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A MODEL INTERCOMPARISON OF THE WELFARE EFFECTS OF REGIONAL COALITIONS FOR AMBITIOUS CLIMATE MITIGATION TARGETS

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This paper presents the overall and distributional welfare effects of alternative multi-regional emissions trading coalitions relative to unilateral action. It focusses on meeting Paris Agreement pledges and more emissions reduction targets consistent with 2°C and 1.5°C temperature pathways in 2030. The results from seven computable general equilibrium (CGE) models are compared. Across all models, welfare gains are highest with a global market and increase with the stringency of targets. All regional coalitions also show overall welfare gains, although lower gains than the global market. The models show more variability in the gains by a participant. Depending on the model, participants may benefit more from some regional arrangements than from a global market or face modest losses compared to the domestic reductions alone, due to interactions between carbon targets and fossil fuel markets. The scenario with a joint China–European Union emissions trading system in all sectors is consistently favorable for participants and provides the highest economic gains per unit of emissions abated.

Keywords: Climate mitigation; regional cooperation; emissions trading; welfare.

1. Introduction

Cooperation, such as joint carbon pricing e.g. via linked emissions trading systems, 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). While some countries and subnational regions have engaged in regional emissions trading arrangements, more expansive cooperation involving multiple jurisdictions and countries up to a global scale has been relatively slow to emerge (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 carbon pricing coalitions.

In this paper, the costs and trade implications of a set of hypothetical regional emissions trading coalitions are evaluated using seven computable general equilibrium (CGE) models to identify the benefits of trading markets for carbon dioxide (CO_2). More specifically, the gains or losses in terms of welfare for regional coalitions in 2030 are compared to achieving the same emission reductions without trading for existing pledges under the Paris Agreement (which are termed National Determined Contributions — 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 joint carbon pricing and linking emission-trading markets have identified the benefits of integration. This study contributes three new insights to this literature: First, we review a more comprehensive range of possible emissions trading coalitions in a model intercomparison and different emission pathways that meet more stringent climate mitigation targets of 1.5°C of the Paris Agreement. Second, we make use of the CGE frameworks to evaluate how the interactions between the carbon mitigation costs and the fossil fuels markets combine to determine the overall benefits from joint emissions trading. Third, we evaluate the variability in the results through a model intercomparison that informs about their ability to produce consistent findings across different model structures, 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 pricing coalitions.

2. Literature Review

Trading carbon permits has been a 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. Emissions 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 emissions trading (Aldy *et al.*, 2016). The agreement also allowed for the possibility of linkages between regional emissions trading efforts as a bottom-up approach to developing more global trading arrangements, sometimes also referred to as “carbon market clubs” (Keohane *et al.*, 2017). These linkages, however, have been slow to develop (Bodansky *et al.*, 2016).

The benefits of emissions 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 emissions trading will moderate costs, there are fewer investigations of the gains from joint carbon pricing given stringent emissions targets at the country or regional levels, especially within a CGE modeling framework to provide an economy-wide perspective. Table 1 lists several recent studies that have estimated the global benefits of joint carbon trading for the NDCs. The gains relative to unilateral carbon pricing are unambiguous and often substantial.

Recognizing that the global markets have not emerged but that regional emissions trading may be politically feasible, a growing literature has reviewed potential regional

Table 1. Selection of estimated global benefits of emissions 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	Reduction of global welfare loss from 1.4–3.4% without emissions trading, depending on the assumed burden-sharing scheme, to 1.4–1.7% with global emission trading.	Fujimori *et al.* (2016)
Direct abatement costs	All countries meet unconditional NDC reductions	Reduction in total GHG mitigation costs from \$1.71 trillion to \$0.4 trillion, or 77%.	Rose *et al.* (2017)
Direct abatement costs	All countries meet unconditional NDC reductions	Aggregated CO_2 mitigation costs in the power and industry sector in 90 countries reduce from \$0.91 trillion to \$0.25 trillion (in 2015 dollars) in 2030, a savings of 72%.	Rose *et al.* (2018)
Direct abatement costs as a percentage of GDP (Global average of emission reduction costs per unit of GDP)	All countries meet NDC reductions	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)

emissions trading identifying conditions that reveal benefits. Most literature focuses on the expansion of the EU Emissions 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 coalitions 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).

Taken as a whole, studies of ETS find that countries exporting emission allowances can lose in the globally linked ETS coalitions if an extended coalition 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 coalition. 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 emissions 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 ETS (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 coalitions 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 carbon pricing coalitions 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. In analyzing the equity implications of reaching the NDCs as specified in COP21, Rose *et al.* (2017) also compare a scenario where countries unilaterally reach their NDCs to a scenario with a joint emissions trading scheme. They find that these lead to cost savings of 77%. 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 CO_2 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, where savings reach 72% (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 coalitions and the studies that apply game theory models to identify stable coalitions cannot be directly compared. However, information about country-level welfare gains and losses under hypothetical coalitions can be used to provide insight into whether any given country would find a trading coalition favorable.

