The Strategic Value of Carbon Tariffs[*]

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Abstract

We ask whether the threat of carbon tariffs might lower the cost of reductions in world carbon emissions by inducing unregulated regions to adopt emission controls. We use a calibrated simulation model to generate the payoffs of a game in which a coalition regulates its own emissions and chooses whether or not to employ carbon tariffs against unregulated regions. Unregulated regions respond by abating, retaliating, or ignoring the tariffs. In the unique Nash equilibrium, the use of tariffs is a credible and effective threat. It induces cooperation from non-coalition regions that lowers the cost of global abatement substantially relative to the case where the coalition undertakes this abatement alone.

Keywords: climate policy, border tax adjustments, carbon leakage.

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1 Introduction

A central preoccupation of the international climate-change debate is the question of when developing nations should accept binding targets on their carbon emissions. Developing countries argue that, in the near term, it is unfair to ask them to cut back on their emissions without compensation for the effect it would have on their prospects for economic growth. At the same time, the unilateral carbon policies currently being pursued (or contemplated) by developed countries are likely to be highly inefficient due to the fact that these countries have relatively high abatement costs. Unilateral policies are also subject to carbon leakage — an increase in demand for carbon pollution outside of the regulated jurisdiction due to a policy's effect on the prices of pollution-intensive goods and fossil fuels — which reduces the global cost effectiveness of subglobal action even further (Hoel 1991, Felder and Rutherford 1993).

In theory, a global emissions cap-and-trade system (or a global carbon price and a set of transfers) could deliver on the demands of developing countries and control world emissions in a cost-effective way. Yet the international policy process remains far from reaching the level of consensus that would be required to implement such a scheme.

Against this background, many policy analysts have noted that trade policies could serve as a means to regulate carbon emissions in countries that have no domestic emission controls. The rationale for these measures stems from the observation that developed countries are currently (and increasingly) net importers of embodied carbon emissions from their developing-world trade partners (Peters, Minx, Weber and Edenhofer 2011). In fact, the European Union has already resorted to the use of a "border carbon adjustment" to regulate emissions in international air travel.[1] Border carbon adjustments were also a feature of H.R. 2454, the climate legis-

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[1] A concise description of the specific regulation is provided at: `http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm`.

lation passed in the United States House of Representatives in 2009.

One way that trade measures could function as an instrument of climate policy is by directly stifling demand for carbon-intensive goods produced in unregulated countries. In this capacity, carbon tariffs — tariffs levied on the direct and indirect carbon emissions embodied in imported goods — have support from the theory of second-best environmental regulation; if governments cannot regulate foreign emissions at the source, tariffs may be justified (Markusen 1975, Hoel 1996). They also have a clear political attraction to climate-concerned countries as a way to protect the competitiveness of energy-intensive, trade-exposed (EITE) industries.

Implementing carbon tariffs, however, could come with substantial costs. Whether or not they could be designed in a manner that is legal under current international trade agreements is an on-going and intensively contested debate.[2] Moreover, the task of calculating tariff rates based on foreign pollution levels is likely to be difficult and contentious [3] For both

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[2] Most scholars focus on implementing taxes on imports as we do in our experiments here. A principle of product taxation under Article III of the General Agreement on Tariffs and Trade (GATT) is that "like" products of domestic and foreign origins should be treated equally under the domestic tax system. It remains unclear whether or not two goods that are identical in all respects except for the embodied carbon emissions generated in their respective production processes would be deemed "like" products or what equal treatment would require. It may rule out, for example, taxing imported goods more heavily if they exhibit a larger carbon footprint. If so, this could limit the effectiveness of the tariffs. There are many informative discussions of the legal issues surrounding border carbon adjustments in the literature. See Pauwelyn (2007), Brewer (2008), Howse and Eliason (2008), Charnowitz, Hufbauer and Kim (2009), Cosbey, Dröge, Fischer, Reinaud, Stephenson, Weischer and Wooders (2012), McAusland and Najjar (2013).

