Reframing International Climate Policy: Essays on Development Issues and Fragmented Regimes

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Abstract

The research presented in this thesis is based on the hypotheses that (a) one of the main reasons why recent climate negotiations have failed to achieve significant progress is that they have not paid sufficient attention to the priorities of developing countries, and that (b) international climate policy will increasingly be conducted within fragmented regimes in which the spatial or temporal flexibility to reduce greenhouse gas emissions is constrained.

Our empirical estimates for a cross-section of countries suggest that leapfrogging to more efficient and cleaner technologies in poor countries does not occur automatically and that without binding commitments to reduce GHG emissions, continued economic growth can be expected to bring energy consumption and carbon emissions in emerging and developing countries close to levels prevailing in industrialized countries.

For the case of China, we identify economic growth as the dominant factor behind increasing carbon emissions. Using an extended Kaya-decomposition, we find that the effect of economic growth exceeds the impact of the pronounced shift to coal that has taken place in China's energy systems in 1971-2007 by one order of magnitude. Numerical model results reaffirm China's important role for a global, cost-efficient mitigation effort and underline the importance of lowering the carbon intensity of energy production to achieve emissions reductions in China.

Comparing the results from three state-of-the-art climate-energy-economy models emphasizes the importance of spatial and temporal flexibility of mitigation efforts: postponing a global climate agreement to 2020 could raise the costs of a 450ppm CO_2-only target by at least about half; with a delay to 2030 it may become infeasible to achieve. We also show that for individual regions early action can in fact reduce mitigation costs if the effect of avoiding lock-in of carbon-intensive energy infrastructure prevails over the higher costs associated with the additional mitigation burden borne by early movers.

In the absence of a global climate agreement a global carbon market could emerge in a bottom-up fashion by linking of emissions trading systems. In this scenario the occurrence of carbon leakage actually depends on which industries are linked under a joint permit market: a symmetric link from the EU to a system without full cap bears some negative implications but can still increase welfare if the gains-from-trade dominate. In the case of asymmetric linking (i.e. when the respective output goods are imperfect substitutes) leakage is prevented and may even become negative.

The occurrence of carbon leakage in a fragmented climate regime does not automatically justify the use of trade measures, such as border tax adjustments. We show that neither production- nor consumption-based approaches of accounting for carbon emissions constitute optimal policy instruments. Whether a consumption-based policy prevents or reduces leakage depends on specific parameter values. Empirical data suggest that if the EU or the US were to apply border tax adjustment on imports from China, carbon leakage would in effect increase.

Zusammenfassung

Die Untersuchungen dieser Dissertation stützen sich auf die Hypothesen dass (a) die unzureichende Berücksichtigung der Prioritäten von Entwicklungsländern einer der wesentlichen Gründe für das Stocken der derzeitigen Klimaverhandlungen darstellt und dass (b) sich internationale Klimapolitik zunehmend im Rahmen fragmentierter Regimes mit eingeschränkter zeitlicher oder örtlicher Flexibilität zur Vermeidung von Treibhausgasemissionen abspielen wird.

Empirische Schätzungen an einem Länderquerschnitt legen nahe, dass ein Übergang zu effizienteren und saubereren Technologien nicht automatisch stattfindet und dass ohne bindende Verpflichtungen zur Emissionsminderung ein Angleich des Energieverbrauchs und der CO_2-Emissionen in Entwicklungs- und Schwellenländern an das Niveau der Industrieländer aufgrund fortgesetzten Wirtschaftswachstums zu erwarten ist.

Für China stellt sich das Wirtschaftswachstum als dominierender Faktor zur Erklärung des Anstiegs der CO_2- Emissionen heraus. Anhand einer erweiterten Kaya-Dekomposition wird gezeigt, dass der Effekt des zwischen 1971 und 2007 stark angestiegenen Anteils an Kohle in Chinas Energieversorgung um eine Größenordnung geringer ist als der Einfluss des Wirtschaftswachstums. Modellergebnisse bestätigen die wichtige Rolle Chinas für global kosteneffizienten Klimaschutz und unterstreichen die Bedeutung einer weniger karbonintensiven Energieproduktion, um Emissionsminderungen in China zu erzielen.

Ein Vergleich dreier anerkannter Klima-Energie-Ökonomie Modelle zeigt die Relevanz zeitlicher oder örtlicher Flexibilität zur Vermeidung von Treibhausgasemissionen: Eine Verzögerung eines globalen Klimaschutzabkommens bis 2020 könnte die Kosten eines ambitionierten Klimaschutzziels um mindestens ca. die Hälfte erhöhen, und eine Verzögerung bis 2030 könnte dieses unerreichbar machen. Falls der Vermeidung von „lock-in“ Effekten eine wichtigere Rolle zukommt als den zusätzlichen Kosten, die mit einer höheren Reduktionsverpflichtungen für „early mover“ einhergehen, könnten Regionen, die ohne Verzögerung Klimaschutz betreiben ihre Minderungskosten sogar senken.

Ohne globales Klimaschutzabkommen könnte ein globaler Kohlenstoffmarkt „bottom-up“ durch das Linking von Emissionshandelssystemen aufgebaut werden. Ob es in diesem Szenario zu Carbon Leakage kommt hängt davon ab, welche Sektoren der Wirtschaft in einem gemeinsamen Markt für Emissionsrechte eingebunden sind. Ein symmetrischer Link von der EU zu einem System ohne gesamtwirtschaftliche Emissionsbeschränkungen bringt einige negative Auswirkungen mit sich, kann jedoch wohlfahrtssteigernd wirken, falls Handelsgewinne überwiegen. Bei einem asymmetrischen Link (d.h. wenn die jeweiligen Güter imperfekte Substitute sind) wird Leakage vermieden oder kann sogar negativ werden.

Ferner rechtfertigt das Auftreten von Carbon Leakage in fragmentierten Klimapolitik-Regimes nicht automatisch den Einsatz von Handelsbeschränkungen, wie z.B. border-tax adjustment. Es wird gezeigt, dass weder solche Ansätze, welche produktionsbedingte Emissionen regeln noch solche, die auf im Konsum enthaltene Emissionen abzielen, optimale Politikinstrumente darstellen. Ob Carbon Leakage durch konsumbasierte Ansätze verringert oder vermieden wird hängt von spezifischen Parametern ab. Empirische Daten legen den Schluss nahe, dass border-tax adjustment in der EU oder den USA gegen Importe aus China Carbon Leakage in der Tat verstärken würde.

Chapter 1

Introduction

Even though it seems likely that some of the most serious impacts of climate change could be averted by ambitious measures to mitigate greenhouse gas emissions (Stern, 2007), a global climate agreement setting binding emission targets for all participants remains elusive. The research presented in this dissertation is guided by the hypothesis that one of the most serious obstacles to agree on universal commitments to reduce greenhouse gas emissions has been the insufficient consideration of development aspects within the negotiations. As it seems unlikely that such a global climate agreement will be reached in the near future, international climate policy will probably be dominated by so-called 'second-best' approaches, at least in the short- to mid-term. To shed some light on the implications of these issues, this thesis assembles five essays examining (a) the relationship between energy use, carbon emissions, and economic development, and (b) international climate policy in fragmented regimes (i.e. regimes in which the spatial or temporal flexibility to impose a price on emissions is restricted).

This chapter - which serves as an introduction - proceeds as follows: Section 1 describes the science, economics, and politics behind climate change. Section 2 presents the need to reframe international climate policy to attribute increased consideration to development issues and deal with climate change in the scope of fragmented regimes. Section 3 derives a number of guiding research questions. Section 4 briefly outlines the structure of the dissertation.

1 Background: The Science, Economics, and Politics of Climate Change

This section first gives a brief overview of the scientific evidence regarding the potential impacts of climate change. It then proceeds to discuss the economic aspects involved and highlights the political challenge of achieving collective action in the form of a global climate agreement.

1.1. The Challenge of Climate Stabilization

The IPCC's Fourth Assessment Report (AR4) in 2007 (IPCC, 2007a) has left little doubt that climate change is a global problem of unprecedented scale triggered by anthropogenic influences. More recent research has highlighted that global warming might proceed more rapidly than previously anticipated because (1) CO_2 emissions have increased at a higher rate than projected (Raupach et al., 2007), (2) the oceans' capacity to act as natural carbon sinks has declined (Canadell et al., 2007), and (3) a future decrease of the cooling effect caused by aerosols seems probable (Ramanathan and Feng, 2008). Therefore, it is likely that both human and natural systems will be severely impacted by unabated climate change. Based on a survey of recent literature, Smith et al. (2009) caution that the impacts for each 'reason for concern' (IPCC, 2001) are more severe at any given temperature increase than had previously been assumed (Figure 1). In addition, a substantial number of 'tipping points' (i.e. critical thresholds at which small perturbations can induce large shifts in the climate system) that were identified in recent literature, including melting of the Greenland ice-shield and the West Antarctic ice-shield, turnover of the Atlantic Thermohaline Circulation, the El-Nino Southern Oscillation, the Indian summer monsoon, and the dieback of Amazon rainforest are covered by the range of warming that could result if carbon emissions stayed on their business-as-usual path (Lenton et al., 2008). Working group II of the IPCC has quantified climate damages associated with unabated global warming between 1 to 5% of GDP (IPCC, 2007b), while the Stern Review concludes that consumption losses could be even as high as 20% of GDP if non-market impacts are included (Stern, 2007). A considerable fraction of this loss could be avoided by strong mitigation policy, providing the rationale of the accord that emerged as a result of the 15th conference of the parties to the Kyoto protocol (COP15) in Copenhagen to explicitly acknowledge the need to limit global warming to below 2°C (UNFCCC, 2009).

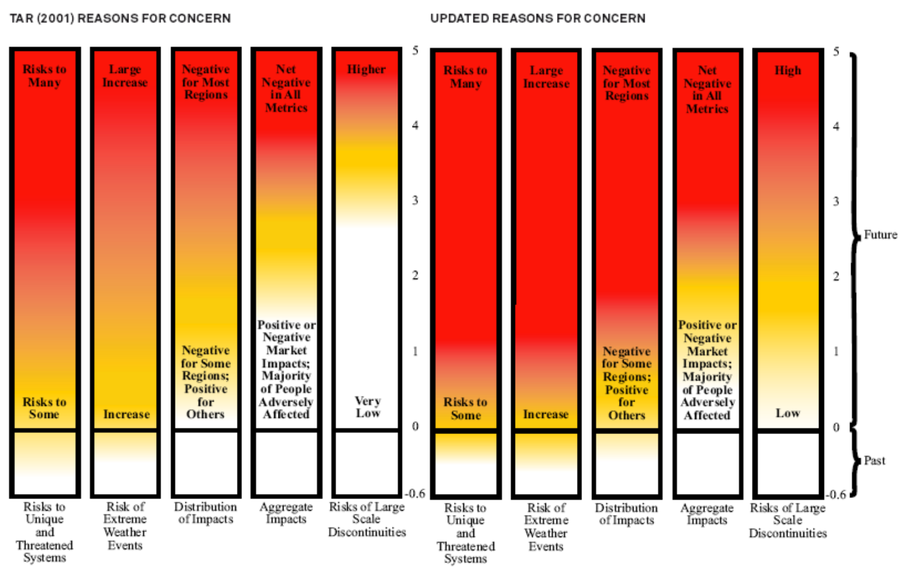


Figure 1: Original (left) and updated (right) 'reasons for concern'
Source: Smith et al. (2009)

Historic emissions of greenhouse gases over the last two centuries have raised the global mean temperature by approximately 0.76°C (IPCC, 2007a). Due to oceanic thermal inertia, the 'global warming commitment' (i.e. the future warming likely to occur if concentrations of greenhouse gases and aerosols in the atmosphere were fixed at their current values) could be as high as 1°C (Wigley, 2005), while stabilizing the climate at the current temperature would require reducinge emissions to practically zero (Matthews and Caldera, 2008). This means that even if ambitious cuts in emissions can be achieved, changes in the Earth's climate system that are already 'in the pipeline' will likely have adverse impacts on ecosystems, water availability, agricultural yields, sea levels, tropical storms etc. Hence, adaptation measures to alleviate the most serious damages as a complement to the mitigation of greenhouse gas emissions will be an indispensible aspect of climate policy (Parry et al., 2008). However, large uncertainties regarding climate-related damages (IPCC, 2007b), limited technological opportunities to substitute for natural resource inputs (Sterner and Persson, 2008), as well as social and institutional barriers to implementation (Adger et al., 2009) mandate serious doubt that adaptation can act as a perfect substitute for mitigation efforts. The same applies to 'geo-engineering' technologies (i.e. large-scale interventions in the Earth system to either directly manage solar radiation or remove carbon dioxide from the atmosphere) whose feasibility remains largely unproven and which are likely to entail a number of serious adverse side effects (see Royal Society, 2009, for an overview). Hence, the notion that the socially desirable approach to deal with the danger of climate change consists in 'avoiding the unmanageable and managing the unavoidable' (Bierbaum et al., 2007) seems highly plausible.

Aggregating the results from various climate-models suggests that cumulative CO_2 emissions over the period 2000–50 must be limited to 1,000 Gt CO_2 in order to have a 75%chance of keeping global warming below 2°C (Meinshausen et al., 2009, Figure 2). Pathways of global emissions that are in accordance with the target of keeping global warming below 2°C compared to pre-industrial levels as envisaged by the Copenhagen Accord very likely require reductions of CO_2 emissions in industrialized countries by 25-40% below 1990 levels by 2020 (IPCC, 2007c). However, such reductions would be insufficient to achieve a peak of global emissions in 2020 and reductions of 50% below 1990 levels by 2050 as e.g. suggested by Stern (2007) if no measures to de-carbonize energy systems in developing countries are taken.

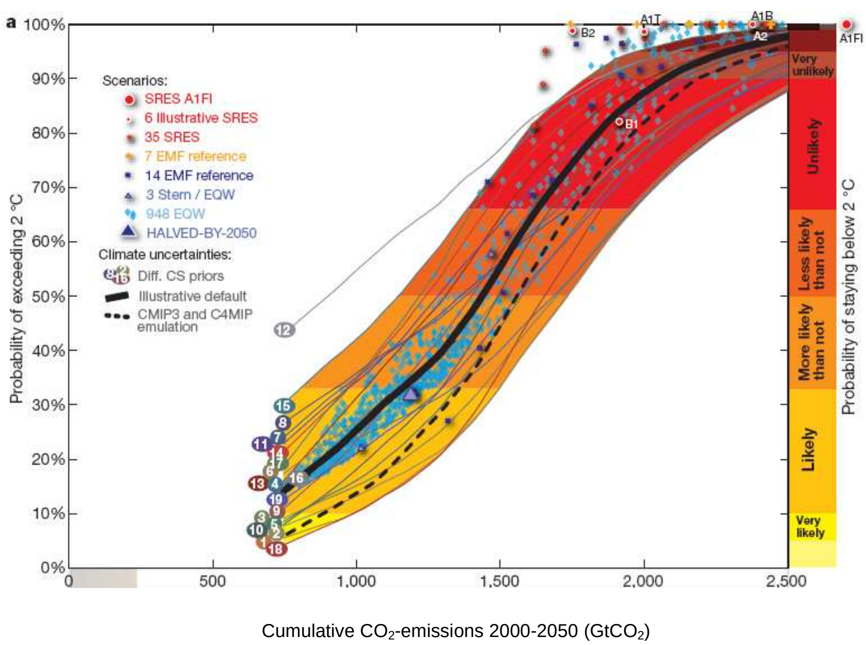


Figure 2 : Likelihood of exceeding the 2°C target as a function of the cumulative CO_2-emissions over the period 2000-50. Source: Meinshausen et al. (2009)

1.2. *The Economics of Climate Change Mitigation*

A broad portfolio of energy technology options, including renewables, increased use of biomass, carbon capture and sequestration, nuclear power, and improved energy efficiency is available to reduce CO_2 emissions (IEA, 2008), some at low or even negative costs (McKinsey, 2009). Comprehensive energy-economy-climate modeling suggests that under the assumption of global cooperation and full availability of key technologies the transformation of the global energy system needed to meet ambitious stabilization targets can be achieved at consumption losses that do not exceed 2.5% of world GDP (Knopf et al., 2009). Additional promising low-cost measures to curb global warming include the reduction of emissions from deforestation and forest degradation (Kindermann et al., 2008) and abatement of emissions of non-CO_2 greenhouse gases, such as CH_4, N_2O and HFCs (Weyant et al., 2006).

The optimal policy to deal with a global environmental problem recommended by economic theory requires a globally uniform price equal to the marginal damage caused by the externality (Baumol and Oates, 1975). This can either be achieved by taxing greenhouse gas emissions, or by limiting the total amount that can be emitted by a cap and introducing tradable emission permits. Both approaches have their advantages as well as drawbacks: (1) as pointed out by Weitzman (1974) and more recently Newell and Pizer (2003), uncertainty on climate damages and abatement costs raises a trade-off between preserving environmental integrity and keeping costs under control when choosing the appropriate policy instrument. (2) In contrast to capping emissions at a certain level, a carbon tax could significantly lower the world market prices of fossil fuels through unintended supply side interactions and achieve only minor emission reductions (Sinn, 2008). (3) If banking and borrowing of emission permits is allowed, tradable permits offer a higher degree of flexibility, as the permit price as well as the distribution of permits over time can be determined by the market, whereas a social planner would have to prescribe the exact value of a tax for every period (Leiby and Rubin, 2001). (4) Policy-makers have more discretion regarding the distribution of emission permits to regulated entities as compared to recycling carbon tax revenue, which can help to increase support for climate policies, but also incite rent-seeking behavior (Newell et al., 2005). In any case, while there is still some debate among economists which instrument should be preferred, the political reality is that the large majority of proposed climate legislation is centered on emissions trading systems instead of carbon taxes. The foremost example is the EU ETS which covers about 40% of the EU's greenhouse gas emissions (Ellerman et al., 2010).

Besides the choice of an appropriate economic instrument, the most crucial decision a policy-maker faces is determining a stabilization target for the atmospheric concentration of greenhouse gases. An often employed tool for this kind of problem is cost-benefit-analysis (CBA), which aims at choosing the abatement level which maximizes the difference between the benefits from avoided climate damage and the associated mitigation costs. However, CBA applied to climate change (as for instance by Nordhaus and Yang, 1996) is fraught with several fundamental problems: (1) large uncertainties prevail with regard to the impacts of climate change on particular regions and sectors (IPCC 2007b). This uncertainty is greatly exacerbated by ignorance of the socio-economic responses to changes in the Earth system. (2) Economic valuation of climate damages for which no direct market value can be derived (e.g. biodiversity or ecosystem services) poses a further serious difficulty for CBA (Dasgupta, 2001). (3) Due to its long-term nature, climate change not only has adverse effects on current but also (and especially) on future generations. The question of how to weigh current versus future welfare involves far-ranging normative considerations (Portney et al., 1999), which influence the parameters employed in the CBA (i.e. the rate of pure time preference). (4) In the presence of potentially catastrophic risks that follow a 'fat-tailed' probability distribution, CBA runs into serious conceptual difficulties (Weitzman, 2009). For the above reasons, a number of alternative - less ambitious but more practicable approaches - have been devised. These include e.g. the tolerable windows approach, which aims at identifying development pathways that do not violate certain pre-defined (environmental, social, as well as economic) sustainability guardrails (Petschel-Held et al., 1999). While determining the optimal stabilization level might turn out to be an elusive goal, ambitious climate targets (such as for instance the target to limit global warming to 2°C compared to pre-industrial levels) pass the latter test, whereas a business-as-usual scenario, under which emissions continue to rise unchecked, does not.

Last but not least, in order to make a global climate agreement acceptable to all participants, not only economic efficiency but also concerns about equity need to be taken into account. While industrialized countries are responsible for the lion's share of historic emissions, developing countries (whose economies depend to a larger extent than industrialized countries on agriculture and possess significantly less resources to adapt to adverse impacts) are the most vulnerable to the adverse impacts of climate change (Füssel, 2010). Therefore, regardless of whether a country's obligations to contribute to the global public good of 'climate stabilization' are based on its historical responsibility, its ability to pay, or a needs assessment, equity considerations suggest that industrialized countries should bear the largest part of the mitigation burden (Baer et al., 2008). Several authors (Stern, 2008; Edenhofer et al., 2008) have outlined blueprints for a comprehensive global climate agreement in which equity considerations play a central role.

1.3. The Challenge of International Cooperation

From an economic perspective the atmosphere constitutes a prime example of a 'global commons'. In the absence of institutions that enable collective action on a global scale, polluters do not take into account the harmful effects of their actions on others and hence pollute more than what would be socially desirable. Yet, it has for a long time been argued that international environmental agreements can sustain only a small number of participants because of free-rider incentives (Carraro and Siniscalco, 1993). Being a global externality, climate change clearly qualifies as a case in which the 'paradox of international environmental agreements (IEAs)' identified by Barrett (1994) applies. This paradox states that those IEAs for which collective action would yield the largest welfare gains compared to the business-as-usual case (in which each actor unilaterally maximizes its own welfare) are inherently unstable, while broad participation can be achieved with IEAs that do not require large deviations from the unilateral Nash-equilibrium.

This line of reasoning is frequently invoked to explain why negotiations for a global climate architecture to enter into force after the expiry of the Kyoto Protocol in 2012 are currently stuck in a dead-lock and current national emissions targets correspond to a greater than 50% chance that global warming will exceed 3°C by 2100 (Rogelj et al., 2010). One of the most serious obstacles towards a global climate agreement is the North-South divide caused by disagreements over the question of how the costs of emission reductions should be divided between industrialized and developing countries. The so-called Bali Roadmap

(UNFCCC, 2007) which was adopted at COP13 in December 2007, lays down two separate negotiation tracks: (a) the 'UNFCCC track' under the auspices of the Ad-Hoc Working Group on Long-Term Cooperative Action (AWG-LCA), and (b) the 'Kyoto track' under the Ad-Hoc Working Group on Further Commitments for Annex-I Parties to the Kyoto Protocol (AWG-KP). In the aftermath of COP15, major developing nations such as China and India have repeatedly reaffirmed their support for the continuation of this two-track negotiation process, under which non-Annex-I countries are so far exempt from legally binding emission reductions according to the principle of 'common but differentiated responsibilities', and have emphasized their conviction that the Copenhagen Accord should not establish a new track of negotiations (TWN, 2010).

However, more recent game-theoretic research has painted a more optimistic picture for global cooperation. If heterogeneity in mitigation costs as well as benefits from avoiding dangerous climate change are taken into account, appropriate transfer schemes could render significantly larger coalitions possible, such that abatement levels close to the social optimum can be achieved (Carbone et al., 2009). The same is true for coalitions which successfully decrease free-rider incentives by aiming at abatement levels below the one that would maximize their members' joint welfare (Finus and Maus, 2008). Furthermore, it has been pointed out that linking climate issues to e.g. trade policy (Lessmann et al., 2009), joint R&D (Lessmann and Edenhofer, in press) or ancillary benefits such as health and energy security (Pittel and Rübbelke, 2008) offers a means to significantly increase the size of stable coalitions. Hence, these authors suggest that the participation as well as the level of ambition of IEAs can be significantly increased with the right mechanisms in place.

To date, the future of international climate policy is uncertain: on the one hand, prominent figures such as UN Secretary-General Ban Ki-moon and India's environment minister Jairam Ramesh doubt that a global agreement will be achieved in the near term (Reuters, 2010) and efforts to establish a cap-and-trade system in the US have been dealt a serious blow in the wake of the financial and economic crisis. The conclusion that "there is now no possibility of comprehensive climate-change legislation in America for years" (Economist, 2010) does not seem far-fetched. On the other hand, the Copenhagen Accord acknowledges the need to provide fast-start finance of US$ 30bn to developing countries in the period 2010-2012 (to be scaled up to US$ 100bn annually in 2020) and the outcome of COP16 at Cancún can be seen as a pragmatic step forward to spell out the terms under which international climate policy will be undertaken in the future (Drexhage, 2010).

2 Reframing International Climate Policy

This dissertation is based on the hypothesis that one of the main reasons why climate negotiations have failed to achieve significant progress so far is that they have not paid sufficient attention to the priorities of developing countries. Given the current political stalemate, a climate agreement to limit global emissions of greenhouse gases seems unlikely to emerge in the near future. Hence, it seems reasonable to expect that in the short- and mid-term international climate policy will predominantly be conducted within fragmented regimes in which the spatial or temporal flexibility of abatement is restricted.

2.1. *Energy Use, Carbon Emissions, and Economic Development*

Access to energy is arguably a necessary precondition for economic development (Cleveland et al., 1984). It has been argued that the ability to tap into seemingly unlimited stocks of energy - stored in the form of fossil fuels - has been a crucial feature of the industrial revolution (Krausmann et al., 2007) as well as continuous productivity gains (Schurr, 1984), such that modern societies can be characterized as 'high-energy civilizations' (Smil, 2000). Currently roughly one billion people in industrialized countries account for about half of global energy consumption and carbon emissions, in close correspondence to the unequal distribution of global income (WEO, 2009, Figure 3). For instance, in 2007 annual energy-related CO_2 emission per capita amounted to 1.2 tCO_2 in India and 4.6 tCO_2 in China, while the respective values were 7.5 tCO_2 for OECD Europe and 19.1 tCO_2 in the US (IEA, 2009).

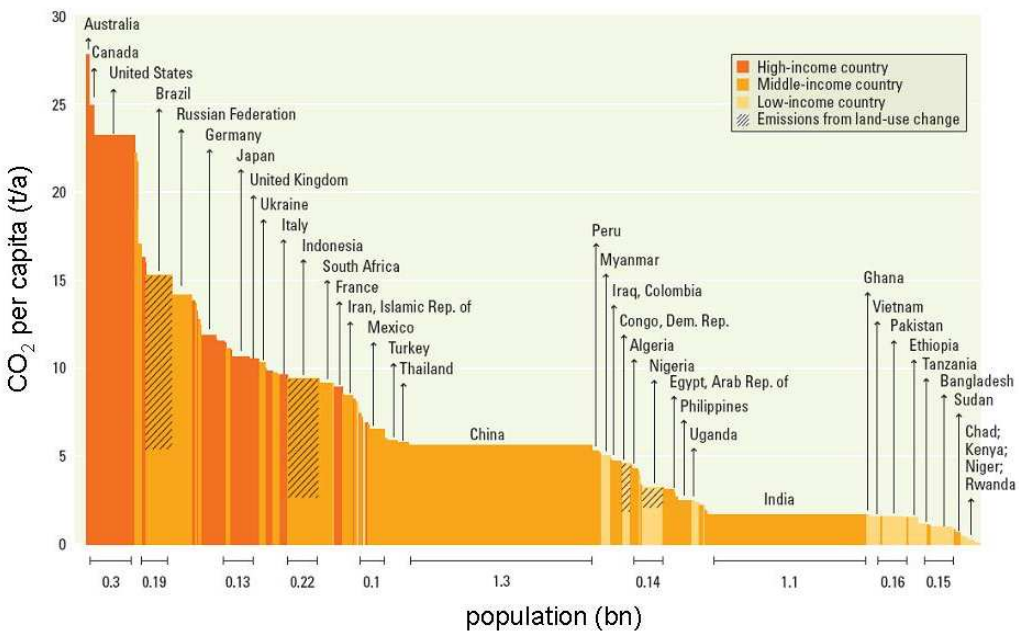


Figure 3: Annual CO_2-emissions (including land use, land use change, and forestry) per capita for selected countries. Areas under the curve are proportional to economy-wide emissions. Source: WDR (2010)

However, recent years have not only witnessed rapid economic growth in a number of developing countries, but also sharp increases of carbon emissions. About 50% of the total increase in global annual CO_2 emissions since 2002 can be attributed to China alone (Raupach et al., 2007, see also Figure 4). If other countries repeat China's success in reducing poverty[1] and start reaching for living standards comparable to those prevailing in industrialized countries, this trend can be expected to not only continue but even accelerate. It has further been pointed out that without mitigation action in developing

[1] Ravallion and Chen (2007) estimate that in the 20-year period after 1981, the proportion of China's population living in poverty fell from 53% to 8%.

countries even reducing emissions to zero in industrialized countries would not prove sufficient to meet ambitious climate targets, such as for instance the 2°C target (WEO, 2008). Although the financial and economic crisis has dampened short-term emissions growth and triggered stimulus spending for a 'green recovery' (Bauer et al., 2009), it is unlikely to affect greenhouse gas emissions in the long run. In addition, private sector spending on clean energy projects has suffered a severe downturn due to a shortage of available credit financing (UNEP and New Energy Finance, 2009), and economic hardship has reduced voters' support for measures to tackle climate change, at least in the US (Kahn and Kotchen, 2010).

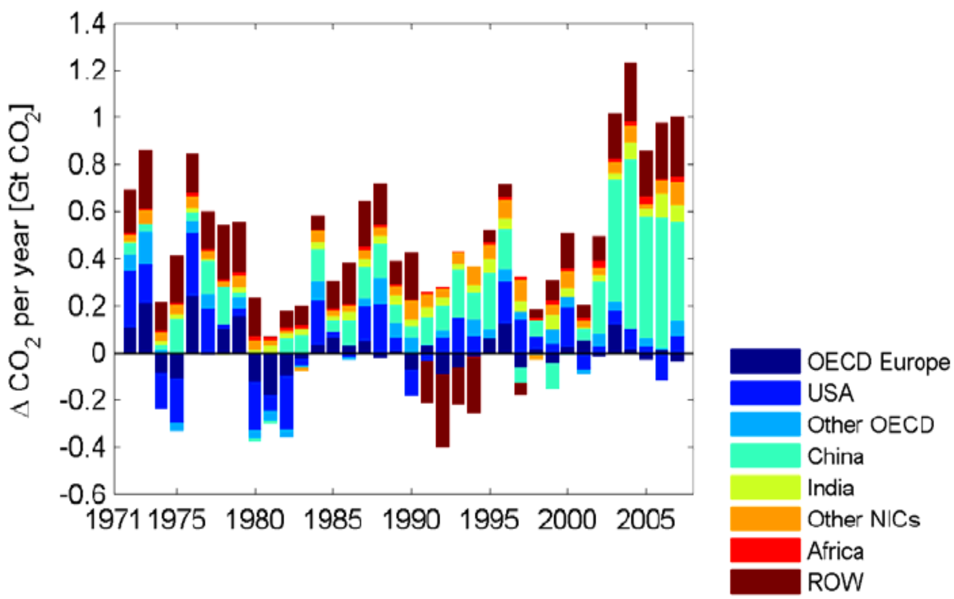


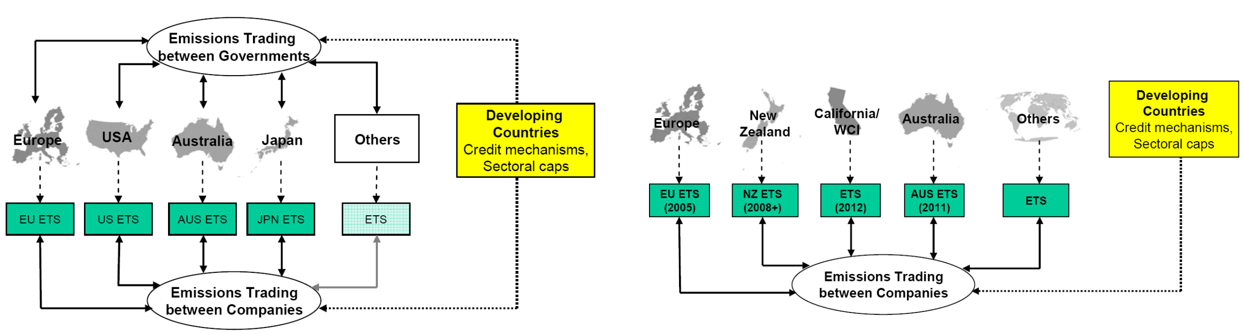
Figure 4: Change in annual CO_2-emissions by region
Source: Steckel et al. (submitted)

The important role that fossil fuels have played for economic growth in industrialized countries helps to explain developing countries' reluctance to accept legally binding commitments to reduce their emissions. In fact, it is often considered that accepting such commitments would be a means to distribute future wealth and perpetuate current inequalities between rich and poor countries. This view is for instance expressed by Lumumba Stanislaus Di-Aping, head of the G-77 group, who during the COP-15 in December 2009 had voiced his concern that "[the draft text] asks Africa to sign a suicide pact, an incineration pact in order to maintain the economic dominance of a few countries" (BBC, 2009). Another case in point is the assessment by India's environment minister Jairam Ramesh that the failure to agree on binding global reduction targets in Copenhagen had protected the right to continued economic growth for India, China, South Africa and Brazil (ABC News, 2009). These statements clearly show that energy access is often equated with economic growth, and climate policy is regarded as an obstacle to development. And indeed, reducing energy consumption does not appear to be a feasible option for developing countries in which an estimated 1.5 billion people are still lacking access to electricity and more than 2.5 billion still rely on traditional biomass for cooking

(WEO, 2010). However, efficient use of end-use energy technologies on a broad scale could provide considerable living standards at relatively low levels of energy use (Goldemberg et al., 1985), and adverse effects on the climate could be minimized by relying mainly on low-carbon energy sources. As many developing countries will face severe difficulties in financing the associated technologies – which are often more costly and capital-intensive compared to their conventional counterparts – a clear mandate for North-South cooperation emerges, in which industrialized countries lend financial as well as technological support to developing countries in order to facilitate 'technology leapfrogging' (Goldemberg, 1998) towards low-carbon development pathways.

2.2. Fragmented Climate Policy Regimes

Delaying the inception of a global climate agreement does not necessarily imply that climate change has to continue unabated. In the absence of a first-best solution, several alternative, 'second-best' approaches to reduce carbon emissions have been proposed. One possibility is to strive towards a global carbon market in a stepwise fashion by the means of bottom-up linking of regional emissions trading systems (Flachsland et al., 2009). The option of OECD-wide emissions trading is an important building block of the EU's climate strategy (EU, 2009) and several cap-and-trade initiatives in the US and Australia have signaled interest in linking their systems (Tuerk et al. 2009). Moreover, several international forums have attempted to reduce the complexity of the negotiation process by establishing a dialogue between the world's most important emitting countries. Such forums were put in place even before the current stalemate of the UNFCCC negotiations had fully materialized. These include e.g. the Heiligendamm Summit of the G8 in 2007 (G8, 2007) and the Global Partnership for low-carbon and climate-friendly technologies (MEF, 2009) hosted by the Major Economies Forum on Energy and Climate.



(a) Top down **(b) Bottom up**

Figure 5: Options to achieve a global carbon market in a (a) top-down (i.e. international agreement) and (b) bottom up (i.e. linking of emissions trading systems) framework. Source: Flachsland et al. (2008)

Further options for second-best climate policies include the definition, implementation, and non-carbon market funding of 'nationally appropriate mitigation actions' (Sterk 2010), mechanisms to reduce emissions from deforestation and forest degradation (UK Office of Climate Change, 2008), voluntary 'no-lose' reduction targets in key sectors of developing countries (Schmidt et al., 2008), reform of the Clean Development Mechanism (Schneider, 2009), funding of adaption projects (Swart and Raes, 2007), technology protocols that could either serve to provide additional incentives to participate in emissions-based policies (de Coninck et al., 2008) or as substitutes for emission reduction targets (Barrett, 2003), as well as mainstreaming climate considerations in official development assistance (European Think-Tanks Group, 2010). In addition, it has been emphasized that a portfolio of loosely coordinated smaller scale agreements each addressing a different aspect of the climate challenge (e.g. land-use, or non-CO_2 GHG emissions) can limit the complexity of the negotiation process and make participation attractive to a broader range of countries (Barrett and Toman, 2010), and that complex multi-level governance structures instead of exclusive reliance on the nation state may be conducive for collective action (Ostrom, 2009).

As pointed out above, cost-effective mitigation of carbon emissions requires global harmonization of carbon prices with full 'where' and 'when' flexibility. Departing from the first-best setup identified by economic theory (i.e. global carbon pricing, starting immediately) involves some important disadvantages. Including only a sub-set of countries or sectors in an agreement via linking of emissions trading systems and/or sectoral caps restricts the spatial and temporal flexibility of mitigation efforts, which is likely to create or exacerbate existing technological lock-ins in carbon-intensive energy infrastructures (Acemoglu et al., 2009) and result in considerable cost increases that render attaining the most ambitious levels of stabilization infeasible (Clarke et al., 2009). Furthermore, delaying action can create strategic incentives to increase current emissions in order to strengthen their bargaining position in future negotiations (Beccherle and Tirole, 2010).

Another issue of serious concern is that without a global carbon price, ambitious climate policies in one region can (at least partially) be offset by 'carbon leakage', i.e. relocation of energy intensive industries to regions with lower (or zero) carbon prices (Copeland and Taylor, 2005) as well as by downward pressure on the price of internationally traded fossil fuels that increases the consumption of the latter in regions with less stringent climate policies (Sinn, 2008). Indeed, several studies observing rising imports of carbon embedded in trade with non-Annex-I countries have raised serious concerns about the effectiveness of unilateral climate measures (e.g. Davis and Caldeira, 2009). Measures proposed to create a 'level playing field' for imported and domestically produced goods include border tax adjustment (Ismer and Neuhoff, 2007) and the adoption of consumption- instead of production-based inventories to account for national CO_2 emissions (Peters and Hertwich, 2008).

3 Thesis Objective

This thesis aims to contribute to the economics of climate change literature by addressing two key dimensions regarding the role of developing countries in international climate policy: (a) examining how economic development is related to energy use and carbon emissions and (b) investigating problems and promises of second-best climate policies.

The first set of research questions addresses the relationship between economic development and energy use, on the global level as well as from the perspective of China, the world's most populous country with one of the highest rates of economic growth and also the largest emitter of CO_2:

- How are energy use patterns (i.e. energy consumption disaggregated by primary energy carriers and economic sectors) related to individual countries' levels of development? Do developing countries that close the gap with industrialized countries' per capita incomes use less energy by adopting more efficient technologies? Have industrialized countries' economies entered a stage of 'de-materialization', in which economic growth can continue unabated without increasing energy use and carbon emissions?

- What are the main factors responsible for the rapid increase in CO_2 emissions in China since 2002? What role could China assume in a global mitigation effort, and what are feasible options to transform the Chinese energy system? Are current Chinese policies compatible with ambitious climate stabilization goals in the short- to mid-term?

The second set addresses different aspects of second-best climate policies, namely the effect of limited participation in (or the delayed inception of) a global climate agreement, the potential for carbon leakage when emissions trading systems are linked, and appropriate policy instruments to minimize leakage:

- What are the economic costs of delaying climate policies? How are these additional costs distributed across world regions? Are there regions that can benefit from unilateral early action, even if climate measures in other parts of the world are delayed?

- How can an emissions trading system be linked with a region which puts a cap on certain economic sectors but not on total domestic emissions? Under which conditions does carbon leakage take place, and how can it be avoided? What are the welfare effects of linking?

- To what extent can trade policy be employed to prevent carbon leakage and support unilateral climate measures? What is the optimal mix of domestic taxes and import tariffs? In which situations does consumption-based accounting of emissions yield superior results compared to production-based accounting?

4 Thesis Outline

The two fundamental research questions - namely the role of energy in economic development and the economic implications of second-best climate policies – are addressed in five journal publications, which are reproduced as Chapters 2 to 6. The first part (Chapters 2 and 3) investigates the relationship between energy and economic growth in order to further our understanding of future changes in energy use patterns that can be expected to take place in developing countries in the absence of climate policies and to assess possibilities to shift to low-carbon growth paths. The second part (Chapters 4 to 6) evaluates problems which are endemic to a broad spectrum of second-best policy settings, paying special attention to questions of environmental effectiveness (i.e. carbon leakage), economic efficiency (i.e. costs), and equity (distributional issues). Chapter 7 summarizes the results, draws conclusions, and proposes directions for future research in this area.

Chapter 2 employs panel data for 30 developing and 21 developed countries over the period 1971-2005 to empirically examine how patterns of energy use (characterized by consumption of primary energy carriers and sectoral energy use, and carbon emissions) change in the process of economic development. It examines if evidence of 'decoupling' of energy use from economic activity in industrialized countries or of 'leap-frogging' to modern, efficient forms of energy in developing countries without going through stages of high energy- and carbon-intensities can be detected.

Chapter 3 performs a decomposition analysis of historical and projected emissions data for China along the lines of the Kaya-identity and confronts the results with reduction requirements implied by globally cost-effective mitigation scenarios and current Chinese policy targets. An enhanced Kaya-decomposition method is applied to identify the driving forces behind the persistent rise in carbon intensity observed throughout the entire time-horizon of the analysis. Finally, this chapter also compares China's current targets for energy intensity and carbon intensity of GDP with projections for global cost-effective stabilization scenarios.

Chapter 4 compares the results of the three state-of-the-art climate-energy-economy models (IMACLIM-R, ReMIND-R, and WITCH) to assess the costs of climate stabilization in scenarios in which the implementation of a global climate agreement is delayed or major emitters decide to participate in the agreement at a later stage only. It considers a broad spectrum of plausible scenarios of international cooperation and disaggregates mitigation costs at the regional level in order to identify individual regions' incentives to participate in an international agreement. Special care is taken to analyze the economic mechanism behind the results, in particular with regard to the trade-off between avoiding lock-in of carbon intensive infrastructure and cost savings that can be obtained from less strict commitments to reduce emissions in early periods if action is delayed.

Chapter 5 uses a two-sector general equilibrium Ricardo-Viner model of two countries to study the impacts of sectoral linking of emissions trading systems on carbon leakage, competitiveness, and welfare. It analytically examines how leakage can arise if one country lacks a comprehensive cap on total emissions, analyses distortions between the non-covered domestic and the international sector, and shows how the welfare effects from linking can be decomposed into gains-from-trade and terms-of-trade contributions.

Chapter 6 develops a two-country general equilibrium trade model to determine the socially optimal mix of unilateral climate policy instruments (such as domestic taxes and import tariffs) in an open economy setting. It then proceeds to assess the effectiveness of frequently discussed trade policy instruments such as border tax adjustment and consumption-based accounting of emissions and confronts the model with empirical data to derive conclusions for the current policy debate.

Chapter 7 presents a synthesis of the main results of this thesis and provides an outlook for further research.

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Chapter 2

Economic Convergence and Convergence of Energy Use Patterns[*]

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Will History Repeat Itself?
Economic Convergence and Convergence of Energy Use Patterns

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Abstract

Ambitious climate targets require reducing CO_2 emissions in industrialized countries and limiting their increase in developing countries. This paper employs a difference-in-differences estimator on panel data for 30 developing and 21 developed countries over the period 1971-2005 to examine how patterns of energy use (characterized by consumption of primary energy carriers, sectoral energy use and carbon emissions) change in the process of economic development. The results indicate that for the average developing country in our sample economic catch-up has been accompanied by convergence towards the global average for the use of most primary energy carriers, the consumption of final energy in most sectors, and total CO_2 emissions. For OECD countries we find that economic growth is partially decoupled from energy consumption and that above average rates of economic growth were accompanied by larger improvements in energy efficiency. These results emphasize the need to identify the relevant engines of economic growth, their implications for energy use, and possibilities to achieve low-carbon growth centered on productivity and efficiency improvements rather than capital accumulation.

Key words: Structural Change, Convergence, Energy Use Patterns, Decoupling, Leap-frogging

JEL classifications: O13, O33, Q43, Q56

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1 Introduction

Significant reductions of global carbon emissions - at least in the mid- to long-term - are a necessary prerequisite to prevent dangerous anthropogenic climate change, e.g. Stern (2006) recommends that emissions peak no later than 2020 and a reduction of at least 50% below 1990 levels by 2050. Ambitious climate targets require reducing CO_2 emissions in industrialized countries and limiting their increase in developing countries (IPCC, 2007). In theory, 'leapfrogging' to more efficient and cleaner technologies in poor countries could allow for improvements in human development without increasing the pressure on limited fossil fuel resources and the natural environment (Goldemberg, 1998). However, recent developments point in the opposite direction. For instance, Raupach et al. (2007) demonstrate that in the period 2000-2004, economic growth in developing and least developed countries has been the main driver of increasing global CO_2 emissions. Gaining a deeper understanding of how development issues are related to climate policy requires information on how patterns of energy use and carbon emissions change in the process of economic development, which will be the subject of this paper.

The ability to control energy and material flows arguably is one of the most crucial factors for the socio-economic development of any society (Cleveland et al., 1984). For instance, the Industrial Revolution can be regarded as a 'socio-ecological regime transition' (Krausmann et al., 2007), characterized by profound changes in the way societies interact with their natural environment and resource base and transform themselves into 'high-energy civilizations' (Smil, 2000). The Industrial Revolution also marks the beginning of the 'great divergence' (Pomeranz, 2000), marked by steady increases in per-capita incomes in a small number of countries, while the rest of the world's population remained mired in a state of persistent poverty. Only recently, coinciding with the acceleration of the 'second wave of globalization' (Baldwin and Martin, 1999), industrialization has become more widespread, promising convergence of poor countries' per-capita incomes to those of the industrialized world. However, if the process of catching-up in developing countries follows the energy- and carbon-intense growth paths of industrialized countries, it will very likely aggravate existing environmental pressures and become a major challenge for global sustainability (Haberl, 2006).

The analysis conducted in this paper picks up from the idea that – maybe with the exception of a small number of heavy resource exporters – catching up economically to the rich world involves a process of successful industrialization with structural changes that affect all aspects of society, including the way energy is used. We posit that it is possible to identify broadly characteristic patterns of energy use (defined by the mix of primary energy carriers and the economic sectors in which final energy is consumed), corresponding to particular stages of economic development. Hence, we expect that structural changes taking place in the economic system during the development process are mirrored in corresponding transitions in the energy system.

The econometric approach applied in this paper employs a difference-in-differences estimator on panel data for 30 developing and 21 developed countries over the period 1971-2005. We regress growth rates (i.e. first differences) of per-capita consumption of primary energy carriers, energy use in economic sectors as well as CO_2 emissions per capita (relative to the world average) on the growth rate of per-capita income (relative to the world average). Hence, the estimated coefficients show in which way economic convergence (divergence) towards (away from) the global average has resulted in convergence (divergence) of energy use patterns over the sample period.

Our results indicate that for the average developing country in our sample economic catch-up has been accompanied by above average growth of the consumption of most primary energy carriers, the use of final energy in most sectors, and total CO_2 emissions. Therefore, countries that converge towards similar income levels also converge towards broadly similar patterns of energy use. We conclude that these energy use patterns can indeed be regarded as being characteristic for a certain stage of economic development. Furthermore, our estimates point to the fact that developing countries - instead of embarking on less energy and carbon-intensive development paths - closely follow the growth paths exemplified by wealthier countries in the past.

For OECD countries we find that the relationship between growth of per capita income relative to the world average and growth of energy use relative to the world average is statistically insignificant for all primary energy carriers, energy consumption in most sectors, and total CO_2 emissions. This is consistent with the hypothesis that economic growth in industrialized countries has partially decoupled from energy consumption, albeit at levels of energy use and carbon emissions not compatible with ambitious climate protection. Additional estimates suggest that OECD countries with above average rates of economic growth also experienced larger improvements in energy efficiency. This finding suggests a connection between gains in total factor productivity and energy efficiency improvements, emphasizing the need to identify the relevant engines of economic growth, their implications for energy use, and possibilities to achieve low-carbon growth centered on productivity and efficiency improvements rather than capital accumulation.

Overall, we conclude that countries located at the world income frontier can maintain economic growth without experiencing significant increases in energy consumption, while catch-up growth by developing countries is much more energy intensive, reproducing the development models of industrialized countries which heavily rely on the provision of energy derived from fossil fuels. Devising a paradigm of 'low-carbon development' which reconciles human development goals with environmental concerns could hence become one of the major future challenges for sustainability science.

The organization of this paper is as follows: Section 2 briefly reviews the relevant literature to establish the link between economic convergence, energy transitions, and convergence of energy use patterns. Section 3 describes the data and the estimation technique. Section 4 presents and discusses the results. Section 5 concludes.

2 Economic Convergence and Energy Transitions

The question of whether poorer countries catch up to the rich world has received widespread attention in growth theory and development economics. Seminal contributions, by e.g. Barro and Sala-i-Martin (1992) and Mankiw et al. (1992) focus on the concept of 'conditional convergence' in the context of cross-section growth regressions. A robust conclusion of this literature is that if one compares countries with identical steady states, the poorer ones can be expected to grow more quickly. However, as steady states across countries differ, no answer to the question if incomes per capita converge or diverge in absolute terms is provided. Carlino and Mills (1993) introduce the concept of 'stochastic convergence', examining the stationarity properties of GDP relative to the group average for US regions. Jointly rejecting the null hypothesis of a unit root in all regional time series (which was the case for their sample) means that after a random shock, a region's GDP tends to revert back to the group average in the long-term, which can be interpreted as convergence behaviour. Quah's (1993) non-parametric estimates using Markov transition matrices to describe the evolution of the world income distribution in the period 1962-1985 suggest that countries' per capita GDPs tend towards two extremes (the so-called 'Twin-Peaks'). Finally, in a study of long-run data sets, Pritchett (1997) points out that historically divergence was the prevalent phenomenon as the ratio between incomes in the richest and the poorest countries increased six-fold between 1870 and 1985.