3. Modeling Approaches, Data, and Scenario Design

We conducted a model intercomparison for a range of hypothetical emissions trading coalitions for different levels of climate stringency and sectoral coverages. Seven CGE modeling teams from Europe, Asia, and North America participated in this modeling effort.

In this analysis, we evaluate the costs of climate policies globally and regionally for different levels of cooperation through joint carbon pricing relative to a no-policy scenario, using two cost measures: carbon prices and welfare measured in Hicksian Equivalent Variation (HEV). We derive emission targets for each modeled region from the submitted NDCs that we scale up to be in line with the global carbon budget for a 2°C and 1.5°C temperature target (see Sec. 3.3. for details). In the analysis, we first report the global and regional gains from many plausible carbon pricing coalitions. Second, we investigate the drivers of these welfare effects focusing in particular on fossil fuel markets. Finally, we make use of the multi-model effort to analyze the consistency and sources of uncertainty in the desirability of the carbon pricing coalitions for any given participant.

In our set-up global emissions are the same for all scenarios based on a given ambition level (NDC, 2°C and 1.5°C), independent of whether any emissions trading coalition is implemented or not. Since countries outside coalitions are still forced to reach their given emission reduction targets, there is no carbon leakage. Yet, 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 carbon pricing coalition. 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 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. Our focus is not on the stability of coalitions. Thus, we did not design our coalitions in order to find stable coalitions.

3.1. ***Model descriptions***

Seven models participated in this effort: Environment and Climate Change Canada (ECCC) with its 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 its 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 its 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 1 with more information in Supplemental Information (S1). All dollar values are reported in US dollars (USD) and dollar year 2011.

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 CO_2 prices that determine the reductions achieved endogenously.

The models used in this paper possess 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. CO_2 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 disaggregation, the representation of economic activities, and parameter values such as the inter-fuel substitution elasticities. The representation of the electricity sector varies by 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.

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 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, their set of regions still allows results to be aggregated to the same harmonized set of regions (See Supplementary Information, Table S3 for details on regional aggregation for this effort). Put differently, the number and specification of regions is another distinctive model feature but does not hinder the comparison of results. 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, instead of “countries and regions” we only refer to “regions”.

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 CO_2 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-CO_2 greenhouse gases (GHGs) such as CH_4, N_2O, 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

Table 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
ECCC/ EC-MSMR	Recursive dynamic CGE	14	20 + 3 final demand sectors (Government, Consumption, Investment)	Elec. versus fossil fuel aggregate = 0.3667	From Okagawa and Ban 2008 (0.21–0.3)	GTAP values ESUBD(“gas”) = 2 ESUBM (“gas”) = 4
EDF/ EDF-GEPA	Static CGE with target-year forward calibration	20	23	Not provided	e/(KL) = 0.5 (for elec. adjusted to 1.0)	GTAP values ESUBD(“gas”) = 2 ESUBM(“gas”) = 4
CMCC/ICES	Recursive dynamic CGE	25	32 + 3 final demand (Government, Consumption, Investment)	Elec. versus fossil fuel aggregate = 1	KE = 0.5 (KE)L = GTAP (Value Added nest) values [0.2–1.68]	GTAP values ESUBD(“oil”) = 4 ESUBM(“oil”) = 8 ESUBD(“gas”) = 5 ESUBM(“gas”) = 10
IfW Kiel/DART	Recursive-dynamic CGE	22	17	Elec. versus 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
Tsinghua/ C-GEM	Recursive-dynamic CGE	14	21	Elec. versus fossil fuel aggregate = 0.6–0.9 for EITE sectors 0.5 for other	e/(KL): 0.1 for elec. 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

(*Continued*)

Table 2. (*Continued*)

Organization/ model name	Model class	# of regions	Sectors	Inter-fuel substitution	KLE elasticity	Armington elasticities
TU-Berlin/ TU-Berlin Model	Static CGE with target-year forward calibration	14	14 + 3 final demand sectors (Government, Consumption, Investment)	Elec. versus fossil fuel aggregate = 1 Elec. versus 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 ESUBM(oil) = 8 ESUBD(gas) = 5 ESUBM(gas) = 10
ZEW/PACE	Static CGE with target-year forward calibration	14	10	Elec. versus fossil fuel aggregate = 0.5	default: 0.5 (elec. sector: 1)	GTAP

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). We use the same scenarios as in Böhringer *et al.* (2021). 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) and aggregations of sectors and regions.

For the static models, a single projection is needed for 2030. For the recursive dynamic models, projections are required for multiple periods at one- or five-year intervals to 2030. Additionally, most models only use GDP and emissions at the aggregate level for forward projection. However, in some of the models, energy flows are further constrained by using sectoral GDP in addition. Across the models in this study, these two aspects of the projection methods resulted in substantial differences in the economic structure (i.e., sector shares), energy flows, and the resulting emissions intensity. In the forward projection, all models use the projected GDP (i.e., value-added by labor and capital) and emissions at the aggregate level available from external sources such as WEO as the targets and allow the model to endogenously determine the sectoral level of energy flows and economic activities. However, some models also use sector-level energy demand, activity level, and emissions to calibrate. For example, the EC-MSMR for Canada soft-links with its E3MC model for projecting oil and gas supply by technology characteristics. 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 Sec. 4.4 on model uncertainty.

