). Luo and Ye (2011) as well as Marconi and Sanna-Randaccio (2012) emphasized the role of different participants in the market. For the likelihood of TT in a CDM project it matters who acts as a project consultant and CER buyer. This confirms Das (2011) and Schroeder (2009) pointing out that there are several distinct segments in the market for CDM projects. Zheng and Zhang (2012) emphasized the role of the existing knowledge stock which has a negative effect on TT. As domestic renewable technologies in China approach the global technological frontier, the potential for TT decreases. Also among the three studies on China, only Zheng and Zhang (2012) found a robust negative agglomeration effect from similar projects at the national level. In general, findings from international cross-country studies seem to hold for the relatively few included variables describing province characteristics.

This paper therefore aims at extending the analysis of Chinese projects by looking at agglomeration effects at the sub-national level and by investigating the role of province-specific capacity and capability in R&D activities on TT in more detail than in previous studies. Compared to cross-country studies, which rely on cross-country variability, this paper looks at within-country differences. Thus, determinants found significant in an international context might not apply here because all provinces are subject to the same policies, e.g. tariff rates. However, there remain differences between provinces in characteristics, e.g. FDI flows and their technological capabilities.

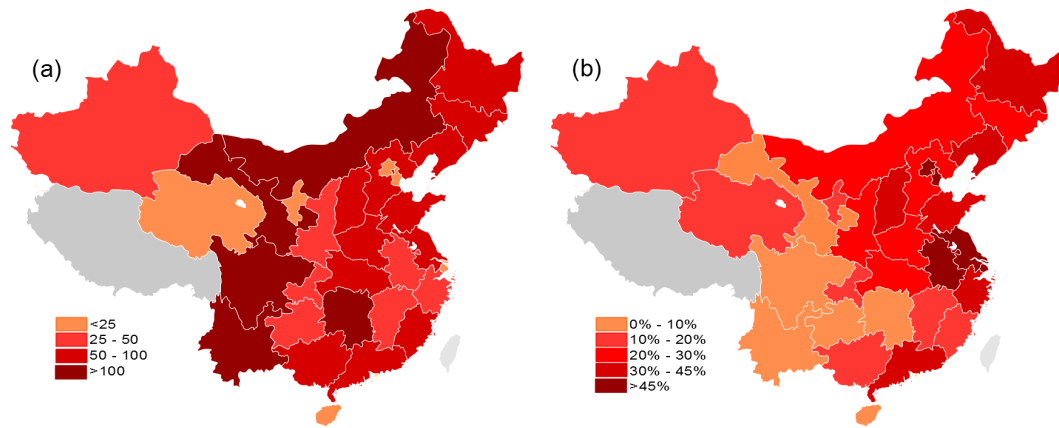
### 3 Data description and Estimation Strategy

The information of whether a given CDM project encompasses TT is taken from the database underlying UNFCCC (2010). PDD data has some limitations as this is an ex-ante description of the planned project. Furthermore mentioning TT in the PDD is not required and there exists no standard way of doing so. Therefore there is some potential of measurement error. The most pronounced error arises from projects that do not mention TT at all, namely, neither its presence nor its absence in a given project. Previous studies have either interpreted these as absence of TT or excluded the projects from the sample. Murphy et al. (forthcoming) carry out a follow-up survey to check for the accuracy of TT coding. While the coding for TT from PDD performs well for projects that either state presence or absence of TT, the results of the other group is mixed as many projects that do not mention TT in fact involve some form of TT. In this study we opt for excluding projects with unclear information on TT. For China, this exclusion does not matter much because only about 10% of projects are coded as unknown TT. Results quantitatively and qualitatively hardly change when using all observations, with one major exception that we comment when illustrating our results. The TT data is merged with CDM project specific information taken from the UNEP Risø CDM/JI Pipeline Database (UNEP Risø Centre, 2012). For China, we have 1799 matched projects that have entered the pipeline between January 1, 2005 and June 30, 2010.<sup>3</sup>

<sup>2</sup>Because of this difference to the other studies, we do not include this study in Table 1.

<sup>3</sup>We exclude two projects which started in 2004 because these rather have to be judged as pilot projects prior to the entering into force of the Kyoto protocol and the set-up of CDM related administrative structures. Out of the 1799 projects, we further

**Figure 1:** Number of CDM projects in different provinces (a) and share of TT in CDM projects (b). Data source: authors' compilation based on data from UNEP Risø Centre (2012), and UNFCCC (2010).



Data on province characteristics include provincial GDP per capita, population size, FDI engagement as proxy for openness, and R&D activities of different innovators. Provincial data are collected from the annual China Statistical Yearbook and annual Chinese Yearbook of Science and Technology for the research period corresponding to the CDM database.