More recently, several of the techniques mentioned above have been employed to examine the convergence behaviour of CO_2 emissions. The first paper in this literature, Strazicich and List (2003), uses panel unit root tests and cross-sectional regressions and finds stochastic as well as conditional convergence of CO_2-Emissions in 21 industrialised countries in the period 1960-1997. Later contributions apply more refined methodologies. Romero-Ávila's (2008) stationarity test allowing for multiple structural breaks and cross-sectional dependence, and Westerlund and Basher's (2008) panel unit root tests with factor models confirm the finding of stochastic convergence of CO_2 emissions for samples of industrialized countries. Aldy (2006) finds convergence of CO_2 emissions for the OECD, but divergence for a global sample of 88 countries (for the period 1960-2000). However, stationarity and unit root tests performed by Barassi et al. (2008), which allow for cross-sectional dependence and account for trend-stationary dependence, reject the null hypothesis of convergence in CO_2-Emissions for OECD countries in 1950-2002. Lee and Chang (2008), implementing a test which takes into account cross-sectional effects and which are able to identify how many members contain unit roots, find stochastic divergence of CO_2 emissions for 14 out of 21 OECD countries. These results are informative, but suffer from considerable limitations due to their focus on the statistical properties of time series without taking into account crucial socioeconomic variables. As we have argued, energy use and carbon emissions are intrinsically linked to economic activity and one should expect that convergence or divergence of CO_2 emissions depends first and foremost on the convergence behavior of the underlying driving variables, such as per-capita income.

The literature on transitions in energy systems provides numerous examples on how energy use patterns vary between economies at different stages of maturity. Leach (1992) as well as Barnes and Floor (1996) exemplify how rising incomes in developing countries allow households to climb the 'energy ladder' and shift from traditional biomass and charcoal to more efficient and convenient (but also more capital-intensive) energy carriers like petroleum products, liquefied or compressed natural gas, and electricity. Marcotullio and Schulz (2007) as well as Grübler (2008) point out that for countries at early stages of industrialization, the energy mix is dominated by solid fuels, mainly in the form of fuel wood and coal and that with proceeding industrialization and rising incomes, a large part of these fuels is replaced by grid-based, high-quality forms of energy such as natural gas and electricity. Burke (2010) presents empirical evidence supporting the hypothesis of national-level energy ladders in electricity generation. Schurr (1984) argues that energy transitions played a major role for continued economic growth in the US after the 1960s, as more efficient and flexible energy use increased the productivity of all factors of production. Schäfer (2005) indicates that structural change in the economy is associated with shifts in final energy use: rising per capita incomes result in a smaller share of final energy use in the residential sector, but larger ones for transportation and the service sector and a reversed U-shape pattern for industry. Hence, the cited studies provide a number of reasons to expect that economic convergence should be related to convergence of energy use patterns, which we characterize by the total amount of energy consumed, the mix of primary energy used for its generation, its use by economic sector and the associated CO_2 emissions.

However, relatively few papers address this particular issue. Ravallion et al. (2000) and Heil and Wodon (2000) estimate an 'Environmental Kuznets Curve' (i.e. inverse U-shape) specification for the relationship between income per capita and CO_2 emissions and project future emissions for a range of plausible GDP scenarios. Their main result is that convergence in incomes indeed results in convergence of CO_2 emissions, and that redistribution of global income from rich to poor countries (which have a higher propensity to emit) is likely to increase global carbon emissions. Padilla and Serrano (2006), performing non-parametric estimation using concentration indices and a decomposition of the Theil inequality index, demonstrate that rising inequality in world income is followed by greater inequality in global emissions. Finally, the paper that in spirit is closest to our analysis is Markandya et al. (2008). The authors employ panel regressions to examine the convergence of energy intensity of 12 countries of Eastern Europe to the EU average. They find that on average a 1% decrease in the income gap between the former and the EU average results in decrease of the gap in energy intensity of 0.7%. While we use a similar estimation approach, the focus of this paper is clearly different: we employ a global sample and disaggregate energy use by primary energy carriers and energy use by sector in order to study the development of energy use patterns in the process of economic growth.

3 Data and Method

Data Sources and Aggregation

Our estimates are conducted using panel data for developing and industrialized countries for the period 1971-2005. We divide these 35 years of data into 7 panels of a length of 5 years each, which leaves us with 6 time steps to estimate of our equation in first differences (see below). Data on population as well as GDP measured in year 2005 US$ at market exchange rates (and in PPP for a robustness check) were extracted from the World Development Indicators 2007 (WDI, 2007).

All data on energy use are measured in MJ per capita per year and were drawn from the IEA energy balances of non-OECD countries (IEA, 2007b) and OECD countries (IEA, 2007c), respectively. The IEA energy balances provide a detailed description of inputs of primary energy carriers into and output of secondary energy from transformation sectors (such as electricity generation or petroleum refineries) as well as consumption of primary and secondary energy in final use sectors (e.g. industry or transportation). To keep the analysis tractable, we clustered inputs of primary energy carriers into four broad aggregates: coal products, oil, natural gas, and renewable energy (including hydro, wind, solar, and biomass). We decided to exclude nuclear energy from our analysis, because access to nuclear technologies is determined by political rather than economic forces and because too few observations of countries employing these technologies are available to generate statistically sound results. However, nuclear energy is included in the aggregate 'total primary energy', which is simply the sum of the economy-wide consumption of all primary energy carriers. Sectoral use of final energy was grouped into the following five categories: industry, services, transport, residential, and agriculture and fisheries[2]. Any of these sectors consumes primary as well as secondary energy (for example, industry uses coal and gas, but also electricity generated from various primary energy carriers). To be able to construct meaningful aggregates from these two distinct types of energy, we converted all secondary energy consumption to primary energy units. Hence, we calculated the ratio between total input of primary energy into and total output of secondary energy from all transformation sectors for each country and each year[3] and expressed secondary energy use in terms of primary energy units by dividing by this ratio. We then added the respective value of direct primary energy use to obtain total energy consumption in each individual sector[4].

Energy use being the central topic of this paper, we limit our analysis of carbon emissions to emissions resulting from the combustion of fossil fuels. Carbon emissions from land use, land use change and forestry, and non-energy CO_2 emissions from industrial processes are not taken into account, neither are non-CO_2 greenhouse gases. The respective data (measured in metric tons of CO_2 per capita per year) come from the IEA's CO_2-Emissions from Fuel Combustion Database (IEA, 2007a).

Countries were classified as belonging to one country grouping (either 'OECD' or 'developing') according to OECD membership at the initial year of the observation period[5]. While this partition of countries is admittedly coarse, it is well suited for our purpose: as we explicitly adopt a perspective from which development is regarded as happening in discrete stages rather than being a smooth process, it seems reasonable to draw a distinction between countries that have industrialized successfully and those where this process is still in its infancy.

As this study focuses on interactions between the macro-economy and the energy system during long-run transitions, we employ panels with a length of five years and take averages to smooth over cyclical fluctuations according to the following rule: if for any five year period three or more observations are available, the average value over this period is taken. Otherwise, the respective value is marked as 'missing'. In order to work exclusively with balanced panels and to ensure that results are comparable across primary energy carriers (sectors), our sample only includes countries for which observations for <u>all</u> primary energy carriers (sectors) and all periods are available. This leaves us with three distinct sub-samples: one for consumption of primary energy carriers, one for sectoral energy use, and one for CO_2 emissions. Sample sizes are reported in Table 1.

[2] A detailed description of primary energy carriers and sectors is provided in Appendix A.

[3] Prior to 1994, the IEA statistics lumped together all solid biomass in the category 'statistical differences'. This means that no information on solid biomass use by sectors is provided for years before 1994. To deal with this issue, we assume that the sectoral shares of solid biomass in 1971-1993 equaled those that were observed in the period 1994-2000. As solid biomass use is largely dominated by the use of traditional biomass in the residential sector, this assumptions seems rather unproblematic.

[4] Due to the way the data is structured, it is impossible to get exact estimates of sectoral energy use. The employed procedure, implicitly assuming identical conversion factors across sectors, understates primary energy equivalents corresponding to consumption of secondary energy in some sectors, and overstates it in others. We argue that, as long as the energy mixes across countries in the sample are similar, the problem is primarily one of scale (i.e. estimated energy use in a certain sector deviates from its true value by a factor which is of similar magnitude for all countries). We run our estimates separately for OECD and developing countries, respectively. For both groupings, the latter condition is approximately satisfied. Hence, we do not expect any serious bias in our regression coefficients.

[5] A list of countries is provided in Appendix A.

		Observations DCs	Observations OECD
Primary Energy Carriers	Coal, Oil, Gas, Renewables, Total Primary Energy	18	14
Sectors	Industry, Services, Transport, Residential, Agriculture and Fisheries	30	21
	CO_2 emissions	50	21

Table 1: Overview of data availability for respective disaggregation of energy by primary energy carriers and sectors

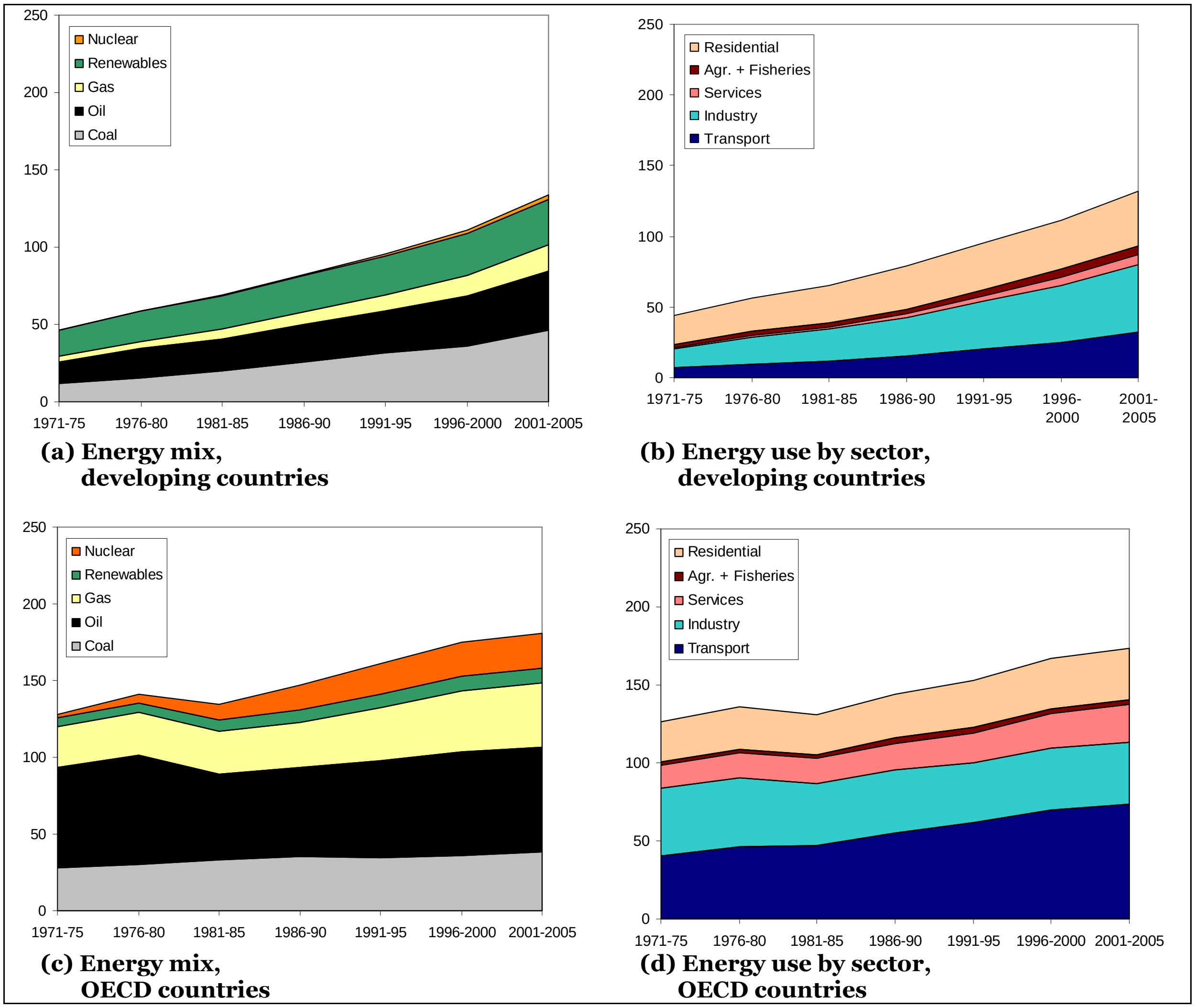
Description of the Data

Average per-capita incomes between developing and OECD countries are marked by a huge gap: while in the period 1971-75 per capita GDP in the OECD was of the order of US$15.500, it was about 20 times lower in developing countries (around US$730). Over the sample period, both groups of countries approximately doubled their per-capita incomes, to US$28.800 in the OECD and US$1.540 in developing countries in the period 2001-2005. Therefore, the relative distance between incomes in both country groups (and hence to the world average) remained relatively unchanged[6].

A quick glance at our energy data (graphically depicted in Figure 1) reveals several interesting observations: first, OECD countries – despite their relatively small share in world population – account for a sizable share of the global energy use. It should be noted that there are large variations in energy use per capita, not only between developing and industrialized countries, but even for countries with very similar per-capita incomes[7]. Second, energy use in developing countries has grown significantly, rising almost threefold from 45 EJ per year[8] in the period 1971-1975 to 133 EJ per year in 2001-2005. For OECD countries, on the other hand, total energy consumption has increased much more slowly, from 128 EJ per year in the period 1971-1975 to 180 EJ per year in 2001-2005. Third, developing and industrialized countries exhibit pronounced differences with regard to their energy mix and sectoral distribution of energy use: for developing countries, the largest part of primary energy consumption is met by coal and renewables (predominantly in the form of traditional biomass) while in industrialized countries oil and natural gas are the most widely employed energy carriers. On a sectoral level of detail, industry and the residential sector account for largest shares of energy consumption in developing countries, while in the OECD, transportation and the service sector are of a relatively higher importance.

[6] This aggregate view, however, does not provide us with information about events of economic convergence or divergence in individual countries.
[7] For instance, in the period 2000-2005, the US consumed 309 MJ per capita per year, while Japan managed to achieve a comparable level of income at 157 MJ.
[8] EJ = Exajoules. 1 EJ = 10^{18} Joules. All values given are averages over a period of five years.

In summary, the impression given by graphical inspection of our data is in line with the hypothesis derived earlier, namely that developing and industrialized countries not only differ in their levels of total energy consumption, but also in the implied patterns of energy use (i.e. total energy consumption disaggregated by primary energy carriers and sectoral energy use).



(a) Energy mix, developing countries

(b) Energy use by sector, developing countries

(c) Energy mix, OECD countries

(d) Energy use by sector, OECD countries

Figure 1: Energy consumption (in exajoules), disaggregated by primary energy carrier and sectors for developing countries (panels a and b) and OECD countries (panels c and d). All sectoral energy use is in primary energy units. Note that due to statistical differences and the conversion of final energy to primary energy units, the sum over primary energy carriers doesn't match the sum over energy consumption by sector.

Empirical Method

Our working hypothesis is that it is possible to identify characteristic patterns of energy use that correspond to an economy's stage of development, and that these patterns undergo transitions in the process of economic growth. Our estimator relates changes in per capita incomes relative to the world average from one time period to the next to changes in the structure of the energy system. For the purposes of this paper, the structure of an economy's energy system is defined by the consumption of primary energy carriers (i.e. the energy mix) and the activities for which final energy is consumed (i.e. energy use by sector). The estimator can be derived from an underlying (ad-hoc) model that assumes that country *i*'s energy system variable ν at time *t*, E_{vit}, relative to the world average[9], $\overline{E}_{vt}$, is a function of country *i*'s GDP relative to the world average. We further allow for a country-specific deterministic trend, given by α_{vi} and a time-specific shift γ_{vt} that affects all countries identically in period *t* (such as a global recession or a price shock), and add an identically and independently distributed error term μ_{vit}:

$$\frac{E_{vit}}{\overline{E}_{vt}} = \left(\frac{GDP_{it}}{G\overline{D}P_t}\right)^{\beta_v} e^{\alpha_{vi}t} e^{\gamma_{vt}} e^{\mu_{vit}} \tag{1}$$

Taking logarithm and the first difference of this equation directly yields the equation to estimate:

$$\Delta(\ln E_{vit} - \ln \overline{E}_{vt}) = \alpha_{vi} + \delta_{vt} + \beta_v \cdot \Delta(\ln GDP_{it} - \ln G\overline{D}P_t) + \varepsilon_{vit} \tag{2}$$

With $\varepsilon_{vit} = \mu_{vit} - \mu_{vit-1}$ and $\delta_{vt} = \gamma_{vt} - \gamma_{vt-1}$

The symbols are defined as follows:

Δ:	first time difference
i:	country index
t:	time period index
v:	index designating energy system variable (either primary energy carrier, sectoral energy use, total energy use, or CO_2-emissions)
α_{vi}:	country fixed effect for energy system variable v, country i
δ_{vt}:	time period fixed effect for energy system variable v, period t
GDP_{it}:	per-capita income in country i in period t
$G\overline{D}P_t$:	average world income in period t
E_{vit}:	value of energy system variable v in country i in period t
$\overline{E}_{vt}$:	world average of energy system variable v in period t
β_v:	relation between growth of energy system variable relative to the world average and growth of per capita income relative to the world average
ε_{vit}:	error term for country i in period t for estimation equation v; $E(\varepsilon_{vit})=0$

[9] Note that for the purposes of this paper, the world average is obtained by averaging over our sample, which (due to limited availability of data) does not contain all countries

We estimate this differences-in-differences equation using ordinary least squares (OLS) on panel data assuming that the independent variables are strictly exogenous. We include country-fixed effects to control for unobserved country-specific characteristics which have an idiosyncratic time-invariant impact (such as geography or resource endowments). In our estimation tables, we report a single constant term equal to the average of all the country-fixed effects. We further include time-fixed effects (i.e. a dummy variable for each five-year period) to control for shocks that have identical impacts on all cross-sectional units in the respective time period (such as oil price shocks). In order to allow for the possibility of heteroscedastic and/or autocorrelated error terms (which - if not controlled - would result in biased estimates of standard errors and could lead to erroneous conclusions with regards to statistical inference), we estimate robust standard errors using the Newey-West (1987) procedure which generates heteroscedasticity and autocorrelation-consistent covariance matrices. As a measure of the goodness of fit, we report the within-R^2, which is obtained by running the regressions on demeaned data. Thus, it focuses on the explanatory power of the independent variables and deliberately excludes the fit provided by the country specific-fixed effects.

The economic interpretation of Eq. (2) is quite straightforward: $\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$ can be understood as the growth rate of energy system variable v for country i relative to the world average, and $\Delta(\ln GDP_{it} - \ln \overline{GDP}_t)$ as the growth rate of its GDP relative to world average. Hence, the dependent and the independent variable capture by how much above or below the global average country *i*'s energy system variable v and its GDP, respectively, have grown and the coefficients β_v relates growth in energy system variable v relative to the world average to growth in GDP relative to the world average. We estimate 11 separate equations (i.e. one equation for each of the four primary energy carriers, each of the five sectors, as well as for total energy use and total CO_2 emissions) for each country group. For each equation, the dependent variable is the difference between period *t* and period *t+1* of (the log of) the respective energy system variable for country *i* relative to the world average. The independent (explanatory) variable is the same for all equations, namely the difference between period *t* and period *t+1* of (the log of) country *i*'s per-capita income relative to the world average.

As an illustration, Figure 2 depicts the relationship between $\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$ and $\Delta(\ln GDP_{it} - \ln \overline{GDP}_t)$ in our pooled sample for total energy consumption and CO_2 emissions for developing as well as OECD countries. Negative signs on either axis indicate growth rates below the world average for GDP or the energy system variable, and above the world average for positive signs, respectively. Pooling the sample data means that each observation is simply treated as one data point. Furthermore, neither country- nor time-specific fixed effects are taken into account, and visual inspection of the data does not provide information about statistical significance. Keeping in mind these caveats, the scatter plots suggest different behaviours for both country groups: for developing countries there appears to be a robust positive correlation, and the trend line shows a slope in the order of one for both energy system variables. For OECD countries, on the other hand, both trend lines appear to be rather flat, and the slope of the regression line describing the relationship between relative GDP growth and relative growth of total energy use is slightly negative. This suggests that for developing countries, above average growth in per-capita income is accompanied by above average growth in total energy use and carbon emissions, while for industrialized countries the relationship appears to be less clear. We will turn to a full analysis of these issues in the next section.

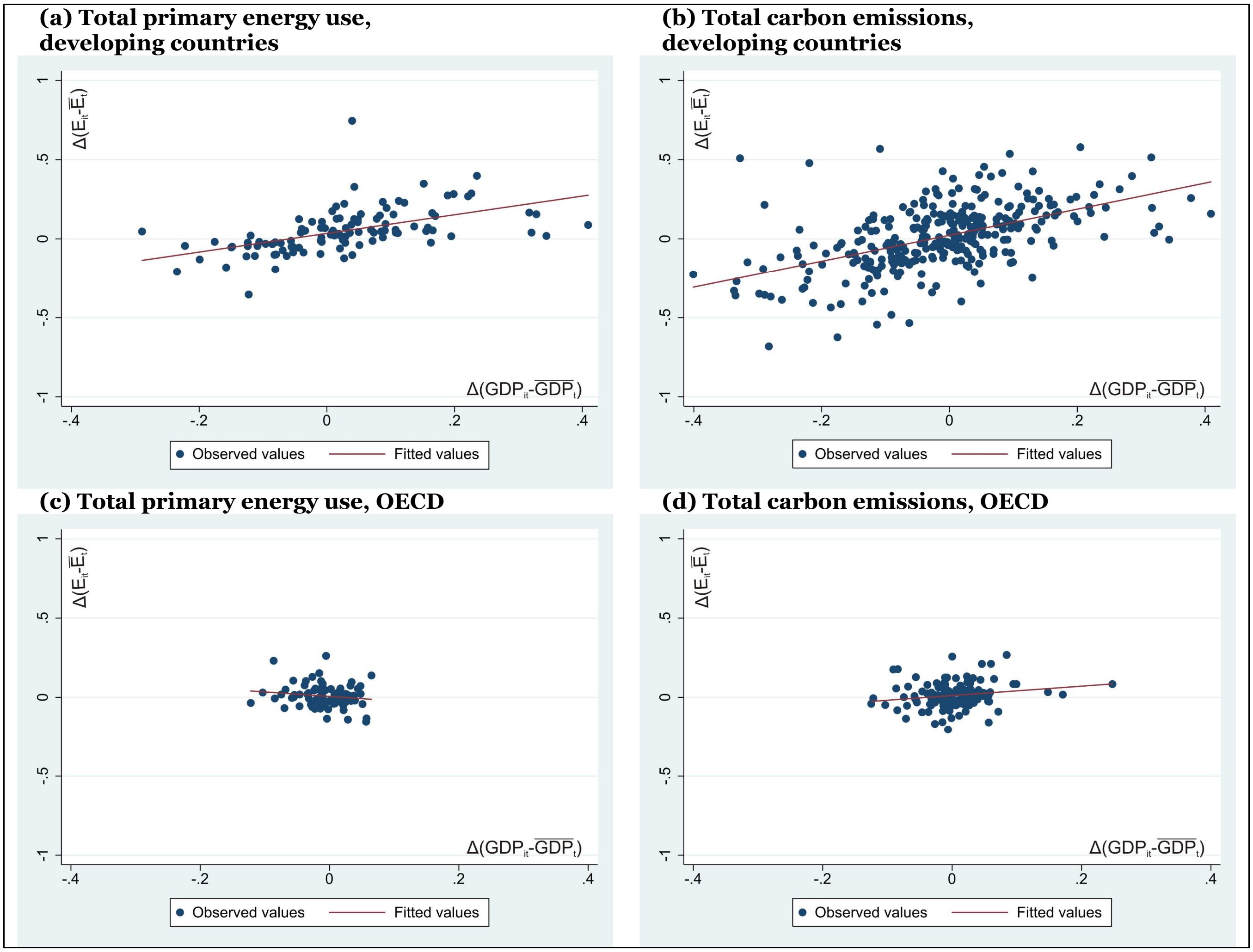


Figure 2: Scatterplots showing the correlation between $\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$ on the y-axis and $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ on the x-axis for total primary energy use and total carbon emissions. Correlations for developing countries are depicted in panels (a) and (b), for industrialized countries in panels (c) and (d).

4 Results

Developing countries

We begin by presenting the results for developing countries, which are summarized in Table 2. The estimated coefficients are statistically significant at conventional levels for all energy system variables (the coefficient for the equations for coal use is significant at the 10% confidence level only) except for oil consumption, renewable energy, and energy use in the residential sector.

Remarkably, all of the statistically significant coefficients except the one for total primary energy use have values close to one. This means that for countries in this group, movements of their relative incomes relative to the global average have their correspondence in very similar changes in coal and gas use as well as energy use in industry, the service sector, transportation and agriculture and fisheries, i.e. countries whose economies grow faster than the global average also exhibit above average growth of the aforementioned energy system variables. Thus, economic convergence, i.e. closing the gap to the global average by a certain percentage, is associated with changes of similar magnitudes in the energy system for the average developing country in our sample and countries that converge towards similar per capita incomes also converge towards broadly similar patterns of energy use. This finding lends support to the hypothesis that energy systems do not evolve independently from the economic system and that a certain energy use pattern is typical for a given level of economic development. However, most estimates show relatively low R-squares indicating that country-specific effects besides per capita income are important explanatory factors and that there is a considerable variation in individual countries' development paths. From the above arguments, it also follows that our results do not support the leapfrogging hypothesis: poor countries which experience increases in per capita incomes that bring them closer to the world average also display above average growth in energy use, such that on average economic growth in newly industrializing countries results in energy use patterns that are not significantly less energy- or carbon-intensive than those prevailing in richer countries.

As already mentioned, the estimated constant term c_v (computed by averaging the country-fixed effects α_{vi}) can be interpreted as a deterministic trend in (the level of) the respective energy system variable. The statistically significant constant terms on oil and gas consumption as well as total energy consumption hence suggest secular increases which affect developing countries as a group beyond what is explained by the trend of per-capita income. Plausible candidates might be transformations taking place on a global scale, such as increasing urbanization, ever greater integration into world trade, or lifestyle changes. However, the trends for oil and gas are not continuous over the entire sample period: for oil, it is offset by statistically significant period fixed effects with coefficients that are of comparable magnitude to the constant c_v for the periods 1986-1990 and 1996-2005 (reported in Appendix C). Likewise, the upward trend for gas is interrupted for the period 1986-1995 due to period fixed effects of similar size as the constant term. Finally, the time specific fixed effects also suggest above average growth rates of energy use in the industry sector during the period 1991-2000.

A plausible explanation for the insignificant coefficients found for renewables and residential energy use could be that these are largely determined by important non-economic factors which are constant over time and hence captured by the country-specific fixed effects. For instance, on the global scale the use of commercial renewable energy (i.e. excluding traditional biomass use) is dominated by hydropower, which accounts for almost 80% of renewables other than biomass (IEA, 2009) and constitutes an important source of low-cost energy for many countries at different stages of economic development. Therefore, it is not unreasonable to expect that natural endowments are the most important factor explaining the use of renewable energies, at least if policies to explicitly further their use are lacking. Likewise, energy use in the residential sector could well be influenced by country-specific factors which are constant over time (such as climatic factors, or habits), with development of disposable household income playing only a lesser role.

Energy System Variable	β_v	c_v	R^2
Coal	1.116* (0.561)	0.0197 (0.067)	0.064
Oil	0.441 (0.318)	0.166*** (0.0425)	0.162
Natural Gas	1.267** (0.548)	0.401*** (0.131)	0.161
Renewables	0.135 (0.177)	-0.0913 (0.0358)	0.039
Industry	1.014*** (0.143)	-0.0522 (0.0446)	0.067
Services	1.048*** (0.339)	0.0670 (0.0900)	0.074
Transport	1.081*** (0.211)	-0.0205 (0.0492)	0.239
Residential	0.084 (0.126)	-0.0081 (0.0173)	0.029
Agriculture and Fisheries	1.402** (0.654)	-0.0137 (0.102)	0.072
Total Primary Energy	0.631*** (0.167)	0.0625** (0.0248)	0.290
CO_2-Emissions	0.935*** (0.0964)	0.0285 (0.0182)	0.325

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2: Relationship between growth (relative to the world average) of energy system variables and growth (relative to the world average) of per capita income for developing countries (β_v). Estimates were performed with 5 year panels for the period 1971-2005, including country- and time period specific fixed effects (time specific fixed effects are reported in Appendix C).

Industrialized countries

Results for OECD countries are shown in Table 3. Obviously, there are significant differences compared to the results found for developing countries. Most notably, none of the coefficients for the equations describing the growth of consumption of primary energy carriers relative to the global average is statistically significant, neither are the coefficients on total primary energy use, CO_2 emissions, and energy use in the residential sector, agriculture and fisheries, or the service sector (albeit the coefficient on energy use in services is on the fringe of significance at the 10%-level). The only statistically significant coefficients are for energy use in industry and transportation.

Finding a large number of insignificant coefficients with regards to changes in consumption of primary energy carriers and sectoral use of final energy relative to the world average is consistent with the presumption that at more advanced stages of economic development, 'dematerialization' plays an important role (Herman et al., 1990). This means that a larger rate of economic growth is (at least partially) counterbalanced by efficiency improvements and structural shifts in demand which result in increased shares of services (which can be assumed to consume less energy than industry per unit of GDP generated) in economic activity. Our results do not lend support to the hypothesis that decreasing consumption of physical units of energy per unit of GDP is mainly a result of switching to higher quality forms of energy (e.g. from coal to oil and gas) instead of real improvements in end-use efficiency, as suggested by Cleveland et al. (2000) and Kaufmann (2004). Confirmation of this hypothesis would require negative coefficient for coal consumption but increasing negative ones for the consumption of oil and gas relative to the world average[10].

The fact that we find a positive, statistically significant coefficient that is smaller than unity for industrial energy use can be seen as a sign that economic growth is not completely decoupled from energy, i.e. that industry continues to be an important driver of energy consumption, albeit with a β_v of 0.415 its growth rate relative to the global average is significantly lower than that of the overall economy (most likely due to structural changes and efficiency gains). The coefficient β_v for energy use in transport, which is statistically significant and very close to unity, suggests that demand for transportation has (not yet) reached the point of saturation and that it suffers from a kind of 'rebound effect' in the sense that technical improvements in energy efficiency are set off by either higher demand or demand for more energy-intensive modes of transportation.

The statistically significant and positive constant term for renewable energy use indicates that over the observation period, renewables on average experienced an upward trend beyond what can be explained by the dynamics of GDP. This is consistent with the small negative coefficient on total CO_2 emissions, which corresponds to a trend towards decarbonisation. Likewise, the negative constant term on industrial energy use in combination with the positive values for services and transport (which are statistically significant at the 10% level) suggest that secular shifts of energy use from the former sector to the latter ones took place (such as changes in the international division of labour and individual mobility patterns), regardless of the behaviour of per capita income. We also

[10] Our results should however not be interpreted as rejecting the aforesaid hypothesis: the cited studies present time series evidence, whose results will only be reproduced in panel estimates if a sufficient degree of parameter homogeneity among countries is available.

find statistically significant time-specific fixed effects for every interval covered by the period 1991-2005 for natural gas (reported in Appendix C) which are large and negative (ranging from -0.236 to -0.277).

In summary, during the observation period, industrialized country growth relative to the global average is found to be not related to increasing consumption of all primary energy carriers and to energy use in most sectors (relative to the world average). Hence, the general behaviour suggested by our estimates is one of stabilization of energy use at high levels[11]. In particular, no mechanism through which increased incomes result in declining energy use or carbon emissions is detected. In this sense, the observed behaviour is probably best described as decoupling of economic growth from energy use.

Energy System Variable	β_v	c_v	R^2
Coal	0.772 (1.157)	-0.00601 (0.0594)	0.082
Oil	0.152 (0.485)	-0.0257 (0.0375)	0.025
Natural Gas	-1.741 (1.593)	0.236 (0.140)	0.101
Renewables	0.302 (0.651)	0.123*** (0.0397)	0.020
Industry	0.415** (0.171)	-0.0351** (0.0146)	0.062
Services	0.716 (0.424)	0.174* (0.0861)	0.060
Transport	1.021*** (0.141)	0.0291* (0.0154)	0.288
Residential	0.378 (0.261)	0.0681 (0.0501)	0.029
Agriculture and Fisheries	0.321 (0.882)	0.0634 (0.0699)	0.016
Total Primary Energy	-0.181 (0.343)	-0.0105 (0.0183)	0.024
CO_2-Emissions	0.129 (0.0914)	-0.0240** (0.0100)	0.027

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 3: Relationship between growth relative to the world average of energy system variables and growth relative to the world average of GDP per capita for OECD countries (β_v). Estimates use 5 year panels for the period 1971-2005, including country- and time period specific fixed effects (time specific fixed effects are reported in Appendix C).

[11] One further concern is that analyzing national energy use and carbon emissions fails to take into account energy used for the production of imported products. From this point of view, more developed countries become cleaner by 'off-shoring' part of their energy intensive production to third countries (see e.g. Davis and Caldeira, 2010).

Energy use and the engine of growth

So far, the results of this paper indicate the existence of fundamental structural differences with regards to the role of energy use in economic activity between developing and industrialized countries. As we have argued, structural change from agricultural to industrial society and, at more mature stages of development, towards an economy based on knowledge and services is one of the defining features of economic development. Our findings emphasize the importance of taking into account different growth drivers and their interplay instead of simply regarding economic growth as a continuous expansion of a stylized one-sector economy[12]. This is done in e.g. Ayres and van der Bergh (2005), whose model is based on (1) the 'resource use (fossil fuel) growth engine', (2) the 'scale cum learning growth engine', and (3) the 'value creation ('dematerialization') growth engine' and generates predictions which - broadly speaking - are in accordance with our estimates. More stylized models built around a neo-classical framework, as e.g. the "Green Solow Model" (Brock and Taylor, 2004), can also explain some of the observed trends by postulating exogenous improvements in energy efficiency: for wealthy countries, which are close to their steady state, growth is largely driven by gains in total factor productivity and increases in economic activity can be counterbalanced by energy efficiency. This can result in slowly increasing, constant, or even decreasing total energy use, depending on the growth rates of total factor productivity and energy efficiency. In contrast, countries which are farther away from their steady state (i.e. poorer) grow more quickly, and accumulation of physical capital plays a more important role for catching-up. For these countries, economic growth is more energy intensive, as it outpaces the rate of energy efficiency improvement and leads to growing energy consumption.

In order to gain further insight into the role of growth drivers, we subject the observation of de-coupling of energy use from economic growth in OECD countries to closer scrutiny. We modify our estimation equation to distinguish economic convergence and divergence in order to identify countries which experienced more rapid or slower growth compared to the average. For this reason, we define two dummy variables: the variable 'div_{it}' has the value one if country *i* experienced economic divergence in period t, i.e. if the gap between its per-capita income and the group average widened from period *t-1* to period *t*, and zero otherwise. The variable '$above_{it}$' equals one if country i's per-capita income in period *t-1* was higher than the world average, otherwise it is set to zero. For instance, div_{it} takes on the value of one for 57 out of the 84 observations on primary energy carriers contained in our sample of OECD countries (18 countries times 6 time-steps), $above_{it}$ for 55 of them, and for 22 observations both div_{it} and $above_{it}$ are one (i.e. in this case a country that displayed per-capita GDP above world average experienced above average growth).

In our set of regression equations, we now include two additional explanatory variables: firstly, the original explanatory variable $\Delta(GDP_{it} - G\overline{D}P_t)$ interacted with the divergence dummy variable, and, secondly, the very same variable interacted with both '*div*' and '*above*'. Our estimation equation becomes:

$$\Delta(\ln E_{vit} - \ln \overline{E}_{vt}) = \alpha_{vi} + \delta_{vt} + (\beta_{v,1} + \beta_{v,2} \cdot div + \beta_{v,3} \cdot div \cdot above) \cdot \Delta(\ln GDP_{it} - \ln G\overline{D}P_t) + \varepsilon_{vit}$$

This allows us to estimate different slopes for three kinds of qualitatively different patterns of per-capita income growth relative to the world average: (a) convergence to the world

[12] That is, structural and technological change play crucial roles for economic development

average (*div* = 0, *above* = 0 or 1) is described by $\beta_{v,1}$, (b) divergence downward (*div* = 1, *above* = 0) by $\beta_{v,1} + \beta_{v,2}$, and (c) divergence upwards (*div* = 1, *above* = 1), by $\beta_{v,1} + \beta_{v,2} + \beta_{v,3}$.

The results are reported in Table 4. Compared to the estimates we performed without interaction terms, none of the significant coefficients $\beta_{v,1}$ (i.e. the ones for industry and transportation) changes its sign or its level of statistical significance, and their values change only by little. For the interaction variables, two observations deserve attention.

Firstly, for the consumption of oil and total energy, we find (on the 5% or 1% level of significance, respectively) quite large negative values for the term $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ interacted with the divergence dummy ($\beta_{v,2}$), and values that are positive and of comparable magnitude for $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ interacted with both the *div* and the *above* dummy variables ($\beta_{v,3}$). This suggests (a) that countries that diverged downwards (i.e. that were initially poorer and grew less quickly than the average and experienced below average economic growth; *above* = 0, and *div* = 1), oil and total primary energy consumption increased at higher rates than the global average and (b) that countries for which per-capita GDP diverged upwards (i.e. that were initially richer and grew more rapidly than the average; *above* = 1, and *div* = 1), consumption of oil and total primary energy relative to the group average remained practically unchanged[13]. Hence, the latter countries experienced above average improvements in energy efficiency, which allowed them to keep their consumption of oil and total energy relative to the world average unchanged but grow more rapidly. Vice versa, energy efficiency growth for the former countries lagged behind.

This finding points to intrinsic links between the underlying drivers of economic growth and efficiency of energy use. As Easterly and Levine (2001) argue, increases in economic growth are mostly driven by increases in total factor productivity (TFP), especially for countries that are close to their steady state levels of income. Therefore, we can assume that countries that economically diverged upwards experienced above average TFP growth, while TFP growth was below average for countries that diverged downwards. This suggests that TFP and energy efficiency very likely developed in the same direction. There are several plausible explanations for this result, but we expect that technological progress to be the main source driving growth of both TFP and energy efficiency. This explanation would also be consistent with the view that more efficient and flexible energy use also increases the productivity of the other factors of production (see e.g. Schurr, 1984). In any case, this finding mandates against viewing energy efficiency as a purely exogenous process (as it is done for instance in the model of Brock and Taylor, 2004, cited above) and

[13] For (a) the coefficient is $\beta_{v,1} + \beta_{v,2}$. F-tests confirm that for both oil and total primary energy use, $\beta_{v,1} + \beta_{v,2}$ is statistically significant and negative. Hence, if economic growth lags behind the world average $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ < 0 and $\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$ > 0. For (b) the coefficient is $\beta_{v,1} + \beta_{v,2} + \beta_{v,3}$ and, according to our F-tests, statistically insignificant for oil as well as gas use. This implies that for countries that diverged upwards (i.e. $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ >0) $\Delta \ln E_{vit}$ was not higher than the world average (i.e. $\Delta \ln E_{vit} = \Delta \ln \overline{E}_{vt}$).

emphasizes the need to gain a more detailed understanding of growth engines, their relation to energy use, and possibilities to achieve low-carbon growth centered on productivity and efficiency improvements rather than capital accumulation.

Secondly, for industrial energy use as well as CO_2 emissions, only $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ interacted with both the divergence and the above dummy variables ($\beta_{v,3}$) is statistically significant (at the 1% and 5% level, respectively) and in the vicinity of one. F-tests confirm that for both energy system characteristics, $\beta_{v,1} + \beta_{v,2} + \beta_{v,3}$ is positive and statistically significant. Hence, countries that experienced growth rates above the world average also experienced above average increases in industrial energy use and CO_2 emissions. For these countries the over-proportional economic expansion was not matched by like increases in total energy use, suggesting that (a) the industry sector increased its share in total energy consumption during growth spells, and (b) that energy system tend to become more carbon-intensive in periods of accelerated economic expansion. The former observation suggests that industry played an important role in accelerating economic growth; a possible explanation for the latter one could be that growth spells are accompanied by higher real interest rates, which divert resources away from investments in capital-intensive energy investments and tilt the balance in favor of less capital-intensive but dirtier energy carriers, such as coal.

Energy System Variable	$\beta_{v,1}$	$\beta_{v,2}$	$\beta_{v,3}$	c_v	R^2
Coal	2.878 (3.213)	-3.756 (3.881)	-0.0323 (1.882)	-0.0202 (0.0723)	0.120
Oil	1.087 (0.672)	-2.645** (0.941)	2.849** (1.232)	-0.0498 (0.0351)	0.148
Natural Gas	-1.985 (3.151)	-0.723 (4.196)	3.399 (3.739)	0.272* (0.127)	0.104
Renewables	0.231 (0.648)	-0.578 (1.114)	2.066 (2.053)	0.0662 (0.0524)	0.036
Industry	0.408** (0.178)	-0.567 (0.362)	1.334*** (0.467)	0.00250 (0.0171)	0.105
Services	0.677 (0.711)	-0.527 (0.822)	1.394 (1.249)	0.158* (0.0893)	0.066
Transport	1.137*** (0.224)	-0.111 (0.204)	-0.312 (0.436)	0.0216 (0.0167)	0.292
Residential	0.0758 (0.448)	0.392 (0.524)	0.566 (0.674)	0.0507 (0.0524)	0.039
Agric.+ Fishery	-0.550 (1.125)	-0.174 (1.261)	4.628* (2.254)	0.0367 (0.0564)	0.052
Total Prim. Energy	0.490 (0.498)	-1.945** (0.701)	2.185*** (0.627)	-0.0265 (0.0165)	0.182
CO_2-Emissions	0.143 (0.179)	-0.408 (0.261)	0.867** (0.310)	0.00726 (0.0100)	0.079

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Elasticities for the relationship growth (relative to the world average) of energy system variables with respect to growth (relative to the world average) of per capita income for OECD countries ($\beta_{v,1}$). To distinguish between different growth patterns, we included two additional interaction terms: one between our original explanatory variable $\Delta(GDP_{it} - G\overline{D}P_t)$ and a dummy variable denoting divergence ($\beta_{v,2}$), and a second between the explanatory, the divergence dummy, and a dummy variable indicating if country i's per-capita income has been above the group average in period t-1 ($\beta_{v,3}$). Estimates were performed with 5 year panels for the period 1971-2005, including country- and time period specific fixed effects (not reported).

Sensitivity analysis

To assess the robustness of our results, we perform a series of robustness checks. For brevity, we only report the general findings; detailed results of these sensitivity checks can be obtained from the authors upon request.

First, our observation period includes the 1970s, which experienced two major oil price shocks and triggered substantial changes in energy use (Popp, 2002). To ensure that our results are not driven by these somehow extreme events, we repeat all estimates with a restricted sample starting in the year 1981. For developing countries, the coefficient on oil consumption is slightly higher while those on coal and gas use have somehow lower values. It seems likely that this observation can be best explained by adjustments to rising oil prices that resulted in shifts towards coal and gas, which emphasized the decreased oil consumption while deemphasizing changes in coal and gas consumption during the economic downturn that manifested itself in many countries. In addition, we find a slightly lower coefficient for energy use in the service sector (0.66 versus 1.08) and the coefficient on energy use in agriculture and fisheries turns insignificant. For OECD countries, the major finding is that energy use in the service and the residential sectors (with values of 0.95 and 0.55 and significance levels of 1% and 5%, respectively) display statistically significant coefficients. This suggests that at least some part of the observed decoupling of economic growth and energy use indeed took place in the 1970s but was not upheld in later periods.

Second, to investigate the effect of smoothing our data, we employ annual data instead of five year averages. For developing countries, none of the coefficients β_v that were found to be statistically significant earlier becomes insignificant or changes its sign. For energy use in the service sector, the level of significance drops from 1% to 5%, while for energy consumption in agriculture and fisheries is now significant on the 1% instead of the 5% level. The major change happens with regard to the value of the coefficients, all of which have values which are roughly half of those that were obtained with panels averaged over 5 years: while in the latter case the statistically significant values ranged between 0.63 and 1.40, they lie between 0.37 and 0.67 in the former. This finding suggests that energy systems display some inertia, as movements in GDP are accompanied by changes in energy use patterns that are more pronounced in the long run than in the short run. For OECD countries, the levels of significance and values of most coefficients remain basically unchanged. However, there are two important differences: the coefficient on energy use in agriculture and fisheries turns negative, probably due to the structural shift out of this sector as countries develop. Moreover, the coefficient on coal consumption is significant and takes on a value of 1.31. This can be regarded as a sign that short term fluctuations due to shocks in per-capita income which result in higher/lower growth of energy demand relative to the global average are met by corresponding changes in the growth of coal use relative to the world average, but that these adjustments do not persist in the long term.

Third, we analyse the effect of measuring GDP in terms of units adjusted by power-purchasing parity (PPP) instead of market exchange rates (MERs) to take into account differences in price levels across countries. Valid arguments exist for and against each of these two measures[14]. For the purpose of this paper, we decided to focus on GDP in MERs firstly to circumvent issues related to the construction of price indices for the cost of living and, secondly, due to data availability reasons. For the full sample of countries, data for GDP measured in PPP is only available from 1975 on, which reduces the length of our

[14] See e.g. Nordhaus (2007) for a discussion

sample by five years. Most coefficients obtained with the PPP measure lie very close to those estimated with MERs. For developing countries, we find coefficients which are slightly lower for coal and gas consumption and energy use in the service sector and slightly larger for oil consumption. However, for OECD countries the coefficient on energy use in the service sector is now significant (on the 5% level) with a value of 0.95 as is the one on residential energy consumption (on the 10% level) with a value of 0.55. The results for OECD countries seems intuitive if we keep in mind that generally in richer countries exhibit higher price levels (Balassa-Samuelson effect) due to higher prices of non-traded goods. For this reason, as countries get richer, their price level also increases and GDP measured in terms of PPP increases proportionally less than GDP measured in MERs. As energy consumption is not affected by our choice of GDP measure, employing GDP in PPP can be expected to result in larger absolute values for coefficient estimates. Therefore, the general conclusion that developing countries' economic convergence is associated with converging energy use patterns while in industrialized countries economic growth is partially decoupled from energy use remains, independent of the employed GDP measure. However, with GDP measured in PPP units the evidence for decoupling of industrialized countries' economic growth from energy use rests on somehow less solid foundations compared to the estimates undertaken with MER units, an issue that might deserve further attention in future research.

Finally, we also apply a random effects (RE) estimator to exclude the possibility that insignificant coefficients are mainly due to a lack of efficiency of our estimation technique. In contrast to the RE estimator, the fixed effects (FE) estimator, is the only estimator that produces unbiased estimates in the face of country-specific unobserved effects that are correlated with one of the independent variables. However, as the fixed effect which is included for each cross-sectional unit absorbs one degree of freedom, the FE-estimator suffers from low efficiency in small-T samples, i.e. samples that contain relatively few observations on the time dimension. Therefore, employing the RE estimator – which has a higher power but produces potentially biased estimates – can help to identify if insignificant coefficients are a result of small sample size[15]. The random effects estimates produce coefficients remarkably close to those obtained with fixed effects. The most important difference is a statistically significant coefficient (at the 5% level) of about 1.2 for energy use in agriculture and fisheries in OECD countries. For developing countries, the coefficients on oil consumption and energy use in agriculture and fisheries are significant at the 1% level (instead of the 5% level for the former and an insignificant one for the latter with fixed effects). These findings strengthen our conviction that the insignificant coefficient estimated for OECD countries do indeed suggest a partial decoupling of energy use from economic activity instead of being just an artefact of limited sample size.

5 Conclusions

Almost a quarter of a century ago, Goldemberg et al. (1985) outlined a vision of an energy strategy to satisfy basic human needs and provide considerable improvements in living standards that can be accomplished with capacities of as little as 1 kilowatt per capita. Their strategy is designed to permit people in developing countries to enjoy a lifestyle comparable to Western Europe without the need for stark increases of per-capita energy use, provided that highly efficient end-use technologies are adopted on a broad scale.

[15] Note that carrying out estimates with annual data instead of five year panels (described above) greatly reduces problems related to sample size, too

More recently, Birdsall et al. (2009) have expanded this idea into a proposal to break the gridlock in climate negotiations. They suggest putting basic energy needs and equal access to energy services in the centre of the debate, taking into account levels of development as well as opportunities to maximize energy efficiency. The results presented in this paper show the magnitude of this challenge: for developing countries, we find an almost one-to-one relationship between economic convergence and convergence of energy use patterns. This means that developing countries that recently have caught up economically to the world average have also experienced changes in their energy systems that resulted in energy use patterns that are not significantly less energy- or carbon-intensive that those in industrialized countries. Only for countries with high per capita incomes, we find a partial de-coupling, i.e. continued economic growth without increasing use of primary energy carriers or energy consumption in most sectors.

Clearly, these findings are worrisome from a sustainability point of view: to keep global warming below 2°C compared to pre-industrial levels, the IPCC (2007) recommends reductions of CO_2 emissions in industrialized countries by 25-40% below 1990 levels by 2020. However, these reductions will prove insufficient unless developing countries also start transforming their energy systems (IPCC, 2007). According to our results, developing countries are currently following development pathways which bring them ever closer towards the unsustainable patterns of energy consumption currently prevailing in wealthier countries. For instance, CO_2 emissions for the average country in our sample are about 4.4 tons per capita globally, and about 2.5 tons for developing countries. If countries that catch-up economically to the world average also attain corresponding emission levels, providing an income close to the world average to all people in developing countries would imply an increase of global energy-related carbon emissions by more than 10 $GtCO_2$ in total (from currently 27 $GtCO_2$).

In order to provide incentives for developing countries to keep their carbon emissions below a critical threshold without hampering their development prospects, any future global climate agreement will have to be evaluated with a compromise put on both emission and development goals. As we have demonstrated in this article, the transformation of growth patterns in developing countries towards ‘low-carbon growth’ is unlikely to happen by itself. Rather, an appropriate institutional arrangement that defines widely accepted and shared responsibilities for the climate as well as human development will be required to stimulate the transfer of technologies and financial resources from industrialized to developing countries and put ‘low-carbon development’ into practice.

