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Modelling international carbon pricing regimes in light of the Paris Agreement

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Eidesstattliche Erklärung gem. §11 Absatz 2 (5)

Hiermit erkläre ich an Eides statt, dass ich die vorgelegte Dissertation mit dem Titel „Modelling international carbon pricing regimes in light of the Paris Agreement“ selbständig und ohne unerlaubte Hilfe angefertigt habe

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.

Abstract

The Paris Agreement is the central pillar of international efforts to combat anthropogenic climate change. Adopted in 2015, it established an architecture in which all signees submit NDCs to pledge their intended greenhouse gas (GHG) emission reductions. This bottom-up approach is complemented with the top-down goal of limiting global mean temperature increase to 2°C, preferably to 1.5°C. As NDCs are to be tightened regularly, global costs associated with reaching national emission reduction targets are expected to rise. This dissertation assesses the role of international carbon pricing regimes against the background of the Paris Agreement. It hopes to shed light on the question which carbon pricing coalitions are suited best to address the challenge of achieving emission reductions efficiently.

The dissertation is a collection of four research papers applying Computable General Equilibrium (CGE) models. The first paper summarizes modelling results of 17 international CGE models over a set of harmonized scenarios. It finds that global carbon pricing achieves the ambitious 2°C temperature target at costs similar to the costs required to achieve the less ambitious NDCs without international cooperation, thereby yielding substantial efficiency gains. Even smaller coalitions can reduce global costs notably. Regions becoming importers of emission permits in a joint carbon market (e. g. the EU) tend to benefit more from the cooperation than regions becoming exporters (e. g. China). Exporters of oil and gas benefit from a global carbon pricing regime, because these fossil fuels are increasingly demanded in a situation when substituting coal on a large scale is the cheapest option to cut emissions.

The second paper further evaluates potential carbon pricing coalitions by analyzing results from seven CGE models. It finds that turning towards the more ambitious 1.5°C target doubles the cost savings reaped by international cooperation compared to the 2°C. A coalition comprising only the EU and China is identified to deliver the highest cost savings per unit of emissions mitigated. Such small coalitions are especially beneficial to importers of emission allowances, while exporters of allowances prefer larger coalitions with more competition for their emission permits. Generally, the paper finds that the cost savings materialized by a coalition does not only depend on the amount of GHG it covers, but also on the difference in pre-linking allowance prices of the coalition partners, weight of each region in terms of emissions, and the global energy market effects resulting from the coalition.

The third study focusses on the EU-China coalition. It analyzes the effects of linking both

regions emission trading systems (ETSs) and identifies measures to make linking more attractive to China, thereby accounting for the uneven distribution of cost savings. The paper deploys the CGE model DART and evaluates scenarios which (i) restrict the amount of allowances traded between the EU and China, (ii) shifts more abatement obligations to the EU, and (iii) alter Armington trade elasticities. It finds that restricting the volume of permit trade is suited best to incentivize China to join the coalition. China gains most when the amount of permits traded between the EU and China is halved, while the EU always favors unrestricted trading. Within the EU, not all member states benefit equally from the link to China, and additional transfer mechanisms could be necessary to achieve consensus on such an agreement.

The fourth paper examines the interactions between the EU ETS and renewable energy policies. It analyzes the effects of policies on inter-sectoral and international carbon leakage and on the distribution of abatement obligations within the EU. Using a static version of the DART model, the paper finds that higher allowance prices foster the use of renewables, while a policy-induced growth of renewables leads to lower allowance prices, and consequently to more coal-based electricity production. When electricity grids are not flexible, this suppresses the use of renewables, and thereby increases the allowance price. A higher allowance price in turn leads to increasing inter-sectoral and international carbon leakage. Thus, fostering renewable energies and improving the flexibility of electricity grids have the potential to avoid carbon leakage. The burden sharing within the EU depends on regional energy portfolios: regions with a high share of coal based energy production and a low share of renewable electricity production face the most adverse effects of rising carbon prices.

Policy implications from this dissertation include a clear mandate to negotiators on the eve of COP26 to foster international carbon trading in order to make more ambitious reduction targets achievable. When considering potential carbon trading partners, policy makers should keep in mind that not only the amount of covered emissions is decisive for the efficiency gains realized by a coalition, and that also rather small coalitions can yield large cost savings.

Future research could deploy Integrated Assessment Models, a political economy perspective and game theoretic approaches to complement the findings from this dissertation.

Zusammenfassung

Das Pariser Abkommen ist der Fixpunkt internationaler Bemühungen zur Bekämpfung des anthropogenen Klimawandels. Es wurde 2015 beschlossen und etablierte eine Architektur, in der alle Mitglieder NDCs einreichen, in denen sie ihre beabsichtigten Treibhausgasemissionen (THG) angeben. Dieser *bottom-up*-Ansatz wird ergänzt durch das übergeordnete *top-down*-Ziel, den Anstieg der globalen Durchschnittstemperatur auf 2°C, vorzugsweise auf 1,5°C, zu begrenzen. Da die NDCs regelmäßig nachgeschärft werden sollen, sind steigende globale Kosten im Zusammenhang mit dem Erreichen nationaler Emissionsreduktionsziele zu erwarten. Diese Dissertation untersucht die Rolle internationaler Kohlenstoffbepreisungssysteme vor dem Hintergrund des Pariser Abkommens. Sie soll dazu beitragen, Koalitionen zu identifizieren, die geeignet sind Emissionsreduktionen effizient zu verwirklichen.

Die Dissertation besteht aus vier Forschungsaufsätzen, die berechenbare allgemeine Gleichgewichtsmodelle (engl. *Computable General Equilibrium*, CGE) nutzen. Der erste Aufsatz präsentiert die Ergebnisse aus einer Reihe harmonisierter Szenarien, die von 17 internationalen CGE-Modellen geliefert wurden. Mit Hilfe globaler Kohlenstoffbepreisung kann das ehrgeizige 2°C-Ziel zu ähnlichen Kosten erreicht werden wie die weniger ehrgeizigen NDCs ohne solche internationale Zusammenarbeit; es werden also erhebliche Effizienzgewinne erzielt. Auch kleinere Koalitionen können die globalen Kosten deutlich senken. Regionen, die in einem gemeinsamen Kohlenstoffmarkt zu Importeuren von Emissionszertifikaten werden (z. B. die EU), profitieren tendenziell stärker von der Kooperation als Regionen, die Exporteure werden (z. B. China). Öl- und Gasexporteure profitieren von einer globalen Kohlenstoffbepreisung. Diese fossilen Energieträger werden unter einem globalen Kohlenstoffmarkt zunehmend nachgefragt, wenn in großem Maßstab Kohle substituiert wird, was die kostengünstigste Option zur Emissionsreduzierung darstellt.

Der zweite Aufsatz legt den Fokus auf potenzielle Klimakoalitionen und analysiert hierzu die Ergebnisse von sieben CGE-Modellen. Es stellt sich heraus, dass sich die die Kosteneinsparungen durch die internationale Zusammenarbeit verdoppeln, wenn anstelle des 2°C-Ziels das ehrgeizigere 1,5°C-Ziel verwirklicht wird. Von allen untersuchten Koalitionen erzielt eine Koalition aus EU und China die höchsten Kosteneinsparungen pro Einheit reduzierter Emissionen. Solche kleinen Koalitionen sind besonders für Importeure von

Emissionszertifikaten von Vorteil, während Exporteure von Zertifikaten mehr von größeren Koalitionen mit mehr Wettbewerb um ihre Emissionszertifikate profitieren. Generell hängen die durch eine Koalition erzielten Kosteneinsparungen nicht nur von den abgedeckten THG-Emissionen ab, sondern auch von der Differenz der Zertifikatspreise der jeweiligen Koalitionspartner vor dem Zusammenschluss, dem Anteil jeder Region an den abgedeckten Emissionen und den aus der Koalition resultierenden globalen Energiemarkteffekten.

Der dritte Aufsatz legt den Fokus auf die EU-China-Koalition. In ihm werden die Auswirkungen der Verknüpfung der Emissionshandelssysteme (ETS) beider Regionen analysiert und Maßnahmen identifiziert, welche die Verknüpfung für China attraktiver machen. Damit wird der ungleichen Verteilung der Kosteneinsparungen zwischen der EU und China Rechnung getragen. Die Arbeit nutzt das CGE-Modell DART und bewertet Szenarien, in denen (i) die Menge der zwischen der EU und China gehandelten Zertifikate eingeschränkt, (ii) die Emissionsminderungsziele der EU verschärft und (iii) die Armington-Handelsselastizitäten verändert werden. Die Beschränkung der gehandelten Zertifikate ist am besten dazu geeignet, China einen Anreiz zu geben der Koalition beizutreten. China profitiert am meisten von der Verknüpfung, wenn die Menge der zwischen der EU und China gehandelten Zertifikate halbiert wird, während die EU stets uneingeschränkten Zertifikatehandel bevorzugt. Innerhalb der EU profitieren nicht alle Mitgliedstaaten gleichermaßen von der Verknüpfung mit Chinas ETS, und es könnten zusätzliche Transfermechanismen erforderlich sein, um einen innereuropäischen Konsens über ein solches Abkommen zu erzielen.

Der vierte Aufsatz untersucht Wechselwirkungen zwischen dem EU ETS und Politiken, welche die erneuerbaren Energien adressieren. In ihm werden die Auswirkungen auf intersektorale und internationale Carbon Leakage Effekte sowie auf die Lastenteilung innerhalb der EU analysiert. Unter Verwendung einer statischen Version des DART-Modells zeigt sich, dass höhere Zertifikatspreise die Nutzung erneuerbarer Energien fördern, während ein durch die Politik induziertes Wachstum erneuerbarer Energien zu niedrigeren Zertifikatspreisen und folglich zu einer stärkeren Verstromung von Kohle führt. Unflexible Stromnetze erschweren die Nutzung erneuerbarer Energien und erhöhen somit den Zertifikatspreis. Ein höherer Zertifikatspreis wiederum führt zu zunehmender intersektoraler und internationaler Verlagerung von GHG-Emissionen. Die Förderung erneuerbarer Energien und die Flexibilisierung der Stromnetze können also dabei helfen, Carbon Leakage zu vermeiden. Die Lastenverteilung innerhalb der EU hängt von den Energieportfolios der Mitgliedsstaaten ab: Länder mit einem hohen Anteil

an kohlebasierter Energieerzeugung und einem geringen Anteil an erneuerbarer Stromerzeugung sind den nachteiligen Auswirkungen steigender Zertifikatspreise am stärksten ausgesetzt.

Zu den politischen Implikationen dieser Dissertation gehört (kurz vor der COP26) ein klarer Auftrag an die Verhandlungsführer, internationale Kohlenstoffmärkte zu fördern, um ehrgeizigere Reduktionsziele durch die damit einhergehenden Effizienzgewinne in erreichbare Nähe zu rücken. Bei der Evaluation potenzieller Partner für einen gemeinsamen Kohlenstoffmarkt sollte die Politik bedenken, dass nicht nur die Menge der in dem gemeinsamen Markt abgedeckten Emissionen entscheidend für die Effizienzgewinne einer Koalition ist. Auch eher kleine Koalitionen können große Kosteneinsparungen erzielen.

Zukünftige Forschung könnte integrierte Bewertungsmodelle (engl., *Integrated Assessment Models, IAM*), eine politökonomische Perspektive und spieltheoretische Ansätze nutzen, um die Ergebnisse dieser Dissertation zu ergänzen.

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List of selected abbreviations

BaU	Business as Usual
CBDR	Common but Differentiated Responsibilities
CGE	Computable General Equilibrium
EITE	Energy Intensive Trade Exposed
EMF	Emergy Modeling Forum
ETS	Emission Trading System
DART	Dynamic Applied Regional Trade
GHG	Greenhouse Gas
GTAP	Global Trade Analysis Project
MAC	Marginal Abatement Costs
NDC	Nationally Determined Contribution
ToT	Terms-of-Trade
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1

General Introduction

1.1 Background

Anthropogenic climate change is one of the most pressing environmental problems of our times. Many human activities cause emissions of greenhouse gases (GHG), which lead to increasing temperatures, rising sea levels, and an amplified probability of extreme weather events. The single most important source of GHG emissions is the combustion of fossil fuels for energy production and in industrial processes, accounting for two thirds of global GHG emissions. (IPCC, 2014)

Although the spatial distribution of GHG emissions is heterogeneous, the resulting climate change is a global problem. According to IEA (2020), the top three emitters alone, i. e. China, the USA, and the EU, were responsible for more than half of the global CO₂ emissions in 2019. Still, some of the most dramatic ramifications of climate change are observed in areas as remote as the Arctic (e. g. Box et al., 2019) or Pacific island states (e. g. Klöck and Nunn, 2019).

This alone indicates that efforts to combat climate change must imply an international perspective. But climate change is also a public good (or rather, a public bad, see e. g. Kolstad, 2011), meaning that it motivates free-riding (see e. g. Nordhaus, 2019; Heitzel et al., 2011): Each country has the incentive to benefit from other countries taking the burden of abating their GHG emissions, without cutting its own emissions. At the same time, no single actor, nor even single group of actors, can solve the climate change problem alone, which is therefore a problem of collective action (Hare et al., 2010).

Under these conditions, the necessity to tackle climate change on a global level has widely been acknowledged. The United Nations Framework Convention on Climate Change (UNFCCC) has been the central platform for catalyzing international climate policies since its formation in Rio in 1992. Its 1997 Kyoto Protocol was a first landmark in the

international collaboration on GHG mitigation efforts. Celebrated as a breakthrough by negotiators, the scientific community was less optimistic even at the time the treaty was launched (Rosen, 2015). In retrospective, the assessment of the latter group was more precise than that of the former: Global CO₂ emissions have been growing ever since, with no perceivable effect of the Kyoto Protocol counteracting this development, but rather an increase in CO₂ emissions by more than ten billion tons since 1997 (see Figure 1-1).

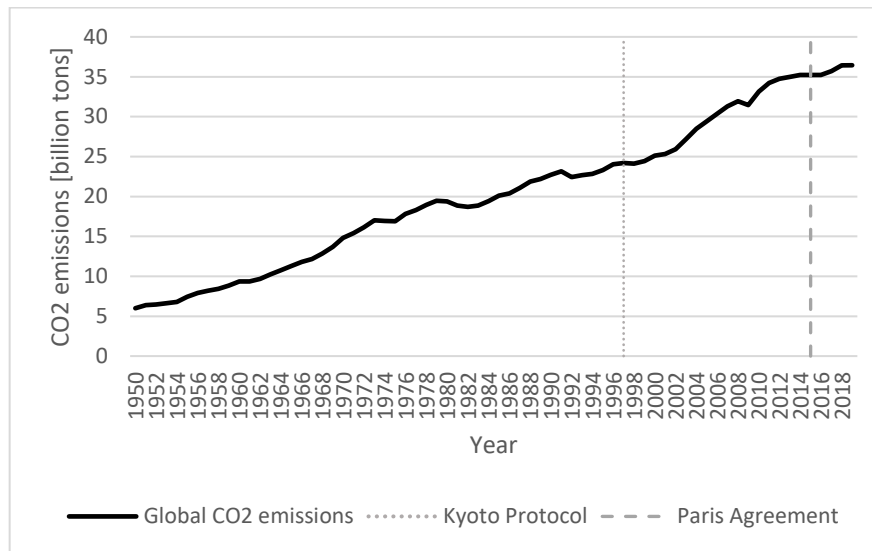


Figure 1-1: Global CO₂-emissions in billion tons between 1950 and 2019. Own representation based on Ritchie and Roser (2020).

In the scientific literature, there is broad consensus that the Kyoto Protocol has failed in many aspects (e. g. Prins and Rayner, 2007; Helm, 2012; Rosen, 2015). Besides major emitters like the USA, Canada or Australia not ratifying or withdrawing from the treaty, there are two major reasons for its failure: First, it applied the principle of Common but Differentiated Responsibilities (CBDR) in a binary way, distributing the mitigation obligations in an uneven manner. In an attempt to account for their historic emissions and larger economic potential, the industrialized countries (Annex I countries) were obliged to reduce their emissions, but developing countries were not (Rosen, 2015). This approach does not sufficiently address the recent increase of GHG emissions in some major developing countries like India and even more so China (Blanford et al., 2009). Second, mitigation targets were established in a top-down fashion, not allowing for single countries to decide independently on their mitigation targets. In theory, a top-down

architecture is the most efficient system, as it coordinates global efforts and provides a transparent and environmentally integer pathway towards reaching the joint reduction target (Hare et al., 2010). But in practice, top-down negotiations are hard to enforce and have come to stall because of the global community failing to agree on targets and financial transfers (Green et al., 2014; Helm, 2012).

In an attempt to overcome the Kyoto Protocol's drawbacks, the Paris Agreement of 2015 marks a turning point in the UNFCCC process. On the one hand, it includes emission reduction targets by almost all countries of the world, rather than the industrialized countries alone. Thus, it addresses the fundamental problem of not sufficiently obliging major emitters among the developing countries (Benveniste et al., 2018). The reduction targets are submitted by the parties themselves, rather than determined by the whole community: Each party pledges their nationally determined contributions (NDCs), defining its intended mitigation efforts and, in many cases, pathways to fulfill them¹. Thus, the Paris Agreement implements a bottom-up approach as a central component of its architecture. On the other hand, it also comprises a prominent top-down element: The ratifying parties jointly aim at "*holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*" (UNFCCC, 2015, p. 22).

While a combination of bottom-up and top-down elements may combine both systems' advantages (Green et al., 2014), there is one apparent shortcoming: The current NDC pledges fail to attain the overarching targets of 2°C, let alone 1.5°C temperature increase (see e. g. Rogelj et al., 2016; Fujimori et al., 2016a). Under the term "ratcheting up", parties are expected to submit revised NDCs with stricter emission reduction targets every five years, such that eventually the joint pledges shall fulfill the overarching long term-goal. However, more ambitious NDCs in line with the 2°C or 1.5°C targets imply substantially higher economic adjustment costs (Vandyck et al., 2016; Hof et al., 2017).

¹ There are no top-down guidelines regarding the format and requirements of the NDCs. Consequently, current NDCs are very heterogenous both in terms of included GHG (e. g. CO₂ vs. all GHG), reference (e. g. relative reductions vis-à-vis a reference year vs. vis-à-vis a hypothetical Baseline projection of the submitting party itself), and level of clarity (e. g. absolute reduction target vs. intensity targets vs. description of intended policy measures; see den Elzen et al., 2016). This heterogeneity is mirrored in the large uncertainty range associated with estimating future emission levels against the background of the Paris Agreement (see e. g. Fawcett et al., 2015; den Elzen et al., 2016; Vandyck et al., 2016 and Rogelj et al. 2016; Benveniste et al., 2018).

Thus, when analyzing economic effects of policies associated with the Paris Agreement, it is important to distinguish the different targets of NDCs and/or long-term temperature targets. This holds especially true when the 1.5°C target is considered, which is strictly recommended by the respective IPCC's special report (IPCC, 2018).

While the Paris Agreement implements emission reduction targets, it does not account for the political instruments applied to reach these targets. Policy makers draw on a large toolkit of climate policy instruments including efficiency standards, renewable energy quotas, tax incentives, subsidies, and carbon pricing (Legget, 2011). Economic literature considers carbon pricing as an effective and efficient instrument to reduce GHG emissions (e. g. van den Bergh and Botzen, 2020; Baranzini et al., 2017; Cramton et al., 2017). It is effective because it drives all decisions within an economy and thereby closes both behavioral and economic loopholes to circumvent emission abatements (van den Bergh and Botzen, 2020). It is efficient because it equalizes the marginal abatement costs across all subjected emitters. Furthermore, carbon pricing provides emitters with flexibility regarding whether and where to abate emission. In combination, this implies that a given level of abatement can be achieved at least global cost (Stavins, 2020; Baranzini et al., 2017). Yet another argument for carbon pricing is that it generates revenues which can be utilized e. g. to alter the incidence of climate policies (Fullerton and Muehlegger, 2019)².

The efficiency of carbon pricing regimes increases with the amount of emissions subject to a uniform price (e.g. Alexeeva and Anger, 2016, Nong and Siriwardana, 2018, Fujimori et al. 2016b): The more emitters face equal marginal abatement costs, the more options are there for relatively cheaper abatements, enlarging the so-called where-flexibility of the carbon market. With regard to the Paris Agreement, global costs of achieving the NDCs are estimated to reduce by as much as 75 % with the implementation of a global carbon pricing regime, as opposed to reaching NDCs with domestic action only (Fujimori et al., 2016b). In the awareness of these potential efficiency gains, Article 6 of the Paris Agreement encourages countries to work together and jointly reach their NDCs (UNFCCC, 2015).

While the overall efficiency gains from joint carbon markets are undisputed, these gains are typically distributed unevenly among the participants of the joint market. Especially

² See Baranzini et al. (2017) for a review on the benefits of carbon pricing.

energy exporters and providers of the cheapest abatement options, e. g. China, are prone to face negative terms-of-trade (ToT) effects when they engage in joint carbon markets. In some cases, this can even lead to welfare losses in selected regions (Peterson and Weitzel, 2016; Fujimori et al., 2016b; Marschinski et al., 2012). Consequently, the incentives to participate in a joint carbon market may vary strongly among potential participants.

These incentives can be amplified by implementing measures to balance the uneven distribution of efficiency gains. Major emitters among the developing countries, e. g. China, are predestined to be targeted by such measures for three reasons: First, their GHG emissions have been on the rise in recent years, and are expected to remain so without rigorous climate policies (Blanford et al., 2009); their engagement in international climate agreement, e. g. via carbon pricing regimes, is key to cutting global emissions (Clarke et al., 2009). Second, they can offer large amounts of cheap mitigation opportunities to potential carbon trading partners (Fujimori et al., 2016b). This is especially valuable for participants from the industrialized countries, which are typically characterized by high marginal abatement costs. Efficiency gains from joint carbon markets are highest when the marginal abatement costs of their participants differ strongly (Nong and Siriwardana, 2018). Consequently, developing countries with cheap mitigation options are highly eligible carbon trading partners from an industrialized country's perspective. At the same time, and this is the third reason, they are prone to face negative ToT effects and might therefore be hesitant towards joining an international carbon market (Fujimori et al., 2016b).

The above discussion raises three central questions regarding the formation of international carbon pricing coalitions:

1. Which potential coalitions yield the highest efficiency gains? While a global carbon pricing regime is the first best solution (see e. g. Tuerk et al., 2009), under the Paris Agreement's bottom-up architecture it is more likely that smaller coalitions will form. Each potential coalition will yield specific global efficiency improvements dependent on the participating countries characteristics in terms of abatement costs, trade flows, energy endowments etc. These factors are also determinant for the second question:

2. Which coalitions are likely to form? As outlined above, costs and benefits can be unevenly distributed to respective carbon trading partners. Central players in terms of energy endowments, GHG emissions, and low-cost mitigation options are likely to have low incentives to join an international carbon market, which could render some of the most efficient coalitions infeasible. To circumvent this undesirable discrepancy, the third question is vital:
3. Which measures are suited to make international carbon markets more attractive to regions with otherwise low incentives to join? Literature suggests transfer payments (Peterson and Weitzel, 2018) and restriction of the carbon markets trading volume (Li et al., 2019; Gavard et al., 2016), but which tools are suitable to which coalitions, and under which circumstances, e. g. regarding global trade restrictions, will have to be assessed on a case study level.

This dissertation hopes to shed some light on these pressing issues.

So far, the discussion focused on the formation of joint carbon markets in order to reap the cost saving associated with international cooperation. While carbon pricing is expected to play a major role in the global efforts to limit climate change, it is widely acknowledged that additional policies are advisable and necessary to reach climate targets (van den Bergh and Botzen, 2020; Rosenbloom et al., 2020).

At the same time, overlapping policies can hamper each policy's efficiency (Böhringer et al., 2016;). Several studies find negative interference between carbon pricing on the one hand and renewable electricity policies on the other hand (e. g. Liu and Wei, 2016; Böhringer and Rosendahl, 2010; Abrell and Weigt, 2008). However, if the respective policies are well designed, it is also possible to foster synergies of jointly implementing carbon pricing and renewable energy policies (del Río Gonzáles, 2007). To achieve synergies and avoid disergies, a detailed understanding of the interactions between carbon pricing and renewable energy policies is key.

This leads to a fourth question this dissertation hopes to address:

4. How do carbon pricing regimes and renewable energy policies interact? In the light of the Paris Agreement's ratcheting up approach with steadily tightened emission targets, carbon prices are expected to increase. Given their direct effect

on energy markets, it can be assumed that mutual impacts of carbon pricing and renewable energies will further accelerate.

These four questions form the central objectives of the dissertation at hand.

1.2 Relevance of the Study

In addressing the four central objectives of this dissertation, the study contributes to the existing literature in several ways. First, the studies in chapters 2 and 3 are the first to address the issue of identifying the most efficient bottom-up carbon pricing coalitions with the combined expertise of modelling teams from 17 and 7 internationally acknowledged institutions, respectively. Central findings, which are consistent over all deployed models, are especially robust against this background. While there are studies addressing individual coalitions, e. g. Gavard et al. (2016) and Liu and Wei (2016) for the China-EU case, the systematic analysis of several potential coalitions is new. Second, we develop a consistent approach to harmonize current NDCs³ and make the results available in an easily accessible format (see Appendix A.2 in chapter 2). Given the heterogeneous nature of current NDCs, this contribution could prove valuable especially to the modelling community. Third, in addition to the overarching topic of extending international carbon pricing, the dissertation contributes to several issues currently debated also in the policy realm: recycling of revenues from carbon pricing (chapter 2); linking the EU ETS to other carbon pricing schemes (chapter 4); and measures to avoid international carbon leakage (chapter 5). Fourth, the findings regarding measures to make linking ETS more attractive (chapter 4) and the interconnection between carbon pricing and renewable energy policies (chapter 5) deliver clear policy messages on timely topics.

1.3 Thesis Structure

This dissertation is organized as a collection of four research papers. Chapter 2 gives an overview on the core results from the project “Carbon Pricing after Paris (CarPri)”, which was realized under the umbrella of Stanford University’s Energy Modelling Forum

³ This includes conditional and unconditional NDCs as well as targets in line with the 2°C and 1.5°C targets. We only account for CO₂ from combustion of fossil fuels.

(EMF)⁴. The study presents and analyses results from energy-economy models of 17 internationally renowned institutions on a set of harmonized core scenarios. These core scenarios were implemented by each modelling team and include two baselines (one optimistic; one pessimistic), three ambition levels (conditional NDCs; unconditional NDCs; emission reduction targets in line with the 2°C target), and five levels of global cooperation (domestic action only; two carbon-club trading scenarios; global carbon trading across energy intensive sectors and electricity production; global carbon trading across all sectors). One central result is that in a situation without global cooperation in carbon trading, reaching conditional NDCs (i. e. the lowest ambition level) is not cheaper than reaching emission reductions in line with the 2°C target (i. e. the highest ambition level) in a situation with full international carbon trading. Hence, cost savings through increased where-flexibility can pay the bill for a more ambitious international climate policy. At the same time, the uneven distribution of costs associated with cutting GHG emissions is confirmed. The paper also presents results from a sub-group of eight models on the effects of lump-sum recycling of revenues from carbon pricing, which is found to be capable of reducing the regressive effects of carbon pricing.

The study in chapter 3 is structured in a similar way by including seven models running a harmonized set of scenarios. It delivers a detailed analysis of potential cooperation partners' costs and benefits, as well as of the ratio of abated emissions vs. achieved cost savings, thereby putting a stronger focus on identifying the most efficient coalitions. By including also the stricter 1.5°C target, the study emphasizes that the gains from international cooperation increase with rising ambition levels. While the overall cost savings (compared to a situation without international carbon trading) are largest in global trading, there are individual regions reaping higher benefits in less extensive carbon coalitions. A joint carbon market comprising China and the EU is the most favorable arrangement in terms of cost savings per unit of emissions mitigated.

Following up to this finding, chapter 4 takes a closer look at this very coalition. It analyses the effects of linking the EU ETS with a Chinese ETS. Deploying the computable general equilibrium (CGE) model DART, the focus of the study is to analyze under which circumstances the linking of ETS is equally attractive to both partners. In three sets of

⁴ Note that also the studies in chapters 3 and 4 are part of CarPri.

scenarios, both partners' welfare gains, CO₂ emissions and carbon prices are analyzed: The first set restricts the tradeable allowance volume, thereby creating a gradient along the degree of linking. The second set shifts a larger share of abatement obligations towards the EU by gradually tightening the emission reduction targets for the EU, while decreasing the Chinese targets. This approach mimics transfer payments from the EU to China. The third set of scenarios implements different Armington elasticities in order to model trade-openness. A central finding is that, on the one hand, the EU always favors unrestricted emission trading with China, even if this is combined with high transfer payments. China, on the other hand, benefits most when emission trading is restricted to 50% of the traded allowances in a scenario without restriction, even if they receive high transfer payments. For China, the gains from linking are higher when global trade is fostered (modelled by higher Armington elasticities), meaning that facilitated trade in goods can increase China's motivation to also trade in emission allowances.

In chapter 5, the interaction between EU ETS allowance prices and renewable energy policies is analyzed with a static version of the DART model. The study also examines the burden sharing of emission reductions among the EU members, thereby contributing to the discussion of uneven distribution of costs in an international carbon pricing regime. Furthermore, it discusses inter-sectoral and international carbon leakage associated with the following scenario assumptions: In addition to a baseline and a scenario with an increased allowance price, the study comprises four policy scenarios, addressing (i) an accelerated development of renewable energy technologies, (ii) higher consumer flexibility to adapt to changing energy prices, (iii) binding emission reduction targets also in the sectors not covered by the EU ETS, and (iv) less flexible electricity grids impeding the use of renewable energies. Fostering renewable energies and improving flexibility of electricity grids are key to decrease both inter-sectoral and international carbon leakage. Higher allowance prices (as induced e. g. by ratcheting up the EU's NDC) lead to inter-sectoral carbon leakage, if no counter measures are adopted. EU regions with high shares of coal-based electricity and low shares of renewables are most adversely affected by higher allowance prices.

Chapter 6 draws the central conclusions of this dissertation, presents policy implications, and provides an outlook on future research potentials.

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Chapter 2

Climate Policies after Paris: Pledge, Trade and Recycle *

Christoph Böhringer, Sonja Peterson, Thomas F. Rutherford, Jan Schneider, Malte Winkler

Abstract

This article summarizes insights from the 36th Energy Modeling Forum study (EMF36) on the magnitude and distribution of economic adjustment costs of greenhouse gas emission reduction targets. Under the Paris Agreement, countries have committed to emission reduction targets – so-called Nationally Determined Contributions (NDCs) – in order to combat global warming. The study suggests that aligning NDCs with the commonly agreed 2°C temperature target will induce global economic costs of roughly 1% in 2030. However, these costs are unevenly distributed across regions. Countries exporting fossil fuels are most adversely affected from the transition towards a low-carbon economy. In order to reduce adjustment costs at the global and regional level, comprehensive emissions trading which exploits least-cost abatement options is strongly desirable to avoid contentious normative debates on equitable burden sharing. Lump-sum recycling of revenues from emissions pricing, in equal amounts to every household, appeals as an attractive strategy to mitigate regressive effects and thereby improving the social acceptability of stringent climate policy.

Key Words: Paris Agreement; emissions pricing and trading; revenue recycling

JEL classification: D58, H23, Q54, Q58

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2.1 Introduction

Anthropogenic climate change may cause irreparable harm to the ecosystems on which mankind depends. The international community has recognized the threat represented by man-made climate change since the early 1990s, and called for rigorous abatement of greenhouse gas emissions to prevent “dangerous human interference with the climate system” (UNFCCC, 1994). However, attempts to halt global warming have been met with limited progress so far. One reason is that climate protection constitutes a global public good. Each single country has a strong incentive to benefit from the emission abatement of other countries while cutting back on its own emission reduction to reduce abatement costs. International agreements lack real teeth when it comes to coercing common action since they lack a supranational authority. Another fundamental impediment to climate protection is the asymmetric timing of costs and benefits from emission abatement. While the decarbonization of production and consumption patterns induces economic adjustment costs in the short- and mid-term, most of the benefits of avoided climate damages will take decades to materialize given the physical inertia of the climate system.

This discrepancy in the time scale of costs and benefits explains why climate policy has historically been dominated by heated debates on the magnitude of emission abatement costs and their distribution. The United Nations Framework Convention on Climate Change (UNFCCC) refers to international burden sharing through the notion of Common but Differentiated Responsibilities (CBDR), where all countries share the obligation to address the threat of climate change but responsibilities differ due to different historical contributions to global emissions and different capabilities. The CBDR principle is reflected in the Kyoto Protocol which placed the focus of greenhouse gas emission reduction on industrialized countries, while developing countries were exempted from binding climate targets. While celebrated as the first international climate treaty to become effective in 2005, the Kyoto Protocol fell short of providing a blueprint for effective climate policy based on common burden sharing. First of all, the US – responsible for a large part of historical greenhouse gas emissions – withdrew from the Kyoto Protocol in 2001. The US government expressed concerns about the domestic compliance costs and feared that other big emitters such as China or India would gain competitive advantage from the Kyoto deal without emission reduction commitments. For similar reasons, Canada ceased to be a Party to the Kyoto Protocol in 2012 and other

major industrialized regions such as Japan and Russia indicated that they will not accept new Kyoto-type commitments after the initial five-year commitment period ranging from 2008-2012.

Aware of the difficulties of reaching mandatory agreements for industrialized countries only, the Paris Agreement in 2015 marked a major shift in focus. The Paris Agreement sets out a global framework to avoid dangerous climate change with the goal to limit global warming to well below 2°C, preferably to 1.5°C, compared to preindustrial levels. The change in emphasis is twofold. First, the Paris Agreement calls for the contribution of all countries to mitigate global warming – not only from industrialized countries as in the case of the Kyoto Protocol. As of December 2020, all 196 members of the UNFCCC have signed the agreement and 189 have become parties⁵. Hence, the Paris Agreement is the first universal, legally binding global climate change agreement. Second, the Paris Agreement marks a shift away from top-down mandated reduction targets towards a bottom-up strategy where individual countries voluntarily commit themselves to Nationally Determined Contributions (NDCs) (UNFCCC, 2020).

The Paris Agreement is celebrated as an international breakthrough to deal with the challenge of global warming in a comprehensive manner. However, individual NDCs submitted so far fall short of aligning emission pathways with the target to limit global warming below 2°C⁶. Recognizing that the initial voluntary pledges are inadequate to achieve the long-term temperature goal of the Paris Agreement, countries are asked to review and revise their NDCs every five years until the collective pledges are deemed sufficient to achieve the objective – with the hope that the effectiveness of the voluntary NDC approach could be fostered by naming and shaming of defaulting countries. Meanwhile, more stringent climate policy actions up to 2030 which are in line with the Paris temperature goal will cause substantially higher economic adjustment costs

⁵ The only significant emitters still not parties are Iran and Turkey. The United States announced its withdrawal from the agreement on June 1, 2017 under then-President Donald Trump which took effect on November 4, 2020, one day after the 2020 presidential election, but the nation rejoined the agreement in 2021 immediately after the inauguration of President Joe Biden (Viseret et al., 2020; United Nations, 2021).

⁶ Several studies including Vrontisi et al. (2018), Fujimori et al. (2016) and van Soest et al. (2017) find that the NDCs are not in line with the 2°C target.

(Vandyck et al., 2016; Hof et al., 2017).

On critical inspection, the Paris Agreement may not be perceived as a gamechanger but rather as the acknowledgement that international climate policy critically hinges on voluntary, bottom-up consensual decision making. This insight not only echoes the experience of the preceding Kyoto Protocol but also reflects the limitations met by international negotiators when it comes to feasibility, determined by the domestic political environment: Emission reduction pledges submitted abroad must indeed build on sufficient political support at home. Although the societal awareness of the risks imposed by climate change has grown significantly over the last decade in many countries – not least because of grassroots movements such as Fridays for Future – decision makers are concerned about the adverse economic effects of more stringent climate policies not only on the national economy as a whole, but more specifically on competitiveness for emission-intensive industries and in particular on the economic burden for lower-income households. Concern over the regressive impacts of climate policies across households are well justified. Putting a price on energy or energy-related pollutants such as CO₂ will raise consumer prices for energy goods such as electricity, natural gas, heating oil, or gasoline. In countries where these goods constitute a larger share of the budget in poor households compared to richer households, higher energy or emission prices tend to be regressive. Even in countries which are seemingly rich on average, populist protests for economic justice have been initially sparked by rising fuel prices –the yellow vests movement in France that started in October 2018 is a case in point.

In this context, the 36th Energy Modeling Forum study on “Carbon Pricing after Paris” (EMF36) is designed to help policy makers chart sensible climate policies which balance the unequivocal need for drastic greenhouse gas emission abatement with normative considerations on fair burden sharing both at the international level but also within domestic boundaries. Our starting point is to take stock of the economic impacts associated with the implementation of the initial NDCs under the Paris Agreement by 2030, thereby exclusively considering CO₂ emissions from fossil fuel combustion which is the major source of anthropogenic greenhouse gas emissions. We assume that individual countries have a vested interest in meeting their domestic emission reduction pledges at minimum compliance costs, and therefore strong impetus to exploit the cheapest abatement options domestically. Cost-effective emission reduction will be

achieved by uniform emissions pricing which can be implemented in terms of an economy-wide emissions tax or an emissions cap-and-trade system. We next investigate the question of how the magnitude and regional distribution of economic adjustment costs changes as we transit towards more ambitious emission reduction targets, ultimately aligning the current NDCs by 2030 with the long-run 2°C temperature goal. Starting from this reference situation, our primary objective is to sketch the design of climate policies associated with lower economic costs for emission reduction at the international and domestic level and thereby help to increase the likelihood of reaching the ambitious Paris temperature targets through collective action. Economic theory provides fundamental guidelines which can be translated into tangible numbers by means of applied economic analysis, such as the EMF36 study. The first fundamental guideline is to exploit efficiency gains from where-flexibility at the international level. Since greenhouse gas emissions are a global externality it does not matter where emissions are reduced, as long as they are removed from the atmosphere. Cost-effective global climate policy then implies to abate greenhouse gases where it is the cheapest, i.e., to equate the costs of abatement at the margin across all abatement options. Basic economic theory suggests that NDC parties should strive for uniform global emissions pricing through international trade in emission pledges. The EU emissions trading system, which started 2005, provides a landmark for cost-efficient where-flexibility in abatement across multiple countries. There is widespread evidence of substantial cost savings from emissions trading, both at the level of subnational as well as multilateral jurisdictions (Weyant and Hill, 1999; Metcalf, 2009; Böhringer et al., 2009; Akimoto et al., 2017; Fujimori et al., 2016). The second guideline is that emissions pricing creates revenues of which recycling can drastically affect the overall incidence of emission reduction policies (Fullerton and Muehlegger, 2019). More specifically, economic theory suggests that lump-sum recycling of revenues from emissions pricing to households can more than compensate the regressive effects of emissions pricing (Chiroleu-Assouline and Fodha, 2014; Klenert and Mattauch, 2016). Indeed, since each household receives an equal share of revenues, the lump-sum transfer constitutes a larger share of additional disposable income for lower-income households; if sufficiently high, the transfers can mitigate or even overcompensate initially regressive effects of emissions pricing.