3.3. *Scenario design*

Trading coalitions 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). The welfare effects of each trading coalition 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). We use the targets as specified in Böhringer *et al.* (2021) who translate the NDCs into region-specific CO_2 emission reduction requirements in percent from the 2030 business-as-usual emission levels. So, for example, to translate NDCs given at the county level to regional NDCs they calculate the implied absolute emission reductions for each country relative to their set 2030 business-as-usual emission level, aggregate these absolute reductions and derive a percentage reduction for the entire region. Also, the assumed GDP path in the business-as-usual scenario

Table 3. Scenario design.

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

determines the reductions implied by intensity targets as e.g. in China. 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 CO_2 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 CO_2 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 (Supplementary Information, Table S4). 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 Appendix A.

The multi-region coalitions modeled in this effort are shown in Table 3, Panel 1. The selection of these emissions trading coalitions was informed by the coalitions 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 coalitions. In principle, it would be ideal to look at all the potential combinations of trading coalitions. However, in practice, a balance was needed between evaluating a wide number of plausible trading coalitions and the ability of each modeling team to generate results. Thus, other trading coalitions are also plausible but are not included here.

Emissions from the EITE sectors are projected to be around 38% of global emissions for 2030. For the partial trading scenarios, the regional emission targets for the combined trading sectors (EITE sectors and power sector) equal the emissions of these sectors in a reference (REF) unilateral action only scenario (a no-trading/no-linkages scenario). The regions not participating in trading coalitions 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.

4. Results and Discussion

Overall, the results from this effort confirm that substantial reductions in the costs of mitigation can be achieved through emissions trading. However, the relative gains across these trading coalitions depend on the difference in 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 coalitions. Nonparticipants may also be affected due to the indirect effects of imports and exports.

Looking across models, while the magnitude and the direction of the change in welfare are generally consistent, there are also some regional trading coalitions where the models show divergent results for some participants. This inter-model variability indicates on the one hand where results are most sensitive to the diverse modelling choices and on the other hand where the simulated effects are most reliable, because they are not affected by those choices.

4.1. *Global welfare effects of regional trading coalitions*

Figure 1 shows the change in global welfare across all coalitions by climate target and model for both all-sector and EITE-only trading scenarios. The gains from joint carbon pricing 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 two

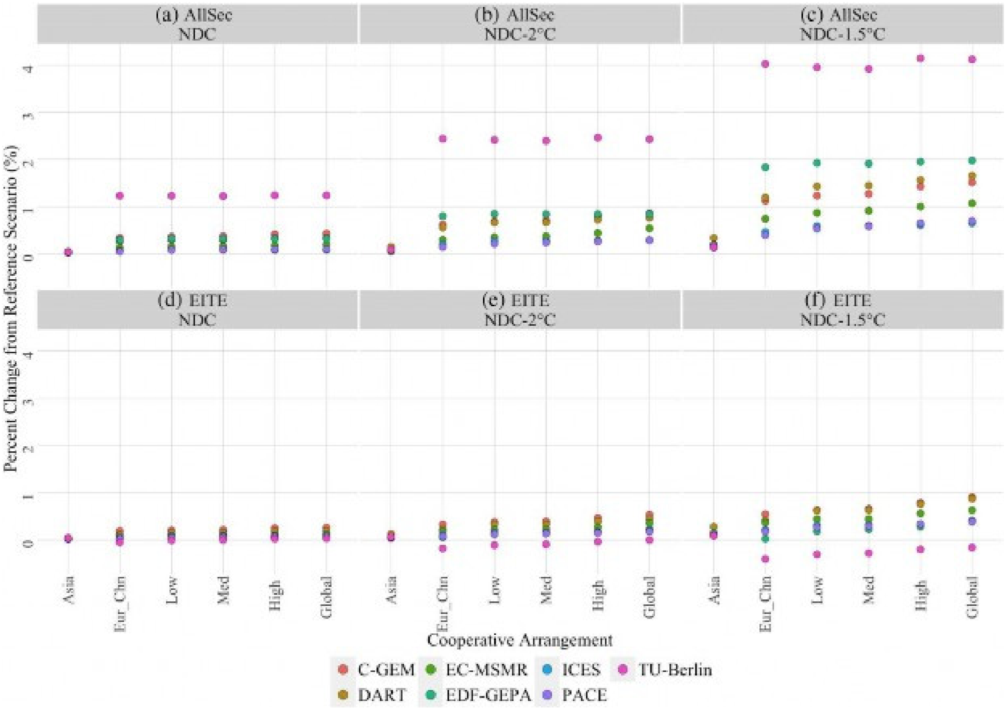

Figure 1. Change in global welfare by coalition size and stringency with all sectors (panels (a)–(c)) and for EITE sectors only (panels (d)–(f)). Panels (a) and (d) are the NDC pathways. Panels (b) and (e) are the NDC pathway augmented to approximate the emission reductions consistent with a 2°C end-of-century 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.

to three times when shifting from NDC to NDC-2°C, and again by roughly two 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 0.1–0.4% for NDC and 0.3–0.9% for NDC-2°C. There is only one outlier, the TU-Berlin model, where welfare gains are much larger (NDC: 1.2%; NDC-2°C: 2.4%). This result can be explained by less flexibility in national abatement due to low energy efficiencies and trade elasticities. 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 0.7–2.0%, and again one outlier (TU-Berlin) showing a 4.1% gain in global welfare.