CDM projects are not evenly distributed among provinces (see Figure 1a). More than 100 projects are implemented or projected in each Inner Mongolia, Hunan, Sichuan, Yunnan, and Gansu. These provinces have large potential for renewable energy projects like hydro energy (Hunan, Sichuan, Yunnan, and Gansu) or wind energy (Inner Mongolia and Gansu). Projects related to hydro and wind energy constitute the majority of CDM projects in these provinces and China in total. Because of different geographical features, different provinces are more likely to engage in different technologies which in turn unevenly involve TT. The share of CDM projects with TT is thus very different between provinces (Figure 1b). Overall about 21% of the projects involve TT, but the share is higher in coastal provinces, especially in the municipalities of Beijing, Tianjin, and Shanghai (although they do not host many CDM projects). Part of the differences might be due to geographical characteristics which make different project types more suitable for different provinces, which is of policy relevance in itself. However it is also interesting to gain more insights into whether different policies have a direct effect on the likelihood of TT in CDM projects. We adopt an econometric approach to highlight such information.

In order to investigate the determinants of the TT of CDM projects, we construct a baseline model consisting of four groups of potential determinants for estimation. The TT variable is binary, therefore we apply a non-linear approach and carry out probit estimates. The basic idea of our empirical models can be presented as follows:

$$y_i^* = x_i\beta + \varepsilon_i \quad (1)$$

where  $i$  denotes individual CDM projects,  $y_i^*$  is a latent variable that is related to the dependent variable of interest – TT,  $x_i$  refers to the exogenous variables that are expected to affect the TT of CDM projects (Section 2) and  $\varepsilon_i$  represents a random error term.

The latent variable  $y_i^*$  is unobserved but is linked to TT in CDM projects. More concretely, the

exclude 5 projects implemented in more than one province and can thus not be used in our econometric strategy. By including technology effects in the estimations, 47 observations must be dropped because all geothermal and N<sub>2</sub>O abatement projects contain TT, while all afforestation, reforestation, solar energy, household energy efficiency, industry energy efficiency, and oil flaring reduction projects contain no TT. We are left with 1752 observations.

dummy variable  $TT_i$  is equal to 1 (indicating the implicit occurrence of TT in the  $i$ -th CDM project) if the latent variable is larger than zero and it is equal to 0 (no technology transfer) otherwise. Assuming a standard normal distribution of the error term  $\epsilon_i$ , we end up with probit models as follows for estimation:

$$Pr(TT = 1|x) = Pr(y^* > 0|x) = \Phi(x\beta) \quad (2)$$

with  $\Phi(\cdot)$  referring to a standard normal cumulative distribution function.

The dependent variable is equal to 1 when technology transfer was explicitly documented to be carried out in the CDM application documents and 0 otherwise. This variable and the explanatory variables discussed below are described in Table 2. Some basic statistics are provided there as well.

In our baseline models we focus on the following four groups of project-specific determinants.

$$x_i = \left( x_i^{basic} \quad x_i^{yr} \quad x_i^{ind} \quad x_i^{agg} \right) \quad (3)$$

$x_i^{basic}$  consists of three basic project characteristics – project size in log (*lnsize*), whether it is a small-scale project which is characterized with more simple documentation procedures (*smallscale*) and whether it is a unilateral project, i.e., started without foreign partners (*unilateral*). These three basic project characteristics were in the previous literature found of significant relevance for determining the probability of TT of the CDM projects.

The second group of project-specific determinants,  $x_i^{yr}$ , considers the time effect. The starting year of the CDM projects is coded in five year dummy variables (*year2006*, *year2007*, *year2008*, *year2009*, and *year2010*), assuming the year of 2005 as reference year. We expect a larger TT probability in earlier CDM projects. Table 2 gives us some first support for this expectation, where the share of TT is generally larger for the projects started in earlier years. Considering the fast development experienced by China, it is likely that the potential for technology catch-up in receiving provinces diminished over time as these provinces reduced their gap to the technological frontier.

Industry dummies,  $x_i^{ind}$ , are thus considered as our third group of determinants, to investigate possible industry effects on the presence of TT in CDMs. The reference group used in the estimations is biomass energy, a category with medium TT intensity. As shown in Table 2, share of TT differs strongly among projects from different industries.