The EMF36 study provides quantitative insights into the magnitude and distribution of

Post-Paris climate policy designs up to 2030, paying special attention to the role of where-flexibility and revenue recycling for making stringent emission reduction politically feasible. Based on simulations with several established energy-economy models operated by internationally recognized experts, our key findings are as follows. First, narrowing the NDCs towards 2030 in line with the 2°C temperature target will induce global economic adjustment costs of roughly 1% by 2030 relative to a business-as-usual case. Across regions, countries exporting fossil fuels are most adversely affected from the transition towards a low-carbon economy. Second, international emissions trading can substantially reduce adjustment costs at the global and regional level, thereby reducing the propensity for contentious normative debates on equitable burden sharing. Global cost savings from comprehensive global emissions trading as compared to only domestic action range from 50-90% depending on the stringency of the NDC pledges. Third, lump-sum revenue recycling in equal shares to households offsets the regressive effects of emissions pricing which might be crucial to improve the social acceptability of more ambitious climate policy.

Our main findings can be summarized in a climate policy triad of ‘Pledge, Trade, and Recycle’: To achieve the Paris temperature target, more ambitious reduction pledges are necessary in the short-term. Their political feasibility will hinge on cost reductions through international emissions trading and progressive revenue recycling at the domestic level.

The remainder of this article is organized as follows. Section 2 lays out the study design with respect to key research questions and specific policy scenarios to be shared across all modeling groups. Section 3 presents a cross-comparison of model results. Section 4 concludes.

2.2 Study design

Our analysis is based on a systematic cross-comparison of results from 17 internationally established energy-economy models – 15 multi-region models and two single-country models – which simulate pre-defined policy scenarios with harmonized assumptions. Seven of the participating models are static and ten are recursive-dynamic. Table 2-1 provides a summary of the groups participating in the model-comparison study, their

models, institutions, and people involved.

Hereafter we briefly discuss model characteristics and data inputs. We then layout and motivate the policy scenarios that are investigated in the model-cross comparison.

2.2.1 Models and data

All models that participate in the cross-comparison are computable general equilibrium (CGE) models. CGE models constitute a powerful numerical simulation method to perform economy-wide impact assessments of policy reforms based on microeconomic theory and empirical data. More specifically, CGE models are rooted in general equilibrium theory that combines assumptions regarding the optimizing behavior of economic agents with the analysis of equilibrium conditions (Shoven and Whalley, 1992). Producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers maximize their well-being subject to budget constraints and preferences. Substitution and transformation possibilities in production and consumption are typically described by means of continuous functional forms where economic responses are driven by empirical estimates of elasticities and initial value shares derived from empirical economic accounts.

A key strength of CGE models is their comprehensive coverage of market interactions through price and income-responsive supply and demand reactions on behalf of economic agents. The disaggregation of macroeconomic production, consumption, and trade activities at the sector level based on regional input–output matrices enables to track structural change.

Policy reforms such as CO₂ pricing do not only affect the prices of consumer goods, but also sources of income, such as wages and returns to capital. Compared to partial equilibrium approaches as bottom-up energy system models or microsimulation models for instance, CGE models do not only capture the incidence of changes in relative prices on the expenditure side but also on the income side. With an explicit representation of different economic agents such as firms, households, and governments, CGE models can quantify the distributional impacts of policy measures.

Table 2-1 Expert teams participating in the EMF36 model comparison study

Expert teams participating in the EMF36 model comparison study.

Model	Institution	People
CEPE ^b	ETH Zürich	Florian Landis, Gustav Fredriksson, Sebastian Rausch
ICES ^c	Euro-Mediterranean Center on Climate Change (CMCC)	Ramiro Parrado
DART Kiel ^c	Kiel Institute for the World Economy (IfW)	Sonja Peterson, Malte Winkler, Sneha Thube
DREAM ^c	Fudan University	Haoqi Qian, Shuaishuai Zhang, Libo Wu
EC-MSMR ^c	Environment and Climate Change Canada	Nick Macaluso, Peter Johnston, Madanmohan Ghosh, Elisabeth Gilmore
EDF-GEPA ^b	Environmental Defense Fund (EDF)	Gökçe Akin-Olçum, Ruben Lubowski, Margaret McCallister
JRC-GEM-E3 ^c	European Commission - Joint Research Centre (JRC)	Toon Vandyck, Matthias Weitzel, Krzysztof Wojtowicz, Luis Rey Los Santos, Anamaria Maftei, Sara Riscado
ENVISAGE ^c	Purdue University	Maksym Chepeliev, Israel Osario-Rodarte, Dominique van der Mensbrugge
SNoW ^b	Statistics Norway	Taran Fæhn, Hidemichi Yonezawa
TEA ^c	COPPE - Universidade Federal do Rio de Janeiro (UFRJ)	Rafael Garaffa, Bruno Cunha, Talita Cruz, Paula Bezerra, André Lucena, Angelo Gurgel
TUB ^b	Technical University (TU) Berlin	Mohammad M. Khabbazan, Christian von Hirschhausen
C-GEM ^c	Tsinghua University	Duan Maosheng, Li Mengyu
UOL ^b	University of Oldenburg	Christoph Böhringer, Jan Schneider
WEGDYN ^c	Wegener Center for Climate and Global Change - University of Graz	Jakob Mayer, Anna Dugan, Gabriel Bachner, Karl Steininger
PACE ^b	Zentrum für Europäische Wirtschaftsforschung (ZEW)	Sebastian Rausch
IEG ^{a,c}	Institute of Economic Growth India (IEG)	Basanta Pradhan, Joydeep Ghosh
BC3 ^{a,b}	Basque Centre for Climate Change (BC3)	Xaquín Garcia Muros, Iñaki Arto, Mikel González-Eguino

^aSingle-country model.^bStatic model.^cRecursive-dynamic model.

To summarize: CGE models incorporate key dimensions of economy-wide impact assessment in a micro-consistent framework, thereby accommodating a systematic quantitative trade-off analysis between policy objectives for economic performance, income distribution, and environmental quality.

As is customary in applied general equilibrium analysis, baseyear data together with exogenous elasticities determine the free parameters of functional forms. For baseyear calibration the modeling groups of the EMF36 study use input data of the Global Trade Analysis Project (GTAP) database which includes detailed accounts of production, consumption, bilateral trade, as well as data on physical energy flows and CO₂ emissions for up to 141 regions and 65 sectors. The modeling groups use either version 9 (Aguiar et al., 2016) with the most recent base year of 2011, or version 10 (Aguiar et al., 2019) with the most recent base year of 2014. Some modeling groups use the GTAP-Power extension (Peters, 2016; Chepeliev, 2020), which includes a disaggregated electricity sector. As discussed below, the business-as-usual projection of the models towards 2030 is based on common data inputs from the International Energy Outlook (IEO) 2017 (EIA, 2017) and the World Energy Outlook (WEO) 2018 (IEA, 2018), respectively.

The regions and sectors of the GTAP dataset are aggregated towards the specific requirements of the EMF study. With respect to regional coverage, the composite dataset includes major industrialized and developing regions which play a key role in the international climate policy negotiations. With respect to sectoral coverage, the composite dataset maintains all primary and secondary energy carriers in GTAP: coal, crude oil, natural gas, refined oil products, and electricity. The explicit treatment of these primary and secondary energy carriers is essential in order to distinguish energy goods by CO₂ intensity and the degree of substitutability (fuel switching). In addition, we incorporate a composite sector for energy-intensive and trade-exposed industries (EITE) which are most vulnerable to emissions pricing. The remaining sectors of the GTAP dataset are categorized in four additional composite sectors: transport, agriculture, other manufacturing, and services.

Table 2-2 lists the set of regions covered by the fifteen multi-region models, and the set of sectors (commodities) covered by all models – including the single-country models – to warrant a coherent cross-comparison of results. Note that some models include a more

detailed regional and/or sectoral disaggregation. In these cases, results were aggregated to meet the requirements listed in Table 2-2.

2.2.2 Scenarios

The primary objective of our analysis is to quantify the medium-term economic impacts of CO₂ pricing in the aftermath of the Paris Agreement for alternative NDC ambition levels and for different degrees of international cooperation through emissions trading. We take 2030 as the policy-relevant target year for the impact assessment which constitutes the milestone to which most Paris parties have submitted their first-round NDCs. Against this background, we devise the EMF36 core scenarios along two dimensions which are critical for the magnitude and distribution of economic adjustment costs to Post-Paris climate policies: (i) the stringency of future NDCs (ambition), and (ii) the scope of international emissions trading across sectors and regions (co-operation). Table 2-5 at the end of this section presents an overview of the fifteen core scenarios that emerge as the cross-product of the two scenario dimensions for three NDC variants and five emissions trading variants. The default policy instrument to achieve emission reduction is emissions pricing which can be equally implemented via an emissions tax or an emissions cap-and-trade system. To address public concerns on the regressive impacts of emissions pricing, revenues are recycled lump-sum to the consumers. A subgroup of models (see Table 2-3) distinguishes consumers by income deciles and investigates the extent to which the progressive effect of an equal-per-household rebate offsets the regressive effect of higher energy prices⁷⁸. CO₂ revenues are recycled lump-sum in equal shares to households. Since CO₂ pricing typically depresses other government tax

⁷ The single-country models BC3 and IEG use business-as-usual projections and CO₂ emission reduction targets for the countries under investigation (BC3 – Spain; IEG – India) which are in line with our specifications in Sections 2.2.2.1 and 2.2.2.2.

⁸ The CEPE modeling group's analysis is based on household-level data from Eurostat's 2010 Household Budget Survey (HBS) and Eurostat's 2010 European Union Statistics on Income and Living Conditions (EU-SILC). The responsibility for all conclusions drawn from these data lies entirely with the CEPE modeling group. The results and conclusions are solely those of the CEPE modeling group, and not those of Eurostat, the European Commission or any of the national statistical authorities whose data have been used.

revenues, we adopt the convention that the government recycles the remaining CO₂ revenues after balancing its budget in order to keep government expenditures constant.

Table 2-2 EMF36 sectors and regions

Countries and regions	Sectors
<i>Countries</i>	<i>Energy</i>
United States (USA)	Coal
Canada (CAN)	Petroleum and coal products
Japan (JPN)	Crude oil
South Korea (KOR)	Natural gas
Russia (RUS)	Electricity
China (CHN)	<i>Other sectors/aggregates</i>
India (IND)	Energy-intensive and trade-exposed (EITE) ^b
Brazil (BRA)	Transport
<i>Aggregated regions</i>	Agriculture
Australia and New Zealand (ANZ)	Other manufacturing
Europe (EUR) ^a	Services
Middle East (MEA)	
Africa (AFR)	
Other Americas (OAM)	
Other Asia (OAS)	

^aIncludes EU27 + UK + EFTA members.

^bIncludes chemical products; basic pharmaceutical products; rubber and plastic products; non-metallic minerals; mining of metal ores; iron and steel; non-ferrous metals; paper, pulp, and print.

The impacts of a policy reform (in our case: the implementation of NDCs) are usually quantified with respect to a reference situation where the reform is not in place, the so-called business-as-usual (BaU). Comparative-static analysis then provides a comparison of two different economic situations, before and after a change in specific exogenous parameters such as the imposition of emission reduction pledges. If policy targets and measures refer to the future there is the need to establish a business-as-usual projection which captures the hypothetical evolution of the economy in the absence of these targets and measures. In the following, we describe our business-as-usual assumptions and subsequently lay out the two core scenario dimensions, i.e., the ambition level of NDCs and the degree of cooperation in multilateral climate policies through international emissions trading.

Table 2-3 Models with household impact analysis

Model	Specification	Specific country
BC3	Single-country	Spain
IEG	Single-country	India
TEA	Multi-region	Brazil
CEPE	Multi-region	Belgium, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Latvia, Lithuania, Poland, Portugal, Slovakia, Slovenia, Spain, United Kingdom, Bulgaria, Croatia, Romania
JRC-GEM-E3	Multi-region + soft-link ^a	Austria, Belgium, Czech Republic, Germany, Estonia, Greece, Spain, Finland, France, Italy, Romania
SNoW	Multi-region	Norway
DREAM	Multi-region	China
UOL	Multi-region	Germany

^aJRC-GEM-E3 feeds its macroeconomic results for 11 European countries into the EUROMOD-ITT (Indirect Tax Tool) in order to perform the household impact assessment.

Table 2-4 BaU projections on CO₂ and GDP in 2030

Region	CO ₂			GDP		
	2011	2030		2011	2030	
		IEO	WEO		IEO	WEO
	Mt of CO ₂	2011 = 1	2011 = 1	Billion USD	2011 = 1	2011 = 1
United States (USA)	5107	0.89	0.90	15 533	1.51	1.46
Canada (CAN)	523	1.08	1.02	1 778	1.38	1.45
Japan (JPN)	1028	0.90	0.80	5 905	1.13	1.18
South Korea (KOR)	501	1.20	1.44	1 202	1.57	2.14
Russia (RUS)	1503	0.95	1.05	1 904	1.26	1.33
China (CHN)	7098	1.14	1.28	7 567	2.72	2.92
India (IND)	1771	1.86	2.47	1 880	3.01	3.80
Brazil (BRA)	372	1.25	1.19	2 476	1.32	1.39
Australia & New Zealand (ANZ)	411	1.10	1.32	1 550	1.64	2.14
Europe (EUR)	4211	0.89	0.80	19 182	1.29	1.34
Middle East (MEA)	1808	1.28	1.29	3 372	1.74	1.77
Africa (AFR)	952	1.33	1.40	2 076	1.98	2.00
Other Americas (OAM)	1167	1.15	1.12	3 471	1.60	1.55
Other Asia (OAS)	2128	1.48	1.70	3 569	2.07	2.31

2.2.2.1 *Business-as-usual (BaU) projections*

The costs of complying with future emission constraints are directly linked to the structural characteristics of an economy exhibited in a hypothetical business-as-usual (BaU) situation without such emission constraints (Dellink et al., 2020). The BaU projections do not only determine the magnitude of the effective abatement requirement, i.e. the difference between the future business-as-usual emissions and the exogenous emission ceiling, but also the ease of emission abatement as reflected by the curvature of marginal abatement cost curves.

Due to the importance of BaU projections for the economic impact assessment of future climate policy constraints, we perform sensitivity analysis with respect to assumptions on future GDP growth and CO₂ emissions in 2030 from two official, widely-used sources: the International Energy Outlook (IEO) 2017 (EIA, 2017) and the World Energy Outlook (WEO) 2018 (IEA, 2018).

Table 2-4 shows the CO₂ emissions and GDP values for 2011 which, based on the GTAP data, serve as the historical base-year for the model study together with the respective growth indices up to 2030 that are derived from the IEO and WEO projections.

2.2.2.2 *Nationally determined contributions (NDCs)*

We use the initial NDCs submitted by the Paris parties to the UNFCCC (UNFCCC, 2020) to derive three different ambition levels for emission reductions – referred to as *NDC*, *NDC+*, and *NDC-2C*.

Our starting point are the NDCs under the Paris Agreement as listed in Kitous et al. (2016). Various countries have provided two different pledges – unconditional pledges which we label as *NDC* and more ambitious pledges that are conditional on reduction efforts of other regions, financial support, or other types of assistance, which we label as *NDC+*. We translate these NDCs into region-specific reduction requirements for CO₂ emissions from fossil fuel combustion in percent from the 2030 business-as-usual emission levels projected by IEO and WEO⁹. Given that total emission reduction pledges

⁹ Note that we impose a minimum reduction target of 5% for countries that state their NDCs as an emission

even for the more ambitious *NDC+* fall substantially short of what is deemed to be necessary in 2030 for meeting the long-run Paris temperature goal, we construct a third ambition level – called *NDC-2C*. For the *NDC-2C* targets we scale emission levels in *NDC+* uniformly across regions in order to comply with an emission reduction for 2030 compliant with the 2°C emission trajectory suggested by integrated assessment analysis¹⁰.

Figure 2-1 visualizes the region-specific reduction targets across the three ambition levels with respect to BaU emissions projected by IEO and WEO. The blue bars represent reduction targets under *NDC*, and the orange and green incremental bars illustrate the additional reduction requirements under *NDC+* and *NDC-2C*, respectively. For regions without an orange incremental bar, *NDC* and *NDC+* are identical.

Global reduction requirements are of roughly 10% for *NDC* and 12% for *NDC+* compared to the BaU projections. For a 2°C emission trajectory (*NDC-2C*), the global reduction requirement is of 27% for the BaU based on WEO and 21% for the BaU based on IEO. The difference is primarily due to higher projected CO₂ emissions growth in China and India in WEO as compared to IEO. Our budget approach for *NDC-2C* where we scale to a given level of global emissions then implies a higher reduction requirement against WEO than IEO projections.

Compared to global average reduction requirements we see that Africa, Middle East, and Russia have rather low reduction targets under *NDC*, while Brazil, Canada, Europe, and South Korea have substantially stricter targets. The consideration of conditional targets (*NDC+*) primarily plays a role in Africa, Middle East, as well as Other Americas and

intensity target assuming that such a target will lead to some degree of effective CO₂ pricing, even if BaU projections suggest that targets are reached without CO₂ pricing. These minimum targets are binding for China and India against both BaU projections, such that they have the same reduction targets of 5% under *NDC* despite different CO₂ emission projections in IEO and WEO. For countries that state their target as a physical emission level (e.g. by specifying an own BaU emission path), we translate this emission level into effective reduction targets against the IEO and WEO BaUs. For more details on the derivation of BaU projections and NDCs, see Appendix A.

¹⁰ We use an average value for reductions in global CO₂ emissions from energy use in 2030 compared to 2011 in 2°C scenarios derived from data provided by the IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (Huppmann et al., 2019).

Other Asia.

A region generally faces a higher reduction target against that BaU – WEO or IEO – which projects higher CO₂ emissions for the respective region in 2030. For example, Europe has an effective target of 25% against IEO projections and of 20% against WEO projections, whereas South Korea faces a higher reduction target against WEO projections.

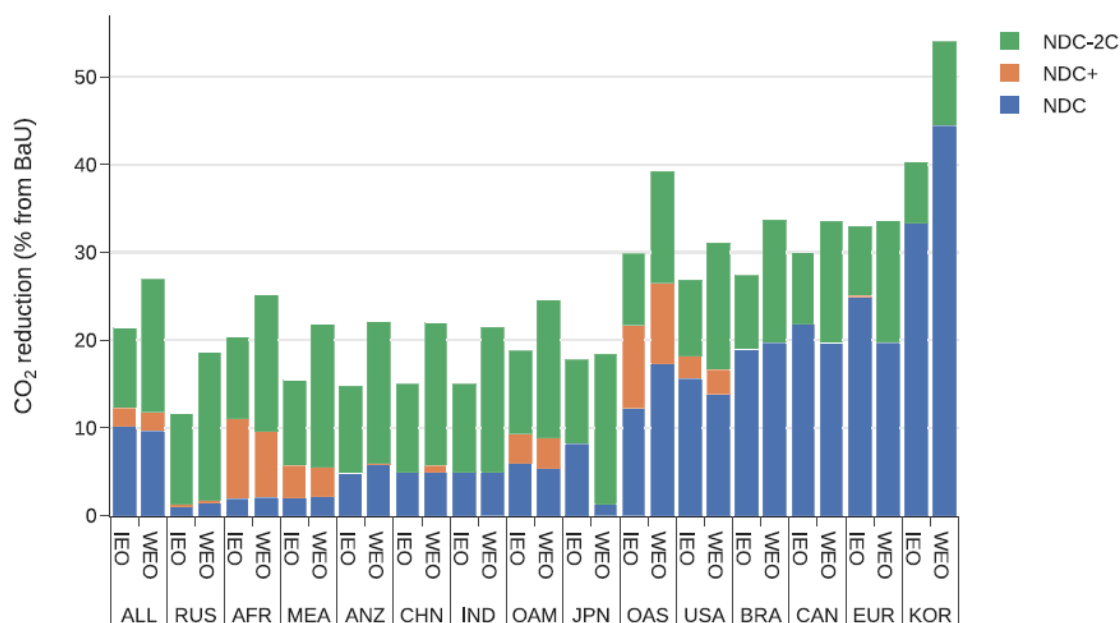


Figure 2-1: Reduction targets for CO₂ emissions from fossil fuel combustion for different ambition levels (in % from 2030 BaU projections based on IEO or WEO). Note: ALL — Global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

2.2.2.3 International emissions trading

Our second scenario dimension considers five different degrees of international cooperation via emissions trading across sectors and regions. On the one extreme (*ref*), we assume that there is no international emissions trading at all, i.e., regions meet their reduction targets by strictly domestic emissions pricing¹¹. On the other extreme (*global*), we assume full where-flexibility such that there is only one global emission price

¹¹ Note that composite regions reach their reduction targets through one overall emissions budget constraint, i.e., implicitly we assume that there is emissions trading within composite regions.

applying to all sectors and regions. In between the two polar cases, we specify three intermediate cases that sketch more likely variants of cross-country cooperation in coordinating abatement efforts via joint emission markets. The variant *partial* prescribes emissions trading only in energy-intensive and trade-exposed (EITE) sectors (as well as the power sector) where stakeholders are most concerned on adverse impacts of stringent emission constraints¹². In this case, regional CO₂ emissions in other sectors are kept at *ref* levels. Furthermore, we set up two “Club-Trading” cases which might occur within the next few years: Variant *eur-chn* considers emissions trading between Europe and China while variant *asia* considers emissions trading between China, Japan, and South Korea. For both “Club-Trading” cases, we assume partial trading across sectors, i.e. there is a joint emission market for EITE and power sectors, while all other sectors face a domestic emission constraint set at the *ref* emission level. Note that across all where-flexibility specifications, global emissions remain constant at the same level warranting a coherent cost-effectiveness analysis.

Table 2-5 EMF36 core scenarios

Acronyms	Description
<i>Ambition</i>	
<i>NDC</i>	Translation of unconditional nationally determined contributions
<i>NDC+</i>	Translation of conditional nationally determined contributions
<i>NDC-2C</i>	Scaling of <i>NDC+</i> emission levels to reach 2°C temperature goal
<i>Cooperation</i>	
<i>ref</i>	Reference case where each region reaches its reduction target without further international emissions trading
<i>global</i>	Emissions trading across all regions and sectors
<i>partial</i>	Emissions trading across all regions in EITE and power sectors
<i>eur-chn</i>	Emissions trading between Europe and China in EITE and power sectors
<i>asia</i>	Emissions trading between China, Japan and South Korea in EITE and power sectors

We denote specific scenarios composed of one ambition level and one international cooperation variant with their respective acronyms separated by a slash (“/”). For example, the scenario where regions implement their unconditional nationally determined contributions domestically without international emissions trading is labelled *NDC/ref*.

¹² These sectors are also covered in existing national and supranational emissions trading schemes such as the EU emissions trading scheme.

We also refer to scenario *NDC/ref* as the central case, since it describes the status quo of the Paris Agreement.

2.3 Results

We focus on results for the year 2030 and begin our presentation with global (average) CO₂ prices and global welfare impacts. Subsequently, we discuss regional effects, before summarizing findings on welfare implications of equal-per-household revenue-recycling across income deciles.

CO₂ prices are measured in 2011-USD per tCO₂. Welfare changes are measured in terms of Hicksian equivalent variation (HEV) in income denoting the amount of money that is necessary to add to or deduct from the BaU income of households so that they enjoy a utility level equal to the one in the counterfactual policy scenario on the basis of BaU prices. A negative HEV hence indicates a welfare loss as compared to the BaU welfare. We aggregate welfare results from a utilitarian welfare perspective, that is, we adopt an agnostic position regarding cost distribution across regions when exposing global welfare results, and regarding cost distribution across households when exposing regional welfare results. Across all scenarios, we do not account for the (monetized) benefits from avoided climate damages acknowledging the wide spread of estimates on the social cost of carbon. Thus, negative welfare impacts must be interpreted as gross economic adjustment costs to emission reductions from BaU and cannot be taken as an indicator for the desirability of emission reductions from a more comprehensive cost-benefit perspective. Global emission levels are constant across the different emissions trading variants such that we can perform meaningful global cost-effectiveness analysis at each respective ambition level *NDC*, *NDC+*, and *NDC-2C*. Note that our reduction targets relate to CO₂ emissions from fossil fuel combustion only, which is by far the most important source for greenhouse gas emissions.

Since important parameterizations are streamlined in common assumptions in the business-as-usual and the counterfactual climate policy scenarios, variations across models can be explained to a large extent by structural differences across models that capture the price responsiveness of production, consumption, and trade to CO₂ emission constraints. These differences drive the marginal and inframarginal costs of the

represented economies to substitute away from carbon-intensive inputs. The abatement options include fuel switching, substitution of energy with non-energy in-puts (energy efficiency), as well as output and demand reductions (energy savings). The costs of different abatement options are governed by cross-price elasticities and cost shares between various energy goods with different CO₂ intensities, as well as between energy and non-energy goods. Three models also include representations of advanced technologies such as carbon capture and sequestration (CCS), which can become profitable under stringent emissions constraints and provide additional abatement opportunities. However, in the 2030 time horizon these technologies play a negligible role. Other important drivers of economic impacts triggered by emission constraints include the representation of existing or anticipated climate policies and assumptions about future international energy prices or technological change with respect to carbon and energy efficiency up to 2030, that are employed to meet the streamlined regional GDP values and CO₂ emissions in the 2030 BaU projections. In recursive-dynamic models which incorporate vintage capital the paths of capital accumulation prior to 2030 determine the sectoral capital stocks which are no longer malleable. Adjustment costs to emission constraints are typically amplified compared to models where capital can freely move across sectors. All these choices translate into model-specific marginal abatement cost (MAC) curves that provide a first-round approximation on the direct costs of emission abatement as the area under the MAC curve. The MAC curves are convex, indicating that it gets increasingly more expensive to abate the next unit of CO₂ as we decarbonize the economy. With the option for emissions trading the direct adjustment costs to domestic emission constraints will be adjusted by cost savings through exports or imports of emission allowances. Furthermore – as captured in a general equilibrium framework – there are potentially important income effects, most notably via policy-driven changes in international prices, the so-called terms of trade, that will increase or decrease the initial direct costs of emission restrictions depending on the structural characteristics of a specific economy in international trade.

In our exposition of the results, we focus on policy-induced changes from the BaU projection by IEO, and point to differences in results as compared to the BaU projection by WEO where relevant.

2.3.1 Global impacts

We report global impacts for the two polar cases in emissions trading, *ref* and *global*, across the three different ambition levels in emission reductions *NDC*, *NDC+*, and *NDC-2C*. The resulting six scenarios comprise the full range on where-flexibility in emissions trading and on the stringency in emission reductions. On the low-cost end we have the combination of least ambitious emission reduction targets (*NDC*) and full where-flexibility (*global*). On the high-cost end we have the most ambitious emission reduction targets (*NDC-2C*) and a purely domestic implementation (*ref*) which does not exploit cost savings from international emissions trading.

Figure 2-2 shows the global average CO₂ prices in *ref* and *global* for the different ambition levels. In *ref* this refers to the emission-weighted average across regional CO₂ prices, whereas in *global* it refers to the globally uniform (tradable) CO₂ price. We first focus on *ref*, where regions implement their reduction targets domestically without international emissions trading. As expected, the global average CO₂ price increases with the ambition level reflecting the monotonicity of regional MAC curves. In the central case (*NDC/ref*), we find a range of 10 USD per tCO₂ to 69 USD, with a mean of 33 USD. For the most ambitious reduction targets in *NDC-2C/ref*, global average prices range from 26 USD per tCO₂ to 164 USD with a mean across models of 78 USD. These results are consistent with the range of findings of the High Level Commission on carbon pricing which “concludes that the explicit carbon-price level consistent with achieving the Paris temperature target is at least [...] USD50–100/tCO₂ by 2030” (Stiglitz et al., 2017).

Considering comprehensive global emissions trading, note that for each ambition level, the global average CO₂ price is necessarily lower in *global* compared to *ref* and the wedge between the two prices indicates cost-saving potentials¹³. We find that moving to *global* roughly halves the required (then globally uniform) CO₂ price in most models.

¹³ This is the case because for each ambition level the global emission reduction is the same in *ref* and *global*, but in *ref* marginal abatement costs (CO₂ prices) differ across regions. Given convex MAC curves, the emission-weighted average in *ref* must be higher than in *global*.

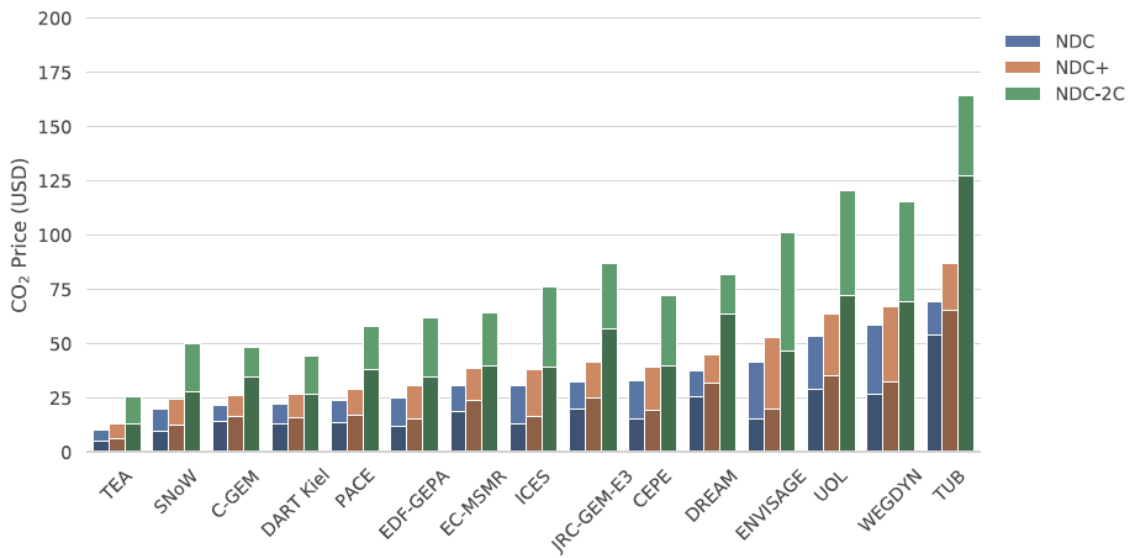


Figure 2-2: Global average CO₂ prices for three different ambition levels (*NDC*, *NDC+*, *NDC-2C*) and two polar cases of emissions trading (*ref*, *global*). Note: The lighter shaded bars represent CO₂ prices in *ref*. The darker shaded bars represent CO₂ prices in *global*.

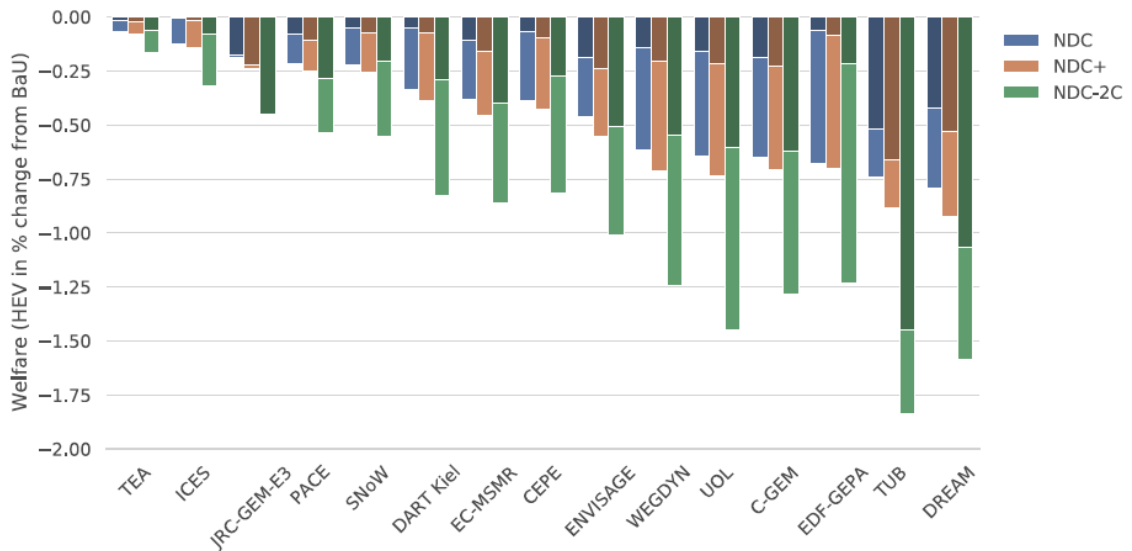


Figure 2-3: Global welfare effects for three different ambition levels (*NDC*, *NDC+*, *NDC-2C*) and two polar cases of emissions trading (*ref*, *global*). Note: The lighter shaded bars represent welfare changes in *ref*. The darker shaded bars represent welfare changes in *global*.

Figure 2-3 shows the global welfare impacts in *ref* and *global* for the three different ambition levels on emission reduction *NDC*, *NDC+*, and *NDC-2C*. We find that at the global level welfare effects roughly mirror the results for CO₂ prices, where higher CO₂ prices correspond to higher economic adjustment costs. Under *NDC/ref*, we find a range of 0.07% up to 0.8%, and a mean of 0.43% for the global economic adjustment costs

compared to the BaU. Under more restrictive emission caps that are in line with a 2°C path in 2030 (*NDC-2C*) global adjustment costs in most models more than double, ranging from 0.16% to 1.84%, with a mean of 0.94%¹⁴. From a global perspective, *NDC+* leads to very similar adjustment costs as *NDC*, reflecting that conditional Paris pledges by individual regions only lead to roughly 2% additional global emission reduction compared to unconditional pledges.

Comprehensive international emissions trading (*global*) provides substantial global cost savings of 50%-90% in most models, which is in line with earlier studies on emissions trading in the context of the Paris Agreement (Rose et al., 2018; Fujimori et al., 2016). The mean global welfare loss is 0.15% in *NDC/global* and 0.47% in *NDC-2C/global*¹⁵. Welfare gains through global emissions trading thereby increase with the stringency of the reduction targets. Under the actual Paris pledges (*NDC*) moving from *ref* to *global* increases global welfare on average by 0.28%. For the most stringent reduction targets under *NDC-2C*, this figure is 0.47%¹⁶¹⁷.

A policy-relevant message arises from the comparison between *NDC/ref*, which depicts the status quo of the Paris Agreement, and (*NDC-2C/global*). In most models, the global adjustment costs for *NDC-2C/global* are quite similar to the costs of *NDC/ref*. This gets reflected in the mean global adjustment costs, which are 0.43% in scenario *NDC/ref*, and

¹⁴ This amounts to additional global costs in *NDC-2C/ref* of 0.5% percentage points compared to the central case (*NDC/ref*). For the alternative BaU based on WEO projections we find average global economic adjustment costs of 0.36% (*NDC/ref*) and 1.2% (*NDC-2C/ref*), which corresponds to slightly lower global reduction requirements under *NDC*, and to higher reduction requirements under *NDC-2C* (see Figure 2-1). The additional global adjustment costs thus amount to 0.84% percentage points.

¹⁵ Note that we implicitly assume emissions trading in composite regions even in *ref*, compare footnote 11, meaning that our results provide lower bound estimates for the cost-saving potential of where-flexibility.

¹⁶ As a subtlety it should be noted that cost savings from comprehensive international emissions trading tend to decrease in relative terms, i.e. as a fraction of *ref* adjustment costs with higher ambition levels. The logic behind is that it becomes increasingly expensive to substitute away from carbon when production and consumption patterns are getting less carbon intensive.

¹⁷ UB and DREAM find considerably lower cost savings from trading as indicated by their rather small CO₂ price wedges between *ref* and *global*, while JRC-GEM-E3 finds almost no differences between the reference case and full trading from a global perspective. Note that the JRC-GEM-E3 model incorporates power market decarbonization behavior that might lead to second-best emission abatement choices.

0.47% in *NDC-2C/global*. The key message here is that – from a global welfare perspective – the actual reduction pledges under the Paris Agreement can be ratcheted up roughly cost-neutrally towards much more stringent pledges in line with the 2°C temperature goal if at the same time the where-flexibility through international cooperation towards globally uniform CO₂ emissions pricing is fostered¹⁸. Hence, cost savings through where-flexibility pay the bill for a more ambitious international climate policy.

For the intermediate cases of where-flexibility *eur-chn*, *asia*, and *partial* (omitted in Figure 2-3 for the sake of clarity) most models prompt a ranking in terms of global welfare impacts that roughly mirrors the share of global CO₂ emissions eligible for international trading. In *global* the share by definition amounts to 100%, in *partial* to around 55%, in *eur-chn* to 25%, and in *asia* to around 20%.

2.3.2 Regional incidence

Welfare effects at the regional level are driven by two effects. First, regions face abatement costs in line with their emission reduction targets and abatement options that are reflected in the regions' CO₂ prices (marginal abatement costs). Second, regions are subject to indirect spillover effects due to policy-induced price changes on international markets – i.e., terms-of-trade effects – both for energy and non-energy goods. Fossil fuel demand and thus fossil fuel prices decline under emissions pricing, which benefits fuel importers and hurts fuel exporters. Production costs for energy- and trade-exposed (EITE) goods increase due to emissions pricing. This does not only affect changes in comparative advantage, but the heterogeneous nature (imperfect substitutability) of traded commodities makes it possible for EITE exporters to pass through part of their domestic abatement costs via higher prices to the respective importers.

Variations across models can be traced back to modeling choices that govern the magnitude of these effects. Direct abatement costs are driven by the shape of the MAC curves that are in turn determined by cost and expenditure shares in production and

¹⁸ This finding becomes weaker in the BaU based on projections from WEO. Here, global adjustment costs are on average 1.8 times higher in *NDC-2C/global* compared to *NDC/ref*, see also footnote 14.

consumption and the cross-price elasticities of substitution across production inputs and consumption goods. International spillovers are driven by cost shares and elasticities in international trade, which determine the ease of substitution away from more expensive imported goods in domestic production and consumption; terms-of-trade effects on international fuel markets are governed to a larger extent through the choice of supply elasticities in fossil fuel production.

We begin our exposition of regional effects with the status quo of the Paris Agreement where regions implement their Paris emission reduction pledges without further international emissions trading (scenario *NDC/ref*). We then explore implications of increasing the ambition level and the degree of international cooperation.

2.3.2.1 Regional compliance with Paris pledges

Figure 2-4 shows a summary of regional CO₂ prices (marginal abatement costs), which depend on the effective reduction targets shown in Figure 2-1 and the regions' abatement abilities. As expected, regions with higher reduction targets face higher CO₂ prices. More specifically, the regions with the highest reduction targets (Brazil, Canada, Europe, and South Korea) also face the highest CO₂ prices, while regions with lower targets like Africa, China, India, the Middle East, and Russia exhibit low CO₂ prices.