[3] The complexity of calculating defensible measures of embodied carbon for goods with long and complicated supply chains would likely limit tariff coverage to a fraction of the total emissions embodied in trade. Furthermore, regulators would ideally trace out supply chains for individual firms and all of their upstream partners to calculate individualized tariff rates but this is a challenging and expensive task. In practice, the tariffs rate would likely be calculated based on industry-average measures of embodied carbon in each country. A number of authors have proposed establishing default rates (based on industry-average data, industry-average data from the country imposing the tariffs or data from best available technologies) combined with a process whereby firms can pay to have a third party document their specific emission profile (Cosbey et al. 2012,

of these reasons, there might be a real risk to disrupting the regime of relatively free trade that has emerged under the World Trade Organization (WTO) if climate and trade policies are linked via carbon tariffs.[4]

The effectiveness of tariffs would also be limited to the extent that countries can find alternative, unregulated markets in which to sell their carbon-intensive products.[5] There is a sizable literature employing numerical partial and general equilibrium models to evaluate the performance of border carbon adjustments. Many of these studies find that these instrument can be effective at curbing carbon leakage and offsetting competitivness losses but have a relatively limited ability to decrease the global efficiency cost of meeting abatement targets. With respect to carbon tariffs, many also identify a strong distributional effect from their use, shifting the burden of climate policy to the countries subjected to them.[6] [7]

To date, research has focused almost entirely on the effectiveness of carbon tariffs as a form of direct regulation. However, trade measures

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McAusland and Najjar 2013). This would have the twin advantages of increasing the likelihood of WTO compatability and reducing administrative costs.

[4] See Ederington (2010) for a review of the arguments for and against linking the WTO to the negotiation and enforcement of environmental standards.

[5] See Markusen (1975), Hoel (1996) and Copeland and Taylor (2004). Another potential reaction to carbon tariffs is "re-shuffling" of production, where less carbon-intensive varieties of a good are shipped to regulated countries while more carbon-intensive varieties are reallocated to unregulated ones (Bushnell, Peterman and Wolfram 2008).

[6] For example, see the special issue on the evaluation of border carbon adjustments in Energy Economics, December 2012. Böhringer, Balistreri and Rutherford (2012a) provides an overview of the issues and model results.

[7] It is also worth noting that, for relatively modest abatement targets, quantitative studies tend to find that the competitiveness losses to domestic EITE sectors are also modest. For example, see Ho, Morgenstern and Shih (2008), Interagency Competitiveness Analysis Team (2009) and Aldy and Pizer (2011) for analysis of impacts on U.S. industries. The impetus for carbon tariffs to combat adverse competitiveness effects is reduced in this case. There are also less politically-inflammatory policy instruments than carbon tariffs that have been proposed with a similar ability to offset competitiveness effects provided the abatement target is not too ambitious. Output-based rebating (an output subsidy combined with a pollution tax) or free allocation of permits under a cap-and-trade system are widely discussed alternatives (Fischer and Fox 2007, Fischer and Fox 2012, Böhringer, Carbone and Rutherford 2012b).

could also work to control pollution indirectly — as an environmentally-sanctioned punishment that speeds the adoption of emission controls in unregulated countries. The burden-shifting effect identified by the quantitative literature suggests that carbon tariffs have the potential to confer substantial trade gains to countries that use them and trade losses to those subjected to them (Böhringer et al. 2012b). Thus the threat of carbon tariffs — rather than their actual application — could lead to more effective carbon abatement policy if unregulated countries prefer to adopt domestic emission controls than to face tariffs. It is this role for carbon tariffs that we explore here.

The Montreal Protocol, the international agreement responsible for regulating the use of ozone-depleting substances, is a prominent example of this idea put into practice.[8] While the trade sanctions it specifies have never been envoked, the credible threat of their use is thought to be important in sustaining the widespread participation it has produced. It has been argued that this approach may be applicable to international climate negotiations (Barrett 2010, Barrett 2011). Game-theoretic analyses also show that international cooperation on transboundary pollution control may be advanced by the use of trade sanctions as an enforcement tool (Spagnolo 1999, Ederington 2004, Limao 2005).

On the other hand, countries subjected to carbon tariffs may prefer to adopt countervailing tariffs of their own rather than suffer the cost of emissions regulation, a response that could significantly increase costs of combating global warming. Many policymakers have expressed concern that the specter of the tariffs could disrupt on-going international climate policy negotiations or trade relations (Houser, Bradley and Childs 2008, ICTSD 2008).

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[8] Currently, all member of the United Nations have ratified the Montreal Protocol. It must be acknowledged, however, that the scope and cost of the problem it addresses are also considered to be far less than for carbon pollution. Achieving international cooperation on carbon abatement has, thus far, proven to be a more difficult undertaking.

In this paper we ask: which of these regimes is likely to arise from the self-interested policy choices of countries and what does it mean for the prospect of designing effective international responses to climate change? To answer these questions we use a computable general equilibrium (CGE) model of the world economy and carbon emissions to generate the payoffs of a policy game.