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Appendix A: aggregation of energy carriers and sectors

Primary Energy Carriers

Category used in this paper	IEA classifications included
Coal	HARDCOAL, BROWN, PEAT
Oil	CRUDEOIL, CRNGFEED, NGL
Gas	NATGAS
Renewables	HYDRO, GEOTHERM, SOLARPV, SOLARTH, TIDE, WIND, OTHER, INDWASTE, MUNWASTER, MUNWASTEN, SBIOMASS, RENEWNS

Sectors

Category used in this paper	IEA classifications included
Industry	TOTIND
Services	COMMPUB
Transport	TOTTRANS
Residential	RESIDENT
Agriculture and Fisheries	AGRICULT, FISHING

List of countries

Primary Energy Carriers Sample	Developing Countries	Algeria, Argentina, Bangladesh, Brazil, Chile, China, Colombia, Egypt, Hungary, India, Indonesia, Iran, Malaysia, Mexico, Morocco, Nigeria, Pakistan, Peru, Venezuela
	OECD	Australia, Austria, Belgium, Canada, Denmark, France, Germany, Italy, Japan, New Zealand, Spain, Switzerland, UK, USA
Sectors Sample	Developing Countries	Argentina, Bangladesh, Brazil, Chile, China, Colombia, Cote d'Ivoire, Ecuador, Ghana, Guatemala, Hungary, India, Indonesia, Kenya, Korea, Mexico, Morocco, Nepal, Nicaragua, Pakistan, Peru, South Africa, Sudan, Thailand, Tunisia, Turkey, Uruguay, Venezuela, Zambia, Zimbabwe
	OECD	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK, USA
CO_2 Emissions Sample	Developing Countries	Algeria, Argentina, Bangladesh, Bolivia, Brazil, Cameroon, Chile, China, Colombia, Costa Rica, Cote d'Ivoire, Dominican Republic, Ecuador, Egypt, El Salvador, Gabon, Ghana, Guatemala, Haiti, Honduras, Hungary, India, Indonesia, Israel, Jamaica, Kenya, Korea, Malaysia, Mexico, Morocco, Nepal, Nicaragua, Nigeria, Pakistan, Panama, Paraguay, Peru, Philippines, Saudi Arabia, Senegal, Singapore, South Africa, Sri Lanka, Sudan, Syria, Thailand, Togo, Tunisia, Turkey, Uruguay, Venezuela, Zambia, Zimbabwe
	OECD	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK, USA

Appendix B: Summary Statistics

Developing Countries

Variable		Obs	Mean	Std. Dev.	Min	Max
$\Delta(\ln GDP_{it} - \ln \overline{GDP}_t)$		318	-.0112574	.129422	-.4008747	.4091505
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Coal)	108	.1173839	.6295505	-2.022027	2.448736
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Oil)	108	.0899562	.198262	-.4286912	.9182542
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Natural Gas)	108	.1783573	.4441855	-1.280106	2.118199
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Renewables)	108	-.001688	.1386114	-.5216306	.5659307
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Transport)	180	-.0396693	.3306098	-1.65539	2.469683
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Industry)	180	.0221006	.3140105	-1.030114	2.402532
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Services)	180	-.0101361	.4885146	-1.513225	2.738359
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(AgFish)	180	.044537	.5817607	-2.489336	2.785594
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Residential)	180	-.0149455	.1598764	-.4185912	1.313983
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(PE total)	108	.05072	.1402223	-.3533883	.7451087
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(CO2)	318	.0139367	.202659	-.6818457	.5786324

OECD

Variable		Obs	Mean	Std. Dev.	Min	Max
$\Delta(\ln GDP_{it} - \ln \overline{GDP}_t)$		126	.0016222	.0515991	-.1249773	.2477313
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Coal)	84	.0007355	.2302915	-.620154	1.094191
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Oil)	84	.000168	.1002331	-.2307934	.3905244
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Natural Gas)	84	.1985175	.7246808	-.3156953	6.083865
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Renewables)	84	.0771991	.2286973	-.2931615	9788129
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Transport)	126	.0150056	091201	-.2782761	.273298
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Industry)	126	.0021843	.096495	-3276298	2660823
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Services)	126	.0705971	.2587065	-.5204809	1.315602
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(AgFish)	126	.0234924	3526242	-.7576253	2.200555
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Residential)	126	.032735	.1586562	-.3469217	1.138372
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(PE total)	84	.0083154	.0710868	-.1531306	.2618958
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(CO2)	126	.0121113	.0804804	-.2042449	.2676824

Appendix C: Time-specific fixed effects[16]

Developing Countries (time specific effects for the period centred on t, e.g. δ_{1983} is the fixed effect for the period 1981-1985)

Energy System Variable	δ_{1983}	δ_{1988}	δ_{1993}	δ_{1998}	δ_{2003}
Coal	0.0490 (0.139)	0.219 (0.169)	0.041 (0.155)	0.118 (0.200)	-.0216 (0.137)
Oil	-0.0270 (0.073)	-0.128** (0.060)	-0.052 (0.051)	-0.171** (0.066)	-0.148** (0.062)
Natural Gas	-0.261 (0.171)	-0.351** (0.164)	-0.385** (0.160)	-0.304 (0.181)	-0.238 (0.209)
Renewables	0.014 (0.056)	-0.014 (0.035)	0.038 (0.068)	-0.030 (0.049)	0.015 (0.060)
Industry	0.024 (0.055)	-0.016 (0.042)	0.231*** (0.069)	0.203*** (0.070)	0.014 (0.104)
Services	-0.090 (0.111)	-0.163 (0.105)	-0.040 (0.157)	0.034 (0.127)	-0.194 (0.144)
Transport	-0.013 (0.053)	-0.080 (0.060)	0.013 (0.077)	0.030 (0.068)	-0.300*** (0.102)
Residential	-0.033 (0.025)	-0.028 (0.034)	0.003 (0.032)	-0.015 (0.029)	-0.065 (0.047)
Agriculture and Fisheries	0.035 (0.103)	-0.109 (0.158)	0.105 (0.173	0.154 (0.141)	0.013 (0.152)
Total Primary Energy	-0.019 (0.038)	-0.066 (0.039)	0.030 (0.035)	-0.063 (0.042)	-0.055 (0.025)
CO_2-Emissions	-0.088*** (0.026)	-0.017 (0.027)	0.021 (0.030)	0.068* (0.034)	-0.008 (0.018)

Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

[16] Note that time-specific fixed effects account for idiosyncratic changes to the growth rate of the respective energy system variable relative to the global average that have identical impacts on all countries in the respective time period (cf. Eq.(1))

OECD Countries (time specific effects for the period centred on t, i.e. δ_{1983} is the fixed effect for the period 1981-1985)

Energy System Variable	δ_{1983}	δ_{1988}	δ_{1993}	δ_{1998}	δ_{2003}
Coal	0.109 (0.118)	-0.024 (0.064)	-0.044 (0.067)	-0.043 (0.090)	0.046 (0.113)
Oil	0.040 (0.045)	0.025 (0.064)	0.038 (0.054)	0.021 (0.040)	0.011 (0.038)
Natural Gas	0.252 (0.456)	-0.115 (0.173)	-0.236** (0.107)	-0.277* (0.131)	-0.275** (0.119)
Renewables	-0.023 (0.056)	0.013 (0.047)	0.027 (0.065)	-0.019 (0.072)	-0.001 (0.067)
Industry	-0.017 (0.023)	-0.024 (0.029)	0.003 (0.027)	-0.019 (0.022)	-0.014 (0.025)
Services	-0.112 (0.098)	-0.112 (0.117)	-0.102 (0.114)	-0.130 (0.109)	-0.143 (0.107)
Transport	0.007 (0.016)	-0.008 (0.028)	0.004 (0.024)	-0.020 (0.021)	-0.021 (-0.025)
Residential	-0.000 (0.048)	-0.025 (0.066)	-0.025 (0.069)	-0.039 (0.066)	-0.038 (0.065)
Agriculture and Fisheries	-0.018 (0.111)	-0.007 (0.134)	-0.075 (0102)	-0.071 (0.092)	-0.101 (0.100)
Total Primary Energy	0.025 (0.029)	0.017 (0.032)	0.017 (0.029)	0.005 (0.018)	0.007 (0.018)
CO_2-Emissions	0.007 (0.019)	-0.002 (0015)	0.000 (0.018)	-0.013 (0.014)	-0.008 (0.015)

Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Chapter 3

Carbonization and Decarbonization in China[*]

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From Carbonization to Decarbonization? Past Trends and Future Scenarios for China's CO_2 Emissions

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Abstract

Along the lines of the Kaya identity, we perform a decomposition analysis of historical and projected emissions data for China. We compare the results with reduction requirements implied by globally cost-effective mitigation scenarios, and official Chinese policy targets. For the years 1971-2000 we find that the impact of high economic growth on emissions was partially compensated by a steady fall in energy intensity. However, the end–and even reversal–of this downward trend, along with a rising carbon intensity of energy, resulted in rapid emission growth during 2000-2007. By applying an innovative enhanced Kaya decomposition method, we also show how the persistent increase in the use of coal has caused carbon intensity to rise throughout the entire time-horizon of the analysis. These insights are then compared to model scenarios for future energy system developments generated by the ReMIND-R model. The analysis reaffirms China's indispensable role in global efforts to implement any of three exemplary stabilization targets (400, 450, or 500 ppm CO_2-only), and underscore the increasing importance of carbon intensity for the more ambitious targets. Finally, we compare China's official targets for energy intensity and carbon intensity of GDP to projections for global cost-effective stabilization scenarios, finding them to be roughly compatible in the short- to mid-term.

Keywords: *China, Carbon Intensity, Kaya-Decomposition, Climate Policy*

1 *Introduction*

China's breath-taking economic growth during the last decades has helped to lift hundreds of millions of people out of poverty. But, this success has also turned China into the world's largest emitter of carbon dioxide.[1] Figure 1 depicts the influence of different countries on global emissions growth for the period of 1971-2007. It highlights the rapid increase of China's 'weight' in recent years. In fact, the data indicate that around 50% of the total global increase in CO_2 emissions since 2002 can be attributed to China alone.[2]

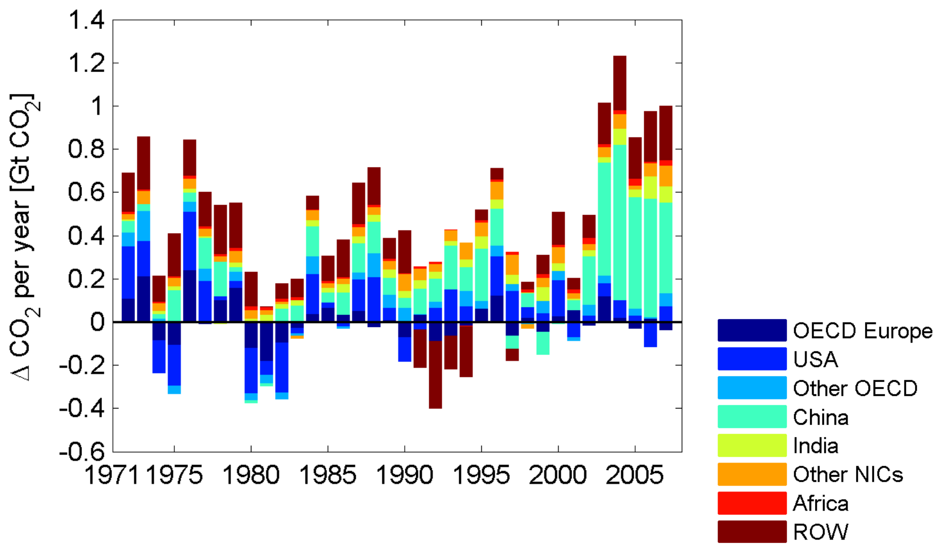

Figure 1: Influence of selected countries and country groups on global CO_2 emissions growth.

In the face of anthropogenic climate change, China's emission intensive growth poses a serious challenge for the success of global mitigation efforts. However, from an equity point of view, China and other developing countries cannot be denied the right of economic catch-up with industrialized countries, which have supported their economic development with cheaply available fossil fuels for centuries. Solving this dilemma will be crucial for successfully averting dangerous climate change.

Given its dramatic emission increase, its persistent economic growth on a high level, and its high reliance on carbon-intensive coal, China is often considered to be a case of its own. This is also reflected by the high attention given to China in the academic literature, which we will review in the first part of this paper. However, what are specific characteristics to turn China into a special case? And what are feasible strategies for putting the Chinese economy on a path towards low-carbon growth, without compromising the need for

[1] Unless otherwise specified, all historical data used in this paper are taken from IEA (2009a) and refer to CO_2 emissions from fossil-fuel combustion (IEA sectoral approach). GDP data are expressed in purchasing power parity (PPP).

[2] Interestingly, it also shows that hardly any country ever managed to reverse the trend of positive emissions growth, except in times of economic crisis (former Soviet-Union countries in early 1990s), and as a reaction to the 1973 and 1979 oil crises.

development? More precisely, are the country's own targets sufficient?

To answer these questions we first systematically investigate historical emissions and their driving forces along the lines of the Kaya decomposition (Kaya 1990), considering in particular energy intensity, i.e. energy used per unit GDP, and carbon intensity, i.e. carbon emissions per unit energy. We find that decreasing energy intensity has primarily contributed to decelerating emission growth in the last decades of the 20th century, while a reversed trend of energy intensity and a continuously carbonizing and fast growing economy were responsible for China's accelerated emissions growth in the first decade of the 21st century. We then introduce an enhanced decomposition technique for analyzing the carbon intensity time-series to determine how the influence of coal has evolved over the last three decades. It turns out that exploiting coal indeed had a significant impact on China's emission growth as compared to other transitional countries, industrialized countries, and the global average; however, the scale of China's economic growth very clearly constitutes the main driver behind its increasing emissions.

The article then confronts the characteristics of China's energy system with a set of globally cost-effective mitigation scenarios obtained from the integrated assessment model ReMIND-R (Leimbach et al. 2010a; Leimbach et al. 2010b; Bauer et al. 2011). Our results suggest that under business-as-usual assumptions, China's emissions could increase about threefold by 2050, underlining its status as a crucial actor in global mitigation efforts. In fact, in a globally cost-optimal scenario aiming at stabilization of atmospheric CO_2-concentrations at 450 ppm CO_2-only, China's emissions would be 43% lower than in the baseline. Applying the decomposition methodology previously used with historical data on model results further indicates that in addition to energy efficiency improvements, reversing the trend in carbon intensity is essential for transforming the Chinese energy system. Renewable energies are identified as the most important option for decreasing carbon intensity, with significant but smaller roles for the expansion of biomass, nuclear energy, and CCS.

Finally, we present an evaluation of China's current energy and mitigation policies and international pledges. In fact, even though China as a developing country has so far refused to accept binding emission targets, it has put a number of policies into place which directly or indirectly aim to reduce energy- as well as carbon intensity. We find China's short- to mid-term targets for energy- and carbon-intensity of GDP to be in line with the values suggested by our cost-optimal 450 ppm stabilization scenario, while the target for renewable energy falls short. The Chinese government's objective formulated for nuclear energy in 2020 lies significantly above our benchmark values.

2 Literature Review

Numerous previous studies have applied decomposition methods to analyze the driving forces behind past changes in China's energy use and carbon emissions: Raupach et al. (2007) point out the importance of China's high rates of economic growth that – together with other developing countries – account for the lion's share of global emission increases. This conclusion is confirmed by Zhang et al. (2009), who show that for China economic activity had the largest effect on CO2 emission changes during 1991–2006, while energy intensity declined. CO2 intensity of energy and structural changes are found to have relatively small overall impacts. In the same vein, Liao et al. (2007) decompose industrial energy intensity in China into sectoral composition of energy use and efficiency improvements and find that the decline in energy intensity between 1997 and 2002 can mainly be attributed to efficiency improvements. Zhao et al. (2010) show that energy savings from efficiency improvements have occurred in China's industrial sector, but that the expansion of production scale and a heavier industrial structure contribute to increases in total energy use. Finally, Guan et al.'s (2009) decomposition of carbon emissions by economic sectors emphasizes the role of global trade for China's development model, as it indicates that Chinese export production is responsible for half of the emission increase in the period 2002 - 2005.

The bottom-up model presented by Cai et al. (2008) suggests that China's emissions will continue to grow quickly until at least 2020 in any case, but that a sustainable development strategy and additional future unilateral policies might help to slow down the increase. All bottom-up studies reviewed (Dai and Zhu, 2005; IEA, 2007; Cai et al., 2008; Ma et al., 2009) agree in their evaluation of energy efficiency and renewable energies as the dominant mitigation options. Dai and Zhu (2005) as well as the IEA World Energy Outlook (IEA, 2007) further emphasize the potential role of structural change and restructuring of energy-intensive sectors. Ma et al. (2009) stress the pivotal role of decarbonizing the power sector (while they identify a significantly lower mitigation potential in transportation) and mandate R&D in solar and CCS for future deployment.

The importance of energy efficiency improvements and renewable energies as the most prominent mitigation options is confirmed by several top-down studies that construct long-term scenarios for the Chinese energy system (Larson et al. 2003; van Vuuren et al. 2003; Wang and Watson 2008). Larson et al. (2003), also suggest that coal gasification technologies (that co-produce electricity and liquid and gaseous energy carriers) combined with some CCS might be a viable low-cost mitigation option, while Wang and Watson (2008) underline the importance of economic and industrial structural change in order to achieve the reductions required in their climate policy scenarios.

The decomposition studies cited above heavily focus on changes in industrial structure and efficiency improvements to explain changes in energy intensity, but devote little attention to the factors affecting the carbon intensity of energy production, i.e. the energy mix. Modeling results, on the other hand, often feature a technology-rich description of the energy system, but suffer from a lack of empirical backing and do not discuss the implications of their findings with regard to energy and climate policies that are either already implemented or currently under discussion. To fill these gaps and contribute to the existing literature, this paper (1) introduces an enhanced decomposition methodology for emissions time series that encompasses changes in the energy mix, (2) applies this decomposition to plausible future scenarios that are consistent with historical developments, and (3) uses the insights gained to evaluate China's current energy and mitigation policies and international climate policy pledges.

3 China's Carbon Emissions in Retrospective

This section investigates the evolution of China's energy-related emissions between 1971 and 2007 and identifies major emission drivers at the macro level. To this end, we consider the time-series of the standard Kaya factors (Kaya 1990), which are commonly used to study emission dynamics (see e.g. Rogner et al. 2007), and include: population, GDP per capita, energy intensity of GDP, and carbon intensity of energy. In order to determine the characteristics of historical emission dynamics, data for China are confronted with world averages, and an aggregate of six newly industrialized countries composed of Brazil, India, Indonesia, Mexico, South Africa and South Korea. At the starting point of our analysis in 1971, the NIC aggregate had a total population nearly on par with China's (884 million versus 845 million) and GDP and emissions per capita were of similar magnitude, too.

Analysis along Kaya Factors

Analyzing historical emissions data in terms of the underlying Kaya components and carrying out a comparison between world average, OECD,[3] China, and NIC provides a number of insights. First, we observe that China and NIC have followed a similar general trend of per-capita CO_2 emissions until the early 2000s, when emission growth in China accelerated substantially (Figure 2b). Initially, NIC had a higher GDP per capita but were surpassed in the year 2000 by the faster growing China (Figure 2a).

Second, for both China and NIC the evolution of carbon intensity of energy has been characterized by an upward trend, albeit with a much faster overall rise and higher base level in China. Although China's and NIC's carbon intensity were initially below the world average, a persistent rise in China and the negative trend in the world average has driven Chinese carbon intensity above the global and OECD average by the early 1980s, while NIC's carbon intensity converged towards global and OECD levels (Figure 2d). Today, China's carbon intensity is about 30%-35% higher than global and OECD averages, since - after half-a-decade of stabilization and short decline after 1995 - it has again strongly risen after 2001.[4]

Third, the starkest difference with respect to all other regions is seen in China's extremely high energy intensity in the 1970s, and its subsequent sharp drop (Figure 2c). It fell below world averages in the late 1990s, and touched the even lower OECD level shortly thereafter.[5] Although it eventually returned to world average levels, it has recently started to fall again, which could be explained by the latest 2006-2010 five-year-plan to reduce energy intensity by 20 percent and related measures (see also Section 5 in this paper). For NIC, energy intensity was initially below world and even OECD levels, but gradually converged to the (steadily declining) OECD level.

Fourth, by today China's per capita emissions and energy intensity are very close to world averages, while GDP per capita is still below the world average and carbon intensity is considerably higher. Overall, we can conclude that China–as compared to NIC–was actually quite an average country also in the past, except for two aspects: its persistently high growth of GDP until today and its dramatically high initial energy intensity that fell just as dramatically until the year 2000. With regard to CO2 emissions, the two 'particularities' worked in opposite directions, at least until the year 2000. Thereafter, energy intensity reached 'normal' levels, which in combination with rising carbon intensity resulted in the well-known boost in Chinese per-capita and absolute emissions.

[3] For the analyses presented here, OECD covers all OECD countries but Korea and Mexico.
[4] However, it has been suggested that manipulations in the official statistics of energy supply from coal–rather than real changes in the energy system–were responsible for this drop-and-rebound effect in carbon intensity (Streets et al. 2001, Peters et al. 2007).
[5] This observation holds when GDP is considered in PPP. See below for a detailed discussion on the sensibility of this assumption.

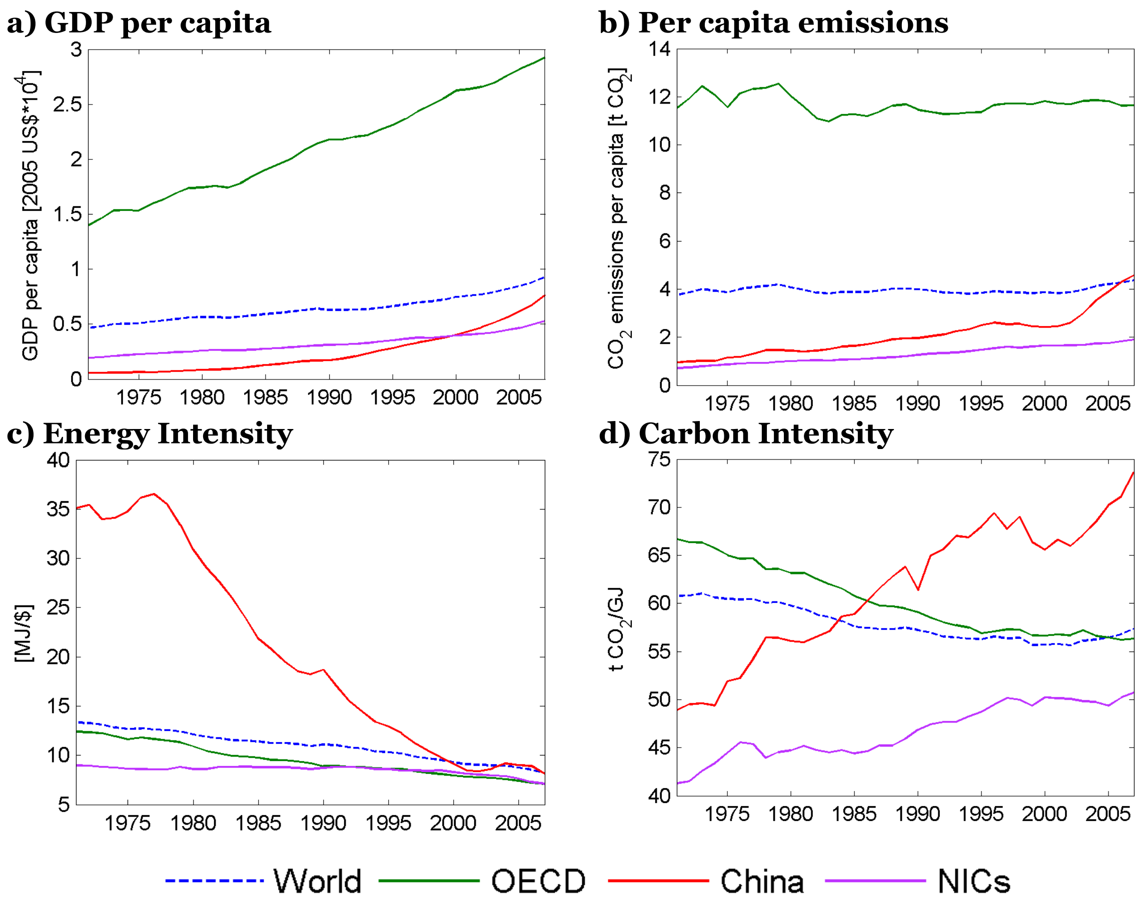

Figure 2: Key indicators of the Chinese economy compared to values for OECD, NIC and world average. NIC represents an aggregate of six newly industrializing countries (Brazil, India, Indonesia, Mexico, South Africa and South Korea).

Influence of the GDP accounting method

The findings presented above are sensitive on whether we choose GDP considered in market exchange rates (MER) or in purchase power parities (PPP) as presented in Figure 3.

Using MER the pattern of energy intensity development does not change considerably compared to using PPP as shown in Figure 2. However, we find that China's energy intensity in 2007 was about twice the world average and three times the OECD average. This implies that there is some room for improvement with respect to energy intensity improvements in the future. With respect to the question, which approach should be preferred, some difficulties have been identified using either approach and there has been a lively debate for years. Briol and Okugu (1997) argue that PPP systematically leads to higher energy efficiency levels in developing countries. Nordhaus (2007) underlines the shortcomings of both approaches and proposes an alternative approach, which shall not be considered here. For the Kaya analysis that is presented in the following, the differentiation does not cause major deviations, as we concentrate on relative changes, which are majorly independent from the choice of the GDP reporting. In the IPCC AR4

(Rogner et al. 2007) PPP is used for a comparable analysis. Therefore, in the remainder of the paper, we will refer to PPP if not otherwise stated.

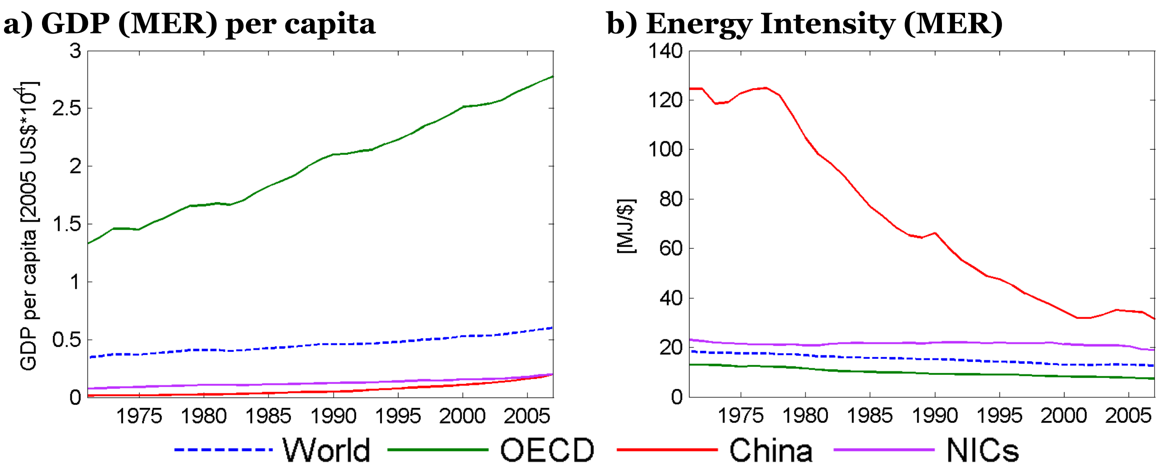

Figure 3: GDP and energy intensity for the World, OECD countries, China and newly industrializing countries (NIC) in MER

Kaya analysis

To corroborate the qualitative findings presented above, we draw on the Kaya decomposition, as shown in Figure 4. We break up emissions-growth along the factors of the Kaya identity (Kaya 1990), which expresses carbon emissions F as a product of the underlying factors GDP G, primary energy E, and population P:

$$F = P\left(\frac{G}{P}\right)\left(\frac{E}{G}\right)\left(\frac{F}{E}\right) =: P\,a\,e\,k\,, \qquad (1)$$

The right-hand-side refers to the relative variables per-capita GDP (affluence) $a = G/P$, energy intensity $e = E/G$, and carbon intensity of energy $k = F/E$. Using the Laspeyres index method[6] (Sun and Ang 2000), a change over time in emissions ΔF can be expressed as the joint contribution of the four underlying effects (indicated by subscript f),

$$F(t + \Delta t) - F(t) = \Delta F = P_f + a_f + e_f + k_f \qquad (2)$$

where each effect can be derived from multiplication, as done here exemplarily for population,

[6] Different methods can be used to decompose the Kaya identity into additive effects, see, e.g. Ang (2004) for a review of different approaches.

$$
\begin{aligned}
P_f &= \Delta P \cdot a_t \cdot e_t \cdot c_t \\
&+ \frac{1}{2} \cdot (\Delta P) \cdot \left[(\Delta a) \cdot e_t \cdot c_t + a_t \cdot (\Delta e) \cdot c_t + a_t \cdot e_t \cdot (\Delta c) \right] \\
&+ \frac{1}{3} \cdot (\Delta P) \cdot \left[(\Delta a) \cdot (\Delta e) \cdot c_t + (\Delta a) \cdot e_t \cdot (\Delta c) + a_t \cdot (\Delta e) \cdot (\Delta c) \right] . \\
&+ \frac{1}{4} \cdot (\Delta P) \cdot (\Delta a) \cdot (\Delta e) \cdot (\Delta c)
\end{aligned}
\tag{3}
$$

The first part of Eq (3) ($\Delta P \cdot a_t \cdot e_t \cdot c_t$) can be interpreted as the partial effect of the population component on the change of CO_2 emissions between time step *t'* and the preceding step *t*. The following parts capture interactions between the remaining variables and form the so called residual term. Results are shown in Figure 4 for China and NIC, where the color-coded stacked bars indicate the contributions from the different effects. For example, in 2007 we find that for China population growth (red) barely contributed to overall emissions growth (0.5%), whereas the increase in per capita GDP (orange) and carbon intensity (green) would jointly induce a 16% increase, were it not for the countervailing effect of decreased energy-intensity (-9%). The convenient property of the Kaya decomposition consists in its completeness: adding the values of the four components gives again the total change of emissions, namely +7.5% in 2007, as indicated by the small black triangle.[7]

a) China **b) NIC**

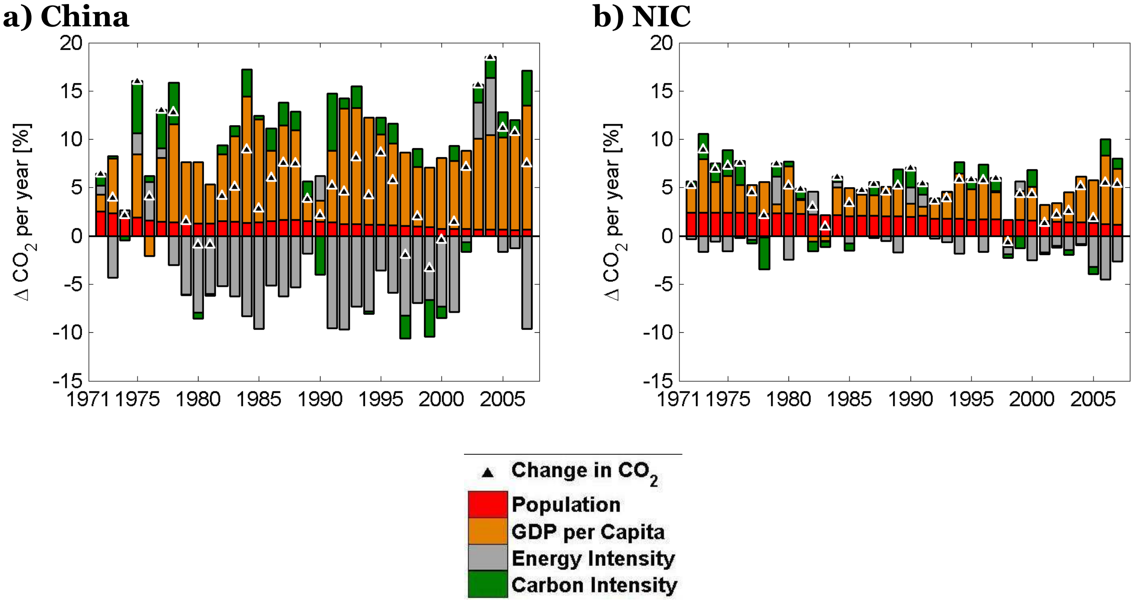

Figure 4: Kaya decomposition of (a) China's and (b) NIC energy related CO_2 emissions as a sum of contributions from population (red), GDP per capita[8] (orange), energy intensity (grey) and carbon intensity (green). Black triangles indicated the resulting net change of CO_2 emissions in the time period.

[7] Likewise, the first year in the graph for China, where all Kaya factors contributed positively to emission growth, has the triangle simply located on top of the bar.

[8] Results are shown in PPP. Decomposition results that use GDP in MER (not shown) show very similar results with only very minor deviations compared to PPP.

The main difference between China and NIC is the significantly stronger emission impact of GDP-growth in the former, which was–at least until the year 2001–partly offset by strong negative impacts from improved energy intensity. In both regions population has had a similar steadily positive but declining effect on emissions, whereas the effect of carbon intensity was more erratic, but with an overall tendency to raise emissions.

Extended Kaya-Decomposition for Carbon-Intensity: Method

In view of the Kaya decomposition of emission drivers it is evident that policy measures to reduce emissions must address energy intensity and–in the long run–especially carbon intensity, while the effects due to growth of GDP and population are either hard to control, judged to be unavailable for political reasons, or face moral controversies. Hence, in order to get a better understanding of the specific dynamics of China's carbon intensity, we subject its time-series to an extended decomposition that allows expressing the change in carbon-intensity as a sum of changes in the supply from specific energy carriers. Namely, carbon intensity $k_{t'}$ at time *t'* can be expressed relative to a preceding time step *t* as

$$k_{t'} = k_t \frac{E_t}{E_{t'}} + \sum_j \left(\frac{k_{jt'} E_{jt'} - k_{jt} E_{jt}}{E_{t'}} \right), \tag{4}$$

where j indexes the different energy carriers, e.g. natural gas, coal etc., and k_{jt} represents the specific carbon intensity of energy carrier *j* at time *t*,[9] which supplies carrier-specific energy E_{jt}. Given that by definition we have

$$E_t = E_{t'} - \sum_j \left(\Delta E_j \right), \tag{5}$$

where DE_j denotes the change between *t* and *t'* in energy supply E_j, one can write

$$k_{t'} = k_t \frac{E_{t'} - \sum_j \left(\Delta E_j \right)}{E_{t'}} + \sum_j \left(\frac{k_{jt'} E_{jt'} - k_{jt} E_{jt}}{E_{t'}} \right). \tag{6}$$

The first part of the expression can be interpreted as the energy carrier's changing contribution to the overall energy mix, while the second term of the expression indicates the change of the energy carriers' specific carbon intensity. This can be reformulated to express the change Dk in carbon intensity between t and t' as a sum over contributions from all energy carriers:

$$\Delta k = \frac{1}{E_{t'}} \sum_j \left(k_{jt'} \cdot E_{jt'} - k_{jt} \cdot E_{jt} - \Delta E_j k_t \right) \tag{7}$$

Δk so far only captures the partial effect. In a complete Laspeyres decomposition, all residuals are taken into account, implying that the effect of carbon intensity k_f can be

[9] Changing specific carbon intensity over time might be confusing at first sight. However, the composition of energy carriers, e.g. coal, changes over time, as for example lignite is replaced by hard coal or vice-versa.

written as $k_f = \Delta k \cdot R$, where *R* represents the residual (compare also Eq (3)). *R* can then be written as:

$$R = (P_t \cdot a_t \cdot e_t) + \frac{1}{2} \cdot (\Delta P \cdot a_t \cdot e_t + \Delta a \cdot P_t \cdot e_t + \Delta e \cdot P_t \cdot a_t) + \frac{1}{3}(\Delta P \cdot \Delta a \cdot e_t + \Delta P \cdot \Delta e \cdot a_t + \Delta e \cdot \Delta a \cdot P_t) + \frac{1}{4} \cdot \Delta P \cdot \Delta a \cdot \Delta e) \tag{8}$$

In order to adapt the decomposition of carbon intensity, i.e. the effect k_f of carbon intensity on the change of emissions, we need to multiply Dk (Eq.7) by *R* on both sides. This leads to the graphs shown in Figure 5, which allow to directly observe the influence of specific changes in the energy mix on emissions.

Applying the Extended-Decomposition: The Role of Coal

The expansion of coal-based power generation in China has recently received a lot of attention (e.g. Rosen and Houser 2007; Ma and He 2008). In fact, Figure 5 confirms that the factor coal explains almost all of the historical changes in China's carbon intensity. However, the general trend of steadily increasing carbon intensity due to an expanding coal sector has been present throughout the last 35 years. Thus, one cannot actually single out the last years for being exceptional in terms of the role of coal. What can be affirmed is that due to the greater absolute economic size of China, the same percentage increase in carbon intensity now leads to much higher absolute emission increases than 30 years ago. This 'scaling effect' is also manifest in the graph for global carbon intensity, where the influence of Chinese coal becomes visibly more pronounced at the end of the time-horizon.

At the global level, the results indicate that in the past a major driver of decarbonization has been the massive expansion of nuclear power in the 1970s and 1980s. As seen in the graph, this specific option has had a particularly strong role for the group of OECD countries. A priori, such a development could also constitute a plausible scenario for China, at least under business-as-usual assumptions. With respect to natural gas and oil, a persistent effect towards either rising or declining emissions cannot be affirmed, as strong fluctuations prevail throughout the observation period. Qualitatively, oil tends to have a decreasing effect, implying that its share in the overall energy mix has fallen, while natural gas shows a slightly positive effect. In fact, global shares of primary oil in the total primary energy supply decreased from roughly 45% to 35%. At the same time, the share of natural gas has increased from 16% to 20%.[10]

[10] Biomass and waste also contributed to decarbonization, but as traditional biomass is included in the data, the effect of a rising population in least developing countries using more traditional biomass cannot be separated from other effects, as for example the wider use of biofuels in the transportation sector, or co-fired waste in power generation.

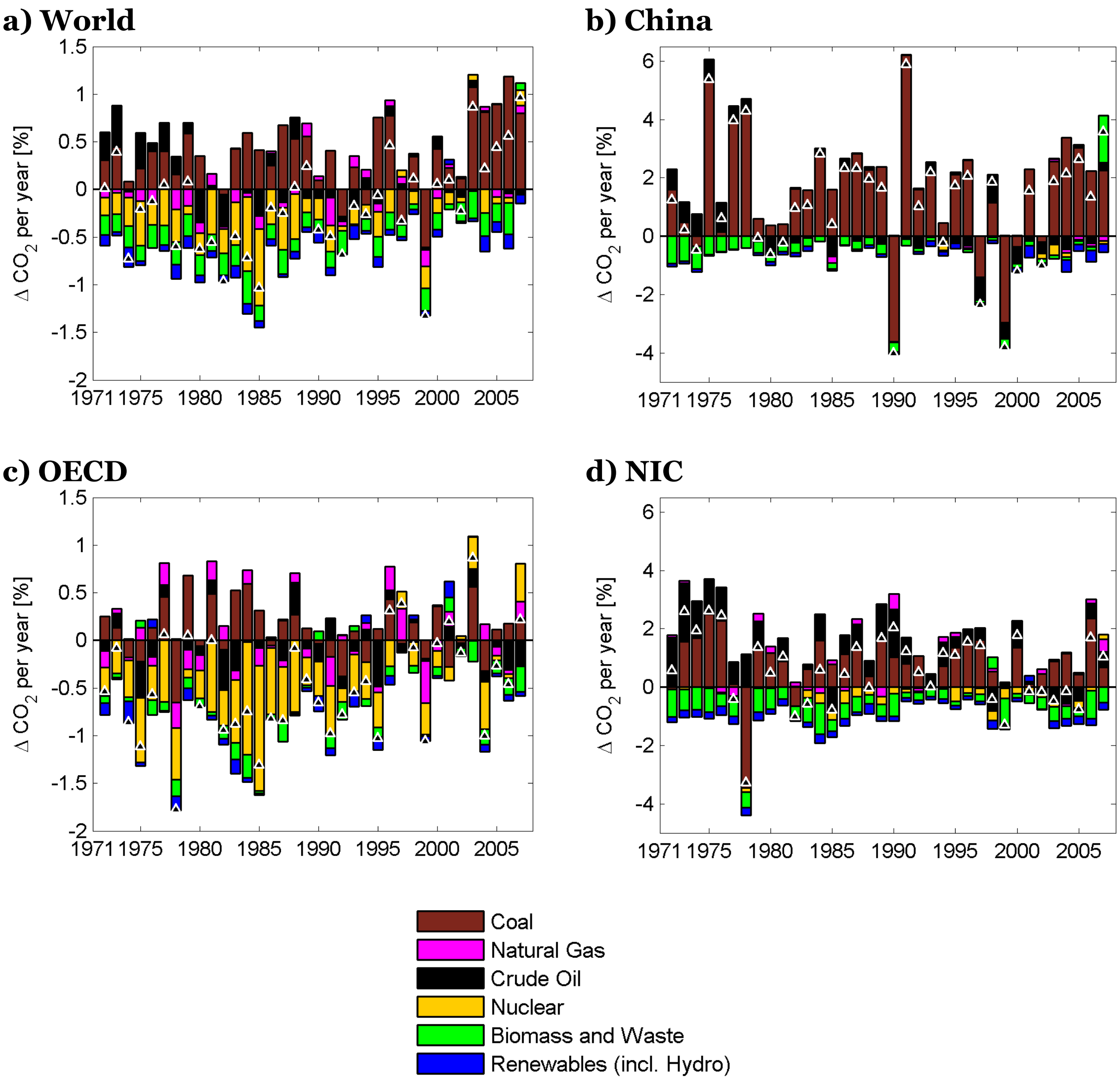

Figure 5: Extended decomposition for the Kaya contribution from carbon intensity on overall emissions, in terms of energy carriers coal (brown), natural gas (pink), crude oil (black), nuclear (yellow), biomass and waste (green) and renewables (blue). Black triangles indicate the net effect of carbon intensity on CO_2 emission change. Note the different scales on the Y-axis.

Table 1 summarizes the findings from the extended decomposition of carbon-intensity and puts them into perspective with regard to the 'size' of the other Kaya factors, indicating each factor's net contribution to emissions-growth, averaged over the entire time horizon. It confirms that coal dominated the trend towards carbonization of energy in China, which could not be reversed by renewables or nuclear power at any time. Compared to the world average, the effect caused by the increased usage of coal is much larger in China (1.6% vs. 0.4%), with a less pronounced difference to NIC (0.9%).

Overall, the table suggests four main conclusions regarding the *evolution* of emissions over the last 35 years: first, the overall very high annual percentage growth in emissions is a special characteristic of both China and NIC. Second, among the Kaya factors, growth of GDP per capita has for both regions been the largest single driver of emissions growth. Third, the main difference between China and NIC consists in the former's relatively stronger economic growth and its resulting larger contribution to emission growth (7.5% vs. 2.8%), and not primarily in different dynamics of carbon intensity or coal. Fourth, the most characteristic feature of China is the exceptionally high contribution of energy intensity, which partially counterbalanced the high growth in per-capita GDP.

		World	**OECD**	**NIC**	**China**	**China 2000-2007**
Population		1.59	0.71	1.93	1.29	0.67
GDP per Capita		1.96	2.07	2.84	7.51	9.27
Energy Intensity		-1.36	-1.55	-0.66	-4.13	-2.34
Carbon Intensity		-0.16	-0.47	0.59	1.2	1.37
CI attributed to	***Coal***	0.36	0.1	0.86	1.61	1.9
	Gas	-0.04	-0.06	0.04	-0.02	-0.07
	Oil	0.02	-0.01	0.52	0.004	-0.19
	Nuclear	-0.24	-0.37	-0.15	-0.04	-0.11
	Biomass and Waste	-0.18	-0.09	-0.49	-0.24	0.08
	Renewables (incl. Hydro)	-0.08	-0.05	-0.18	-0.11	-0.24
Net Annual CO_2 Growth		2.02	0.76	4.71	5.88	8.97

Table 1: Average annual change (1971-2007) of regional CO_2 emissions in percent that can be attributed to specific energy carriers, here compared to the regions' average annual CO_2 growth. Note: Any differences between sums and stated values for 'Carbon Intensity' and 'Net Annual CO_2 Growth' are due to rounding.

One could use the findings above for a naive exploration of future Chinese emissions under business-as-usual assumptions, assuming that carbon intensity eventually falls and reaches the world-average level, which would imply a drop in emissions by around 20%. However, due to the required changes in energy infrastructure, it seems unlikely that this could be achieved in the near-term. Low-hanging fruits in form of further drastic improvements of energy intensity as in the past also do not seem plausible, since China has practically reached the world-average level on this measure. This is not to say that energy intensity could not be reduced much further, as, e.g., a comparison with the current level of Japan (in 2005 6.4 MJ/$ vs. 9 MJ/$ in China) might suggest. However, further improvement will likely need significant (and costly) efforts.

If continued high economic growth prevails, the trend in per-capita emissions in China can be expected to continue on the path taken since 2002/03, implying an emissions growth-rate exceeding 5% per year. Such a value would, however, be well above official reference estimates of 2.6% average annual growth from 2010-2015 (EIA 2009), or 3.6% from 2008 to 2020 (IEA 2010). Most probably, this reflects the extrapolation of global long term trends and the incorporation of the various domestic measures the Chinese government has announced recently, e.g. on energy efficiency, renewables, and carbon intensity of GDP, which will be discussed in detail in Section 5.

4 *Future Options for Decarbonization*

Wheras the previous section has been concerned with the historical development of energy use and carbon emissions in China, this section analyses plausible future scenarios using the integrated assessment model ReMIND-R[11] (Leimbach et al. 2010a, Leimbach et al. 2010b, Bauer et al. 2011). A more detailed model description of ReMIND-R is provided in the Appendix. Two of the scenarios outlined here (baseline and 450 ppm stabilization) are identical to those described in detail in the RECIPE project (see Luderer et al. 2011, Bauer et al., 2011). After outlining the baseline scenario, this section assesses China's role in cost-efficient global mitigation efforts. We then contrast the energy system developments required to achieve emission reductions with historical trends by subjecting our numerical model results to the decomposition introduced in the previous section. Finally, this section concludes by comparing China's energy mix in the baseline and one selected stabilization scenario (450 ppm CO_2) and presents estimates of energy system investments for both scenarios.

Baseline Assumptions in ReMIND-R

To assess the role of China in globally efficient mitigation efforts, we use a set of plausible, self-consistent scenarios as generated by the multi-region integrated assessment model ReMIND-R (Leimbach et al. 2010a, b; Bauer et al. 2011). ReMIND-R is a hybrid model that combines a Ramsey-type optimal growth model of the macro-economy with a technology-rich energy system model. It is characterized by joint inter-temporal optimization of both model components, thus assuming perfect foresight by all economic agents. It incorporates a detailed description of energy carriers and conversion technologies (including a wide range of carbon free energy sources) and allows for unrestricted inter-temporal trade relations and capital movements between the eleven macro-regions that are represented. Due to the model's optimizing behavior and the assumption of perfect foresight the resulting stabilization scenarios should not be interpreted as forecasts but rather as first-best scenarios regarding a cost-optimal transition towards a low-carbon energy system. Therefore they could be seen as a benchmark outcome, against which real world developments can be compared.

The baseline scenario describes plausible future developments in a world without climate mitigation policy (Jakob et al. 2009).[12] China's population is assumed to keep growing at a relatively low rate until 2030 and to stabilize at about 1.4 billion people afterwards (UN 2004). Its GDP per capita is projected to grow at an average of slightly above 4%,[13] corresponding to increases in average income per capita from currently roughly US$ 1,800 in 2005 to US$ 14,000 in 2050. As improvements in energy efficiency are outpaced by growing economic activity, total primary energy consumption grows steadily at around 2% per year, increasing almost threefold throughout the first half of the century. Without additional measures to limit carbon emissions, China's energy system will likely remain

[11] In its structure the ReMIND-R model is comparable to other integrated assessment models, e.g. RICE (Nordhaus and Yang 1996) or MERGE (Manne et al. 1995), but features a detailed resolution of the energy sector. The model as well as its baseline assumptions are discussed in more detail in the Appendix..

[12] Economic damages caused by climate change are not taken into account by this version of REMIND-R.

[13] Economic growth is assumed to slow down from currently about 8% per year to 4.5% in 2030 and 3% in 2050

dominated by fossil fuels (especially coal) and continue the past trend of carbon intensive growth and rising carbon emission. According to our scenarios, CO_2 emissions would increase more than threefold between 2005 and 2050[14].

In the short- to mid-term - i.e. until 2030 - our assumptions on population growth and GDP are practically identical to the ones used by the IEA in its World Energy Outlook 2010 (IEA 2010), resulting in very similar projections for energy demand[15]. One considerable difference, however, concerns carbon emissions: while WEO2010 expects carbon emissions to rise by 2.4% per year in the period 2008-2035, our baseline assumes coal to account for a larger share of total energy consumption, which leads to an increase of CO_2 emissions of 3.9% per year in the period 2005-2030.

The Role of China in Global Mitigation

Table 2 lists global as well as Chinese carbon emissions for several scenarios: the baseline (BAU) scenario as well as several climate policy scenarios aiming at stabilization of atmospheric concentrations at 400, 450, and 500 ppm CO_2-only with minimized global costs. Note that in the baseline scenario the model maximizes welfare without taking into account any additional constraints, i.e. already existing energy or climate policies are not included in the baseline.