Figure 2-5 shows a summary of regional welfare impacts across models. We find that direct abatement costs from compliance with the reduction target as inferred from the regional CO₂ prices (Figure 2-4) are strongly outweighed by terms-of-trade effects largely transmitted via changes in international fuel prices¹⁹. Individual regions may even benefit from emission reduction constraints. This is the case for India and Japan as large importers of fuels, where terms-of-trade gains more than offset the direct costs of emission abatement. The major share of the burden of global emission reductions falls on the fuel exporting regions Middle East and Russia, although both regions have relatively low reduction targets and associated CO₂ prices.

¹⁹ Note that all participating models implement international trade based on the standard assumption of product heterogeneity (Armington, 1969), which gives rise to substantial terms-of-trade effects when parameterized with empirical estimates of trade elasticities (Balistreri et al., 2018).

An interesting example showcasing the two effects driving regional adjustment costs is South Korea, where outcomes range from more than 2% gain in welfare to a loss of 2.6%. South Korea has the highest effective reduction target among all regions (33%, see Figure 2-1), leading to relatively high direct abatement costs. At the same time, South Korea is a fossil fuel importer, profiting from declining fuel prices, and an exporter of EITE goods. Which of these effects is dominating differs across models due to differences in the structure of the BaU economies and the choice of elasticities.

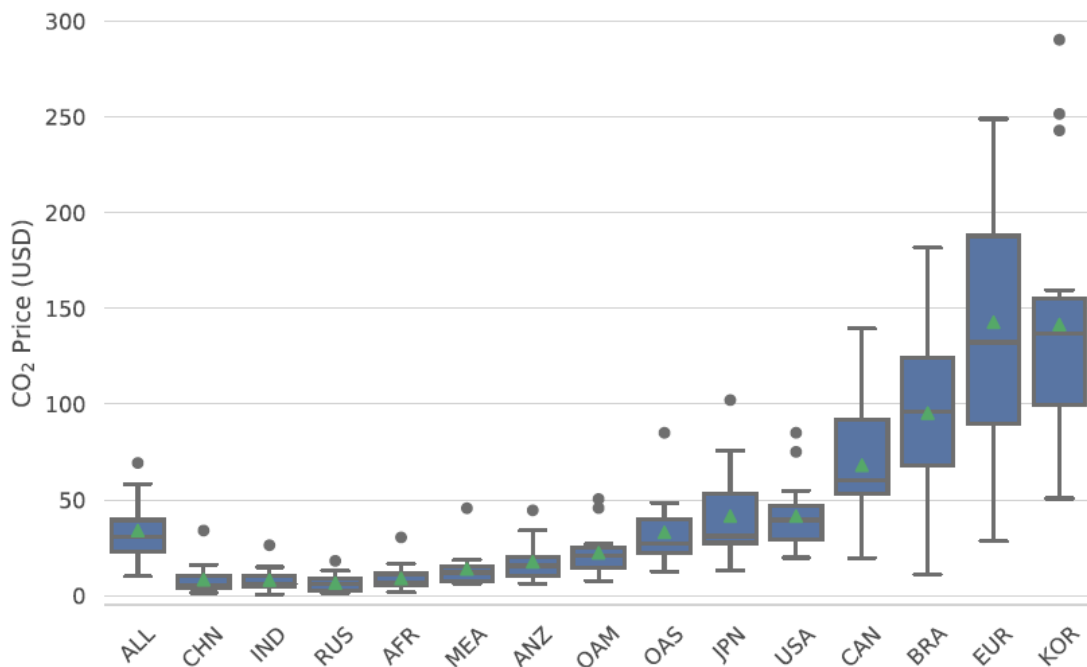


Figure 2-4: Regional CO₂ prices in *NDC/ref*. Note: Box–Whisker plot shows the median (line), mean (green triangle), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Dots indicate outliers. Region keys: ALL — Global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

We observe more heterogeneity across models on the regional level than on the global level. The cross-model variation in welfare is especially large for regions which have the most ambitious climate targets and regions where international feedback effects play an important role. The largest divergence is found for Russia and Middle East as large exporters of fossil fuels. However, South Korea and Europe, with strict targets and large

imports of fossil fuels also show a huge variation²⁰.

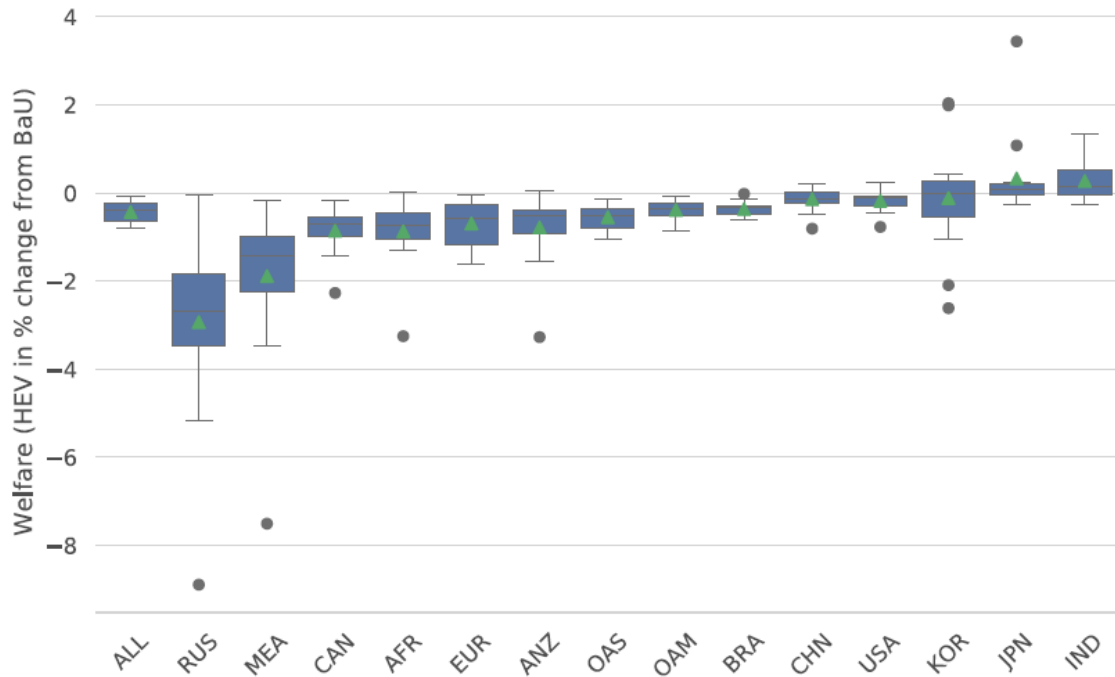


Figure 2-5: Regional welfare across all models in *NDC/ref*. Note: Box-Whisker plot shows the median (line), mean (green triangle), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Dots indicate outliers. Region keys: ALL — Global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

2.3.2.2 Ambition level and international cooperation

Figure 2-6 summarizes how regional welfare is affected as we move towards higher ambition levels *NDC+* and *NDC-2C*. Welfare effects are stated in percentage points from the respective values in *NDC/ref*²¹. Note that we still assume compliance via strictly domestic action, i.e., no international emissions trading. We observe that the difference

²⁰ For most regions the alternative BaU based on WEO projections entails rather similar welfare impacts. Europe is better off under the WEO projections due to the lower effective emission reduction requirement (see Figure 2-1). That in turn slightly benefits Russia, as European oil and gas imports drop less. Only for South Korea is the incidence sharply more pronounced, as its effective reduction requirement is higher, and at the same time international oil and gas prices decline slightly less.

²¹ As an example, a value of 1% would indicate that the region is better off by one percentage point measured in BaU welfare compared to the *NDC* case.

between *NDC* and *NDC+* is rather small for most regions. For regions that step up their emission reduction pledges markedly in *NDC+*— Africa, Middle East, Other Americas and Other Asia — welfare declines; also fossil fuel exporters suffer slightly more under the additional negative demand shock. The highest emission reduction ambition level (*NDC-2C*) leads to additional global adjustment costs of 0.5% compared to *NDC*²². We find that the additional global adjustment costs for scaling up emission reduction targets towards a 2°C trajectory is unevenly distributed²³. India, Japan, and South Korea do not face higher adjustment costs compared to the lowest ambition level (*NDC*). The gains from indirect international spillovers for these regions increase with the level of emission abatement, as direct abatement costs clearly increase as well. The fuel exporters Middle East and Russia lose overproportionally. All other regions lose roughly up to an additional 1% of BaU welfare compared to *NDC*.

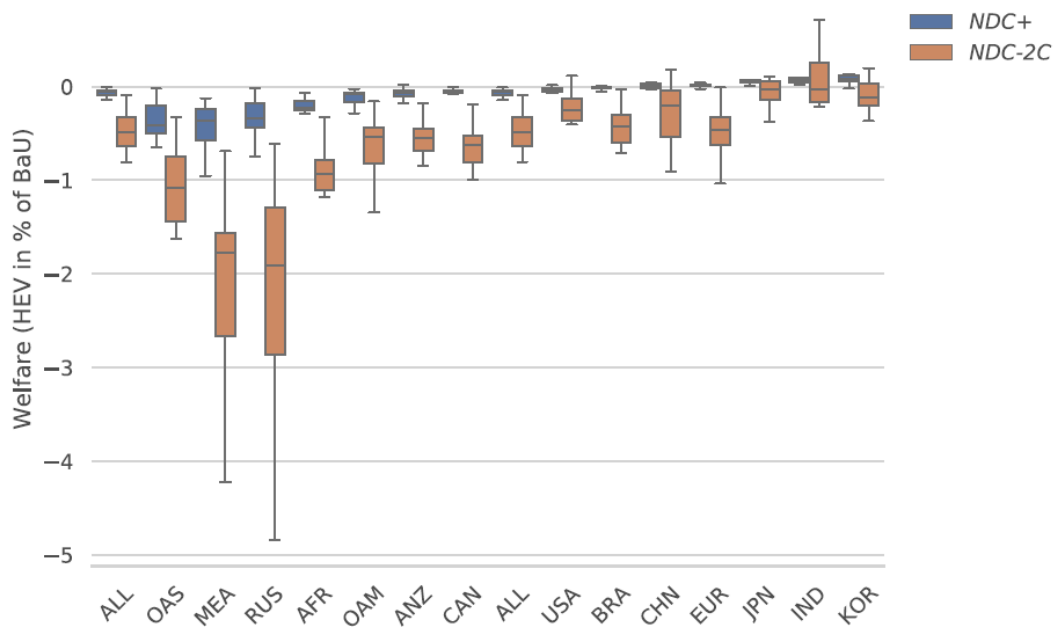


Figure 2-6: Differences in regional welfare under ambition levels *NDC+* and *NDC-2C* compared to *NDC* without emissions trading (*ref*). Note: Box-Whisker plot shows the median (line), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers omitted. Region keys: ALL — Global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS - Other Asia; RUS — Russia; USA — United States.

²² Compare Section 2.3.1.

²³ Recall that the reduction targets in *NDC-2C* emerge from a uniform scaling of emission levels in *NDC+* and do not take into account more subtle fairness considerations.

Concerning regional welfare impacts of increased where-flexibility through international emissions trading two mechanisms are of paramount importance: (i) unequivocal direct cost savings from emissions trading through the equalization of marginal abatement costs; and (ii) ambiguous indirect welfare effects through changes in the terms of trade on energy and non-energy markets that can play out both favorable or unfavorable for individual regions. More specifically, emission allowance selling countries face higher CO₂ prices under emissions trading variants compared to *ref*, while the opposite is true for allowance buying countries. These changes in the CO₂ prices affect the cost of EITE production and thereby the scope for terms-of-trade changes on EITE markets.

Figure 2-7 summarizes regional welfare impacts across models for the cases with worldwide trading schemes *global* and *partial* compared to *ref* for the case of the unconditional Paris pledges (*NDC*). We first focus on *global* and find that most regions gain through a comprehensive global emissions trading scheme as compared to the *ref* situation – gains are most pronounced for Russia, Middle East, and Europe. However, the only regions where we unambiguously find welfare gains through global cooperation are Brazil, Canada, Europe, and Other Asia. For all other regions, individual models find welfare losses from engaging in comprehensive global emissions trading, which points to the importance of terms-of-trade income effects when assessing the welfare impacts of climate policies in a more comprehensive (general equilibrium) manner.

We find, however, a robust pattern driven by changes in fossil fuel prices. Comprehensive global cooperation leads to a shift of global abatement to China and India, where cheap abatement options via reduced coal consumption can be exploited. This increases oil and gas prices and depresses coal prices vis-à-vis *ref*, and thereby leads to a shift in regional incidence from oil and gas producers (Middle East and Russia) to coal producers. India is even worse off under *global* compared to *ref* in most models, although still with a welfare gain compared to the BaU on average. Japan is in most models slightly worse off under *global* compared to *ref*, due to higher international oil and gas prices under *global*.

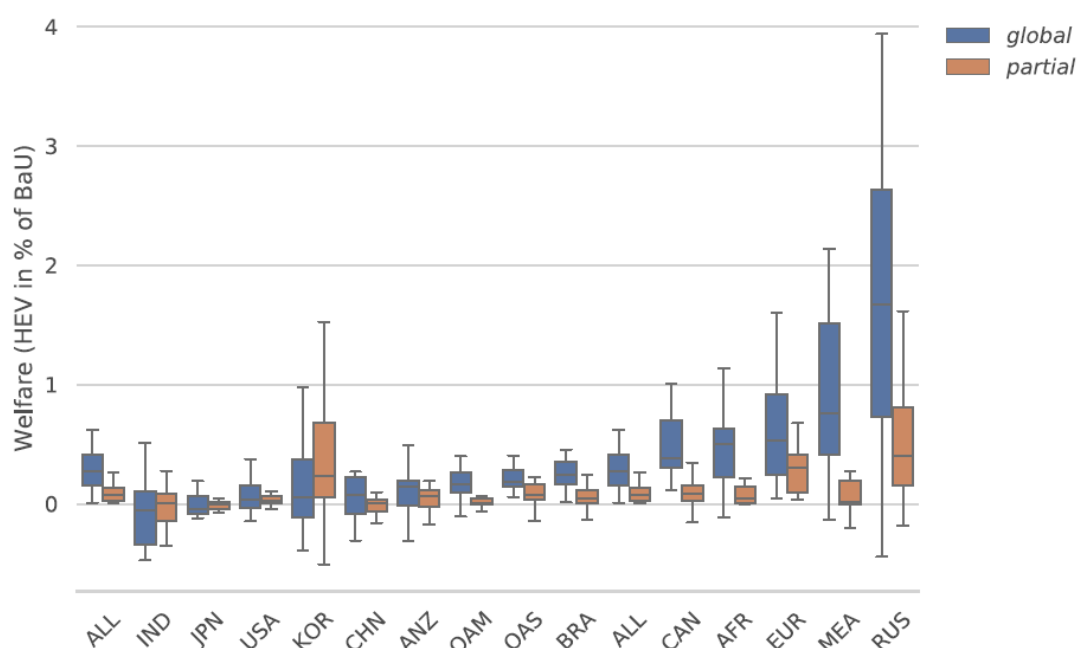


Figure 2-7: Differences in regional welfare in *global* and *partial* compared to *ref* under *NDC*. Note: Box–Whisker plot shows the median (line), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers are omitted. Region keys: ALL — Global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS - Other Asia; RUS — Russia; USA — United States.

South Korea again shows a huge spread in results across models. On the one hand, South Korea can gain from emissions trading as it exhibits the highest CO₂ prices under *ref* (together with Europe). On the other hand, South Korea benefits substantially from depressed oil and gas prices under *ref*, an effect that is weakened under *global*.

When only EITE sectors and the power sectors are eligible for international emissions trading (*partial*), we find that Europe, South Korea, Middle East, and Russia can gain most compared to *ref*. While Europe and South Korea benefit from partial trading due to their high CO₂ prices in *ref*, the Middle East and Russia benefit from a shift towards coal abatement in *partial*. South Korea is thereby the only region that favors *partial* over *global*. The reason is that under partial trading, South Korea can reap gains from emissions trading, while the global shift from oil- and gas-related abatement towards coal is less accentuated. This is also reflected in welfare outcomes for Middle East and Russia, where we find the most pronounced gains under *global* attenuated under *partial*.

Emissions trading leads to an equalization of regional (or sectoral) CO₂ prices via exports

and imports of emission allowances that constitute financial transfers between regions. For regions and sectors that form part of a trading coalition, their *ref* CO₂ price in relation to the tradable CO₂ price will determine whether the country becomes an exporter or importer of emission allowances and hence shows higher or lower emission reductions as stated in their Paris pledges. Figure 2-8 shows that regional buying and selling positions of emission allowances are rather stable across models: China, India, and Russia, which have the lowest CO₂ prices under *ref* (see Figure 2-4), become large exporters of emission allowances; South Korea, Europe, Canada, and Brazil become large importers²⁴.

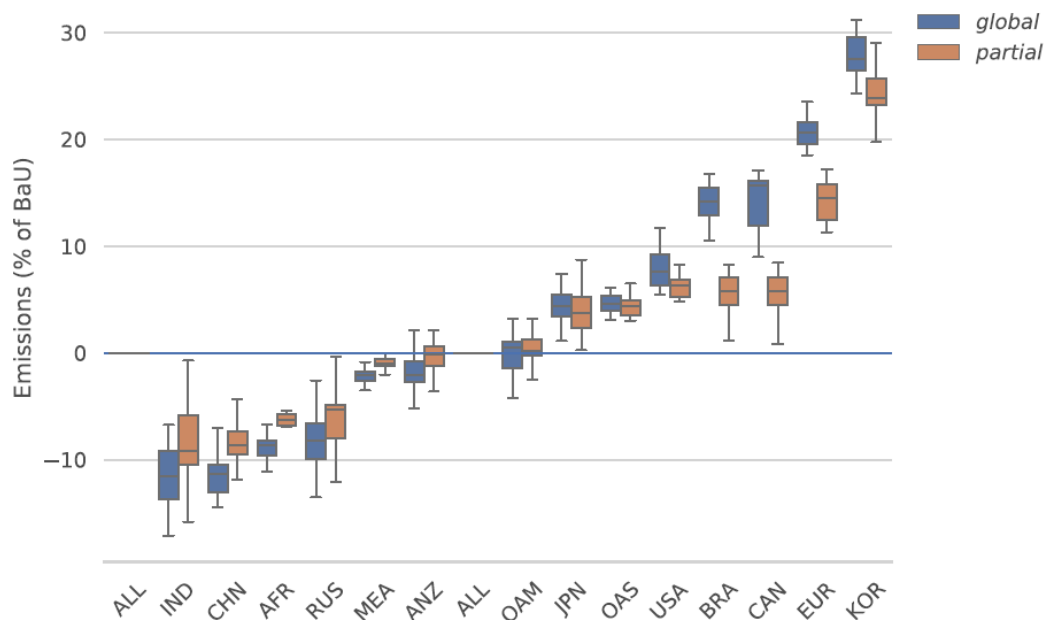


Figure 2-8: Differences in regional CO₂ emissions in *global* and *partial* compared to *ref* under NDC. Note: Box–Whisker plot shows the median (line), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers are omitted. Region keys: ALL — Global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

Figure 2-9 shows the differences in regional welfare in the club-trading scenarios *asia* and *eur-chn* compared to *ref*. We see that Europe and South Korea can gain from club trading, as they start off from very high CO₂ prices under *ref*. The other regions face only

²⁴ Note that Brazil is a large importer of emission allowances as our analysis focuses on CO₂ emissions from fuel combustion. Accounting for emissions from agriculture, forestry, and land use (AFOLU) would most likely make Brazil a net exporter of emission allowances.

minor changes in economic adjustment costs triggered by club trading.

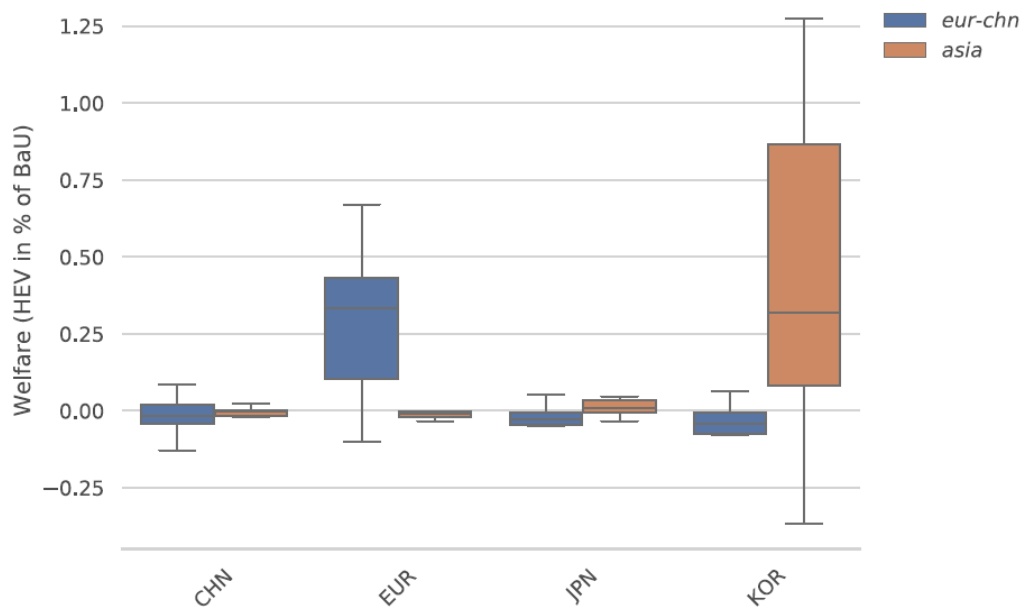


Figure 2-9: Differences in regional welfare in *eur-chn* and *asia* compared to *ref* under *NDC*. Note: Box–Whisker plot shows the median (line), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers are omitted. Region keys: CHN — China; EUR — Europe; JPN — Japan; KOR — South Korea.

2.3.3 Household level incidence

Our analysis on global and regional welfare implications of Post-Paris emissions pricing so far has been agnostic on the incidence across heterogeneous households within countries. For the political feasibility of emissions pricing reforms, however, a critical question is who bears the burden of higher energy prices. Taking into account distributional effects of CO₂ pricing across heterogeneous households is thus central to climate policy design.

Emissions pricing creates costs and rents which translate into incidence for households via changes in prices for consumption goods on the expenditure side and via changes in factor remuneration (plus potential transfers) on the income side. On the expenditure side emissions pricing is often found to be regressive to the extent that it drives up prices for consumption goods for which lower-income households tend to spend larger shares of their budgets. This is typically the case for electricity, home heating fuels, gasoline, and other energy-intensive goods whose prices will overproportionally increase under CO₂ pricing. On the income side emission pricing affects the productivity and thus the

remuneration of the primary factors labor, capital, and specific resources (e.g., fossil fuel resources). Lower-income households tend to obtain larger shares of their income through labor and transfers, while higher-income households earn more through capital income. The incidence of climate policies on the income side hinges to a large extent on how governments will use revenues from emissions pricing. To address policy concerns on the regressive impacts of CO₂ pricing, we focus on revenue-neutral lump-sum transfers to households in equal shares. Such a rebating scheme is clearly progressive. Since each household receives an equal share of CO₂ revenues, the recycled amount marks a larger share of additional disposable for lower-income households. If sufficiently high, transfers can mitigate or even overcompensate the (expected) regressive effects of emissions pricing.

We present results for our central case scenario (*NDC/ref*) where regions meet their unconditional Paris pledges (*NDC*) through purely domestic action (*ref*). Figure 2-10 shows the total welfare impact on income deciles (h01,...,h10) as the mean across five models and 35 (partly overlapping) European countries (blue line with circle marker). On average, we find a progressive impact. While the lowest-income households gain more than 3% in real income (HEV), the highest-income households experience losses of roughly 2%. The underlying reason becomes clear if we decompose total welfare impacts into expenditure and income effects. The Box-Whisker plots in Figure 2-10 summarize expenditure and income effects across models and countries. We find that the expenditure effect – although varying sharply across countries due to different levels of CO₂ prices, emission intensities, and expenditure patterns – is negative and slightly regressive throughout. The income effect, on the other hand, which includes the lump-sum rebates received by households, is strongly progressive and dominates such that the overall welfare effect is progressive²⁵.

²⁵ Note that only European countries are represented in the Box-Whisker plots in Figure 10. In our central case, CO₂ prices in Europe are quite high, leading to high revenues and thus a strong income effect for households through lump-sum rebates.

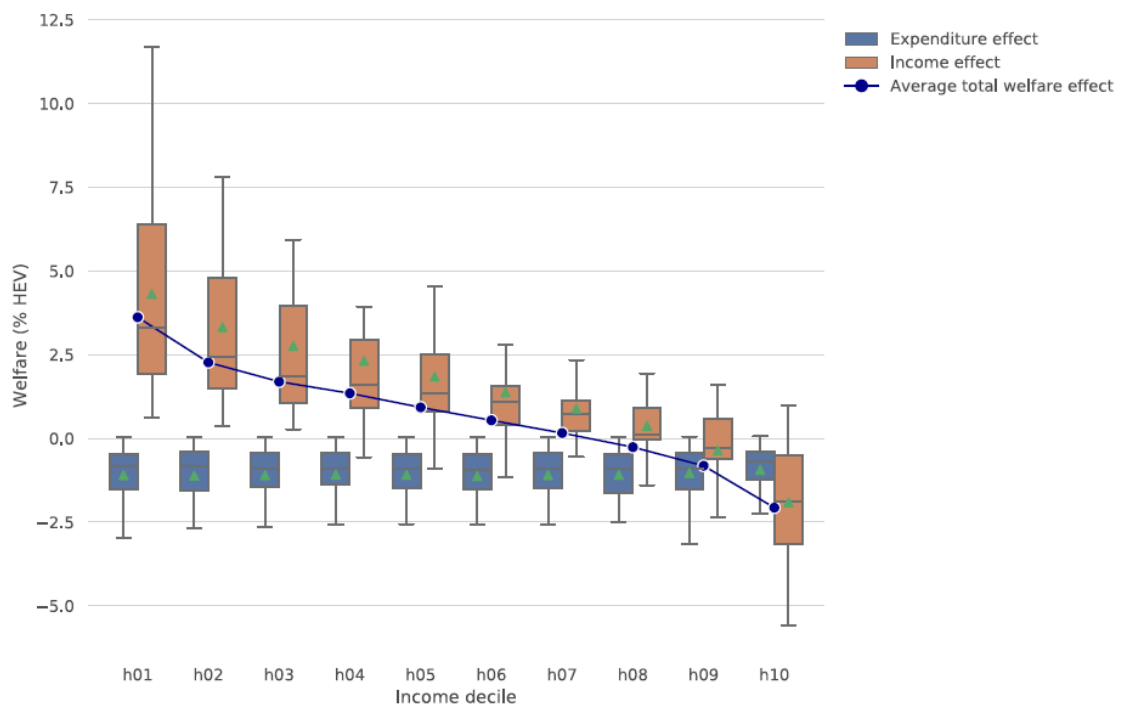


Figure 2-10: Summary on decomposition of households' total welfare into expenditure and income effects across models and regions. Note: Box-Whisker plot shows the median (line), mean (green triangle), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers omitted. Graph incorporates values from the models BC3 (Spain), IEG (India), UOL (Germany), SNoW (Norway), JRC-GEM-E3-EUROMOD-ITT (11 European countries), and CEPE (21 European countries).

We can summarize the individual effects on different households from a societal perspective when adopting a social welfare function where we capture alternative degrees of inequality aversion. We report social welfare as changes in the equally distributed equivalent income as defined by Atkinson (1970)²⁶. In Figure 2-11 we present social welfare changes for China, India, and Brazil, as well as for individual European countries Germany, the United Kingdom, France, Spain, and Norway. Countries are distinguished by color, and models are distinguished by markers, as for several European countries results are available from more than one model. With an inequality aversion of zero we adopt a utilitarian perspective where we are agnostic over the distribution of economic adjustment costs across different income deciles in social welfare. As we increase the

²⁶ For a given degree of inequality aversion, the equally distributed equivalent income is defined as the level of income that – if obtained by every individual in the income distribution – would enable the society to reach the same level of welfare as is the case with actual incomes.

inequality aversion, we find progressiveness of the lump-sum rebates in equal shares to households across all considered countries²⁷. Higher degrees of inequality aversion imply higher values of social welfare. For an infinite aversion to inequality, i.e., when only the welfare of the lowest-income household matters, the associated social welfare actually increases beyond business-as-usual levels. Norway stands out for high productivity (efficiency) losses, which are due to very high CO₂ prices associated with a high emission reduction target and the low BaU emission intensity of the Norwegian economy. The redistributive effect of CO₂ pricing with lump-sum rebates to households is quite strong rendering initial efficiency losses from a utilitarian perspective into marked social welfare gains as inequality aversion increases, i.e. poorer households matter more and more. For China and India, on the other hand, the CO₂ pricing (at relatively low levels – see Figure 2-4) and lump-sum recycling involves very moderate economy-wide costs which leaves the income distribution across households relatively unaffected.

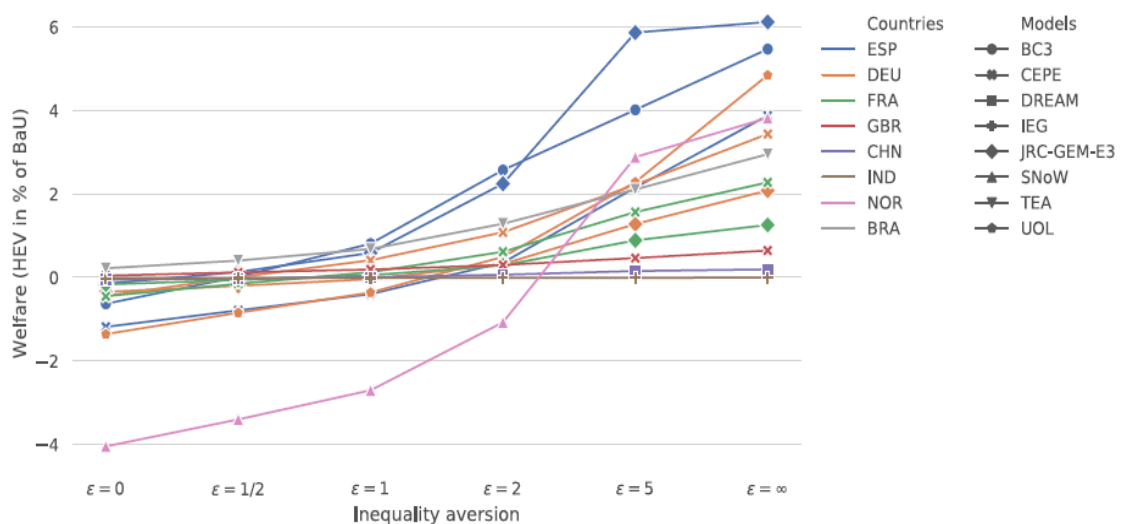


Figure 2-11: Social welfare for different degrees of inequality aversion across models and regions. Note: ESP — Spain; DEU — Germany; FRA — France; GBR — United Kingdom; CHN — China; IND — India; NOR — Norway; BRA — Brazil.

²⁷ Note that for some countries in our cross-comparison CO₂ emissions pricing is already progressive without lump-sum rebates of CO₂ revenues. This can e.g. be the case when expenditure shares are rather homogeneous across households and emissions pricing leads to a significantly bigger impact on capital income than on labor income, burdening higher-income households stronger. However, the marked progressive effect illustrated in Figure 11 stems from the recycling mechanism.

Our robust policy-relevant insight is that lump-sum recycling of revenues in equal shares to households can offset the regressive impacts of CO₂ pricing and even deliver social welfare gains with a reduction in CO₂ emissions if inequality aversion is sufficiently high.

2.4 Concluding remarks

Most of the benefits of emission abatement will not materialize in terms of avoided climate damages before decades due to the inertia of the climate system. The costs of emission abatement on the other hand will occur in the short- to mid-term. It is therefore not surprising that the contemporary climate policy debate is still focused on the magnitude and distribution of economic adjustment costs of stringent emission constraints, as implied by the Paris Agreement in the pursuit of the 2°C temperature target. The United Nations Framework Convention on Climate Change has codified the challenge of international burden sharing as the principle of Common but Differentiated Responsibilities. However, the initial top-down approach on burden sharing applied in the Kyoto Protocol failed, not least due to the hard-ship to agree on common equity principles. The Paris Agreement inaugurated anew, bottom-up approach where countries pledge their emission reduction commitments voluntarily as so-called Nationally Determined Contributions (NDCs). The downside of such voluntary bottom-up approach is that it may not enforce sufficient collective abatement efforts to keep the average global temperature increase below 2°C from pre-industrial level. As a matter of fact, the individual abatement pledges under the Paris Agreement submitted so far fall substantially short off what is required to meet the long-run Paris temperature target. It is thus necessary to ratchet up the current NDCs towards much more restrictive targets even in the short run.

The unequivocal pressure to increase the ambition level in climate policy while securing societal approval calls for climate policy designs that are cost-effective and appear as fair to the citizens. Inherently, these two central requirements are intertwined since a reduction in compliance costs can substantially relax normative tensions on fair burden sharing.

The discipline of economics has identified two important instruments to decrease the overall compliance costs of emission reduction pledges and to increase societal support for stringent climate policies. Indeed, international emissions trading plays a decisive role

in the cost effective containment of climate damages. Under purely domestic compliance to NDCs, there can be large differences in marginal abatement costs across countries, indicating a huge potential for cost savings. International emissions trading facilitates cost savings by allowing markets to identify where emissions reductions are the cheapest worldwide. With respect to equity concerns within societies, the recycling of additional revenues from emissions pricing is of critical importance. CO₂ pricing will at first glance have regressive impacts on households since poorer households tend to spend larger shares of their income on energy-related consumption categories such as electricity, heat or transport which will become more expensive. However, the regressive impacts of rigorous CO₂ emissions pricing can be alleviated, if not offset through lump-sum recycling of additional revenues to households in equal shares.

The findings of the EMF36 study confirm the potential of both instruments –international emissions trading and lump-sum revenue recycling to households – to facilitate ambitious Post-Paris climate policies that are in line with the 2°C temperature target. Under comprehensive global emissions trading, the 2°C target is placed within reach under approximately the same range of cost implicitly agreed upon by individual countries with their NDCs. CO₂ emission pricing can be implemented in a progressive manner when additional revenues are recycled lump-sum to households in equal shares. The progressive revenue-recycling effect dominates the regressive effects of higher energy prices. In the end, CO₂ pricing in combination with lump-sum recycling of additional revenues on an equal-per-household basis cannot only make economies greener, but also societies fairer in terms of overall income distribution.

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Appendix A: Business-as-usual (BaU) projections and Nationally Determined Contributions (NDCs)

Our BaU projections are indexes for GDP and CO₂ from 1990-2030 (2011=1). We construct two alternative BaU projections denoted IEO and WEO. Against both BaU projections we derive effective reduction targets for CO₂ emissions from fossil fuel combustion in 2030 for our model regions for three different ambition levels covering (i) unconditional NDC pledges and lower bounds (NDC), (ii) conditional pledges and upper bounds (NDC+), and (iii) an ambition level called NDC-2C where we scale emission levels in NDC+ uniformly across regions in order to comply with an emission reduction for 2030 which is on the 2°C emission trajectory path suggested by integrated assessment analysis. The notation used in this section is summarized in Table B 2-1.

We map all the primary IEO and WEO data to GTAP regions, so the procedures described below apply to the individual GTAP regions from where we aggregate numbers towards the composite model regions (see Table 2-2). In what follows we sketch our data sources and the steps involved to establish BaU projections from IEO and WEO as well as the respective region-specific effective reduction targets in 2030. An Excel file with the data in use and the computational steps involved is available from the authors upon request.

A.1: BaU projections

We construct two alternative BaU projections based on IEO and WEO data for GDP and CO₂ emissions as indexes from 1990-2030 (2011=1) across all GTAP regions. IEO represents projections from the International Energy Outlook 2017 of the U.S. Energy Information Agency (EIA, 2017). WEO represents projections from the World Energy Outlook 2018 of the International Energy Agency (IEA, 2018). For historical data, we use World Bank (2019) for GDP and EIA (2019) for CO₂. For years without data, we interpolate linearly. We then aggregate the BaU data from the more disaggregate GTAP

regions to our composite model regions using the weighted sum for the respective BaU items— here GDP and CO₂ emissions – indexed to 2011 as the base year (2011=1).

A.2: NDC projections

Building on Kitous et al. (2016) we compile a dataset with regional NDCs as submitted by individual countries (see UNFCCC, 2020, for the NDC registry). The regions in our dataset cover more than 95% of global CO₂ emissions from fossil fuel combustion. The dataset includes for most countries a low and a high NDC pledge (equivalent to our *NDC* and *NDC+*) as well as the NDC base year, the target year for meeting the NDC, the coverage of greenhouse gas emissions, and the type of the target. Countries state their NDCs typically as a percentage reduction target against a certain base year (which can be historical or a future business-as-usual), or as a percentage reduction target for emission intensity of GDP (e.g., China and India). For countries that state their targets with respect to a business-as-usual in a future target year (typically 2030) and that provide a BaU projection for 2030 of their own, we use the implied physical emission level to go forward. We translate NDCs into percentage CO₂ emission reduction targets vis-a-vis the BaU in 2030.

For countries stating their NDC as an emission reduction target we calculate the effective emission reduction requirement as:

$$R_{r,c}^B = 1 - (1 - ndc_r^e) \cdot \frac{B_r^{CO_2}(by_r)}{B_r^{CO_2}(ty_r)}, \quad (1)$$

For countries stating their NDC as an intensity target we calculate the effective emission reduction requirement as:

$$R_{r,c}^B = 1 - (1 - ndc_r^e) \cdot \frac{B_r^{CO_2}(by_r)}{B_r^{GDP}(by_r)} \cdot \frac{B_r^{GDP}(ty_r)}{B_r^{CO_2}(ty_r)} \quad (2)$$

If the NDC target year is not 2030, the required percentage reduction from 2016 (last available historical year) to the NDC target year is linearly perpetuated to 2030.

For countries that have stated their NDCs for all greenhouse gas emissions (not only CO₂),

we convert the reduction targets towards CO₂ emission reduction targets from fossil fuel combustion only as the latter constitute the relevant emission base for our model cross-comparison. The scaling factor is derived from Kitous et al. (2016):

$$F_r = \frac{1 - \left(\frac{CO_2^{NDC}}{CO_2^{REF}} \right)}{1 - \left(\frac{GHG_r^{NDC}}{GHG_r^{REF}} \right)} \quad (3)$$

that is, the ratio of the %-reductions of CO₂ from fuel combustion over greenhouse gas emissions²⁸. We only apply scaling factors lower than 1 being cautious on the scope for more stringent emission reductions. Brazil is adjusted based on expert opinion²⁹. For countries with an intensity target, we set a minimum reduction target of 5% against the 2030 baselines, reflecting the assumption that such a target will lead to some degree of effective carbon pricing, even if baseline projections suggest that targets are reached without carbon pricing.

To define the *NDC-2C* scenarios we follow a budget approach, where we target a global level of CO₂ emissions that is 11.58% below 2011 emissions³⁰. We apply a uniform scaling factor to the regional emission levels in *NDC+* in order to achieve that target.

The reduction requirements under *NDC-2C* then are

$$R_{r,NDC-2C}^B = 1 - S * (1 - R_{(r,NDC+)}^B) \quad (4)$$

where *S* is the scaling factor.