In the game, we assume that a coalition of Annex-I countries (those countries that agreed to take on abatement responsibilities under the Kyoto Protocol) is commited to reducing global emissions below business-as-usual levels. To achieve this goal, the coalition regulates its domestic emissions. Coalition members also choose whether or not to deploy carbon tariffs against non-coalition countries with unregulated emissions. Non-coalition countries may respond by adopting emission regulations of their own, retaliating against the carbon tariffs with countervailing measures, or by taking no action — leaving their emissions unregulated (and suffering the consequences of the carbon tariffs should they be employed.) We consider Nash equilibria of a simultaneous-move game in which no coalition member wishes to change its policy with regard to the use of carbon tariffs and no non-coalition region wishes to change how it responds to the coalition given the policies of other model regions.

In our baseline policy experiments, there is a unique Nash equilibrium prediction. We find that the threat to use carbon tariffs is credible for all coalition regions. In response, China and Russia — two major polluters outside the coalition — respond by adopting binding abatement targets. All other non-coalition countries prefer to retaliate.

Cooperation by China and Russia lowers the global welfare cost of achieving a 10% reduction in global emissions by half relative to the case where coalition countries undertake all of this abatement on their own.

China and Russia are motivated to cooperate for two main reasons. First, they avoid the punishment of carbon tariffs by doing so. Second, they are dependent on the economic performance of coalition economies — as a destination market for their exports and as the origin of imports. When China and Russia take on some of the abatement responsibility, less is required of coalition countries to meet the assumed global reduction target. In addition, the overall efficiency of the global economy improves when these countries take on more of the global abatement burden because they are the source of low-cost abatement opportunities. Thus, the global pattern of abatement effort moves closer to a first-best allocation. Both of these effects benefit China and Russia.

These findings are robust to a number of key assumptions regarding the structure of the policy game, the ambition of the coalition in reducing global emissions and key parameter values in the calibration of the CGE model used to generate the game payoffs.

Our analysis contributes to the large literature on quantitative assessment of border carbon adjustments, as it is the first to consider the role of these instruments as an inducement to cooperation rather than a direct source of environmental improvement. It is also connected to the game-theoretic literature examining whether or not linking international trade and environmental agreements can promote more effective cooperation on transboundary pollution problems (Spagnolo 1999, Ederington 2004, Limao 2005); none of the experiments in that literature attempt to quantify these outcomes or develop applications to the problem of climate change policy.

The rest of the paper proceeds as follows. Section 2 describes the structure of the CGE model and the data we use to generate the payoffs for our policy game. Section 3 explains the structure of the policy game. Section 4 reports on the results of our main policy experiments. Section 5 describes sensitivity analysis with respect to key assumptions in the CGE model and the structure of the policy game. Section 6 concludes with a discussion of the policy significance of our results.

2 Model and Data

In our analysis, we adapt a generic multi-region, multi-sector CGE model of global trade nd energy use established for the analysis of greenhouse gas emission control strategies by Böhringer and Rutherford (2010).[9] The model features a representative agent in each region that receives income from three primary factors: labor, capital, and fossil-fuel resources. Labor and capital are intersectorally mobile within a region but immobile between regions. Fossil-fuel resources are specific to fossil fuel production sectors in each region. Production of commodities, other than primary fossil fuels is captured by three-level constant-elasticity-of-substitution (CES) cost functions describing the price-dependent use of capital, labor, energy and materials. At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital, and labor subject to a constant elasticity of substitution. At the second level, a CES function describes the substitution possibilities between intermediate demand for the energy aggregate and a value-added composite of labor and capital. At the third level, capital and labor substitution possibilities within the value-added composite are captured by a CES function whereas different energy inputs (coal, gas, oil, and electricity) enter the energy composite subject to a constant elasticity of substitution. In the production of fossil fuels, all inputs, except for the sector-specific fossil fuel resource, are aggregated in fixed proportions. This aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution.

Final consumption demand in each region is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment (i.e., a given demand for savings) and exogenous government provision of public goods and services. Total income of the representative household consists of net factor income and tax revenues.

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[9] A detailed algebraic model summary as well as schematic representations of the main production structures is provided in Appendix A.

Consumption demand of the representative agent is given as a CES composite that combines consumption of composite energy and an aggregate of other (non-energy) consumption goods. Substitution patterns within the energy bundle as well as within the non-energy composite are reflected by means of CES functions.