The results illustrate the efforts that need to be undertaken to stabilize emissions at various climate policy targets. It gets obvious that China needs to take more responsibility in global mitigation the more ambitious climate policy targets are set, both in absolute numbers as well as relatively to other world regions. The share of global emission reductions that is undertaken in China increases with more ambitious climate targets, ranging from 11% in the 500 ppm to 14% in the 400 ppm scenario. This corresponds to cumulative emission reductions ranging from 27% (in the 500 ppm scenario) and 43% (in the 450 ppm scenario) to 71% (in the 400 ppm scenario) below business-as-usual. The fact that such sizable reductions in China are needed is intuitively clear: stabilizing atmospheric CO_2 concentrations requires limiting cumulative carbon emission in the period 2005-50 to 1350 $GtCO_2$ globally (in the 450 ppm scenario). This corresponds to about 4.5 t CO_2 per person per year, i.e. very close to China's current level and well below the baseline, which projects an almost threefold increase of Chinese annual per-capita emissions by 2050.

[14] Trade is frequently mentioned as a driving factor for China's emission growth (Guan et al. 2009). First, trade is likely to have an impact on China's emissions by driving economic growth. Our scenario takes into account that China cannot indefinitely increase current account surpluses, projecting average per-capita GDP growth of roughly 4% per year in the period 2005-2050, substantially below the growth rates that China displayed in the last decades. Secondly, trade plays a role for China's emissions if the carbon per value embedded in exported goods is significantly different compared to production for domestic consumption. Several studies point out that the amount of carbon embedded in Chinese exports is very similar to the emissions avoided by imports (i.e .the emissions that would have been generated if imported goods had been produced in China instead) such that the composition of China's exports does not significantly influence the country's emissions (Peters and Hertwich 2008).

[15] WEO2010 projects energy demand to increase by 2.6% per year in the period 2008-2035, while for ReMIND the respective figure is 3% in 2005-2030

	BAU	500ppm	450ppm	400ppm
Global cumulative emissions 2005-50 [Gt CO_2]	2604	1655	1350	642
Global reduction below BAU [%]	-	36%	48%	75%
China's cumulative emissions 2005-50 [Gt CO_2]	381	278	218	110
China's share in global emissions [%]	15%	17%	16%	17%
China reduction below BAU [%]	-	27%	43%	71%
Share of global reduction [%]	-	11%	13%	14%

Table 2: Role of China in global reduction efforts.

Table 3 shows results of the enhanced Kaya decomposition for absolute emission changes between 2005 and 2050 for different scenarios. For population and GDP per capita we find a decreasing contribution to emission changes with more ambitious climate policy targets, which can be explained by the lower total emission levels in the policy scenarios. For example, in a relatively carbon-neutral economy, a unit of GDP per capita or population growth will contribute less to emissions growth than in a carbon-intense economy. Most importantly, Table 3 illustrates the interplay between energy- and carbon intensity for different stabilization targets. With increasingly ambitious climate policy targets the importance of energy intensity decreases, while carbon intensity reductions get more and more important. In the BAU scenario energy intensity contributes most, which can – as explained above for population and GDP per capita – be explained with higher absolute emission levels. Thus, significant emission reductions that can be derived from energy intensity improvements are already undertaken in the BAU scenario[16], but only limited additional reduction potential from decreasing energy intensity can be realized when climate targets become more ambitious. Therefore a focus on carbon intensity becomes increasingly important. Determining the drivers of carbon intensity in more detail, we find that its reduction is mainly triggered by renewable energy in the 450 ppm scenario, while CCS and a decrease in the use of coal are majorly important for the 400 ppm low stabilization scenario. [17]

Crucial assumptions for the policy scenarios in this analysis are (a) immediate action on climate change mitigation, and (b) the presence of an international carbon market. Therefore, mitigation of carbon emissions features full 'where-flexibility', i.e. it can be undertaken at the location where it generates the lowest costs. In the intertemporal optimization framework applied here, this implies that the allocation of emission rights among nations only affects the incidence of mitigation costs, while, for a given mitigation target, the distribution of physical emission reductions remains independent of allocation (Manne and Stephans 2005). The sizable physical emission reductions in China projected here thus point to the presence of ample low-cost mitigation options, but not as an

[16] This could be interpreted to be in line with static marginal abatement cost analyses, which see negative abatement costs for a significant share of energy efficiency improvements, i.e. measures to decreases energy intensity. As REMIND-R is an intertemporal optimization model these options will naturally be realized in the BAU case. For a more detailed discussion see Van Vuuren et al. (2009).

[17] REMIND-R allows for negative emissions that are generated by biomass in combination with CCS. This mitigation option gets particularly important for very low stabilization scenarios, such as the 400ppm scenario considered here. For a more detailed discussion see Edenhofer et al. (2010).

indicator of the reduction target in terms of emission rights. It does not imply that China will necessarily bear a large share of the costs of climate stabilization.

		BAU	500ppm	450ppm	400ppm
Population		20.0	14.3	12.2	10.1
GDP per Capita		481.5	373.2	331.2	291.3
Energy Intensity		-333.0	-288.0	-252.9	-182.1
Carbon Intensity		39.8	-55.0	-95.5	-167.6
CI attributed to	***Coal w/o CCS***	58.7	13.4	-3.3	-20.7
	Gas	-0.3	0.2	0.1	0.6
	Oil	-1.3	-1.0	-0.7	-0.9
	Nuclear	0.3	-6.9	-6.9	-2.9
	Biomass w/o CCS	-13.6	-21.9	-23.9	-13.7
	Renewables (incl. Hydro)	-4.0	-31.8	-50.1	-52.1
	CCS	0.0	-7.0	-10.8	-78.1
Absolute emission change in 2050 compared to 2005 [%]		208.4	44.5	-5.0	-48.3

Table 3: Decomposition of China's absolute emissions change from 2005 to 2050 in different scenarios in percent.

Macroeconomic Effects of Climate Policy

To keep the analysis tractable, we discuss macroeconomic effects of climate policy, mitigation options, and investment needs taking the 450 ppm target as an example. Depending on assumptions about emissions of other greenhouse gases, this target corresponds to overall GHG concentrations of 500–550 ppm CO_2-eq. (Fisher et al. 2007). In terms of temperature changes, the cumulative emission budget until mid-century corresponds to a probability of slightly less than 50 % of keeping global warming below 2°C compared to preindustrial levels (Meinshausen et al. 2009).

Figure 6 illustrates the driving forces of carbon emissions as observed in the past and projected for the future under business-as-usual as well as for the 450 ppm stabilization scenario. As can be seen from the Kaya decomposition in panel (a), robust economic growth in China has put - and is supposed to continue to do so in the future – considerable upward pressure on emissions, while population growth (which is expected to turn negative from 2030 on) has only minor impacts. Even in the baseline scenario declining energy intensity acts as a counterweight to economic expansion, limiting the increase of energy consumption to rates well below the rate of economic growth. Without policy intervention, the move towards higher shares of (abundantly available) coal in the energy mix increases the carbon intensity of energy production, especially in the near term (panel b). However, this effect is by an order of magnitude smaller than the effects of changes in GDP and energy intensity.

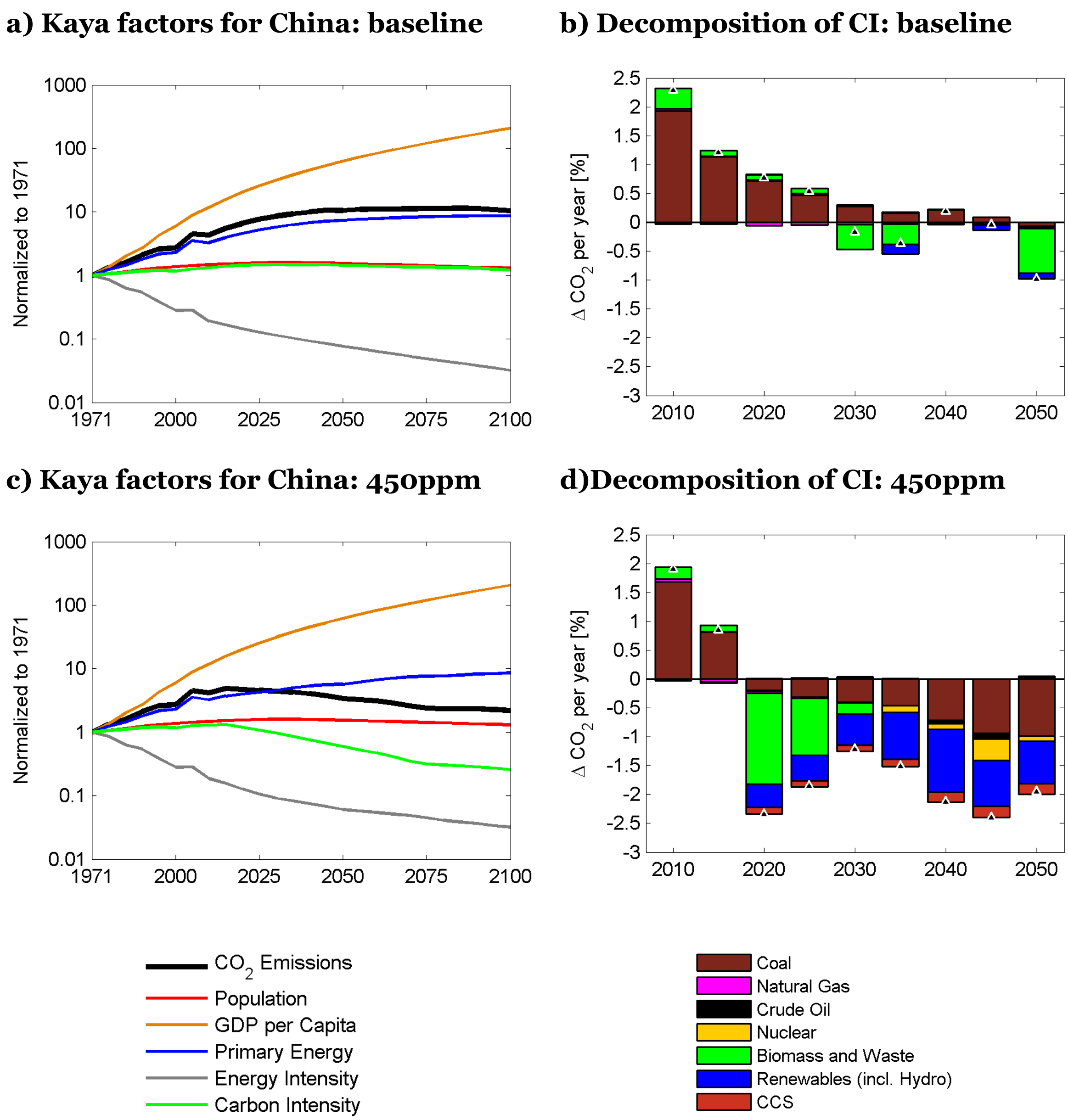

Figure 6: Kaya decomposition factors for historic data[18] and model results for the baseline and the 450 ppm scenario (a, c), results are shown normalized to 1971 and decomposition of carbon intensity for model results (b, d).

In the 450 ppm CO_2 climate policy scenario Chinese emissions peak in 2020 and decline constantly after that date. Climate measures can be targeted at decreasing the energy intensity of GDP (e.g. through energy efficiency improvements or industrial policies to shift the production structure towards less energy intensive sectors) or lowering the carbon intensity of energy production (e.g. by encouraging the use of low-carbon energy

[18] Out of consistency reasons with model results, historic GDP data are shown in MER for this analysis.

technologies). The most remarkable feature of the stabilization scenario, depicted in panel (c), is the continued decrease in carbon intensity from 2020 onwards, triggered by structural changes in China's energy system. With improvements in energy efficiency that only partially compensate economic growth, lowering carbon intensity is essential to reduce carbon emissions without compromising development. The differences in per-capita CO_2 emissions between the baseline (where they grow by about 2.2% per year on average) and the policy scenario (where they slightly decline) can to a large part be explained by the different trends in carbon intensities: While in the baseline carbon intensity grows by a little less than 1% per year on average, this trend is reversed in the policy scenario, in which it declines by roughly 2% per year. The decomposition of carbon intensity shown in panel (d) reveals that decreasing the consumption of coal and increasing use of renewables and biomass can make the largest contribution to reverse the current trend and achieve lower carbon intensity, with additional but smaller roles for nuclear power and CCS.

Assessment of Mitigation Options

According to the baseline scenario (i.e. in the absence of climate policies) China's energy system will remain carbon-intensive, with the largest share of primary energy demand met by fossil fuels (Figure 7a). Even in the absence of climate policy it can be expected that oil and gas become scarce. As they are replaced by coal, this results in increasing shares of coal (but also of biomass and renewable energies) in China's energy mix, while nuclear energy is projected to remain at a negligible level.[19]

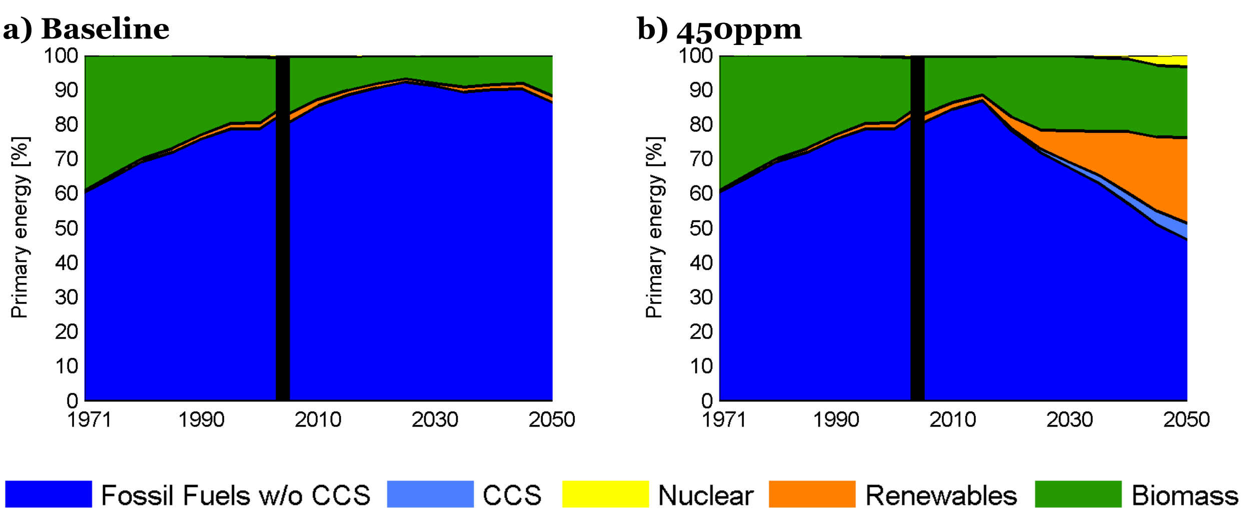

Figure 7: Composition of energy supply in the Chinese energy system from 1971 to 2050 for (a) the baseline and (b) the 450 ppm CO_2 only policy scenario. The vertical black line indicates the change from historic data (IEA) to model results (ReMIND-R).

[19] Without climate policy, no incentives to apply CCS exist. Hence, this option is not employed in the baseline scenario.

As we have argued above, stabilizing atmospheric CO_2 concentration at 450 ppm CO_2-only is only feasible with significant reductions of carbon emissions below business-as-usual and contingent on a timely transformation of the Chinese energy system. As in the short- and mid-term the capital stock in the energy system is relatively inflexible, energy efficiency improvements can make a significant contribution to abate carbon emissions, such that energy consumption in the policy scenario grows at lower rates and is about one third below business-as-usual in 2050.

Initiating a transition towards a low-carbon energy system implies quickly phasing out conventional fossil fuel based capacities, which are projected to peak around 2015 and become continuously replaced by renewables, biomass, and CCS. However, the model results suggest that in the year 2050 almost half of total primary energy will still be supplied by conventional fossil fuels. Renewables, which grow from 2015 on and account for about 25% of primary energy by 2050 (not including biomass) in the policy scenario, can arguably make the largest contribution to limiting the increase of carbon emissions in China. Increasing use of biomass (which is an important energy carrier in the baseline, too), CCS, and nuclear energy are expected to constitute less important mitigation options. The model results further suggest that decarbonization of electricity generation is key to mitigating carbon emissions in China. In the stabilization scenario, by 2050 roughly 40% of electricity is generated from renewables and 20% from biomass, while transportation and the stationary sector display relatively low mitigation potentials.

Investment Needs

In order to satisfy China's growing energy demand (directly linked to its rapid economic growth) sizable energy system investments will be needed in the next couple of decades – even in the case that climate change is not addressed in the country's energy strategy. The bulk of these investments occur in the power sector (see Figure 8). In the baseline case (depicted in panel a), our scenarios suggest that investments in the power sector will predominantly be focused on conventional fossil-fuel based generation capacities with some investments in renewables and biomass, triggered by scarcity induced price increases of fossil resources. Over the period 2005-2050, the scenario projects a relatively flat trend with annual energy system investments between US$ 50 bln and US$ 100 bln.

The effect of climate policy on the investments is twofold: A rapid switch toward low-carbon technologies occurs, and the overall investment volume increases markedly (panel b). Since the low-carbon energy carriers are highly capital-intensive, on the long run the annually required energy system investments are projected to exceed baseline investment by a factor of two and reach about US$ 200 bln in 2035. ReMIND-R projects a complete phase-out of investment in conventional fossil fuel based forms of energy by 2015, suggesting that from this point on, renewable energy generation is likely to attract the largest part of investments, while considerably smaller shares will be targeted at biomass, nuclear and CCS.

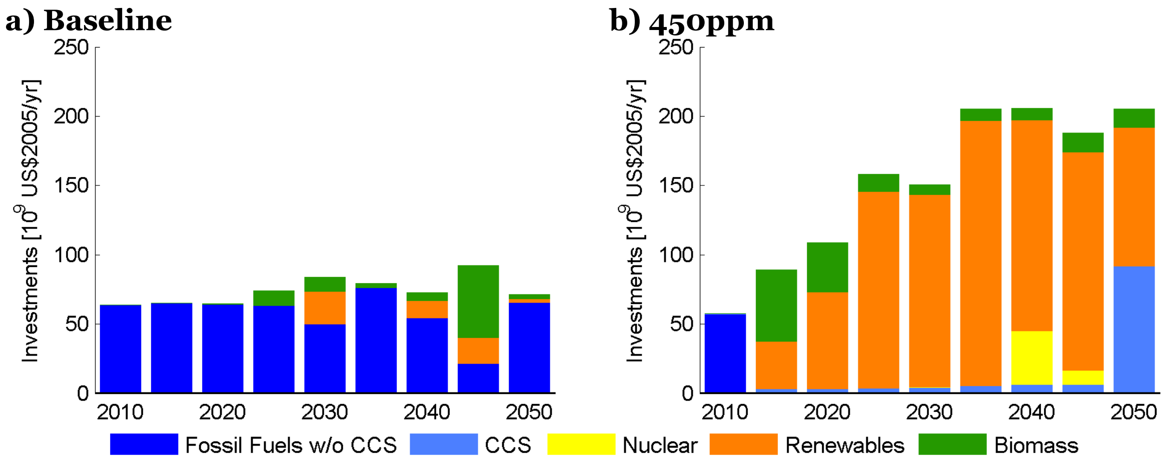

Figure 8: Investments in the Chinese power sector from 2010 to 2050 according to the ReMIND model in billion year 2005 US$ per year for (a) the baseline and (b) the 450 ppm policy scenario.

5 *Assessing China's Energy and Climate Policies*

In the first sections of this paper we have analyzed historic drivers of China's energy-related emissions and measures needed to restructure the energy system in the future. In this section we discuss the contribution of current domestic policies to a decarbonisation of the energy system.

Climate Change and Sustainable Development in China

China has repeatedly expressed its intention to address climate change in the context of implementing a sustainable development strategy. A recent White Paper (State Council 2008) emphasizes that economic development is regarded as the core objective of policy making. Hence, policies related to climate and energy issues are evaluated according to their potential to further this objective along multiple dimensions, which include safeguarding environmental integrity, but also economically efficient resource use, limiting dependency from energy imports, etc.

In international negotiations, China has declared its will to limit global warming to 2°C but refused to take binding reduction commitments (at least until 2020), and emphasized that according to the principle of 'common but differentiated responsibility', industrialized countries should take the lead in reducing emissions. Within the current UNFCCC process, the country is the most important host for CDM projects and is continuously lobbying for an enlarged technology transfer scheme as a foundation for strengthening international cooperation.

Domestic Measures

After energy intensity had fallen significantly for decades,[20] this trend reversed in the early 2000s. As a reaction, the 11th five-year-plan includes a target to reduce energy intensity by 20% below 2005 levels by 2010. Even though not an official target, energy intensity is envisaged to be further reduced to 40% below 2005 levels by 2020, which can be derived from the Chinese government's national development goal to quadruple GDP while only doubling energy demand in the period 2000 to 2020[21]. This target is backed by a number of different measures, including specific energy conservation targets for China's 1000 most energy-consuming enterprises, forced phase-outs of inefficient power plants, a requirement to use commercially viable state-of-the art technology for all new coal-fired power plants, and vehicle fuel efficiency standards. In addition, targeted industrial policies, such as export taxes on energy-intensive exports, aim at limiting the expansion of energy-intensive industries and promote structural change towards service-based and high-tech industries (Price et al. 2008).

In the run-up to COP15 held in Copenhagen, the Chinese government announced to reduce carbon intensity of GDP by 40 – 45% below its year 2005 level until the year 2020. Proposals to implement a carbon tax in China are currently discussed (Reuters 2009), and it does not seem to be completely unlikely that a uniform carbon tax will be implemented in the next five-year-plan.

Several laws and regulations promote the uptake of low-carbon technologies: the renewable energy law, enacted in 2005, provides specific targets for different energy carriers,[22] feed-in tariffs and privileged grid access for wind energy, solar energy and energy from biomass. It aims at raising the share of renewables in the national energy mix to 15% by 2020 (NDRC 2007). Nuclear energy, which currently plays only a minor role in China's current energy portfolio, is planned to be expanded to 86 GW until 2020,[23] and several pilot projects for CCS have been recently built or are currently under construction (Fenn 2009), showing a principle interest of Chinese energy planners to develop this technology.

Evaluation of Chinese Climate Change Policy

Table 4 compares China's announced policies with the simulation results for our baseline as well as 450 ppm stabilization scenario. The energy intensity target is only slightly more ambitious than the improvements projected under business-as-usual (-40% versus -37.6% by 2020, respectively), strengthening the presumption that economic efficiency rather than environmental concerns might be the primary motivation behind its adoption. However, it is basically still sufficiently close to the energy intensity reduction suggested by the 450 ppm stabilization scenario (45% reduction), which highlights the fact that energy

[20] As shown in Section 3, China's energy intensity was nearly three times higher than the OECD average in 1971, but only 14% higher (and slightly below the global average) in 2007 using GDP in PPP.
[21] The goal was set by the 16th National Congress of the Chinese Communist Party in 2004 as reported by Wang and Tao (2009)
[22] Wind capacity for example shall be expanded to 100 GW
[23] The initial goal of 40 GW was revised in 2009, see http://www.chinadaily.com.cn/china/2009-07/02/content_8346480.htm [February 2010]

efficiency improvements have a limited scope if they are to be cost-efficient.[24]

Policy	China – targets	Baseline scenario	450ppm stabilization scenario
Energy Intensity	40% reduction in 2020 compared to 2005[25]	- 37.6% in 2020	- 45 % in 2020
Carbon Intensity of GDP	40 – 45% reduction until 2020 compared to 2005	- 24.8% in 2020	- 44.8% in 2020
Renewable energy (all)	15% of total energy by 2020	9.2% in 2020	21% in 2020
Nuclear	86 GW until 2020	5 GW in 2020	5 GW in 2020 (111 GW in 2050)
CCS	no official target	N/A	0.6% in 2020

Table 4: China's technology targets for carbon-free technologies compared to actual values in ReMIND projections.

Our business-as-usual scenario foresees significantly lower carbon intensities of GDP than other projections (e.g. IEA 2009b; IEA 2010; EIA 2009)[26]. This is due to the fact that the latter are mainly based on the extrapolation of long-run trends and also incorporate recent policy developments, while our baseline assumes a continuation of the more recent shift towards coal, at least in the short- and mid-term.[27] Unlike the energy intensity target, the target set for the carbon intensity in 2020 of GDP (-40% to -45%) is considerably below the baseline (about -25%), and well in line with the development path suggested by our 450 ppm stabilization scenario (about -45%). However, it should be noted that transforming China's energy system requires sustained effort over several decades, and that no long-term targets extending beyond 2020 have been formulated.

With regard to renewable energies, our cost-effective policy scenario calls for a larger share than what the current renewable energy target envisages for 2020 (21% versus 15%), while the proposed 86 GW of nuclear capacity in 2020 are multiple times above what our simulations suggest. However, in the longer term up to 2050, nuclear energy plays a role that is more congruent with ReMIND scenarios. As ReMIND-R projects only a limited amount of abatement via CCS in the short- and mid-term, China's engagement in pilot projects can be seen as appropriate to explore the potential of this technology within the overall portfolio of mitigation options.

[24] However, small differences in energy efficiency improvements can have significant effects if they are maintained over long intervals. This explains the importance of energy efficiency as a mitigation option in our stabilization scenario.
[25] Note that this is not an official target, see also footnote 22
[26] For instance, IEA (2010) projects energy intensity in China to decrease by 3.3% per year over the period 2008-2035. Applying this rate for the period 2010-2020 yields a decrease of 38.4%, very similar to our figure of 37.6%. For carbon intensity of GDP, however, the IEA projects an annual decrease of 3.1%, which corresponds to 36% over the period 2010-2020. This decrease is hence much more pronounced than the 24.8% found with our model.
[27] See Bosetti et al. (2009) for a discussion

6 Conclusions

In the analysis of historical emission patterns, we show that China can in two respects be seen as a special case, indeed: first of all, China has grown at an exceptional rate over the last decades, which can be identified as the main driver for the growth of emissions. At the same time, emission increase has been decelerated by improving energy intensity levels. However, this effect of partial off-set only lasted until the early 2000s, when energy intensity levels started to increase again. As a consequence emissions growth accelerated significantly. Second, over the entire time horizon of 1971-2007 coal has contributed more significantly and more consistently to emissions growth in China than in other regions considered in this paper. However, the effect is small compared to the effect of economic growth.

For the future, a strong contribution to international mitigation efforts *taking place* in China (independent of who bears the costs) is seen as necessary to achieve stabilization of the atmospheric CO_2 concentration. Model results underline the importance of physical reductions in China if global costs are to be kept at acceptable levels. It is important to point out that these reduction needs are independent from equity considerations, which should be addressed independently, e.g. by initial allocations in emission trading schemes (Schmidt and Marschinski 2010).

The trend reversal of decreasing energy intensity in the mid 2000s suggests that future options to reduce CO_2 emissions will be much more limited than in the past, as the general level of energy efficiency has nearly reached OECD levels. This is backed by model results showing that China's energy intensity target is only slightly more ambitious than our business-as-usual projection. Even though energy efficiency improvements are surely one important aspect, the decarbonization of the energy system requires the promotion of carbon-neutral energy carriers to reach the announced goal of bringing down the carbon intensity of GDP by 40-45% below 2005 levels by 2020. China has implemented a number of policies to increase energy efficiency and make energy supply cleaner and more secure,[28] which are an important first step. However, as long as coal retains its position as dominant energy carrier, the effects of promoting renewables, CCS and nuclear power will only have a minor impact.

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[28] Whether the motivation is always triggered by climate change or whether climate friendly policies are rather a co-benefit of other policy priorities is not always easy to say.

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Appendix

Model description

ReMIND-R is a multi-regional hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model. Macro-economic output, i.e. gross domestic product (GDP), is determined by a constant elasticity of substitution (CES) production function with labor, capital and final energy as input factors. GDP can be used for consumption, investments into the macroeconomic capital stock (for which a depreciation rate of 5% is assumed), all expenditures in the energy system (fuel costs, investment costs and operation and maintenance costs) and for the export of a final good. Final energy is modeled as a CES production function comprising transport energy and stationary energy. REMIND-R takes into account exogenous technical change in the macroeconomic system (expressed as changes in factor productivities) as well as endogenous technological evolution in the energy system (i.e. learning curves for energy technologies).

The energy system module (ESM) comprises a detailed description of energy carriers and conversion technologies. It is embedded into the macroeconomic growth model through the techno-economic characteristics and the system of balance equations that set up the energy system. Multiple primary energy sources are available in the ESM. These include renewable primary energy sources defined by region-specific and energy source-specific potentials, which are classified into different grades. In addition, there are exhaustible primary energy sources (coal, oil, gas, and uranium). These are tradable and characterized by region-specific and energy source-specific extraction cost functions, which increase with cumulative extraction.

Each region is modeled as a representative household maximizing an inter-temporal utility function that depends on instantaneous utility in each time-step (discounted at a pure rate of time preference of 3%), which is derived from per capita consumption. The individual regions are linked by trade relations. The present version of ReMIND distinguishes 11 world regions, linked through trade in coal, gas, oil, uranium, goods, and emission permits. Trade and capital mobility (implied by trade in the composite final good) are driven by differences in factor endowments and technologies and modeled as exports into in and imports from a common pool. The balance between exports and imports for each kind of good in each period is guaranteed by adequate trade balances. For individual regions, current account deficits and surpluses in any period are permitted as long as inter-temporal trade is balanced.

Baseline description

The baseline scenario depicts future developments in a world without climate mitigation measures. Based on UN projections, global population is expected to keep growing and reach roughly 9 billion in 2050. GDP is assumed to grow at rates close to historical values in industrial regions but more rapidly in newly industrializing and most (but not all) developing and least developed countries. The underlying storyline is that the US, Europe, and Japan are expected to remain the regions with the highest incomes in 2050, with other countries, especially China and India, closing the gap. Thus, global GDP is projected to grow at an average of 3.1% per year, resulting in income levels in 2050 which are almost 4 times their 2005 value. This corresponds to a rise in GDP per capita from roughly US$

6,800 in 2005 to US$ 18,400 in 2050.

ReMIND-R projects a strong initial growth of energy use, which slows down considerably after 2040. Total energy use increases from 400 EJ in 2005 to 830 EJ in 2050, an annual increase of 1.6%. Energy use in the US, Europe, and the rest of Annex I countries, which currently account for approximately 50% of global consumption, rises steadily but at low rates. Considerable increases are predicted for the group of developing countries. Fossil fuels are expected to account for almost 90% of total primary consumption in 2050. However, due to scarcity of fossil fuels and technological progress in the renewable energy sector, fossil fuels become more expensive compared to renewables and from 2030 on, and non-fossil sources of energy (i.e. renewables and nuclear) are projected to gain in importance, even in the absence of climate policy.

The model assumes continuous improvements in energy efficiency due to technological progress, resulting in an average annual decline in energy intensity of about 1.5%. Due to the pronounced rise in energy demand and the continued dominance of fossil fuels, amplified by the growing share of coal in the energy mix, ReMIND-R projects a more than doubling of global annual CO_2-emissions, from 32 Gt CO2 in 2005 to almost 65 Gt CO_2 in 2050 (i.e. an annual growth rate of about 1.6%).

Chapter 4

The Costs and Benefits of Early Action[*]

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Time to act now? Assessing the costs of delaying climate measures and benefits of early action

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Abstract

This paper compares the results of the three state of the art climate-energy-economy models IMACLIM-R, ReMIND-R, and WITCH to assess the costs of climate change mitigation in scenarios in which the implementation of a global climate agreement is delayed or major emitters decide to participate in the agreement at a later stage only. We find that for stabilizing atmospheric GHG concentrations at 450 ppm CO_2-only, postponing a global agreement to 2020 raises global mitigation costs by at least about half and a delay to 2030 renders ambitious climate targets infeasible to achieve. In the standard policy scenario - in which allocation of emission permits is aimed at equal per-capita levels in the year 2050 - regions with above average emissions (such as the EU and the US alongside the rest of Annex-I countries) incur lower mitigation costs by taking early action, even if mitigation efforts in the rest of the world experience a delay. However, regions with low per-capita emissions which are net exporters of emission permits (such as India) can possibly benefit from higher future carbon prices resulting from a delay. We illustrate the economic mechanism behind these observations and analyze how (i) lock-in of carbon intensive infrastructure, (ii) differences in global carbon prices, and (iii) changes in reduction commitments resulting from delayed action influence mitigation costs.

Keywords: Climate Change Economics, Model Comparison, International Climate Policy, Delayed Participation

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1. *Introduction*

The accords that emerged as a result of recent UNFCCC negotiations in Copenhagen and Cancún recognize the scientific case for limiting global warming to below 2°C (cf. UNFCCC, 2009). This is in line with the assertion that some of the most serious impacts of climate change could be averted by strong mitigation policy (Stern, 2006). A large number of integrated assessment modeling studies suggest that ambitious climate measures can be implemented at global consumption losses not exceeding 2% (Stern 2006; Knopf et al. 2010). For instance, the model comparison by Luderer et al. (2011a) concludes that stabilizing atmospheric concentrations at 450ppm CO_2-only[2] can be achieved at costs ranging from 0.1 to 1.4% of world GDP relative to the baseline, provided that full 'where' and 'when' flexibility (i.e. a global climate agreement that enters into force immediately) can be realized. However, ongoing negotiations for a global climate agreement show few signs of progress and it seems unlikely that a full agreement with globally binding targets to limit greenhouse gas emissions can be reached in the near future.

The question how to balance the environmental risks from too little or too late emission reductions against the economic risks from too much or too early abatement has received much attention in the run-up to the signature of the Kyoto protocol. Whereas some authors have argued that concentration pathways with higher near-term emissions entail lower abatement costs (Wigley et al. 1996) and that a slow 'ramping-up' of mitigation efforts constitutes the most cost-efficient approach to slow down global warming (Nordhaus 1992; Nordhaus and Yang 1996), others have emphasized that inertias in the energy system increase the costs of deferring abatement to the future (Ha-Duong et al. 1997).

More recently, the debate on the implications of delayed action has reemerged as bottom-up approaches that suggest building a global carbon-market in a stepwise fashion if a global agreement fails to materialize have attracted considerable attention (see e.g. Flachsland et al. 2009). It has for instance been pointed out that if global annual emissions decline at a rate of 1% per year with the inception of a global agreement, delaying action by more than a decade would preclude stabilization of atmospheric CO_2-concentrations below a doubling of pre-industrial levels (Mignone et al. 2008), and delayed action in a global climate regime has been addressed by several integrated assessment modeling studies (Keppo and Rao 2007; Edmonds et al. 2008; Bosetti et al. 2009; Van Vliet et al. 2009, Richels et al. 2007). Two key insights from this literature can be summarized as follows: (i) the larger the non-participating regions' abatement potential and the longer the delay before they join a global climate agreement, the larger the increase in overall mitigation costs, and (ii) the more ambitious the stabilization target, the larger the increase in mitigation costs caused by delayed participation. This is in line with the findings of the 22nd Stanford Energy Modeling Forum, which employed ten leading integrated assessment models to generate scenarios in which BRIC countries start participating in the global effort to mitigate GHG emissions by 2030, and other non-Annex-I countries by 2050. Practically all models agree that delaying participation makes the most ambitious 450 ppm CO_2-eq. stabilization target impossible to achieve and significantly raises mitigation costs for the intermediate 550 ppm CO_2-eq. scenario (which more than double for some models), while impacts for 650 ppm CO_2-eq. are much less severe (Clarke et al., 2009).

This study contributes to the existing literature on limited spatial and temporal flexibility of mitigation efforts by extending previous research on at least three accounts: first, it

[2] This stabilization target corresponds to medium probabilities of keeping global temperature rise below 2°C (cf. Section 2.2.2).

minimizes the role of uncertainty from model design by comparing the results from three state-of-the art energy-economy models IMACLIM-R, ReMIND-R, and WITCH, which were calibrated on harmonized socio-economic baseline assumptions. Second, it sheds some light on the regional distribution of mitigation costs in a rich set of delayed participation scenarios. Third, it thoroughly discusses how differences in model structures and assumptions impact on the numerical results, elaborates on the underlying economic intuition behind the observed model behavior, and performs a number of decompositions to gain a better understanding of the factors contributing to changes in mitigation costs.

This paper proceeds as follows: Section 2 describes the research design, including a brief description of the models, the model comparison framework, the baseline as well as the standard policy scenarios (in which full flexibility prevails). Section 3 presents the delayed action scenarios with restricted 'when' and 'where' flexibility on a global as well as regional level of aggregation, proposes a decomposition of changes in mitigation costs into changes of domestic abatement costs and changes of the carbon trade balance, and shows how these are related to the cumulative mitigation burden, marginal abatement costs, and the global carbon price. Section 4 concludes and discusses the policy implications of our results.

2. *Research Design*

2.1. The Model Comparison Framework

The economic analysis of climate change is concerned with parameter uncertainty (i.e. incomplete knowledge with regard to economic and technology parameters) as well as model uncertainty (i.e. having several plausible model structures). Carrying out model comparisons to deal with model uncertainty is an often used concept in climate economics (see e.g. Edenhofer et al., 2006)[3]. The three models employed in this model comparison represent very similar assumptions regarding underlying socio-economic drivers of energy use and carbon emissions (i.e. population growth and world GDP, which were partly harmonized across models) but different visions of development and diffusion of new technologies as well as of economic mechanisms[4]. IMACLIM-R (Sassi et al., 2010) is a recursive computable general equilibrium model in which agents behave semi-myopically with adaptative expectations, leading to sub-optimal investment decisions and unused production factors. Therefore, climate policies can be a means of remedying market failures. ReMIND-R (Leimbach et al., 2009) assumes inter-temporal optimization of global welfare with perfect foresight. The model includes a detailed description of energy carriers and conversion technologies as well as unrestricted inter-temporal trade relations and capital movements between regions. WITCH (Bosetti et al., 2006; 2007) is an optimization model accounting for the non-cooperative nature of international relations. It models the emergence of carbon-free backstop energy technologies as well as endogenous improvements in energy efficiency.

Comparing the results obtained for our benchmark stabilization with those of the delayed

[3] In this context, one should be aware that models are not designed to predict the future, but to generate plausible, self-consistent scenarios which can serve as tools for scientists and policymakers to explore the scope of possible developments, discuss the plausibility of underlying assumptions, and derive appropriate courses of action.
[4] Model designs and the associated assumptions are discussed in the synthesis paper (Luderer et al., 2011a)

stabilization scenarios for these three models sheds some light on how different assumptions on technologies and economic dynamics translate into differences in mitigation costs[5]. To derive meaningful conclusions on a regional scale, we aggregate the results from each model to six 'macro-regions', which are similar (albeit not identical) across models: The European Union (EU), the US (USA), Rest of Annex-I (R-AI), China (CHN), India (IND), and Rest of non-Annex-I (R-NAI). The economic impacts of delays in climate policy are computed by comparing the macro-economic consumption paths that are obtained in the respective delayed action scenario with the one in the benchmark stabilization scenario (which features full 'where' and 'when' flexibility). The difference between these two trajectories determines the increase in mitigation costs due to delayed action. Based on standard economic theory, consumption losses can be considered an appropriate measure of the economic costs of climate policy[6]. To make costs that arise in different points in time comparable, all costs are converted to net present values with a constant discount rate of 3%.[7] Damages caused by climate change are not part of this analysis[8] and the model results do not constitute a cost-benefit-analysis but an assessment of how limited spatial and temporal flexibility influences the costs of stabilizing the atmospheric CO_2 concentration at a certain pre-determined level.

2.2. *Benchmark Mitigation Costs*

2.2.1. *The Reference Scenario*

Our reference scenario depicts future developments in a world without climate mitigation measures. The three models employed use identical assumptions with regard to the development of global population and partially harmonized assumptions regarding economic activity[9]: world population is assumed to keep growing, with a peak at 9.5 billion in the year 2070 and thereafter slightly decline to roughly 9 billion in 2100. GDP is projected to grow at rates close to historical values in industrial regions but more rapidly in newly industrializing and most (but not all) developing and least developed countries. The underlying storyline is that the US, Europe, and Japan are expected to remain the regions with the highest per capita incomes at the end of the 21st century with other countries, especially China and India, closing the gap. Over the entire century, world GDP is assumed to increase on average between 2.1% (WITCH) and 2.4% (ReMIND) per year.

In all three models, energy demand is projected to rise throughout the whole of the 21st century, with increases of total primary energy consumption by factors between two-and-a-half (WITCH) and four (IMACLIM-R). Due to an energy mix that remains largely dominated by fossil fuel use, carbon emissions at the end of the century are several times their 2005 level. The IMACLIM-R baseline projects the highest CO_2 emissions (124 $GtCO_2$ in 2100) with a continuous increase beyond 2050 due to the availability of cheap coal as a substitute for oil, which prevents the penetration of non-fossil energies (Figure 1a). In contrast, due to an energy demand 19% lower than the IMACLIM-R reference and a higher

[5] A more detailed description of the model comparison framework can be found in Jakob et al. (2009b).
[6] To take into account inter-temporal consumption smoothing (i.e. shifting current consumption into the future by saving), we adjusted current consumption for REMIND-R by adding investments and the current account balance.
[7] Section 3.5. includes a sensitivity study which assesses the robustness of the main results with respect to the discount rate.
[8] i.e. for WITCH - the only model that includes a damage function - damages were set to zero.
[9] The reference scenarios and their underlying storylines are described in Jakob et al. (2009a).

penetration of carbon-free energy (biomass and renewable), emissions in the ReMIND-R baseline decline after 2050 (after a high growth up to 2040) to reach 72 $GtCO_2$ in 2100. The WITCH baseline reaches 86 $GtCO_2$ emissions in 2100, with low emission growth in the second half of the century. It is in aggregate close to the ReMIND-R scenario, with a lower energy intensity but a higher carbon intensity of its energy mix, compared to ReMIND-R and IMACLIM-R. The resulting carbon emissions give rise to atmospheric concentrations in the year 2100 between 730 ppm CO_2 (WITCH), 750 ppm CO_2 (ReMIND-R), and 840 ppm CO_2 (IMACLIM), see Figure 1b.

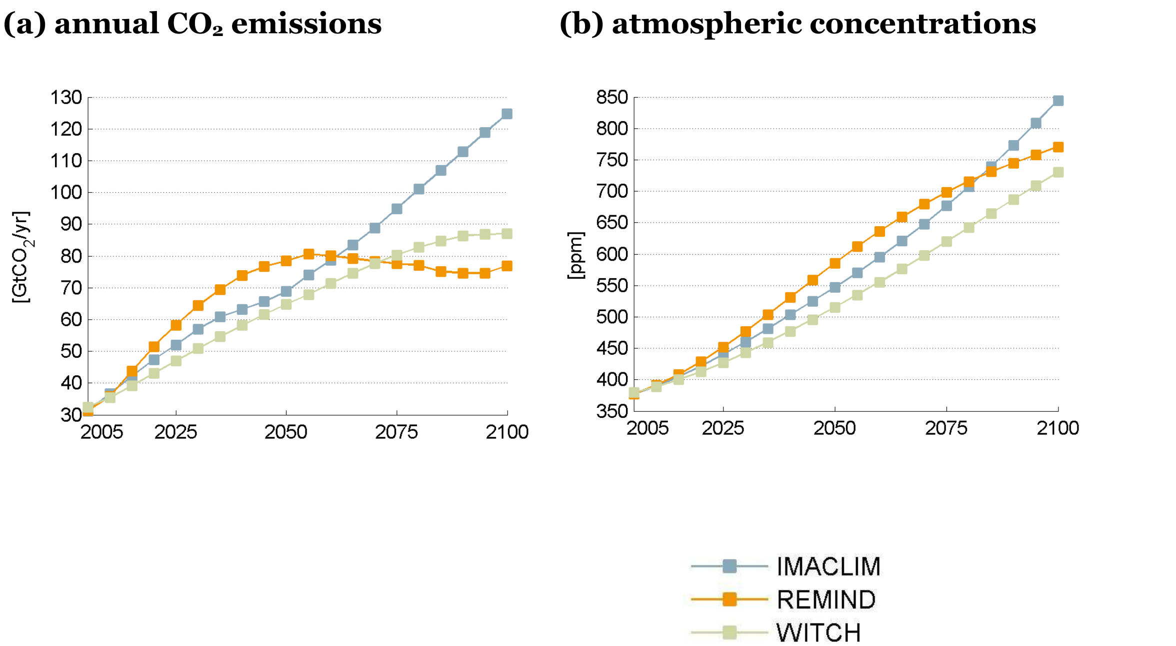

Figure 1: Annual CO_2 emissions (panel a) and atmospheric concentrations (panel b, CO_2-only) in the reference scenario for IMACLIM-R, ReMIND-R, and WITCH

2.2.2. The Benchmark Stabilization Scenario with Full Flexibility

Our stabilization scenario considers a benchmark stabilization target of 450 ppm CO_2 in the year 2100[10]. Depending on assumptions about emissions of other greenhouse gases such as CH_4, N_2O and fluorinated gases, this corresponds to overall GHG concentrations of 500-550 ppm CO_2-eq. (Fischer et al., 2007). According to the metric of cumulative emission budgets as proposed by Meinshausen et al. (2009) - which in our case lie between 1455 and 1533 Gt CO_2 for the first half of the 21st century depending on the respective model - the mitigation effort envisaged by the stabilization scenarios results in medium probabilities (ranging from 42 to 49%) of keeping global temperature rise below 2°C.

[10] IMACLIM-R allows for unlimited overshooting (i.e. exceeding the 450 ppm CO_2 limit in any year prior to 2100) as long the constraint is met in the year 2100, while for WITCH overshoot was limited to 460 ppm CO_2 and ReMIND imposed a maximum overshoot concentration of 470ppm CO_2 in 2070.

Due to their structural differences and different representations of the energy system, the models project different economic effects of climate policy. The aggregated discounted mitigation costs in terms of consumption losses relative to the baseline[11] accrue to 0.1% (IMACLIM-R), 0.7% (ReMIND-R), and 1.4% (WITCH). The size and temporal evolution of mitigation costs and the carbon price are shown in Figure 2. The differences in model approaches are reflected in the structural differences of carbon price trajectories. In IMACLIM-R, under imperfect foresight very high carbon prices are required initially to create a sufficiently strong signal to overcome the technical inertias constraining the transition to a low-carbon energy system (Figure 2a). These high prices result in very high transitional mitigation costs and welfare losses in the first 30 years of the modeled period (Figure 2b). Once this transition is accomplished, IMACLIM-R projects negative mitigation costs due to additional technical change and the implementation of climate friendly transport infrastructure policy (two parameters that increase overall efficiency and help correcting the main source of sub-optimality in the baseline scenario i.e. the volatility of oil markets and the imperfect foresight of 'peak oil'). ReMIND-R and WITCH, by contrast, are perfect foresight intertemporal optimization models and therefore envisage a smoother development of the carbon price and almost steady (approximately exponential) increases until the middle of the 21st century. Endogenous technological progress (i.e. learning-by-doing) and non-linearities in the carbon cycle result in slower increases of the carbon price after 2050. WITCH exhibits significantly higher consumption losses compared to ReMIND-R, and long-term mitigation costs also exceed those estimated by IMACLIM-R on the global scale. Due to the relatively more conservative assumptions concerning technology substitution within the energy sector, a larger share of the emissions reduction has to be delivered by curbing the economy's energy demand, resulting in a reduction of economic output. In ReMIND-R, the carbon price is projected to remain on a moderate level, as the model allows for more flexibility to bring about transformations of the energy system. Learning processes reduce the cost of low-carbon technologies, most notably renewables. The availability of cheap alternative energy sources reduces CO_2 abatement costs and allows focusing the mitigation effort on decarbonization, while the reduction of energy demand plays a less important role.

The regional distribution of mitigation costs will be discussed in the next section in combination with the cost implication of delayed mitigation. With a global climate agreement the regional (but not the global) costs of mitigation measures critically depend on the burden sharing principle which determines the allocation of emission rights across regions. For the remainder of this paper, we presume that the Contraction and Convergence scheme (Meyer, 2004), which envisages a smooth transition of emission shares from status quo (i.e. emissions in 2005) to equal per capita emissions in 2050, is adopted. This allocation scheme combines elements of grandfathering – allocation based on historic emissions – and equal per capita emissions and can be considered a compromise between a pure egalitarian regime and a grandfathering approach[12]. Different degrees of participation to this scheme imply that non-committed countries are entitled to larger emissions, i.e. to emit as they would in the absence of any climate regulation.

[11] We employ a discount rate of 3% over the period from 2005 to 2100.
[12] The role of different allocation rules on regional mitigation costs is discussed in Luderer et al. (2011b).

(a) carbon prices (year 2005 USD) **(b) global consumption losses (percent of total)**

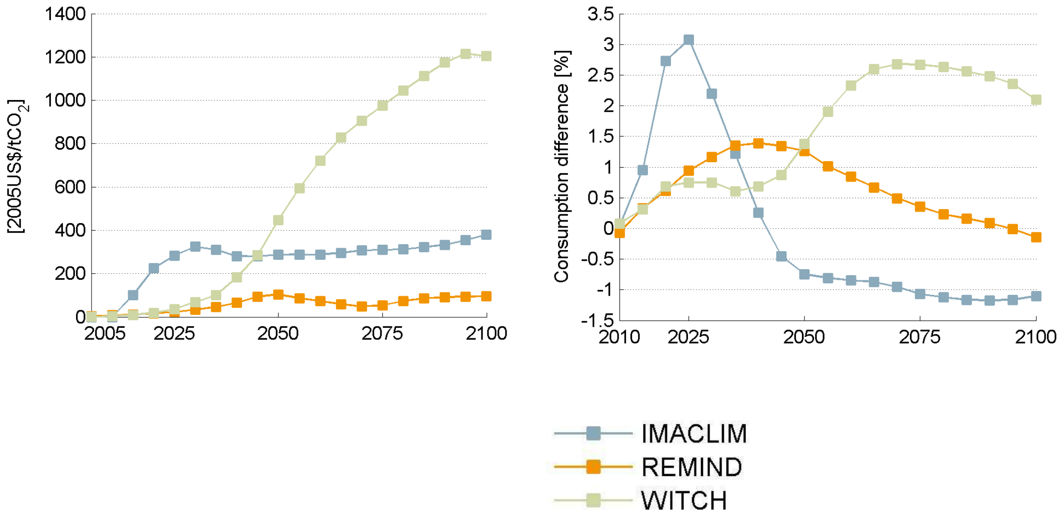

Figure 2: Carbon prices (panel a) and consumption losses (panel b) in the benchmark 450 ppm stabilization scenario (with full spatial and temporal flexibility) for IMACLIM-R, ReMIND-R, and WITCH

3. *Effects of Delayed Participation*

Three distinct effects determine the impact of delayed mitigation efforts on abatement costs: first, regions that do not commit to reduce their emission in early years carry a lower share of the total mitigation effort undertaken globally over the century, which lowers their mitigation costs compared to the benchmark stabilization scenario. Second, acting myopically leads to a build-up of capital stock dedicated to carbon-intensive patterns of generating and using energy and increases future domestic mitigation costs. Third, myopic behavior and lock-in of carbon intensive energy infrastructure[13] also affect global carbon prices that will be higher than in the benchmark stabilization scenario with full participation. As will be discussed in more detail below, this can have positive as well as negative effects on any region, depending on whether it is a net-seller or a net-buyer of emission permits (which, in turn, depends on its reduction commitment as well as the structure of its energy system). Depending on the relative magnitude of these effects, the welfare effects of delayed action for late movers are ambiguous.