Last but not least, we consider a potential agglomeration effect of CDM projects on TT probability by controlling for the amount of CDM projects which were already in place in the same area and industry at the timing as the CDM project of focus started ( $x_i^{agg}$ ). We expect that the greater the number of already existing projects in the same industry in the same area (agglomeration), the more is the experience with new technology and the smaller the potential for further TT (under the very likely assumption for China of on-going technological catching-up). In order to investigate whether the provincial boundary is too limited for analyzing the agglomeration effect, we replace the province-level count variable (*provcount*) by a region-level count variable (*regcount*) which is constructed in the same way as its province-level counterpart. For this we classify the 31 provinces in China into four regions following the official classification defined for regional economic policy: north-eastern, coastal, central, and western region. As an alternative regional classification we also aggregate the provinces into four regions according to their dominant technology (wind, hydro, energy efficiency in own generation, other) in the observation period (*techregcount*). For comparison with previous studies, we also consider the nation-wide agglomeration variable (*natcount*). We consider the four groups of independent variables in sequence for estimation.

In order to control for the robustness of our results, we further extend our model by including two groups of province-specific characteristics, while sticking to our estimation strategy above. In this

**Table 2:** Summary statistics and variable description based on the observations from 2005 to 2010.

Variable	Description	Mean	Std. Dev.	Min/Max	%TT
TT	Dummy for TT	0.19	0.40	0/1	19.46
lnsize	Project size in log for expected 1000 CERs annually	4.49	1.02	1.79/9.25	-
smallscale	Projects applying simplified modalities and procedures for small scale	0.29	0.46	0/1	2.92
unilateral	Projects without an Annex I Party letter of approval at the time of registration	0.05	0.22	0/1	19.77
year2006	Year dummy for 2006	0.09	0.28	0/1	52.32
year2007	Year dummy for 2007	0.27	0.44	0/1	24.84
year2008	Year dummy for 2008	0.26	0.44	0/1	13.22
year2009	Year dummy for 2009	0.25	0.44	0/1	9.66
year2010	Year dummy for 2010	0.12	0.32	0/1	10.24
hydro	Hydro energy projects	0.47	0.50	0/1	0.61
wind	Wind energy projects	0.23	0.42	0/1	30.30
eeown	Energy efficiency in own generation projects	0.13	0.34	0/1	35.34
eesupply	Energy efficiency in supply projects	0.01	0.07	0/1	62.50
distribution	Energy distribution projects	0.01	0.08	0/1	27.27
switch	Fuel switch projects	0.02	0.13	0/1	89.66
minemethane	Mine methane projects	0.03	0.17	0/1	51.85
methaneavoid	Methane avoidance projects	0.02	0.14	0/1	17.65
landfill	Landfill gas projects	0.03	0.18	0/1	64.29
hfcs	HFC-23 destruction projects	0.01	0.08	0/1	90.91
cement	Cement sector projects	0.01	0.08	0/1	10.00
provcount	Number of projects already in the pipeline with same technology and in the same province at project start	35.19	44.94	1/195	-
regcount	Number of projects already in the pipeline with same technology and in the same region (geographically defined) at project start	144.85	172.04	1/634	-
natcount	Number of projects already in the pipeline with same technology in China at project start	289.43	251.15	1/882	-
techregcount	Number of projects already in the pipeline with same technology and in the same region (technologically oriented) at project start	236.46	250.06	1/839	-
gdp_pc	real per capita GDP in RMB (in prices of 2000)	13827	6740	4019/56262	-
lnpopulation	Log of Population (population in 10,000)	8.39	0.55	6.30/9.17	-
trcf	Total investment of (partially) foreign funded companies in stock relative to GDP	2.33	2.03	0.43/11.82	-
rd_ml	R&D expenditure of companies as percentage of GDP	0.50	0.26	0.03/1.32	-
rd_uniri	R&D expenditure of universities and research institutes as percentage of GDP	0.31	0.31	0.06/2.96	-

Data source: authors' calculation based on data from NBSC (2004–2010a), NBSC (2004–2010b), UNEP Risø Centre (2012) and UNFCCC (2010). Note: Each variable has 1752 observations (confinned by the validity of TT variable).



way we can better take into consideration whether the considered province-specific characteristics strengthen or weaken the probability of TT in CDM projects, taking as given the project-specific characteristics.

$$x_i^{prov} = \begin{pmatrix} x_i^{gen} & x_i^{rd} \end{pmatrix} \quad (4)$$

The group of general provincial characteristics ( $x_i^{gen}$ ) consists of three variables: the development level of provinces (real GDP per capita,  $gdp\_pc$ ), their population size in log ( $lnpopulation$ ) and their openness to foreign investors in the world ( $trcf$ ).<sup>4</sup>