²⁸ E.g., if a country in scenario NDC reduces 10% of GHG emissions and also 10% of CO₂ from fuel combustion, then $F_r = 1$.

²⁹ Experts from Brazil identify reduction potential of 100-210 Mt CO₂ in 2030 (excl. AFOLU). We stay rather conservative and use the lower value in order to calculate effective reduction requirements.

³⁰ This value is derived as an average emission trajectory suggested by integrated assessment analysis for scenarios that target a 2°C path (Huppmann et al., 2019).

Finally, we aggregate the effective reduction targets across GTAP regions towards our composite model regions based on CO₂ emission weighted averages of GTAP data for our base year 2011.

Table B 2-1 Definitions and notations in NDC translation

Symbol	Description
r	Set of GTAP regions
B	Set of BaU projections $\{IEO, WEO\}$
c	Set of NDC scenarios $\{NDC, NDC+, NDC - 2C\}$
$R_{r,c}^B$	Reduction requirement in region r and NDC scenario $c \in \{NDC, NDC+, NDC - 2C\}$ as share of emissions in baseline $B \in \{IEO, WEO\}$ in 2030
ndc_r^c	Nationally intended contribution in region r and $c \in \{NDC, NDC+\}$
by_r	Base year of NDC in region r
ty_r	Target year of NDC in region r
$CO_2_r^c$	CO ₂ level in Kitous et al. (2016) in region r and scenario c
GHG_r^c	GHG level in Kitous et al. (2016) in region r and scenario c
F_r^c	Correction factor to scale from GHG to CO ₂ reduction requirement in region r and $c \in \{NDC, NDC+\}$
S	Scaling factor to translate the implied emission level in $NDC+$ to $NDC-2C$

Chapter 3

A model intercomparison of the welfare effects of regional cooperation for ambitious climate mitigation targets*

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Abstract

Multiple studies confirm that cooperation through a global emissions trading market reduces the total costs of abatement and the welfare effects. However, there are fewer systematic analyses of the welfare effects on participants of regional emission trading markets, which may be more likely to emerge. This paper evaluates the overall welfare and distributional effects of multi-regional emission trading arrangements using results from seven computable general equilibrium (CGE) models, capturing the interactions between carbon markets, trade flow, and the economy. Welfare effects in 2030 of meeting current Paris Agreement pledges, known as the Nationally Determined Contributions (NDCs), and more stringent emissions reduction targets consistent with 2°C and 1.5°C

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are evaluated. These arrangements cover 15 – 80% of global non-land based emissions depending on whether the market covers all sectors or is limited to energy-intensive sectors. While the welfare gains are less than the potential gains in a global market, regional arrangements have lower aggregate costs, and these gains increase with the stringency of targets. Some participants, however, may benefit more from some regional arrangements than from a global market or face modest losses compared to the domestic reductions driven by interactions with fossil fuel markets. Some arrangements are consistently favorable, namely the China - European Union trading arrangement is favorable for participants, providing the highest economic gains per unit of emissions mitigated. Across models, differences in the magnitude and the directionality of the welfare effects are mainly due to differences in the forward projections of the energy and emissions intensity of the economy and the resulting abatement costs.

Key Words: climate mitigation, regional cooperation, emissions trading, welfare

JEL classification: F130, F180, Q580, Q540

3.1 Introduction

Cooperation, such as market-based mechanisms for international emission trading, can dramatically lower the costs of climate mitigation efforts. The possibility of cooperation among parties was recognized at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in Article 6 of the Paris Agreement, which sets out the principles for any bottom-up cooperation that involves “internationally transferred mitigation outcomes” (ITMOs). Böhringer et al. (forthcoming) show potentially considerable cost savings globally from emission trading. While some countries and subnational regions have engaged in regional emission trading arrangements, more expansive cooperation involving multiple jurisdictions and countries up to a global scale has been relatively slow to emerge (Bodansky et al., 2016; Ranson and Stavins, 2016). Differences in expectations of the benefits, the potential for more considerable benefits under alternative arrangements, and the potential for interactions with international trade patterns, especially for fossil fuels, may explain why countries are not equally interested in forming these coalitions.

In this paper, the costs and trade implications of a set of hypothetical regional emission trading arrangements are evaluated using seven computable general equilibrium (CGE) models to identify the benefits of trading markets for carbon dioxide (CO₂) emissions. More specifically, the gains or losses in terms of welfare for regional cooperation in 2030 are compared to achieving the same emission reductions without trading for existing NDCs and for more stringent emission reduction pathways with assumed country-level commitments that meet 2°C and 1.5°C temperature targets. Previous efforts on the benefits of cooperation and linking emission-trading markets have identified the benefits of integration. This study contributes new insights to this literature as follows:

1. We review a more comprehensive range of possible emission trading arrangements in a model intercomparison and different emission pathways that meet more stringent climate mitigation targets of 1.5°C of the Paris Agreement.
2. We leverage CGE frameworks to evaluate how the interactions between the carbon mitigation costs and the fossil fuels markets combine to determine the overall benefits from emission trading.
3. We evaluate the variability in the results through a model intercomparison that informs what elements of the model structure affect the potential welfare effects, expanding on a conventional sensitivity analysis on model parameters.

In this paper, we were able to show that the benefits of regional trading coalitions can still be substantial even when they comprise a relatively low share of emissions. Additionally, while the differences between models are modest under small emission reductions (e.g., only minor deviations from the model baseline), these differences can be pronounced under more stringent climate targets. To the extent that these models influence decision-makers, this uncertainty in whether their country or a closely allied partner may benefit from these arrangements may make them less inclined to form carbon clubs. This study was conducted as part of Stanford's Energy Modeling Forum 36 (EMF-36). More detailed information on the larger modeling effort can be found in Böhringer et al. (forthcoming).

3.2 Literature review

Trade in carbon permits has been proposed as the cornerstone of climate mitigation policy since the Kyoto Protocol. This trading can reduce overall compliance costs, moderate

competitiveness and trade impacts, and possibly promote higher levels of ambition for emission reductions. Emission trading carbon markets are now the largest class of environmental trading markets globally (Newell et al., 2013). Recognizing the importance of moderating costs, the Paris Agreement laid out a framework for joint mitigation measures among countries, including linkages such as international emission trading (Aldy et al., 2016). The agreement also allowed for the possibility of linkages between regional emission trading efforts as a bottom-up approach to developing more global trading arrangements, often referred to as “carbon market clubs” (Keohane et al., 2017). These linkages, however, have been slow to develop (Bodansky et al., 2016; Ranson and Stavins, 2016).

The benefits of emission trading are well understood theoretically and empirically, with a substantial amount of literature on the benefits of emissions trading at the subnational, national, regional, and to some extent at the global level for climate policy primarily related to the Copenhagen pledges and reductions through 2020 (Dellink et al., 2010). While it is generally understood that emission trading will moderate costs, there are fewer investigations of the gains from cooperation given stringent emissions targets at the country or regional levels, especially within a CGE modeling framework to provide an economy-wide perspective. Table 3-1 tabulates several recent studies that have estimated the global benefits of trading for the NDCs. The gains relative to no trading are unambiguous and often substantial.

Recognizing that the global markets have not emerged but that regional emission trading may be politically feasible, a growing literature has reviewed potential regional emission trading identifying conditions that reveal benefits. Most literature focuses on the expansion of the EU Emission Trading System (ETS) - i.e., linking the EU ETS to the emerging national Chinese ETS (Gavard et al., 2016; Hübler et al., 2014; Li et al., 2019; Liu and Wei, 2016), Swiss ETS (Vöhringer, 2012), Brazil ETS (Oliveira et al., 2019), and potential arrangements with developed countries (Alexeeva and Anger, 2016). Other papers focus on the potential for Asian ETS (Massetti and Tavoni, 2012; Zhang et al., 2018), linking the Australian ETS to another ETS (Nong and Siriwardana, 2018), and other multilateral linking options (Böhringer et al., 2014; Dellink et al., 2014; Gavard et al., 2016; Qi et al., 2013).

Table 3-1: Selection of estimated global benefits of emission trading for climate mitigation in 2030

Measure of economic effects	Target	Benefits over no trading	Source
Direct abatement costs	All countries meet unconditional NDC reductions	56% reduction in global costs	Hof et al. (2017)
	All countries meet conditional and unconditional NDC reductions	44% reduction in global costs	Hof et al. (2017)
Welfare	All countries meet NDC reductions	75% reduction in welfare effects (from 0.47% to 0.16%)	Fujimori et al. (2016)
	2°C target	Without emissions trading led to a global welfare loss of 1.4%– 3.4%, depending on the burden-sharing scheme used, whereas emissions trading reduced the loss to around 1.5% (a range of 1.4%- 1.7%).	Fujimori et al. (2016)
Direct abatement costs	An emission trading system involving all countries and regions that made unconditional pledges at COP21	Reduce total GHG mitigation costs from an estimated \$1.71 trillion to \$0.4 trillion (in 2015 dollars), a savings of 77%.	Rose et al. (2017)
Direct abatement costs as a percentage of GDP (Global average of emission reduction costs per unit of GDP)	An emission trading system with all countries attaining their NDCs	0.38% global GDP loss for regionally differentiated carbon price compared to only 0.16% with a uniform carbon price	Akimoto et al., (2017)
GDP losses (% of GDP)	2°C	Global GDP losses decrease by 69% (GDP loss without trading is 1.3%)	Li and Duan (2020)
	1.5°C	Global GDP losses decrease by 50% (GDP loss without trading is 2.6%)	Li and Duan (2020)

Taken as a whole, studies of ETS find that countries exporting emission allowances can lose in the globally linked trading arrangements if an extended arrangement including more sellers leads to a drop in the allowance price. Conversely, if a trading system is extended to countries with higher national carbon prices, the permit price increases, and permit importing regions may lose even as the aggregate effect is a positive welfare gain. The relative gains or losses in terms of welfare for any given participant depend on the regional market's composition. Additionally, countries may face more indirect effects and complex interactions of the permit markets and trade in more energy-intensive goods even if they do not participate in a regional arrangement. The trade position of countries on international crude oil and coal markets is one of the major determinants of the differences in regional economic gains from permit trading and generally drives the welfare effects of international climate policy (Böhringer and Rutherford 2002). Furthermore, the direct economic gains from emission trading can be offset by distorted energy markets and adverse terms-of-trade effects (Babiker et al., 2004). Still, the overall gains are large such that there is the potential for compensation; thus, efforts to generate regional and global markets may still be warranted (Dellink et al., 2014).

While studies have confirmed the benefits of linking regional trading arrangements (e.g., Lanzi et al., 2012), few studies have reviewed the regional effects in a single study. Also, the full range of potentially beneficial regional arrangements and the distributional effects to the participants have not been evaluated. Hof et al. (2017) found that the benefits to non-OECD countries of global trading arrangements were substantial, reducing costs of meeting unconditional NDCs of up to 85%. However, these scenarios envisage modest emission reductions and may not provide sufficient insight into pathways extending the NDCs to the 2°C and 1.5°C Paris Agreement temperature targets. Rose et al. (2018) investigated how regional markets can extend to reduce costs. They identify the possibility of savings of more than 59% in mitigation costs through the progressive coverage of the allowance market for CO₂ emissions in the power and industry sectors for Canada, China, and the United States in 2020 and then linking to all G20 in 2025 and finally to a global level in 2030 (Rose et al., 2018). Game-theoretic approaches have also been applied to evaluate whether these regional coalitions are stable (e.g., Lessmann et al., 2015, Böhringer et al., 2016). Stable coalitions can be identified by looking at the size of the welfare gains or losses and opportunities for compensation for losses.

However, these studies are often implemented in less computationally intensive integrated assessment models. Studies that look at the changes in welfare from hypothetical arrangements and the studies that apply game theory models to identify stable arrangements cannot be directly compared. However, information about country-level welfare gains and losses under hypothetical arrangements can be used to provide insight into whether any given country would find a trading arrangement favorable.

3.3 Modeling approaches, data, and scenario design

In this paper, a model inter-comparison is conducted for a range of hypothetical cooperative trading arrangements for different levels of climate stringency and sectoral coverages. Seven CGE modeling teams from Europe, Asia, and North America participated in this modeling effort under Stanford's Energy Modeling Forum 36 (EMF-36).

In this analysis, the costs of climate policies globally and regionally for different levels of cooperation are evaluated relative to the no-policy scenario, using two cost measures: carbon prices and welfare measured in Hicksean Equivalent Variation (HEV). Emission targets were set for each modeled region by constraining the total emissions for each temperature target and allocating through NDC commitments as a guide. First, the global and regional gains from cooperation are reported, looking across many plausible trading arrangements. Second, the drivers of these welfare effects are investigated, namely the effect of fossil fuel trading arrangements. Finally, the multi-model effort is leveraged to analyze the consistency and sources of uncertainty in the desirability of the trading arrangement for any given participant.

Assuming that global emissions are kept constant for a given ambition level, our setup implies no carbon leakage. Thus, regional carbon prices differ depending on whether other countries form coalitions or not. The assumption of no carbon leakage may be realistic where targets are reached via emissions trading, as in the EU, but would imply less realistic adjustments for non-trading partners. Thus, we interpret the change in regional carbon prices as an indication of how the relative challenge of attaining national targets is affected by climate policy outside the country. Additionally, we do not consider climate damages as influencing the willingness to participate in any regional trading

arrangement. Since the emissions are held constant, the avoided damages are fixed for any temperature target; thus, we can compare within a scenario without any loss of generality only HEV. However, avoided damages increase as the degree of stringency increases (e.g., shifting from a 2°C to a 1.5°C temperature target), such that intercomparisons between these sets of scenarios do not account for the fact regions incur is different from climate damages. Additionally, we do not undertake any game-theoretic analysis of the stability of a coalition. This is beyond the scope of this paper. Though we discuss incentives for different participants, the focus is not on the stability of coalitions. Thus, we did not design our coalitions in order to find stable coalitions. Instead, we started from the most likely coalitions (see also Böhringer et al. (forthcoming)) of the European Union and China (EUR_CH) and a regional Asian market (ASIA). We then expanded to a global coalition.

3.3.1 Model descriptions

Seven models participated in this effort: Environment and Climate Change Canada (ECCC) with the EC-MSMR model, Environmental Defense Fund (EDF) with the EDF-GEPA model, Euro-Mediterranean Center on Climate Change (CMCC) with the ICES model, Kiel Institute for the World Economy (IfW) with the DART model, Institute of Energy, Environment, and Economy at Tsinghua University (Tsinghua) with the C-GEM model, Berlin University of Technology (TU-Berlin) referred as TU-Berlin model here, and Leibniz Centre for European Economic Research (ZEW) with the PACE model. The models of all teams are multi-regional global scale computable general equilibrium (CGE) models calibrated to the International Energy Agency's (IEA) World Energy Outlook 2018 (IEA, 2018) to 2030 and the global trade analysis project (GTAP) database. Summary descriptions of the models with sources for complete documentation are provided in Table 3-1 with more information in Supplemental Information (S1)³¹. All dollar values are reported in US dollars (USD) and dollar year 2011.

³¹ Note that the extensive Supplemental Information is not included in this dissertation. It is available from the author of this dissertation upon request.

CGE models are frequently employed to evaluate the impacts of climate and trade policy. They consider the direct and indirect effects of a policy intervention in a simultaneous multi-market economy-wide equilibrium context. At the macro level, impacts are measured as GDP, consumption, or welfare changes between a baseline and a policy scenario. At the micro-level, impacts can be assessed as changes in output, trade, and prices at the sector level. Equilibrium in the models involves market-clearing of goods, factors of production, and all other markets in each region of the model through endogenous changes in prices, demand, and supply. Emission limits by economic activities can be established by exogenous constraints, which in effect determine the emission prices required endogenously, or through exogenous CO₂ prices that determine the reductions achieved endogenously.

The models used in this paper represent common features such as a single representative agent in each region who owns the factors of production (i.e., labor, capital, and, in some models, land) and makes allocation decisions to maximize the objective function of household utility. The production and consumption functions follow multi-level nested constant elasticity of substitution (CES) functions. The resource sectors (i.e., coal, crude oil, and gas) typically feature sector-specific resource factors to represent the increasing cost of extraction. CO₂ emissions are brought into each model through a differentiated coefficient coming from the GTAP database, which links fossil fuel use and the level of emissions. Although the core structure of the seven models used in this effort is the same, they differ in terms of sectoral and regional dimensions, the representation of economic activities, and parameter values such as the inter-fuel substitution elasticities. The representation of the electricity sector varies by the model with different levels of disaggregation in the types of electricity generation. The crude oil extraction activity in EC-MSMR is disaggregated by type of extraction technology, while most models do not go into that level of detail. More importantly, the models differ in their structure and choice of elasticities of substitution. While the EDF-GEPA, PACE, and TU-Berlin models use a static comparative approach, the others are recursive-dynamic models. Thus, the models also differ in terms of the roles of investment and forward expectations.

Table 3-2 Models used in this paper and their key characteristics. ESUBD is the Armington elasticity that determines the degree to which regions substitute between domestically produced goods and imported goods. ESUBM is the Armington elasticity determining the degree to which imported goods are substituted amongst different importing regions. ESUBDM is a nested Armington elasticity that determines the degree to which domestic and imports are traded off by fuel type.

Organization model name	Model class	# of Regions	Sectors	Inter- fuel substitution	KLE elasticity	Armington Elasticities
EDF EDF-GEPA	Static CGE with target- year forward calibration	20	23	Not provided	$e/(KL) = 0.5$ (for electricity adjusted to 1.0)	GTAP values ESUBD("gas") = 2 ESUBM("gas") = 4
TU-Berlin TU Berlin Model	Static CGE with target- year forward calibration	14	14 + 3 final demand sectors (Government, Consumption, Investment)	Elec vs fossil fuel aggregate =1 Elec vs fossil fuel aggregate in fossil fuel production =0.75	KL=0 in Fossil- fuel production KL=GTAP values in Non- fossil- fuel Production, KLE=0.5	ESUBD(oil) = 4 ESUBD(gas) = 5 ESUBM(oil) = 8 ESUBM(gas) = 10
ZEW PACE	Static CGE with target- year forward calibration	14	10	Ele vs fossil fuel aggregate = 0.5	default: 0.5 (electricity sector: 1)	GTAP
CMCC ICES	Recursive dynamic CGE	25	32 + 3 final demand (Government, Consumption, Investment)	Elec vs fossil fuel aggregate = 1	KE= 0.5 (KE)L = GTAP (Value Added nest) values [0.2 - 1.68]	GTAP values ESUBD("oil")=4 ESUBD("gas")=5 ESUBM("gas")=10 ESUBM("oil")=8
IfW DART Kiel	Recursive- dynamic CGE	22	17	Elec vs fossil fuel aggregate = 0.75	$e/(KL) = 0.5$ (adjusted for IND and BRA), KL = 1	GTAP values * 1.5 crude oil and gas maximum 12

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Organization model name	Model class	# of Regions	Sectors	Inter- fuel substitution	KLE elasticity	Armington Elasticities
ECCC EC-MSMR	Recursive dynamic CGE	14	20 + 3 final demand sectors (Government, Consumption, Investment)	Elec vs fossil fuel aggregate = 0.3667	From Okagawa & Ban 2008 (0.21-0.3)	GTAP values ESUBD("gas") = 2 ESUBM("gas") = 4
Tsinghua C-GEM	Recursive- dynamic CGE	14	21	Elec vs fossil fuel aggregate = 0.6-0.9 for EITE sectors 0.5 for other	e/(KL): 0.1 for electricity 0.3 for agriculture 0.5 for other sectors. K/L: 1	All ESUBD = 3 ESUBD(ele)=0.3 All ESUBM = 5 ESUBDM(ele)=0.5 ESUBDM(gas)=4 ESUBDM(crude oil)=4 ESUBDM(coal)=6 ESUBDM(oil)=5

All CGE models used in this comparison use an Armington specification for international trade and adopt GTAP values for Armington elasticities; modelers may also alter an elasticity to improve model calibration. Notably, the models may apply different values for the elasticity of substitution between domestic and imported goods and then within different sources of imports, as reported in Table 3-2. For example, the Armington value of the elasticity of substitution for natural gas is often higher than the GTAP estimates.

Although some models differ in terms of regional disaggregation, inter-comparison results are presented following the same aggregation scheme as in the EMF36 core scenarios (See Supplemental Information Table S.2 for details on regional aggregation for this effort). While some of the modeled regions map to countries, others are aggregated either by political entities (such as the EU) or as geographic regions (Africa and the Middle East). In the text, to avoid confusion, the model regions are consistently referred to as "regions" rather than countries.

3.3.2 Data and calibration

The key sources of data for all models are the GTAP database version 9 or 10 (Aguiar et al., 2016), reflecting the economic flows and emissions for 2011 or 2014, and the International Energy Agency's (IEA) World Energy Outlook 2018 (IEA, 2018). The GTAP database features global multisector, multi-regional input-output data, values of economic transactions including production, consumption, and bilateral trade for 57 sectors and 140 regions or 65 sectors and 141 regions in Version 9 and Version 10, respectively. This database also provides information on initial tax margins for inputs, outputs, trade, fossil fuel-related CO₂ emissions by sector by fuel, and parameter values relevant to CGE models, e.g., the value of elasticity of substitution in value-added and trade. Parallel to its core database in a satellite table, GTAP also provides detailed data for emissions of non- CO₂ greenhouse gases (GHGs) such as CH₄, N₂O, and F-gas for the base year. GTAP Power expands the GTAP databases by including a disaggregated electricity sector (Peters, 2016). The use of these extensions depends on the model. Some models also have modified data and calibrations for specific regions of interest (e.g., EC-MSMR has extended representation of Canada).

Single-year representation of the economy and calibration for 2011 or 2014 is followed by a forward projection to 2030 to calibrate the models to the same 2030 regional GDP and emission data from the International Energy Agency's (IEA) World Energy Outlook (WEO) 2018 (IEA, 2018). The CGE models are optimized to reproduce these pathways. However, differences in the final pathway persist due to the model structure (e.g., static versus dynamic models), aggregations of sectors and regions, and more importantly assumptions and constraints used in the forward calibration of the model to 2030. This is discussed in more detail in Section 3.4.4.

For the static models, a single projection is needed for 2030. For the recursive dynamic models, projections are required for multiple periods at 1 or 5-year intervals to 2030. Additionally, most models only use GDP and emissions at the aggregate level for the forward projection. However, in some of the models, energy flows are further constrained by using sectoral GDP in addition. For further details on the state of baseline projection in CGE models, refer to Fæhn et al. (2020). These differences and their implications are discussed in more detail in Section 3.4.4 on model uncertainty.

3.3.3 Scenario design

Trading arrangements are designed for seven multi-regional configurations, two sectoral (energy-intensive trade-exposed (EITE) sector and power sector only and entire economy) coverage levels, and three stringency levels, for a total of $7 \times 2 \times 3 = 42$ scenarios (Table 3-3). The welfare effects of each trading cooperation at each level of stringency are compared to the scenario in which all regions meet their emissions target in 2030 by domestic reductions only, i.e., without emissions trading.

The modeled reduction levels are based on the countries' existing NDC pledges as given in Kitous et al. (2016). As in Böhringer et al. (forthcoming), we translate the NDCs into region-specific CO₂ emission reduction requirements in percent from the 2030 business-as-usual emission levels. These unconditional NDC reductions are far from what would be required for reaching the 2°C target (or the 1.5°C target). Thus, these pledges are scaled up uniformly across regions for the more stringent pathways, following a budget approach. We base our calculations on the Intergovernmental Panel for Climate Change (IPCC) scenario database (<https://www.ipcc-data.org/>). To determine the budget available

for the 2°C (1.5°C) target, we filter the scenario database for scenarios according to a 2°C (1.5°C) trajectory and calculate the compound annual growth rate of CO₂ emissions between 2011 and 2030 for each of these scenarios (which is negative, as emissions decline over time). The mean compound annual growth rate is applied to calculate the required relative emission reduction between 2011 and 2030. For 2030, global CO₂ emissions are 12% (for the 2°C target) and 33% (for the 1.5°C target) below 2011 emissions. The resulting regional reduction targets of all three scenarios can be found in the Supporting Information (Table S2.1). A detailed description of how the region-specific reduction targets for NDC, NDC-2°C, and NDC-1.5°C ambition levels are derived from official data sources is provided in Supplemental Information Section S3.

The multi-region arrangements modeled in this effort are shown in Table 3-3, Panel 1. The selection of these emission trading arrangements was informed by the arrangements previously modeled in the literature and discussed in climate and trade negotiations and in consideration of the inclusion of developing countries that could benefit from these arrangements. In principle, it would be ideal to look at all the potential combinations of trading arrangements. However, in practice, a balance was needed between evaluating a wide number of plausible trading arrangements and the ability of each modeling team to generate results. Thus, other trading arrangements are also plausible but are not included here.

All scenarios for regional trading are examined for emission-intensive trade-exposed (EITE) and the power sectors only and then for trading in the entire economy. Emissions from the EITE sectors are projected to be around 38% of global emissions for 2030. As is in the EMF36 core scenarios, the emissions targets for the combined trading sectors under partial trading are the emission level resulting in these sectors under unilateral action in a reference (REF) domestic action only scenario (a no trading/linkages scenario). The regions not participating in a trading arrangement continue to reach their emission targets through domestic only action. All these scenarios are simulated under the three emissions reduction ambition levels as described in Panel 3.

Table 3-3 Scenario design

1. Regional engagement						
No Linkages (REF)	Asia	EUR_CHN	Low	Med	High	Global
	China (CHN)	Europe (EUR)	EUR	Low plus	Med plus	High plus
	Japan (JPN)	CHN	CHN	Brazil (BRA)	South America (OAM)	Middle East (MEA)
	South Korea (KOR)		JPN	Australia/New Zealand (ANZ)	India (IND)	Africa (AFR)
			KOR		USA	Rest of Asia (OAS)
			Canada (CAN)			Russia (RUS)
2. Sectoral Coverage in for Cooperation Option						
Energy Intensive and Trade Exposed (EITE) sectors + Power sector						
All sectors						
3. Ambition level						
Baseline Ambition = EMF 36 NDC	Includes a translation of unconditional NDCs into percentage regional emission reduction requirements for 2030 relative to the baselines in 2030.					
Medium Ambition = EMF 36 NDC-2°C	Includes percentage regional emission reduction targets for 2030 extrapolating NDCs such that the global emission level is on a 2°C path.					
Very High Ambition (a pathway for 400 Gt by 2050 or 1.5°C target) path	Includes percentage regional emission reduction targets for 2030 extrapolating NDCs such that the global emission level is on a 1.5°C path.					

3.4 Results and discussion

Overall, the results from this effort confirm that substantial reductions in the costs of mitigation can be achieved through emission trading. However, the relative gains across these trading arrangements depend on the difference of the carbon prices of the participating regions under domestic only action, the weight of each region in terms of emissions, and the global energy market effects. The indirect effects on economic activity and changes in imports and exports of other goods, especially fossil fuels, can result in lower-than-expected gains or even losses in welfare for some participants in some regional trading arrangements. Non-participants may also be affected due to the indirect effects of imports and exports.

Looking across models, while the magnitude and the directionality of the change in welfare are generally consistent, there are also some regional trading arrangements where the models show divergent results for some participants. This inter-model variability can be interpreted as a measure of the precision to which the effects of the trading arrangements can be estimated in a CGE framework. Specifically, the importance of decisions in the initial calibration of the model on the resulting welfare estimates is highlighted.

3.4.1 Global welfare effects of regional trading arrangements

In Figure 3-1, the change in global welfare across all cooperation arrangements by climate target and model for both all-sector and EITE-only trading scenarios are shown. The gains from cooperation are increasing across all models with the degree of stringency in the scenarios we covered. While there is some heterogeneity across models about the level of the global welfare gains relative to unilateral action, global gains increase by roughly 2 – 3 times when shifting from NDC to NDC-2°C, and again by roughly 2 times from NDC-2°C to NDC-1.5°C. For the NDC and NDC-2°C targets, six out of seven models find welfare gains in the range of 0.1 % to 0.4 % for NDC and 0.3 % to 0.9 % for NDC-2°C. In the TU-Berlin model, the welfare gains are larger than the other models (NDC: 1.2 %; NDC-2°C: 2.4 %) for all sector trading, but not for the EITE only trading arrangements. For the more stringent 1.5°C target, where technological flexibility and options play an increasing role, the range of welfare gains is larger with six out of seven models showing

welfare gains of 0.7 % to 2.0 %, and again one outlier (TU-Berlin) showing a 4.1 % gain in global welfare. There are differences in the TU-Berlin model's calibration process and its elasticities of substitution that account for these higher gains for all sector trading. Specifically, the TU-Berlin model's base calibration approach introduces carbon prices to replicate the CO₂ emission pathways; however, these carbon prices are applied without additional autonomous energy efficiency improvements. The result is lower flexibility in national abatement as these baseline carbon prices result in an EITE sector that is less carbon-intensive (i.e. has higher marginal abatement costs). Thus, EITE-only coalitions will not much improve the overall welfare. On the contrary, marginal abatement costs of non-EITE sectors decrease, and hence all-sector scenarios become highly welfare-increasing. (See Section 3.4.4 for a more detailed discussion of how these differences arise and the implications).

Generally, as more regions and sectors participate in trading, the global welfare gains can increase, as there are more opportunities for mutually beneficial trades. Most models report that global carbon markets generate the largest welfare gain over the domestic only emission reductions. However, the global welfare is found to be slightly higher in the EDF-GEPA model for low participation (ASIA) with all sectors trading (under the NDC and NDC-2°C targets) and in the TU-Berlin model for high participation with all sectors trading for all targets and the EU - China market with all sectors trading for NDC-2°C. (See Section 3.4.4)

Figure 3-2 shows how much of the efficiency gain from a global trading market is observed in the different trading arrangements and the sectoral coverage. Multi-regional trading arrangements consisting of only a few participants, such as trading in EITE and power sectors in an Asian market or a China and EU market, generate substantial gains relative to a hypothetical global market. Trade arrangements with fewer countries can comprise a substantial percentage of the global emissions as shown in the upper panels: ASIA covers on average one-third of global emissions when all sectors are included in the emission trading, and EUR_CHN covers up to 38% of global emissions. By comparison, the high participation arrangement covers around three-quarters of global emissions. In the EITE sectors (see Supplemental Information, Figure S4.1), the share of emissions is very similar across six of the models, although TU-Berlin has substantially lower EITE emissions. When only EITE sectors are included in the emission trading, the

median value from the model shows that 22% of global emissions are included in the smaller coalitions (ASIA and EUR_CHN), and 43% for the larger (HIGH); a global market with only EITE sectors would cover 56% of global emissions under the NDCs. As the emission targets become stricter, EITE emissions decrease and the EITE share of global emissions also decreases.

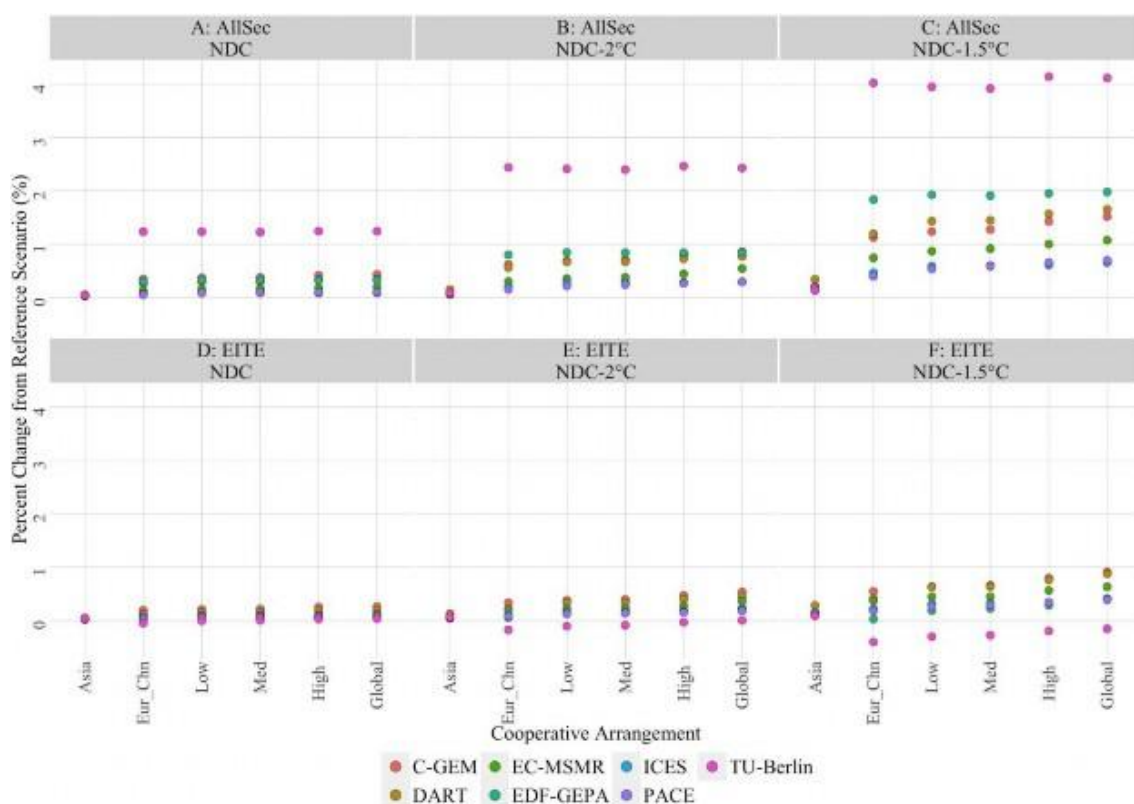


Figure 3-1: Change in global welfare by cooperation level and stringency with all sectors (panels a, b, c) and for EITE sectors only (panels e, f, g). Panels a and d are the NDC pathways. Panels b and e are the NDC pathway augmented to approximate the emission reductions consistent with a 2°C end-of-century temperature target. Panels c and f are the NDC pathway augmented to approximate the emission reductions consistent with achieving a 1.5°C end-of-century temperature target. These results are shown by model.

In general, the global welfare gains increase with increases in regional participation, regardless of whether all sectors or only EITE sectors are covered. However, the variability across models in the projected gains by trading arrangement is substantial - up to 66% difference between models. Figure 3-2 also highlights the cases where welfare gains are larger in trading arrangements other than a global market (Global_AllSec). When only the EITE sectors are included in the trading arrangements, the welfare changes are smaller than when all sectors are included, in line with the smaller share of global

emissions covered in these scenarios.

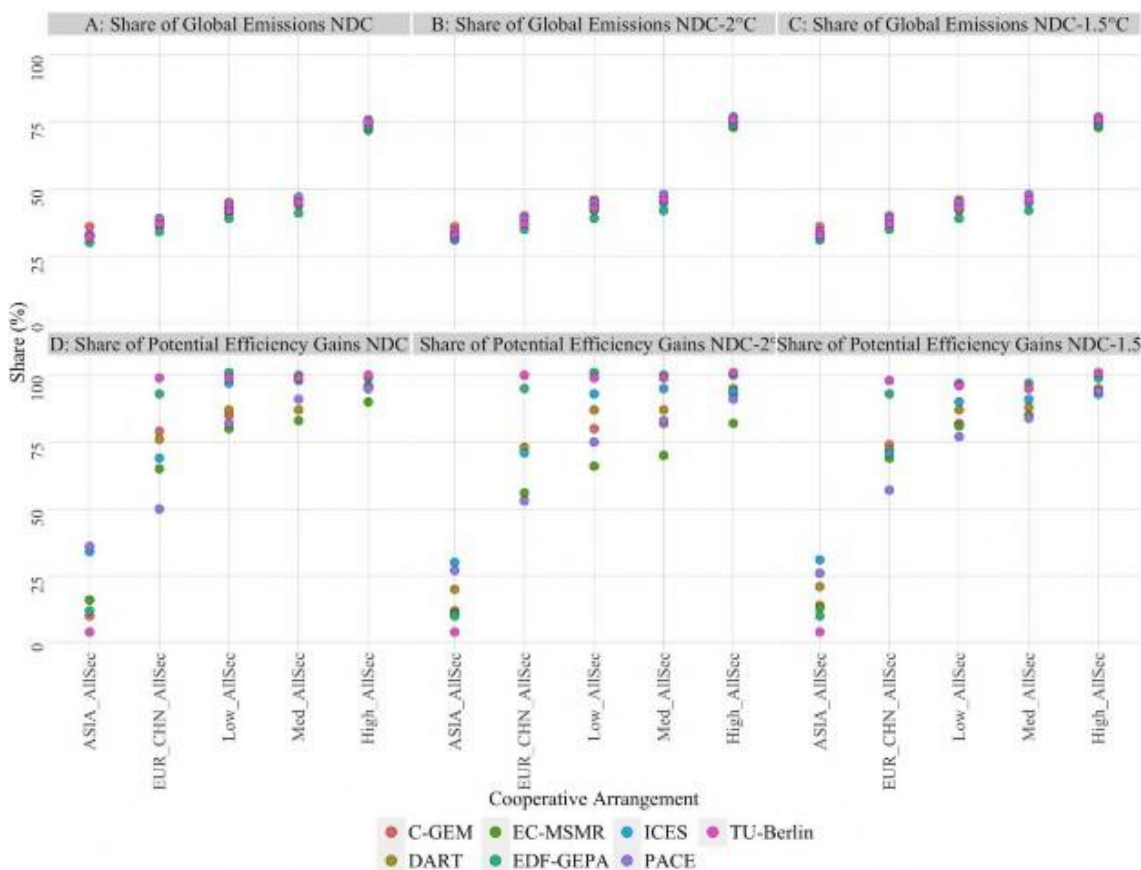


Figure 3-2: Shares of emissions covered by the trading arrangement as a percentage of the global emissions and share of welfare gains from the trade arrangement as a percentage of the gains in a global all sector market in 2030 under different emission reduction targets. In some cases, the welfare gains from trading arrangements exceed those from the global all sector trade that is used as reference. This generates values higher than 100%.

For the welfare gains for all sector trading, the emissions share is a poor indication of the relative welfare gains from the trading arrangements, such that a careful analysis of welfare is needed to identify favorable trading arrangements. For a trading arrangement that consists of all sectors in the EU and China (model median of 37% of global emissions), the welfare gains are on average 72 % to 76 % (depending on the stringency of the emission reduction target) of the welfare gains from global participation. The welfare gains fall from 25 % to 34 % (depending on the stringency of the emission reduction target) of the global gains when only EITE sectors are included in the trading arrangement (which is closer to their emission share). By contrast, only 12 % to 16 % of the possible efficiency gains are achieved for the ASIA trading arrangement compared to

a global market.