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 the regional participation scenario “Low” 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. As Babiker *et al.* (2004) point out, this can e.g. be the case due to pre-existing distortionary taxes. See also Sec. 4.4 for more information on model heterogeneity.

Figure 2 shows how much of the efficiency gain from a global trading market is observed in the different trading coalitions and the sectoral coverage. Multi-regional trading coalitions 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 coalitions with fewer countries can comprise a substantial percentage of the global emissions: ASIA covers on average one-third of global emissions when all sectors are included in the emissions trading, and EUR_CHN covers up to 38% of global emissions. By comparison, the high participation coalitions covers around three-quarters of global emissions. In the EITE sectors, 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 emissions 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.

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 coalition is substantial — up to 66% difference between models. Figure 2 also highlights that there are further coalition scenarios besides a global carbon market (scenario Global_AllSec) where positive welfare gains relative to the individual carbon pricing scenario (REF) exist.

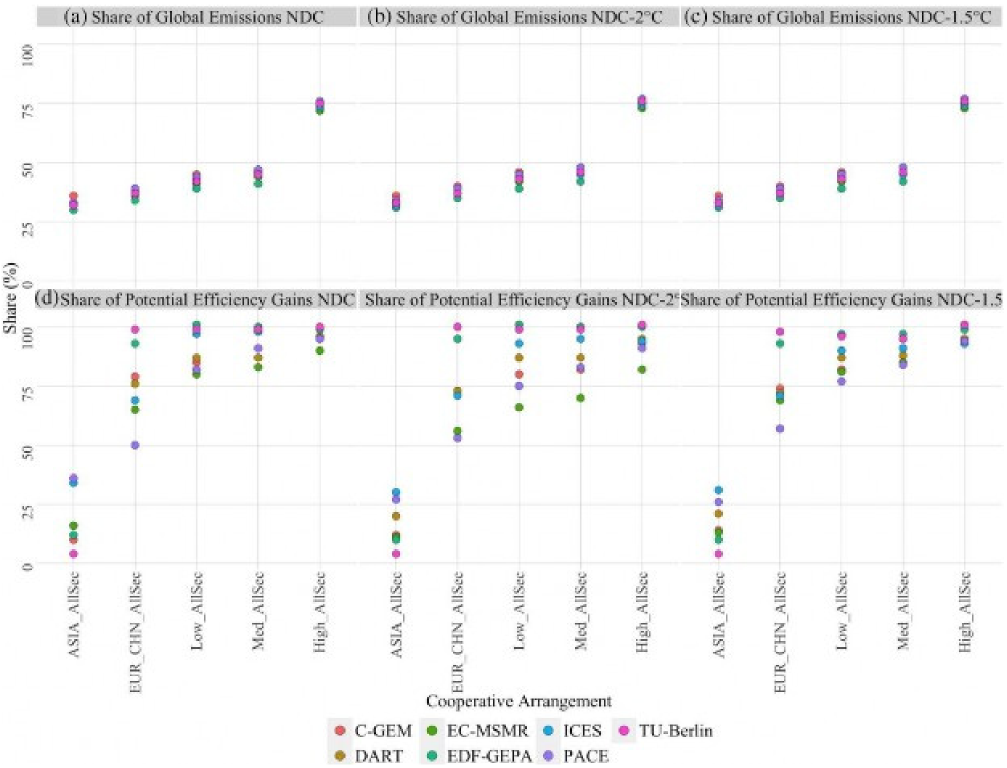

Figure 2. Shares of emissions covered by the joint emissions trading system as a percentage of the global emissions and share of welfare gains as a percentage of the gains in a global all sector market in 2030 under different emission reduction targets. The median and range (minimum and maximum) across models are displayed. All negative values result from one outlier (TU-Berlin). A corresponding EITE figure is included in the Supplementary Information (Supplementary Information, Fig. S11).

When only the EITE sectors are included in the trading coalitions, the welfare changes are smaller than when all sectors are included, in line with the smaller share of global emissions covered in these scenarios.

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

In the regional participation scenario "Low", the emissions covered in the trading coalition increase by 5–6% (2% when only EITE sectors are covered) with an increase of 11–15% (12–13%, 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 coalition. 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 (1–4%) in the medium participation coalition 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 coalitions, the increase in the share of emissions (29% for all sectors versus 12–17% for EITE sectors only) is substantially higher than the increase in the efficiency gains (5–7% for all sectors versus 3–8% for EITE sectors only). In this coalition, the USA and OAM now face a lower carbon price. However, their relatively low welfare gains in this coalition are offset by the higher prices for the other participants, including India. The energy markets and trade effects (Sec. 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.