The second group of province specific characteristics ( $x_i^{rd}$ ) takes into account the technological capabilities of the province considered. It consists of two variables, namely the R&D expenditure of companies ( $rd\_mle$ ) and of universities and research institutes ( $rd\_uniri$ ) as percentages of GDP. Different types of innovators may have different strengths and focuses regarding innovation. Thus, their innovation behavior might affect the TT probability in CDM projects to varying extents. All six province-specific characteristics are calculated as two-year moving averages. In other terms we use data at times  $t - 2$  and  $t - 1$  to calculate the average for the CDM project  $i$  which started at the year  $t$ . We do so in order to smooth out short-term fluctuations and to deal with potential endogeneity issues. It is often customary in fact to use past lags of variables as instruments of current variables in many field of economics on the basis of a weak exogeneity argument. However, here there is no theoretical exclusion restriction not to insert past variables directly into the model. Therefore we believe we offer the best model specification possible. For estimations we consider first the group of general provincial characteristics and we later add in our empirical models the R&D-related province-specific characteristics.

All models are estimated using the province-clustered sandwich estimator. This relaxes the usual requirement that the observations are independent and standard errors allow for intra-group correlations. Since the probit models are non-linear models, the estimated coefficients in the results should not be interpreted as marginal effects on the probability directly. They show us instead the general direction of the effects of certain explanatory variables on the TT probability of the CDM projects.<sup>5</sup>

## 4 Estimation Results

Estimation results for the baseline models are presented in Table 3, while we will add province specific factors in Table 4. We illustrate our results accordingly. In the appendix we report the same estimations using all observations, coding unclear TT as no TT.

In Table 3, we start our estimation with a simple model (1) only including basic project characteristics, time, and industry effects. We find a positive and highly significant coefficient for the project size which is commonly found in the literature (see Table 1). The coefficient of “small scale” is negative but not significant. Some earlier studies (see Table 1) found that unilateral projects (i.e., without a known buyer for CERs) were less likely to include TT. We cannot confirm this, as a likely result of project consultants' action, who nowadays can also serve as technology brokers (Das, 2011). Therefore, the lack of statistical significance of the “unilateral” variable can descend from the fact that the absence of a direct connection with foreign CER buyers does not necessarily preclude TT.

In the simple specification as well as in all the extensions we find a highly significant declining trend of TT over time. This trend cannot be explained by a possible shift in CDM composition

<sup>4</sup>*trcf* refers to the total investment of (partially) foreign funded companies in stock relative to GDP. We consider *trcf* as a proxy for a province's relative openness to the world investors in our estimations.

<sup>5</sup>We additionally compute marginal effects (elasticities) for the variables of main concern for our analysis, namely significant agglomeration variables and those regarding provincial characteristics (end of Section 4).

**Table 3:** Project-specific determinants of TT probability of CDM projects (Baseline models).

	(1)	(2)	(3)	(4)	(5)
lnsize	0.425***	0.445***	0.432***	0.440***	0.445***
smallscale	-0.135	-0.151	-0.142	-0.174	-0.169
unilateral	0.080	0.085	0.078	0.113	0.140
year2006	-1.522***	-1.465***	-1.488***	-1.390***	-1.402***
year2007	-1.886***	-1.795***	-1.835***	-1.676***	-1.710***
year2008	-2.682***	-2.540***	-2.604***	-2.349***	-2.428***
year2009	-3.033***	-2.839***	-2.930***	-2.579***	-2.707***
year2010	-3.115***	-2.854***	-2.992***	-2.570***	-2.715***
hydro	-1.830***	-1.675***	-1.704***	-1.458***	-1.459***
wind	0.439*	0.574**	0.489*	0.687**	0.643**
eeown	0.661**	0.683**	0.684**	0.784***	0.707**
eesupply	1.328***	1.253***	1.290***	1.157**	1.223***
distribution	0.451	0.368	0.410	0.266	0.338
switch	2.049***	1.979***	2.019***	1.912***	1.959***
minemethane	0.511*	0.501*	0.504*	0.483*	0.481*
methaneavoid	0.762*	0.745*	0.751*	0.694*	0.741*
landfill	1.676***	1.646***	1.664***	1.615***	1.637***
hfcs	-0.301	-0.304	-0.296	-0.233	-0.273
cement	-0.829	-0.833	-0.830	-0.838	-0.832
provcount		-0.005***			
regcount			-0.001		
natcount				-0.002	
techregcount					-0.002
_cons	-0.535	-0.740	-0.630	-0.858	-0.845
Wald Chi <sup>2</sup>	2907.73***	2994.64***	3737.01***	3101.34***	3791.85***
observations	1752	1752	1752	1752	1752