In the following we examine the aforementioned effects in detail. We start with a description of the delayed action scenarios, discuss their impact on global and regional mitigation costs, and then decompose changes in consumption losses into changes in domestic mitigation costs and changes in the carbon trade balance. The final sub-section presents the economic intuition behind the numerical results and illustrates the possible

[13] Please note that in all three models energy infrastructure (such as generation capacity) is employed until the end of its life-time without the possibility of early retirement. Hence, the infrastructure in place constitutes a constraint for the stabilization target that can be achieved. See Davis et al. (2010) for a recent analysis of future CO_2 emissions from existing energy infrastructure.

benefits of early action by analyzing the determinants of mitigation costs for the EU and the US.

3.1. Stabilization Scenarios with Limited Spatial and Temporal Flexibility

The default policy scenarios presented earlier were based on the assumption of global collaborative action on climate change from 2010 on, ensuring full spatial and temporal flexibility of mitigation efforts. However, current negotiations on a post-2012 climate regime indicate that substantial climate policy efforts may be lacking in some world regions in the near future. Against this background, we assess the costs of delaying the implementation of ambitious climate policy in some regions. The five scenarios which examine the most relevant configurations of commitments given the current negotiations (listed in Table 1) differ in their timing of introducing regional climate policy and represent plausible participation structures marked by different levels of political ambition. As a sensitivity check, we also examine a scenario with a longer delay, which assumes complete absence of climate policy until the year 2030.

Scenario name	Scenario assumptions
all2010	Global carbon market by 2010, regional allowance allocation by Contraction and Convergence (2005 as base-year)
IC + CHN + IND	All Annex-I countries plus China and India adopt cap-and-trade by 2010, the rest of the world by 2020
IC only	Participation of all Annex-I countries by 2010, with the rest of the world joining the emissions trading regime by 2020
EU only	The European Union acts as an early mover, the rest of the world by 2020
delay2020	Complete absence of climate policy until the year 2020

Table 1: Description of delayed action scenarios

In the early action scenarios the allocation of emission permits to regions that undertake climate policy during the years 2010 to 2020 equals their endowment in the ‘all2010’ scenario. International allowance trade can then occur between all regions with binding emission targets. Between 2010 and 2020, the regions that delay participation are assumed to behave myopically, i.e. they do not expect the introduction of carbon constraints and follow their business-as-usual development pathway[14]. It is assumed that

[14] This is a somehow extreme modeling assumption, as governments will build agreements on growing credibility of international negotiations and firms will start to respond to this expectation some time beforehand. However, it is hardly the case that anticipation of policy will go beyond 5 years, which is the time step used for ReMIND-R and WITCH in the comparison exercise, while for IMACLIM-R, expectations exclusively depend on past developments.

from 2020 on allowances are allocated according to the Contraction and Convergence rule with 2005 as the base year and 2050 as the convergence year. Therfore, regions' relative shares in global emissions remain unchanged compared to the default C&C scenario[15]. However, to compensate for the excess emissions produced during the period of delay, regional caps are contracted proportionally starting in 2020. Thus, in the delay scenarios, the cumulative emissions across regions are shifted in favor of late movers who emit more than in the 'all2010' scenario with the world jointly making up for these excess emissions post-2020.

3.2. Impact of Delayed Action on Global Mitigation Costs

Even with a global delay of mitigation action until 2020, our numerical results indicate that stabilization at 450 ppm CO_2 by 2100 remains feasible, albeit at significantly higher costs than in the 'all2010' scenario. Discounted global consumption losses over the course of the 21st century increase from 1.4% to 2% in WITCH, from 0.6% to 1% in ReMIND-R and from 0.1% to 0.8% in IMACLIM-R (Figure 3). In these simulations no constraints were put on the availability of technologies. Clearly, with a restricted set of technology options it would become increasingly difficult to achieve the 450 ppm target if countries delay action on climate change[16].

Including a larger number of key regions in the climate coalition of those taking early action by 2010 markedly decreases the global costs of stabilization. The participation of the Annex-I countries, as well as that of China and India is found to be critical for the magnitude of mitigation costs, with different accentuations depending on the respective model: all models project that early participation of Annex-I countries is particularly important, with global consumption losses in the 'IC only' scenario between 22% (WITCH), 38% (ReMIND-R), and 59% (IMACLIM-R) lower than in the 'delay2020' scenario. In IMACLIM-R, the EU is found to play a lesser role for global mitigation costs, as consumption losses in the 'EU only' scenario are only slightly lower than in the 'delay2020' scenario, while pursuing climate policy in all Annex-I regions from 2010 on ('IC only') brings down global mitigation costs by more than half. For ReMIND-R and WITCH, on the other hand, the differences between the 'delay2020' and the 'EU only' scenarios are of comparable magnitude to those between the 'EU only' and the 'IC only' scenarios, respectively. This suggests that participation of both the EU as well as the US and the rest of Annex-I are important determinants of global mitigation costs. According to IMACLIM-R and WITCH early participation of China and India will also result in significant cost decreases; because of a higher degree of technological optimism that leads to lower carbon prices, this effect is less pronounced in ReMIND-R. None of the three models suggests that it is of particular importance for global mitigation costs to implement climate policies before 2020 in the rest of non-Annex-I (i.e. non-Annex-I excluding China and India)[17].

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[15] Of course, alternative political outcomes in which late movers are rewarded with laxer reduction commitments are conceivable. However, game theoretic considerations related to the formation of coalition and incentives to contribute to the provision of a global public good are clearly beyond the scope of this paper

[16] It should be noted that among the three models used in this study only ReMIND-R allows for the use of biomass in conjunction with CCS (which allows achieving negative emissions).

[17] Global mitigation costs in IMACLIM-R are in fact projected to be lower if action in the rest of non-Annex-I is delayed. This result comes from the larger consumption losses of EU, US, RAI and CHN in the scenario 'all2010' than in the scenario 'IC+CHN+IND' which over-compensate the larger gains of IND and RNAI (see

Finally, a delay of global climate policy until the year 2030 renders stabilization at 450 ppm CO_2 infeasible[18] in all models[19]. This holds even in the case of ReMIND-R, which embodies the most optimistic assumptions on flexibility and availability of low-cost carbon-free technologies. This finding can be explained by the fact that (if no future reductions are anticipated) large amounts of carbon will already have been emitted to the atmosphere up to this date and substantial additional fossil energy conversion capacities will have been put into place. Due to the long-lived nature of the capital stock in the energy sector, the world would be committed to a large amount of further CO_2 emissions after the onset of climate policy, which would make it impossible to keep atmospheric concentration below 450 ppm CO_2.

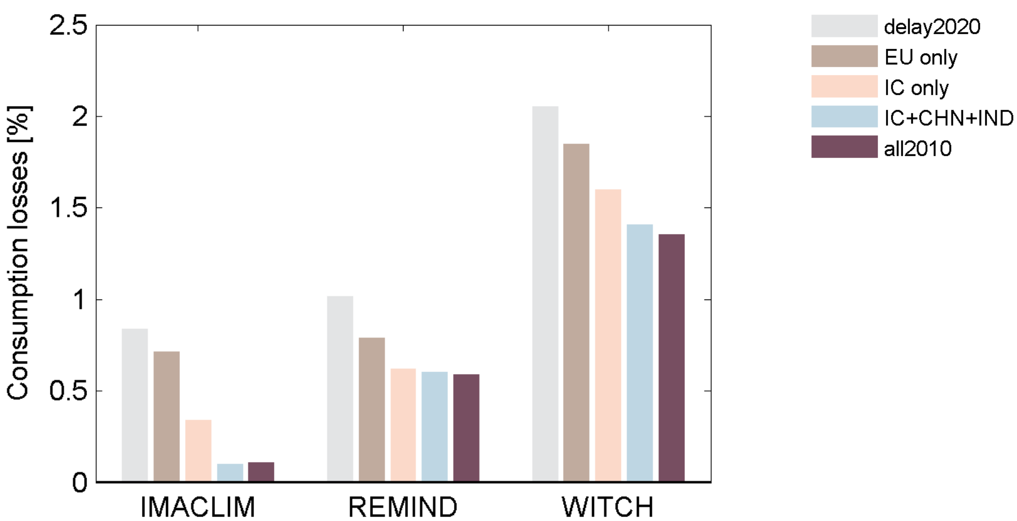

Figure 3: Global consumption losses (%) relative to the BAU scenario for the delayed participation scenarios and the 'all2010' scenario with full flexibility

3.3. Impact of Delayed Action on the Regional Cost Distribution

The changes of mitigation costs accruing to each region due to restricted spatial and temporal flexibility (compared to the 'all2010' scenario) are depicted in Figure 4. We observe the (perhaps counter-intuitive) result that in all models, unilateral adoption of an emissions cap in 2010 by the EU (i.e. scenario 'EU only') results in lower mitigation costs for the EU, compared to the 'delay2020' scenario. Remarkably, this effect holds both for the forward looking models WITCH and ReMIND-R in which the EU strongly benefits

Figure 4). These differences are explained by a higher carbon price during the period 2010-2020 due to the absence of the RNAI in the global carbon market.

[18] For the purpose of this paper, feasibility is defined as a model's ability to find a numerical solution (i.e. achieve convergence of the solution algorithm).

[19] For ReMIND-R, the only model for which the option of generating negative emissions by combining biomass with CCS (BECCS) is available, stabilization at 450 ppm CO_2 in 2100 is only feasible if the constraint on overshooting is removed. In this case, the the CO_2 concentration reaches 535 ppm in 2055 before declining. Constraining overshooting at 520 ppm CO_2 or lower makes stabilization at 450 ppm CO_2 in 2100 infeasible.

from the anticipation of future climate policy constraints as well as the recursive model IMACLIM-R, where the EU's energy system benefits from being pushed into a more efficient mode of operation early. This indicates that even if the other regions do not participate immediately there is an incentive for the EU to act, with early action decreasing mitigation costs from 2.1% to 1.2% in IMACLIM-R, from 1.5% to 0.5% in ReMIND-R, and from 1.1% to 0.8% in WITCH[20]. Similarly, mitigation costs for the US decrease if they join a climate policy regime alongside other Annex-I countries by 2010 compared to the case where only the European Union adopts limits on carbon emissions. For the US, IMACLIM-R estimates that early action decreases mitigation costs from 1.2% to a slightly negative value (i.e. net gains compared to business-as-usual); ReMIND-R indicates a drop from 1.5% to 0.8%, and WITCH from 2.2% to 1.8%.

According to IMACLIM-R and WITCH, if all Annex-I countries are committed to climate policy China will increase its welfare if it - together with India - participates in the reduction effort early on, while ReMIND-R suggests that the early and the delayed action scenarios result in very similar levels of consumption for China. As IMACLIM-R presumes suboptimal technology choices in the Chinese energy sector, a higher carbon price proves in fact beneficial in internalizing part of these non-environmental market failures and results in smaller consumption losses for China in all delay scenarios compared to the scenario with full flexibility. For India, by contrast, the effect of early participation of China and India in a global carbon market is expected to be roughly neutral. Countries with low per-capita emissions which are net-sellers of emission permits can potentially reap benefits if action in other regions is delayed because of a higher carbon price and the associated extra revenues from emissions trading. IMACLIM-R and ReMIND-R suggest that this might indeed be the case for India, as in most delay scenarios India's consumption losses are smaller than in the 'all2010' scenario. Finally, the results for the rest of non-Annex-I countries appear to contain little conclusive evidence at this level of disaggregation, an issue that will be addressed in more detail in the next section.

Hence, we conclude that for the majority of regions, even though appealing from the short term perspective, delaying action on climate policy does not turn out to decrease long run consumption losses. Even though late movers have the advantage of laxer reduction commitments regarding their cumulative emissions over the century[21], this effect is countered by increased future mitigation costs arising from the build-up of long-lived carbon-intensive infrastructure. By contrast, early action provides more leeway for adjustments of the energy system and opportunities to utilize the least expensive mitigation options (i.e. 'picking the low-hanging fruit'). As avoiding lock-in effects and faster learning in wind and solar technology (plus investments in energy R&D in WITCH) bring down costs, emission reductions beyond 2020 become less expensive. For this reason, early adoption of climate policy by a subset of regions is projected to prove beneficial by the time a global climate policy is incepted, not only for regions which can take a 'free-ride' (as they will be bound to less stringent reduction commitments later on), but even for the early adopters themselves.

[20] Short term losses and competitiveness issues associated to energy intensive sectors are compensated by medium term gains, hence these results hold as we keep a medium term horizon in evaluating losses.
[21] i.e. the additional abatement to be performed is divided between all regions and the increase of the burden for late movers is less than the abatement foregone in early years.

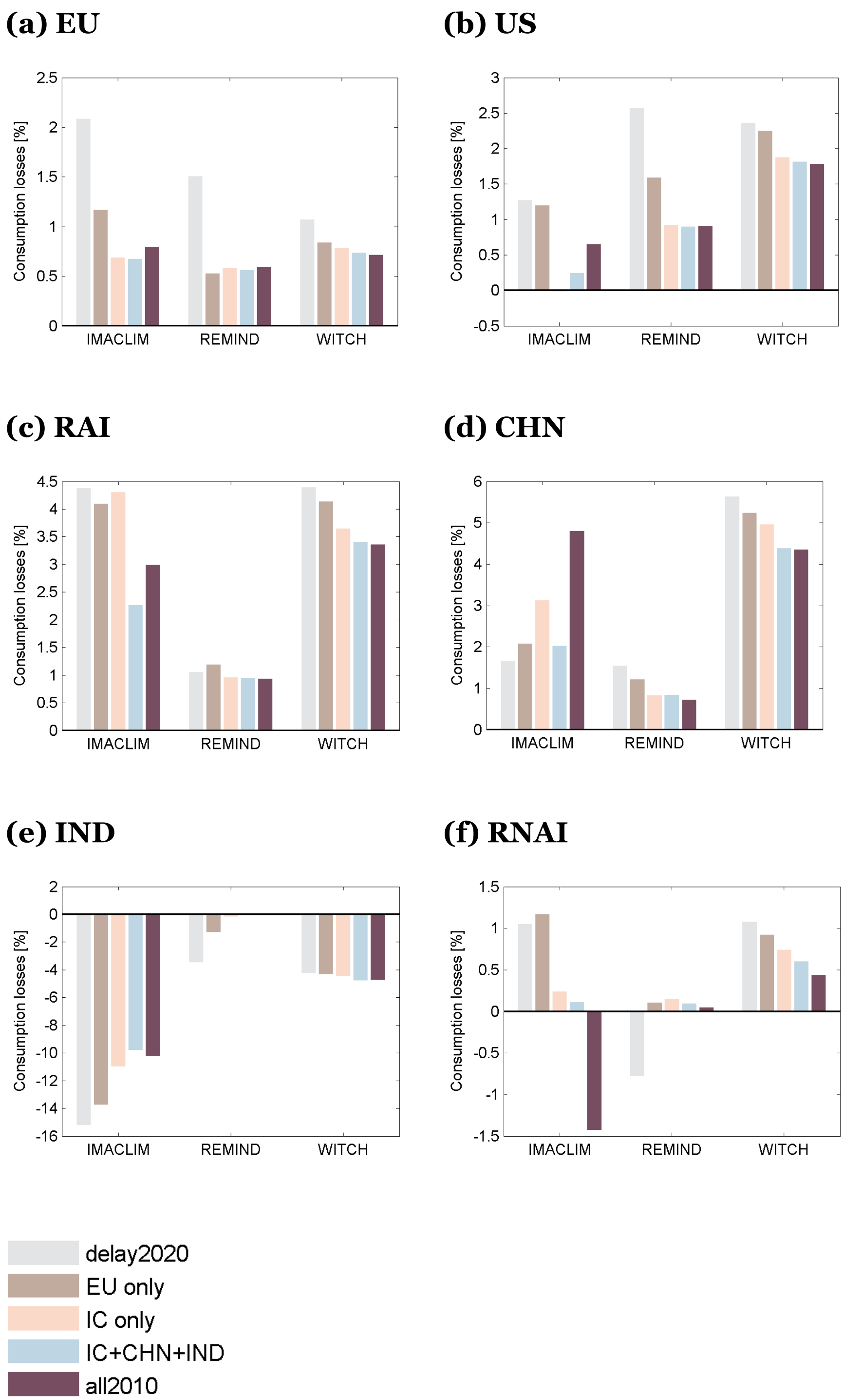

Figure 4: Consumption losses (%) for the delayed action scenarios as well as the 'all2010' scenario relative to the BAU scenario, disaggregated by world regions. Please note different scales.

3.4. Decomposing Regional Mitigation Costs

Total consumption losses for each region are determined by the costs of mitigating domestic carbon emissions minus net exports of emission permits (i.e. the carbon trade balance, defined as the net monetary value of emissions permits sales on the global carbon market). Regions that meet part of their reduction commitments by importing emission permits face a negative carbon trade balance, which raises their total consumption losses beyond the costs incurred for domestic abatement. To gain a deeper understanding with regard to the effects of delayed action, we decompose changes in regional consumption losses into changes of domestic mitigation costs and changes of the carbon trade balance relative to the 'all2010' scenario (see also Luderer et al., 2011b):

$$NPV(CL_i^{delay} - CL_i^{all2010}) = NPV(DMC_i^{delay} - DMC_i^{all2010}) - NPV(CTB_i^{delay} - CTB_i^{all2010}) \quad \text{(Eq. 1)}$$

NPV: net present value

CL_i^{delay}, $CL_i^{all2010}$: consumption losses for region i for the delay and the 'all2010' scenarios, respectively

$DMC_i^{delay}, DMC_i^{all2010}$: domestic mitigation costs for region i for the delay and the 'all2010' scenarios, respectively

$CTB_i^{delay}, CTB_i^{all2010}$: carbon trade balance for region i and period t for the delay and the 'all2010' scenarios, respectively

This decomposition (Figure 5) reveals that the break-down of additional consumption losses caused by delayed climate policy varies between models and world regions. In all models the EU and the US are net importers and India and the rest of the non-Annex-I countries net exporters of allowances in all scenarios, with ambiguous outcomes for China and the rest of Annex-I. For WITCH differences in total consumption losses can to a large part be attributed to changes in domestic mitigation costs, while carbon trading plays a less important role. For IMACLIM-R and ReMIND-R, however, the domestic mitigation cost effect and the carbon trade balance effect are of comparable magnitudes. For the EU and the US, both these models project that delaying action will result in significant extra spending on imports of allowances (caused by more imports and/or higher global carbon prices) and a widening deficit of the carbon trade balance accounts for most of the increase in total consumption losses.

The decomposition also confirms our earlier conjecture that delayed action can have ambiguous effects for net exporters of emission permits (especially India and the rest of non-Annex-I): on the one hand, domestic mitigation costs can increase due to lock-in of carbon-intensive energy infrastructure, on the other hand, due to a higher global carbon price, revenues from selling emission permits are likely to rise as well. This interaction of two effects helps to understand (a) why for IMACLIM-R and ReMIND-R delayed action lowers consumption losses for India (and the rest of non-Annex-I in some scenarios) which is a large exporter of emission permits, whereas for WITCH (where the carbon trade balance is less affected by a delay), additional revenues from exporting allowances are insufficient to offset increases in domestic mitigation costs, and (b) the ambiguous results for rest of non-Annex-I countries mentioned above.

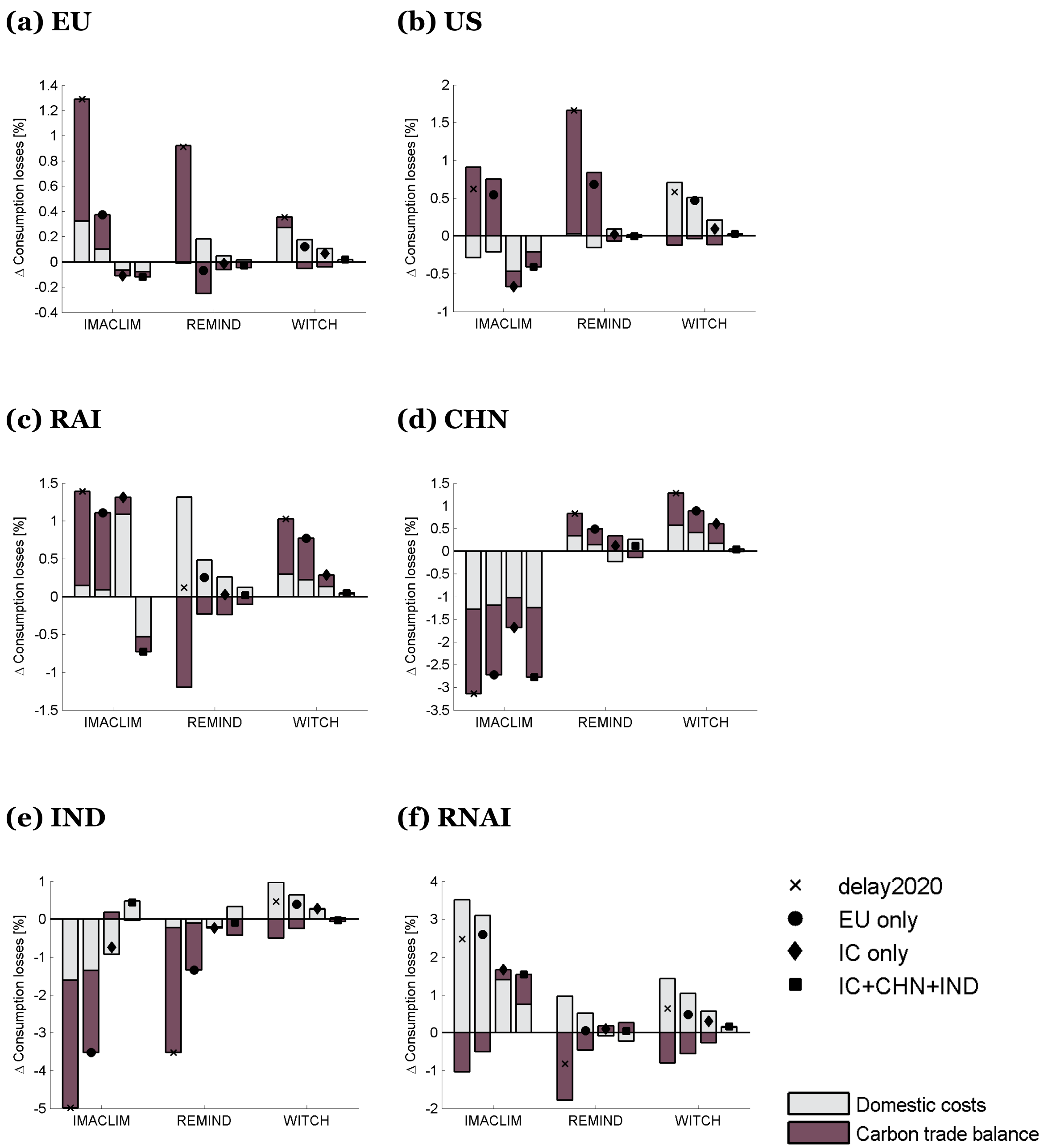

Figure 5: Differences in consumption losses (%) between the delayed action scenarios and the 'all2010' scenario by world regions, disaggregated into changes in domestic mitigation costs and changes in the carbon trade balance. Please note different scales.

3.5. Understanding the Benefits of Early Action

For some regions (including the EU and the US, if it acts within a coalition of all Annex-I countries) early action can result in lower consumption losses in the long run. Compared to the delay scenario, early action implies additional costs to abate carbon emissions prior to 2020. However, these find their correspondence in lower consumption losses in later periods due to three reasons (see Figure 6): first, as lock-in in carbon intensive infrastructures can be avoided by early action, marginal abatement costs are lower after 2020 (shifting MAC to MAC'). Second, abatement in early periods reduces the mitigation burden in later periods (such that D shifts left to D'). However, this reduction in the individual mitigation burden is only a fraction of the abatement undertaken as an early mover prior to 2020, as the reduced commitment at later periods is divided between all countries according to the burden sharing rule (i.e. early effort has the character of a public good). Third, early action implies less global abatement in later periods, which in combination with less costly mitigation options in the early moving regions results in a lower global carbon price (P_w shifts down to P_w') compared to the delayed action scenario. For net importers of emission permits all three effects contribute to lower consumption losses, which decrease from area ABCD to area A'B'C'D'[22]. The level of domestic abatement (E and E', respectively) and imports of allowances (D-E and D'-E', respectively) can, however, go either way (the numerical results indicate that for our model setup early action consistently leads to more domestic abatement and reduces the import of emission permits).

(a) pre-2020 **(b) post-2020**

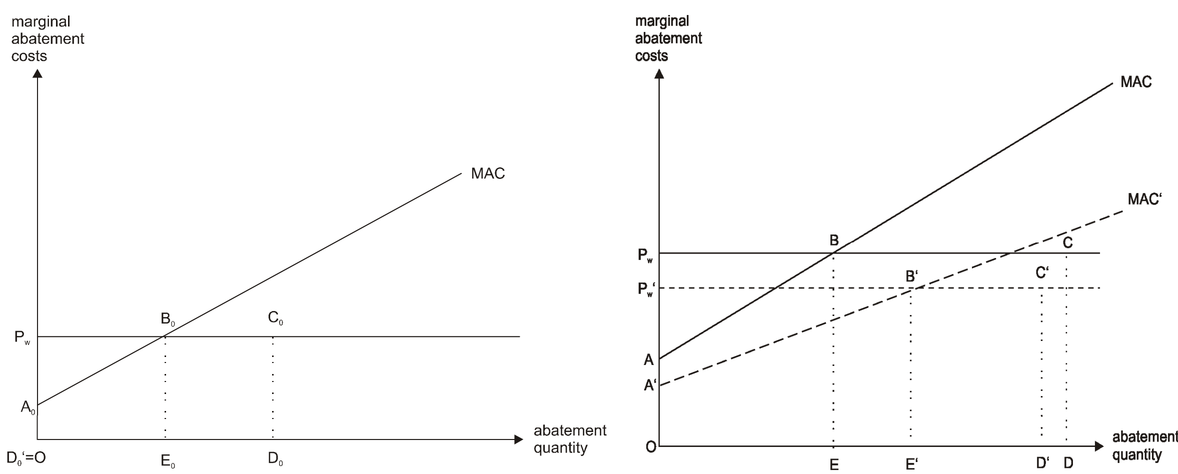

Figure 6: Compared to delayed action, early action increases consumption losses in the pre-2020 period by the area $A_0B_0C_0D_0$ (panel a), but decreases consumption losses in the post-2020 period from area ABCD to A'B'C'D' (panel b). Cost savings post-2020 are realized by reductions in (i) marginal abatement costs, (ii) the total quantity of emissions to be abated over the period, and (iii) the global carbon price

[22] For net exporters, the overall effect is ambiguous, as the first two effects have a positive welfare effect while the impacts of a lower global carbon price is negative

To discern the impacts of the individual effects discussed above on changes of consumption losses between the early action 'all2010' and the respective delay scenario, we separately apply the following (complete) decomposition to the pre-2020 as well as the post-2020 period:

$$
\begin{aligned}
&NPV(\Delta CL_i) = NPV(\Delta DMC_i) - NPV(\Delta CTB_i) = \\
&NPV(\Delta DMC_i) + NPV\left\{p_w^{early} \cdot (D_i^{early} - E_i^{early}) - p_w^{delay} \cdot (D_i^{delay} - E_i^{delay})\right\} = \\
&NPV(\Delta DMC_i) + NPV\left\{\Delta p_w \cdot (D_i^{early} - E_i^{early}) + p_w^{early} \cdot \Delta(D_i - E_i) + \Delta p_w \cdot \Delta(D_i - E_i)\right\} = \qquad \text{(Eq. 2)} \\
&\underbrace{NPV(\Delta DMC_i)}_{(1)} + \underbrace{NPV\left\{\Delta p_w \cdot [(D_i^{early} - E_i^{early}) - \frac{1}{2}\Delta(D_i - E_i)]\right\}}_{(2)} \\
&\underbrace{+ NPV\left\{\Delta(D_i - E_i) \cdot [p_w^{early} - \frac{1}{2}\Delta p_w]\right\}}_{(3)}
\end{aligned}
$$

Here, Δ denotes the difference between the respective early action and the 'delay2020' scenario, p_w the carbon price in those regions that undertake climate policy, D the commitment to reduce emissions, and E domestic abatement (i.e. the difference between BAU and actual domestic emissions). Consequently, (1) is the change in costs for abatement that is performed domestically, (2) the change in the carbon trade balance that can be attributed to the different carbon prices, and (3) the change in the carbon trade balance due to a different quantity of traded permits.

Figure 7 displays the differences in consumption losses between the respective early action scenario for the EU and the US (i.e. 'EU only' for the EU, and 'IC only' for the US) and the 'delay2020' scenario. For all three models, the numerical results confirm that consumption losses are higher during the pre-2020 period in the early action scenario compared to the 'delay2020' scenario, but these expenses are more than compensated by cost savings in the years after 2020, such that early action turns out to be unambiguously beneficial over the period 2005-2100.

Due to high initial carbon prices necessary to shift the energy system away from its carbon-intensive trajectory, IMACLIM-R calculates a net present value of additional consumption losses of about 0.5% for the EU as well as the US in the period up to 2020, but cost savings in the post-2020 period of about 2% of domestic consumption for the EU and 2.8% for the US. The later periods witness significantly lower domestic mitigation costs as well as decreased spending on imported emissions permits. For the EU, the lower volume of permit imports is the main effect responsible for a more favorable carbon trade balance, whilst for the US the effects of reduced quantities of imported permits and of lower carbon prices are of similar magnitude. For ReMIND, the additional costs (in terms of consumption) of early action are 0.3% for the EU and 0.2% for the US; for the EU (which as a single first mover has no possibility to engage in carbon trading) these costs of early action are exclusively and for the US to the largest part determined by the costs of domestic abatement. For both regions, post-2020 domestic mitigation costs in the early action scenario hardly differ from the 'delay2020' scenario, but the costs associated to imports of emissions permits decline by 1.4% for the EU and 2% for the US, indicating a shift in abatement strategies in which imports of emission permits are substituted by domestic abatement. As for IMACLIM-R, the quantity effect dominates for the EU, while for the US, the price effect is of comparable magnitude to the quantity effect (which seems quite intuitive, considering that early action by all Annex-I countries in the 'IC only' scenario can very likely be expected to decrease the price of carbon). In WITCH, where carbon trading plays a less important role, the costs and benefits of early action are mainly determined by differences in the costs of performing domestic abatement, and to a lesser extent by the amount of permits traded. For Europe, early action thus results in additional consumption losses of roughly 0.1% in the pre-2020 period but decreases mitigation costs over the century by about 0.4%; for the US the corresponding figures are 0.1% and 0.7%, respectively.

(a) EU **(b) US**

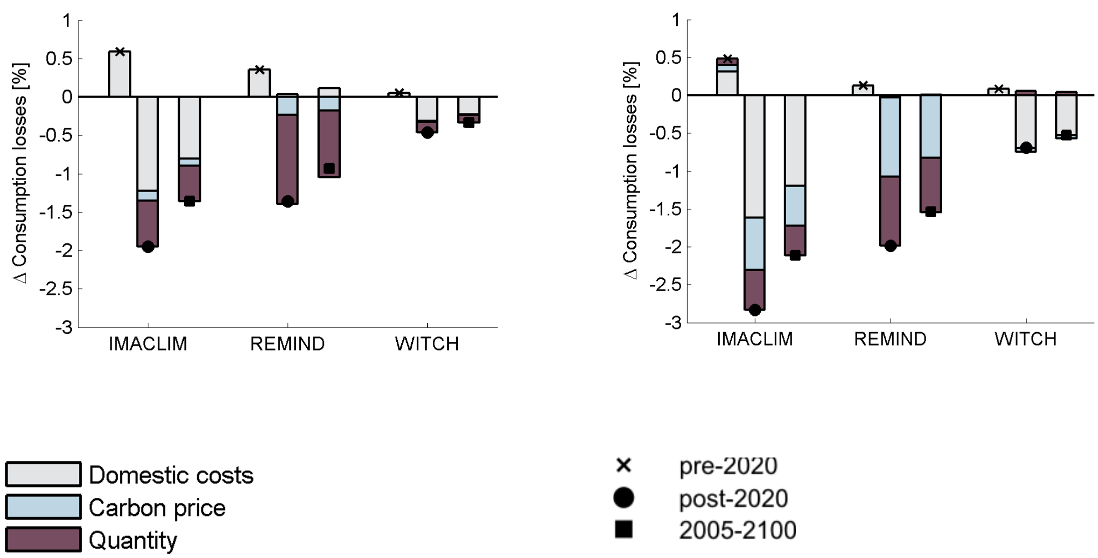

Figure 7: Differences in consumption losses (%) between early action scenarios (i.e. 'EU only' (a) for the EU and 'IC only' (b) for the US) and the 'delay2020' scenario for the periods pre-2020, post-2020, and 2005-2100. Cost differences are due to (1) changes in domestic mitigation costs, (2) different carbon prices, and (3) different quantities of traded permits

The result that early action reduces consumption losses implies that the benefits of undergoing a smoother transition of the energy system and preventing lock-in effects exceed the costs related to the increased cumulative mitigation burden borne by early movers. As early action involves additional costs in the short run which are counterbalanced by cost savings in the long run, the discount rate (which is used to make costs that occur in different points in time comparable by converting them to net present values) is a crucial factor in determining whether early action turns out to be beneficial.

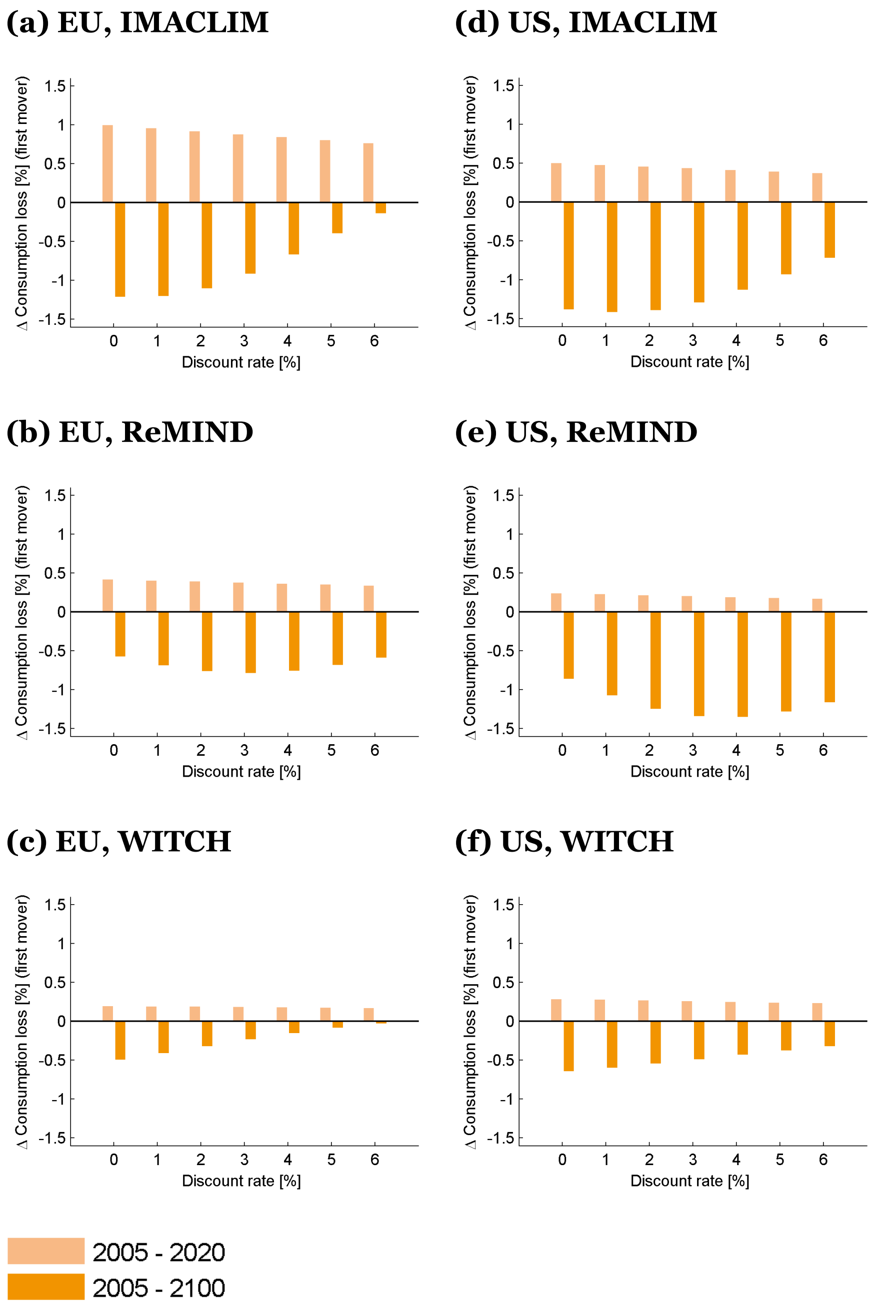

Figure 8: Differences in consumption losses (%) between the respective early action scenario and the 'delay2020' scenario for the EU (a-c) and the US (d-f) in the short-term (2005-20) and the long-term (2005-2100), applying discount rates ranging from 0 to 6%

Figure 8 shows differences between the respective early action scenario and the 'delay2020' scenario as a function of the discount rate for the periods 2005-2020 (light bars) and 2005-2100 (dark bars). It confirms the conclusion that early action entails considerably lower consumption losses for the EU and the US across a wide range of discount rates, ranging from 0 to 6%. The total net benefits of early action (as a percentage of total consumption) can be regarded as a weighted average of avoided consumption losses in all periods, with higher discount rates putting less weight on cost savings that materialize in the farther future. Therefore, net benefits strictly decrease with a higher discount rate for WITCH, as for this model a large part of cost savings materialize in later periods. For IMACLIM-R and ReMIND-R, in turn, the largest cost savings take place in the first half of the century and cumulated net benefits only start decreasing with higher discount rates after the latter exceeds a certain level, resulting in a slightly hump-shaped relationship between the discount rate and the benefit of early action.

4. Concluding Remarks

This paper compares the results of three state-of-the-art climate-energy-economy models in order to analyze the economic implications of delaying climate policies in certain world regions. Our results indicate that globally, reducing 'where' and 'when' flexibility significantly raises the costs of achieving stabilization of atmospheric concentration at 450 ppm CO_2-only: postponing a global agreement to 2020 raises global mitigation costs by at least about half and a delay to 2030 renders ambitious climate targets infeasible to achieve. With a larger number of key players participating in global mitigation efforts by 2010, global costs of stabilization decrease markedly and we find that the participation of the Annex-I countries as well as China and India is particularly relevant if large increases in mitigation costs are to be avoided.

For each region the effect of delayed action on mitigation costs is determined by the change in required emission reductions under the respective burden sharing scheme as well as differences in energy system developments and global carbon prices between scenarios. Assuming convergence of per-capita emissions in 2050, regions in which climate measures are implemented with a delay have to commit to smaller reductions of cumulative emission and hence bear a lower share of global mitigation costs. However, lock-in into carbon-intensive energy infrastructures can work in the opposite direction and increase mitigation costs by restricting the availability of low-cost options to abate carbon emissions. Reduced spatial and temporal flexibility raises the global carbon price and thus results in further consumption losses for regions which are net-importers of emission permits, but softens the adverse effects (and can even lead to net gains) for regions which are net-exporters of permits.

An important result is that regions with above average per-capita emissions, such as the EU and the US alongside the rest of Annex-I countries, can lower their mitigation costs by taking early action, even if mitigation efforts in the rest of the world experience a delay. For regions with low per-capita emissions which are net sellers of emission permits (such as India) we find that delayed mitigation efforts in other regions can be desirable, as they derive higher incomes from the sale of emission permits, stemming from the higher carbon prices implied by restricted spatial and temporal flexibility. Finally, decomposing the consumption losses for the EU and the US confirms the intuition that early action involves additional costs in early periods, but significant cost savings in later years. A sensitivity analysis shows that the finding that early action reduces consumption losses is robust over a wide range of discount rates.

It should be noted that the results crucially hinge on the assumption that (i) a universal climate agreement will eventually enter into force in 2020 and that (ii) regions' relative shares in global emissions remain unchanged compared to the default C&C scenario. Yet, several authors have shown that if a global climate agreement is expected in the future, delaying action can influence strategic decisions and provide incentives to invest less in abatement technologies to increase their future bargaining position (Harstad 2009; Beccherle and Tirole 2010). We thus expect that developing a richer set of scenarios motivated by game-theoretic considerations will be one of the major challenges for future studies on delayed action.

We conclude that taking early action is crucial for stabilizing atmospheric GHG concentrations at 450 ppm CO_2-only in a cost-efficient manner. The results of this paper suggest that if this stabilization target will be universally agreed upon in the future, early action on climate change constitutes a no-regret option for Annex-I countries, independent of the current state of climate policy in other parts of the world. If global action, however, is delayed for another decade, the above target can only be attained at significant additional costs, decreasing its political acceptability while increasing the likelihood that policy makers will favor a less ambitious climate agreement instead, including the related adverse environmental impacts.

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Chapter 5

Linking of Emissions Trading Systems and Carbon Leakage[*]

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Linking Carbon Markets: A Trade-Theory Analysis

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Abstract

Linking emission trading systems (ETS) is a widely discussed policy option for the time after the Kyoto Protocol's obligations end in 2012. Benefits are expected from efficiency gains and the alleviation of concerns over competitiveness. However, from trade-theory it is known that due to general equilibrium effects and market distortions, linking may not always be beneficial for all participating countries. Following-up on this debate, we use a Ricardo-Viner two-sector general equilibrium model of two countries to study the impacts of *sectoral* linking on carbon leakage, competitiveness, and welfare. By comparing pre- and post-linking equilibria, we show analytically how leakage can arise if one of the countries lacks a comprehensive cap on total emissions, although in case of a link across idiosyncratic sectors also anti-leakage is possible. If–as a way to address concerns about competitiveness–a link between the EU ETS and a hypothetical US system is established, the partial emission coverage of the EU ETS can lead to the creation of new distortions between the non-covered domestic and international sector. Finally, we show how the welfare effects from linking can be decomposed into gains-from-trade and terms-of-trade contributions, and how the latter can lead to an overall ambiguous welfare effect.

Keywords: Emission Trading, Linking, Trade Theory, Leakage, Competitiveness

1. *Introduction*

In view of the expiry in 2012 of the Kyoto Protocol's reduction obligations, the bottom-up linking of existing and independent emission trading systems (ETS) has become a widely discussed policy option (Buchner and Carraro 2007, Flachsland et al. 2009a, b). For example, the creation of an OECD-wide carbon market that in some way becomes linked to developing countries is now a central pillar of the European Union's climate strategy (EU Commission 2009), in line with various legislative cap-and-trade initiatives in the United States and Australia that have signaled a strong willingness to link their systems (Tuerk et al. 2009).[1] In fact, after COP-15 in Copenhagen did not yield a legally binding multilateral agreement, this approach appears ever more relevant (Stavins 2009).

The merits of international emission trading are well-understood and include efficiency-gains (e.g. Tietenberg 2006), but also the alleviation of competitiveness concerns through the elimination of carbon price differentials and access to cheap abatement options in developing countries (e.g. Alexeeva-Talebi et al. 2008). Some observers, however, have cautioned that in the presence of market distortions and general-equilibrium price effects, the linking of regional emission trading systems may not always be beneficial (Babiker et al. 2004; Anger 2008), and, in addition, might facilitate undesirable international spillovers of shocks in permit markets (McKibbin et al. 2008).[2]

The present contribution follows up on this debate and employs an analytic Ricardo-Viner two-country, two-sector general equilibrium model with international trade in goods and fossil-fuel resources to study the impacts of sectoral linking on emission leakage, competitiveness, and welfare. The scenarios under investigation are designed to mimic the most important strategic options for permit market links between some of the major players in international climate policy, namely Europe, United States and China.

The EU has specified a comprehensive climate policy package for the time up to 2020, featuring *inter alia* an economy wide emission reduction target to be implemented on one hand by means of the EU ETS–which covers around 40% of European GHG emissions–and on the other hand by various policies and measures aimed at the remaining sectors (European Union 2009a, b). One focus of our analysis is on the potentially adverse impacts such a segmented policy approach may entail. In contrast, if the United States were to implement a climate policy package along the lines of the Waxman-Markey draft, its economy-wide cap-and-trade system would cover about 85% of US greenhouse gas emissions (Larsen and Heilmayr 2009). For China we analyze scenarios representing the implementation of a scaled-up Clean Development Mechanism or sectoral trading scheme (EU Commission 2009, Schneider and Cames 2009), but we also take into account the possible simultaneous presence of an economy-wide intensity target.[3]

By comparing the pre- and post-linking equilibria between two countries, we find that global emissions can rise if one of the 'linked' countries lacks a comprehensive cap on its total emissions. In this case, an increased uptake of fossil fuel resources in the non-capped

[1] OECD regions preparing the implementation of cap-and-trade systems include the United States, Australia, Japan, South Korea, California as well as individual US States and Canadian Provinces organized in the Western Climate Initiative (WCI) or Midwestern Greenhouse Gas Reduction Accord.
[2] For a review of merits and demerits of linking cap-and-trade systems, see, e.g., Flachsland et al. (2009b).
[3] Prior to the COP-15 meeting at Copenhagen, China announced its intention to reduce the carbon intensity of its economy by 40-45% by from 2005 to 2020.

sector–what we will call linking-induced leakage or simply leakage in short– would be observed.[4] However, whether or not this type of leakage actually occurs turns out to depend on which industries are linked in the joint permit market: if their respective output goods are imperfect substitutes, leakage does not occur or may even become negative (what we will denote as anti-leakage). As an extension of this analysis, one mechanism that is shown to be ineffective as a means to prevent leakage is an economy-wide intensity target, which has been suggested as a politically more feasible option than an absolute cap, at least for developing countries.

If the EU ETS was to establish a link with a hypothetical US system, leakage would not be an issue. But besides gains-from-trade, a major driver for implementing such a policy option would be to address concerns about competitiveness, i.e. the idea of harmonizing permit prices in order to 'level the carbon playing-field'[5]. However, our results indicate that due to the EU ETS' partial coverage of total EU emissions, this can only be achieved to a limited extent. As will be shown, under such circumstances linking can create (or increase) a distortion both between the EU's own sectors as well as between the EU's non-ETS sector and its US counterpart.

Finally, our analysis provides an explicit representation of the welfare effects of linking in a general-equilibrium setting. Namely, the overall effect is decomposed into an always positive gains-from-trade and a terms-of-trade effect. Because the sign of the latter depends on which good a country exports, the net effect turns out to be ambiguous.

The remainder of this article is organized as follows: The next section reviews the relevant literature. Section 3 sets out our model. Results are derived and discussed in Section 4 and–for the special case in which one good becomes non-traded–in Section 5. The article ends with its final conclusions in Section 6.

2. Literature Review

Studies on linking regional emissions trading systems can roughly be categorized into three strands: (i) qualitative-institutional studies, (ii) game-theoretic approaches, and (iii) numerical partial and general equilibrium analyses.

The first category contains a number of studies which have investigated the institutional aspects involved in the linking of regional cap-and-trade systems, focusing on system design compatibility as well as qualitative economic and political impacts (e.g. Sterk et al. 2006, Tuerk et al. 2009, Flachsland et al. 2009a,b). They mainly provide detailed analyses of proposals for new cap-and-trade systems, identify needs for harmonization of system design features, or compare different institutional arrangements for the governance of joint carbon markets. However, due to the nature of these studies, the scope for economic analysis remains rather limited.

[4] In its original meaning, leakage denotes the increase in emissions elsewhere in response to a tighter emissions policy at home. This is, strictly speaking, not what happens in our case, in which the home country does not change its level of emissons, but only links its emissions trading system to that of another country. However, because it aptly conveyes the idea of an unintended emissions increase outside the regulated system, we still chose to employ the term in the present context.
[5] A term apparently coined in Houser (2008).

The second strand of more game-theoretic research focuses on strategic interactions between countries that unilaterally implement domestic trading systems and consider linking, i.e. international emissions trading, as a policy option. Helm (2003) provides evidence that in such a case the anticipation of linking creates an incentive for low-damage countries to relax their cap in order to benefit from increased permit sales. Rehdanz and Tol (2005) discuss suitable instruments, in particular import quotas, which enable buyers to contain such inflationary tendencies on the sellers' side. Carbone et al. (2009) employ a computable general equilibrium (CGE) framework with international trade in goods, resources, and permits, and allow countries to anticipate the impact of their quota allocation decision. Their key finding is to identify the possibility of oligopolistic behaviour, i.e. the incentive of net permit sellers to raise permit prices by increasing the stringency of their cap may actually outweigh their incentive to relax the cap, especially in the presence of additional positive effects on world resource markets.