In the low participation arrangement, the emissions covered in the trading arrangement increase by 5 % to 6 % (2 % when only EITE sectors are covered) with an increase of 11 % to 15 % (12 % to 13 %, if only EITE sectors are covered) in efficiency gains. This gain can be explained by the difference in prices between the participating regions. For example, the carbon price in EITE in South Korea under NDC targets is on average 12.8 times higher than the carbon price in an EU-China trading arrangement. When South Korea and developed countries join, the carbon price is 16% higher for the EU and China. South Korea sees a 90 % lower price than with domestic action only. Consequently, the "new" participants generate a larger welfare effect than the emission contribution. The share of welfare gains (1 % to 4 %) in the medium participation arrangement is comparable to the additional emissions (3 %) for all sectors and EITE only markets. Here, the carbon prices of the "new" members Australia/New Zealand and Brazil are on average 1.1 times and 4.3 times, respectively, higher than the price of the old coalition (under NDC and with all sectors covered). Furthermore, the higher price in Brazil has less weight, as the total emissions of Brazil comprise only 2% of the medium participation emissions. Consequently, the welfare gains obtained in the "new" members have a negligible effect on global efficiency gains.

Under high participation arrangements, the increase in the share of emissions (29 % for all sectors vs. 12 % to 17 % for EITE sectors only) is substantially higher than the increase in the efficiency gains (5% - 7 % for all sectors vs. 3 % to 8 % for EITE sectors only). In this arrangement, the USA and OAM now face a lower carbon price. However, their relatively low welfare gains in this arrangement are offset by the higher prices for the other participants, including India. The energy markets and trade effects (Section 3.4.3) also become more important with this higher participation. The welfare gains and losses are offset between importers and exporters, and thus, the net effect of welfare is less pronounced.

3.4.2 Incentives to participate in regional trading arrangements

The divergence of the carbon prices for unilateral action compared to the price in a trade arrangement also measures the incentive to participate in regional emission trading. In

Figure 3-3, the carbon prices for domestic only reductions are shown for each region in 2030. In Figure 3-4, the global uniform carbon price for all sectors (Global_AllSec) and the trading arrangements by emission pathway and model are shown. The different models produce different marginal costs for any given region, although the patterns of countries with higher or lower abatement costs are generally consistent. For example, all models report that South Korea has the highest carbon price for reaching its NDC emissions reduction target through domestic action only. These higher prices reflect the emission reduction targets for South Korea and its low carbon intensity that limits lower-cost abatement opportunities. By contrast, China, India, and Russia have the lowest carbon prices. The lower abatement costs reflect their relatively low emission reduction targets and above-average energy intensities allowing for cheaper abatement opportunities in economic sectors like electricity. However, the differences between models are more pronounced at higher levels of mitigation in the NDC-1.5°C pathways. For example, the average modeled carbon prices across the regions ranges from approximately 20 \$/tCO₂ to 38 \$/tCO₂ in 2030 for the NDC pathway to 110 \$/tCO₂ to 287 \$/tCO₂ for the NDC-1.5°C pathway, respectively. The EITE results are compared in Supplemental Information, Figure S4.2.

The global carbon price ranges from approximately \$10 to \$20/ tCO₂ in the NDC pathway to \$60 to \$240/tCO₂ in the NDC-1.5°C pathway. For the NDC pathway, South Korea, Europe, Canada, the USA, Brazil, and the Other Asia Region (ordered from most to least) are net permit importers, while China, India, Africa, Middle East, and Russia are net permit exporters (ordered from most to least). For the higher emission reduction pathways, the Middle East becomes a net permit importer. These patterns of import and export under global trading are consistent across all models. Only Africa and Russia may shift from exporters to importers depending on the model as the stringency increases. Finally, the models do not agree on the directionality of the trade for Australia/New Zealand at any level of stringency. More information on the volume and direction of the trade in emissions for all sector and EITE only are found in Supplemental Information, Tables S4.1 and S4.2.

While all trading arrangements generate gains in welfare, different regions may prefer more limited trading arrangements that favor their position as an importer or exporter of carbon permits. For regions like the EU and South Korea with above-average abatement

costs for unilateral mitigation, it is beneficial to cooperate with China, which has lower abatement costs. High carbon price regions may prefer to be the only trading partner with China, as shown by the lower carbon prices in Europe - China (EUR_CHN_AllSec) and South Korea, Japan, and China (Asia_AllSec) trading arrangements. This can be compared to arrangements where other permit importers such as Canada (Low_AllSec), Australia/NZ, and Brazil (Med_AllSec) would join and benefit from permit importing while increasing the CO₂ price. For the scenarios run in this paper, when the EU-China arrangement expands to include additional permit importing regions, the carbon price increases. China benefits as a permit exporter. However, the EU is now worse off than when it was the single importer. Additionally, the direction of the carbon price as trade arrangements expand to more countries varies by model. Whether adding additional countries to these trading arrangements (Med_AllSec and High_AllSec) raises or lowers the modeled carbon price is ambiguous. For stricter targets, four models show that India's low carbon price leads to a decrease in the traded carbon price, but three models show that the price increases. Additionally, non-participant carbon prices also change. Generally, carbon prices decrease for non-participants relative to the non-climate policy scenario. There are a few exceptions where very modest price increases are observed (a less than 5% increase).

Looking at the regional welfare effects under different trading arrangements, all models show that trading arrangements with limited regional participation provide economic gains at the aggregate level for the participants. These gains increase with the stringency of climate targets (see Supplemental Information Figure S4.3). The trading arrangements with the highest aggregate economic gains for the participants in terms of change in welfare relative to the no trading scenario are an EU-China market and markets with low and medium participation levels. However, these high aggregate gains do not necessarily result in gains for all participating regions. Additionally, as the model results are further disaggregated to the regional level, the size and the direction of the effects across the models show more variation.

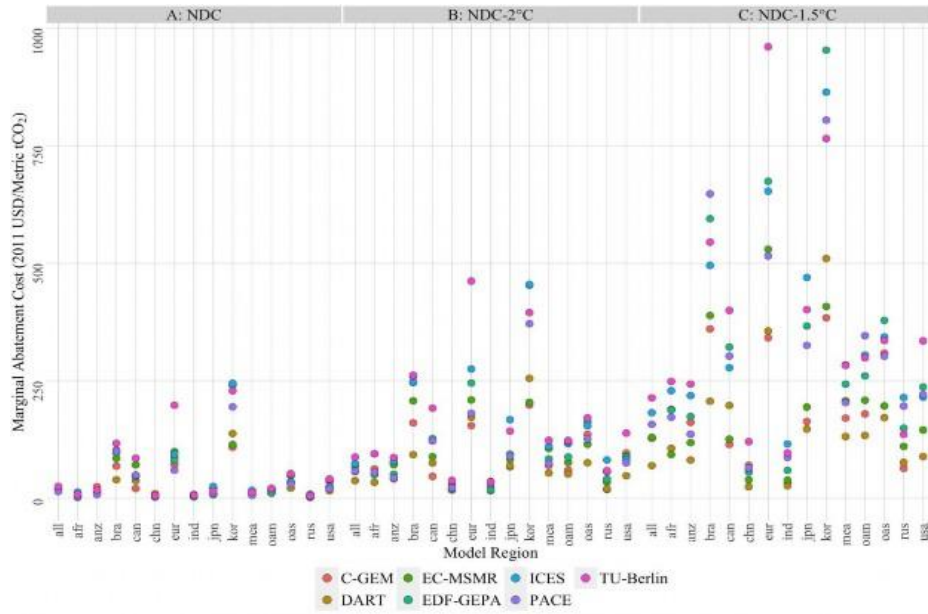


Figure 3-3: Marginal abatement costs (in \$/tCO₂ abated) for domestic only mitigation action by model region in 2030. Panel a is the NDC pathway. Panel b is the NDC pathway augmented to approximate the emission reductions consistent with a 2°C end-of-century temperature target. Panel c is the NDC pathway augmented to approximate the emission reductions consistent with achieving a 1.5°C end-of-century temperature target.

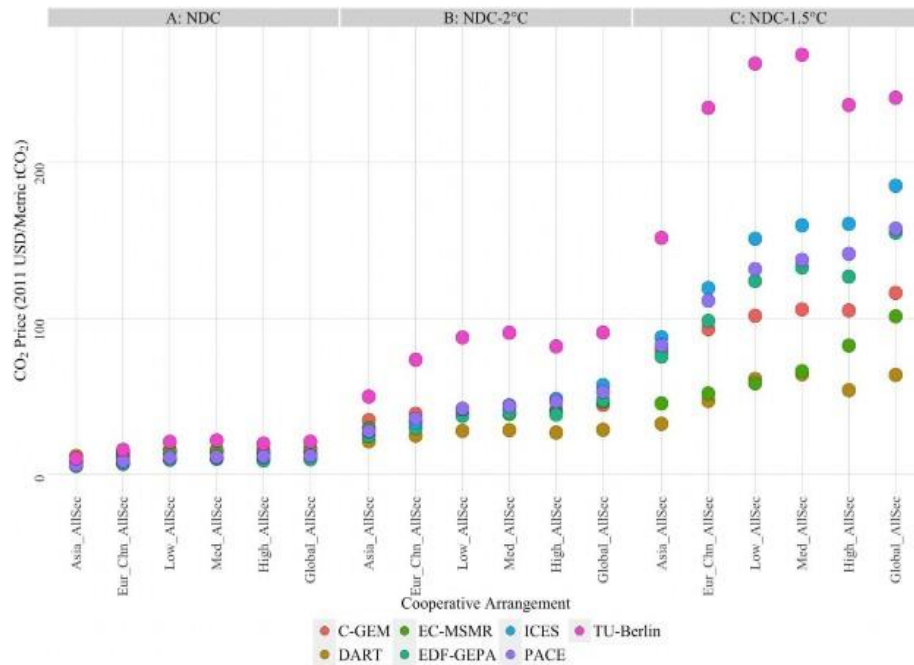


Figure 3-4: CO₂ price (in USD/tonne of CO₂) for participants in the multi-region trading arrangement for all sectors. Panel a is the NDC pathway. Panel b is the NDC pathway augmented to approximate the emission reductions consistent with a 2°C end-of-century temperature target. Panel c is the NDC pathway augmented to approximate the emission reductions consistent with achieving a 1.5°C end-of-century temperature target. These results are shown by model.

When the gains are evaluated compared to no trading baseline for the participating regions, the relative gains as more participants join depends on the relative abatement prices of the new entrants. These gains, however, are still large. At the same time, the participants may find that their welfare gains are reduced under some trading configurations and thus may be less inclined to develop further linkages even if the overall benefits still increase. While a game-theoretic analysis of the stability of coalitions is beyond the scope of this paper, Table 3-4 indicates the incentives for the different regions to participate in trading arrangements by whether the arrangements are welfare-enhancing over meeting their commitments through domestic action. Looking at EITE-sector trading, for each participant, we show how many models find that this participant benefitted in terms of welfare compared to the number that shows losses. Disaggregated welfare gains by participant are shown in Supplemental Figures S4.4 (all sector) and S4.5 (EITE only).

There is no coalition where all models unambiguously find that the coalition is beneficial for all its members. All models report that the EU benefits from all coalitions but that a market of Europe and China generally results in the highest welfare gains for the EU. Thus, the EU would prefer the smaller coalitions with China. Similarly, Korea unambiguously experiences economic gains from participation in emission trading markets over domestic-only action. It also has little incentive to join in larger coalitions where it has to compete for Chinese permits. By contrast, the stricter the target, the more models report that the global market provides the greatest welfare gains for China. As a net permit exporter, China observes welfare gains from participation in almost all market arrangements. However, for smaller coalitions and especially for EITE only emission coverage, some models report that China would do better under domestic only reductions. For the other regions, most models report that coalitions are beneficial. By contrast, most models find that Japan (JPN) does not benefit from trading arrangements. Only about half of the models report that India gains from permit trading when India participates in the market.

For full sector trading (see Supplemental Information Table S4.3), more regions gain for all coalitions. Still, the only unambiguously beneficial coalition for its members is a coalition between the EU and China under the NDC targets. It thus becomes clear that incentives for regions that do not benefit in a coalition have to be created through side

payments and other incentives to make the overall beneficial coalitions possible.

Table 3-4 Participants' welfare gains in a given trading arrangement for EITE sector emission coverage relative to meeting emission targets through domestic reduction only. The x/y values indicate the number of models that show gains (x) compared to the number of models that show losses (y). Where results can differ across emission reduction targets, this is indicated in brackets. The darker the shade, the more models report gains.

Participants	Regional Trading Arrangement					
	ASIA	EUR_CHN	LOW	MED	HIGH	GLOBAL
EUR		7/0	7/0	7/0	7/0	7/0
CHN	4/3 (NDC) 5/2	5/2 (NDC) 4/3 (2C) 6/1 (1.5C)	5/2 (NDC) 6/1	5/2 (NDC) 6/1	5/2 (NDC) 6/1	5/2 (NDC) 6/1
JPN	0/7 (NDC) 7/0		1/6 (NDC) 3/4 (2C) 7/0 (1.5C)	1/6 (NDC) 3/4 (2C) 6/1 (1.5C)	1/6 (NDC) 3/4 (2C) 7/0 (1.5C)	1/6 4/3 (1.5C)
KOR	7/0		7/0	7/0	7/0	7/0
CAN			7/0 (NDC) 6/1	7/0 (NDC) 6/1	7/0 (NDC) 6/1	7/0 (NDC) 6/1 (2C) 5/2(1.5C)
BRA				6/1 5/2(1.5C)	6/1 5/2(1.5C)	6/1 4/3(1.5C)
ANZ				6/1 4/3 (1.5C)	5/2 4/3 (1.5C)	5/2 3/4 (1.5C)
OAM					5/2 (NDC) 6/1	5/2 (NDC) 6/1
IND					3/4 5/2 (1.5C)	3/4 (NDC) 5/2
USA					4/3	4/3 (NDC) 3/4
AFR						5/2 (NDC) 7/0 (2C) 6/1 (1.5C)
RUS						7/0
MEA						6/1 (NDC) 7/0

3.4.3 The effects of trade patterns on fossil fuels and energy-intensive goods

Whether gains or losses accrue to participants depends on complex interactions of the variation in abatement costs between participants and domestic production and trade effects. Changes in international prices in fossil fuels and energy-intensive goods can impose indirect trade impacts, often reported as "*terms-of-trade effects*," on regions even when they are not actively participating in any unilateral or multilateral climate policy. The main finding is that the size of the indirect effects mostly depends on the trade position in fossil fuel markets and the fuel substitution capability of the EITE and electricity sector.

There is the interaction of changes in regional demand for fossil fuels under the climate targets. The lower demand for fossil fuels that accompanies emission reductions can impose welfare losses on regions that export fossil fuels, while energy importing regions may benefit at these lower prices. Since with permit trading, the decrease in the global demand for energy inputs is not as large, net energy importers may become disadvantaged relative to no emission trading. Fuel switching also affects trade patterns, especially for natural gas markets. However, the effects are less consistent by model. As models also differ in their assumptions about technology and substitutability in the electricity and energy sector, these differences are not unexpected. For regions that show different net trade positions in primary energy markets (see Table S2.8 in the Supplemental Information), the aggregate welfare outcome depends on a region's position in the permit market, trade patterns, and the relative price changes in international energy markets.

There are also spillovers in the EITE sectors. The differences in countries' abatement costs influence the international competitiveness, especially of their more EITE goods. For example, in an economy, which can easily substitute energy goods both in its production chain and in its power production, the impact of the EITE sector may be more modest when compared to the effects via fossil fuel markets. As shown in Section 3.4.2, domestic only reductions can result in different marginal costs across the regions. Under these conditions, regions with low abatement costs, such as China and India, may have a competitive advantage over regions with higher costs, such as the EU and South Korea. The extent of this spillover effect depends on how much an economy is exposed through EITE trade and the potential to substitute energy goods in their production chain to dampen the impact of national carbon prices. Despite some quantitative differences, the models generally identify the export orientation and the EITE composition of those exports. The trade composition of some regions, namely Russia and India, shows less agreement across the models. As the changes in initial trade positions to those under emissions trading can account in part for whether a region observes gains or losses in a permit market, this variability also affects the overall and distributional outcomes of these markets. See Table S4.4 in Supplemental Information on the model variability for trade flows of fossil fuels.

Exporters of energy-intensive goods may also benefit if the regions they compete with do not participate in allowance trading or have higher regional carbon prices. The magnitude

of these benefits depends heavily on the EITE export share of GDP and the emission intensity of EITE sectors (see Table S4.5 in the Supplemental Information). The interactions between international trade in fossil fuels, spillover effects in domestic production, and carbon trading can be highlighted through the following cases.

- For Russia, all models report economic gains following domestic action with other regions cooperating in permit trading. These economic gains occur because the direct positive impacts of permit trading are minor for Russia compared to the secondary terms-of-trade impacts. As the trading arrangement grows in regional scope, Russia can sell more gas. Trading arrangements result in an overall higher reduction in coal demand in participating regions than would have occurred under unilateral action. Russia's gains continue to increase as it benefits from the trade effects more than it would from permit trading. The Middle East has a similar pattern to Russia. However, since the Middle East region competes with Russia in crude oil and gas exports, the positive welfare change in the Middle East is minor and slightly negative under the 1.5°C pathway.
- In higher participation scenarios, China generates income by expanding its energy-intensive production at the expense of losing its share in the international permit market to India. The net effect is a lower welfare gain in the arrangements with higher participation than low- and medium participation.
- Japan relies on importing oil and gas and thus, benefits more when stringent climate policy targets are met without any regional trading. In this case, international gas and oil prices decrease more than when there are trading arrangements since there is a lower global demand for coal.
- India is dependent on international imports of energy and exports of other goods. As a result, India experiences welfare losses under regional permit trading arrangements where India is not a participant. Secondary terms-of-trade effects drive this loss. While permit trading drives down the carbon market price and may allow participants to expand domestic production beyond the limits of domestic action, the trading drives up international fuel prices, which adversely affects the Indian economy. As a net permit exporter, the Indian economy receives considerable income from permit trading which is not possible if they are not part of the trading coalition. India can also expand its share on the international goods markets in the scenarios where they are

part of the trading coalition. These two gains compensate for potential losses arising from increased energy prices when joining the coalition in about half of the models.

- For the USA, the welfare results also vary by model for all-sector and EITE trading. Two models show that trade arrangements would result in a welfare loss, while other models report economic gains. The USA is a net importer of oil and a net exporter of coal. Thus, in some models, the transfers from the permit trading are not offset by the changes in the trade and domestic production.

3.4.4 Observations on the variability between CGE models and implications for carbon market clubs

While a global carbon permit market will reduce the overall costs of abatement, the model inter-comparison highlights the challenges in unambiguously identifying welfare-enhancing emissions trade conditions for all regions. It is beyond the scope of this study to quantify the relative contribution of the differences between the models to the observed difference in the welfare estimates or attribute the difference to a single model feature. Additionally, this type of analysis in a CGE model would be very challenging as these models differ along multiple dimensions that would be difficult to isolate and harmonize.

Many of the observed differences across the models arise from variations in the baseline state of the economy for 2030. These differences arise from the forward projection approaches. Each model is calibrated to the same benchmark GTAP data. However, in 2030, there is more variability in the sectoral composition, trade orientation, energy use, and emissions intensity across the models. For example, the TU-Berlin model estimates much higher global welfare gains for all sector trading than the other models. Here, the calibration approach has a large effect on the modeled welfare for all sector trading. Other differences arise due to constraints placed on the projections by modeling teams and the allocation of GDP and emissions into different sectoral representations. For example, the EC-MSMR model uses the projection of energy flows and output at the sector level from the in-house Energy Economic Model for Canada. Model structure (e.g., recursive-dynamic versus static) and assumptions on the substitution elasticities, which govern substitution and income effects, also contribute to the variability between models. For example, the TU-Berlin model generally has low substitution elasticities compared to the

DART model. Assumptions about improvements in technology, the inclusion of backstop technologies, the calibration of fuels and sector shares, and the recycled revenues may also affect the range of results. Examining each one of these effects could be a fruitful next step.

However, to the extent that these models inform decision-makers, the variability may generate concerns that these arrangements are not necessarily favorable. The interactions between South Korea, Japan, and China illustrate how model variability could inform market design. All models agree that cooperation is beneficial globally. While the gains are not distributed evenly, it can be challenging to be precise about their magnitude. While Korea always gains most in all arrangements and with all models, Japan faces losses in several trading arrangements, and China loses in a few arrangements (and in 3 out of 7 models). Thus, although some of the regions may face welfare losses when involved in carbon market clubs, these losses can be addressed by compensation since the welfare effects of the regionally linked arrangements as a whole are always positive. However, ambiguity in the size and direction of the welfare changes may hinder negotiations on the degree of compensation.

3.5 Conclusion

This paper assesses the welfare effects of emission trading arrangements with different regional participation under climate target stringency and sectoral coverage using a set of CGE models. All models confirm that global cooperation provides economic gains over domestic-only mitigation actions, which increases with the degree of climate target stringency. Thus, extensive international cooperation is likely to be critical in achieving more ambitious climate targets by lowering the welfare impacts. The analysis further shows that even the trading arrangement with more limited regional participation provides economic gains at the aggregate level. These gains also increase with the stringency of climate targets. Reaching the NDC-1.5°C target in a global market covering all sectors leads in the model average to global welfare only 1.1% lower than the global welfare associated with reaching the NDC target with unilateral action. Furthermore, cooperation may encourage countries to scale up their mitigation efforts and reduce administrative challenges regarding accounting and market rules (Keohane et al., 2017).

However, these conclusions are limited to the 2030 period. Costs could be substantially different in the post 2030 period.

Broad cooperation would likely enable reaching stricter targets with relatively little extra costs compared to a situation with only national policies. In many cases, the models show agreement. Specifically, the EU and China have strong welfare incentives to engage in regional trading. However, the current design of EU and Chinese climate policies, such as EU's renewable energy targets, the difference between the absolute target in the EU compared to the intensity-target in China and political acceptability of ETSs more generally (Liu and Wei, 2016), can hinder these linkages in practice. In most cases though, the aggregate economic gains from increased participation do unfortunately not necessarily benefit all participating regions, so side payments or other incentives would be necessary to achieve these coalitions. The distribution of the welfare gains by region vary by model depending on complex interdependent effects from permit trading and international trade flows. While the models generally confirm that trading generates overall welfare gains by lowering the abatement costs, these indirect effects often moderate these gains and, in limited cases, reverse them. These findings, however, do not address the effects on account balances or exchange rates that would be accompanied by these large financial flows implied by the permits between regions.

Furthermore, the inter-model comparison highlights the limits of the precision with which the regional welfare effects can be estimated in CGE models. Differences in the magnitude and the direction of welfare effects are observed for some regions under some trading arrangements and climate stringency levels. The forward projection approaches that are used to establish the baseline conditions appear to drive most of the differences, although model structure, elasticities, and assumptions about technological progress also matter. As decision-makers may be especially concerned about the uncertainty of the benefits, further investigation of these distributional aspects may be the key to providing sharpened insights to decision-makers in ways to generate regional incentives for increased cooperation worldwide.

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Chapter 4

Gains associated with linking the EU and Chinese ETS under different assumptions on restrictions, allowance endowments, and international trade*

Malte Winkler, Sonja Peterson, Sneha Thube

Abstract

Linking the EU and Chinese Emission Trading Systems (ETS) increases the cost-efficiency of reaching greenhouse gas mitigation targets, but both partners will benefit – if at all – to different degrees. Using the global computable-general equilibrium (CGE) model DART Kiel, we evaluate the effects of linking ETS in combination with 1) restricted allowances trading, 2) adjusted allowance endowments to compensate China, and 3) altered Armington elasticities when Nationally Determined Contribution (NDC) targets are met. We find that generally, both partners benefit from linking their respective trading systems. Yet, while the EU prefers full linking, China favors restricted allowance trading. Adjusted allowance endowments that shift reduction obligations to the EU cannot sufficiently compensate China to make full linking as attractive as restricted trading. Gains associated with linking increase with higher Armington elasticities for China, but decrease for the EU. Overall, the EU and China favor differing options for linking ETS.

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Moreover, heterogeneous impacts across EU countries could cause dissent among EU regions, potentially increasing the difficulty of finding a linking solution favorable for all trading partners.

Key Words: Paris Agreement, NDC, Emission Trading, Linking ETS, China, EU

JEL classification: F130, F180, Q580, Q540

4.1 Introduction

The Paris Agreement abandoned the top-down approach of the Kyoto protocol, which defined an overall emission reduction target to be distributed among individual countries. Instead, following a bottom-up approach, individual countries are called upon to submit new pledges and emission reduction targets regularly, ideally adding up to a pre-determined global target (UNFCCC, 2020). Within the context of the Paris Agreement, these pledged emission reduction targets are termed *Nationally Determined Contributions (NDCs)*. Article 6 of the Paris Agreement (UNFCCC, 2015) outlines the possibility of reaching the NDCs through international cooperation, and includes the option of linking Emission Trading Systems (ETS) to do so. This is a recognized mechanism for increasing the cost-efficiency of international greenhouse gas mitigation (e.g. Alexeeva and Anger 2016, Nong and Siriwardana 2018, Fujimori et al. 2016), and the linking of national ETS is perceived as a fallback option when international top-down approaches have failed (e.g. Ostrom 2010, Tuerk et al. 2009).

However, several studies find that linking existing ETS does not necessarily benefit all participating countries but can instead lead to welfare losses in the allowance selling region through terms-of-trade (ToT) effects (e.g. Flachsland et al. 2009). ToT is a country's ratio of export prices to import prices. In this context, ToT refers to the decreased competitiveness faced by allowance sellers as they connect to an ETS with a higher emission allowance price. Indeed, the allowance prices of all participating regions converge in the linked ETS, leading to an increase in the domestic allowance price of selling regions. As a consequence, the export prices of energy intensive goods increase, thereby decreasing the international competitiveness of allowance selling regions and potentially causing welfare loss. In Fujimori et al. (2016), several regions including China face negative economic impacts through the ToT effect when engaging in a global

emission trading system compared to unilateral carbon pricing. Peterson and Weitzel (2016) find that transfer payments to energy exporters are necessary to counteract indirect market effects in a global ETS, with targets calibrated to a regionally equal loss of welfare. A similar situation applies to emission allowance exporters when ToT effects prevail over the revenue gains from selling emission allowances.

The EU and China have implemented the two largest ETS in the world. The EU-ETS was established in 2005 and covers energy intensive industries and the power sector. The Chinese ETS officially started in February 2021 and applies to the power sector alone, with plans to further extend its coverage to the energy intensive industry sectors. Several studies have already analyzed the effects of linking a stylized EU and Chinese ETS. Hübler et al. (2014) find that China benefits marginally at best when a link to the EU ETS with restricted trading volume is established. In Liu and Wei (2016), both EU and China benefit from linking their ETS. Li et al. (2019) show that import quotas can avoid the negative effects of unrestricted linking between the EU and Chinese ETS. In case of full linking, China's net imports of chemicals, non-ferrous metals and refined oil increase, indicating a worsening of the ToT. If the number of permits traded is limited, Chinese exports (imports) of energy intensive goods increase (decrease), implying that a smaller tradeable permit quota protects the energy intensive industries in China. Gavard et al. (2016) model scenarios with a full link between the EU and Chinese ETS as well as allowance trading with different degrees of restrictions. They find that China suffers welfare loss when the ETS are fully linked, since the revenues from selling allowances do not offset the losses associated with the higher carbon prices induced by linking. Furthermore, China experiences welfare gains when the trading of allowances between the EU and China is limited. Welfare effects depend on the permit price (which decreases with a higher degree of linking) and on the traded volume (which increases with a higher degree of linking). Consequently, revenue from allowance selling and welfare effects are not linear (Gavard et al., 2016).

In this study, we use the computable-general equilibrium (CGE)-model DART Kiel to evaluate the drivers behind these partly contradicting results. We implement the EU ETS along with a disaggregated representation of the electricity sector. The model horizon for all scenarios is 2030, which is the target year of most currently submitted NDCs (UNFCCC, 2021). We establish a full link between the EU and Chinese ETS (aligned

with its stylized current design plans) and develop a set of scenarios to analyze under which circumstances linking is most beneficial to the EU and/or China. These scenarios include 1) limits to traded allowance volume; 2) altering emission reduction targets in both regions so that EU has to abate more and China less, simulating transfer payments from EU to China; and 3) altering Armington trade elasticities³¹. Thus, we address three main topics which are referred to in the literature: restricted trading, the opportunity for transfer payments (modelled as adjusted allowance endowments), and ToT effects.

Our study is part of a broader cross-model comparison study of the Energy Modelling Forum which is denoted “EMF36 - Carbon Pricing after Paris” and summarized in Böhringer et al. (forthcoming). We add to the existing literature by systematically addressing the problem of unequal gains from ETS linking between allowance buyer and allowance seller. This topic has been addressed by a number of papers, albeit with diverse results. To the best of our knowledge, this study is the first to conduct a systematic analysis of how different measures affect these inequalities. We also at some points discuss inner-European heterogeneity stemming from different linking options and equalizing schemes.

This paper proceeds as follows. In section 2, we describe the model and our scenarios. In section 3 we present and discuss the modelling results, focusing on the gains from linking ETS in the EU and China. In section 4 we discuss our findings against the literature. Section 5 concludes.

4.2 Model description and scenario runs

The analysis in this paper is undertaken with the multi-regional, multi-sectoral, recursive-dynamic CGE model DART of the Kiel Institute for the World Economy (DART Kiel), which is designed to analyze climate and energy policies and calibrated to the GTAP9 power database (Aguilar et al. 2016). A non-technical description of the model can be found in the Appendix. The regional disaggregation of the model is displayed in Table

³¹ Armington trade elasticities describe the substitutability between a domestically produced good and an imported good. With higher Armington elasticities, domestic goods can be substituted by imported goods more easily; thus, higher Armington elasticities can be interpreted as more trade openness.

4-1. The sectoral aggregation is in line with the EMF36 core scenarios (see Böhringer et al., forthcoming), but we further disaggregate the electricity sector into eight different technologies (coal, oil, gas, wind, solar, nuclear, and hydro based electricity and electricity based on other inputs) based on the GTAP9 Power database (Peters 2016). With the remaining four energy sectors (crude oil, refined oil products, coal, gas) and five production sectors (energy-intensive trade-exposed goods, transport, agriculture, other manufacturing, services) we model a total of 17 sectors.

Table 4-1 List of regions modelled in DART Kiel. Grey shading indicates EU ETS regions.

Region code	Countries / regions
CHN	China
FRA	France
GER	Germany
GBR	United Kingdom, Ireland
BLX	Belgium, Netherlands, Luxembourg
SEU	Italy, Spain, Portugal, Greece, Austria, Cyprus, Malta
SCA	Denmark, Finland, Sweden, Norway
EEU	Poland, Czech Republic, Slovakia, Slovenia, Hungary, Baltic States, Croatia, Romania, Bulgaria
REU	Rest of Europe (non-ETS): Switzerland, Albania, Belarus, Ukraine, Serbia, Rest of EFTA

The remaining 12 regions are in line with the EMF36 harmonization (Böhringer et al., forthcoming): USA, Canada, Russia, Japan, India, South Korea, Brazil, Australia + New Zealand, Other Americas, Other Asia, Middle East, Africa.

For the **Baseline** scenario, we calibrate DART Kiel to meet the GDP and CO₂-emissions projections of the World Energy Outlook 2018 (WEO; IEA 2018) in the year 2030. In this process we adjust constant annual regional total factor productivity growth rates and increase the GTAP Armington elasticities by a factor of 1.5 while allowing for a maximal value of 12 in order to achieve the given GDP growth rates³². Table A 4-3 in the Appendix

³² This is necessary to achieve the given GDP growth in China, which turns out to be only possible in DART if there is enough flexibility for increased exports.

displays key model parameters including Armington elasticities. To calibrate 2030 CO₂-emissions we adjust the autonomous energy efficiency (AEEI) improvements as well as the elasticity of substitution between fossil fuels and a fixed resource. The Baseline scenario also includes EU emission trading in the energy intensive industry sectors and the power sector subsequently referred to as the ETS-sectors (opposed to the remaining non-ETS sectors). Note that Rest of Europe (REU) does not participate in the EU ETS. Throughout this paper, we use the term “EU” as a synonym for “regions participating in the EU ETS”; hence, REU is excluded. By imposing a carbon price, the CO₂-emissions of the EU ETS sectors are calibrated to the emission targets proposed by the EU rather than the path outlined in IEA (2018)³³.

Next, we implement a policy scenario **NoLink**, in which China and the EU (and all other model regions) unilaterally reach their 2030 NDC emission reduction targets. DART Kiel only includes CO₂-emissions from the combustion of fossil fuels and we use the NDCs as quantified in Böhringer et al. (forthcoming). They disaggregate the NDCs from Kitous et al. (2016) (weighted by 2030 emissions) to the GTAP9 regional disaggregation to make them available for any desired aggregation. In our case, we aggregate the targets to the EU-regions in DART Kiel, which logically sum up to a joint EU target as shown in Table 4-2. The Chinese NDC is in reality formulated as an emission intensity target (emissions per unit of GDP) however similar to Gavard et al. (2016), Böhringer et al. (forthcoming) translate this into an absolute target. Intensity targets are sensitive to the calibrated CO₂ and GDP path. Based on the calculations of Böhringer et al. (forthcoming) in the case of China, this leads to zero emission reduction against the Baseline. However, given the current Chinese emission reduction efforts, this seems unrealistic. Thus, Böhringer et al. assume a 5% reduction against the Baseline, acknowledging that China has installed or will install at least moderate policies leading to effective carbon pricing. Though this approach ignores that changes in the GDP growth of China resulting from a linking of ETSS can affect the emission reduction efforts, any linking would probably include

³³ The EU proposes the following targets: 21% reduction (against 2005 emissions) in 2020, 43% reduction in 2030; see https://ec.europa.eu/clima/policies/effort_en. This adjusted target for CO₂-emissions in ETS sectors is the only difference between our baseline and the harmonized EMF36 Baseline_WEO from Böhringer et al. (forthcoming), as in the latter, the EU is not disaggregated into individual regions.

measures to ensure that it does not lead to extra emissions in China. Thus, our approach can be justified.

Table 4-2 CO₂-emission targets for EU regions and China relative to CO₂-emissions in the Baseline scenario in 2030

Region	NDC
CHN	-5%
FRA	-18%
GER	-27%
GBR	-19%
BLX	-21%
SEU	-22%
SCA	-21%
EEU	-30%
EU	-23%

We then run the model so that all NDC targets are reached by a uniform national carbon price covering all sectors. For China and the EU, we use the resulting emissions in the ETS sectors and non-ETS sectors as targets for the following scenarios. For the EU we use these targets also in the final NoLink scenario to model a joint EU ETS price and seven differing national prices to reach the non-ETS targets. This stylized approach makes our results comparable to other EMF36 results³⁴ but implies that we do not implement actual regional EU ETS allowance allocation.

We define three sets of scenarios to address our research questions. With the first set of scenarios (labeled “**restricted trading**”), we analyze the impacts of a joint EU - Chinese emissions trading scheme for the ETS sectors by restricting the traded allowance volume between the two ETSs. In the scenario with unrestricted allowance trading between the EU and Chinese ETS (labeled **FullLink**), 709 MtCO₂ are traded in 2030 between the EU and China. In nine additional scenarios, only 10%, 20%, ..., 90% of the 709 MtCO₂ can

³⁴ Except for the EU-ETS, the scenario NoLink is equivalent to the REF scenario in Böhringer et al. (forthcoming), and the scenario FullLink is equivalent to the EURCHN scenario.

be traded between the two ETS. The impact of this restriction on individual EU regions is determined endogenously in the model through the EU ETS. While we acknowledge that – strictly speaking – neither NoLink nor FullLink meet the “restricted trading” criterion, we include both scenarios in the discussion of results from this set of scenarios, since the total of eleven scenarios (NoLink, FullLink, and nine restricted trading scenarios) allows us to create a gradient of the of traded allowance volumes.

In the second set of scenarios (labeled “**adjusted allowance endowments**”), we change the reduction targets of the EU and China by shifting more abatement obligations to the EU. This is to simulate transfer payments from the EU towards China, which could be used to partly offset economics losses in China due to linking of the two ETS. We run scenarios in which the respective EU emission target for the ETS sectors is increased by 10%, 20% ,..., 50%³⁵, and the respective Chinese target for the ETS sectors is decreased by the same amount of emissions so that joint reduction efforts remain constant. The adapted reduction targets are defined for each EU region, which adds up to EU-wide reductions due to inner-European emission trading. The adapted targets are applied to FullLink and half linking (restricted to 50% of the volume traded in FullLink; subsequently labelled as **HalfLink**). We do not model scenarios including adjusted allowance endowments without linking of ETS because the adjusted allowance endowments are implemented to equalize effects from linking. Thus, no adjustments are required in the absence of linking. Running FullLink and HalfLink scenarios for the five compensation scenarios altogether leads to 10 scenarios, which again allows the creation of a gradient of the strictness of the EU emission reduction target.

Previous studies have shown that climate policy analysis with CGE models is highly sensitive to the chosen trade elasticities (see e.g. Paltsev 2001). Therefore, with the third set of scenarios (labeled “**Armington elasticities**”), we analyze the impacts of different Armington elasticities since international trade is the main channel for international feedback effects influencing the gains from linking carbon markets of the EU and China. This allows for an in-depth analysis of ToT effects, which play a crucial role in the costs and benefits of emission trading regions. We run scenarios in which Armington elasticities

³⁵ Note that an increase of emission reduction targets means that the number of allowed emissions decreases: Hence, in this scenario allowed emissions in the EU decrease and those in China increase.

are doubled and halved relative to the elasticities used in the Baseline scenario. This change is applied either to all sectors or only to ETS sectors and for three linking situations: NoLink, FullLink, and HalfLink. It should be noted that altering Armington elasticities is not a policy scenario but changes the model settings. Thus, the Baseline scenario is simulated again with these four alternative Armington assumptions (halved in all sectors; halved in ETS sectors; doubled in ETS sectors; doubled in all sectors).

In conclusion, we obtain a total of 38 scenarios to include in our analysis, which are listed in Table 4-3.

4.3 Description of results from scenario runs

In this section we sequentially discuss the key results of our three sets of scenarios, focusing on the implied efficiency gains from trading for both partners (EU and China) and the resulting burden-sharing for reaching the joint target. We also briefly discuss the implications for different EU countries/regions. Throughout the paper, the term “efficiency” refers to cost-efficiency, meaning that the climate policy is termed more efficient when the same emission reduction is reached with lower costs. As common in CGE literature, we use welfare measured in terms of Hicks Equivalent Variation (HEV) as a measure for economy-wide costs. HEV is a better measure of national welfare than GDP since it takes price changes into account. It is defined as the change in income at current prices that would have the same effect on welfare as would the change in prices, with income unchanged. Note that DART Kiel does not include welfare effects resulting from (decreased) environmental damages through climate policy³⁶. All results displayed refer to the year 2030.

³⁶ For all climate policy scenarios though, the global emission level is fixed, so that there is no difference in climate damages among these scenarios.

Table 4-3 Summary of scenario names and assumptions on traded allowance volume, Armington elasticities and emission reduction target.