Data source: authors' estimation based on data from NBSC (2004–2010a), NBSC (2004–2010b), UNEP Risø Centre (2012) and UNFCCC (2010). Note: \*\*\*/\*\*/\* significant at 1%/5%/10% (two-tailed tests).

towards projects with either less or no TT, because this would be captured in the technology effects. The coefficients on the time dummies should instead be better interpreted as a *general* decline in TT in CDM in China. The increasingly negative year dummies (relative to the 2005 projects) show a pronounced drop already for 2006 projects. Various factors can explain this trend over time. When CDM was introduced, the Chinese government did not promptly promote it. However, foreign firms, looking for CO<sub>2</sub> reduction opportunities, were more active in the sector and they also fostered TT. Later the Chinese government became more proactive by building institutions and spreading relevant information, which led to the entrance of many inexperienced project consultants of lesser quality and with little experience in international TT in 2007 (Schroeder, 2009). As a consequence, the declining time trend continued. Marconi and Sanna-Randaccio (2012) attribute this finding to a general trend of technological progress in China – not limited to CDM projects – which made TT less likely over time. However, an alternative explanation cannot be ruled out based on our estimations. Consultants might have learnt that TT is not a necessary condition for acceptance of CDM projects. They need to demonstrate that a project would not have been carried out without the CDM. However, when overcoming financial and administrative barriers to adopt foreign technology is not necessary to demonstrate this additionality, consultants might prefer less bureaucratic projects relying on domestic technology.

As expected, different technologies are not equally likely to include TT. As our reference technology for the analysis we use biomass. Hydro energy projects rarely include TT, as this is a mature

technology used in China for a long time. China even exports this technology to be used in CDM projects in other countries (Murphy et al., forthcoming). Contrary to hydro energy, the other widely used renewable energy technology in the CDM, wind energy, has a higher likelihood of TT.

The likelihood for TT in energy distribution, destruction of hydrofluorocarbons (HFCs), and cement projects is not statistically different from biomass energy. Partly this is due to the small number of projects in the bespoken categories. The coefficient of cement projects is negative but not significant as a possible result of the fact that cement technology, now widely used in China, was imported from Japan before CDM projects came into existence (Wang, 2010). This technology, therefore, is likely to be close to the technological frontier nowadays in China.

Capturing methane from landfills, mines, or waste water (most projects in the category “methane avoidance”) on the other hand is likely to involve TT; this is also a priority area as specified by the government. Schneider et al. (2008) report that in these projects mostly end-of-pipe technologies are used and projects are often initiated by international partners. Fuel switch projects mainly consist of gas fired power plants which were built instead of coal fired plants. As these power plants are relatively large, it is likely that at least in some areas there is TT. This also holds for improvements of energy efficiency in own use (eown) and supply (eesupply). Energy efficiency is also defined as priority area as specified by the government.

In general, there is evidence that more advanced technologies and some technologies that are supported by the government (this is not the case for all energy technologies) are more likely to involve TT. This broadly confirms the conclusions by Dechezleprêtre et al. (2008), stating that high technological capability favors TT in energy sector and chemical industry.

We can confirm negative agglomeration effects from similar – either already planned or existing – close-by projects in the same province (2). While this finding is robust in international cross-country studies, Zheng and Zhang (2012) also find this for China but Marconi and Sanna-Randaccio (2012) observe this only for wind energy projects. However, both studies consider the national level, while our variable *provcount* captures the sub-national level.

When we move from the provincial level to the regional level (3), we do not find evidence for significant agglomeration effects anymore. The same happens when either considering the national level (4) or when not using the administrative regions, but regions constructed on the basis of the suitability for different technologies (5). When using all observations including unclear TT, the count variables in models (4) and (5) are significant at the 5% level (see Table A.1). This is however not our preferred specification because TT is measured with more uncertainty. Here, we group a province into one of four (wind, hydro, eown or other) regions according to the technology with the most projects. Therefore we can conclude that local agglomeration effects can be better captured at the province level, which is plausible given the size of Chinese provinces.

Going beyond project specific characteristics, we add some province specific drivers in Table 4. Estimations with province fixed effects were less informative because just a few province dummies were significant.<sup>6</sup> While this indicates that provinces are, in general, relatively similar when accounting for CDM project characteristics, it might not be so when considering specific aspects of theirs. Furthermore, in this way, we can offer comparison with international studies that considered similar variables.