4.2. *Participant incentives to participate in regional coalitions*

The divergence of the carbon prices for unilateral action compared to the price in a trade coalition also measures the incentive to participate in regional emissions trading. Figure 3 shows the carbon prices for individual, nonlinked carbon pricing for each region in 2030, while Fig. 4 shows the carbon prices in the different coalitions covering all sectors both by emission pathway and model. 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

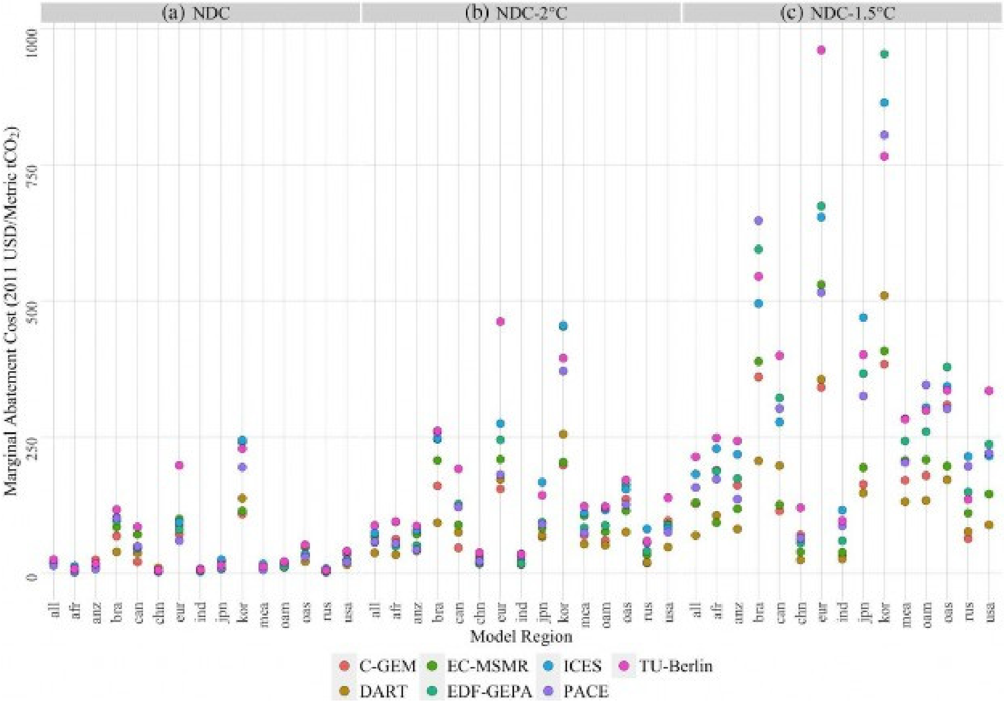

Figure 3. Marginal abatement costs (in $/tCO$_2$ abated) for individual, nonlinked carbon pricing by model region in 2030. Panel (a) is the NDC pathway. Panel (b) is the NDC pathway augmented to approximate the emission reductions consistent with a 2°C end-of-century temperature target. Panel (c) is the NDC pathway augmented to approximate the emission reductions consistent with achieving a 1.5°C end-of-century temperature target.

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 $/tCO$_2$ to 38 $/tCO$_2$ in 2030 for the NDC pathway to 110 $/tCO$_2$ to 287 $/tCO$_2$ for the NDC-1.5°C pathway, respectively. This difference in the prices across models is largely due to the model structure, key parameter values such as inter-fuel substitution elasticities, and, most importantly, the calibrated structure of the economies in different models in 2030. For example, TU-Berlin has higher carbon prices as it also has the lowest carbon intensity of all the models.

The global carbon price ranges from approximately \$10 to \$20/tCO$_2$ in the NDC pathway to \$60 to \$240/tCO$_2$ 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