No. of scen.	Scenario names	traded allowance volume	Armington assumption	emission reduction target
1	Baseline	0%	Standard	EU-ETS target
1	NoLink	0%	Standard	NDC
1	FullLink	100%	Standard	NDC
9	Link_X; X= 10, 20,..., 90)	X%	Standard	NDC
5	Link_full_comp_X; X= 10, 20, ...50	100%	Standard	NDC ± X%
5	Link_50_comp_X; X= 10, 20, ...50	50%	Standard	NDC ± X%
2	BAU_ / NoLink_Arm_halveETS	0%	standard /2 in ETS	-
2	BAU_ / NoLink Arm_doubleETS	0%	standard *2 in ETS	-
2	BAU_ / NoLink Arm_halveAllSec	0%	standard /2 in all sectors	-
2	BAU_ / NoLink Arm_halveAllSec	0%	standard *2 in all sectors	-
2	Link_full_ / Link_50_Arm_halveETS	50%	standard / 2 in EITE	NDC
2	Link_full_ / Link_50_Arm_doubleETS	50%	standard *2 in EITE	NDC
2	Link_full_ / Link_50_Arm_halveAllSec	50%	standard / 2 in all sectors	NDC
2	Link_full_ / Link_50_Arm_doubleAllSec	50%	standard *2 in all sectors	NDC

4.3.1 Core-linking scenarios

When we implement the described NDC emission targets, on the one hand, we see all EU regions lose in terms of welfare relative to the Baseline scenario, with the loss being larger without linking the EU ETS with the Chinese ETS (scenarios NoLink; Figure 4-1). China, on the other hand, receives welfare gains when NDCs are implemented globally. There are two reasons for this occurrence. First, as described by Peterson and Weitzel (2016), the demand for fossil fuels decreases as a consequence of global climate policy, bringing net prices of fossil fuels down. This is beneficial to energy importing regions such as China. Second, reduction targets in China are relatively low compared to the EU (see Table 4-2). Thus, China is relatively less affected by the introduction of the NDCs and consequently becomes more competitive compared to the EU and other regions with stricter targets.

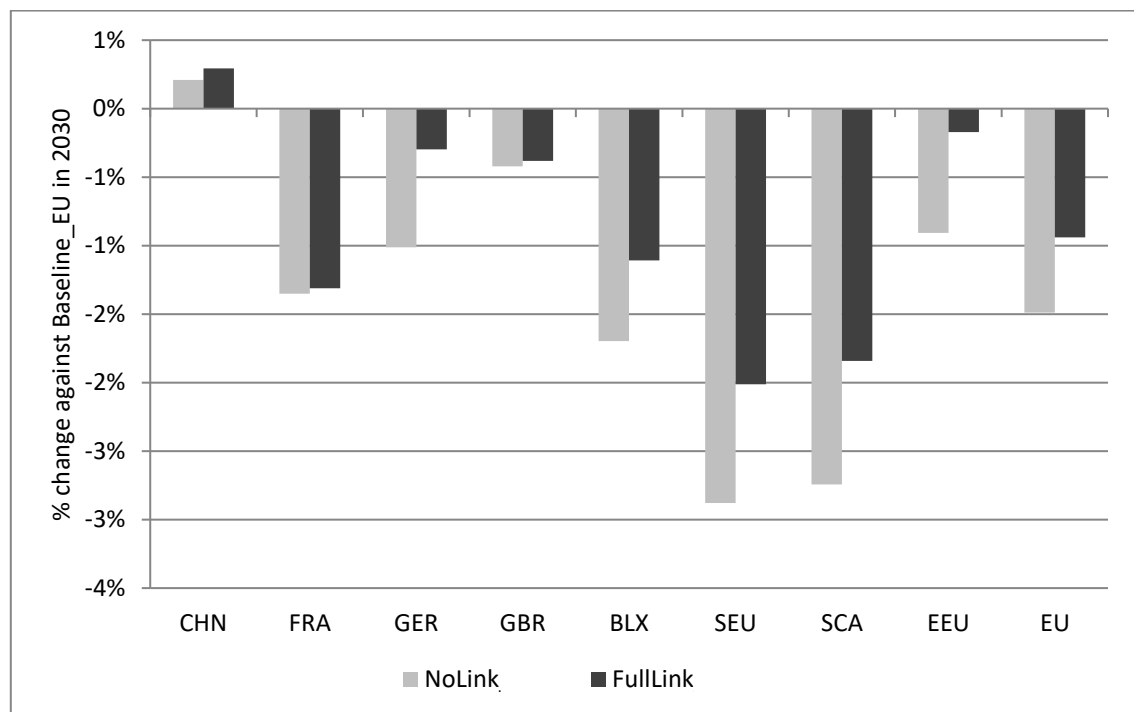


Figure 4-1: Welfare changes in NoLink and FullLink scenarios in 2030 relative to Baseline.

When both regions link their ETS, the EU buys allowances covering a total of 709 MtCO₂ from China. While EU emissions in 2030 increase by 30.3% relative to NoLink, Chinese emissions decrease by 8.4% (see Table 4-4). This linking is beneficial for both the EU and China. Figure 4-1 reveals that not just the EU at large, but every EU region benefit from fully linking to the Chinese ETS, since the welfare costs relative to the baseline are

lower in FullLink than it is in NoLink. Yet, Figure 4-1 also illustrates that the gains from linked emissions trading systems are significantly larger for most individual EU countries and certainly for the EU as a whole than they are for China. For instance, when moving from NoLink to FullLink, welfare improves by 0.08% in China, against 0.55% in the EU. Throughout the rest of this study, we analyze how our different assumptions affect these regionally unequal gains. In order to do so, we now turn towards the three sets of scenarios introduced in section 2.

Table 4-4 Percentage and absolute change between NoLink and FullLink scenarios. The absolute allowance price marks differences between NoLink and FullLink; e.g. the allowance price in the EU is 61.23 \$/tCO₂ lower in FullLink than it is in NoLink.

	Region-China	Region-EU
% change in welfare	0.08%	0.55%
% change in CO ₂ emissions	-8.4%	30.3%
% change in allowance price	29.0%	-82.0%
Difference in absolute price	3\$/tCo2	-61.2\$/tco2

4.3.2 Restricted trading scenarios

Core results for the “restricted trading” scenarios are shown in Figure 4-2. The more trading is allowed, the lower the allowance price in the EU becomes, and the more CO₂ the EU emits. We see that the EU as whole benefits in terms of welfare not only from fully linking to the Chinese ETS, but also in all other “restricted trading” scenarios. The results for individual EU regions, which are not displayed here, reveal that the main sellers of allowances in the NoLink scenario within EU do not benefit under the highly restricted linking of EU and Chinese ETS. This arises from the fact that under linked ETS these regions lose part of their market to cheaper CO₂ allowances provided by China. Only for linked shares beyond 60% do all EU regions experience welfare gains, due to the benefits from lower carbon prices.

Different effects are observable in China. While we do not find a negative effect in welfare as a result of the linking of ETS, there is an optimum point where the trading of allowances is restricted to around 50% of the traded volume in scenarios with fully linked

ETS³⁷. China's welfare thus forms an inverted U-shape when depicted as a function of the volume of allowance traded between China and the EU (see Figure 4-2). This inverted U-shape is driven by the same factors as in Gavard et al. (2016): Revenue that China gains from selling allowances is a function of the allowance price (which decreases with more linking) and the traded volume (which increases with more linking). The carbon prices converge in EU and China as the traded volume increases. Thus, carbon revenues generated with higher linking no longer compensate for the losses associated with sharing a stricter emission constraint with the EU. The relative changes in welfare against NoLink reach a maximum of 0.17% in China and 0.53% in the EU. As expected, the allowance price and CO₂ emissions in China develop contrary to that in the EU i.e. the allowance price increases with higher trading volume and the emissions decrease.

4.3.3 Adjusted endowments scenarios

For the “adjusted allowance endowment” scenarios, we compare the FullLink and HalfLink scenarios (the latter being optimal for China) to the NoLink scenario to analyze gains from allowance trading. Remember, that we model adjusted allowance endowments to the EU and Chinese ETS sectors to generate transfer payments, keeping the sum of ETS emissions of both regions constant overall compensation scenarios. For example, the scenario called “130%” assumes that the EU ETS CO₂ emission reduction target is tightened by 30% relative to the regular NDC i.e. instead of an emission reduction to 452 MtCO₂ (according to the regular NDC pledge) the target is now strengthened by 30% to get a reduction to 316 MtCO₂ (130%). Simultaneously, emission targets for the Chinese ETS sectors are loosened by the same amount, such that joint EU-Chinese ETS emissions remain constant. The main results of this comparison are displayed in Figure 4-3.

Both China's and the EU's total CO₂ emissions remain almost unchanged for all compensation scenarios relative to the NoLink scenario when ETS are fully linked, and the same holds for all the regions in the EU. Also, the allowance price in a fully linked ETS is almost independent of the level of compensation. Both emissions and allowance

³⁷ This optimum at 50% is also the reason we introduce the „HalfLink” scenarios for the two following sets of scenarios.

prices are unaffected, since the EU target becomes stricter by an amount equal to the weakening of the Chinese target, so that the EU simply buys the extra demand for allowances from China in all scenarios and the income effects are negligible. This is also the reason why such a scenario is a good approximation of general transfer payments.

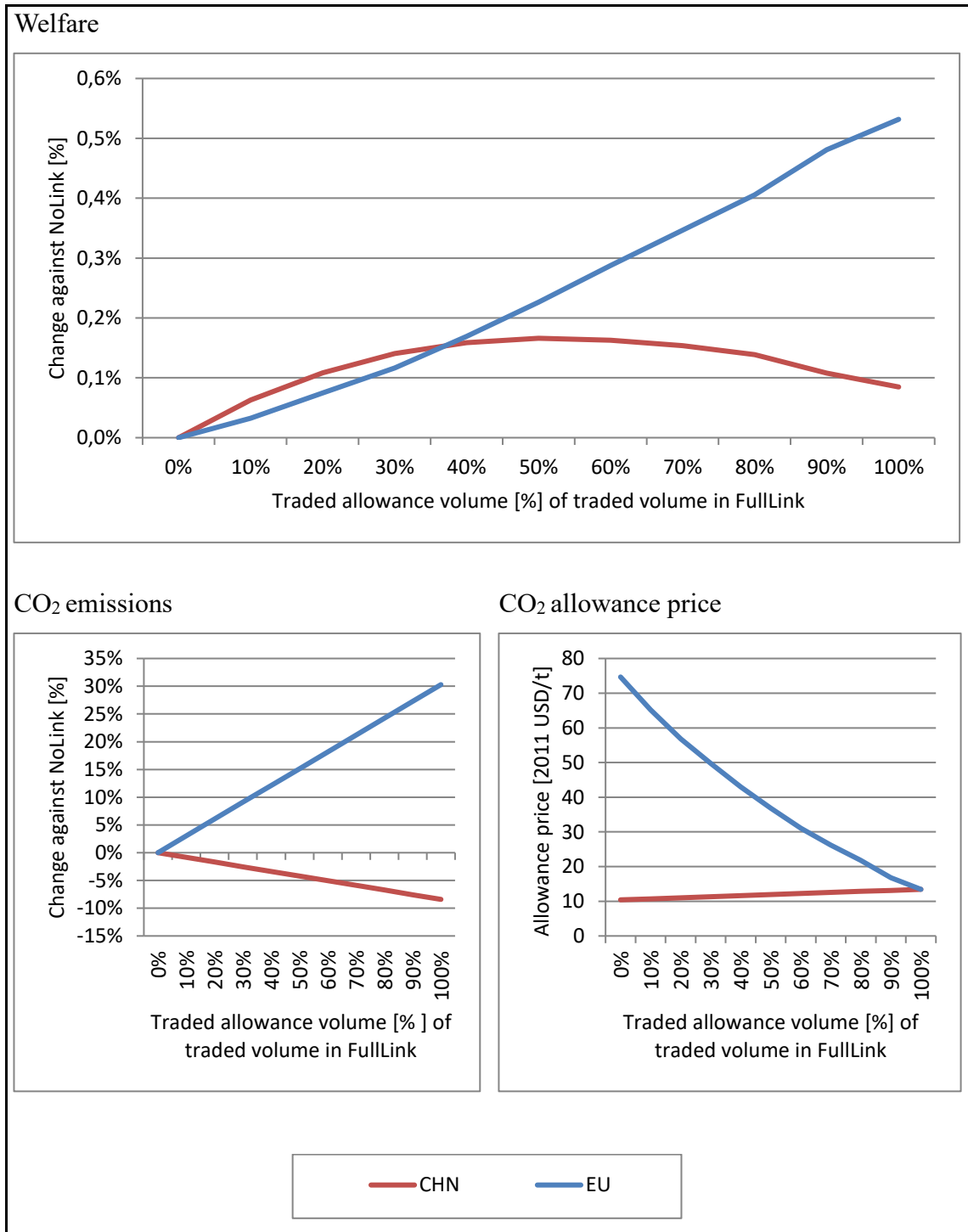


Figure 4-2: Main results of the “restricted trading” scenarios relative to NoLink in 2030.

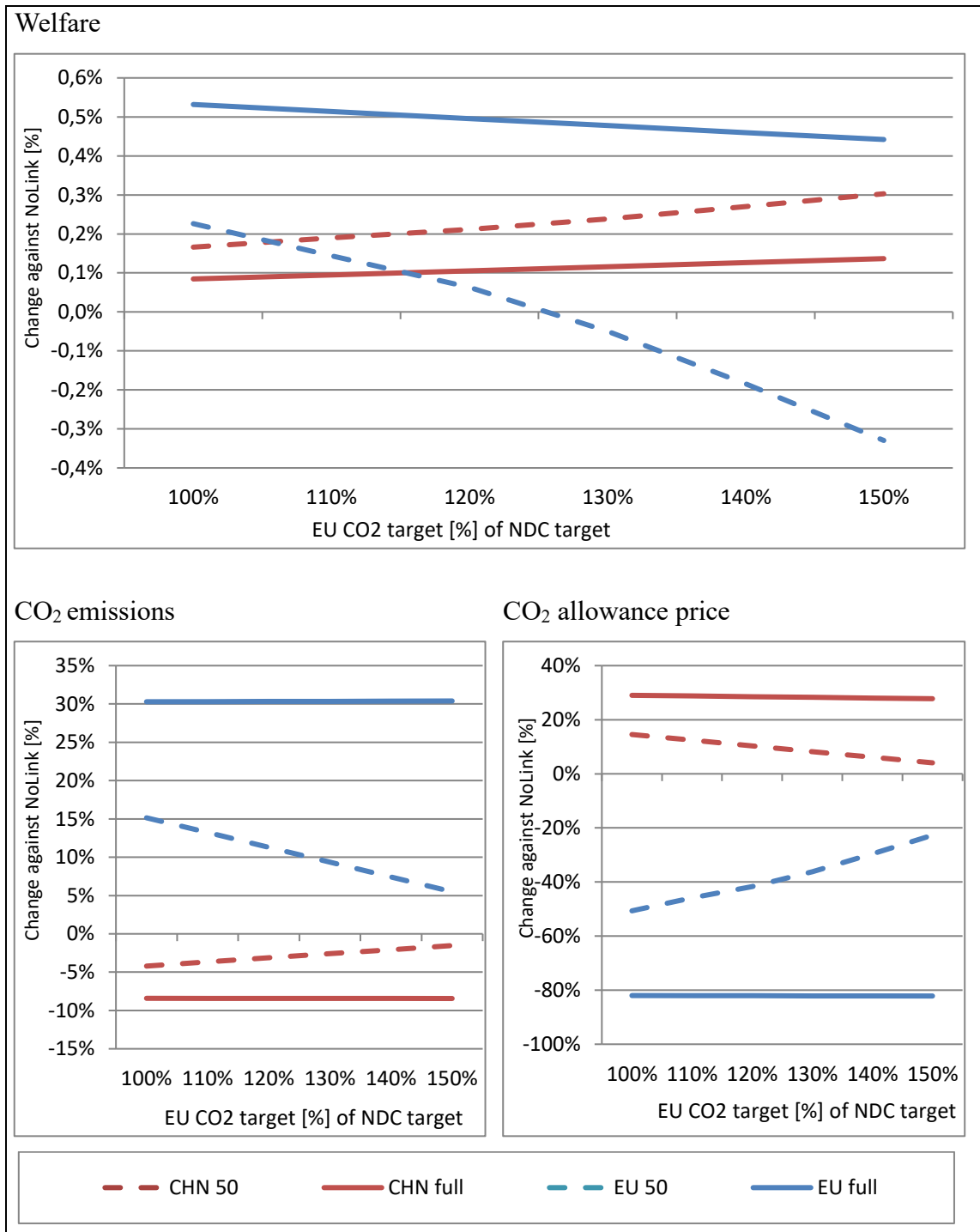


Figure 4-3: Main results of the “adjusted endowments” scenarios relative to NoLink in 2030.

When allowance trading is limited to 50%, emissions in the EU decrease and emissions in China increase with higher compensation (relative to the NoLink scenario), since allowance trading cannot fully compensate for the differing allowance allocation. Thus, in this case, there are not only income effects from the adjusted allocation but also ToT

effects. The CO₂ price in the EU is considerably higher and reaches 58\$/tCO₂ if emission trading is restricted compared to the price of 13\$/tCO₂ under FullLink trading. The allowance price in China decreases only slightly. Also, Chinese emissions are higher under HalfLink trading compared to FullLink. As a result, for both the EU and China, the ToT effects follow the same direction as the effects of adjusted endowments – China benefits from larger endowments not only through higher allowance revenues from a relaxation of its NDC targets but also from improved ToT. In turn, welfare in the EU decreases. As expected, effects are larger with higher compensations. In line with the ToT effects, the increase for China is higher if emission trading is restricted to 50% compared to unrestricted emission trading. The magnitude of this increase is comparable to the gains from “restricted trading” scenarios.

For the EU, even a 50% increase in emission reductions (relative to the stated NDC target) is favorable in combination with a full link compared to a situation with no link. Though welfare gains from linking are reduced by the stricter targets in the EU, they are still positive compared to a situation without linking. Again, not all EU regions benefit equally. Only an increase of reduction targets up to 20% of emissions would be beneficial for all the EU regions in FullLink (relative to NoLink).

For HalfLink, where ToT effects negatively impact the EU, a maximum compensation of 20% of their emissions is beneficial in terms of aggregated EU welfare. Yet, it is also the case that some EU regions never gain in welfare, regardless of the size of endowment adjustments. For scenarios where the EU gains as a whole but not all individual EU regions do, internal distribution mechanisms need to be implemented to compensate the losing EU regions.

While EU might consider to pay transfers to China under full trading in order to induce China to agree to a joint trading system, the resulting welfare gains in China are rather small. Under FullLink, adjusted allowance endowments of 50% increase welfare compared to NoLink by 0.1%. In the case of 20% transfers under HalfLink (the maximum that is still beneficial for the EU as a whole), 0.2% are gained in terms of welfare.

4.3.4 Armington elasticities scenarios

While the two former sets of scenarios were concerned about different climate policy actions of the EU and China (restricting emissions trading / agreeing on transfers), the last set of scenarios is about different assumptions regarding the underlying trade elasticities. This implies that also the Baseline and the NoLink scenarios, which do not include further climate policies or linking of ETS, are affected. Before we turn to the gains from linking under different Armington elasticities, we investigate the effects of adjusting these elasticities.

Figure 4-4 shows the development of key variables for the Baseline and the NoLink scenarios relative to the corresponding scenarios with regular Armington elasticities. It turns out that Armington elasticities (i.e. restriction or relaxation of international trade) have a much stronger influence on welfare than a restriction of traded allowance volume or adjustments of allowance endowments. The relative changes against a baseline with regular Armington elasticities are in the range of -7% to 8% compared to changes below 1% for “restricted trading” scenarios. Effects are significantly stronger for adjusting all elasticities compared to only ETS elasticities. While the direction of welfare effects is the same in China, in the EU as a whole, and in all individual EU regions (all lose when Armington elasticities are reduced, and gain when they are increased, which is in line with the usual gains from trade), China is much more sensitive to these changes than the EU. This is driven mainly by a strong reaction in Chinese exports (-18% against regular Armington elasticities, when Armington elasticities of all sectors are reduced in the baseline and a 6% increase when Armington elasticities of all sectors are increased). Furthermore, Chinese imports decrease with increasing Armington elasticities. The EU exports hardly react to the altered Armington elasticities (minimal increase with higher elasticities), while imports into the EU increase with elasticities. Adjusting only ETS elasticities does not affect EU welfare.

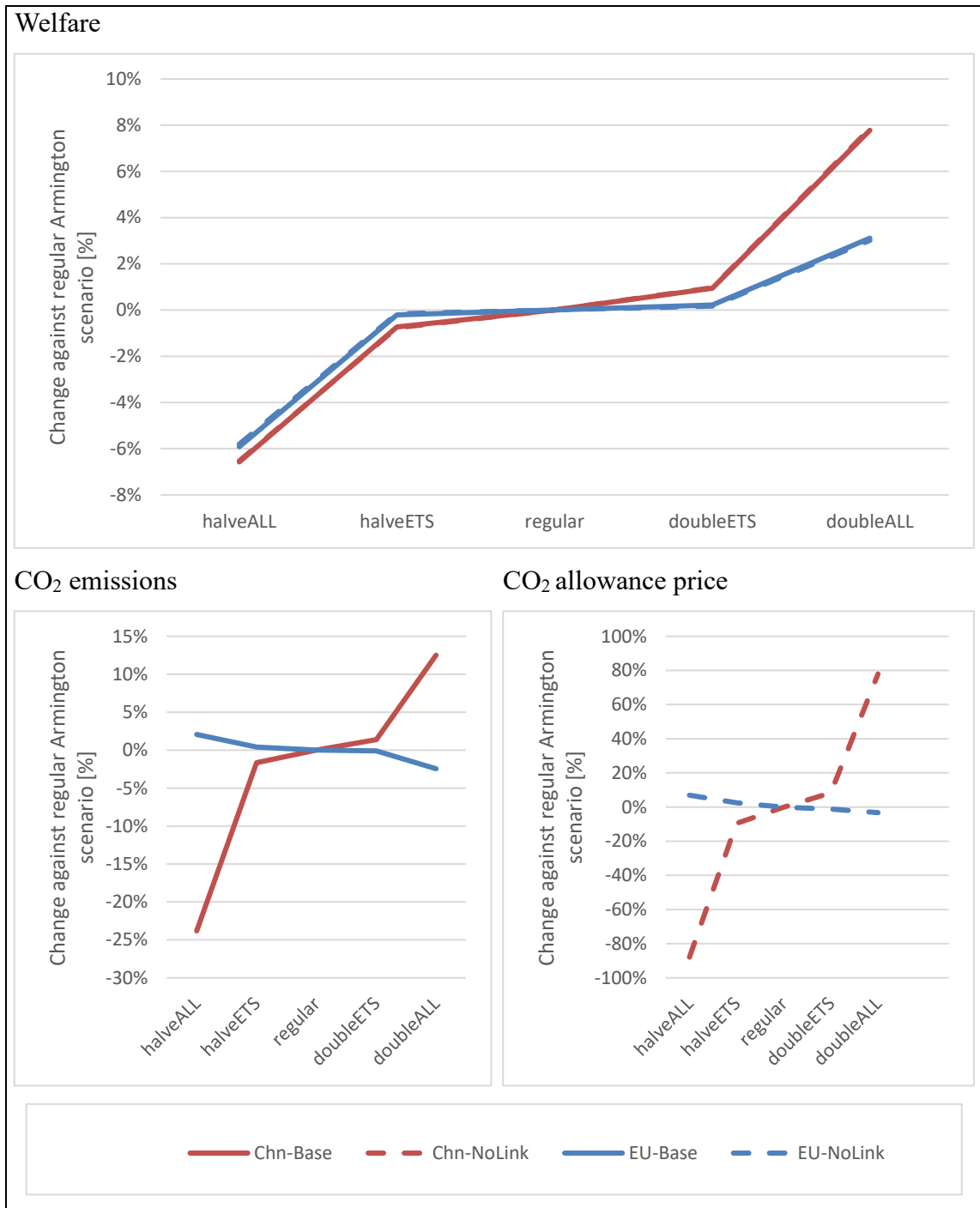


Figure 4-4: Implication of different “Armington elasticities” for (1) no-climate policy (labelled “Base”) and (2) NoLink scenarios (labelled “NoLink”) in 2030. All changes are relative to the regular Armington scenario with the same linking assumption. Note that CO₂-emissions in NoLink are by design always equal to the regular case and are thus not shown. Also, there is no allowance price in the baseline.

For China, the relative changes in welfare correspond to stronger relative changes in emissions; as an example, a welfare increase of 8% in doubleAll corresponds to an increase in emissions of 12.5%. This is because China is a net exporter of emissions embodied in trade (see e.g. OECD statistics on emissions embodied in international trade <https://stats.oecd.org>). With increasing trade, their exported emissions increase. Also note that in halveAll China's emissions decrease so strongly that the carbon price reduced to 1.3\$/tCO₂ and strongly weakens the NDC target³⁸. For the EU, being a net importer of emissions embodied in trade, as well as for all EU regions, the effect is the opposite. As Armington elasticities increase, the EU outsources the production of emission intensive EITE sectors, so that EU emissions from ETS sectors decrease. As domestic production is replaced with imports, emissions decrease. When only the Armington elasticities for ETS sectors are doubled, the national emissions increase by a small amount because of a slight increase in production and emissions from the transport sector.

The effects for welfare in NoLink are almost identical to those in the Baseline for China, overall EU as well as the single EU regions. Overall CO₂ emissions remain unchanged, because both the EU and China reach their given targets themselves, regardless of Armington assumptions. The impact is now on carbon prices, which change in line with the emission changes in the baseline. Higher Armington elasticities in all the sectors (doubleAll) increase baseline emissions and carbon prices under NoLink in China and decrease them slightly in almost all EU regions.

After explaining the effects of altering Armington assumptions on the Baseline and NoLink scenarios, we now turn to our focal question, which is how gains from linking ETS change for different trade elasticities. For this, we compare the FullLink and HalfLink scenarios relative to the respective (i.e., with the same Armington assumption) NoLink scenarios. The results of these comparisons are displayed in Figure 4-5.

³⁸ This result is in line with other modeling studies that show a non-binding NDC target for China (e.g., Liu and Wei 2016).

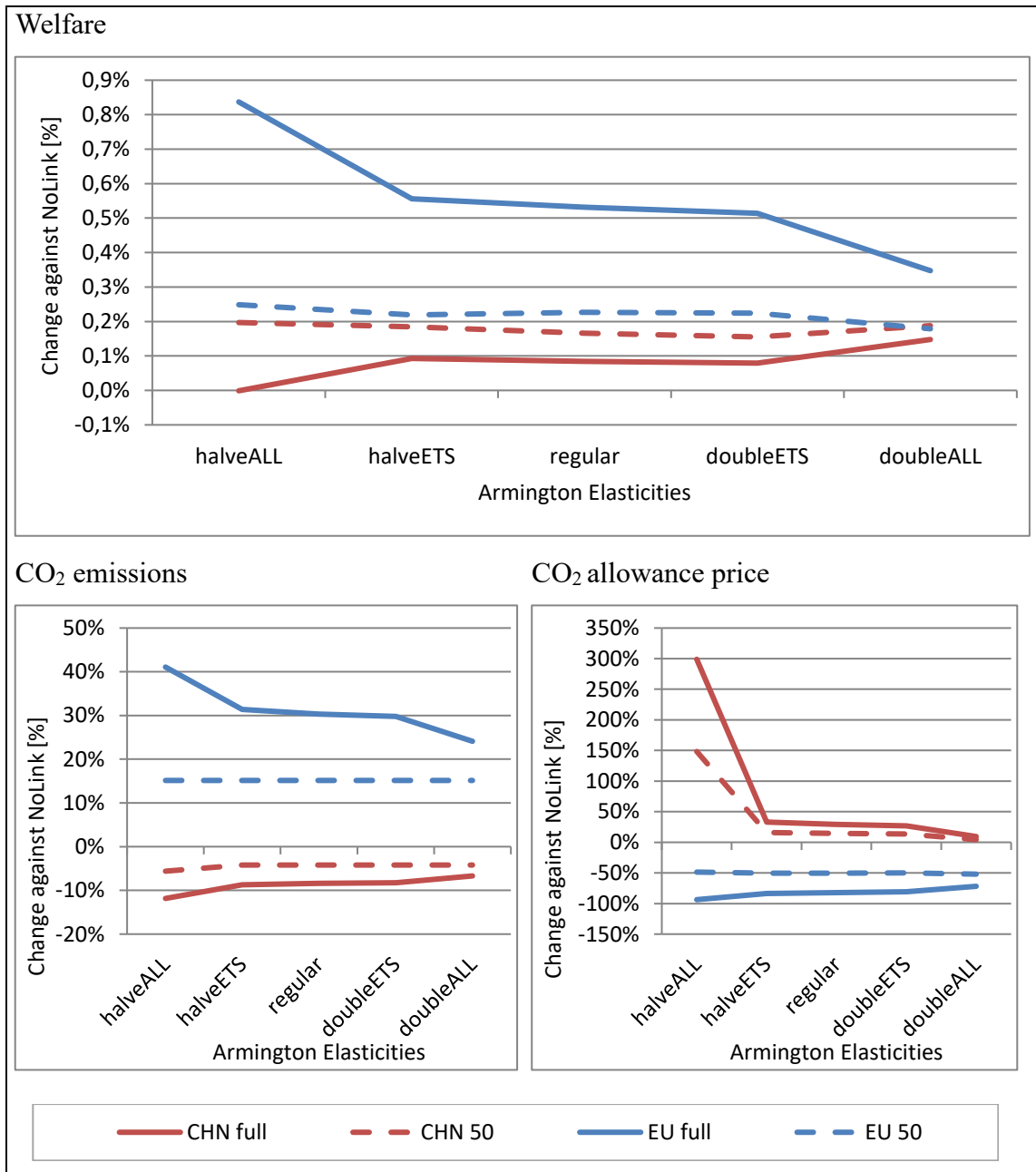


Figure 4-5: Main results of the “Armington elasticities” scenarios in 2030. All changes are relative to the NoLink Scenario with the same Armington assumption; e.g. EU CO₂ emissions in a fully linked ETS (EU full) under “halfAll” Armington assumption are ca. 41% higher than in NoLink under “halfAll” Armington assumption.

As in the “restricted trading” and “adjusted allowance endowments” scenarios, also in all “Armington elasticities” scenarios China benefits significantly more when linking is restricted to 50% compared to full linking, while for the EU full linking is preferable. Both for China and the EU the effects of altered Armington elasticities only in ETS sectors

are negligible (flat slope between `halveETS` and `doubleETS` in Figure 4-5), both in `FullLink` and `HalfLink`, because trade in ETS goods and trade in ETS emission allowances are substitutes, and the trading of allowances offsets effects from altered Armington elasticities. This argument is also supported by the lack of significant changes in emissions and allowance prices for half/doubleETS relative to the regular case. For `HalfLink`, also adjusting all Armington elasticities does not affect these results much. This is different for `FullLink`, where altered elasticities in all sectors (`halve/doubleAll`) have visible effects. Now, trade in goods and trade in allowances are not full substitutes anymore, and the trend observed in the Baseline - higher Armington elasticities increase emissions in China and decrease emissions in the EU - is visible. Most importantly, higher Armington elasticities decrease the EU's gains from linking its ETS to the Chinese ETS, while they increase the gains for China. This makes the gains from trading more equal. On the contrary, lower Armington elasticities imply a more unequal distribution of the gains from trading. Under `HalfLink` this relationship is less pronounced, but one interesting result is that for `HalfLink` and `doubleAll` both China and EU gain welfare by the same percentage.

When ETS are fully linked, all individual EU regions exhibit the same pattern as the EU. Yet, it can happen even in `FullLink` (in our setting in France), that with higher Armington elasticities in all sectors, linking decreases national welfare. In `HalfLink`, there is no Armington scenario where all individual EU regions concurrently gain in welfare relative to `NoLink`.

As for welfare, changes in CO₂ emissions are only significant, when we alter all elasticities (`halve/doubleAll`) and implement fully linked emission trading. In this case, CO₂ emissions in the EU and all of its individual regions decrease with higher Armington elasticities and the resulting increasing imports into the EU. This is because domestic production decreases and the EU imports more embodied carbon. For China, the opposite is true: emissions increase with higher Armington elasticities and resulting in increasing exports plus decreasing imports, depending also on the EU demand for allowances. As Chinese emissions from ETS sectors increase with higher Armington elasticities (the incentive for China to abate gets lower with increasing opportunities for exports), also the allowance price increases with higher Armington elasticities. This also leads to a higher allowance price in the fully linked EU-Chinese ETS. However, the CO₂ price in a joint

EU-China ETS is still much lower than in NoLink or HalfLink scenarios, regardless of the Armington assumptions.

When Armington elasticities are halved in all sectors and allowance trading with the EU is allowed (both half and full trade), the total CO₂ target in China is not binding anymore. ETS emissions are lower than in the scenario without allowance trading because China decreases its emissions to sell allowances to the EU. Also, emissions from non-ETS sectors, which in the scenario without allowance trading equalize these decreases, are low in the scenarios with the lowest Armington elasticities and do not equalize the reduced ETS emissions. Thus, the total combined CO₂ emissions of the EU and China are slightly lower in these scenarios than they are in the other scenarios, and the CO₂ price for non-ETS emissions in China becomes zero.

4.4 Discussion

The the purpose of this paper is to identify the gains associated with linking an EU and a Chinese ETS for the ETS sectors. Thus, although for the EU linking is generally beneficial, there are possibilities to distribute the gains in favor of China and thus avoid increasing welfare inequalities between the two regions. The scenario with halved Armington elasticities in all sectors and fully linked ETS yields no positive welfare impacts for China, which is the least favorable option for China. In the current situation where trade-barriers are clearly on the rise and voices are talking about de-globalization, such a scenario might become more likely.

Table 4-5 summarizes these gains for all sets of scenarios. We are aware that the changes are partly small, as is often the case for comparable scenarios (see also Böhringer et al., forthcoming), yet we see a clear pattern resulting from the policy interventions.

We find that in almost all scenarios, linking the EU and the Chinese ETS proves beneficial to both regions but to different degrees. In most scenarios, the EU gains more than China (0.53% rel. to 0.08% under NDC targets and full trading). Exceptions are seen if (shown in red in Thus, although for the EU linking is generally beneficial, there are possibilities to distribute the gains in favor of China and thus avoid increasing welfare inequalities between the two regions. The scenario with halved Armington elasticities in all sectors

and fully linked ETS yields no positive welfare impacts for China, which is the least favorable option for China. In the current situation where trade-barriers are clearly on the rise and voices are talking about de-globalization, such a scenario might become more likely.

Table 4-5):

- allowance trade between EU and China is restricted to less than 30%;
- the EU transfers 10% or more of their allowances to China and if trading volume is restricted to 50%;
- under NDC targets Armington elasticities are doubled for all sectors, and trading volume is restricted to 50%.

Thus, although for the EU linking is generally beneficial, there are possibilities to distribute the gains in favor of China and thus avoid increasing welfare inequalities between the two regions. The scenario with halved Armington elasticities in all sectors and fully linked ETS yields no positive welfare impacts for China, which is the least favorable option for China. In the current situation where trade-barriers are clearly on the rise and voices are talking about de-globalization, such a scenario might become more likely.

Table 4-5 Gains (in terms of welfare relative to NoLink scenarios) from linking the EU and Chinese ETS for all scenarios

“Restricted trading” scenarios

Scenario \ Region	10	20	30	40	50	60	70	80	90	100
CHN	0.06%	0.11%	0.14%	0.16%	0.17%	0.16%	0.15%	0.14%	0.11%	0.08%
EU	0.03%	0.07%	0.12%	0.17%	0.23%	0.29%	0.35%	0.41%	0.48%	0.53%

“Adjusted allowance endowments” scenarios

Region \ Scenario	Linking	100%	110%	120%	130%	140%	150%
CHN	FullLink	0.08%	0.09%	0.11%	0.12%	0.13%	0.14%
	HalfLink	0.17%	0.19%	0.21%	0.24%	0.27%	0.30%
EU	FullLink	0.53%	0.51%	0.50%	0.48%	0.46%	0.44%
	HalfLink	0.23%	0.14%	0.06%	-0.05%	-0.18%	-0.33%

“Armington elasticities” scenarios

		Scenario				
Region	Linking	halfALL	halfEITE	Regular	doubleEITE	doubleALL
CHN	FullLink	-0.001%	0.09%	0.08%	0.08%	0.15%
	HalfLink	0.20%	0.18%	0.17%	0.16%	0.19%
EU	FullLink	0.84%	0.56%	0.53%	0.51%	0.35%
	HalfLink	0.25%	0.22%	0.23%	0.22%	0.18%

Overall, our results indicate that the EU, should it aspire to link the EU ETS to the Chinese ETS, will have to take measures to make the linking of an EU and Chinese ETS more beneficial for China. This is true especially since the linking of ETS becomes more popular and other regions will compete for the cheap Chinese allowances. As with other studies, we find that a restriction of traded volume can significantly increase benefits for China. In our “restricted trading” scenarios we found China’s gains in welfare highest when allowance trading is restricted to 50% of the volume traded in the FullLink scenario. Even though the restricted trading scenario reduces the benefits for the EU compared to unrestricted linking, these are still significant and in relative terms about twice as high as those of China. Also, any allowance trading with China, be it restricted or not, is beneficial for the EU in terms of welfare.

Transfer payments from the EU to China are modelled through changing the allowance allocation to the EU and Chinese ETS sectors, keeping total emissions of both regions constant over all “adjusted endowments” scenarios. Thus, EU emission targets for the ETS sectors become stricter and Chinese emission targets for the ETS sectors become weaker by the same amount of emissions. Transfers through adjusted allowance endowments are most valuable to China under restricted trading, while the effects for China are minimal for full trading and thus, not a solution for more equalized welfare gains. For the EU, transfers through adjusted allowance endowments also imply little losses for full trading but come at a significant cost in case of restricted trading. In our scenarios, if more than 20% of allowances are transferred to China and trading is restricted to 50%, potential benefits from trading are eliminated. It should also be noted that – as mentioned in section 3 – adjusted allowance endowments are no longer a good representation of more general transfer payments under restricted trading, since the resulting emission reduction efforts change. Still, our findings indicate that under restricted trading, transfer payments have little benefit for the EU. Thus, if at all, one

should consider trade restrictions and adjusted allowance allocation as complements.

If we consider restricted trading on the one hand, and transfers through adjusted allowance endowments on the other hand as two uncombined alternatives, then China benefits more from the former compared to the latter. This holds even in the scenario where the EU transfers 50% of their allowances to China, which is a very extreme and politically unlikely scenario. Yet, even these high transfers through adjusted endowments would still be much more beneficial to the EU than restricting trading. The welfare gain is almost 50% higher when 50% of EU allowances are transferred to China than it is under HalfLink without such transfers. Hence, the potential trading partners prefer different linking scenarios: While the EU benefits more from full trading and would possibly pursue transfer payments as a measure to make linking more attractive to China, China will aim for a restriction of the trading volume. Analyzing possible outcomes of such hypothetical negotiations from a political economy perspective could provide fruitful avenues for future studies.