Model (1) includes macro variables at the province level. Openness, measured by *trcf*, has a positive coefficient, confirming earlier studies concluding that interaction with foreign firms via FDI fosters TT. Model (2) extends the existing literature by adding different types of R&D to GDP ratios. In the existing literature only Schmid (2012) used R&D to GDP ratios in a cross-country sample. Not using a differentiated measure for R&D as this paper does, she found insignificant coefficients with

<sup>6</sup>This hampers a two-stage-estimation strategy as in UNFCCC (2010) or Haites et al. (2012).

**Table 4:** Extended models considering province-level determinants of TT probability of CDM projects

	(1)	(2)	(3)	(4)
lnsize	0.442***	0.427***	0.442***	0.454***
smallscale	-0.108	-0.126	-0.083	-0.093
unilateral	0.054	0.060	0.040	0.043
year2006	-1.507***	-1.506***	-1.485***	-1.457***
year2007	-1.851***	-1.896***	-1.847***	-1.801***
year2008	-2.660***	-2.702***	-2.636***	-2.560***
year2009	-2.959***	-3.058***	-2.944***	-2.845***
year2010	-3.014***	-3.199***	-3.039***	-2.894***
hydro	-1.775***	-1.816***	-1.840***	-1.713***
wind	0.514**	0.510**	0.554**	0.610**
eeown	0.678**	0.656**	0.652**	0.666**
eesupply	1.262***	1.228**	1.224**	1.184**
distribution	0.517	0.485	0.555	0.463
switch	1.986***	2.053***	2.029***	1.982***
minemethane	0.578*	0.499	0.572*	0.577*
methaneavoid	0.750*	0.675	0.653	0.625
landfill	1.687***	1.691***	1.711***	1.676***
hfcs	-0.384	-0.357	-0.431	-0.434
cement	-0.757	-0.754	-0.742	-0.773
provcount				-0.004**
gdp_pc	-0.000		-0.000	0.000
lnpopulation	0.078		0.156	0.145
trcf	0.066**		0.076**	0.062**
rd_mle		0.251	-0.243	-0.372
rd_uniri		0.380***	0.418***	0.368***
_cons	-1.427	-0.792	-2.141	-2.148
Wald Chi <sup>2</sup>	3102.06***	3970.85***	5283.28***	5180.29***
obs	1752	1752	1752	1752

Data source: authors' estimation based on data from NBSC (2004–2010a), NBSC (2004–2010b), UNEP Risø Centre (2012) and UNFCCC (2010). Note: \*\*\*/\*\*/\* significant at 1%/5%/10% (two-tailed tests).

varying signs. When adding the R&D variables to the equations, only R&D activities of universities and research institutes have a positive and highly significant coefficient. This kind of research, which is often basic and not applied research, could very well be a complement to TT because these activities foster higher education and a general level of technological understanding. Other types of R&D (in firms) on the other hand yield negative, yet insignificant coefficients. In our view this means that a higher level of general-purpose knowledge can foster TT, while more applied kinds of it can rather substitute for TT. The latter finding is common in the literature, for instance UNFCCC (2010) and Zheng and Zhang (2012) find a negative effect of knowledge stocks on TT. In these studies, the knowledge stock was approximated by a patent stock in renewable energy technologies, i.e., much closer towards the technology in question. Thus the negative coefficient there (similar to the negative but not significant coefficient for R&D in firms) can be seen as an indicator for substitution between existing specific knowledge and TT.

The coefficients for the variables in  $x_i^{basic}$ ,  $x_i^{yr}$ , and  $x_i^{ind}$  are robust to the inclusion of additional variables in the extended models. In particular, model (4) captures all the aspect we stressed in our analysis: agglomeration, FDI and R&D effects. Putting focus on the role of province-specific variables, we compute for this model the three corresponding elasticities at mean values. *Provcount* has an elasticity of -0.29, *trcf* of 0.31 and *rd\_uniri* of 0.24. The first two are statistically significant

at the 5% level, while the third at the 1% level. For this specification of ours we also carried out a Lagrange multiplier normality test of the residuals after Diallo (2010) obtaining a statistic of 0.07 with a p-value of 0.97. Normality was therefore not rejected. Furthermore, we implemented for Model (4) also a semi-nonparametric (SNP) estimator after Gallant and Nychka (1987) and Luca (2008). Results hardly changed. What is more important is that a likelihood ratio test of the probit model against SNP reported a statistic of 0.27 with a p-value of 0.67, favoring the former over the latter one. Skewness and kurtosis of the distribution of the residuals were very close to the Gaussian values 0 and 3, being 0.17 and 3.06 respectively.

## 5 Conclusions

Our estimations on the determinants of TT in Chinese CDM projects largely confirm the existing literature, yet also bring attention to new aspects, such as the role of agglomeration effects and specific types of R&D. These variables are of particular policy relevance because they could be influenced by policy makers more than other determinants of TT.