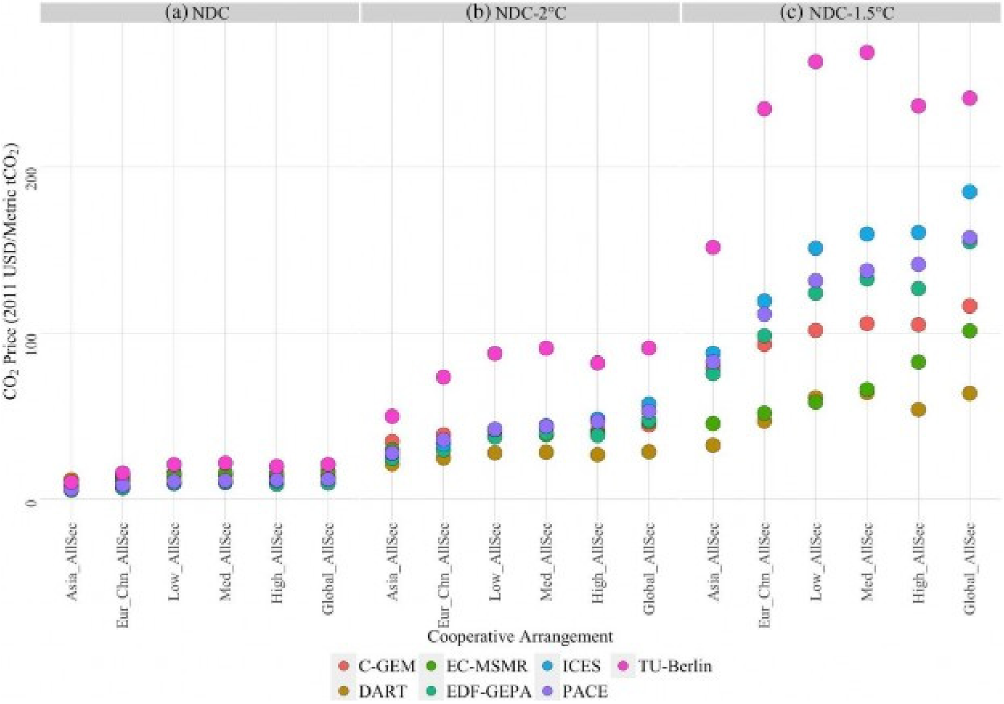

Figure 4. CO_2 price (in USD/tonne of CO_2) for participants in the multi-region trading coalitions for all sectors. Panel (a) is the NDC pathway. Panel (b) is the NDC pathway augmented to approximate the emission reductions consistent with a 2°C end-of-century temperature target. Panel (c) is the NDC 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.

as the stringency increases. Finally, the models do not agree on the direction of the trade for Australia/New Zealand at any level of stringency. More information on the volume and direction of the trade in emissions is found in Supplementary Information, Table S5. The same analysis was conducted for the EITE sector only (See Supplementary Information, Fig. S7).

While all trading coalitions generate gains in welfare, different regions may prefer more limited trading coalitions 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 coalitions. This can be compared to coalitions 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 CO_2 price. For the scenarios run in this paper, when the EU–China coalition 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 coalitions expand to more countries varies by model. Whether adding additional countries to these trading coalitions (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, nonparticipant carbon prices also change. Generally, carbon prices decrease for nonparticipants relative to the nonclimate 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 coalitions, all models show that trading coalitions with more limited regional participation provide economic gains at the aggregate level for the participants. These gains increase with the stringency of climate targets (see Supplementary Information, Fig. S12). The trading coalitions 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.

When the gains are evaluated off a no-trading baseline for the participating regions, the relative gains as more participants join depend 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 4 indicates the incentives for the different regions to participate in trading coalitions by whether the coalitions 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 of models that shows losses. If results differ across reduction targets this is shown in brackets. In addition, the darker a cell, the higher the number of models finding gains. To give an example, for the coalition between China and Japan and South Korea (ASIA), four models show that this is welfare enhancing for China under the NDC targets and relative to the no-trade scenario and three show that welfare in China decreases. For both the 1.5°C and the 2°C targets, five models show that this coalition is welfare enhancing for China and two show that welfare in China decreases. Given that the results are mixed, but still more models show gains than losses, the cell has a light grey color.

Among the EITE-coalitions 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

Table 4. Participants' welfare gains in a given trading coalition for EITE sector emission coverage relative to meeting emission targets through individual, nonlinked carbon pricing 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.

	Regional trading coalitions					
Participants	Asia	EUR_CHN	Low	Med	High	Global
EUR		7/0	7/0	7/0	7/0	7/0
CHN	4/3 (NDC)	5/2 (NDC)	5/2 (NDC)	5/2 (NDC)	5/2 (NDC)	5/2 (NDC)
	5/2	4/3 (2C)	6/1	6/1	6/1	6/1
		6/1 (1.5C)				
JPN	0/7 (NDC)		1/6 (NDC)	1/6 (NDC)	1/6 (NDC)	1/6
	7/0		3/4 (2C)	3/4 (2C)	3/4 (2C)	4/3 (1.5C)
			7/0 (1.5C)	6/1 (1.5C)	7/0 (1.5C)	
KOR	7/0		7/0	7/0	7/0	7/0
CAN			7/0 (NDC)	7/0 (NDC)	7/0 (NDC)	7/0 (NDC)
			6/1	6/1	6/1	6/1 (2C)
						5/2 (1.5C)
BRA				6/1	6/1	6/1
				5/2 (1.5C)	5/2 (1.5C)	4/3 (1.5C)
ANZ				6/1	5/2	5/2
				4/3 (1.5C)	4/3 (1.5C)	3/4 (1.5C)
OAM					5/2 (NDC)	5/2 (NDC)
					6/1	6/1
IND					3/4	3/4 (NDC)
					5/2 (1.5C)	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

the highest welfare gains for the EU. Thus, the EU would prefer smaller coalitions with China. Similarly, Korea unambiguously experiences economic gains from participation in emissions 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 coalitions. 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 coalitions. Only about half of the models report that India gains from permit trading when India participates in the market.

For full sector trading (see Supplementary Information, Table 2.8), more regions gain for all coalitions. Under the NDC targets there is one unambiguously beneficial coalition for its members which is the coalition between the EU and China. There are also little incentives for most regions to move to larger coalitions (see Supplementary Information, Table S12). 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.

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 fuel substitution capability of the EITE and electricity sector. 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.