Finally, with a focus on the internal dynamics of the EU ETS, Dijkstra et al. (2008) as well as Böhringer and Rosendahl (2009) analyze the partition between ETS and non-ETS sectors as a strategic game of EU countries against each other, constrained by the fixed EU ETS total emission cap. While the former specify the conditions for welfare gains and losses when additional trading sectors enter the system, the latter pursue an empirical analysis and find evidence for a strong role of political economy forces.

Partial equilibrium analyses of permit markets using regionally and sectorally specified marginal abatement cost (MAC) curves allow studying the impact of carbon market linkages on allowance prices and regional abatement cost (Anger 2008, Anger et al. 2009, Stankeviciute et al. 2008, Russ et al. 2009). One main conclusion to draw from partial market modeling is that unless linking is assumed to be accompanied by the introduction of severe market distortions, it will be welfare enhancing for all countries due to the standard gains-from-trade effect (Anger 2008, Anger et al. 2009). Linking cap-and-trade systems to the CDM offers particularly high efficiency gains due to the expected large supply of low cost abatement options in developing countries. However, by definition these models ignore the general equilibrium effects of permit trade, e.g. a loss of competitiveness or carbon leakage occuring due to changes in relative prices.

To capture such effects in the context of climate policy, several computable general equilibrium (CGE) models were developed and first applied to assess the economic implications of the Kyoto Protocol (e.g. Bernstein et al. 1999, McKibbin et al. 1999) and, more recently, the impacts of bi- and plurilateral linking. For example, Babiker et al. (2004) and Paltsev et al. (2007) show that an increase in the domestic price of carbon after joining international emissions trading can reinforce pre-existing distortions associated with inefficiently high fuel taxes – up to the point where the corresponding welfare losses outweigh the primary gains in efficiency from emissions trade. Most closely related to our work–in terms of the issues addressed–is Alexeeva-Talebi and Anger (2007) and Alexeeva-Talebi et al. (2008): the first study finds that whenever linking the EU ETS to another country's system leads to an inefficient emission allocation between ETS and non-ETS sectors in the latter (assuming perfectly efficient policies in the no-linking case), the link is welfare decreasing for the EU partner country and has hardly any impact on EU welfare. The subsequent study is more focused on the competitiveness impacts on the EU economy from unilateral climate policy, and finds them to be largely negligible if the EU ETS establishes a link with the CDM market, due to the significantly reduced allowance price. However, because of the numerical character of CGEs, such analyses can only provide limited insights on the underlying mechanisms at work, which is the main scope of our contribution.

Thus, our study aims to complement previous contributions by its analytical general equilibrium formulation of a trade-theory model. This allows for a theoretical investigation into the economic and environmental impacts of linking carbon markets, taking into account the interplay of permit trade and trade in sectorally differentiated goods and fossil fuel resources. In that sense, our adoption of a trade-theory point of view is similar to the work of Copeland and Taylor (2005), although–differently from us–they focused on the strategic effects of trade in a model with endogenous emissions choice.

3. *Model Definition and Country Specification*

Model definition

We consider an extended Ricardo-Viner model with two countries, home *h* and foreign *f* (index *i*), as main protagonists, and an additional country *s* as supplier of fossil fuel resources *R*, which are an essential input factor for production in both *h* and *f*.

Each country's economy is composed of two sectors, producing goods *X* and *Y* (index *j*).[6] The corresponding constant-returns-to-scale technologies, *F* and *G*, use fossil fuel resources and other inputs for production. However, while the fossil fuel resource is assumed to be perfectly mobile across sectors, other inputs are taken to be sector specific and hence immobile, at least in the short-run. Thus, we adopt the short- to midterm point of view of the Ricardo-Viner (or specific factor) model (Mayer 1974, Neary 1978). This approach has the merit of avoiding the tendency towards full specialization that arises in a Heckscher-Ohlin model when factors become traded (Markusen 1983).

Emissions are assumed to be identical to the amount of fossil fuel resources employed in production; the two terms are therefore used interchangeably throughout this article. For given technologies, and sectorally fixed levels of human capital and other input factors, the formal structure of the model can be specified as:

(1) $$X^i = F^i(R_X^i) \qquad\qquad Y^i = G^i(R_Y^i) \quad ,$$

with strictly concave functions F^i and G^i (declining factor returns), and $R_X^i + R_Y^i = R^i$ capturing the sectoral allocation of resource inputs in country *i*. In view of the symmetry of the problem, we choose the resource price as the numeraire, and p_x and p_y as the price of good *X* and *Y*, respectively.[7] Firms in each country maximize profits and hence satisfy the usual first-order conditions for the marginal product of the resource input

(2) $$1 = p_x\, F_R^i(R_X^i) = p_y\, G_R^i(R_Y^i)$$

where the subscript *R* is used to denote the derivative with respect to *R*, i.e. the marginal product. Inverting the latter allows obtaining the resource demand function of country *i*:

[6] The resource supplier's production of *X* and *Y* is supposed to be negligibly small throughout the paper.
[7] Admittedly, this is a somewhat unusual choice, but it turns out to actually improve the clarity of results.

$$R^i = F_R^{i\,inv}(p_x) + G_R^{i\,inv}(p_y) \tag{3}$$

In line with the short-run character of this analysis, we ignore potential changes in the environmental damage level resulting from variations in the amount of fossil fuel combustion (i.e. emissions).[8] That is, in this model consumer preferences U are functions only of the realized consumption bundle and are assumed to be homothetic, linearly homogeneous, and to be the same in all countries. Thus, taken prices as given, all consumers spend the same fraction η of their income I^i on good X and $1-\eta \equiv \tilde{\eta}$ for consumption of good Y, where η depends only on the parameters of the preference function and the relative price between goods, which for convenience we denote in shorthand by $p_{x/y} \equiv p_x / p_y$. Demand for good X and Y in country i is thus given by, respectively, $\eta(p_{x/y}) I^i / p_x$ and $\tilde{\eta}(p_{x/y}) I^i / p_y$. Using the indirect utility function, the attained level of welfare can be written in terms of real income as

$$W^i = U\left[\frac{I^i}{\phi(p_x, p_y)}\right] \tag{4}$$

where ϕ is the price index function for one unit of utility. Finally, we assume that the resource supply side can be characterized by a conventional supply function S

$$R = S[\phi(p_x, p_y)] \quad , \tag{5}$$

that is strictly decreasing in ϕ.[9] Since R is taken as the numeraire, its nominal price remains constant. Supply, however, is determined by its real price, i.e. the nominal price divided by the price index ϕ. As rising goods prices decrease the real price of R, its supply is negatively related to p_x and p_y. Formally, such a functional form can be derived by assuming that in the resource supplying country goods X and Y are necessary inputs for the extraction of R, i.e. a production function $R=H[Z(X^s,Y^s)]$, where Z stands for a function with constant elasticity of substitution and H for an increasing, strictly concave function.[10] For given prices p_x and p_y the dual function of Z, say $Z^{dual}[p_x,p_y]$, then corresponds to the minimum costs for increasing Z by one unit. Consequently, one can express the net income of country s as $R\text{-}H^{inv}[R]*Z^{dual}$, which implies that the optimal supply of R is determined by the first-order condition $1= Z^{dual}\ d/dR\ H^{inv}[R]$. Solving this for R and setting $Z^{dual}[p_x,p_y] = \phi[p_x,p_y]$ leads to the functional form of Eq.(5).[11]

To summarize, in this model, a global competitive equilibrium is defined by prices p_x and p_y such that (i) firms maximize profits, i.e. Eq.(2) is satisfied in both countries, (ii) consumers maximize utility, i.e. their demand is determined by $\eta(p_{x/y})$, (iii) each country's

[8] Climate change is a stock pollutant problem with a significant delay between emissions and damages.
[9] We sometimes use the brackets [..] to emphasize the argument of a function.
[10] Such a 'reciprocal' formulation is common in CGE modeling.
[11] We thank Gabriel Felbermayr for suggesting this derivation. Alternatively, one may assume that the resource supplier's welfare depends on utility from consumption, but is also negatively affected by resource extraction – either because of disutility from supplying labor, or because if R is not extracted now, it can be sold in the future. If the two components are additively separable, the supplier's welfare can be written using the indirect utility function for the first component) as $W^s=R/\phi\text{-}D(R)$, with $D'<0$, implying for the optimal supply $1/\phi=D'(R)$ and hence $R=D'^{inv}[1/\phi]$, as in Eq.(5).

income I^i equals its GDP, i.e.

(6) $$I^i = p_x X^i + p_x Y^i - R^i \quad ,$$

(iv) world markets for goods clear, i.e. (here shown only for X)

(7) $$\frac{\eta(p_{x/y})}{p_x}\left(I^h + I^f + I^s\right) = X^h + X^f \quad ,$$

and, finally, (v) the resource market clears, i.e.

(8) $$S\left[\phi(p_x, p_y)\right] = R^h(p_x, p_y) + R^f(p_x, p_y) \ .$$

Any trade equilibrium will comprise flows of resource R from s to h and f, and flows of goods X and Y towards s, as well as–possibly–an exchange of Y and X between h and f. For example, the production functions of h and f could be strongly asymmetric, such that h produces almost only good X, and f almost only good Y. In this case both countries would trade with the resource supplier but also with each other. On the other side, if h and f are perfectly symmetric, they will still trade with the resource supplier but not with each other. In other words, the home and foreign country will always be net exporters of either Y or X, or of both. Note that the latter case would not be possible in a conventional Ricardo-Viner (or specific factors) model, where the mobile factor is not traded but part of the countries' endowment. Trade will then occur only in the form of an exchange of Y against X-goods between the two countries.[12]

Country specification

The model has the aim to provide a stylized representation of the climate policies of the United States, Europe, and China. For the case of the United States we assume the adoption of the Waxman-Markey Bill as described in Larsen and Heilmayr (2009). Europe has already adopted a comprehensive climate policy package (European Union 2009a, 2009b), and China is assumed to implement a scaled-up CDM or sector-based trading mechanism (EU Commission 2009), possibly on top of its currently proposed economy-wide intensity-target.

The Waxman-Markey cap-and-trade system would cover 85% of US greenhouse gas emissions and is therefore modeled as an economy-wide cap-and-trade system with an

[12] A formally very similar model to ours is employed by Eichner and Pethig (forthcoming) to study the so-called Green Paradox (Sinn 2008). It also features two commodity-producing countries and one resource supplier. Moreover, although presented as a dynamic two-period model, it is possible to reinterpret the two periods as two sectors in a static model. In fact, in formal terms the two models only differ in the resource supply function, which–differently from us–they assume to be perfectly inelastic, i.e. there may be shifts between sectors/periods, but the total amount of supplied fossil fuel (or emissions) always remains the same. They also investigate a different question, namely the reaction of the foreign country–assumed to have no emissions constraint at all–to a tightening of the emissions cap of the home country in the first or second sector/period. The effects of emissions trading are not discussed at all. We thank the editor, Sjak Smulders, for calling our attention to this publication.

upper bound $\overline{R}^h$ on national emissions.[13] As a consequence, this policy always leads to an efficient domestic sectoral burden sharing of the abatement effort, which in formal terms means that in both sectors the same gap arises between the value of the marginal product and the (normalized) world price of the resource:

$$(9) \qquad p_x\, F_R^h(R_X^h) = p_y\, G_R^h(\overline{R}^h - R_X^h) > 1$$

Due to the policy-prescribed limit on national resource intake, the market clearing condition for the global resource market from Eq.(8) simplifies to

$$(10) \qquad S\left[\phi(p_x, p_y)\right] = \overline{R}^h + R^f(p_x, p_y)$$

In Europe, the EU ETS encompasses only 40% of all GHG emissions.[14] To model this case of a far more limited coverage of the trading system, we assume one sector, say X, to be the cap-and-trade sector with a given upper limit $\overline{R}_X^h$ on the resource intake, while the other sector, Y, is regulated by an adjustable command-and-control policy or resource tax τ_y.[15] Constraining the production in sector X by a fixed absolute resource cap $\overline{R}_X^h$ implies for the marginal product in this sector

$$(11) \qquad p_x\, F_R^h(\overline{R}_X^h) > 1 \quad .$$

The other sector's resource intake can then be viewed as being subjected to a tax τ_y [16]

$$(12) \qquad p_y\, G_R^h(R_Y^h) = 1 + \tau_y^h$$

which is set in a way to ensure that the resource demand of sector Y always stays at the level needed for compliance with the economy's overall emissions cap:

$$(13) \qquad R_y^h \stackrel{!}{=} \overline{R}^h - \overline{R}_X^h \qquad \Rightarrow \quad \tau_y^h = p_y\, G_R^h(\overline{R}^h - \overline{R}_X^h) - 1 \quad .$$

The market clearing condition in the resource sector is the same as in the case above for the United States, Eq.(10). However, since in this case the internal burden-sharing between sectors may not be efficient, a representation of the equilibrium in terms of allowance price (or implicit resource tax) τ_x and emission tax τ_y must be written in a sector-

[13] Sectors not covered by the cap-and-trade system envisaged by Waxman-Markey are: (i) sources below the ETS compliance threshold, (ii) land-use and land-use change, (iii) landfill gases, (iv) HFC, (v) CFCs, (vi) nitrous oxide from nitric acid plants, and (vii) coal mine methane emissions. Given that sectors (ii) to (vii) do not use fossil fuel resource inputs, we assume them to be negligible in the context of our analysis.
[14] The major non-covered sectors are road transport and heating fuels.
[15] The European Union aims at a 20% economy-wide emission reduction relative to 2005 by 2020. Since the policy package allows the use of CDM credits in order to achieve the envisaged reductions for the non-ETS sectors (European Union 2009a), one may argue that a crediting mechanism should also be incorporated in our model. However, since there is a comparatively low 3% limit on CDM use in the non-ETS sectors, and a total reduction target of 10%, we assume that domestic policies–here represented by an emission tax–will nevertheless be the principle means for meeting the objective.
[16] The tax is supposed to be recycled back to households via lump-sum transfer. Note that for the purpose of our analysis, there is no need to include the tax receipts in Eq.(6) or elsewhere, since they have no influence on the country's total income, which only depends on its GDP measured in international prices.

wise differentiated way as

$$(14) \qquad S\left[\phi(p_x, p_y)\right] = R_X^h(\tau_x, p_x, p_y) + R_Y^h(\tau_y, p_x, p_y) + R^f(p_x, p_y)$$

China and other developing countries currently reject binding economy-wide emission caps, but might implement crediting mechanisms modeled on the Kyoto Protocol's Clean Development Mechanism (CDM). Since the current project-based CDM approach is plagued by doubts over additionality (Schneider 2007) and lack of scale (Stern 2008), several suggestions have been made on how an upscaling of the present framework could be achieved. These include proposals for absolute or intensity-based no-lose crediting baselines for emissions on a sectoral level, as well as policy or programmatic approaches that would bundle single projects to reduce transaction costs (EU Commission 2009, Schneider and Cames 2009).

Within our model, these approaches are equivalent since all imply the setting of a business-as-usual baseline–or any other cap–against which emission reductions are credited. Hence, we represent this mechanism by an absolute sectoral cap $\overline{R}_j^f$ for sector *j*, while the other sector faces no resource constraint. Since the presence of such a crediting mechanism implies that the affected sector faces an additional opportunity cost when using the resource input, it leads to the same first-order condition for the marginal product that holds for the EU ETS sector in Europe, Eq. (11). The difference to the European policy case is the absence of an economy-wide reduction target and corresponding resource tax (or command-and-control policy) for the non-ETS sector.[17]

Although China's position on the non-acceptance of a binding absolute emission target has remained firm, its government recently announced that it plans to reduce the carbon intensity of the national product (i.e. CO_2 emissions per unit of GDP) by 40 – 45% below its 2005 level by the year 2020. If implemented, any type of crediting mechanism would operate in parallel to this domestic intensity policy. In our model, this can be represented by introducing the additional constraint

$$(15) \qquad \overline{R}^f(\overline{\gamma}) = \overline{\gamma}\, I^f \quad ,$$

where $\overline{\gamma}$ represents the policy-imposed intensity level.

4. *Economic Impacts of Linking*

Focusing on the linking options from the point of view of the European Union towards the United States and China, we analyze the following linking scenarios in terms of their economic and environmental consequences (leakage), and discuss impacts on competitiveness and welfare:

1. EU ETS and sector *X* in China

[17] Another difference consists in the non-binding character of the business-as-usual cap, which, however, is irrelevant in a model without uncertainty like ours.

2. EU ETS and sector *Y* in China

3. EU ETS and sector *X* in China, with China under national intensity target

4. EU ETS and economy-wide United States ETS

Case 1: EU ETS and China link along X-sectors (symmetric link)

The European Union officially envisages a link of its EU ETS to sectoral crediting schemes in major developing countries such as China (EU Commission 2008, Russ et al. 2008). In this scenario, we consider economic impacts of linking the European trading scheme (here denoted as 'home') to sectors in China ('foreign') that are symmetric to those covered by the EU ETS, i.e. power generation and a number of emission intensive industries such as iron and steel, aluminum, and cement production.

Proposition 1: *Let the home country be fully capped at* $\overline{R}^h$, *with an ETS in sector X holding* $\overline{R}_x^h$ *permits, and an adaptable emissions tax* τ_y^h *in sector Y that ensures a constant intake* $\overline{R}_y^h$. *If the foreign country adopts a sectoral target* $\overline{R}_x^f$ *for its X-sector and an emissions-trading link with home's X-sector ('linking') is established, then*

- *(i) the price* p_x *of good X falls,*
- *(ii) the price* p_y *of good Y rises,*
- *(iii) the resource R appreciates in real terms*
- *(iv) the resource intake (=emissions) in foreign's Y-sector increases, i.e. leakage occurs, and*
- *(v) the emission tax* τ_y^h *must rise.*

Proof: See Appendix A.1

When foreign implements a BAU cap[18] for its *X*-sector and links with home's ETS, the joint output of the two *X*-sectors rises to its efficient level. In response to increased supply, the price p_x falls. Good *Y* becomes relatively more expensive, and hence there is an incentive to expand its production in foreign's uncapped sector *Y*, leading to linking-induced cross-sectoral leakage. Because firms' incentive to produce good *Y* also increases in the home country, the corresponding resource tax τ_y^h has to be increased in order to keep the

[18] We focus on a BAU cap since in the context of a sectoral link with a developing country this appears to be an empirically relevant case. However, our results from Propositions 1,2,3 and 6 also hold if country 'f' has already implemented a more stringent sectoral cap before joining the linking agreement.

resource intake constant. For a segmented system like the EU's, this means that if the 'price of carbon' was initially equalized across trading and non-trading sectors, this will no longer be the case after linking, since the latter leads to a reduction of the permit price in home's sector *X*, and at the same time to a higher fossil resource tax in sector *Y*.

In terms of welfare, there are several effects of linking that must be taken into account: the direct effect from emissions trading, the terms-of-trade effect due to changes in p_x and p_y, and the expansion of foreign's *Y* sector, although to first-order the latter can be neglected. In our analysis, we also ignore the negative environmental effects associated with the increased fossil fuel usage.

Proposition 2: *Under the conditions of Proposition 1, the total welfare effect of linking is ambiguous for at least one of the two 'linked' countries. A necessary condition for a loss of welfare of country i (i=home, foreign) is that its terms-of-trade effect, determined by*

$$(16)\qquad dW^i = \frac{U'}{\phi}\left[\left(X^i - C_x^i\right)dp_x + \left(Y^i - C_y^i\right)dp_y\right] \quad ,$$

is negative, which is always the case for at least one country. On the other side, the terms-of-trade effect is always positive for the resource supplier country.

Proof: See Appendix A.2

Linking leads to an increase in the joint output of X-goods. Dividing the achieved surplus between the two linked countries gives the expected positive gains-from-trade effect on welfare for both. The foreign country, in addition, reaps in the benefits from the increased production of its Y-sector. However, the terms-of-trade effect captured in Eq.(16) is ambiguous, and can–if it turns out to be negative and sufficiently large–outweigh the gains and lead to an overall loss of welfare from linking.

Depending on the functional specification of the production functions, the home country may be a net exporter of both or only one good (e.g. if home and foreign are ex-ante rather symmetric it will export both goods). As an inspection of Eq.(16) shows, if home is a net exporter of good *X*, or a net importer of good *Y* (or both), then the linking-induced fall of p_x and rise of p_y can result in a deterioration of home's terms-of-trade and thus– somewhat resembling the well-known immiserizing growth effect–in an overall loss of welfare from linking. Conversely, to ensure that home (or, likewise, foreign) will gain from linking it must be a net exporter of good *Y* and a net importer of good *X*.

Hence, the specific changes of the countries' terms-of-trade depend on the prevailing trade pattern; however, since terms-of-trade adjustments represent a zero-sum-game at the global level, and because the supplier country always improves its position (the resource price appreciates in real terms, otherwise supply would not increase), home's and foreign's combined terms-of-trade effect must be negative, implying that one of them experiences improving and the other deteriorating terms-of-trade, or that they deteriorate for both. Interestingly, the latter case means that there is a theoretical possibility that both countries suffer a loss of welfare from linking. This would be the case if the resource appreciates strong enough so as to dominate all other effects.

Therefore, in the present scenario of symmetric linking the resource supplier is the only guaranteed winner. Home and foreign both realize efficiency gains, the distribution of which will depend on the functional specification of the production functions. In addition, the foreign country also benefits from the increase in p_y by expanding its *Y* sector, a possibility from which the home country is excluded due to its economy-wide emissions cap. With regard to terms-of-trade, no more than one of the two countries can benefit, which–in the face of a falling price for good *X* and a rising price for good *Y*–will be the country that is relatively more specialized in the production and export of good *Y*.

Case 2: EU ETS and China link between X and Y sector (asymmetric link)

In view of the previous analysis, a natural question to ask is whether it would make any difference if the link between the EU ETS and a Chinese sector is established in an anti-symmetric manner, i.e. from sector *X* in the European Union to sector *Y* in China. The following proposition confirms that this is indeed the case:

Proposition 3: *If, under the same conditions for the home country as in Proposition 1, the foreign country adopts a sectoral BAU target* $\overline{R}_y^f$ *for its Y-sector, such that the link for emission trading is established between sectors X in the home and Y in the foreign country, then*

(i) the price p_x *of good X falls,*

(ii) the price p_y *of good Y rises,*

(iii) the resource R depreciates in real terms,

(iv) global resource intake (=emissions) is reduced, i.e. negative leakage occurs, and

(v) the emission tax τ_y^h *must rise.*

Proof: See Appendix A.3

In principle, asymmetric linking produces the same kind of effects as symmetric linking: sector X in the home country imports 'emission permits' and expands, thereby increasing the world supply of good *X* and inducing a fall of p_x. The difference is that foreign has to reduce the output of *Y* in order to enable the profitable generation and sale of credits to home's capped sector *X*. In this case the fall of p_x gives foreign's *X* sector an incentive to reduce its production and, hence, its usage of resources. This reduction in both of foreign's sectors–while emissions remain controlled at the 'cap-plus-credits' level in the home country–leads to what may be termed linking-induced 'anti-leakage'.

In practical terms this scenario may represent a hypothetical sector crediting mechanism implemented in China's transport or heating sector, which on the one hand would induce cost-effective emission reductions in these sectors, and on the other lead to lower

European Allowance (EUA) prices in the EU ETS. European ETS industries will expand their production in the presence of lower EUA prices, thereby lowering world prices for these products, with the effect of crowding out some industrial production in China. Hence, from an environmental perspective an asymmetric linking to crediting schemes appears preferable to a symmetric one, since it avoids the leakage effect discussed before. However, as in case 1 the rise of p_y necessitates an increase in the fossil resource tax τ_y at home, which can aggravate distortions stemming from differing values of the marginal product of resource use in home's *X* and *Y* sectors. Finally, also Proposition 2 remains valid in terms of the linking-induced changes of the two countries' welfare, except for the resource supplier, who now experiences a negative terms-of-trade and welfare effect.

In terms of welfare, the implications from symmetric *X*-*X* linking largely carry over to the present case. In fact, the overall welfare impact is again determined by the sum of the same effects: gains-from-trade, changes in the terms-of-trade, and (for foreign only) output adjustment. If one of the countries engaged in linking–due to its trade specialization–experiences a terms-of-trade deterioration, then the overall welfare impact becomes again ambiguous for this country. However, since under asymmetric linking the supplier's terms-of-trade deteriorate, this can be the case only for either home or foreign, or for none of them. In other words, in contrast to symmetric linking it is not possible that both home and foreign lose from linking, but instead they could both gain. As the direction of the price changes is the same as for symmetric linking, the same specialization favorable under an *X*-*X* link is favorable under an *X*-*Y* link, i.e. a country's terms-of-trade position will improve if it is an exporter of *Y* and importer of *X*.

As a consequence of the similarity of the induced effects, it is also not possible to derive general conclusions about which type of linking, symmetric or asymmetric, countries would prefer. For example, China would in both cases reap in some of the efficiency gains generated by trading the resource *R*, and would in both cases be affected by the fall of p_x and rise of p_y. The difference between the two types of linking is that under symmetric linking China increases its output of good *Y*, but it must also pay a higher real price for the input *R*, whereas under asymmetric linking its *X*-sector contracts, but in turn it benefits from the depreciation of *R*. Also because the specific rise or fall of the real price of *R* in part depends on the supplier's function *S*, one cannot a priori tell which of the two types of linking dominates the other in terms of welfare.

Case 3: Symmetric link between EU ETS and China, with intensity target in China

In the run-up to COP15, the Chinese government announced its intention to unilaterally reduce the carbon intensity of China's national product (CO_2 emissions per unit of GDP) by 40 to 45 percent below the year 2005 level. In view of the possibility for symmetrical sectoral links to induce leakage discussed in case 1, the question arises of whether the implications of Proposition 1 could be averted if China's total emissions are constrained by an intensity target, or, in other words, whether or not an intensity target could serve as a safeguard mechanism against unintended leakage. To assess this question, we consider a symmetric link between the *X*-sectors of home and foreign just as in case 1, but assume that in addition a binding but not too stringent (to ensure foreign is an exporter of permits) intensity target for total emissions is implemented in the foreign country.[19]

[19] There is no need to discuss output-based sectoral intensity targets, i.e. limits on the emissions per unit of

Proposition 4: *Let home's total emissions be capped at* $\overline{R}^h$*, with an ETS in sector X endowed with* $\overline{R}_x^h$ *permits, and an adaptable emission tax in sector Y. Furthermore, assume foreign's total emission level to be constrained by a binding intensity target* $\overline{R}^f = \overline{\gamma} \cdot I^f$*, which, however, implies a lower emission price than in home's ETS. In order to establish an emission trading link with home's X-sector, resource use in foreign's X-sector now becomes capped at its pre-linking level* $\overline{R}_x^f$*. An adaptable emission tax is levied in foreign's Y-sector to ensure compliance with its intensity target. In this case,*

(i) *the price* p_x *of good X falls,*

(ii) *the price* p_y *of good Y rises, and*

(iii) *resource intake (=emissions) in foreign's Y-sector can increase or decrease (i.e. positive or negative leakage), depending on the net effect of linking on foreign's GDP.*

Proof: See Appendix A.4

As in case 1, linking home's ETS to foreign's less strongly constrained *X*-sector results in an efficiency-enhancing reallocation of resource inputs to the home country, raising the global output of *X* while keeping the combined resource use of both countries' *X*-sectors constant at $\overline{R}_x^h + \overline{R}_x^f$. As a consequence of the increased supply of good *X*, good *Y* will become relatively more expensive, creating an incentive for firms in both countries to increase their production of *Y*.

The difference to the standard symmetric linking of case 1 is that in presence of a binding intensity target, foreign's *Y*-sector cannot expand unless its GDP has grown due to linking. Under an intensity target, the allowed emission level is proportional to GDP, meaning that any additional emissions would exceed the target unless GDP has grown. As discussed before, gains-from-trade in the *X*-sector in combination with the ambiguous terms-of-trade effect due to the changing prices p_x and p_y mean that foreign's GDP might be both higher or lower than in the no-linking case. Therefore, positive or negative leakage equal to the intensity target times the change in foreign's GDP occurs, demonstrating that the intensity target cannot substitute a comprehensive absolute emissions cap as an effective safeguard against linking-induced leakage.[20]

output. In our framework the choice of production technologies is fixed in the short-term, and hence an absolute cap $\overline{R}_x$ in the *X*-sector is fully equivalent to a sectoral intensity target of $\overline{\gamma}_x = \overline{R}_x / F(\overline{R}_x)$.

[20] We do not consider the case of asymmetric linking with an intensity target. As we have demonstrated in case 2, asymmetric linking leads to negative leakage. In this case, an additional 'emissions per GDP' intensity target would simply become non-binding and hence irrelevant.

Case 4: Link between EU ETS and United States ETS

This scenario involving two fully capped systems can be interpreted as a stylized representation of a hypothetical link between the current EU ETS and a Waxman-Markey like US system. One would expect the US to become a net exporter of permits in this case, given that the EU Commission (2008) expects a year 2020 EU allowance price of 30€/tCO_2, while a study by the EPA (2009) suggests a lower price of about 16$/t$CO_2$ for US allowances. Besides efficiency gains, the main motivation for such a linking project would be to harmonize the price of emissions across regions and thereby address the issue of competitiveness. Because both regions have binding national emission targets, there is no concern with regard to linking-induced leakage in this case. However, the fact that the EU's policy is built on an internal segmentation with a trading and non-trading sector gains particular relevance.

Proposition 5: *Let foreign have an economy-wide cap-and-trade system and home a cap on total emissions implemented through a sectorally segmented policy, with an ETS in the X-sector and an adaptable emission tax* τ_y^h *in the Y-sector. Suppose the (implicit) price of emissions in home's two sectors is initially the same, and higher than in the foreign country. If the two countries establish a link between foreign's ETS and home's X-sector,*

(i) *the price p_x of good X falls,*

(ii) *the price p_y of good Y rises,*

(iii) *the permit price in home's X-sector decreases, while the emission tax in its Y-sector must increase, and*

(iv) *the emission tax differential between home's and foreign's Y-sector (competitiveness) may become greater, e.g. if foreign's post-linking output of Y has increased with respect to the pre-linking level.*

Proof: See Appendix A.5

The proposition shows that linking may fail to 'level the carbon playing-field'. With an internally inefficient policy such as the EU's, the first-best prescription of creating a joint market in order to harmonize emission-permit prices actually enlarges the internal domestic distortion between trading and non-trading sector, and might increase the gap in competitiveness between home's and foreign's *Y*-sector. The latter formally depends on the details of production and utility function, but in the plausible scenario where the gains in global efficiency are used to increase the global output of both *Y* and *X*, the assertion always holds.[21] This can be seen by recalling that before linking the marginal product in the *Y*-sector is higher at home than in the foreign country, implying that a uniform global increase in p_y would already enlarge the emission-tax gap (which is given by the difference

[21] The efficiency gains from linking allow re-producing the global pre-linking output and having some resource left. Unless *X* and *Y* are close substitutes, this extra *R* will be used to obtain more units of both.

in the value of the marginal products). If, in addition, foreign's *Y*-sector expands, thereby further decreasing its marginal product, the gap becomes even larger.

In terms of welfare, the results of Proposition 2 carry over in a straightforward way: both countries benefit from the gains-from-trade associated with the linking of their emission trading schemes, but they might nevertheless lose welfare if their terms-of-trade deteriorate very strongly. In fact, since in the present case the supplier's terms-of-trade remain unchanged (otherwise the global supply of *R* would not remain constant), they must improve for one of the two countries–the one more specialized on good *Y*–and necessarily deteriorate for the other–the one more specialized on good *X*.

To see that in this case one of the two countries, say home, might indeed lose welfare from linking, consider the special case in which home is fully specialized on the production of good *X,* and foreign on the production of good *Y*. After linking, home will have some additional *X*-goods as its share of the gains-from-trade surplus, but at the same time the value of its output decreases due to the fall of p_x. Since the former, i.e. home's share of the gains-from-trade, is mainly determined by the characteristics of the production functions, it is well possible that it becomes too small to compensate for the latter, the negative price effect. This would imply a loss of income for home, which– given that the price index ϕ of Eq.(4) remains constant under EU-US linking–amounts to a reduction of welfare.

5. *Extension: The Case of Non-Traded Goods*

The above discussed model with two main countries and traded goods is oriented on the standard approach in trade economics and allows developing an intuition about the potential effects and forces at work. Admittedly, the stylized character of these models–indispensable for an analytical treatment–is often at odds with the idiosyncrasies of reality. In this section, we explore a formal modification of the model aiming to acknowledge the empirical fact that a large share of emissions arises in the production and consumption of goods–such as electricity–that are not heavily traded, at least not between far distant regions such as Europe and China. Specifically, we are referring to the transport and building (i.e. heating) sectors, and in particular to the energy sector (mainly electricity), which in total make up about 65% of all CO_2 emissions in the EU (EEA 2009). Prominent sectors that are emission intensive and characterized by heavy trade include, e.g., the cement, steel, and aluminum industries.

In view of a potential linking scheme involving such 'domestic' sectors, the question arises in how far the previously derived results still hold. E.g. the EU could link its ETS to China's electricity sector, or the transport sector, as suggested by Schneider and Cames (2009). To explore such a scenario, we modify the general model by assuming that the sector *Y* is a purely domestic industry in both countries. As a consequence, the price for good *Y* will in general be different across countries, and trade will not occur in the absence of linking. In formal terms, a competitive general equilibrium in this model is now described by the following conditions for the prices p_x and p_y^i: (i) profit maximization, i.e.

$$(17) \qquad p_x\, F_R^i(R_X^i) = p_y^i\, G_R^i(R_Y^i) = 1 \quad ,$$

(ii) consumers maximize utility, i.e. their demand is determined by $\eta^i := \eta\left(p_x / p_y^i\right)$, (iii) each country's income I^i is given by its GDP, i.e. $I^i = p_x X^i + p_y^i Y^i - R^i$, (iv) markets for all goods clear, i.e.

(18) $$\eta^h I^h + \eta^f I^f + R = \left(X^h + X^f\right) p_x \quad ,$$

(19) $$\tilde{\eta}^h I^h = Y^h p_y^h \quad ,$$

(20) $$\tilde{\eta}^f I^f = Y^f p_y^f$$

for good X and good Y from home and foreign, respectively, and

(21) $$S\left(p_x\right) = R^h(p_x) + R^f(p_x)$$

for the resource market. Note how the resource supply function in Eq.(21) has simplified, since it is now an argument only of the relative price p_x of good X. In fact, because goods of type Y are not internationally traded, their prices p_y^i play a role only for internal accounting, and do not matter at the international level. On the other hand, the share η of income spent on good X can now be different across regions, since it depends on the ratio of the international price p_x and the country-specific price p_y^i of the domestic good.

To analyze the impacts of linking, it is assumed that an 'emissions market' for trade in R is established between the EU ETS and one of the sectors of China (without economy-wide emission target), either the one integrated in international trade, e.g. the cement sector, or the domestic sector, e.g. electricity or transport.

Proposition 6: *Let the home country be fully capped at $\overline{R}^h$, with an ETS in sector X having $\overline{R}_x^h$ permits, and an adaptable emission tax τ in sector Y that ensures a constant intake of $\overline{R}_y^h$. If the foreign country adopts a sectoral target $\overline{R}_x^f$ for its X-sector and an emissions-trading link with home's X-sector ('linking') is established, then*

- *(i) the price p_x of good X falls*
- *(ii) resource intake (=emissions) in foreign's Y-sector increases, i.e. leakage occurs across sectors.*

If instead foreign's Y-sector is capped at the BAU level and linked to home's X-sector,

- *(iii) global resource intake remains constant, i.e. leakage does not occur.*

Proof: See Appendix A.6

The intuition essentially remains the same as in the model where both goods are traded internationally: Linking the X-sectors has the direct effect of increasing the supply of good

X in the foreign country, which then transforms some X into Y-goods by expanding production in its Y-sector and paying for the additional resource intake–i.e. leakage–with X-goods. The leakage effect will, however, be relatively weaker than in the case where both goods are traded, since the foreign country expands its Y-sector only to supply its own consumers, and not also those of the other country.

In case of an asymmetric link from home's X to foreign's Y-sector, the foreign country receives additional X-goods as 'compensation' for the amount δR of inputs that is re-allocated from foreign's domestic Y-sector to home's X-sector. Foreign's only degree of freedom is to adjust its X-sector, since the Y-sector is held fixed as part of the linking agreement. However, the first-order condition 'resource price equals value of marginal product' for efficient production in the X-sector remains unaltered by the linking-induced trade in R. As a consequence, positive leakage would necessarily require a rise of p_x, in contradiction to the supply side relation Eq.(21), which necessarily requires p_x to fall in order for global resource supply to grow.

Overall, the introduction of a domestic good has to some extent dampened our previous results, without, however, changing them qualitatively. This effect is in line with intuition, in as much as all of our results are driven by trade effects, which can be expected to become weaker when one good is by definition excluded from trade, as in this section. Nevertheless, it could be shown that our principal results are robust against this modification of the model framework.

6. Conclusions

This paper has analyzed the impacts of linking emission trading systems on carbon leakage, competitiveness, and welfare within a tractable Ricardo-Viner general equilibrium model with international trade in goods and resources. The considered scenarios were designed to mimic the strategic options for future permit-market linkages between some of the major players in international climate policy, namely Europe, United States, and China.

By analytically comparing pre-linking and post-linking market equilibria, we have shown that a link involving an economy without national emissions cap can provoke leakage in form of an expansion and increased fossil fuel use in the non-capped sector. However, the actual occurrence of this linking-induced leakage depends on which industries are linked to form the joint permit market: in case of asymmetric linking, i.e. when the respective output goods are imperfect substitutes, leakage is prevented and may even become negative. These results were shown to prevail qualitatively even in the presence of a nontradable good.

Hence, from the point of view of environmental integrity, a link of the EU ETS to a sectoral trading system in China (or elsewhere) that covers similar sectors bears some negative implications. Linking across asymmetric sectors (e.g. transport, heating, and in fact any sector producing non-tradable goods) tends to reduce global emissions and thus appears favorable from the EU perspective.

One approach for regulating economy-wide emissions in developing countries is the intensity target, which was recently adopted as a voluntary policy by China. However, our analysis has shown that such a target does not constitute a substitute for an absolute cap, i.e. it does not prevent the occurrence of leakage when one of China's sectors is linked to the EU ETS, and–in terms of policy implications–should therefore not be viewed as an instrument to facilitate participation in emissions trading.

If the EU ETS establishes a link with a hypothetical US system, their total emissions will remain constant since both regions have an economy-wide cap. The main motivation for pursuing this policy option would be to address concerns over competitiveness, i.e. the idea of harmonizing permit prices in order to 'level the carbon playing-field'. However, our results indicate that due to the EU ETS' internal segmentation this can only be partially achieved, as linking can create and increase distortions both between the EU's two sectors as well as between the EU's non-trading sector and its US counterpart.

The modeling analysis of Böhringer et al. (2009) of the EU 2020 climate policy package suggests that non-ETS sectors face higher marginal abatement costs than the EU ETS sectors. Linking the EU ETS to a US system could intensify such concerns. An obvious remedy is to include all EU sectors in the EU ETS. Alternatively, the segmented caps can be adjusted to harmonize marginal abatement costs across sectors. In the context of our model this implies tightening the EU ETS cap after linking to a US system (e.g. in form of a buy-back of permits by the EU regulator), a step that may require ex ante policy coordination if e.g. the resulting increase of the US allowance price raises political concerns.

Finally, the analysis allowed to recognize the potentially ambiguous welfare effect of linking in a general-equilibrium setting. Each country's welfare change can be decomposed into an always positive gains-from-trade effect, and a terms-of-trade effect, where the sign of the latter depends on the country's trade specialization, i.e. its export and import position. In the presence of strongly deteriorating terms-of-trade, the welfare impact of linking on the individual country can then become negative, following a logic similar to that of immiserizing growth. Such a possibility of losing welfare from emissions trading is a characteristic feature of our model set-up and contrasts with the established findings for the standard Ricardo-Viner model, where individual sectors may lose, but the country as a whole always gains when engaging in international trade. However, this is fully consistent in view of the fact that our model differs from conventional trade models in two fundamental ways, namely by (i) introducing trade in inputs and (ii) comparing two equilibria which both comprise international trade in output goods.

Appendix

A.1 *– Proof of Proposition 1*

Emissions trading–in our model in the equivalent form of resource trading–will take place since the home country's binding resource constraint implies that the value of its marginal resource product is higher than in the foreign country. In the post-linking equilibrium, the marginal products F_R^i become equalized and world production of *X* becomes efficient, implying a larger world supply of good *X*. The size of this increase, denoted with a superscript *w* for 'world' by δX^w, only depends on the properties of the production functions, which is also true for the amount of traded resource, denoted by δR. In the following, we can therefore treat both quantities as given–yet undetermined–positive constants.

By taking the ratio of the global clearing conditions for the *Y*- and *X*-markets following from Eq.(7), we obtain for the post-linking equilibrium

$$\text{(A1)} \qquad \frac{\tilde{\eta}\, p_{x/y}}{\eta} = \frac{\bar{Y}^h + Y^f}{\bar{X}^w} \quad ,$$

where a bar indicates a constrained, fixed variable. Since sector *X* is fixed after linking, i.e. it does not respond to price movements (assuming, as we do, that the constraint remains still binding after linking), the post-linking equilibrium can be characterized by investigating the comparative statics of the last equation, and of the supply side relation implied by Eq.(8)

$$\text{(A2)} \qquad S[\phi(p_x, p_y)] = \bar{R}_X^w + \bar{R}_Y^h + R_Y^f[p_y]$$

with respect to an exogenously given small increase dX^w –the effect of linking–in the world supply of *X*. The left hand side of Eq.(A1) is a function only of the prices p_x and p_y, while the world supply Y^w depends only on p_y, and hence for the total differential one obtains

$$\text{(A3)} \qquad \sigma\left(\frac{dp_x}{p_x} - \frac{dp_y}{p_y}\right) = \frac{1}{Y^w}\frac{\partial Y^f}{\partial p_y}dp_y - \frac{dX^w}{X^w}$$

where σ>0 denotes the elasticity of substitution of the underlying utility function. Likewise, written in differential terms Eq.(A2) becomes

$$\text{(A4)} \qquad S'\phi_x dp_x = \left(\frac{\partial R_Y^f}{\partial p_y} - S'\phi_y\right)dp_y \quad \Rightarrow \quad \frac{dp_x}{p_x} = \frac{\left(p_y\left(\partial R_Y^f / \partial p_y\right) - \phi S'\tilde{\eta}\right)}{\phi S'\eta}\frac{dp_y}{p_y},$$

where we used Roy's identity to derive the identity $\frac{p_x \phi_x}{\phi} = \eta$. In view of $S'<0$ and the positive dependence of the foreign *Y*-sector's resource intake on the price p_y, the first term on the right-hand-side must be negative. This implies that dp_y and dp_x have always opposite signs. Substituting Eq.(A4) into Eq.(A3) yields

(A5) $$\frac{dX^{w}}{X^{w}}=\left(\frac{p_y}{Y^{w}}\frac{\partial Y^{f}}{\partial p_y}+\frac{\sigma}{\eta}\left(1-\frac{p_y\left(\partial R_Y^{f}/\partial p_y\right)}{\phi S'}\right)\right)\frac{dp_y}{p_y} \quad ,$$

which demonstrates that linking ($dX^{w}>0$) always leads to a positive dp_y and negative dp_x, given that the term in parenthesis is unambiguously positive. Moreover, since the resource intake in foreign's Y sector depends positively on p_y, $dp_y>0$ is a sufficient condition for leakage to occur and–by Eq.(12)–for the need to increase the resource tax τ_y^{h} in order to keep the resource intake in home's Y sector constant. Finally, in order for Eq.(5) to be consistent with an increased global supply, the real price of the resource must rise. Ñ

A.2 *– Proof of Proposition 2*

Following Proposition 1, the impact of linking on each country consists of a direct gains-from-trade effect and the effect from changes in p_x and p_y. In addition, the foreign country also increases its output in the Y-sector, which obviously represents a positive welfare contribution for foreign, given that p_y rises in the course of linking.

The gains-from-trade effect can be represented as an increased availability of X for both countries. To see this, let us first note that the permit price, say p_E, does not need to be taken into account explicitly, since it is fully determined by the value of the marginal product in the X-sector, and hence proportional to p_x:

(A6) $$p_E = p_x F_R^{h}(R_x^{h}+\delta R)=p_x F_R^{f}(R_x^{f}-\delta R)\,,$$

where δR can be interpreted as the number of permits that are traded in the course of linking. For home, the partial income effect associated with the gains-from-trade generated by emissions trading can thus be expressed as

(A7) $$\begin{aligned}\Delta I^{h} &= \left(p_x F^{h}(\overline{R}_x^{h}+\delta R)-p_E\,\delta R\right)-p_x F^{h}(\overline{R}_x^{h})\\ &= p_x\left(F^{h}(\overline{R}_x^{h}+\delta R)-\delta R\,F_R^{h}(\overline{R}_x^{h}+\delta R)-F^{h}(\overline{R}_x^{h})\right)=:p_x\left(X^{h}+\delta X^{h}\right)\end{aligned}$$

i.e. as a fixed increase of available X-goods denoted by $dX^{h}>0$, the size of which only depends on the properties of the production functions F^{i}. This effect is, therefore, always positive. For the foreign country we get dX^{f}, in complete analogy.

With welfare as a function of real income as defined in Eq.(4), the terms-of-trade effect on home/foreign can be computed by evaluating:

(A8) $$dW^{i}=\frac{\partial W^{i}}{\partial p_x}dp_x+\frac{\partial W^{i}}{\partial p_y}dp_y=\frac{dW^{i}}{d(I^{i}/\phi)}\left(\frac{\partial\left(I^{i}/\phi\right)}{\partial p_x}\frac{\partial p_x}{\partial X^{w}}+\frac{\partial\left(I^{i}/\phi\right)}{\partial p_y}\frac{\partial p_y}{\partial X^{w}}\right)$$

Applying the envelope theorem we obtain the following expression, valid for both countries:

(A9) $$\phi\, dW^i = U' \cdot \left(\left(X^i - C_x^i \right) dp_x + \left(Y^i - C_y^i \right) dp_y \right) \quad .$$

The two terms in parenthesis represent the net exports of good X and Y, respectively. Hence, if home is a net exporter of good X or a net importer of good Y (or both), then the linking-induced fall of p_x and rise of p_y can lead to a terms-of-trade deterioration and thus to a negative welfare contribution. Given that the other contributions are always positive, the negative terms-of-trade effect constitutes a necessary condition for an overall loss of welfare due to linking.

Finally, to see that at least one country (between home and foreign) must experience a negative terms-of-trade effect, consider the sum of the terms-of-trade contributions for home and foreign from Eq.(A9):

(A10) $$\left(X^h - C_x^h + X^f - C_x^f \right) dp_x + \left(Y^h - C_y^h + Y^f - C_y^f \right) dp_y = C_x^s\, dp_x + C_y^s\, dp_y \quad ,$$

Apart from a reversed sign, this expression represents the terms-of-trade effect experienced by the resource supplier country, and thus illustrates how terms-of-trade adjustments constitute a zero-sum-game at the global level. Since the last expression can be written as $I^s \left(\eta\, \hat{p}_x + \tilde{\eta}\, \hat{p}_y \right)$, which can be shown to be negative if global resource supply increases, i.e. $dS > 0 \quad \Rightarrow \quad \eta\, \hat{p}_x + \tilde{\eta}\, \hat{p}_y < 0$, we can conclude that the supplier country's terms-of-trade always improve due to linking. As a consequence, the terms-of-trade of either home or foreign, or both, must deteriorate. ☐

A.3 *– Proof of Proposition 3*

In this case, home (EU) imports resources R from foreign (China) until the price-weighted marginal products becomes equalized, i.e.

(A11) $$p_x\, F_R^h (\overline{R}_X^h + \delta R) = p_y\, G_R^f (R_Y^f - \delta R)$$

Thus, the amount of traded permits δR now depends not only on the functions F^i, but also on the price ratio $p_{x/y}$. However, assuming that emissions trading from foreign to home actually takes place, the resulting effect will in all cases be some increase in X-output at home and a corresponding fall in Y-output abroad. Thus, let us assume the world supply of X rises by dX^h, and that of Y falls by dY^f. Consider again Eq.(A1) written in differential form as in Eq.(A3), now modified for the case of X-Y linking:

(A12) $$\sigma \left(\frac{dp_x}{p_x} - \frac{dp_y}{p_y} \right) = \frac{dY^f}{Y^w} - \frac{dX^h}{X^w} - \frac{1}{X^w} \frac{\partial X^f}{\partial p_x} dp_x \quad ,$$

which can be rearranged to

(A13) $$\left(\sigma + \frac{p_x}{X^w} \frac{\partial X^f}{\partial p_x} \right) \frac{dp_x}{p_x} = \frac{dY^f}{Y^w} - \frac{dX^h}{X^w} + \sigma \frac{dp_y}{p_y} \quad ,$$

where the term in parenthesis is always positive, and–by assumption–we also have $dX^h > 0$ and $dY^f < 0$. It follows that if p_y falls, then also p_x must fall. Next, consider the clearing condition for the resource market, and its total differential, in analogy with Eq.(A4):

$$\text{(A14)} \quad S[\phi(p_x, p_y)] = \overline{R_X^h + R_Y^f} + \overline{R}_Y^h + R_X^f[p_x] \quad \Rightarrow \quad \left(\eta - \frac{p_x}{S'\phi} \frac{\partial R_X^f}{\partial p_x} \right) \frac{dp_x}{p_x} = -\tilde{\eta} \frac{dp_y}{p_y}$$

Because the last parenthesis is always positive, it follows that dp_y and dp_x must have opposite signs. But then p_y cannot fall, since this would also require p_x to fall, by Eq.(A13). Therefore p_y must rise, which, by Eq.(A14), means that p_x falls. Finally, since the resource intake of foreign's *X* sector only depends on p_x, and p_x falls, the resource intake and output of this sector must fall, i.e. negative sectorial leakage occurs. In contrast to the case of *X*-*X* linking, the relative rise of p_y is in this case less pronounced, i.e. it does not overcompensate the fall of p_x, leading to a net increase of the cost ϕ for one unit of utility (i.e. $\eta\, \hat{p}_x + \tilde{\eta}\, \hat{p}_y > 0$) and–consistent with negative leakage–a drop of the (real) price of *R*.
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A.4 – Proof of Proposition 4

In principle, this proof follows the same line of argumentation as the one for Proposition 1. Again, the amount of resource traded between foreign's and home's *X*-sector in the course of linking is fully determined by the condition of marginal product equalization, i.e. it is only a function of $\overline{R}_X^h, \overline{R}_X^f$, and the production technologies, as in Eq.(A7). Also as before, the global efficiency gains in the production of good *X* imply a fall of p_x and–for consistency with the supply relation Eq.(8)–a simultaneous rise of p_y.