With regard to “standard” determinants like project size or technology categories, we can confirm results from previous cross-country studies and studies for China. More advanced technologies and larger projects are more likely to involve TT. This is very intuitive given an extra fixed cost of implementing TT that only pays off when the project is sufficiently large. We also find a declining trend of TT probability over time. The specific pattern of changes in the likelihood of TT in certain years can be well explained by policy developments that affected the participants in the markets for CDM projects in the affected years. While the trend can also be observed in international studies, the particular values can best be explained on a country level, taking into account policy developments specific to the country.

Regarding the macro-economic factors, we find that FDI stocks and R&D at universities and research institutes can foster TT. The analysis of different types of R&D rather suggests that basic R&D instead of applied R&D is complementary to TT of CDM projects. When looking at the macroeconomic determinants of international TT, the provinces along the coast generally have better prerequisites for TT. Improving the conditions for TT in other provinces by fostering e.g. R&D at universities and FDI can encourage more TT to support knowledge-based economic growth in these provinces in the future.

The negative agglomeration effect provides evidence for the presence of an externality, because the likelihood of TT of a given project is influenced by previous projects applying the same technology. This agglomeration effect is found on the provincial rather than on the national level. The presence of an externality could serve as justification for policy intervention. With the present dataset we can however not clearly determine the channel of the agglomeration effect. It is likely that the channel is through learning from TT in previous projects. In other words, local stakeholders may already learn quite a lot through obtaining technologies transferred from the existing CDM projects. The room for CDM latecomers for further TT is then restricted. It is, however, also possible that carrying out CDM projects in a province where a large pool of technologically similar CDM projects exists may intensify competition among the project holders which makes it difficult for transparent cooperation with local stakeholders, thus reducing the TT likelihood. In both cases, policy intervention may be justified to encourage especially the technologically diversified CDM projects and project holders' cooperation with local stakeholders.

But before calling for support of TT, it is important to note that fostering TT as such is not necessarily an economic goal that should be strived for at any cost. TT can be more costly than developing local technologies. If the costs of TT exceed the benefits, it might be inefficient to

artificially foster TT. To measure the benefits and costs of TT, one would need to carefully take into account the potential positive/negative externalities resulting from the agglomeration of CDM projects. A complete analysis is beyond the scope of this study.

While we assess determinants for TT in CDM projects in China up to 2010, it is difficult to make projections for the future. Most of the emission reductions from Chinese CDM projects in the sample were intended for use in the EU emission trading scheme (ETS). Starting from 2013, CERs from new projects to be used in the EU ETS have to come from least developing countries (Directive 2003/87/EC, Article 11a (4)). This led to a collapse in the number of new Chinese projects after 2012. While 1812 projects were registered in 2012, only 42 new projects were registered in the first half of 2013. It is more likely that Chinese emission reduction certificates will be used in the new Chinese emission trading systems. Without the direct incentives from foreign firms to gain access to CERs, it is also likely that TT will decline. On the other hand, domestic TT could increase, at least in some technologies. A reason for this is that the pilot emission trading schemes are located in the more advanced provinces and there is a technological gap to the inland provinces.

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## A Appendix

**Table A.1:** Baseline models (observations with unclear TT included in the estimation and coded as no TT)

	(1)	(2)	(3)	(4)	(5)
lnsize	0.362***	0.381***	0.373***	0.383***	0.384***
smallscale	-0.121	-0.140	-0.131	-0.164	-0.159
unilateral	0.087	0.078	0.085	0.124	0.143
year2006	-1.184***	-1.130***	-1.138***	-1.038***	-1.069***
year2007	-1.447***	-1.354***	-1.372***	-1.195***	-1.264***
year2008	-2.262***	-2.118***	-2.150***	-1.871***	-2.000***
year2009	-2.492***	-2.295***	-2.342***	-1.948***	-2.149***
year2010	-2.595***	-2.338***	-2.416***	-1.947***	-2.182***
hydro	-1.850***	-1.686***	-1.664***	-1.399***	-1.445***
wind	0.329	0.478**	0.410*	0.652**	0.567**
eeown	0.538**	0.565**	0.575**	0.702**	0.595**
eesupply	0.877**	0.798**	0.820**	0.666*	0.761**
distribution	0.464	0.384	0.405	0.243	0.347
switch	1.255***	1.224***	1.239***	1.195***	1.217***
minemethane	0.341	0.343	0.339	0.332	0.326
methaneavoid	0.573	0.565	0.561	0.511	0.564
landfill	1.441***	1.421***	1.429***	1.390***	1.415***
hfcs	0.025	0.032	0.037	0.113	0.066
n2o	1.790***	1.785***	1.783***	1.775***	1.780***
cement	-0.805	-0.811	-0.811	-0.834	-0.814
provcount		-0.006***			
regcount			-0.001		
natcount				-0.002**	
techregcount					-0.002**
_cons	-0.688	-0.894	-0.827	-1.089**	-1.017**
Wald Chi <sup>2</sup>	2975.91***	2842.82***	3125.87***	2956.93***	4098.78***
obs	1953	1953	1953	1953	1953