First, 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. However, when combined with permit trading, the decrease in the global demand for energy inputs is not as large. Now, net energy importers may become disadvantaged relative to no-emissions 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 S13 in the Supplementary 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.

Second, there are spillovers in the EITE sectors. The differences in countries' abatement costs influence the international competitiveness, especially of their more EITE goods. As shown in Sec. 4.2, domestic-only reductions along the NDC pathways 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. In Supplementary Information, Table S14, the projections for the exports and EITE trading positions for the different model regions are shown for EITE-onlydomestic-only NDC emission reductions. 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.

All net importers of fossil energy benefit if climate policy decreases the global demand for fossil fuels as their prices net of carbon costs also decrease. In contrast, the opposite is true for net exporters 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 S14 in the Supplementary 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 coalition grows in regional scope, 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 coalitions 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 coalitions.
- India is dependent on international trade for energy and other export goods. As a result, India experiences welfare losses under regional permit trading coalitions 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. India can also expand its share of the international goods markets. These two gains compensate for potential losses arising from increased energy prices 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 coalitions 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.

4.4. *Observations on the variability between CGE models and implications for carbon market coalitions*

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 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, even though the models are calibrated to the same regional GDP an emission levels, there is more variability in the sectoral composition of GDP and emissions, trade orientation, energy use, and emissions intensity across the models. These differences arise since modeling teams use different approaches and constraints to calibrate their models. 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. These differences in methodology result in variations in economic 'structures' across models.

Other factors such as 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, and it tends not to show as many positive welfare results. 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 coalitions are not necessarily favorable.

The interactions between South Korea, Japan, and China illustrate how model variability is an obstacle to market design. All models agree that joint emissions trading 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 coalitions and with all models, Japan faces losses in several trading coalitions, and China loses in a few coalitions (and in 3 out of 7 models). Thus, although some of the regions may face welfare losses when involved in carbon market coalitions, these losses can be addressed by compensation since the welfare effects of the regionally linked coalitions 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.

5. Conclusion

This paper assesses the welfare effects of emissions trading coalitions with different regional participation under climate target stringency and sectoral coverage relative to unilateral action using a set of CGE models. All models confirm that global cooperation through joint emissions trading systems 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 coalitions with more limited regional participation provide 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 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).

Broad emissions trading coalitions 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 other cases, the aggregate economic gains from increased participation do not necessarily benefit all participating regions. The distribution of the welfare gains by region varies 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 sensitivity of CGE models to individual modelling choices. Differences in the magnitude and the direction of welfare effects are observed for some regions under some trading coalitions 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 co-operation in carbon pricing worldwide.

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Supplementary Information

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References

Aguiar, A, B Narayanan and R McDougall (2016). An overview of the GTAP 9 database. *Journal of Global Economic Analysis*, 1, 181–208.

Akimoto, K, F Sano and BS Tehrani (2017). The analyses on the economic costs for achieving the nationally determined contributions and the expected global emission pathways. *Evolutionary and Institutional Economics Review*, 14, 193–206.

Aldy, J, W Pizer, M Tavoni, LA Reis, K Akimoto, G Blanford, C Carraro, LE Clarke, J Edmonds and GC Iyer (2016). Economic tools to promote transparency and comparability in the Paris Agreement. *Nature Climate Change*, 6, 1000–1004.

Alexeeva, V and N Anger (2016). The globalization of the carbon market: Welfare and competitiveness effects of linking emissions trading schemes. *Mitigation and Adaptation Strategies for Global Change*, 21, 905–930.

Babiker, M, J Reilly and L Viguier (2004). Is international emissions trading always beneficial? *The Energy Journal*, 25(2), 33–56.

Bodansky, DM, SA Hoedl, GE Metcalf and RN Stavins (2016). Facilitating linkage of climate policies through the Paris outcome. *Climate Policy*, 16, 956–972.

Böhringer, C and TF Rutherford (2002). Carbon abatement and international spillovers. *Environmental and Resource Economics*, 22(3), 391–417.

Böhringer, C, B Dijkstra and KE Rosendahl (2014). Sectoral and regional expansion of emissions trading. *Resource and Energy Economics*, 37, 201–225.

Böhringer, C, JC Carbone and TF Rutherford (2016). The strategic value of carbon tariffs. *American Economic Journal: Economic Policy*, 8(1), 28–51.

Böhringer, C, S Peterson, TF Rutherford, J Schneider and M Winkler (2021). Climate policies after Paris: Pledge, trade and recycle. Insights from the 36th Energy Modeling Forum study (EMF36). *Energy Economics*, 103, 105471. https://doi.org/10.1016/j.eneco.2021.105471.

Dellink, R, G Briner and C Clapp (2010). Costs, revenues, and effectiveness of the Copenhagen Accord emission pledges for 2020. OECD Environment Working Papers, No. 22, OECD Publishing, Paris, https://doi.org/10.1787/5km975plmzg6-en.

Dellink, R, S Jamet, J Chateau and R Duval (2014). Towards global carbon pricing: Direct and indirect linking of carbon markets. *OECD Journal: Economic Studies*, 2013, 209–234.