A rising price for *Y* constitutes an incentive for firms in the foreign country to increase their production of this good and thus use more resources, such that leakage would occur. However, for a scenario in which foreign has adopted an intensity target, the supply side relation Eq.(A2) has to be rewritten as

$$\text{(A15)} \qquad S[\phi(p_x, p_y)] = \overline{R}_X^w + \overline{R}_Y^h + \min\left\{ R_Y^f[p_y], \overline{\gamma} \cdot I^f - \overline{R}_X^f \right\} \quad ,$$

implying that in the present case a higher resource intake is only consistent with the intensity target if foreign's income has become higher in the course of linking. In fact, the emission-of-GDP intensity target may even become non-binding, if the increase of foreign's income is sufficiently high. In this case, however, the scenario with intensity target would simply reduce to case 1, i.e. Proposition 1 holds. On the other side, if linking has an adverse effect on foreign's GDP, the intensity target tightens the constraint on emissions and leads to negative leakage.

Specifically, let us consider gross domestic product (as defined by the expenditure method), which is given by the value of consumption plus exports minus imports:

$$\text{(A16)} \qquad I^f = p_x X^f + p_y Y^f - \overline{R}_X^f - R_Y^f \quad .$$

Hence, in presence of a binding emission-per-GDP target $\bar{\gamma}$, resource use in foreign's Y-sector can be expressed as:

$$\text{(A17)} \qquad R_Y^f = \bar{\gamma}\left(p_x X^f + p_y Y^f - \bar{R}_X^f - R_Y^f\right) \quad ,$$

which in differential terms implies

$$\text{(A18)} \qquad dR_Y^f = \frac{\bar{\gamma}}{1+\bar{\gamma}}\left(p_x dX^f + X^f dp_x + Y^f dp_y + p_y\, G_R^f\, dR_Y^f\right)$$

and, by rearranging,

$$\text{(A19)} \qquad \left(1 - \frac{\bar{\gamma}}{1+\bar{\gamma}}\, p_y\, G_R^f\right) dR_Y^f = \frac{\bar{\gamma}}{1+\bar{\gamma}}\left(p_x dX^f + X^f dp_x + Y^f dp_Y\right) \quad .$$

The term $\bar{\gamma}\, p_y\, G_R^f$ represents the marginal increase in foreign's emission allowances 'granted' by the intensity target if sector Y increases its resource input by one marginal unit. Clearly, in case of a binding intensity target any expansion of the Y-sector (and thus GDP) must lead to less new allowances than would be needed to cover the additional resource input. Therefore we can conclude that $\bar{\gamma}\, p_y\, G_R^f$ must be smaller than one and, as a consequence, that the parenthesis on the left hand side of Eq.(19) is always positive. The parenthesis on the right hand side represents the partial (i.e. when holding the production of Y constant) income effect arising from linking in form of gains-from-trade and price changes. Thus, foreign's production of Y increases (decreases) and positive (negative) emission leakage occurs, if the income effect induced by linking is positive (negative). Ñ

A.5 *– Proof of Proposition 5*

Since foreign has by assumption the lower permit price, the initial effect of linking is that home buys 'permits' and imports resources into its X-sector. If the barred variables denote pre-linking allocations, then the post-linking equilibrium is characterized by a common implied resource tax τ in all but home's Y-sector:

$$\text{(A20)} \quad 1+\tau = p_x\, F_R^h(\bar{R}_X^h + \delta R_X^h) = p_x\, F_R^f(\bar{R}_X^f + \delta R_X^f) = p_y\, G_R^f(\bar{R}_Y^f + \delta R_Y^f)$$

subject to $\delta R_X^h + \delta R_X^f + \delta R_Y^f = 0$, as the trading system is neutral with respect to total resource use. Because foreign has an economy-wide ETS, the last part of Eq.(A20) is valid at all times, also during the linking process, and can thus be used for comparative statics. In differential terms it becomes:

$$\text{(A21)} \qquad \frac{p_x}{p_y} = \frac{G_R^f(R_Y^f)}{F_R^f(R_X^f)} \quad \Rightarrow \quad \frac{dp_x}{p_x} - \frac{dp_y}{p_y} = \frac{G_{RR}^f}{G_R^f} dR_y^f - \frac{F_{RR}^f}{F_R^f} dR_x^f \quad .$$

At the same time, the differential of the global supply-demand constraint Eq.(A1), in analogy with Eq.(A3), is given by

$$\text{(A22)}\quad \sigma\left(\frac{dp_x}{p_x}-\frac{dp_y}{p_y}\right)=\frac{dY^f}{Y^w}-\frac{dX^w}{X^w}=\frac{G_R^f}{Y^w}dR_y^f-\frac{F_R^f}{X^w}dR_x^f-\frac{F_R^h}{X^w}dR_x^h \quad .$$

Substituting Eq.(A21) into Eq.(A22) leads to the following expression:

$$\text{(A23)}\quad \left(\sigma\frac{G_{RR}^f}{G_R^f}-\frac{G_R^f}{Y^w}\right)dR_y^f=\left(\sigma\frac{F_{RR}^f}{F_R^f}-\frac{F_R^f}{X^w}\right)dR_x^f-\frac{F_R^h}{X^w}dR_x^h \quad .$$

The factors in parenthesis are clearly negative. Hence, given our assumption that home will be a net importer of resource permits, i.e. $dR_x^h>0$, the term dR_x^f cannot be positive, since this would imply also a positive dR_y^f, which in turn would mean foreign is a net importer of permits. Therefore, linking must lead to a reduction of foreign's production of good *X*. Although for foreign's *Y*-sector the change in output remains ambiguous, the change in the price ratio $p_{x/y}$ is uniquely determined: if $dR_y^f>0$, then the right-hand-side of Eq.(A23) becomes negative, and hence $d(p_{x/y})<0$. If, on the other hand, $dR_y^f<0$, then $dY^w<0$ and $dX^w>0$ follow, which means that the middle-part of Eq.(A22) becomes negative, and again $d(p_{x/y})<0$ must hold. Moreover, since total global resource supply must remain constant under the considered cap-and-trade system, the cost of utility function ϕ, which actually represents the inverse of the real price of one unit of the resource, must also stay constant, which by Eq.(5) requires $\eta\,\hat{p}_x+\tilde{\eta}\,\hat{p}_y=0$, i.e. the change in p_y and p_x must be of opposite signs. Therefore we can conclude that p_x falls and p_y increases, which proves assertion (i) and (ii).

Given the rise in p_y, it also becomes evident that the tax τ_y^h in home's *Y*-sector must be increased in order to keep this sector's total resource intake constant, as the latter is governed by $1+\tau_y^h=p_y\,G_R^h(\overline{R}_y^h)$. On the other hand, if home's *X*-sector is to expand, despite the falling price of p_x, then the corresponding resource tax (or emission permit price) must have decreased due to linking, thus completing the proof of assertion (iii).

It remains to show that it is possible and plausible for the gap between the emissions prices in home's and foreign's *Y*-sector to increase. In formal terms, this requires

$$\text{(A24)}\quad d\tau_y^h=G_R^h(\overline{R}_y^h)\,dp_y\;>\;d\tau^f=G_R^f(\overline{R}_y^f)\,dp_y+p_y\,G_{RR}^f(\overline{R}_y^f)\,dR_y^f$$

to be true. Given that we have $G_R^h>G_R^f$ by assumption, the inequality holds whenever dR_y^f is positive, or negative but sufficiently close to zero, i.e. whenever linking leads to an expansion or only small contraction of foreign's *Y*-sector. Conversely, a closing of the emissions-price gap can only occur if foreign's *Y*-sector contracts sufficiently. This would correspond to a case in which resources from both foreign sectors are reallocated to home's *X*-sector. Although theoretically possible, such a scenario is not very plausible, as it would mean that all efficiency gains realized in the global production of good *X* are used to produce more only of good *X*, and that the global production of *Y* actually decreases.

Eq.(A23) implies that this could happen if X and Y are very close substitutes, since for $\sigma\rightarrow\infty$ one infers that the sign of both dR_x^f and dR_y^f must be negative. Conversely, if X and Y are perfect complements, i.e. $\sigma\rightarrow 0$, Eq.(A22) requires that both dX^w and dY^w must be positive, and thus $dR_y^f > 0$. Ñ

A.6 – Proof of Proposition 6

Consider first a symmetric X-X link. As before, we assume that the foreign country sells some amount δR of resource to the home country, receiving an amount of δX in return which exceeds the loss of domestic X production and which is defined solely by the condition of marginal product equalization, and hence does not depend on any prices. Prior to linking, the foreign country's firms and consumers–taking the price p_x as given–implicitly maximize

$$\text{(A25)} \qquad \max_{R_x^f, R_y^f} U^f\left[F^f(R_x^f) - \frac{\left(R_x^f + R_y^f\right)}{p_x}, G^f(R_y^f)\right] \quad .$$

Regarding the optimal choice for sector Y, a linearly homogeneous utility implies

$$\text{(A26)} \qquad \frac{\partial_x U^f}{\partial_y U^f} =: MRS\left(\frac{C_y^f}{C_x^f}\right) = p_x\, G_R^f \quad ,$$

where MRS denotes the utility's marginal rate of substitution. After linking to the home country's X-sector, the maximization problem Eq.(A25) is simplified to one of a single variable, namely R_y^f, because foreign's X-sector is now fully determined by the condition of marginal product equalization. Foreign's general equilibrium reaction to a positive 'shock' δX can thus be evaluated by considering the comparative statics of Eq.(A26), written as

$$\text{(A27)} \qquad MRS\left(\frac{G^f(R_y^f)}{\overline{X}^f + \delta X - \left(\overline{R}_x^f + R_y^f\right)/p_x}\right) = p_x\, G_R^f \quad ,$$

where the pre-linking equilibrium defines the parameters $\overline{X}^f$ and $\overline{R}_x^f$. Computing all derivatives yields

$$\text{(A28)} \quad \left(\frac{\partial\left(C_y^f / C_x^f\right)}{\partial X^f} dX^f + \frac{\partial\left(C_y^f / C_x^f\right)}{\partial R_y^f} dR_y^f + \frac{\partial\left(C_y^f / C_x^f\right)}{\partial p_x} dp_x\right) MRS' = G_R^f\, dp_x + p_x\, G_{RR}^f\, dR_y^f \quad .$$

Noting that the derivative MRS' is positive and since, evidently, we have

$$\text{(A29)} \qquad \frac{\partial\left(C_y^f / C_x^f\right)}{\partial X^f} < 0 \qquad \frac{\partial\left(C_y^f / C_x^f\right)}{\partial R_y^f} > 0 \qquad \frac{\partial\left(C_y^f / C_x^f\right)}{\partial p_x} < 0$$

the equation can be written in a qualitative way ('neg' denoting negative terms, 'pos' positive ones) as

(A30)

$$\left(G_R^f - [...neg...]\cdot MRS'\right)dp_x + \left(p_x\, G_{RR}^f - [...pos...]\cdot MRS'\right)dR_y^f = [...neg...]\cdot MRS'\, dX^f$$

The still needed relation linking dp_x and dR_y^f can be obtained from the resource supply relation Eq.(21). With a binding constraint, the resource intake for all sectors except foreign's *Y*-sector remains constant, and thus any change in the global supply must be due to a change in R_y^f :

(A31) $$dS = dR_y^f = S'\, dp_x \quad .$$

Substitution into Eq.(A30) yields

(A32) $$dp_x = \frac{[...neg...]\cdot MRS'}{\left(G_R^f - [...neg...]\cdot MRS' + p_x\, S' G_{RR}^f - [...pos...]\cdot S'\, MRS'\right)} dX^f \quad ,$$

which–given the unambiguous negative sign of the coefficient–demonstrates that linking leads to a fall in the price p_x. By virtue of Eq.(A31), it follows that foreign's *Y*-sector expands, i.e. leakage occurs. Finally, the efficiency condition $p_y^f\, G'(R_y^f) = 1$ also implies that the price p_y^f increases.

In case of an asymmetric link from home's *X* to foreign's *Y*-sector, the foreign country receives additional goods *X* as 'payment' for the amount δR of resource that is traded from its domestic *Y*-sector to home's *X*-sector. Foreign's only degree of freedom is to adjust its *X*-sector, since the *Y*-sector is held fixed as part of the linking agreement. However, the first-order condition for efficient production in the *X*-sector remains unaltered by the linking-induced trade in *R*, since foreign's maximization problem after linking

(A33) $$\max_{R_x^f} U^f \left[F^f(R_x^f) + \delta X - \frac{\left(R_x^f + \bar{R}_y^f\right)}{p_x}, G^f(\bar{R}_y^f - \delta R) \right]$$

only implies the equalization of resource price and value of marginal product:

(A34) $$p_x\, F_R^f(R_x^f) = 1 \quad .$$

Therefore, foreign's *X*-sector expands only if p_x increases. But since the supply relation Eq.(31) allows an increase in global resource supply only for a decrease in p_x, this cannot happen, allowing to conclude that global resource intake must remain unaltered . Ñ

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Chapter 6

Unilateral Climate Measures and Trade Policy[*]

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Between a Rock and a Hard Place: A Trade-Theory Analysis of Leakage under Production- and Consumption-Based Policies

Michael Jakob,* Robert Marschinski, Michael Hübler

Abstract

Without a comprehensive global climate agreement, carbon leakage remains a contentious issue. Trade policy – in particular the two equivalent concepts of border tax adjustment (BTA) and consumption-based emission accounting – is currently discussed as a potential means for increasing the effectiveness of unilateral climate policy. Based on a theoretical analysis of a general equilibrium trade model, the results of this paper cast doubt on the effectiveness of BTA: First, the optimal domestic carbon tariff depends on the carbon intensity differential between the foreign country's exporting and non-exporting sector, and not the foreign country's and the home country's exporting sector, as suggested by the BTA approach. Second, implementing a consumption-based policy does not generally prevent or even reduce leakage. Third, for the case of EU as well as US unilateral climate policy, the empirical data suggest that applying BTA on imports from China or most other countries would in effect increase leakage.

JEL classifications: F11, F18, Q54, Q56

Keywords: leakage, carbon tariff, consumption-based accounting, border tax adjustment, climate policy.

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1 Introduction

The Kyoto Protocol establishes upper limits for the greenhouse gas emissions of industrialized (Annex-B) signatories, but exempts developing countries from any binding commitment. Under the Copenhagen Accord, which was adopted at the 2011 Cancún climate summit, all countries are free to choose their own emission targets, including none. In this context of a fragmented policy regime, a frequently discussed issue is the possibility that in response to ambitious reduction targets adopted by some countries, energy intensive industries might migrate to countries with a less stringent or non-existent regulation of emissions (e.g., Van Asselt and Brewer, 2010). Hence, in absence of a global climate agreement, domestic emission reductions of early-movers could to a significant part be offset by increased emissions in other parts of the world, a phenomenon commonly referred to as carbon leakage (e.g. Felder and Rutherford, 1993).

Underpinning this concern, empirical studies have recently exposed the large imbalances in 'embedded' carbon associated with merchandise trade flows between industrialized and developing countries, suggesting that the former to some extent 'outsource' their emissions to the latter in order to meet their Kyoto commitments (Davis and Caldeira, 2010). Measures proposed to tackle this issue include approaches in which countries with emission caps are held accountable for their consumption instead of their production-related emissions (Peters and Hertwich, 2008b; Pan et al., 2008), or in which carbon prices are levied on imported goods by means of a border tax adjustment, or BTA (Ismer and Neuhoff, 2007).

The debate on these instruments has mostly focused on two issues: technical feasibility and conformity with international trade law. On the first aspect, it has been pointed out that putting a price on carbon emitted in the production process of imported goods would face a serious obstacle due to the limited availability of information on the total carbon content of goods (Dröge, 2009). Second, international trade legislation (WTO) clearly limits countries' ability to impose tariffs on imports. However, in certain circumstances it permits collecting taxes to protect the natural environment if they do not discriminate against foreign products (Perez, 2005), leading several authors to argue that BTA on carbon embedded in imported goods may be compatible with WTO regulations (Bhagwati and Mavroidis, 2007).

Even though a number of numerical CGE studies conclude that BTA could moderately reduce carbon leakage (cf. Section 2), the theoretical foundations behind this result have received surprisingly little attention. Against this backdrop, the present article re-examines the economic rationale behind the use of carbon-tariffs by employing a stylized 2x2 general equilibrium trade model, which generalizes the framework of Markusen (1975). We adopt the point of view of one region ('Home') implementing climate policy in face of the rest of the world ('Foreign'), where the latter region does not impose any policy measures. Three main results are derived: First, it is demonstrated that border tax adjustment and consumption-based accounting of emissions do not generally constitute optimal policy instruments for a country pursuing unilateral climate policies. The reason for this is that the optimal domestic carbon tariff depends on the carbon intensity differential between Foreign's exporting and non-exporting sectors, and not Foreign's and Home's exporting sector, as would be suggested by the BTA approach. Second, implementing a consumption-based policy does not generally prevent or even reduce leakage; instead, the effect is shown to be ambiguous and to depend on parameter values. Third, for the case of EU and US unilateral climate policy, the empirical data suggests that applying a BTA on imports from China would in effect increase leakage.

These findings cast considerable doubt on the practical feasibility of trade measures to effectively reduce carbon leakage. Consumption-based accounting of emissions - or equivalently BTA - is fraught with substantial uncertainty regarding economic effects and parameters and their alleged positive effects remain unproven. We conclude that it seems debatable if these measures rightly deserve the prominent place they occupy in the current debate and raise the question if their surprisingly wide-spread support in the political arena can perhaps rather be explained by protectionist motives than by environmental considerations.

This article proceeds as follows: Section 2 provides a survey of the relevant literature. Section 3 introduces our theoretical model. Section 4 examines the optimal design of unilateral climate policy. Section 5 examines production- and consumption-based policies and shows that the latter is equivalent to a border tax adjustment. Section 6 compares the policy measures examined before. Section 7 confronts our theoretical results with empirical data and discusses the results critically. Section 8 concludes.

2 Literature Review

The literature on unilateral climate policies has identified several channels through which carbon leakage can occur. These include (i) free-riding on one actor's provision of the global public good 'abatement' (e.g. Carraro and Siniscalco, 1993; Barrett, 1994), (ii) supply side interactions in which reduced demand for fossil fuels in countries that adopt a climate policy depresses their price and results in increased consumption elsewhere (Sinn, 2008), and (iii) changes in specialization patterns such that the production of emission intensive goods shifts to countries with a lower (or zero) carbon price (c.f. Siebert, 1979). Since the current debate on competitiveness - and the ensuing calls for 'leveling the carbon playing field' (Houser et al., 2008) - is mainly related to specialization leakage, which also constitutes the most relevant channel in terms of trade policy considerations, our analysis will focus on this particular channel of leakage.

Despite the fact that for most industries energy accounts for only a small fraction of total costs and that therefore leakage should not be expected to render unilateral climate policies grossly ineffective (Hourcade et al., 2008), several numerical models have come up with rather high estimates of leakage rates of up to 45% (e.g. Felder and Rutherford, 1993; Babiker and Rutherford, 2005; Elliott et al., 2010).[1] Moreover, empirical studies analyzing the trade flows between industrialized and developing countries repeatedly find that the former are significant net importers of carbon emissions embedded in traded goods, especially with regard to China (Davis and Caldeira, 2010; Peters and Hertwich, 2008a; Wang and Watson, 2008; Shui and Harriss, 2006; Pan et al., 2008). Peters and Hertwich (2008a), for instance, estimate that China's net carbon exports amounted to about 18% of its total carbon emissions in 2001.

As a consequence, it has been concluded that either measures that target carbon emissions on a consumption instead of a production basis (Peters and Hertwich, 2008b),

[1] Naturally, leakage estimates depend on which countries join the policy regime and on the carbon tax level.

or policies in which carbon prices are levied on emissions arising from the production of imported goods in the form of border taxes (Ismer and Neuhoff, 2007; Monjon and Quirion, 2010) would be appropriate to address carbon leakage. However, several studies based on numerical models have found that border tax adjustments would have a rather limited potential to reduce carbon leakage (Babiker and Rutherford, 2005; Böhringer et al., 2010), leading several authors to conclude that border tax adjustments would strengthen sectoral competitiveness rather than decrease overall carbon leakage (Alexeeva-Talebi et al., 2008; Kuik and Hofkes, 2010).

The role of trade policy in the presence of international pollution has also been investigated from a theoretical point of view, albeit to lesser extent. Markusen's (1975) seminal analysis of unilateral environmental policy – on which our model is based – emphasizes that the only means to influence foreign producers' emissions by trade policy is through changes in the terms of trade. He also derives the result that in general two policy instruments (such as a production tax and a tariff) are needed to achieve an optimal outcome. This is confirmed by Hoel (1994) and Golombek et al. (1995), who show that with limited participation in an international climate agreement, the participants' optimal policy mix consists of taxing both the production and consumption of fossil fuels. In a similar vein, Hoel (1996) finds that a differentiation of carbon prices between sectors is not needed as long as one can use import and export tariffs on all traded goods.

One of the few theoretical studies addressing tariffs in proportion to the pollution content of imports is Copeland (1996), who demonstrates that such a tariff is an optimal way for dealing with transboundary pollution whenever the latter arises only from "border-zone production", i.e. from a sector that produces exclusively to meet demand in the importing country. For the case of climate change, of course, such a restriction cannot be applied. This is where the present contribution aims to add to the literature: by building on the theoretical literature cited above, but not restricting the analysis to optimal policies (be they first- or second-best), we study the theoretical foundations underlying the economic rationale of BTA and consumption-based accounting. In particular, we can provide – in a fairly general setting – the conditions under which these 'real world' policies reduce leakage or not.

3 The Model

In order to study the effects of unilateral climate policies in an open economy, we take the reduced-form general equilibrium trade model employed by Markusen (1975) as a starting point. This two-country, two sector model has the advantage of being general (consistent with both Heckscher-Ohlin and Ricardo-Viner framework) and easily tractable. However, while Markusen adopts the common assumption[2] that pollution arises only in the production of one of the two goods, our model is more general and allows each sector in each country to have a specific (but fixed) pollution intensity. As will be shown in the course of this analysis, the more restrictive – and seemingly innocent –assumption of only one polluting sector might lead to fallacious policy conclusions with regard to measures designed to counteract carbon leakage.

[2] This assumption is also adopted in e.g. Copeland (1996) and Elliott et al. (2010).

Specifically, let us assume a world of two regions, $r = \{h, f\}$, Home (h) and Foreign (f) producing two tradable goods, X and Y. Let Home – without loss of generality – offer both goods X and Y on its domestic market but only good X on the international market; conversely, let Foreign offer goods X and Y on its domestic market, too, but only good Y on the international market. Thus, X is traded from Home to Foreign, while Y is traded from Foreign to Home.

Let X be the numéraire good (i.e. $p_X = 1$), $p = p_Y / p_X = p_Y$ the domestic price ratio in Home, and p^* the world market price ratio. For convenience, let us assume that Foreign does not implement any relevant policy so that economic agents in Foreign face the world market price p^* . Both countries' production is described by their production possibility frontier, i.e. the feasible set of combinations of output quantities Q of X and Y produced by using fixed factor supplies and technologies:

$$F^r(Q^{Xr}, Q^{Yr}) = 0 \tag{1}$$

Since Home and Foreign generally differ in their production possibility frontiers, each region has a comparative advantage in the production of one of the goods (here assumed to be good X for Home), making it rational to participate in international trade.[3] We can also reformulate Eq.(1) as a transformation function T^r describing the output of X as a concave, decreasing function of the output of Y:[4]

$$Q^{Xr} = T^r(Q^{Yr}), \quad T^r_{Q^{Yr}} < 0, \quad T^r_{Q^{Yr}Q^{Yr}} < 0 \tag{2}$$

Because output is implicitly determined by profit maximization of competitive producers, an increase in the price ratio p of good Y relative to good X shifts production towards Y, such that the output ratio Y / X rises.

As our model is static, we do not allow for international debt and require trade to be balanced. Let E^{Xh} denote Home's exports of X and M^{Yh} its imports of Y. Then[5]

$$E^{Xh} + p^* M^{Yh} = 0 \tag{3}$$

The consumption side is characterized by a representative agent in each region drawing utility from the consumption of goods X and Y.[6] In formal terms, we assume homothetic preferences over consumption in form of a concave, increasing function U^r of C^{Xr} and C^{Yr}:

$$U^r(C^{Xr}, C^{Yr}), \quad U^r_{C^{Xr}} > 0, \quad U^r_{C^{Xr}C^{Xr}} < 0, \quad U^r_{C^{Yr}} > 0, \quad U^r_{C^{Yr}C^{Yr}} < 0 \tag{4}$$

From Home's point of view, consumption is related to exports and imports by:

[3] Nevertheless, full specialization is excluded in our model since the marginal product of production factors will rise towards infinity when production levels approach zero.
[4] We denote derivatives with respect to a certain variable by subscripts throughout the analysis.
[5] This is equivalent to $p^* E^{Yf} + M^{Xf} = 0$ from Foreign's point of view. Our two-region setting naturally implies market clearance on all markets such that $E^{Yf} = M^{Yh}$, $E^{Xf} = M^{Xf}$.
[6] Imported and domestically produced goods are perfect substitutes from the consumer's point of view.

$$C^{Xh} = Q^{Xh} - E^{Xh},\ C^{Yh} = Q^{Yh} + M^{Yh} \tag{5}$$

Next, we introduce the global environmental externality in the form of climate change damages D^r caused by total emissions Z. Damages are assumed to reduce the utility drawn from consumption but leave productivity unaffected ('eyesore' pollution). To keep matters simple and transparent, let us assume that Home's welfare function W^h is linearly separable in U^h and D^h:

$$W^h = U^h(C^{Xh}, C^{Yh}) - D^h(Z), \quad D_Z^h > 0 \tag{6}$$

As a further simplification, let us assume that damages D^h are linear in global carbon emissions Z.[7] Since impacts of climate change in Foreign do not influence Home's utility, we only consider climate damages in Home. These are characterized by constant marginal damages ε:

$$D^h(Z) = \varepsilon Z, \quad \varepsilon > 0 \tag{7}$$

Global emissions are the sum of emissions in Home and Foreign, which we assume to be proportional to the output of X and Y in each region. To this end, we define sector and country specific emission intensities γ^{Xr}, γ^{Yr} that denote the quantity of carbon emissions per (physical) unit of output:

$$Z = Z^h + Z^f = \gamma^{Xh}Q^{Xh} + \gamma^{Yh}Q^{Yh} + \gamma^{Xf}Q^{Xf} + \gamma^{Yf}Q^{Yf} \tag{8}$$

This assumption follows Markusen (1975) and implies that the production of one unit of a certain good in a certain region requires a certain fixed amount of fossil fuel inputs, and that there is no possibility to substitute among inputs to alter this ratio. Of course, long-run changes in production technologies, such as fuel switches and measures to increase energy efficiency, can be expected to influence these emission factors. However, the assumption of fixed emission factors seems plausible for a short-term analysis, and, more importantly, allows us to concentrate on the central general equilibrium aspects.

Finally, we assume that Home has market power on international markets. With a unique Foreign excess supply for any world market price p^*, Home's influence on p^* can be represented by a function G^h:[8]

$$\frac{dp^*}{dM^{Yh}} = p^*_{M^{Yh}} \equiv G^h > 0, \quad p^*_{E^{Xh}} < 0 \tag{9}$$

In other words, the price of Y rises due to an increased excess demand for Y through imports into Home. Similarly, the relative price of X falls due to an increased excess supply of X through exports from Home. Obviously, Home's market power influences Foreign's production and consumption through the change in the relative price p^*. It allows Home to behave strategically by influencing the terms of trade. Let us assume that Foreign on the contrary acts as a price taker who does not react strategically. With Home

[7] The results can also be derived for the more general form, where ε is replaced by $\partial W / \partial Z$. However, for the insights to be highlighted in this paper the simpler form is fully sufficient and eases the notation.
[8] This is simply the equivalent of Markusen's (1975) assumption of $E_1 < 0$.

taking its impact on the world market price p^* into account, its imports become a choice variable, which – given the one-to-one correspondence of Foreign demand and price p^* – implicitly determines p^*.

4 Optimal Unilateral Policies

From Home's perspective, optimal policies are those that maximize its welfare as given in Eq.(6), taking into account Eqs.(2) to (5) and (7) to (9). After a simple replacement of output and exports of good *X*, welfare maximization is tantamount to the optimal choice of domestic production and imports of good *Y*:

$$\begin{aligned}\max_{Q^{Yh},M^{Yh}} W^h = \max_{Q^{Yh},M^{Yh}} \{ & U^h[T^h(Q^{Yh}) - M^{Yh} p^*(M^{Yh}),\, Q^{Yh} + M^{Yh}] \\ & - \varepsilon[\gamma^{Xh} T^h(Q^{Yh}) + \gamma^{Yh} Q^{Yh} + \gamma^{Xf} T^f(Q^{Yf}(p^*(M^{Yh}))) + \gamma^{Yf} Q^{Yf}(p^*(M^{Yh}))]\}\end{aligned} \tag{10}$$

implying the two first-order conditions (i) $\frac{dW^h}{dQ^{Yh}} \overset{!}{=} 0$ and (ii) $\frac{dW^h}{dM^{Yh}} \overset{!}{=} 0$.

From condition (i) one obtains:

$$U^h_{C^{Xh}} T^h_{Q^{Yh}} + U^h_{C^{Yh}} = \varepsilon(\gamma^{Xh} T^h_{Q^{Yh}} + \gamma^{Yh}) \tag{11}$$

At Home's optimal point of production, the marginal benefit from producing an additional marginal unit of *Y* (with a corresponding reduction of *X*) balances the associated marginal change in damages. With profit-maximizing producers, the marginal rate of (technical) transformation of producing goods *X* and *Y* equals the producer price *p*. Therefore, we obtain from Eq.(1):

$$p = -T^h_{Q^{Yr}} \tag{12}$$

In the same manner, optimality of consumption is achieved when the marginal rate of substitution equals the consumer price, denoted by *q*:[9]

$$q = \frac{U^h_{C^{Yh}}}{U^h_{C^{Xh}}} \tag{13}$$

Inserting these expressions into Eq.(11) and dividing by $U^h_{C^{Xr}}$ yields:

$$p - q = q^Z(\gamma^{Yh} - p\gamma^{Xh}) \tag{14}$$

[9] Note that there is no need for a country index in the prices *p* or *q*: they always refer to Home, since by assumption Foreign does not employ any policy, and hence all prices in Foreign are given by *p**.

with $\quad q^{Z} = -\frac{\varepsilon}{U^{h}_{C^{Xh}}} \leq 0$ (14b)

where q^Z denotes the price of the environmental externality in terms of X.

Condition (ii) can be written as:

$$U^{h}_{C^{Yh}} - U^{h}_{C^{Xh}}\left(G^{h} M^{Yh} + p^{*}\right) = \varepsilon\, Q^{Yf}_{p*}\, G^{h}\left(\gamma^{Yf} + \gamma^{Xf} T^{f}_{Q^{Yf}}\right) \tag{15}$$

It determines the optimal import quantity of good Y into Home, taking into account its impact on Foreign's emissions via the change in world market prices. In the optimum, the marginal benefit from importing an additional unit of Y (and exporting a corresponding amount of X) exactly balances the associated marginal change in damages due to emissions resulting from Foreign's changed point of production.

Writing the total differential of Eq.(12) – i.e. Foreign's production possibility frontier – and solving for Q^{Yf}_{p*} allows to further specify the producers' reaction to a change in p^*, the world market price of good Y:

$$Q^{Yf}_{p*} = -\frac{1}{T^{f}_{Q^{Yf}Q^{Yf}}} \equiv R^{f} > 0 \tag{16}$$

Finally, inserting Eqs.(12), (14) and (16) into Eq.(15), dividing by $U^{h}_{C^{Xr}}$, and re-arranging terms yields:

$$p^{*} - q = -G^{h}\, M^{Yh} + q^{Z} G^{h} R^{f} (\gamma^{Yf} - p^{*}\gamma^{Xf}) \tag{17}$$

We can now determine the optimal production tax as well as the optimal import tariff on good Y, assuming that these policies only affect relative prices (i.e. are implemented through lump-sum transfers). The former is given by the difference between domestic producer and consumer prices, Eq.(14), and the latter by the difference between the world market price and the domestic consumer price, Eq.(17). This directly yields the expressions for the optimal tax τ on the production of Y and the optimal tariff θ, which are central results of our analysis:

$$\tau = q - p = -q^{Z} (\gamma^{Yh} - p\, \gamma^{Xh}) \tag{18}$$

$$\theta = q - p^{*} = G^{h}\, M^{Yh} \underbrace{- q^{Z} G^{h} R^{f} (\gamma^{Yf} - p^{*}\gamma^{Xf})}_{\theta^{Z}} \tag{19}$$

$$\theta^{Z} = -q^{Z} G^{h} R^{f} (\gamma^{Yf} - p^{*}\gamma^{Xf}) \tag{19b}$$

The interpretation of Eq.(18) is straightforward: As the relative price p is the marginal rate of domestic transformation and substitution, respectively, any marginal change along Home's production possibility frontier that increases the production of good *Y* by one unit decreases the production of good *X* by *p* units. This, in turn, increases emissions by $(\gamma^{Yh} - p\,\gamma^{Xh})$ units and decreases utility by $q^{Z}(\gamma^{Yh} - p\,\gamma^{Xh})$. Hence, Eq.(18) simply states that the optimal production tax on good *Y* should internalize the emission externality arising from a marginal increase of domestic production of *Y*. Since $q^{Z} < 0$, we get $\tau > 0$ only if $\frac{\gamma^{Yh}}{p} > \gamma^{Xh}$, i.e. if production in Home's *Y* sector has a higher carbon intensity (in emissions per output value) than its *X* sector.[10]

Home's optimal tariff, as characterized by Eq.(19), consists of two parts: The first part, $G^{h}M^{Yh}$, does not depend on the environmental externality (as $M^{Yh} > 0$, this expression is non-negative). It represents the gains from influencing the terms of trade to depress the relative price of Home's imports, which is well known from the so-called 'optimal tariff' literature (c.f. Markusen et al., 1995, Ch.15). The second part, which we call the 'optimal carbon tariff' for the remainder of this paper, θ^{Z} (Eq. (19b)), captures the environmental externality associated with the import of good *Y*. According to Eq.(9), one additional import of *Y* raises the world market price by G^{h}. This affects Foreign's production pattern by increasing production of *Y* by R^{f} and decreasing production of *X* by $p^{*}R^{f}$ units. This leads to an increase in global emissions amounting to $G^{h}R^{f}(\gamma^{Yf} - p^{*}\gamma^{Xf})$ and lowers Home's welfare by $q^{Z}G^{h}R^{f}(\gamma^{Yf} - p^{*}\gamma^{Xf})$. The optimal carbon tariff simply internalizes this externality caused by a marginal increase of production of *Y* in Foreign by influencing world market prices (i.e. Foreign's terms of trade) accordingly, reaffirming Markusen's (1975) assertion that "[o]ne country cannot tax foreign producers, for example, but if the country has monopoly power in trade, it can generally influence foreign production by changing world commodity prices".

Proposition 1: *In the presence of a global environmental externality, Home's optimal carbon tariff θ^{Z} will be positive (negative) if – in terms of emissions per output value – Foreign's export sector is more (less) carbon intensive than its non-export sector.*

Proof: The proposition follows directly from the expression for θ^{Z}. ■

In a general equilibrium setting, imposing a positive tariff influences the terms of trade such that the relative price of Foreign's exports declines. This shifts Foreign's production from the export sector to the non-export sector and results in lower emissions in Foreign exactly if its export sector is more carbon intensive than its non-export sector. This finding is in line with Leamer (1980), who argues (i) that comparing a country's imports with its exports does not allow drawing conclusions regarding its comparative advantage and (ii) that trade theory suggests comparing exports with domestic consumption instead. In particular, comparing emissions embodied in Home's exports with those embodied in its imports does not give an indication of the sign of the optimal carbon

[10] The latter condition can perhaps be better understood when written as $\gamma^{Yh}/p_Y > \gamma^{Xh}/p_X$.

tariff. This outcome tends to be overlooked in the current debate, as in a model with only one polluting good (as e.g. Markusen, 1975, or Elliott et al., 2010) comparing exports with imports is identical to comparing exports with domestic consumption.

Corollary 1: *When in both regions emissions are associated only with the production of the good that is imported by Home, then Home's optimal carbon tariff θ^Z will always be positive, and θ^Z will be strictly proportional to the amount of embedded carbon in the imported good.*

To see this, set the emission intensities of sector X to zero, $\gamma^{Xh} = \gamma^{Xf} = 0$, and again evaluate Eqs.(18) and (19), leading to $\tau = -q^Z \gamma^{Yh}$ and $\theta^Z = -q^Z G^h R^f \gamma^{Yf}$, respectively. This reproduces Markusen's (1975) result, which – in a naïve interpretation – could be seen to suggest that the optimal carbon tariff depends *in general* only on the amount of carbon embodied in the imported good. However, in the case in which all goods cause emissions, this line of reasoning can be very misleading.

5 *Existing and Proposed Policies: Production vs. Consumption-Based Approach*

When thinking about actual policy implications, it appears not sufficient to examine exclusively the optimal carbon tariff. In the case of climate policy the use of market power for environmental purposes could be regarded as being highly controversial in political terms, which might explain why policy-makers have so far refrained from openly pursuing such policies. Instead, they resort to regulating domestic emissions, such as in the Kyoto Protocol or the European emissions trading scheme. However, as already discussed, this policy approach has been strongly criticized for its tendency to induce leakage, and policies based on consumed carbon have been proposed as a supposedly superior alternative. In the following section, we compare production- and consumption-based emission policies (also with respect to the optimal policy), and examine their impacts on leakage.

5.1. Production-Based Emission Policy

In this section, we derive the first-order conditions characterizing an equilibrium of the global economy when Home's only policy consists of adopting some production-based carbon constraint.[11] This represents the current state under the Kyoto Protocol, which obliges the large majority of industrialized countries to put a cap on the amount of carbon emissions *produced* on their territory. In our framework, this can be represented by Home implementing a suitable per-unit carbon tax on domestic emissions.

[11] We use the term 'some' to indicate that the level of the policy is not derived by optimization but can be arbitrary. Hence, we do not discuss second-best production-based policies, as done by Markusen (1975).

Formally, a per-unit carbon tax μ on emissions is equivalent to a tax levied on goods X and Y proportional to the emissions generated during their production. As a consequence, the standard first-order conditions equating producer prices (net of taxes) to the marginal rate of transformation and consumer prices to the marginal rate of substitution (c.f. Eqs.(12) and (13)) applying to profit-maximizing firms and utility-maximizing consumers in Home are given by:

$$\frac{q-\gamma^{Yh}\,\mu}{1-\gamma^{Xh}\,\mu} = -T^{h}_{Q^{Yh}} = p \tag{20}$$

$$q = \frac{U^{h}_{C^{Yh}}}{U^{h}_{C^{Xh}}} \tag{21}$$

Consequently, the implied wedge between producer and consumer prices in Home becomes:

$$q - p = \mu(\gamma^{Yh} - p\gamma^{Xh}) \tag{22}$$

This expression is identical to the optimal production tax τ of Eq.(18) whenever the carbon tax μ correponds to Home's social costs of carbon, i.e. $\mu = -q^{Z}$. Since by assumption there are no other taxes or distortions, we have $q = p^{*}$, which is equivalent to a tariff $\theta = 0$. By contrast, in general the optimal tariff described in Eq.(19) is only zero if Home can be considered a small economy, i.e. if $G^{h} = 0$.

Corollary 2: *If it has market power on the world market, a production-based emission policy is not optimal for Home*

This also implies that in the case without market power the production-based emission policy is optimal for Home.

Eqs.(20) and (21), as well as the tax level μ under which Z^h is realized can also be derived by solving Home's welfare maximization problem under the constraint that its *domestic* emissions Z^h do not exceed a certain emission cap $\overline{Z}^{h}$. Given that firms and consumers in Home have by themselves no means to coordinate and employ their (potential) market power, Home can be modelled as taking the international price p^* as given:

$$\begin{aligned} \max_{Q^{Yh},M^{Yh}} W^{h} &= \max_{Q^{Yh},M^{Yh}} U^{h}[T^{h}(Q^{Yh}) - M^{Yh}p^{*},\, Q^{Yh} + M^{Yh}] \\ &\quad s.t. \quad \gamma^{Xh}T^{h}(Q^{Yh}) + \gamma^{Yh}Q^{Yh} \le \overline{Z}^{h} \end{aligned} \tag{23}$$

which implies a relation $\mu(\overline{Z}^{h})$ and, along with the market clearing conditions, also

$p^*(\bar{Z}^h)$. The latter implies that even though Home does not take its impact on world market prices explicitly into account, it actually influences Foreign's emissions via p^* when choosing $\bar{Z}^h$. This, of course, is the potential cause of leakage, i.e. a rise in Foreign emissions in response to a reduction in Home's emissions. To understand whether or not a production-based carbon tax μ causes leakage, we need to analyze the general equilibrium implications of an increase of μ (equivalent to a decrease of $\bar{Z}^h$) on Foreign emissions. The latter are given by:

$$Z^f = \gamma^{Xf} T^f (Q^{Yf}) + \gamma^{Yf} Q^{Yf} \tag{24}$$

Recall Eq.(16) stating $Q^{Yf}_{p*} = R^f > 0$ for the impact of a change in p^* on Foreign's production as well as $-T^f_{Q^{Yf}} = p^*$ from Eq.(12). We thus obtain for the marginal impact of a change in p^* on Foreign's emissions:

$$Z^f_{p*} = \gamma^{Xf} T^f_{Q^{Yf}} Q^{Yf}_{p*} + \gamma^{Yf} Q^{Yf}_{p*} = \left(\gamma^{Yf} - p^* \gamma^{Xf}\right) R^f \tag{25}$$

Lemma 1: *An increase in the relative world market price p^* for Foreign's export good Y will lead to an increase (decrease) in Foreign's emissions if the emission intensity (in terms of emissions per output value) in Foreign's export sector Y is higher (lower) than in its non-export sector X, i.e. if* $\frac{\gamma^{Yf}}{p^*} > \gamma^{Xf}$.

Proof: The term R^f is always positive – producers increase the output of good *Y* if its relative price increases), so that Eq.(25) is positive whenever the term in parenthesis is positive. ■

It is straightforward to see that the increase in the relative price for *Y* will shift Foreign's production towards *Y* and will thus raise Foreign's emissions if the *Y*-sector is the emission intensive sector relative to Foreign's *X* sector.

The general equilibrium effect of an increase in Home's production-based carbon tax μ is captured by the following Lemma:

Lemma 2: *An increase in Home's carbon-based production tax μ leads to an increase (decrease) in the relative world market price p^* if Home's Y-sector is more (less) emission intensive than its X-sector.*

Proof: See Appendix.

Intuitively, if Home's Y-sector is more carbon intensive than its X-Sector, the production-based carbon tax shifts Home's production from Y to X. Instead of demanding the domestic good Y, consumers raise their demand for Y-imports from Foreign, which raises the relative world market price of Y.

Based on Lemma 1 and 2, we can state the conditions under which leakage occurs:

Proposition 2: *A unilateral production tax on emissions in Home leads to leakage if the relatively more emission intensive sectors (in terms of emissions per real output value) in Home and Foreign produce the same good (e.g. good Y).*

Proof: By Lemma 2, if Home increases or introduces a production-based carbon tax μ on the goods produced by Home, the international price of the good with the higher emission intensity increases. By Lemma 1, leakage occurs in case of a price increase of the good that is relatively more emissions intensive in Foreign. ■

5.2. Consumption-Based Emission Policy

In analogy to the formalization of a constraint on production related emissions in Eq.(23), we can derive the market outcome under a consumption-based policy from a welfare maximization problem with a constraint for domestically *consumed* emissions, taking prices as given. This means, emissions that are implicitly exported via exports of goods are subtracted from Home's emission budget, while emissions that are implicitly imported via imports of goods are added. Home's emission constraint, therefore reads:

$$\gamma^{Xh}\left[T^h(Q^{Yh}) - M^{Yh}p^*\right] + \gamma^{Yh}Q^{Yh} + \gamma^{Yf}M^{Yh} \leq \overline{Z}^h \tag{26}$$

Home's behavior can thus be expressed as an optimization problem in terms of the choice variables Q^{Yh} and M^{Yh} . Using ρ as the Lagrange-multiplier that denotes the shadow-price of emissions embodied in Home's consumption - which are constrained to $\overline{Z}^h$ - we obtain:

$$\begin{aligned} \max_{Q^{Yh},M^{Yh}} W^h = \max_{Q^{Yh},M^{Yh}} & U^h[T^h(Q^{Yh}) - M^{Yh}p^*),\, Q^{Yh} + M^{Yh}] \\ s.t.\ & \gamma^{Xh}\left[T^h(Q^{Yh}) - M^{Yh}p^*\right] + \gamma^{Yh}Q^{Yh} + \gamma^{Yf}M^{Yh} \leq \overline{Z}^h \end{aligned} \tag{27}$$

This formulation of the problem does not include explicit carbon-based tariffs or border taxes; demand for Foreign's goods is only constrained by a purely domestic regulation of emissions embodied in consumption.[12]

[12] This representation also shows how the regulation of consumed emissions becomes formally equivalent to the regulation of production-related emissions if the specific intensities (in terms of emissions per value) of Home's imported goods and its exporting sector are identical. In other words, the asymmetry between consumption- and production-based approaches is caused by the difference between different sectors in Home and Foreign, not by the difference between domestic and Foreign goods of the same sector.

With $\sigma = \frac{\rho}{U^h_{C^{Xh}}}$ as the consumption-based carbon tax, the first-order conditions are then straightforward to compute and given by:

Producer: $$p = \frac{q - \sigma \gamma_y^h}{1 - \sigma \gamma_x^h} \quad (28)$$

Consumer: $$p^* = \frac{q - \sigma \gamma_y^f}{1 - \sigma \gamma_x^h} \quad (29)$$

We can now examine the wedges that the consumption tax drives between producer and consumer prices and between consumer and world market prices, respectively:

$$q - p = \sigma\left(\gamma^{Yh} - p\ \gamma^{Xh}\right) \quad (30)$$

$$q - p^* = \sigma\left(\gamma^{Yf} - p^*\ \gamma^{Xh}\right) \quad (31)$$

Hence, the consumption-based policy can be implemented as a combination of a tax on the production of *Y* (Eq.(30)) and a tariff (Eq.(31)). If the consumption-based carbon tax σ equals the social cost of carbon, then - as in the previous section - the resulting tax on the production of good *Y* corresponds to the optimal production tax identified in Eq.(18). From the representative consumer's point of view, the consumption-based carbon tax σ puts a price on the externality caused by embodied emissions. This applies to the choice between domestic *X* and domestic *Y* goods (Eq.(30)), as well as to the choice between domestic *X* and imported *Y* goods (Eq.(31)). In particular, the tariff is equivalent to levying the carbon price on emissions embodied in imports ($\sigma \gamma^{Yf}$) and reimbursing it for domestically produced goods that are exported ($-\sigma p^* \gamma^{Xh}$). This practice is generally known as *border tax adjustment* (BTA).

Intuitively, BTA combined with a production based carbon tax results in a policy that targets the consumption instead of the production of emissions. However, note that the tariff implied by a consumption-based policy (Eq.(31)) deviates from the optimal carbon tariff (Eq.(19)) by (i) not taking into account the reaction of the world market price (G^h) and of Foreign producers (R^f), as well as by (ii) applying the differential in carbon intensity between Home's imports and exports instead of the difference between Foreign's export sector and its non-export sector. Evidently, a tax on carbon intends to internalize the negative impacts brought about by a certain quantity of emissions. The production tax follows this logic. But in a general equilibrium setting the idea of 'putting a price on carbon' cannot simply be transferred to imports. Reducing imports of emissions embodied in traded goods by a certain quantity clearly does not – due to induced changes in Foreign's production and consumption patterns – avoid the same quantity of emissions being released into the atmosphere.

Corollary 3: *A consumption-based emission policy is in general not optimal for Home.*

This observation also raises the question whether the economic logic underlying WTO regulations (cf. Bagwell and Staiger, 2004) can be sensibly applied to carbon taxes: Obviously, BTA constitutes an optimal instrument to internalize externalities arising from local consumption (which are addressed e.g. by taxation of alcohol or tobacco). Yet, this argument does not hold for a *global* consumption externality, as in general Home's government has no more authority to regulate foreign consumers than foreign producers.