Bilateral trade is specified following the Armington's differentiated goods approach, where domestic and foreign goods are distinguished by origin (Armington 1969). The exception is the international market for crude oil, which we assume is perfectly homogenous. All goods used on the domestic market in intermediate and final demand correspond to a CES composite that combines the domestically produced good and the imported good from other regions. A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

CO_2 emissions are linked in fixed proportions to the use of fossil fuels, with CO_2 coefficients differentiated by the specific carbon content of fuels. Restrictions to the use of CO_2 emissions in production and consumption are implemented through exogenous emission constraints or (equivalently) CO_2 taxes. CO_2 emission abatement then takes place by fuel switching (inter-fuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities).[10]

We determine the free parameters of the functional forms (i.e., cost and expenditure functions) such that the economic flows represented in the base-year data are consistent with the optimizing behavior of the model agents. The base-year data stems from the GTAP 8 database which includes detailed national accounts on production and consumption (input-output tables) together with bilateral trade flows and CO_2 emissions for up to 129 regions and 57 sectors for the year 2007 (Narayanan, Aguiar and

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[10] Revenues from emission regulation accrue either from CO_2 taxes or from the auctioning of emission allowances (in the case of a emissions cap-and-trade system) and are recycled lump sum to the representative agent in the respective region.

McDougall 2012).

The responses of agents to price changes are determined by a set of exogenous elasticities taken from the pertinent econometric literature. Elasticities in international trade come from the estimates included in the GTAP database. Substitution elasticities between the production factors capital, labor, energy inputs and non-energy inputs (materials) are taken from Okagawa and Ban (2008). The elasticities of substitution in fossil fuel sectors are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham, Thorpe and Hogan 1999, Krichene 2002).

In our analysis, we adopt the 2007 base year described in the GTAP dataset as the pre-policy equilibrium against which we compare the effects of climate policy regimes. We aggregate the 57 sectors provided by the GTAP database into 13 sectors. The energy goods identified are coal, crude oil, natural gas, refined oil products, and electricity which allows us to distinguish energy goods by CO_2 intensity and to capture the potential for inter-fuel switching. Furthermore, we consider a variety of energy-intensive (non-energy) commodities that are most exposed to unilateral climate policies: chemical products; mineral products; iron and steel; non-ferrous metals; air, land and water transports. At the regional level, we represent 9 major world regions meant to represent the key players in international climate policy negotiations.

Table 1 provides a list of sectors and regions for the composite dataset underlying our analysis. In our experiments, we assume that there is a coalition of countries that reduce their domestic carbon emissions and consider the use of carbon tariffs against non-coalition countries. Our default assumption is that the coalition includes all countries identified as Annex-I members under the Kyoto Protocol minus Russia.[11] The coalition or non-

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[11] Russia was a signatory to the Kyoto Protocol primarily because abatement targets for teh commitment periods (2008-2012) were defined relative to 1990 emission levels. Russia's economic collapse meant that their unregulated emission levels fell dramatically, such that Russia had the potential benefit from signing the agreement by selling

coalition membership is indicated in the table. The carbon tariffs and the retaliatory measures used by non-coalition members are limited to a set of energy-intensive and trade-exposed (EITE) goods that, in practice, have received the most attention from policymakers as potential objects of regulation. The EITE sectors are indicated with the "*" symbol in the table. The mappings of regions and sectors from the fully disaggregate GTAP dataset to our aggregation are described in Appendix B.

Table 2 reports the 2007 base-year GDP, carbon emissions and carbon intensity levels by region from the GTAP data. Two patterns emerge from the data. First, coalition regions are large in terms of the amount of output they contribute to the world economy — collectively they represent over 70% of world output. As a result, they are likely to influence international prices by implementing unilateral emission regulation — both through the choice of how much domestic abatement to pursue and through the decision to employ carbon tariffs. Second, while they also contribute a substantial fraction of world carbon emissions (approximately 45%) they are significantly less carbon intensive per dollar of ouput produced. Among non-coalition regions, China and Russia stand out as the two most carbon-intensive regions.

3 Policy Game

3.1 Game Structure

We assume that — in the absence of any emission or policy response from non-coalition countries — coalition countries are (as a group) committed to reducing their emissions by 20% using a uniform carbon tax across all sectors and regions within the coalition. This is a commitment broadly

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off unused emission permits to other carbon-constrained countries even if no abatement measures were ever undertaken in Russia itself.

consistent with the targets negotiated under the Kyoto Protocol.[12] It translates into a global abatement rate of approximately 10% relative to pre-policy base-year emissions levels.

Figure 1 depicts the structure of our policy game. All players — coalition and non-coalition — make their moves in the game simultaneously. Both coalition members and non-coalition countries are assumed to realize the implications of the policy actions of all players for the general equilibrium adjustments in the world economy.