Since trade in goods and trade in allowances are to some degree substitutes in the ETS sectors, gains from trading for both partners are higher for lower trade elasticities in ETS sectors. In times of increasing international trade restrictions, this is an important finding. Since China is more vulnerable to trade restrictions than the EU, linking could become more attractive under less open trading (i.e. lower Armington elasticities): welfare losses could be equalized to some degree by trading emission allowances when trading of goods is restricted. This is especially true for ETS sectors, since through emission trading losses arising from the trade restrictions in ETS sectors can be equalized. However, we find that the implications of altering Armington assumptions are much larger than the welfare gains which can be achieved by linking ETS. This stresses the potentially large negative effects of protectionism and trade conflicts.

Having a scenario with a negative welfare effect resulting from linking ETS (even though the loss is negligible) confirms the possibly ambiguous effects found in Flachsland et al. (2009). Unlike Fujimori et al. (2016), who found linking to cause negative welfare effects for China, and excepting the scenario mentioned above, linking is beneficial in all scenarios considered in our study. However, Fujimori et al. (2016) analyzed a globally linked ETS, not just a link between China and the EU. Hübner et al. (2014) do evaluate a

link between China and the EU for a case of restricted linking³⁹. Similar to our study, they also find positive welfare effects for China in all but one scenario, albeit rather small ones (about 0.1 percentage point lower welfare loss with linking, relative to a BAU without climate policy). Also in Liu and Wei (2016) linking ETS between the EU and China is for both regions always preferable to a comparable situation with separate ETS. They highlight the fact that the EU always favors a different scenario than China, which also holds true for most of our scenarios, where the EU always favors full linking over restricted linking, whereas the opposite is true for China. Thus, should a link between the EU and Chinese ETS be aspired, the actual design would have to be negotiated carefully. While our results differ from those in Gavard et al. (2016) in that unrestricted allowance trading is not beneficial in their study, the inverted U-shape we find for China's welfare under different degrees of linking (see Figure 4-2) is well in line with their finding of a non-linear relationship between the degree of linking and welfare effect. In Li et al. (2019), the authors find that in terms of welfare, unrestricted allowance trading is preferable over restricted allowance trading not only for the EU but also for China. Still, the authors conclude that restricted allowance trading should be sought after in the mid-term, as such restriction can reduce the negative side effects of full linking, which are not depicted in welfare: the decelerated development of EU's renewable energy production (stemming from the opportunity to buy allowances from China rather than mitigating domestic emissions) and the reduced international competitiveness of China's energy intensive sectors (stemming from higher carbon prices in a fully linked ETS). Such argument in favor of restricted allowance trading gains additional weight against the background of the findings from our study, in which China benefits more under half linking compared to full linking.

We are not aware of any other study analyzing the effects of linking the EU and the Chinese ETS for a disaggregated EU. Therefore, our results provide new insights into whether linking benefiting the EU as a whole will also benefit its member states. The results reveal that unanimous gain in all the EU sub-regions is not systematic and depends on factors such as the degree of linking, choice of mechanism, and the emission target to

³⁹ Trading is restricted to one-third of the EU's reduction (against 2005 emissions) in each year in Hübler et al. 2014.

be met. Overall, all the EU regions experience welfare gains only in the “restricted trading” scenarios, when trading of more than 60% of allowances occurs. Thus, for strengthening the case in support for linking and consequently increasing the likelihood of political acceptance for linking the EU ETS to the Chinese ETS, the creation of transfer mechanisms within the EU is essential.

In this study, we focus on the gains associated with linking under NDCs and model these as absolute reduction targets both for the EU and China, in line with the overall EMF36 round (Böhringer et al., forthcoming). However, China’s ETS integrates an intensity target (see International Energy Agency (IEA)). This implies the possibility for different absolute CO₂ emissions (see e.g. Liu and Wei 2016) and, thus, different results also for carbon prices and, thus, incentives to link. Hübler et al. (2014) implement scenarios with different assumptions regarding China’s economic growth. This is relevant not only with regard to the intensity target, but also concerning the current situation, in which the world faces unforeseeable consequences of the COVID-19 crisis, international trade dispute, and possible de-globalization. However, the overall trends and findings we derive here are not likely to be qualitatively affected by our absolute reduction approach. Another dimension not covered in our study is the interaction of ETS with other climate or energy policies. Liu and Wei (2016) model a combination of linking EU and Chinese ETS plus introducing renewable subsidies and find important interactions between the two policies. Furthermore, we do not include transaction costs or political barriers that might hinder the linking of ETS. While this aspect is beyond the scope of our CGE study, one should keep in mind that these barriers can seriously hamper or even prevent the linking of ETS, be it economically feasible or not (see e.g. Hawkins and Jegou 2014, Flachsland et al. 2009). All these aspects could be subject to future studies on the feasibility and effects of linking the EU and China’s ETS.

4.5 Conclusions

In this study we analyze the assumptions under which linking between an EU ETS and a Chinese ETS in the energy intensive sectors and the power sector is beneficial for each of the trading partners. Furthermore, we disaggregate the EU and analyze our modelling results also at the sub-EU level. We find that restricted allowance trading is more

beneficial to China than full allowance trading, and China's welfare is maximized when the traded volume of allowances is restricted to 50% of the volume traded in a fully linked system. For the EU, full allowance trading is always more beneficial than restricted allowance trading. Another option to make the linking of ETS more attractive to China would be to transfer payments from the EU to China. The EU could favor this option in combination with a full link over a situation with restricted allowance trading but no transfer payments. For China, the opposite is true: restricted trading is favored over transfer payments.

While changes in international trade (modelled in our "Armington elasticities" scenarios) affect China more strongly than the EU, linking of ETS would become more attractive for China with less open trade, especially if trade barriers aim at ETS sectors: Here, trading of emission allowances could offset the loss originating from decreasing trade of goods. Generally, all trading partners benefit from more trade-openness and linking ETS further increases these benefits.

In addition to the different options favored by the EU on the one hand and China on the other hand, there are also competing interests among the single EU regions in several scenarios. Namely, regions which are net allowance sellers in a separate EU ETS (not linked to the Chinese ETS) face potential losses when the cheaper Chinese allowances enter the European allowances market. Consequently, even though the linking of EU and Chinese ETS is beneficial to both the EU and China in all our scenarios except one, designing options which can be agreed upon by all trading partners will be difficult, both inside the EU and between the EU and China. This holds especially true when political feasibility is also considered. The possible outcomes of hypothetical negotiations on designing a joint EU–Chinese ETS from a political economy standpoint should be evaluated in future studies.

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Appendix A: A non-technical description of the DART Kiel model

The DART Kiel model is a multi-region, multi-sector, recursive dynamic CGE model. The version used in this study is based on the GTAP 9 data base for 2011 (Aguiar et al. 2016) and the related GTAP-9 Power data base (Peters 2016) and contains the following sectors and regions (Table A 4-1, Table A 4-2).

Table A 4-1 DART Kiel regions

Europe

GBR	United Kingdom, Ireland
SCA	Denmark, Finland, Sweden, Norway
DEU	Germany
FRA	France
BLX	Benelux
SEU	Southern Europe: Austria, Italy, Spain, Portugal, Malta, Greece, Cyprus
EEU	Czech Republic, Slovakia, Slovenia, Hungary, Estonia, Latvia, Lithuania, Bulgaria, Romania, Croatia, Poland
REU	Rest EU incl. Iceland, Liechtenstein, Switzerland, Albania, Belarus, Ukraine

Americas

CAN	Canada
USA	USA
BRA	Brazil
OAM	Other Americas

Russia & Asia & Pacific

RUS	Russia
IND	India
ANZ	Australia, New Zealand
JPN	Japan

CPA	China, Kong-Kong
KOR	Korea
OAS	Other Asia
<u>Africa & middle East</u>	
MEA	Middle East
AFR	Africa

Table A 4-2 DART Kiel sectors

<u>Energy & Electricity</u>		<u>Other</u>	
Col	Coal	EIT	Energy Intensive Sectors
Cru	Crude oil	TRN	Transport Aggregate
Gas	Natural gas	AGR	Agriculture & Food
Oil	Refined oil products	MFR	Other manufactured goods
ENuclear,	Electricity from Nuclear	SER	Services
ECoal	Electricity from Coal	CGD	Savings good / Aggregate Investment
EGas	Electricity from Gas		
EWind	Electricity from Wind		
EHydro	Electricity from Hydro		
EOil	Electricity from Oil		
ESolar	Electricity from Solar,		
EOther	Electricity from Other		

The economic structure for each region covers production, consumption, investment and governmental activity. Markets are perfectly competitive. Prices are fully flexible. For each region, the model incorporates three types of agents: the producers, distinguished by production sectors, the representative private household and the government.

Producer Behavior

All industry sectors are assumed to operate at constant returns to scale. Output of each production sector is produced by the combination of energy, non-energy intermediate inputs, and the primary factors labor and capital (land in the agricultural sector). Figure A 4-1 and Figure A 4-2 show the nested production structure for non-energy goods and fossil energy.

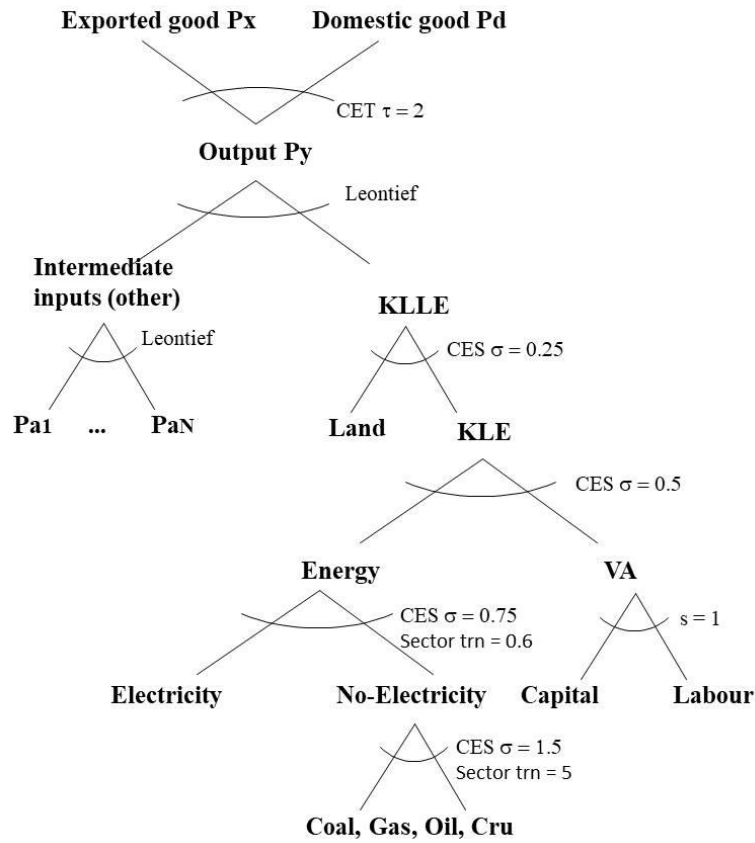


Figure A 4-1: Nesting of non-energy production

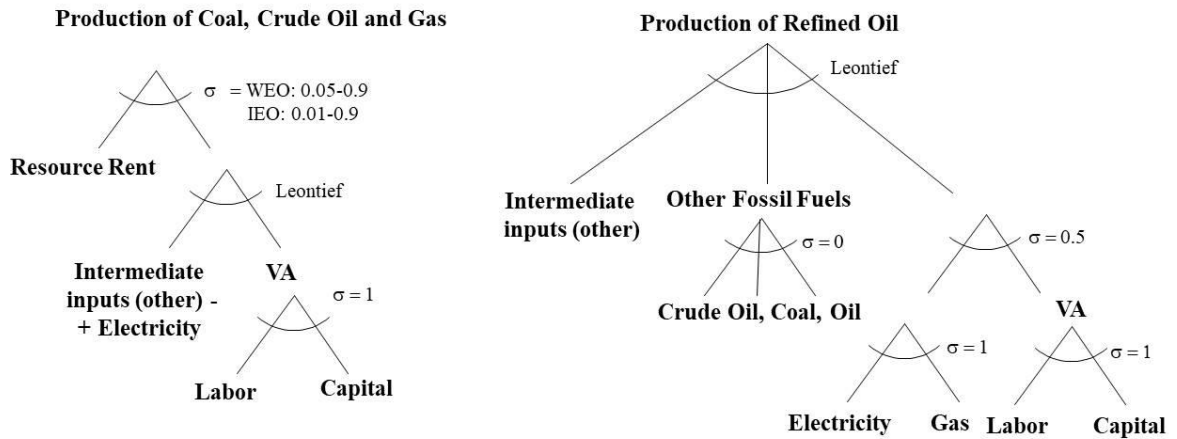


Figure A 4-2: Nesting of fossil fuel production

Electricity production is differentiated between coal, gas, oil, hydro, nuclear, wind and solar based electricity plus other electricity. The elasticity of substitution between the different types of electricity is 12. Note that we do not use the baseload-peak load

disaggregation proposed in Peters (2016), but aggregate e.g. GasBL and GasP to EGas. The nesting structure is depicted in Figure A 4-3.

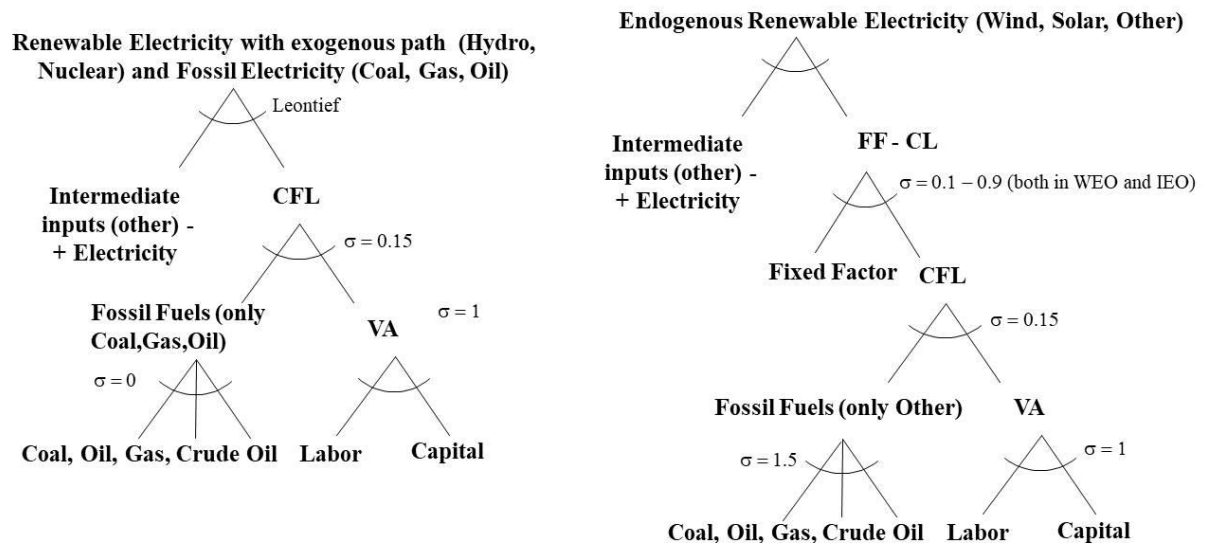


Figure A 4-3: Nesting of electricity production

Composite investment is a Leontief aggregation of Armington inputs by each industry sector. Investment does not require direct primary factor inputs. Producer goods are directly demanded by regional households, governments, the investment sector, other industries, and the export sector.

Consumption and Government Expenditure

The representative household receives all income generated by providing primary factors to the production process. Disposable income is used for maximizing utility by purchasing goods after taxes and savings are deducted. Private consumption is calibrated to a LES, which divides demand into subsistence and supernumerary consumption based on a Stone-Geary utility function. Households first spend a fixed part of their income on a subsistence quantity for each commodity and allocate their supernumerary income to different commodities according to fixed marginal budget shares which are the product of average budget shares and income elasticities of demand. This division of total consumption into fixed subsistence and flexible supernumerary quantities allows for a calibration to non-unitary income elasticities and non-homothetic preferences. To avoid that, the LES will eventually converge to a Cobb-Douglas system and approach homothetic preferences when income grows, the subsistence quantities are updated with

population growth in each period following Schünemann and Delzeit 2019⁴⁰, which also includes further information on the LES calibration.

The third agent, the government, provides a public good which is produced with commodities purchased at market prices. Public goods are produced with the same two-level nesting structure as the household “production” function (see also Figure A 4-4). The public good is financed by tax revenues.

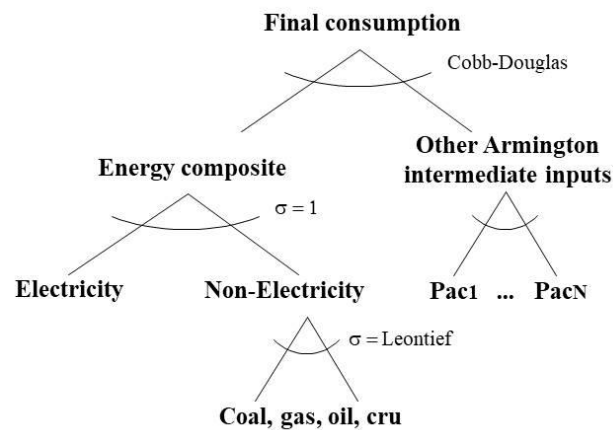


Figure A 4-4: Nesting structure of final consumption

Foreign trade

The world is divided into economic regions, which are linked by bilateral trade flows. All goods are traded among regions, except for the investment good. Following the proposition of Armington (1969), domestic and foreign goods are imperfect substitutes, and distinguished by country of origin. Transport costs, distinguished by commodity and bilateral flow, apply to international trade but not to domestic sales.

On the export side, the Armington assumption applies to final output of the industry sectors destined for domestic and international markets. Here, produced commodities for the domestic and for the international market are not perfect substitutes. Exports are not differentiated by country of destination.

Factor markets

⁴⁰ Schünemann, F., Delzeit, R. (2019). Higher Income and Higher Prices: The Role of Demand Specifications and Elasticities of Livestock Products for Global Land Use. *Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaues e.V.*, Bd. 64, 185-207.

Factor markets are perfectly competitive and full employment of all factors is assumed. Labor is assumed to be a homogenous goods, mobile across industries within regions but internationally immobile. The capital stock is given at the beginning of each time period and results from the capital accumulation equation. Capital is also region specific and a putty-lay vintage capital approach is chosen, so that only new investment is mobile across sectors. In every time period the regional capital stock earns a correspondent amount of income measured as physical units in terms of capital services. The primary factor land is only used in agricultural sectors and exogenously given.

Coverage of GHG emissions

DART covers CO₂-emissions from the burning of fossil fuels taken from the GTAP 9 data base.

Dynamics and Calibration

The DART Kiel model is recursive-dynamic, meaning that it solves for a sequence of static one-period equilibria for future time periods connected through capital accumulation. The major driving exogenous factors of the model dynamics are change in the labor force, the savings rate, the depreciation rate and the gross rate of return on capital, and thus the endogenous rate of capital accumulation. Finally, the rate of total factor productivity (TFP) growth is used to calibrate DART Kiel to a given GDP-path. For the EMF-36 GDP baseline it was in addition necessary to reduce the growth of the labor force for a few regions since already a TFP of zero led to too high growth rates. If this was still not enough also depreciation was increased.

Finally, it turned out that the given Chinese GDP value for 2030 could not be reached with higher TFP in China alone but required import let growth in DART. For this reason, the usual Armington elasticities were increased by 1.5 worldwide. Table A 4-3 below shows the base data and these adjustments.

The savings behavior of regional households is characterized by a constant savings rate over time. This rate is allowed to adjust to income changes in regions with extraordinary high benchmark savings rates, namely China, India, AFR, OAS and KOR. Labor supply considers population growth and the development of the share of the working force in the population.

The supply of the sector-specific factor land is held fixed to its benchmark level over time. Current period's investment augments the capital stock in the next period. The allocation of new capital among sectors follows from the intra-period optimization of the firms.

Furthermore, the baseline path of renewable electricity plus nuclear is calibrated to match the projections of the IEA. The development of electricity from hydro and nuclear is fixed at an exogenous growth path through an endogenous subsidy. For solar- and wind-power as well as other-electricity, we adjust the growth of the fixed factor and the elasticity of substitution between the fixed factor and the other inputs to calibrate to the given path that then also reacts to policy shocks.

Emissions are traditionally calibrated only on global level for CO₂-emissions from gas, coal and oil by adjusting the supply elasticity of these fossil fuels. To achieve a given regional emission level at 2030 for the EMf-36 scenarios we used regional supply elasticities of fossil fuels and in addition adjusted the autonomous energy efficiency improvement (AEEI) which is typically 1% p.a. to achieve the required emission intensity of GDP. In India even very high rates were not sufficient to bring down emission intensity sufficiently so we increased the KLE elasticity as well. Finally, the WEO baseline used in this study is based on carbon prices for the EITE sector and the power sector in Europe (27\$/tCO₂) China (20\$/tCO₂), Canada (36.5\$/tCO₂) and Korea (28\$/tCO₂)⁴¹. We also implemented carbon prices for WEO in EITE sectors starting in 2015 and linearly rising to the given level in 2030. To match the given CO₂ level in 2030 and for the EU the communicated targets for the EU emissions trading scheme, the prices were slightly adjusted to 21\$/tCO₂ in Europe, 18 \$/tCO₂ in Canada, 15 \$/tCO₂ in China and 14 \$/tCO₂ in Korea.

Relevant elasticities and parameter are summarized in Table A 4-3 and Table A 4-4. We use the same method as Böhringer et al. (forthcoming) to calibrate the emissions from ETS and non-ETS sectors in the EU for our Baseline. As a result, in our Baseline the total CO₂ emissions in EU ETS sectors increase by 20.6%, while in the non-ETS sectors they

⁴¹ The values in brackets are extrapolated from the 2025 and 2040 values given by WEO.

reduce by 0.6%, which results in an overall increase of 4.4% in emissions, all relative to Baseline.

Table A 4-3 Core elasticities and adjustments for EMF calibration

Elasticity	Explanation	Value	Adjustment for EMF WEO Baseline
ESUB_ES(*,r)	Elasticity fixed resource in coal, gas, cru production	Default: Coal 0.3, GAS 0.2, CRU 0.2	0-0.8 to calibrate regional emission path
ESUB_ELE(I)	ele vs Non-electricity energy	0.75	
	For Transport	6	
ESUB_NE(I)	Non-electricity energy	1.5	
	For Transport	5	
ESUB_LD(r)	land vs KLE	0.25	
esub_kle(r,i)	Energy vs Capital /Labor	0.5	IND: 0.75; BRA: 0.85
S	Elas. KLE vs material	0	
esub_ele	Diff. ele types	12	
Va	Elas capital / labor	1	
Esub_res(*,r)	Elasticity of fixed resource EWind, ESolar, EOther	Default: 0.1	0-0.8 to calibrate path
preleexp(*,r)	exponent for increase of fixed factor EWind, ESolar, EOther		0-0.9 to calibrate path
ARMEL(i,r)	Imports from diff. regions		Min(12,1.5*armel(i,r));
	All electricity types	2.8	4.2
	COL	3.05	4.6
	CRU, GAS	12.849	12.0
	OIL	2.1	3.2
	EIT	3.239	4.9
	TRN	1.9	2.9
	AGR	2.761	4.1
	MFR	3.529	5.3
	SER	1.917	2.9
ARM_REG(I)	imports vs domestic	Min(14, 2*ARMEL)	=Min(14,1.5*arm_reg(i);

Table A 4-4 Further core parameters and adjustments for EMF calibration

Elasticity	Explanation	Value	Adjustment for EMF WEO Baseline
AEEI	Autonomous Energy Efficiency Improvement p.a.	1% p.a. in all regions	AFR 1%; BLX 2.5%; BRA 0%; CAN 0.5%; CHN 2.4%; EEU 1.3%; FRA 2.5%; GBR 1.5%; GER 0.7%; IND 2.8%; MEA 2.4%;

4. Gains associated with linking the EU and Chinese ETS

			OAM 1.5%; REU 2%; RUS 0.3%; SCA 2.3%; SEU 0.4%; USA 2.1%; OAS 1.8%; JPN 1.7%; KOR 0.6%; ANZ 0.8%
Dep	Depreciation	0.04	OAM: 0.045; MEA: 0.045
ffshare(i,r)	Fixed factor shares in ESolar and EWind	0.1	
sub	Elasticity energy composite and other inputs for final demand	1	
wrkad	Adjustment factor in growth of labor force	1	MEA: 0.8; OAM: 0.8; CHN: 0

Chapter 5

Interaction between the European Emission Trading System and renewable electricity*

Mareike Söder, Sneha Thube, Malte Winkler

Abstract

Changes in the allowance price in the EU emissions trading system (EU-ETS) may cause several side effects: shifts in energy portfolios and inter-sectoral carbon leakage, shifts in inner-European burden sharing of greenhouse gas (GHG) abatement and international carbon leakage. We use the global computable general equilibrium model DART to quantitatively analyse the effects of increased allowance price, technological growth in renewables, flexibility in electricity consumption and technology substitution. Our results show that the allowance price and the share of renewables are the decisive factors for the EU-regions share in GHG abatement. High allowance prices reduce the production of coal based-electricity, thus increasing the share of GHG abatement in EU regions with a large share of coal in their electricity portfolio. Inter-sectoral carbon leakage is highest when households can easily substitute electricity with fossil fuels. It is lowest when sectors outside the EU-ETS are targeted with climate mitigation policies but at the cost of higher EU-ETS prices and international leakage. We identify the decreasing prices for coal as the main channel for international carbon leakage, which increases coal-based electricity production outside the EU. Even though the EU-ETS does not directly target renewables,

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technological improvements in this sector can substantially decrease the allowance price and therefore help mitigate inter-sectoral and international leakage effects of the EU-ETS.

Key Words: EU-ETS, allowance price, carbon leakage, renewable energies, CGE, energy policy

5.1 Introduction

Electricity production plays a central role in the EU's climate policy and in 2016, it accounted for one-third of the European Union's (EU) CO₂ emissions (IEA 2018). The EU follows a two-fold approach to decrease these sectoral emissions: first, by fostering the uptake of renewable energy technologies and second, by pricing CO₂ emissions from fossil-based electricity production via the European Emission Trading System (EU-ETS). In this paper, we examine the interconnection of the two approaches and explore how supporting growth of renewables could interact with the EU-ETS.

Numerous instruments both in the EU and its member states target several aspects related to the strengthening of renewable energies in the electricity portfolio. For example, the EU's Innovation and Modernization Funds⁴², which are financed by revenues from auctioning off the EU-ETS allowances, aim to develop low greenhouse gas (GHG) technologies and improve energy efficiency. While this is a promising approach, there are growing concerns that technological barriers could hinder the integration of renewables on a larger scale due to the incapability of electricity grids in handling the volatile production typical for wind and solar technologies.

The EU Emissions Trading System (EU-ETS) is the central instrument of the EU (Böhringer and Lange 2012; ICAP 2016) to reduce CO₂ emissions from fossil electricity production. The current EU-ETS regulates the GHG emissions of large energy producing

⁴² For further details about EU's Innovation and Modernization Funds, please refer to https://ec.europa.eu/clima/policies/innovation-fund_en and https://ec.europa.eu/clima/policies/budget/modernisation-fund_en, respectively.

facilities (greater than 20 MW), energy-intensive industries (with sector-specific size limits), and inner-European air traffic. In total, roughly one half (~40%) of the total European GHG emissions are covered by the EU-ETS (ICAP 2016; EC 2015)⁴³.

Even though not targeted by the same policy instruments, renewables and fossil-based electricity are closely related, as they produce almost homogenous goods (depending on the flexibility of the electricity net). By increasing the production cost of fossil fuels via the EU-ETS and increasing the learning curve and subsidies of renewables, both policies increase the competitiveness of renewables compared to fossil electricity. Consequently, the share of renewables in electricity generation increased from 14% (431 TWh) in 2000 to 30% (977 TWh) in 2016. At the same time the share of CO₂ emissions from the power sector decreased from 37% (1378 MtCO₂) in 2000 to 34% (1077 MtCO₂) in 2016 (IEA 2018).

However, the two-fold approach comes with some potential pitfalls if the overlapping policies are not well designed. Böhringer and Rosendahl (2010) show that the introduction of quotas for green technologies in the presence of tradeable quotas for fossil technologies could counter-intuitively lead to increased production of the most carbon-intensive fossil technology. Abrell and Weigt (2008) examine the interaction of the EU-ETS and renewable supporting policies in Germany and show that renewable support policies lead to lower carbon prices and that the implementation of a renewable quota in addition to an ETS leads to welfare losses. Liu and Wei (2016) find that lower allowance prices hinder growth in renewable energy production in the EU. Del Rio González (2007) highlight the possibility to foster synergies between ETS and support schemes for renewables by coordinating both instruments' targets.

For the evaluation of the economic and environmental effects of EU climate policies, one needs to examine the emission balance beyond electricity production, since carbon leakage might occur when some goods are burdened with a price on emissions (like sectors, facilities or regions inside an ETS), and others are not (like sectors, facilities or

⁴³ In addition to CO₂ emissions from fossil fuels, the EU-ETS also targets emissions of nitrous oxide (N₂O) from production of nitric, adipic and glyoxylic acids and glyoxal and perfluorocarbons (PFCs) from aluminium production.

regions outside an ETS). The literature highlights two main channels of carbon leakage (Tan et al. 2018): direct competitiveness effects caused by a change in relative prices of goods and indirect competitiveness effects caused by a change in international fossil fuel prices. Both effects can have both an international and a domestic dimension.

Direct competitiveness effects occur when only some goods targeted with a GHG price, making them relatively more expensive. This price change impacts consumption decisions and leads to substitution towards other goods with no-GHG price or the same good produced in a region with no GHG price. This change in consumption decisions could lead to (over-)compensation of GHG abatements in targeted regions or sectors (see e. g. Babiker 2005). To our best knowledge, this is the first study that uses an ex-ante modelling approach to quantify carbon leakage caused by changes in consumption decisions within the EU.

In the international dimension, carbon leakage typically refers to the displacement of sectoral production of a good from a region with a GHG price to a region without a GHG price. This effect has widely been discussed in the literature (e. g. Carbone and Rivers 2017; Branger and Quirion 2014; Martin et al. 2016; Verde 2018; Bernard and Vielle 2009) with regard to competitive disadvantages of firms or sectors facing a price on emissions relative to counterpart firms or sectors in regions without a price on emissions. However, the conclusions from studies depend on modelling assumptions (Carbone and Rivers 2017).

Evidence of carbon leakage in the range of 5-20% is seen in ex-ante studies but not in empirical ex-post econometric studies (Branger and Quirion 2014). Ex-ante studies specific to the EU-ETS only find low leakage rates (Bernard and Vielle 2009; Barker et al. 2007). Other studies also show that no traceable international carbon leakage has been observed (reviews by Verde, 2018 and Martin et al., 2016). This result is mainly attributed to the low EU-ETS allowance price in the period when studies were conducted, along with the practice of the free distribution of allowances to avoid competitive disadvantages to European industries (Demailly and Quirion 2006; Naegele and Zaklan 2019; Joltreau and Sommerfeld 2018). Other studies (Barker et al. 2007; Gerlagh and Kuik 2014) show that if technology spillovers are considered, the EU could also experience negative carbon leakage.

The second channel of carbon leakage causes indirect competitiveness effects through changes in international prices of fossil fuels. Emission pricing and falling production cost of renewables leads to a decrease in fossil-based electricity production. This lowers the demand for fossil fuels and, thus, a drop in the international price of fossil fuels. Such a price drop could increase the demand for fossil fuels in sectors or regions that are outside the carbon pricing regime (Böhringer et al. 2010) and causing carbon leakage.

This paper addresses the interplay between EU-ETS allowance prices and supporting policies for renewable energies. It analyses the effects on different channels and dimensions of carbon leakage in order to evaluate the effectiveness of the two main pillars of EU climate policies. We use a global, static general equilibrium model with a detailed representation of electricity producing technologies for our analysis. We develop three policy scenarios that characterize increased learning of renewables, limited net integration of renewables, and easier technology adaption for private consumers in our analysis. We analyse both inter-sectoral and international carbon leakage effects.

The rest of the paper is structured as follows: Section 2 contains a description of the model version used in this study and the implemented scenarios. Modelling results are described in section 3. Finally, section 4 provides a discussion and concludes.

5.2 Model description and scenario runs

DART is a global multi-sectoral, multi-regional recursive-dynamic CGE model. In this study, we use a static version of DART. Developed at the Kiel Institute for the World Economy, it has been widely applied to analyse international climate policies, (e.g. Klepper and Peterson 2006a, Springer 2002, Springer 1998), environmental policies (Klepper and Peterson 2006b), energy policies (e.g. Weitzel et al. 2012), and agricultural and biofuel policies (e.g., Calzadilla et al. 2016; Delzeit et al. 2018).

In DART, the global economy is represented by 20 regions and 19 sectors (see Table 5-1). Regional markets are assumed to be competitive. Prices are flexible and all markets clear in equilibrium. Production from each sector is defined using a nested Constant Elasticity of Substitution (CES) function. The nesting structures are available upon request. The economic structures in DART are fully specified for each region and covers production,

investment and final consumption by private consumers and the government (Calzadilla et al. 2016). Consumer demand is modelled with non-unitary income elasticities using the linear expenditure system (LES) approach (Stone 1954).

Table 5-1 Regions and sectors in DART. * indicates the EU-ETS regions and sectors

Region	Description	Region	Description
FRA *	France	USA	USA
GER *	Germany	CAN	Canada
ITA *	Italy	PAS	Pacific Asia
GBR *	United Kingdom, Ireland	RUS	Russia
BLX *	Belgium, Netherlands, Luxembourg	FSU	Former Soviet Union (excluding Russia)
SPO *	Spain, Portugal	CPA	China, Hong Kong
SCA *	Denmark, Finland, Sweden, Norway	IND	India
EHC*	Europe high carbon ⁴⁴	LAM	Latin America
ELC*	Europe low carbon ⁴⁵	RAXB	Japan, Australia, New Zealand and Switzerland
AFR	Sub-Saharan Africa	MEA	Middle East, Northern Africa, Turkey
Energy sectors	Description	Non-energy sectors	Description
ECoal*	Coal based electricity	ESolar	Solar based electricity
EGas*	Gas based electricity	EWind	Wind based electricity
EOil*	Oil based electricity	ENuclear	Nuclear based electricity
PPP*	Pulp, paper and print	AGR	Agriculture (no livestock) & forestry
CRP*	Chemical Rubber Products	CTL	Livestock
M_M*	Production of metals and minerals	OTP	Commercial road and rail transport ⁴⁶
EOther*	Electricity from biomass, waste, geothermal, tides	FFP	Fossil fuel production (coal, natural gas, crude oil)
OIL*	Oil Refining to produce oil products	WATP	Commercial water and air transport
EHydro	Hydro based electricity	O_I	Other industry

⁴⁴ Includes countries with more than 20% of coal in the energy sector based on Eurostat (Poland, Czech Republic, Bulgaria, Greece, Slovenia)

⁴⁵ Includes countries with less than 20% of coal in the energy sector based on Eurostat (Romania, Hungary, Slovakia, Baltic States, Cyprus, Malta, Croatia Austria, Liechtenstein, Iceland)

⁴⁶ Note that private road transport is not part of sector OTP, but is included into the model via direct household consumption of fossil fuels. The same accounts to private heating.

DART is based on the GTAP9 Power database (Aguar et al. 2016; Peters 2016), representing the global economy in 2011. Electricity⁴⁷ is produced from renewable (wind, solar, others (incl. biofuels, waste, geothermal, and tidal technologies)), conventional (coal, gas, oil), and nuclear technologies and finally aggregated as a homogenous commodity. We aggregate the baseload and peak load sectors from the original GTAP9 Power database into a single sector. Solar and wind technologies are modelled with a learning curve model using the fixed resource approach (Paltsev et al., 2005) to have a stable production pathway. The fixed resource is a share of the sectoral capital and is set to 10%. We assume that electricity produced from nuclear and hydro technologies are policy-driven rather than market-driven and are therefore stable over time.

A technical description of the implementation of fixed factor in DART is provided in Weitzel (2010). Our model has a detailed accounting of both CO₂ and non-CO₂ emissions based on the GTAP database. The CO₂ emissions account for the emissions produced from fossil fuel combustion and the non-CO₂ emissions cover emissions from methane, nitrous oxide and fluorinated gases.

The EU-ETS is implemented into DART on the regions and sectors highlighted in grey in Table 5-1. The allowance price is modelled by imposing a price on CO₂ emissions from fossil fuel combustion in the EU-ETS sectors. The allowance price is determined by restricting the amount of emissions allowed in the participating regions and sectors and this “endowment” of emissions can be interpreted as the EU wide emission cap.

5.3 Implementation and definition of scenarios

We model one baseline and five policy scenarios as shown in Table 5-2. In order to account for the large increase of the share of renewables between 2011 and 2015 in the European countries, the Baseline is calibrated to meet the European energy portfolios of 2015 based on the shares provided in IEA (2018). The calibrated progress rates for wind

⁴⁷ We use the term “electricity” while we are aware that the sectors of the GTAP-Power sector include also part of sectoral heat production.

and solar are 0.42 and 0.41, respectively. Nuclear and hydro electricity technologies are calibrated to their levels in 2015 and remain fixed throughout all policy scenarios. The EU-ETS cap is chosen in order to meet the average 2015 price of 6 €/tCO₂, and no GHG reduction targets are assumed for the sectors outside the EU-ETS.

Table 5-2 Description of scenarios

Scenario	Description	Policy significance
<i>Baseline</i>	Baseline scenario	
<i>ET100</i>	EU-ETS price is calibrated to 100€/tCO ₂ via a reduction of allowances	Reduction of the EU-ETS Cap
<i>DoubleLearn</i>	Doubled learning rates for wind and solar technologies	Technological advancement in solar and wind electricity
<i>FlexCons</i>	Increased flexibility of substitution between electricity sectors and all non-electric fossil fuel sectors for private and public consumers by increasing elasticity of substitution in the demand function from Cobb-Douglas to 2.	Consumer preferences flexibly adapt to changing energy prices. E.g. substituting fossil based private transport by an electric capturing the shift to electric mobility
<i>SecRed</i>	Sectoral emission reduction targets for EU non-ETS sectors based on the reported reductions in 2011-2015 (UNFCCC 2017)	Effort Sharing Agreement implemented
<i>Eesub7</i>	Elasticity of substitution between different electricity technologies is halved	Hindrance in grid-integration of renewable electricity

Among the policy scenarios, ET100 represents a policy that enforces a stricter GHG emissions reduction target (cap) within the EU-ETS. In the rest of the policy scenarios we keep the same GHG emissions reduction cap for the EU-ETS. Unless stated otherwise (see Table 5-2), the other four policy scenarios carry the same parameter values as in ET100. DoubleLearn represents a policy with steeper learning curves of wind and solar, FlexCons represents more flexible adaptation between types of fossil fuel consumed by private consumers in final demand and SecRed simulates GHG mitigation policies for non-EU-ETS sectors by imposing a cap on these sectors' GHG emissions. To test the sensitivity of our results, we simulate scenario Eesub7 with reduced flexibility in integration of renewables into the electricity grid. In our scenarios we assume that only the EU implements additional climate policies while the rest of the world remains on a

business-as-usual pathway with no further climate policies.