Data source: authors' estimation based on data from NBSC (2004–2010a), NBSC (2004–2010b), UNEP Risø Centre (2012) and UNFCCC (2010). Note: \*\*\*/\*\*/\* significant at 1%/5%/10% (two-tailed tests). Not our preferred specification because TT is measured with more uncertainty.



**Table A.2:** Extended model (observations with unclear TT included in the estimation and coded as no TT)

	(1)	(2)	(3)	(4)
lnsize	0.370***	0.363***	0.371***	0.385***
smallscale	-0.103	-0.123	-0.094	-0.104
unilateral	0.070	0.061	0.052	0.050
year2006	-1.155**	-1.170***	-1.154**	-1.130**
year2007	-1.394***	-1.456***	-1.406***	-1.355***
year2008	-2.202***	-2.277***	-2.198***	-2.118***
year2009	-2.391***	-2.503***	-2.385***	-2.276***
year2010	-2.459***	-2.644***	-2.478***	-2.321***
hydro	-1.822***	-1.840***	-1.867***	-1.721***
wind	0.377*	0.373*	0.406*	0.486**
eeown	0.543**	0.535**	0.529**	0.550**
eesupply	0.802*	0.808**	0.788*	0.729*
distribution	0.511	0.484	0.538	0.439
switch	1.164***	1.180***	1.122***	1.111***
minemethane	0.382	0.333	0.378	0.394
methaneavoid	0.561	0.498	0.479	0.464
landfill	1.437***	1.452***	1.455***	1.429***
hfcs	-0.006	-0.014	-0.043	-0.042
n2o	1.836***	1.774***	1.805***	1.804***
cement	-0.750	-0.749	-0.735	-0.775
provcount				-0.005***
gdp_pc	-0.000		-0.000	0.000
lnpopulation	0.045		0.107	0.097
trcf	0.060**		0.068**	0.054**
rd_mle		0.171	-0.178	-0.335
rd_uniri		0.262***	0.289***	0.233**
_cons	-1.205	-0.859	-1.759	-1.784
Wald Chi <sup>2</sup>	3963.91***	3326.25***	6718.83***	5505.45***
obs	1953	1953	1953	1953

Data source: authors' estimation based on data from NBSC (2004–2010a), NBSC (2004–2010b), UNEP Risø Centre (2012) and UNFCCC (2010). Note: \*\*\*/\*\*/\* significant at 1%/5%/10% (two-tailed tests). Not our preferred specification because TT is measured with more uncertainty.

# Eidesstattliche Erklärung

Ich erkläre hiermit an Eides statt, dass ich meine Doktorarbeit “Essays on the role of emerging economies in international climate policy” selbständig und ohne fremde Hilfe angefertigt habe und dass ich alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehenden Ausführungen meiner Arbeit, besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert habe.

Matthias Weitzel  
Kiel, April 2014

# Curriculum Vitae

## Education

Since 2010	Researcher at the Kiel Institute for the World Economy Participant at the PhD program “Quantitative Economics” at Kiel University
2005 – 2010	Studies in international economics, focal point China, Tübingen University, Diploma thesis “Tradable Permits in Environmental Economics: Compatible with other Instruments?”
2008/09	Exchange year at University of Washington, Seattle, USA
2007	Exchange semester at Peking University, Beijing, China
2004	Abitur in Kassel

## Publications

- Weitzel, M., Ghosh, J., Peterson, S., Pradhan, B. (Forthcoming). Effects of international climate policy for India: Evidence from a national and global CGE model. *Environment and Development Economics*.
- Johansson, D., Lucas, P., Weitzel, M., Ahlgren, E., Bazaz, A., Chen, W., den Elzen, M., Ghosh, J., Grahn, M., Liang, Q., Peterson, S., Pradhan, B., van Ruijven, B., Shukla, P., van Vuuren, D., Wei, Y. (Forthcoming). Multi-model comparison of the economic and energy implications for China and India in an international climate regime. *Mitigation and Adaptation Strategies for Global Change*.
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