Fæhn, T, G Bachner, S Fujimori, M Hamdi-Cherif, E Lanzi, S Paltsev, T Vandyck, R Beach, B Cunha, R Garaffa and K Steininger (2020). Capturing key energy and emission trends in CGE models: Assessment of status and remaining challenges. *Journal of Global Economic Analysis*, 5(1), 196–272.

Fujimori, S, I Kubota, H Dai, K Takahashi, T Hasegawa, JY Liu, Y Hijioka, T Masui and M Takimi (2016). Will international emissions trading help achieve the objectives of the Paris Agreement? *Environmental Research Letters*, 11(10), 104001.

Gavard, C, N Winchester and S Paltsev (2016). Limited trading of emissions permits as a climate cooperation mechanism? US–China and EU–China examples. *Energy Economics*, 58, 95–104.

Hof, AF, MG den Elzen, A Admiraal, M Roelfsema, DE Gernaat, DP Van Vuuren (2017). Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2°C and 1.5°C. *Environmental Science & Policy*, 71, 30–40.

Hübler, M, S Voigt and A Löschel (2014). Designing an emissions trading scheme for China—An up-to-date climate policy assessment. *Energy Policy*, 75, 57–72.

International Energy Agency (IEA). (2018). World Energy Outlook—Executive Summary. OECD/IEA, Paris, France.

Keohane, N, A Petsonk and A Hanafi (2017). Toward a club of carbon markets. *Climatic Change*, 144, 81–95.

Kitous, A, K Keramidas, T Vandyck and B Saveyn (2016). GECO 2016: Global Energy and Climate Outlook: Road from Paris: Impact of climate policies on global energy markets in the context of the UNFCCC Paris Agreement. EUR 27952 EN. doi:10.2791/662470.

Lanzi, E, J Chateau and R Dellink (2012). Alternative approaches for levelling carbon prices in a world with fragmented carbon markets. *Energy Economics*, 34, S240–S250. doi: 10.1016/j.eneco.2012.08.016.

Lessmann, K, U Kornek, V Bosetti, R Dellink, J Emmerling, J Eyckmans, M Nagashima, H-P Weikard and Z Yang (2015). The stability and effectiveness of climate coalitions: A comparative analysis of multiple integrated assessment models. *Environmental and Resource Economics*, doi: 10.1007/s10640-015-9886-0.

Li, M, Y Weng and M Duan (2019). Emissions, energy and economic impacts of linking China's national ETS with the EU ETS. *Applied Energy*, 235, 1235–1244.

Li, M and M Duan (2020). Efforts-sharing to achieve the Paris goals: Ratcheting-up of NDCs and taking full advantage of international carbon market. *Applied Energy*, 280, 115864.

Liu, Y and T Wei (2016). Linking the emissions trading schemes of Europe and China — Combining climate and energy policy instruments. *Mitigation and Adaptation Strategies for Global Change*, 21, 135–151.

Massetti, E and M Tavoni (2012). A developing Asia emission trading scheme (Asia ETS). *Energy Economics*, 34, S436–S443.

Newell, RG, WA Pizer and D Raimi (2013). Carbon markets 15 years after Kyoto: Lessons learned, new challenges. *Journal of Economic Perspectives*, 27, 123–146.

Nong, D and M Siriwardana (2018). The most advantageous partners for Australia to bilaterally link its emissions trading scheme. *International Journal of Global Warming*, 15, 371–391.

Okagawa, A and K Ban (2008). Estimation of substitution elasticities for CGE models. Discussion Paper 08–16. Graduate School of Economics and Osaka School of International Public Policy, Osaka, Japan.

Oliveira, TD, AC Gurgel and S Tonry (2019). International market mechanisms under the Paris Agreement: A cooperation between Brazil and Europe. *Energy Policy*, 129, 397–409.

Peters, JC (2016). The GTAP-power data base: Disaggregating the electricity sector in the GTAP data base. *Journal of Global Economic Analysis*, 1, 209–250.

Qi, T, N Winchester, V Karplus and X Zhang (2013). The energy and economic impacts of expanding international emissions trading. MIT Joint Program.

Ranson, M and RN Stavins (2016). Linkage of greenhouse gas emissions trading systems: Learning from experience. *Climate Policy*, 16(3), 284–300.

Rose, A, D Wei, N Miller and T Vandyck (2017). Equity, emissions allowance trading and the Paris agreement on climate change. *Economics of Disasters and Climate Change*, 1, 203–232.

Rose, A, D Wei, N Miller, T Vandyck and C Flachsland (2018). Policy brief—Achieving Paris climate agreement pledges: Alternative designs for linking emissions trading systems. *Review of Environmental Economics and Policy*, 12, 170–182.

Vöhringer, F (2012). Linking the Swiss emissions trading system with the EU ETS: economic effects of regulatory design alternatives. *Swiss Journal of Economics and Statistics*, 148, 167–196.

Zhang, L, Y Li and Z Jia (2018). Impact of carbon allowance allocation on power industry in China's carbon trading market: Computable general equilibrium based analysis. *Applied Energy*, 229, 814–827.