5.4 Results

5.4.1 Effects on allowance price and GHG emissions in the EU

The introduction of a strict cap in scenario ET100 substantially decreases the GHG emissions of the sectors within the EU-ETS (Figure 5-1). In general, there are two ways by which emissions can be reduced domestically: either by a reduction in overall production or by input substitution (away from emission-intensive fuels and towards non-energy inputs).

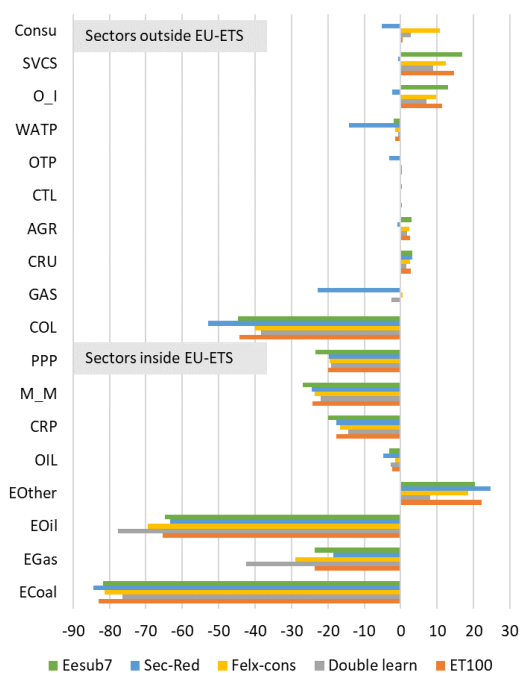


Figure 5-1: Percentage changes in sectoral GHG emissions compared to Baseline for the whole EU

In all scenarios, the highest absolute emission reductions occur in the EU-ETS electricity sectors, namely power generation based on coal, gas, and oil. In fossil-based electricity technologies, emission levels are directly linked to production levels. Coal has the highest implied emission factor in the fossil fuels. Therefore, among the electricity generating sectors, the increase in production cost is highest for coal-based electricity with higher prices in the EU-ETS and thus are emission reductions observed in coal-based electricity production (ECoal) throughout all scenarios (Figure 5-1).

Table 5-3 Regional GHG emissions, renewable shares, and coal share in baseline and % change in policy scenarios (relative to baseline)

	Country	Total GHG Emissions						Share of Renewables in Total Electricity production						Share of Coal in Total Electricity production					
		GHG base- line	Change in GHG Emissions in %					Share base- line	Change in Share (in PP)					Share base- line	Change in Share (in PP)				
			ET100	Double learn	Flex- cons	Sec- Red	Eesub7		ET100	Double learn	Flex- cons	Sec- Red	Eesub7		ET100	Double learn	Flex- cons	Sec- Red	Eesub7
EU - ETS countries	FRA	509	-4.8	-4.9	-4.3	-9.4	-4.6	5.0	0.7	3.4	3.4	0.8	0.6	2.2	-2.2	-2.1	-2.1	-2.2	-2.1
	GER	811	-27.7	-28.2	-25.5	-31.2	-26.6	18.7	19.2	28.6	28.6	19.5	17.9	43.6	-38.5	-36.7	-36.7	-39.5	-35.9
	ITA	456	-10.4	-12.5	-9.6	-13.9	-10.2	13.4	5.2	13.1	13.1	5.0	5.2	16.0	-15.0	-13.3	-13.3	-15.3	-14.1
	GBR	587	-13.2	-15.5	-11.9	-18.9	-12.3	14.9	8.0	22.8	22.8	7.7	7.2	22.8	-18.7	-17.3	-17.3	-19.5	-17.3
	BLX	362	-6.7	-7.4	-6.0	-10.7	-8.1	9.6	2.5	8.0	8.0	2.4	3.2	25.7	-12.7	-11.8	-11.8	-12.8	-16.9
	SPO	431	-16.8	-16.8	-16.2	-20.0	-17.2	22.7	8.2	11.6	11.6	8.1	8.5	20.2	-19.2	-17.2	-17.2	-19.4	-18.6
	SCA	293	-7.7	-8.1	-7.2	-11.0	-7.3	8.9	0.8	5.1	5.1	0.8	0.7	4.3	-4.3	-4.2	-4.2	-4.3	-4.1
	EHC	839	-20.0	-18.4	-17.5	-31.0	-20.6	7.2	5.7	10.5	10.5	5.8	6.2	63.9	-27.2	-21.6	-21.6	-28.9	-27.9
ELC	498	-11.7	-11.9	-10.5	-16.0	-11.1	7.3	3.7	10.5	10.5	3.8	3.2	15.7	-14.7	-13.2	-13.2	-14.9	-13.8	
Countries outside EU-ETS	USA	6100	0.3	0.4	0.3	0.7	0.3	2.9	0.0	0.0	0.0	0.0	0.0	43.2	0.1	0.0	0.0	0.1	0.1
	CAN	691	0.9	0.9	0.8	1.6	1.0	1.6	0.0	0.0	0.0	0.0	0.0	12.2	0.4	0.3	0.3	0.4	0.4
	RAXB	2057	0.9	0.8	0.8	1.2	1.0	1.3	0.0	0.0	0.0	0.0	0.0	31.0	0.3	0.2	0.2	0.2	0.3
	RUS	2268	1.0	0.9	0.9	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	15.3	0.9	0.8	0.8	0.8	0.8
	FSU	1287	1.6	1.2	1.5	1.8	1.9	0.1	0.0	0.0	0.0	0.0	0.0	39.7	0.1	-0.3	-0.3	-0.3	0.3
	CPA	10016	0.8	0.5	0.8	0.7	0.8	1.5	0.0	0.0	0.0	0.0	0.0	78.8	0.3	0.2	0.2	0.2	0.3
	IND	3038	1.2	1.0	1.2	1.0	1.2	2.4	0.0	0.0	0.0	0.0	0.0	66.4	0.6	0.3	0.3	0.3	0.6
	LAM	3093	0.6	0.5	0.5	0.8	0.6	0.4	0.0	0.0	0.0	0.0	0.0	4.8	0.3	0.3	0.3	0.3	0.3
	PAS	3800	1.1	1.0	1.1	1.3	1.1	0.2	0.0	0.0	0.0	0.0	0.0	33.3	1.4	1.1	1.1	1.1	1.2
	MEA	3487	0.5	0.5	0.5	0.7	0.6	0.6	0.0	0.0	0.0	0.0	0.0	8.0	0.6	0.5	0.5	0.5	0.6
AFR	1937	0.7	0.6	0.7	0.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0	60.2	0.9	0.8	0.8	0.8	0.9	
Summary	EU	4787	-15.0	-15.4	-13.7	-20.3	-14.9	12.2	5.9	12.2	12.2	5.9	5.7	24.2	-18.8	-17.1	-17.1	-19.3	-18.4
	Rest of the World	37774	0.8	0.7	0.7	0.9	0.8	1.4	0.0	0.0	0.0	0.0	0.0	43.7	0.4	0.2	0.2	0.2	0.4
	World	42560	-1.0	-1.1	-0.9	-1.5	-1.0	3.1	0.4	1.3	1.3	0.4	0.4	40.7	-1.4	-1.6	-1.6	-1.7	-1.4

Table 5-4 Percentage change in regional electricity, coal and gas consumption in policy scenarios relative to baseline

		Electricity Consumption					Coal Consumption					Gas Consumption				
		% Change in Electricity Consumption					% in Coal Consumption					% in Gas Consumption				
		ET100	Double learn	Flex-cons	Sec-Red	Eesub7	ET100	Double learn	Flex-cons	Sec-Red	Eesub7	ET100	Double learn	Flex-cons	Sec-Red	Eesub7
Price Allowances EU-ETS		100	71	90	106	126	100	71	90	106	126	100	71	90	106	126
EU-ETS sectors	OIL	-10.8	-6.2	-8.4	-14.8	-12.5	-0.6	-1.1	0.3	-3.3	-1.2	-1.7	-3.2	-1.5	-3.5	-2.8
	CRP	-15.3	-8.0	-13.2	-16.6	-17.0	-83.6	-77.1	-81.7	-84.7	-87.2	-26.5	-19.6	-24.6	-26.9	-31.6
	M_M	-5.9	-1.6	-4.6	-6.7	-6.2	-74.6	-67.3	-72.4	-75.9	-79.2	-29.4	-23.7	-27.6	-30.0	-34.5
	PPP	0.1	1.5	0.4	-0.1	0.5	-63.9	-57.3	-61.6	-65.3	-69.3	-18.2	-16.2	-17.4	-18.0	-22.5
	COL	-51.3	-45.3	-46.9	-59.3	-51.6	-0.8	-5.4	1.1	-10.9	3.9	-32.3	-31.9	-29.3	-41.5	-27.8
Sectors outside EU-ETS	GAS	-18.1	-13.0	-15.1	17.2	-20.5	43.2	30.0	41.3	74.8	40.6	3.3	0.2	3.4	-29.8	4.0
	CRU	-13.0	-7.3	-11.2	-15.1	-14.2	30.0	22.2	29.3	29.2	30.9	5.0	3.2	4.4	5.7	5.7
	AGR	-15.5	-8.4	-13.2	-12.2	-17.4	51.4	42.2	47.0	-61.8	53.1	12.0	8.4	10.2	-11.7	14.5
	ctl	-13.9	-7.6	-11.9	-9.5	-15.5	65.7	50.8	58.9	-72.5	70.4	13.8	10.3	11.7	-24.1	16.6
	otp	-20.2	-11.3	-17.6	-15.5	-22.5	41.3	35.8	38.5	-52.1	41.6	8.1	7.7	7.1	-28.2	9.7
	watp	-21.4	-12.0	-18.7	-17.9	-23.9	37.7	35.0	34.7	-71.4	36.3	5.9	6.9	5.0	-49.4	6.9
	O_I	-8.2	-4.7	-7.1	-3.8	-9.1	68.6	50.3	61.6	-62.1	73.0	23.1	14.5	19.7	-10.5	27.2
	SVCS	-7.2	-4.0	-6.2	-3.4	-8.1	75.8	55.7	67.6	-65.3	82.1	23.3	14.5	19.8	-11.4	27.4
	Direct consumption	-28.3	-15.4	-35.7	-29.8	-31.7	28.9	27.6	84.3	-10.6	27.8	2.1	4.6	12.6	-6.3	1.9

When looking at individual EU regions, all except BLX and EHC reduce emissions from ECoal by at least 88% when the strict cap is introduced in ET100. Consequently, countries with the highest share of coal in the electricity portfolio exhibit the highest GHG reductions (compared to Baseline) (see Table 5-3 for countries' share of ECoal and GHG reduction). The share of ECoal is largest in Germany with 44% ECoal and 28% GHG reductions, followed by EHC with 64% ECoal and 20% GHG reductions. On the other hand, France, with only 2% ECoal in electricity production, exhibits only a 5% reduction in GHG emissions in the ET100 scenario.

When the allowance price changes in the other scenarios, emission reductions in the electricity sectors in the EU-ETS adjust accordingly. For example, double learning in renewables leads to a lower price for emission allowances of 71€/tCO₂ (see first line of Table 5-4), and consequently to lower emission reduction of ECoal (by almost 8 percentage points) in the EU compared to ET100.

Even though they face the same change in emission allowance price, in contrast to ECoal, EGas (80%) and EOil (19%) have higher emission reductions in DoubleLearn compared to ET100 (though still on a much lower level than emission reductions of ECoal in absolute terms). With coal having the highest emission factor, decreases in production costs of ECoal are relatively higher compared to EGas and EOil with a lower price in the EU-ETS. Consequently, in DoubleLearn, ECoal exhibits higher levels of production than in ET100 since it increases its relative competitiveness. This overall effect for the EU is dominated by the EU countries with low shares of renewables (see Table 5-4) since in these countries results are driven by the lower price for allowances because the decrease in the production cost of renewables due to steeper learning curves in DoubleLearn has less impact. For example, in Baseline, EHC with a share of renewables of only 12%, increases its total emissions (3% compared to ET100), driven by emissions from ECoal. In contrast, Germany has a high share of ECoal (44%) and a relatively high share of renewables (23%) in Baseline. The share of renewables increases in DoubleLearn (to 53%; 43% in ET100), and therefore Germany decreases its CO₂-emissions from ECoal by 46% compared to ET100.

We observe the same effect in FlexCons, even though on a smaller level. The opposite effect occurs in SecRed, where allowance prices are higher than in ET100 (106€/tCO₂eq,

see Table 5-4). More emissions are reduced from ECoal compared to ET100, and slightly less from EGas and EOil. The higher allowance price increases the relative contribution of ECoal to total emission reductions but decreases that of EGas and EOil. Thus, policy settings outside the EU-ETS (e.g. better promotion of renewables or higher consumer flexibility) affect the contribution of each power generation technology to emission mitigation inside the EU-ETS via the allowance price.

Among the non-energy sectors in the EU-ETS, mineral and metal production (M_M) as well as the chemical sector (CRP) show the highest reduction in emissions, followed by pulp, paper and print (PPP). The emission reduction pattern of these three sectors follows the EU-ETS emission allowances price: The lowest reduction occurs in DoubleLearn (where the allowance price is lowest with 70€/tCO₂eq), the highest in Eesub7 (where the allowance price is highest with 126€/tCO₂eq). In Baseline, these three sectors use small amounts of coal and more oil and gas. When the ETS cap is strengthened in ET100, all three sectors reduce their gas consumption (CRP: 26%; M_M: 29%; PPP: 18%), and coal is hardly used anymore. Interestingly, we observe an increase in the consumption of oil (CRP: 7%; M_M: 13%; PPP: 23%), which in energy terms (mtoe) slightly overcompensates the reduction in coal and gas use. Thus, within these sectors, we observe a substitution effect towards oil, which, due to the lower emission factors for oil in the GTAP database compared to coal, reduces the emission of the sectors without decreasing the overall use of fossil fuels. This effect is less pronounced in DoubleLearn and the strongest in SecRed and Eesub7, where the higher prices for emission allowances increase the relative price differences between the different fossil fuels.

5.4.2 Inter-sectoral leakage effects outside the EU-ETS

While tightening the ETS cap in ET100 (compared to Baseline) does not directly address the non-ETS, we still observe an increase in GHG emissions in these sectors (see Figure 5-1), which indicates inter-sectoral leakage resulting from higher allowance prices. When comparing ET100 to Baseline, the percentage leakage⁴⁸ amounts to 9.4%, meaning that

⁴⁸ We use the concept of percentage leakage, which is defined in (Metz et al. 2007) as the percentage of the increased CO₂ emissions in non-EU regions relative to the emissions abated in the EU-ETS, and apply it

9.4% of the emissions abated within the EU-ETS are offset by additional emissions in non-ETS sectors. These are largest in the service sector, both in relative (15%) and absolute (64 tCO₂eq) terms. The increase in emissions is larger than the emission reduction of EGas (56 tCO₂eq) and EOil (54 tCO₂eq) in the EU-ETS. The sector “Other industries” (O_I) increases its GHG emissions by 30 tCO₂eq, and agriculture by 9 tCO₂eq in the ET100 scenario compared to Baseline. In SecRed, GHG emissions of non-EU-ETS sectors reduce by definition of the scenario. Given the differences in prices for emission allowances within the EU-ETS, across scenarios, the service sector and O_I show the highest increase in emissions in Eesub7 (overall percentage leakage relative to Baseline: 10%), and the lowest in DoubleLearn (percentage leakage: 7.9%). Increased flexibility in private consumption of fossil fuels (FlexCons) slightly decreases emissions, and thus the carbon leakage in these sectors. However, due to the increase in emissions from private households, the overall percentage leakage increases to 16% in FlexCons. In the following, we analyse the drivers of these inter-sectoral leakage effects, focusing on services and O_I.

The price effects of fossil fuels outside the EU-ETS mirror the contributions of electricity generation technologies towards mitigation within the EU-ETS across scenarios, which are discussed above (see Figure 5-2 for changes in input prices of fossil fuels and electricity in the EU). Even though coal prices outside the EU-ETS drop by almost 20% in ET100 compared to Baseline, the smaller price effects on gas and oil are more important since they are the primary fossil energy sources outside the EU-ETS. Additionally, electricity prices need to be considered, as they play an important role in production prices outside the EU-ETS.

also to CO₂ emissions in non-ETS sectors relative to abatements in ETS sectors.

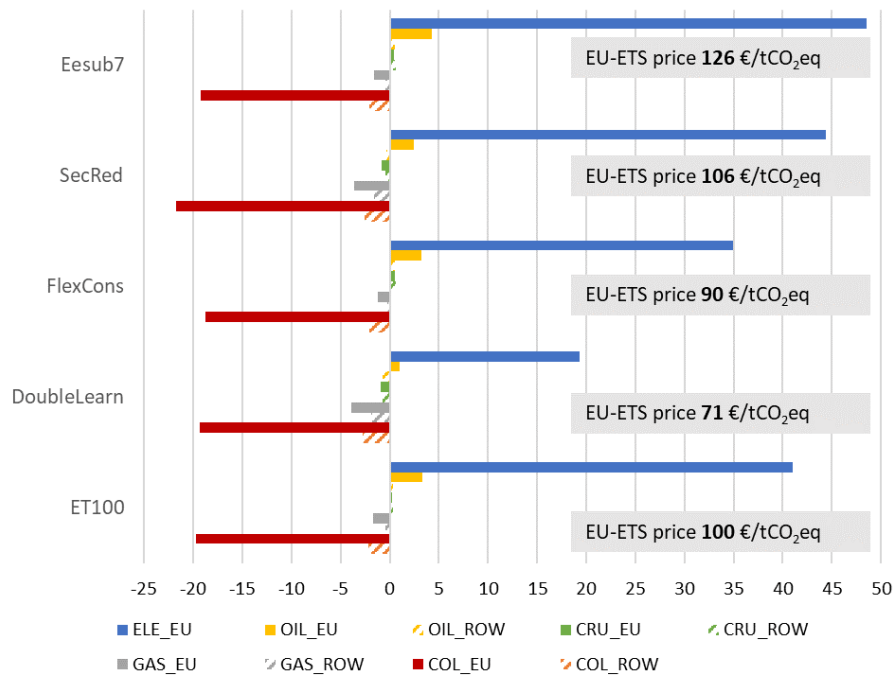


Figure 5-2: EUETS allowance price and changes in input prices of fossil fuels and electricity in the EU and rest of the world (ROW)

This becomes most evident in DoubleLearn, where across scenarios, gas prices show the highest decrease (3.9% compared to Baseline) and oil prices the smallest increase (1.1%). This result is coherent with the lower emissions, lower production and lower demand for fossil fuel input in EGas and EOil (see Table 5-4). While services and O_I increase their gas consumption by 23% each in ET100, this increase is smaller in DoubleLearn (both sectors 15%), despite the lower gas price. This result can be explained by the development of electricity prices and its resulting changes in electricity consumption. Electricity prices increase substantially (over 40% on average in the EU compared to Baseline) with the cap tightening in ET100, and consequently electricity consumption in the sectors outside the EU-ETS decreases. This decrease in the electricity use is compensated by the direct use of fossil fuels, which is not levied with a CO₂ price in non-ETS sectors. However, double learning rates for renewables more than halve the electricity price effect to 19% (compared to Baseline). The relatively lower electricity prices induce a lower reduction in electricity consumption in DoubleLearn compared to ET100 scenario (O_I: 5% vs. 8%; services: 4% vs. 7%). This also implies that less fossil fuels are used to substitute electricity. Thus, in DoubleLearn, electricity consumption is reduced less, and less electricity is substituted by direct fossil fuel consumption in the non-ETS sectors, despite

lower prices for gas and oil. The opposite effect can be observed in EESub7, where decreased flexibility of the electricity net aggravates this effect because of a higher allowance price in the EU-ETS and, thus, higher electricity prices. This leads to a higher substitution of electricity with fossil fuels and thus, to intersectoral leakage.

Among the non-ETS sectors, private consumption plays a unique role. In the GTAP data, private energy consumption includes direct household consumption of fossil fuels primarily for heating purposes, electricity consumption (including district heating), and fuel consumption for private mobility. In Baseline, coal has a share of 0.4% in total household energy consumption, gas of 9.4%, oil of 52.4% and electricity of 37.8% in the EU. The increases in electricity prices substantially reduce electricity consumption in all our scenarios, with the highest decrease (over 35% compared to Baseline) in FlexCons, which by design allows for an easier shift between energy sources for private consumption.

The lowest drop in electricity consumption appears in DoubleLearn (15%), where price effects on electricity are smaller. At the same time, we observe a substantial increase in GHG emissions from private consumption (21 tCO₂eq more than in Baseline) in DoubleLearn. This result is driven by higher gas consumption following the decrease in gas prices (-3.9%). In FlexCons, GHG emissions are even higher (81 tCO₂eq more than in Baseline) due to the easier substitution between different energy types and the resulting increase in consumption of all fossil fuels. Given that the GTAP sector subsumes very different energy systems for heating, household electricity and mobility, one might question the feasibility of higher substitutability between energy types. However, our results indicate that the observed increase in electricity prices and decrease in fossil fuels prices discourages the use of alternative energy sources like electric cars or non-fossil based heating systems.

The introduction of sectoral reduction targets for the non-ETS sectors (SecRed) avoids most of the substitution of energy inputs, despite similar increases in electricity prices compared to the ET100 scenario. However, this comes at the expense of higher mitigation costs inside the EU-ETS. In all EU regions except EHC and GER, EU-ETS sectors increase their GHG emissions, although the allowance price is higher than in ET100. The effect of lower fossil fuel prices (see Figure 5-2, -21.8% for Coal and -3.7% for Gas

compared to Baseline) which result from lower demand in the now restricted non-ETS sectors, offsets the effect of higher allowance prices. As a consequence, EHC and GER, the countries with the highest share of coal based electricity increase their share in climate mitigation within the EU-ETS. Total emissions (including emissions both inside and outside the EU-ETS) decrease between 14% (EHC) and 4% (ITA) in the EU regions, making SecRed the scenario with highest overall net reductions, as the imposed policy avoids the inter-sectoral leakage.

5.4.3 Effects outside the EU

In our model, regions are connected via trade and thus, the effects of the policies in EU are transmitted to the rest of the world. Since in our scenarios we do not implement additional mitigation policies outside the EU, the leakage rate for CO₂ emissions in non-EU regions amounts to 35% to 43% of the emissions abated in the EU. The largest components of the emissions increase come from the sectors ECoal (50%-70%), M_M (10%-20%) and EGas (10%-20%) sectors.

The main driving force behind the international leakage is the change in international fossil fuel prices following the decrease in demand for fossils after tightening the EU-ETS cap, which causes an increase in use of fossil fuels outside the EU. The largest drop in prices occurs in DoubleLearn (3.6% in COL, 1.8% in GAS, 0.7% in CRU, and 0.8% in OIL). Predominantly coal-based economies like China and India take advantage of the lower international fossil fuel prices by marginally reducing domestic production of coal and gas and increasing the now cheaper imports of these commodities. In China, coal imports increase by about 12%, while gas imports increase in the range of 0.2%-3% across scenarios. At the same time, we observe a shift from gas to coal-based electricity in all scenarios, with the highest increase of 1.3% in ECoal production in FlexCons and Eesub7. Even though prices decrease for coal are larger in DoubleLearn, the stronger increase of Ecoal production, and thus leakage effects, in these scenarios follows a relatively low decrease in gas prices (-0.2% in FlexCons and -0.4% in Eesub7) compared to DoubleLearn (-1.9%) (see Table 5-4).

In most non-energy ETS sectors, we see a displacement of production from the EU (with CO₂ pricing) to non-EU (without CO₂ pricing). Outside the EU, there is an increase in

the production within the ETS sectors M_M, CRP, OIL and PPP. This production rise is coupled with an increase in EU's imports in sectors OIL (0.3% to 4.2%), M_M (1.1% to 2.1%) and PPP (0.02% to 0.3%), indicating that there is displacement of production for these sectors from the EU to non-EU regions. Outside the EU, FSU experiences the highest increase in OIL (1.1% to 2.3%) and M_M (1.6% to 2.5%) production. The PPP sectoral production increases by a smaller percentage outside the EU (0.1% to 0.6%), with no single region leading.

5.5 Discussion and conclusion

This study analyses the interplay between the EU-ETS allowance price and the development of renewable energy technologies. We characterize five policy settings for the EU in the CGE model DART. Our results show that renewable energies, albeit not part of the EU-ETS, are strongly interconnected with the ETS allowance price and emissions.

On the one hand, a higher allowance price triggers an increased use of renewables in the EU. Within the individual EU countries, the electricity portfolio determines how the electricity sector and overall emission reductions (as electricity sectors typically dominate them) respond. Increasing allowance prices cause higher overall CO₂ reductions in EU countries with a high share of coal in their electricity portfolio. On the other hand, developments related to renewables play a vital role in the development of allowance prices and sectors inside the EU-ETS, especially in the composition of fossil-based electricity production. For example, increased learning in renewable electricity production technologies leads to higher competitiveness and market shares of renewables. In turn, lower marginal abatement costs within the EU-ETS causes lower allowance prices, and consequently, more coal-based electricity in the portfolio. If the integration of renewable electricity is hindered, e.g. due to grid restrictions, more conventional electricity is needed to meet the demand. Consequently, the allowance price is higher, indicating that marginal abatement costs for decarbonization are higher with reduced flexibility of electricity grids.

Higher allowance price within the EU-ETS increases carbon leakage, both inter-sectoral and international. High allowance prices go hand in hand with high electricity prices and

reduced demand for fossil fuels from the ETS sectors to low prices for fossil fuels, particularly gas. Thus, inter-sectoral carbon leakage occurs by substituting fossil inputs from electricity to direct use in the sectors and regions outside the EU-ETS. Especially the service sector and industries outside the EU-ETS increase their emissions in case of higher allowance prices. Private households react similarly, indicating that the combination of high electricity prices and low fossil fuel prices also decreases their incentives for the transition to low carbon technologies in the absence of additional policies. Intensified production of renewable electricity technologies leads to cheaper electricity, decreasing this type of leakage effect. A binding cap on non-ETS sectors by design obstructs inter-sectoral leakage by avoiding the substitution of electricity with cheaper fossil fuels in non-ETS sectors, however, at the cost of higher prices within the EU-ETS.

On the international level, carbon leakage increases with higher EU-ETS allowance prices, mainly driven by lower international fossil fuel prices. The increase in emissions is the strongest in coal and gas-based electricity and the metals and minerals sectors. In the absence of climate action outside the EU, we also observe a small increase in production of the ETS sectors outside the EU, indicating a displacement of these industries into other world regions.

Summing up, our study identifies three important policy findings. First, the interplay between the ETS and non-ETS sectors must not be neglected when policies aiming at emission reductions are implemented or amended. For example, when measures are taken to strengthen the stability of the EU-ETS market (e.g., the introduction of the Market Stability Reserve in 2019), accompanying policies for non-ETS sectors should be considered to avoid inter-sectoral carbon leakage. Second, inter-sectoral and international leakage can be reduced by strengthening the development of renewable energy technologies, whereas insufficient electricity grid integration has the opposite effect. Thus, the development of renewables and electricity grids should go hand in hand to maximize emission reductions. Third, our results identify fossil fuel prices as the main channel of international leakage. Thus, supporting renewables and electricity grid integration might be an alternative to the currently discussed Border Carbon Tax adjustments to avoid inter-national leakage.

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Chapter 6

General Conclusion

6.1 Conclusion

Climate change puts both human societies and the environment at large risks. It is a collective action problem, which has to be solved jointly by the global community. In order to channel international efforts to combat climate change, the UNFCCC was established in 1992. It set a first milestone with its 1997 Kyoto Protocol, which imposed GHG emission abatements on the industrialized countries in a top-down manner. This approach did not deliver well, and it was replaced in 2015: The Paris Agreement addresses some of the major shortcomings of its predecessor by shifting the abatement obligations to all countries in a bottom-up approach. Countries now submit NDCs to pledge their intended emission reductions. These NDCs are to ratchet up in order to eventually constitute the long-term goal of limiting global mean temperature increase to 2°C, preferably to 1.5°C. But tighter emission reduction targets impose higher costs on economies.

The formation of international carbon markets is a promising approach to address these higher costs. It has the potential to deliver emission reductions both effectively and efficiently. At the same time, carbon pricing generates revenues, which can be used e. g. for redistribution. The associated costs are, however, distributed unevenly among potential participants of the joint carbon market. Energy exporters and providers of cheap mitigation options typically carry a larger burden and have therefore lower incentives to join an international carbon trading coalition. At the same time, it is especially important to involve these regions in international climate actions. Thus, measures to increase their incentives to join can become important when carbon coalitions are to be set in place.

While carbon pricing is a powerful instrument to achieve GHG emission reductions, it should be accompanied by additional policies addressing e. g. the use of renewable energy technologies. At the same time, overlapping policies can derogate both instruments' efficiency. In order to avoid this, the interaction between carbon pricing and renewable energy policies must be better understood. This holds especially true against the background of ratcheting up the NDCs, which will lead to higher carbon prices and increased interaction with related policies.

This dissertation aimed at enhancing the understanding of international carbon pricing regimes against the background of the Paris Agreement. Specifically, it addressed four objectives: (i) identify efficient carbon trading coalitions; (ii) assess the burden sharing across coalition partners, and thereby the likelihood of coalitions to manifest; (iii) identify suitable measures to incentivize otherwise unwilling coalition partners; (iv) examine the interplay of rising carbon prices and renewable energy policies.

To achieve these objectives, this dissertation relied on a group of internationally acknowledged energy-economy models, and especially on the CGE model DART. It comprised of four research papers addressing different aspects of carbon pricing. This chapter summarizes the study's main findings, derives policy implications, and provides recommendations for future research.

6.2 Main findings

Chapter 2 summarized modelling results of 17 international energy-economy models over a set of harmonized scenarios. These scenarios were built along the Paris Agreement's different ambition levels (NDCs vs. 2° C target) and different degrees of international cooperation. From a global perspective, moving from the current focus on domestic action towards a global carbon pricing scheme across all sectors reduces the costs of reaching current NDCs by as much as 50-90%. This finding underlines the large potential of international cooperation in terms of efficiency gains, which increases further with stricter emission targets. Under global emission trading, the 2°C target is about as costly as the less ambitious current NDCs without global cooperation. Also much smaller carbon clubs comprising only few selected regions can reduce global costs notably: China and the EU

sharing a carbon market in EITE and power sectors generates almost halve (45%) of the efficiency gains reaped by global cooperation in the same sectors; for a coalition of China, South Korean and Japan this figure is 36%. In terms of regional burden sharing, a central finding of the study was that oil and gas exporters gain from the installation of a global carbon market. This is because China and India alone almost entirely absorb global emission reductions in such a setting. They extensively substitute coal with oil and gas to achieve cheap abatements. This drives up oil and gas prices, increasing the revenues for these fossil fuels' exporters. India, becoming a major exporter of emission allowances, is worse off in the global trading system compared to a situation without international cooperation, due to ToT effects. Similarly, the paper found that in the abovementioned club-trading scenarios the exporters of emission allowances (mainly China) hardly gain from their engagement in the coalition, while the importers of allowances (the EU and South Korea) benefit substantially. The study also confirmed the potential of lump-sum recycling of revenues from carbon pricing to make climate action progressive.

Chapter 3 put a focus on the dissertation's first objective by closely analyzing a larger set of potential carbon trading coalitions. It comprised results from seven CGE models on a set of harmonized scenarios, which included also the Paris Agreement's 1.5°C temperature target. The modelling results stress the potential for efficiency gains especially under strict abatement targets: Gains from international carbon trading increase by a factor between 2 and 3 (depending on the model) when moving from current NDCs to the more stringent 2°C target, and they double again when moving from 2°C to 1.5°C target. Also small coalitions, especially the EU-China coalition, can generate substantial efficiency gains, which are far higher than these coalitions share in global emissions suggest. As an example, the EU and China jointly account for 37% of global emissions, but the coalition achieves as much as 75% of the costs saved by a global coalition (compared to domestic action only), when all sectors are covered by the trading scheme. Apparently, not only the amount of emissions covered by a uniform carbon price (i. e. the where-flexibility) determines the efficiency gains, but also the difference in pre-linking allowance prices of the coalition partners, weight of each region in terms of emissions, and the global energy market effects resulting from the coalition. With regard to regional incentives to join carbon trading coalitions, a key finding is that for importers of emission

allowances, smaller coalitions are more beneficial, because the competition for cheap allowances and, thus, the allowance price is lower compared to larger coalitions. For exporters of allowances, this effect reverses.

Building on the findings from chapter 3, the study in chapter 3 deployed the CGE model DART to derive tools which are suitable to distribute the emission abatement costs more evenly on the carbon trading partners EU and China. It implemented a joint carbon market in EITE and power sectors in three sets of scenarios addressing different approaches to make linking more attractive to China: (i) restricting the volume of traded emission allowances; (ii) shifting more abatement obligations to the EU to mimic transfer payments from the EU to China; and (iii) altering Armington trade elasticities to make international trade of goods more or less open. The key finding of the paper was that restricting the volume of permit trade is suited best to make linking attractive to China. In all settings, China's gains from linking are higher under restricted allowance trade compared to unrestricted allowance trade. Contrarily, the EU always favors unrestricted allowance trade, regardless of even high transfers to China. The gains from linking increase with facilitated trade in goods for China, indicating that international trade in goods fosters China's incentives to join a linked carbon market with the EU.

Chapter 5 used a static version of DART to examine the interaction between the EU-ETS and renewable energy policies. It analyzes effects of these interactions on international and inter-sectoral carbon leakage and burden sharing. In addition to a baseline and a scenario with an increased allowance price; it comprised four policy scenarios addressing (i) technological growth in renewables; (ii) increased flexibility in electricity and fossil fuel consumption; (iii) imposing a binding carbon price on non-ETS sectors; and (iv) decreasing the flexibility of electricity grids. The study found that higher allowance prices trigger the use of renewables, while a policy-induced growth of renewables leads to lower allowance prices, and consequently to more coal-based electricity production. A low flexibility in electricity grids suppresses the use of renewables and thereby drives up the allowance price. Since carbon leakage increases with EU allowance prices, these interconnections translate into altering inter-sectoral and international abatement burdens. Thus, fostering renewable energies and improving the flexibility of electricity grids decreases both inter-sectoral and international carbon leakage.

6.3 Policy implications

First of all, the findings of this dissertation highlight the potential of international cooperation to cost-efficiently reach the Paris Agreement's emission reduction and temperature targets, especially when ratcheting up NDCs and aiming at the proposed 1.5°C temperature target. While this is rather a confirmation than a new result, the large cost savings found in the analyses of 17 widely acknowledged models further emphasize the urgency for policy makers to foster international carbon pricing. At the next conference of the parties to the UNFCCC (COP 26) in Glasgow, a special focus will lie on the implementation of a rulebook for Article 6 (see e. g. EDF, 2021), giving an opportunity to make substantial progress in this regard.

Kyoto Protocol's failure proved that reaching a large international top-down system is hard to achieve in reality. This dissertation shows, that also smaller initiatives can already generate substantial cost savings, both globally and for the carbon trading partners. Especially the linking of the EU and Chinese ETSs was identified as a promising option. The author of this dissertation acknowledges the numerous difficulties associated with establishing such a link (see Flachsland et al., 2009); however, compared to the obstacles towards a global carbon market, they seem solvable. This holds especially true considering the options for increasing China's incentives to link, which are outlined in this study.

There is another finding to be kept in mind when sounding options for international cooperation: It is not only the amount of GHG covered under the joint system which determines the associated efficiency gains. Other aspects have to be considered as well, e. g. the weight of potential trading partners in terms of emissions, the difference between pre-linking carbon prices and the participants trade patterns, which determine potential ToT effects resulting from the cooperation.

Furthermore, policy makers must not neglect the role of renewable energy technologies as well as of flexible electricity grids with regard to carbon leakage. Via driving down the allowance price of a carbon trading regime, the deployment of renewables can disincentivize both international and inter-sectoral leakage. On the one hand, this is a desirable effect; on the other hand, current discussions rather aim at strengthening carbon

pricing regimes in order to meet ambitious reduction targets like the EU's net zero target (see e. g. Kinch, 2021). When measures to strengthen the allowance price are taken, they should be accompanied with policies aiming at sectors not covered by the carbon pricing scheme in order to avoid inter-sectoral carbon leakage.

6.4 Shortcomings and future research

There are some shortcomings to be considered in this dissertation, which provide future research opportunities. Most importantly, the study relies heavily on CGE modeling. CGE models are a well established tool in climate economic research, and they are well suited to analyze policy interventions due to their comprehensive coverage of market interactions (see chapter 2). However, unlike Integrated Assessment Models (IAM), they do not account for the (monetized) benefits from avoided climate damages. Therefore, CGE models do not consider all aspects regarding the social cost of carbon. The social cost of carbon is an important measure when it comes to the evaluation of climate policy interventions like the formation of an international carbon market. IAM model studies can shed light on this aspect and complement the research objectives addressed in this dissertation.

On a similar note, the dissertation does not take a sound political economy perspective. It rather interprets cost distribution and cost savings from international carbon markets as the only incentives to join or not join a climate coalition. However, other than monetary considerations are decisive for the acceptance of policy interventions. As an example, it can be doubted that the European public would support plans to outsource emission abatements by linking with China's ETS, despite the large cost savings of such a link. Future studies should use political economy approaches to further explore the desirability of different international climate coalitions.

If the EU-China link was to be negotiated, not only the political economy has to be considered, but also the fact that the EU is not a single negotiator in the first place. Rather, consensus will have to be found also within the EU, before a joint EU position can be taken. As outlined in chapter 4, the EU member states do not benefit equally from a joint carbon market with China. Thus, future studies should address both levels of negotiating

a linkage between EU and Chinese ETs: the inner-EU level, and the EU-China level. Game theoretic approaches as well as a more EU-focused CGE approach could yield important findings.

In order to further examine the potential for individual coalitions to be realized, a game theoretic approach could shed further light on whether or not potential carbon trading coalitions are stable. Similarly, the introduction of trade penalties on non-participants, forming a “Carbon Club” in Nordhaus’ sense (Nordhaus, 2015) would contribute to this research question. In light of the Carbon Border Adjustment Mechanism (CBAM) currently under discussion in the EU, the topic gains extra relevance.

In addition, there are some minor topics which could be addressed in future research to enhance the scope of this dissertation: inclusion of all GHG rather than only CO₂ from fossil fuel combustion; a longer time horizon beyond 2030, and inclusion of then relevant negative emission technologies; inclusion of different approaches to international fairness (see Peterson and Weitzel, 2016) when moving from the NDC to the temperature target, which is currently achieved by applying a uniform scaling factor to the regional emission levels in the NDC case.

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If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.



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Concept: Formulation of the basic scientific problem based on theoretical questions which require clarification, including a summary of the general questions which, it is assumed, will be answerable via analyses or concrete experiments/investigations	A
Planning: Planning of experiments/analyses and formulation of investigative methodology, including choice of method and independent methodological development, in such a way that the scientific questions asked can be expected to be answered	A
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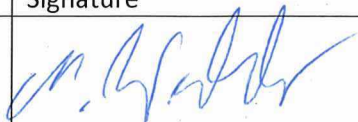
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