We can now use Eqs.(28) and (29) to state the following Lemma:

Lemma 3: *An increase in Home's consumption-based carbon tax σ will lead to:*

(i) *an increase in the world price p^* for Foreign's export good Y if both Home's X- and Y-sector are more emission intensive than Foreign's export sector Y,*

(ii) *a decrease in p^* if both Home's X- and Y-sector are less emission intensive than Foreign's export sector Y,*

(iii) *an ambiguous outcome if one of Home's sectors is more and the other less emissions intensive than Foreign's export sector Y, and*

(iv) *an increase (decrease) in p^* if the X-sector has the same emission intensity in both regions and the Y-sector as well (i.e. in the symmetric case $\gamma^{Xh} = \gamma^{Xf} \neq \gamma^{Yh} = \gamma^{Yf}$) and the Y-sector, which is Foreign's export sector, has a lower (higher) emission intensity than the X-sector.*

Proof: See Appendix.

With the help of Lemma 3, we can now specify the effects of a consumption-based policy on carbon leakage:

Proposition 3: *A policy targeting emissions embodied in Home's consumption has the following effect: if Home's X- and Y-sector are both less (more) emission intensive than Foreign's export sector Y, a consumption-based policy will lower (raise) the international price of Home's import good Y and leakage will occur if Foreign's export sector Y is less (more) emission intensive than its non-export sector X .*

Proof: Lemma 3 can be used to determine whether the price of the imported good increases or decreases, and Lemma 1 can then be applied to assess Foreign's change of emissions and thus the incidence of leakage. ■

If Home's carbon intensity is higher than Foreign's in both sectors, the consumption-based carbon tax shifts Home's demand from domestic production to imports. As a consequence, production in Foreign shifts from the non-export sector X to the export sector Y, increasing emissions if the carbon intensity in Foreign's Y-sector is higher than in its X-sector.

The symmetric case ($\gamma^{Xh} = \gamma^{Xf} \neq \gamma^{Yh} = \gamma^{Yf}$) deserves to be treated separately:

Corollary 4: *If the X-sector has the same emission intensity in both regions and the Y-sector as well, and the Y sector is more (less) emission intensive than the X sector, a consumption-based policy in Home will lower (raise) the international price of Y and in either case lower emissions in Foreign, i.e. induce negative leakage..*

Proof: Applying Lemma 3 (iv) in combination with Lemma 1.

In this special case, consumption based policies affect production in the same direction in both countries due to the assumption of symmetry. Therefore, such policies shift production from the relatively carbon intensive to the less carbon intensive sector in both regions so that leakage is avoided. This result is in accordance with Markusen's (1975) result, who assumes one clean and one dirty sector (i.e. $\gamma^{Xr} = 0$). We generalize this result for the case of two sectors with different emission intensities. However, note that it does not hold in the more general case in which no restrictions regarding the emission factors are imposed.

6 Comparison and Discussion of the Policy Measures

As border-tax adjustment in combination with production-based accounting of emissions and consumption-based accounting constitute equivalent instruments, there is no need to discuss them separately. Having identified the effects of optimal policies as well as those of production- and consumption-based approaches, we can now compare the policy options that are currently debated. According to Eq.(19), Home's optimal tariff consists of two parts, wherein only the second part – the optimal carbon tariff of Eq.(19b) – is related to the environmental externality. We adopt the point of view that the policies under consideration should only be evaluated in terms of their effectiveness regarding the environmental externality, not in how far they can be used as a protectionist device to influence the terms of trade in Home's favor. Therefore, we compare production- and consumption-based policies only with the optimal carbon tariff of Eq.(19b) and not with the overall tariff that would maximize Home's welfare (Eq.(19)). Otherwise, one could, for instance, arrive at the conclusion that a policy that actually increases leakage can increase welfare not because of its environmental effect, but simply because it exploits market power to decrease the relative price of imports.

6.1. Production vs. Consumption-Based Policies under Full Information

Corollaries 2 and 3 have already established that in general neither production- nor consumption-based polices are optimal. Hence, the following question arises: if production-based and consumption-based emission accounting are the only instruments available to policy-makers, which one should be preferred? From the discussion in Section 5 it should be clear that none of these instruments is *a priori* more successful than the other in addressing leakage (as their effects depend on specific parameter values). If the carbon price put on emissions related to production or consumption, respectively, corresponds to Home's social cost of carbon (i.e. $\mu = -q^Z$ and $\sigma = -q^Z$), the wedge between consumer and producer prices is equivalent to the optimal tax levied on the production of Y (Eq.(18)).

In order to establish a ranking between production- and consumption-based policies, we have to distinguish between the following two cases: (i) if the tariff implied by a consumption-based emission policy of Eq.(31) and the optimal carbon tariff of Eq.(19b) have opposite signs, consumption-based accounting would in fact increase leakage compared to the (zero) carbon tariff implied by the production-based measure. Hence, the latter is unambiguously closer to the optimal carbon tariff than the former. (ii) By contrast, if the signs of the consumption-based emission policy of Eq.(19b) and the optimal carbon tariff of Eq.(31) are identical, the tariff implied by a consumption-based emission policy clearly induces less leakage than the production-based one. However, this tariff could be higher than the optimal carbon tariff, with the result that the adverse impacts of price distortions exceed the positive effects of reduced carbon leakage. It is in this case not possible to make general statements regarding the welfare effects of consumption- versus production-based measures without further specifying G^h and R^f.

This leads us to the following proposition:

Proposition 4: *Production-based policies targeting emissions at Home better approximate Home's optimal carbon tariff of Eq. (19b) than consumption-based polices if Foreign's exports are less (more) emission intensive than its non-exporting sector and Home's export and non-export sectors are both less (more) emission intensive than Foreign's export sector.*

Proof: Comparing the expression for the optimal carbon tariff (Eq.(19b)) reveals that if Foreign's exports are less (more) emission intensive than its non-exporting sector, the optimal carbon tariff would be negative (positive). However, with consumption-based policies, the implied tariff given by Eq.(31) would be positive (negative) if Foreign's exports are more emission intensive than its imports from Home. Under the conditions of the proposition, the tariff implied by a consumption-based policy has the opposite sign of the optimal carbon tariff and thus clearly approximates Home's optimal carbon tariff less accurately than a tariff of zero (as implied by a production-based policy). ■

According to Lemma 3, if both Home's export and non-export sector are less (more) emission intensive than Foreign's export sector, a consumption-based policy lowers (raises) the price p^* of Foreign's exports. In this case, a consumption-based policy leads to more leakage than a production-based approach if Foreign's exports of Y are less (more) emission intensive than its non-export sector X (as stated in Lemma 1).

6.2. Border Tax Adjustment Using the Best Available Technology Approach

In view of the substantial informational requirements to successfully implement a consumption-based approach – and to circumvent potential problems related to the WTO-principle of non-discrimination – some alternatives have been proposed. These include the best-available-technology approach as adopted by the proposed Waxman-Markey Bill of the United States, which calculates emissions embodied in imports based on the home country's emission factors, i.e. assuming that the exporting country employs modern and efficient technologies equivalent to industrialized countries' standard (Ismer and Neuhoff, 2007).

Again assuming that the emission tax equals Home's social cost of carbon (i.e. that the production tax implied by Eqs.(22) and (30), respectively, equal the optimal one of Eq.(18), i.e. $\mu = -q^Z$ and $\sigma = -q^Z$), the following holds with regard to the ranking of consumption- versus production-based policies under a best-available technology approach.

Proposition 5: *With respect to consumption-based policies that use a best-available-technology approach, production-based polices better approximate Home's optimal carbon tariff of Eq.(19b) than consumption-based policies if the relatively more emission intensive sector in Home and Foreign produce different goods,production- and consumption-based approaches cannot be ranked with respect to proximity to Home's optimal carbon tariff of Eq.(19b) if the relatively more emission intensive sectors in Home and Foreign produce the same good.*

Proof: Using Eq.(31) and setting Foreign's emission coefficients identical to Home's, the wedge between consumer and world market price becomes:

$$q - p^* = \sigma\left(\gamma^{Yh} - p^* \gamma^{Xh}\right) \tag{32}$$

Comparing Eq.(32) with the optimal carbon tariff of Eq.(19b) reveals that they have opposite signs if the relatively more emission intensive sector in Home and in Foreign, respectively, produce different goods (e.g. the X-sector in Home but the Y-sector in Foreign). Production-based measures (implying a tariff of zero) would then obviously be closer to the optimal carbon tariff than the one implied by the consumption-based policy, which carries the opposite sign. On the other hand, if the relatively more emission intensive sector in Home and Foreign both produce the same good, the tariff implied by the consumption-based policies has the same sign as the optimal carbon tariff. As the former can then either exceed or fall short of the optimal level, ranking consumption- and production-based measures in terms of Home's welfare is in this case impossible without additional information. ■

7 *Practical Implications and Relevance*

7.1. Confronting the Model with Empirical Evidence

This section confronts the propositions derived in the previous sections with the 'real world' empirical context. In particular, we refer to the dataset created by Davis and Caldeira (2010)[13] containing the carbon contents of exports, imports and total production as well as the corresponding values of exported, imported and produced goods. Using this dataset, Table 1 in the Appendix reports our own calculation of carbon intensities for a set of selected countries and regions. We focus on an assessment of trade measures that the European Union or the United States could possibly impose towards developing countries that produce rising amounts of carbon emissions, in particular towards China. In Table 1, the first three columns show the carbon emissions embodied in exports, imports and total production. The fourth column shows the ratio of the carbon intensity of exports to the carbon intensity of total production. A value greater than one thus indicates a higher carbon intensity in exports than in total production, and since total production consists of exports and the non-export sector also a higher carbon intensity in the export than in the non-export sector. Similarly, the last column shows the ratio of the carbon intensities of imports versus exports.

With regard to Proposition 1, the data reveal that the carbon intensity of exports is lower than the carbon intensity of total production and thus of the non-export sector for most countries (77 out of 95 in the full data base), including China. Therefore, according to our theoretical framework, the optimal carbon tariff on imports from these countries would be negative in the majority of cases, and imposing a positive carbon tariff would increase carbon leakage.

In terms of Proposition 2, one can expect that – even though the carbon intensity of energy production widely varies – the ranking of economic sectors by carbon intensity is to a large extent determined by technological factors and hence similar across countries.[14] Hübler (2009), for example, computes carbon intensities of 30 goods based on the GTAP 7 data and finds a very similar ranking of carbon intensities for China, an aggregate of other developing regions, and an aggregate of industrialized countries. Hence, our theoretical results imply that leakage is likely to occur under a production-based policy.

An exemplary comparison reveals that the carbon intensities of exports and total production (and thus necessarily of the non-export sector, too) in the EU and the US are both lower than the carbon intensity of China's exports. Moreover, as for most countries, the carbon intensity of China's exports is lower than that of China's total production. Therefore, according to Proposition 3, leakage is likely to occur under a consumption-based policy or equivalently BTA. Furthermore, according to Proposition 4, if consumption-based policies are applied on imports from China, they are expected to result in higher leakage than production-based policies. Hence, if implemented by the EU or the US, the resulting wedge between world market prices and domestic consumer prices approximates the optimal carbon tariff (which would in fact be negative) less well than production-based policies. One could also imagine that the EU introduces carbon

[13] Their supplementary online material provides data for 95 countries. We aggregated the data of the 24 EU member countries contained in the dataset into one EU region. Data for 'World' was already included.
[14] For example, the production of cement or steel is energy intensive and thus carbon intensive in all countries, while the provision of financial services has in general a rather low energy- and carbon-intensity.

based policy measures towards the US. In this case, the data reveal a lower carbon intensity of EU exports and total production than of both US exports and total production. However, carbon intensities of exports and of total production are almost equal in the US. Therefore, the optimal carbon tariff would be about zero. As a consequence, no matter whether China or the US are targeted, a production-based policy appears as the preferable policy for the EU.

The symmetric case of Corollary 4 requires identical carbon intensities in each sector across different countries. Basically, one can expect to find similar energy intensities because of the use of similar technologies for producing certain goods in similar economies. But the energy mix and thus the emission intensity of energy supply vary greatly across countries. Therefore, an exact match of carbon intensities across countries, which is a necessary condition for Corollary 4, is unlikely in reality. It is not visible in Table 1 either; a detailed examination would require sectoral data, though.

Finally, as the most emission intensive sectors are similar across countries, Proposition 5 suggests that it is not possible to establish a clear ranking between production-based policies and consumption-based policies that use a best-available-technology approach.

7.2. Model Limitations and Caveats

Our model makes several stylized assumptions: It only represents trade between two countries in two goods and abstracts from the sectoral composition of traded goods, current account surpluses or deficits, changes in production technologies and factor inputs, strategic interactions, and additional channels of leakage (such as free-rider and supply-side leakage). Complex numerical models – such as computable general equilibrium (CGE) models – implement some of these aspects. As a consequence, it is conceivable that in these models BTA can to some extent reduce leakage. In this section, we address the stylized assumptions in detail.

First, with trade measures based on carbon contents, a model with multiple countries is likely to predict that trade gets redirected and increasingly takes place between those countries that have implemented climate polices on the one hand (trade creation), and between those countries that do not have such policies on the other hand (trade diversion). Hence, in such a setting the effect of carbon-based border measures can be expected to be diminished. Second, when taking the multi-sectoral composition of traded goods into account, a carbon-based tariff can be expected to shift the composition of trade towards goods with lower carbon intensities. It is not clear if in this case a carbon tariff has a stronger or a weaker effect than in a two-sector model. Third, an analysis of unbalanced trade could only be conducted within a dynamic model, and the question remains in how far environmental and trade policy are appropriate instruments to tackle underlying macro-economic imbalances. Fourth, our model describes emissions in each region by fixed emission factors. It can be argued that carbon-based tariffs pose an incentive for Foreign to adopt cleaner production technologies or switch to less carbon-intensive fuels or intermediate inputs (e.g. Copeland 1996). Fifth, carbon-based tariffs could not only act as an incentive for Foreign to decarbonize, but also trigger retaliation in the form of countervailing tariffs. Accounting for these strategic interactions would require a game-theoretic framework, which we consider to be beyond the scope of this paper. Sixth, even though additional channels of leakage other than specialization are clearly important, it is far from clear how they are affected by trade policy and how they should be represented in a trade model.

However, these limitations of our theoretical model do not invalidate our basic message: the rationale behind environmental policies is to provide the right incentives for firms and consumers by pricing in externalities. As we have demonstrated, trade policies influence patterns of production and consumption through their effect on the terms of trade, i.e. on relative prices. These general equilibrium implications are often overlooked in the current debate, leading to an under-appreciation of the practical consequences of measures like consumption-based accounting of emissions and border tax adjustment. In that sense, the simplifications in our model discussed above actually point to further complex issues that should be considered (and understood) before trade policy is used to advance environmental objectives.

8 Summary and Conclusions

This paper employs a reduced form general equilibrium 2x2 trade model to assess the implications of production- and consumption-based policies for the regulation of carbon emissions, where the latter approach can be implemented by the means of border tax adjustment (BTA). After identifying the optimal tariff to address carbon leakage, it carries out a comparison with existing and proposed policies. Finally, it confronts the theoretical results with empirical data. Our findings indicate that important general equilibrium effects have been neglected in previous analyses, possibly paving the way for misleading conclusions regarding the effectiveness of proposed policies such as consumption-based accounting of emissions and border tax adjustment. The model further reaffirms that trade policies can be expected to have an impact on foreign producers only to the extent to which the imposing country is able to influence world market prices (i.e. possesses market power), thereby emphasizing the limited possibilities to influence other countries' domestic production decisions offered by trade measures.

Comparing production- and consumption-based approaches for putting a price on carbon has revealed that in general neither corresponds to the optimal policy. However, imposing the optimal carbon tariff derived in Section 4 might not be feasible under WTO stipulations and, moreover, requires very specific information, such as the elasticity of world market prices with respect to changes in the home country's imports and the price elasticity of the foreign country's production. Therefore, the only choice left to policy makers might be between production-based and consumption-based approaches to target emissions. We have compared these policies and identified conditions under which one is unambiguously superior to the other (from the perspective of the country putting the policy in place). Based on empirical data, our results suggest that if implemented by the EU or the US towards China, carbon leakage is likely to occur under both production-based and consumption-based carbon policies, but production-based measures are preferable over consumption-based ones, as the latter would lead to an increase in leakage vis-à-vis the former. Similarly, for the EU a production-based policy is also preferable to a carbon-based policy targeted at the US.

From a policy perspective, the findings presented cast considerable doubt on the practical feasibility of trade measures to effectively reduce carbon emissions in other countries. As we have demonstrated, consumption-based accounting of emissions or equivalently BTA are fraught with uncertainty regarding economic effects and parameters. Their implementation would require a large amount of information and considerable political capital, while their alleged positive effects remain unproven. Thus, it seems at least debatable if these measures rightly deserve the prominent place they occupy in the current debate. Their surprisingly wide-spread support in the political arena – despite their questionable effects – can perhaps be explained by pointing to the incentive to use such environmental policies as a means to realize gains from influencing the terms of trade in the home country's favour, a practice that has been criticized as 'green protectionism' (Evenett and Whalley, 2009).

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Appendix: Table 1

Carbon intensity of Country or region	Exports [kg / $]	Imports [kg / $]	Production [kg / $]	**Exports /** production	Imports / exports
Singapore	0.14	0.36	0.48	0.28	2.66
Iran	0.93	1.24	2.66	0.35	1.33
Paraguay	0.20	0.85	0.49	0.42	4.16
Vietnam	0.96	0.86	2.28	0.42	0.90
Malaysia	0.66	0.32	1.51	0.44	0.48
Ecuador	0.47	0.90	0.99	0.48	1.91
Thailand	0.96	0.49	1.65	0.58	0.52
Morocco	0.48	0.67	0.80	0.60	1.39
Nigeria	0.86	0.83	1.42	0.61	0.97
Mauritius	0.33	0.82	0.54	0.61	2.48
Switzerland	0.07	0.42	0.11	0.61	6.09
Hong Kong	0.15	0.78	0.24	0.61	5.30
Costa Rica	0.23	0.47	0.36	0.63	2.07
Taiwan	0.55	0.38	0.85	0.65	0.69
Korea	0.48	0.62	0.73	0.65	1.30
Sweden	0.10	0.46	0.16	0.66	4.45
Pakistan	0.91	1.16	1.37	0.66	1.28
China	**2.13**	**0.49**	**3.05**	**0.70**	**0.23**
Mexico	0.43	0.57	0.60	0.72	1.32
Indonesia	0.91	0.75	1.26	0.72	0.83
Tunisia	0.58	0.53	0.80	0.73	0.92
Bolivia	0.77	0.79	1.03	0.74	1.03
EU	**0.25**	**0.49**	**0.32**	**0.78**	**1.98**
Peru	0.41	0.85	0.48	0.85	2.09
Turkey	0.65	0.79	0.77	0.85	1.21
Egypt	1.73	0.88	1.99	0.87	0.51
Russian Federation	2.43	0.85	2.63	0.92	0.35
World	0.61	0.61	0.66	0.93	1.00
India	2.06	0.88	2.12	0.97	0.43
US	**0.49**	**0.77**	**0.50**	**0.99**	**1.56**
Canada	0.57	0.52	0.57	1.01	0.92
Japan	0.30	0.91	0.28	1.06	3.05
New Zealand	0.36	0.68	0.32	1.12	1.89
Argentina	1.20	0.58	1.04	1.16	0.49
Brazil	0.78	0.78	0.55	1.41	1.00
South Africa	2.80	0.60	1.94	1.44	0.22
Norway	0.32	0.55	0.20	1.60	1.74
Australia	0.93	0.78	0.53	1.74	0.84

Table 1: Carbon intensities of exports, imports and total production, and measured relative to each other for selected countries derived from data in Davis and Caldeira (2010). Full table available upon request.

Appendix: Proof of Lemma 2:

The market clearing condition for the *Y* world market reads: $M^{Yh} + E^{Yf} = 0$, where both M^{Yh} and E^{Yf} depend upon the world market price p^*. Moreover, the budget balance condition Eq.(3) implies: $p^* M^{Yh} = E^{Xh}$. E^{Xh} depends upon p^* as well as μ, which translates into M^{Yh}. This implies for the derivative of the market clearing condition with respect to a change in Home's carbon tax μ (equivalent to a change of the cap $\overline{Z}^h$): $M^{Yh}(p^*, \mu) + E^{Yf}(p^*) = 0$ and thus

$$\frac{\partial M^{Yh}}{\partial \mu} + \frac{\partial M^{Yh}}{\partial p^*}\frac{dp^*}{d\mu} + \frac{dM^{Yf}}{dp^*}\frac{dp^*}{d\mu} = 0 \quad \Rightarrow \quad \frac{dp^*}{d\mu} = \frac{-\dfrac{\partial M^{Yh}}{\partial \mu}}{\left(\dfrac{\partial M^{Yh}}{\partial p^*} + \dfrac{dM^{Yf}}{dp^*}\right)} \tag{A1}$$

Under standard conditions, the terms in the denominator are negative (the 'law of demand').[1] Hence, we only need to compute the sign of the numerator. Using the fact that preferences over consumption are homothetic, Home's imports, $M^{Yh} = C^{Yh} - Q^{Yh}$, can be rewritten by inserting the standard expressions for the consumption of *Y* derived from utility maximizing given an income budget

$$M^{Yh} = \frac{\overline{\eta}}{q} I^h - Q^{Yh} \tag{A2}$$

where $\eta(q)$ denotes the share of Home's real income, I^h, spent on good *X*, and $\overline{\eta}(q) = 1 - \eta(q)$ denotes the share of Home's real income spent on good *Y*. Consumption of *Y* decreases in the relative consumer price of *Y*, denoted by *q*. Since for the moment there are no consumer taxes in place, it is $q = p^*$. Expressing total income as $Q^{Xh} + p^* Q^{Yh}$ leads to:[2]

$$M^{Yh} = \frac{\overline{\eta}}{p^*} Q^{Xh} - \eta\, Q^{Yh} = \frac{\overline{\eta}}{p^*} T^h(Q^{Yh}) - \eta\, Q^{Yh} \tag{A3}$$

Since in Eq.(35) only Q^{Yh} depends explicitly on the production tax, μ, we find

$$\frac{\partial M^{Yh}}{\partial \mu} = \left(\frac{\overline{\eta}}{p^*} T^h_{Q^{Yh}} - \eta\right)\frac{\partial Q^{Yh}}{\partial \mu} = -\left(\overline{\eta}\,\frac{p}{p^*} + \eta\right)\frac{\partial Q^{Yh}}{\partial \mu} \tag{A4}$$

Differentiating the first and the third part of the producers' efficiency condition in

[1] Note that in the present setting both Home and Foreign behave as price-takers

[2] Since both goods, *X* and *Y*, are traded internationally, total income is expressed by applying the international price p^*.

Eq.(20) with respect to Q^{Yh} and solving for $\frac{\partial Q^{Yh}}{\partial \mu}$ yields

$$\frac{\partial Q^{Yh}}{\partial \mu} = \frac{\gamma^{Yh} - q\gamma^{Xh}}{\left(1-\gamma^{Xh}\,\mu\right)^2 \frac{\partial^2 T^h}{\partial \left[Q^{Yh}\right]^2}} \tag{A5}$$

Confronting the last equation with Eq.(16) shows that it will be negative when $\gamma^{Yh} > q\ \gamma^{Xh}$. Therefore, Eq.(A4) will be positive if and only if $\gamma^{Yh} > p^*\ \gamma^{Xh}$, where $p^* = q$. In this case, Eq.(A1) will be positive as well. ■

Appendix: Proof of Lemma 3:

To determine the effect of σ on p^*, we start by differentiating the market clearing condition, obtaining (cf. Eq.(A1)):

$$\frac{dp^*}{d\sigma} = -\frac{\frac{\partial M^{Yh}}{\partial \sigma}}{\frac{\partial M^{Yh}}{\partial p^*} + \frac{\partial M^{Yf}}{\partial p^*}} \tag{A6}$$

Again, both terms in the denominator are negative. To determine the sign of the numerator, we start by further specifying Home's consumption. With homothetic preferences, we have:

$$\frac{C^{Xh}}{C^{Yh}} = \frac{\eta(q)\,q}{\overline{\eta}(q)} \tag{A7}$$

where $\overline{\eta} \equiv 1-\eta$ denotes the share of income spent on good Y, as a function of the domestic consumer price q. Since in equilibrium consumption must exhaust the total real income I^h of home, i.e. $C^{Xh} + p^* C^{Yh} = I^h = Q^{Xh} + p^* Q^{Yh}$, we obtain:

$$C^{Yh} = \frac{\overline{\eta}\, I^h}{\eta\, q + \overline{\eta} p^*} \tag{A8}$$

Using $M^{Yh} = C^{Yh} - Q^{Yh}$, one can simplify M^{Yh} to

$$M^{Yh} = \frac{\overline{\eta}\, Q^{Xh} - \eta\, q\, Q^{Yh}}{\eta\, q + \overline{\eta} p^*} \tag{A9}$$

where the RHS can be expressed completely in terms of p^* and σ, since q and p are dependent via Eqs.(30) and (31). Calculating the derivative $\frac{\partial}{\partial \sigma}$ and collecting terms leads to:

$$\frac{\partial M^{Yh}}{\partial \sigma} = \frac{-\left[\frac{\partial Q^{Yh}}{\partial p}\frac{\partial p}{\partial \sigma}\left(\eta\, q + \overline{\eta} p^*\right)\left(\eta\, q + \overline{\eta} p\right) + \frac{\partial q}{\partial \sigma}\left(\eta\overline{\eta} + q\frac{\partial \eta}{\partial q}\right) I^h\right]}{\left(\eta\, q + \overline{\eta} p^*\right)^2} \tag{A10}$$

The derivative of η with respect to q is connected to the elasticity of substitution Σ of U^h by $\frac{\partial \eta}{\partial q} = \frac{(\Sigma - 1)\eta\,\overline{\eta}}{q}$, leading to the final expression:

$$\frac{\partial M^{Yh}}{\partial \sigma} = \frac{-\left[\frac{\partial Q^{Yh}}{\partial p}\frac{\partial p}{\partial \sigma}\left(\eta\, q + \overline{\eta} p^{*}\right)\left(\eta\, q + \overline{\eta} p\right) + \frac{\partial q}{\partial \sigma}\eta\overline{\eta}\,\Sigma I^{h}\right]}{\left(\eta\, q + \overline{\eta} p^{*}\right)^{2}} \tag{A11}$$

While the denominator is always positive, both terms of the numerator can be either positive or negative, depending on the sign of $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$. Since $\Sigma > 0$, and $\frac{\partial Q^{Yh}}{\partial p}$ is positive as given by Eq.(16), we have the following three cases: (i) Eq.(A11) and hence Eq.(A6) for $\frac{dp^{*}}{d\sigma}$ are positive, i.e. p^{*} increases when σ increases, if $\frac{\partial p}{\partial \sigma} < 0$ and $\frac{\partial q}{\partial \sigma} < 0$ (or if one term is negative and the other term is zero); (ii) Eq.(A11) is negative and hence p^{*} decreases if $\frac{\partial p}{\partial \sigma} > 0$ and $\frac{\partial q}{\partial \sigma} > 0$ (or if one term is positive and the other term is zero); (iii) the impact of σ on p^{*} is ambiguous if $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$ have different signs. To determine the signs of $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$, we obtain from Eq.(31):

$$\frac{\partial q}{\partial \sigma} = \gamma^{Yf} - p^{*}\gamma^{Xh} \tag{A12}$$

while combining Eqs.(30) and (31) yields for p and $\frac{\partial p}{\partial \sigma}$:

$$p = p^{*} + \sigma\frac{\left(\gamma^{Yf} - \gamma^{Yh}\right)}{\left(1-\sigma\,\gamma^{Xh}\right)} \quad \Rightarrow \quad \frac{\partial p}{\partial \sigma} = \frac{\left(\gamma^{Yf} - \gamma^{Yh}\right)}{\left(1-\sigma\,\gamma^{Xh}\right)^{2}} \tag{A13}$$

Therefore, case (i) will hold if both of Home's sectors are more emission intensive than Foreign's export sector *Y*, case (ii) if both of Home's sectors are less emission intensive than Foreign's export sector *Y*, and case (iii) otherwise. In the symmetric case (iv), i.e. when $\gamma^{Xh} = \gamma^{Xf} \neq \gamma^{Yh} = \gamma^{Yf}$, $\frac{\partial p}{\partial \sigma}$ will become zero and Eq.(A11) will simplify so that the sign of $\frac{dp^{*}}{d\sigma}$ only depends on Eq.(A12) for $\frac{\partial q}{\partial \sigma}$. Accordingly, $\frac{dp^{*}}{d\sigma}$ will be positive if the *Y*-sector is less emission intensive than the *X*-sector and negative if it is more emission intensive. ■

Chapter 7

Synthesis and Outlook

This thesis is structured around two fundamental hypotheses: (a) One of the main reasons why climate negotiations have failed to achieve significant progress so far is that they have not paid sufficient attention to the priorities of developing countries. (b) Without a global climate agreement in the short- and mid-term, international climate policy will predominantly be conducted within fragmented regimes. Summarizing and discussing the results presented in this dissertation, this chapter outlines the implications of these hypotheses. It concludes by providing an outlook on possible future research.

1. Economic Development, Energy Use, and Carbon Emissions

The first set of research questions is concerned with the relationship between economic development, energy use, and carbon emissions. Chapter 2 examines the historical development of energy use patterns and carbon emissions in a cross-section of countries. Chapter 3 combines historical data with model projections to evaluate China's current energy and mitigation policies and international pledges.

1.1. Economic Convergence and Convergence of Energy Use Patterns

With regard to the relationship between economic convergence, energy use patterns, and CO_2 emissions, the research presented in Chapter 2 is motivated by the following questions:

- How are energy use patterns and carbon emissions related to individual countries' levels of development?
- Do developing countries that close the gap with industrialized countries' per capita incomes use less energy by adopting more efficient technologies?
- Have industrialized countries' economies entered a stage of 'de-materialization', in which economic growth can continue unabated without increasing energy use and carbon emissions?

The analysis employs a difference-in-differences estimator on panel data to examine how patterns of energy use (characterized by consumption of primary energy carriers and sectoral energy use, and carbon emissions) changed in the process of economic development over the period 1971-2005. The results indicate that for the average developing country economic catch-up has been accompanied by convergence towards the global average for the use of most primary energy carriers, the consumption of final energy in most sectors, and total CO_2 emissions. For OECD countries, on the other hand, economic growth has at least partially been decoupled from energy consumption and our findings suggest that above average rates of economic growth were accompanied by larger improvements in energy efficiency. These results emphasize the need to identify the relevant engines of economic growth, their implications for energy use, and possibilities to achieve low-carbon growth centered on productivity and efficiency improvements rather than capital accumulation.

Clearly, these findings are worrisome from a sustainability point of view: developing countries are currently following development pathways which bring them ever closer towards the unsustainable patterns of energy consumption currently prevailing in wealthier countries. For instance, CO_2 emissions for the average country in the sample employed are about 4.4 tons per capita globally, and about 2.5 tons for developing countries. If countries that catch-up economically with the world average also attain corresponding emission levels, providing an income close to the world average to all people in developing countries would imply an increase of annual global energy-related carbon emissions by more than 10 $GtCO_2$ in total (from currently 27 $GtCO_2$). In order to provide incentives to developing countries to keep their carbon emissions below a critical threshold without hampering their development prospects, any future global climate agreement will have to be evaluated by what it can do to promote development. As demonstrated, the transformation of growth patterns in developing countries towards 'low-carbon growth' is unlikely to happen by itself. Rather, an appropriate institutional arrangement that defines widely accepted and shared responsibilities for the climate as well as human development will be required to stimulate the transfer of technologies and financial resources from industrialized to developing countries and put 'low-carbon development' into practice.

1.2. Carbonization and Decarbonization in China

While Chapter 2 examines the relationship between economic growth and energy use in a cross-section of countries, Chapter 3 focuses on China, the fastest growing major economy and currently the world's number one emitter of CO_2. The central questions under study are:

- What are the main factors responsible for the rapid increase in CO_2 emissions in China since 2002?
- What role could China assume in a global mitigation effort, and what are feasible options to transform the Chinese energy system?
- Are current Chinese policies compatible with ambitious climate stabilization goals in the short- to mid-term?

Along the lines of the Kaya identity, the chapter performs a decomposition analysis of historical emissions data for China. It then confronts the results with reduction requirements implied by globally cost-effective mitigation scenarios, as well as with current Chinese policy targets. The analysis of historical emission patterns reveals that China can in two respects be seen as a special case. First of all, China's economy has grown at an exceptional rate over the last decades, which can be identified as the main driver for the growth of emissions. At the same time, the increase in emissions has been decelerated by reductions in energy intensity. However, this partially off-setting effect was reversed in the early 2000s, when energy intensity levels started to rise again. As a consequence, emissions growth accelerated significantly. Second, over the entire time horizon of 1971-

2007 coal contributed more significantly and more consistently to emissions growth in China than in other regions considered in this chapter. However, the effect is relatively small compared to the effect of economic growth. Confronting these insights with model scenarios for future energy system developments reaffirms China's indispensable role in global efforts to implement an ambitious stabilization target (400, 450, or 500 ppm), and underscore the importance of reductions in carbon intensity for the more ambitious targets.

The trend reversal of decreasing energy intensity in the mid 2000s suggests that future options to reduce CO_2 emissions will be much more limited than in the past, as the general level of energy efficiency has nearly reached OECD levels. This is backed by model results showing that China's energy intensity target is only slightly more ambitious than our business-as-usual projection. Even though energy efficiency improvements are surely one important aspect, the decarbonization of the energy system requires the promotion of carbon-neutral energy carriers to reach the announced goal of bringing down the carbon intensity of GDP by 40-45% below 2005 levels by 2020. China has implemented a number of policies to increase energy efficiency and make energy supply cleaner and more secure, which are important first steps. However, as long as coal retains its position as the dominant energy carrier, the effects of promoting renewables, CCS and nuclear power will only have a minor impact.

2. Fragmented Climate Policy Regimes

The second set of research questions addresses fragmented climate policy regimes. Chapter 4 examines the effect of limited participation in (or delayed inception of) a global climate agreement. Chapter 5 discusses the potential for carbon leakage when emissions trading systems are linked and Chapter 6 is concerned with appropriate policy instruments to minimize leakage.

2.1. The costs of delaying climate measures and benefits of early action

Chapter 4 assesses the economic implications of delaying mitigation efforts. It seeks to shed some light on the following key questions:

- What are the economic costs of delaying climate policies?
- How are these additional costs distributed across world regions?
- Are there regions that can benefit from unilateral early action, even if climate measures in other parts of the world are delayed?

A comparison of the results of the three climate-energy-economy models IMACLIM-R, ReMIND-R, and WITCH indicates that globally, reducing the 'where' and 'when' flexibility of abatement efforts significantly raises the costs of achieving stabilization of atmospheric concentration at 450 ppm CO_2-only. Postponing a global agreement to 2020 raises global mitigation costs by at least about half and a delay to 2030 renders ambitious climate targets infeasible to achieve. With a larger number of key players participating in mitigation by 2010, global costs of stabilization decrease markedly and we find that the participation of the Annex-I countries as well as China and India is particularly relevant if large increases in mitigation costs are to be avoided. For each region the effect of delayed action on mitigation costs is determined by the change in required emission reductions under the respective burden sharing scheme as well as differences in energy system developments and global carbon prices between scenarios. Assuming convergence of per-capita emissions in 2050, regions in which climate measures are implemented with a delay have to commit to smaller reductions of cumulative emission and hence bear a lower share of global mitigation costs. However, lock-in into carbon-intensive energy infrastructures can work in the opposite direction and increase mitigation costs by restricting the availability of low-cost options to abate carbon emissions. Reduced spatial and temporal flexibility raises the global carbon price and thus results in further consumption losses for regions which are net-importers of emission permits, but softens the adverse effects (and can even lead to net gains) for regions which are net-exporters of permits.

An important result is that regions with above average per-capita emissions, such as the EU and the US alongside the rest of Annex-I countries, can lower their mitigation costs by taking early action, even if mitigation efforts in the rest of the world experience a delay. For regions with low per-capita emissions which are net sellers of emission permits (such as India) we find that delayed mitigation efforts in other regions can be desirable, as they derive higher incomes from the sale of emission permits, stemming from the higher carbon prices implied by restricted spatial and temporal flexibility. Finally, decomposing the consumption losses for the EU and the US confirms the intuition that early action involves additional costs in early periods, but significant cost savings in later years. A sensitivity analysis shows that the finding that early action reduces mitigation costs is robust over a wide range of discount rates. This suggests that if a certain stabilization target will be universally agreed upon in the future, early action on climate change constitutes a no-regret option for Annex-I countries, independent of the current state of climate policy in other parts of the world. If global action, however, is delayed for another decade, a given target can only be attained at significant additional costs, decreasing its political acceptability while increasing the likelihood that policy makers will favor a less ambitious climate agreement instead, involving the related adverse environmental impacts.

2.2. Linking Emissions Trading Systems and Carbon Leakage

Linking emission trading systems (ETS) is a widely discussed policy option for the period after the Kyoto Protocol's obligations end in 2012. Chapter 5 aims to further the understanding of linking by providing answers to the following research questions:

- How can an emissions trading system be linked with a region which puts a cap on certain economic sectors but not on total domestic emissions?
- Under which conditions does carbon leakage take place, and how can it be avoided?
- What are the welfare effects of linking?

This chapter examines the impacts of linking on carbon leakage, welfare, and competitiveness within a tractable Ricardo-Viner general equilibrium model with international trade in goods and resources. The considered scenarios were designed to mimic the strategic options for future emission market links between some of the major players in international climate policy, namely the EU, the US, and China. Analytically comparing pre-linking and post-linking market equilibria reveals that a link involving an economy without a national emissions cap can provoke leakage in the form of an expansion of the non-capped sector. However, a key finding is that the occurrence of leakage actually depends on which industries are linked under the joint permit market: in case of asymmetric linking, i.e. when the respective output goods are imperfect substitutes, leakage is avoided and may even become negative. From the point of view of environmental impacts and abatement efficiency, a symmetric link from the EU to a system without a full cap like China bears some negative implications. However, the overall welfare effect from linking can still be positive if the gains-from-trade dominate.

One frequently discussed form of regulating economy-wide emissions in developing countries is the intensity target, which was recently adopted on a voluntary basis by China. However, our analysis shows that such a target cannot work as a substitute for an absolute cap, i.e. it does not prevent the possibility of leakage when one of China's sectors is linked to the EU ETS. If the EU ETS establishes a link with a hypothetical US system, leakage cannot occur since both regions have an economy-wide cap. The major driver for pursuing such a link would be to address concerns about competitiveness, i.e. the idea of harmonizing permit prices in order to 'level the carbon playing-field'. However, the findings here presented here indicate that due to the internal segmentation of the EU ETS this can only be partially achieved, as linking can create and increase distortions both between the EU's trading and non-trading sectors as well as between the EU's non-trading sector and its US counterpart. Finally, the analysis allows for an explicit representation of the ambiguous welfare effects arising from linking in a general-equilibrium setting. Namely, each country's welfare change can be decomposed into a gains-from-trade effect that is always positive, and a terms-of-trade effect, which may be positive or negative, depending on the country's trade specialization, i.e. its export and import positions. If the terms-of-trade effect turns out to be negative, the overall welfare impact of linking becomes ambiguous.

2.3. Unilateral Climate Measures and Trade Policy

Consumption- instead of production-based accounting of carbon emissions (Peters and Hertwich, 2008) and border tax adjustment (Ismer and Neuhoff, 2007) are among the most popular measures proposed to tackle carbon leakage. Chapter 6 contributes to the ongoing debate with respect to the following questions:

- To what extent can trade policy be employed to prevent carbon leakage and support unilateral climate measures?
- What is the optimal mix of domestic taxes and import tariffs?
- In which situations does consumption-based accounting of emissions yield superior results compared to production-based accounting?

This chapter employs a reduced form general equilibrium trade model to assess the implications of production- and consumption-based policies for the regulation of carbon emissions, where the latter approach is shown to be equivalent to border tax adjustment (BTA). The findings indicate that important general equilibrium effects have been neglected in previous analyses, possibly paving the way for erroneous conclusions regarding the effectiveness of proposed policies such as consumption-based accounting of emissions and BTA. The model further reaffirms that trade policies can be expected to have an impact on foreign producers only to the extent to which the imposing country is able to influence world market prices (i.e. possesses market power), thereby emphasizing the limited possibilities to influence other countries' domestic production decisions offered by trade measures.

Comparing production- and consumption-based approaches for putting a price on carbon reveals that in general neither corresponds to the optimal policy. However, imposing an optimal carbon tariff might not be feasible under WTO stipulations and, moreover, requires very specific information, such as the elasticity of world market prices with respect to changes in a country's imports and the price elasticity of trade partners' production. Therefore, the only choice left to policy-makers might be between production-based and consumption-based approaches to target emissions. This chapter compares these policies and identifies conditions under which one is unambiguously superior to the other (from the perspective of the country putting the policy in place). Based on empirical data, its results suggest that if implemented by the EU or the US, carbon leakage is likely to occur under both production-based and consumption-based carbon policies, but that production-based measures should be preferred over consumption-based ones, as the latter would lead to an increase in leakage vis-à-vis the former.

From a policy perspective, the findings presented cast considerable doubt on the practical feasibility of trade measures to reduce carbon emissions in other countries. As is demonstrated, consumption-based accounting of emissions and BTA are fraught with uncertainty regarding economic effects and parameters. Their implementation would require a large amount of information and considerable political capital, while their alleged positive effects remain unproven. Thus, it seems at least debatable whether these measures rightly deserve the prominent place they occupy in the current debate. Their surprisingly wide-spread support they enjoy in the political arena - despite their questionable effects - can perhaps be explained by pointing to the incentive to use such environmental policies as a means to realize gains from influencing the terms of trade in the home country's favour, a practice that has repeatedly been criticized as 'green protectionism'.

3. Discussion

The main narrative that emerges from the research undertaken in this thesis can be summarized as follows: without binding commitments to reduce their GHG emissions, continued economic growth can be expected to bring energy consumption and carbon emissions in emerging and developing countries close to levels prevailing in industrialized countries. The results presented in Chapter 2 give little reason to hope that leapfrogging to more efficient and cleaner technologies in poor countries will occur automatically. We find some evidence of decoupling of economic growth at high levels of income (i.e. for OECD countries); however, this is far from sufficient to achieve the emissions reductions required to achieve ambitious stabilization targets.

For the case of China, our analysis in Chapter 3 confirms that economic growth has been the dominant factor behind past increases in emissions and is expected to remain so for the future. Compared to the impact of economic growth, the pronounced shift to coal in energy supply which took place between 1971 and 2007 had a rather small effect on emission growth. Simulation results reaffirm China's important role for a global, cost-efficient mitigation effort. As the scope for further energy intensity improvements seems limited, lowering the carbon intensity of energy production likely constitutes the most attractive opportunity to achieve emissions reductions in China.

The importance of spatial and temporal flexibility of mitigation efforts is emphasized in Chapter 4. Model results indicate that postponing a global agreement to 2020 would raise global mitigation costs by at least about half and with a delay to 2030 ambitious climate targets may become infeasible to achieve. We find that for late movers lock-in of carbon-intensive energy infrastructure can increase mitigation cost beyond the savings accruing due to their reduced mitigation burden. Hence, early adoption of climate policy by a subset of regions is projected to prove beneficial once a global climate policy is incepted, not only for regions which can take a 'free-ride', but even for the early adopters themselves.

In the absence of a global climate agreement, linking of emissions trading systems could be an attractive option to build a global carbon market in a bottom-up fashion. As Chapter 5 highlights, in this scenario the occurrence of carbon leakage actually depends on which industries are linked under a joint permit market. Linking the EU ETS to regions that also have adopted economy-wide caps on emissions obviously does not result in carbon leakage but can be a way to address competitiveness concerns. A symmetric link from the EU to a system without full cap bears some negative implications, while in the case of asymmetric linking, i.e. when the respective output goods are imperfect substitutes, leakage is prevented and may even become negative.

Finally, the occurrence of carbon leakage in a fragmented climate regime does not automatically justify the use of trade measures, such as border tax adjustment. As Chapter 6 illustrates, neither production- nor consumption-based approaches of accounting for carbon emissions are optimal. Implementing a consumption-based policy does not generally prevent or even reduce leakage; rather, the effect depends on specific parameter values. Empirical data suggest that if the EU or the US were to apply border tax adjustment on imports from China, carbon leakage would in effect increase.

4. *Outlook and Further Research*

The findings presented in this dissertation suggest several avenues along which future research could be conducted.

Additional empirical work could contribute to a broadened understanding of the interrelation between economic development and energy system transformations by considering explanatory variables that were found relevant to structural change in the economy (e.g. demographic structure, schooling, employment by sector, etc.). A further possibility would be to focus on the related question of which factors determine the adoption of certain energy technologies.

It has repeatedly been emphasized that tackling climate change is not only a question of technologies and institutions, but also of "how we should live and what kinds of societies we ought to have" (Gardiner, 2004, p. 586). Thus, studying the impact of climate policies on alternative measures of welfare (cf. Fleurbaey, 2009) and non-monetary factors influencing human well-being (cf. Jones and Klenow, 2010) could yield further insights regarding alternative development models based on changes in life-styles and attitudes that can improve living standards without increasing GHG emissions.

By focusing on per-capita GDP as the dominant indicator, this thesis deals with economic development on purely macroeconomic terms. This aggregated approach omits several important aspects related to people's capabilities to develop (Sen, 2009). One straightforward area of research would be to introduce distributional aspects in the analysis. For instance, Grainger and Kolstad (2010) estimate the impacts of carbon pricing in the US on different income groups. Given that the appropriate data are available, similar analyses should be undertaken for a set of developing countries. Moreover, since future international climate policy will likely involve significant monetary transfers from the North to the South, a related question arises of how these financial flows should be adequately governed in order to bring about real advances in human development.

With regard to early and delayed action, this thesis has been limited to the analysis of the economic effects involved. To complement this analysis, there seems to be a clear mandate for game-theoretic research to shed more light on the incentives and disincentives to act as an early mover. For instance, Harstad (2009) and Beccherle and Tirole (2010) argue that delaying the inception of a global climate agreement can influence strategic behavior, as countries face incentives to lower their investments in abatement technologies in order to improve their future bargaining position. Additional research could for instance focus on the incentives to become an early mover posed by either the associated technology spillovers or reduced cost uncertainty for other regions considering the implementation of mitigation measures. It could also examine if in the presence of asymmetric information early and delayed action can be employed to credibly signal private information.

This thesis has argued that international climate policy will increasingly be conducted within fragmented regimes. For this reason, a comprehensive assessment of design options, ranging from a reformed Clean Development Mechansim and sectoral mechanisms to fund-based, non carbon market approaches (such as e.g. 'nationally appropriate mitigation actions') could be undertaken in order to evaluate the environmental effectiveness, cost-efficiency, and political acceptability (including equity considerations) of these policies.

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Statement of Contribution

The five core chapters of this thesis (Chapters 2 to 6) are the result of collaborations in this PhD project between the author of this thesis and his advisor, Prof. Dr. Ottmar Edenhofer, involving additional colleagues as indicated. The author of this thesis has made extensive contributions to the contents of all five papers, from conceptual design and technical development to writing. This section details the contribution of the author to the five papers and acknowledges major contributions of others.

Chapter 2: The author was responsible for the conceptual design and overall handling of the article. Robert Marschinski contributed by discussing the research design and the framing of the article and gave input to the literature review. Markus Haller contributed by giving valuable advice on energy data and providing Matlab scripts to handle the data.

Chapter 3: The conceptional design and writing of the article has been undertaken by Jan Steckel, who also is responsible for the data analysis. The author of this thesis contributed by providing ideas for the research design and framing as well as by writing parts of the literature review and policy discussion which are part of the article. Gunnar Luderer and Robert Marschinski contributed by discussing the ideas and policy implications as well as writing parts of the introduction, literature review, and conclusions.

Chapter 4: The author was responsible for writing the article, interpreting the data, developing the composition method in Section 3.5. and describing the economic theory involved. The scenarios were outlined by the author jointly with Gunnar Luderer, Stéphanie Monjon, Jan Steckel, and Massimo Tavoni. Simulation results for ReMIND-R, IMACLIM-R, and WITCH were provided by Gunnar Luderer, Stéphanie Monjon, and Massimo Tavoni, respectively. Further, Jan Steckel performed the data analysis, including graphing the figures.

Chapter 5: Robert Marschinski conducted the analytical calculations and wrote the main sections of the paper. The author of this thesis contributed to it by providing ideas for the analytical model, proofing several of the propositions and discussing the manuscript. Moreover, Christian Flachsland contributed by framing the research question, specifying the scenarios, and editing the entire manuscript.

Chapter 6: The author provided the idea and research design of the article, developed the base model, derived optimal policies (Sections 3 and 4), and performed the comparison between optimal and proposed policies (Section 6). Jointly with Robert Marschinski and Michael Hübler, he also was responsible for writing and editing the manuscript. Robert Marschinski provided ideas to the model and worked out the implications of applied and proposed policies in Section 5. Michael Hübler helped to frame the research question, gave inputs to the literature review and was responsible for the discussion of the empirical implications and caveats of the model (Section 7).

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Tools and Resources

All text in this dissertation was written using Microsoft Word 2003.

Data Processing: Regressions in Chapter 2 were performed using STATA/SE, version 10.1. from Statacorp. Figures of energy use patterns were plotted with Microsoft Excel 2003. The empirical data of Chapter 2 as well as model output in Chapters 3 and 4 were analyzed using MATLAB, version 7.10 (R2010) from MathWorks.

Modeling: Chapter 3 uses numerical results from simulation runs with the climate-energy-economy model ReMIND-R (Leimbach et al. 2009). Likewise, Chapter 4 employs results from the models ReMIND-R, IMALCIM-R (Sassi, 2010) and WITCH (Bosetti, 2006).