Each coalition region chooses either to use carbon tariffs against unregulated non-coalition countries (Tariff) or to not use them (No Tariff). Simultaneously, each non-coalition region chooses its response. In response to coalition regions that do not threaten to employ carbon tariffs, a non-coalition region may choose either to cooperate and adopt regional emission restrictions or do nothing and leave its emissions unregulated. Against coalition regions that do threaten tariffs, a non-coalition region may choose between the two options just described as well as the option to retaliate by raising its import tariffs against these coalition members and leaving its emissions unregulated. On a branch of the game tree in which tariffs are threatened, a non-coalition region is subject to carbon tariffs unless they choose cooperation, in which case they are not subject to carbon tariffs.

The policy responses available to non-coalition countries are described in more detail below.

Cooperate (C) — the non-coalition region restricts domestic emissions by an amount equal (as a percentage of its pre-policy base-year emissions) to the reductions undertaken by the coalition. Non-coalition abatement takes place via a regional carbon tax that is uniform across all of the region's sectors (or, equivalently, a regional system of tradable emission permits).

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[12] For detail on the abatement pledges made by countries in the Post-Kyoto period up to 2020, see Appendix I - Quantified economy-wide emissions targets for 2020 available at: `http://unfccc.int/meetings/copenhagen_dec_2009/items/5264.php`.

Retaliate (R) — the non-coalition region raises a uniform import tariff on EITE goods from coalition regions which threaten tariffs such that the added revenue generated by this tariff equals the revenue generated by the carbon tariffs imposed on them. It continues to operate with unrestricted emissions.

Do Nothing (D-N) — the non-coalition region operates with unrestricted emissions.

When coalition regions employ carbon tariffs, the tariff rates are levied on the carbon emissions embodied in EITE imports from non-coalition regions. In our simulations, embodied emissions are comprised of direct emissions (those emerging from the combustion of fossil fuels in EITE production) and indirect emissions from electricity inputs (i.e., emissions caused by the generation of electricity which is used in EITE production). It is straightforward to calculate these emissions from the multi-region, multi-sector GTAP dataset (Böhringer, Carbone and Rutherford 2011). The effective carbon tariffs then emerge as the product of the emission price in coalition regions and the embodied (sector- and region-specific) carbon content of the imported goods.

When non-coalition regions choose to retaliate, they calculate their countervailing tariff rates (uniform across sectors and coalition regions) such that the value of the tariff revenues equal the value of the revenues by the carbon tariffs imposed by coalition regions on them.

3.2 Discussion of Key Assumptions

A number of assumptions underlying the policy scenarios deserve further discussion. We explore the sensitivity of our results to a number of these assumptions in Section 5.

Despite its grounding in the policy process of Kyoto and post-Kyoto emission reduction pledges, the abatement target of the coalition in our baseline policy experiments might be considered an ambitious one. A less stringent target will attenuate the overall economic adjustment cost to emission constraints for the global economy and change the cost incidence across regions. The stringency of the abatement target thereby may have an effect on the credibility of using tariffs for coalition members or on the propensity for non-coalition regions to cooperate.

We hold global emissions constant across all of the policy scenarios. This accommodates a coherent cost-effectiveness comparison of alternative policy regimes without the need to evaluate the (rather uncertain) external costs of CO_2 emissions. There is also a behavioral rationale for holding global emissions constant. Ultimately, the outcome of interest is the non-cooperative determination of global abatement levels. Climate services are a global public good. A central prediction of models dealing with the voluntary provision of public goods is that substantial crowding out of individual contributions will occur when the aggregate supply of the public good increases (Bergstrom, Blume and Varian 1986). In our context, the rational response of coalition regions to increased levels of abatement in non-coalition regions is to curtail their effort. Holding global emissions constant amounts to assuming that there is full crowding out of Annex-I contributions to the public good when non-Annex-I regions increase their contributions.[13]

Coalition regions set carbon-tariff rates based on direct emissions from the burning of fossil fuels in the production of imported goods as well as the indirect emissions embodied in the electricity inputs to that production process. There are alternative assumptions represented in the literature on border carbon adjustments ranging from the use of just direct emissions (Mattoo, Subramanian, Mensbrugghe and He 2009) to the

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[13] A caveat here is that models of the voluntary provision of public goods typically assume that agents are unable to affect the price of contributing to the public good with their choice of contribution level. In our scenario, the price will depend on the performance of regional economies.

use of direct plus full indirect emissions embodied in goods (Böhringer et al. 2011). The measure we use here, direct emissions plus emissions from electricity inputs, is a policy-relevant compromise. It is significantly more comprehensive than using just direct emissions since electricity is an important, carbon-intensive input to many traded goods. However, it is also simple enough to implement (as opposed to those metrics based on the full input-output measures) that it is conceivable it would be practical as a policy design.

In our baseline policy game, the use of carbon tariffs and retaliatory tariffs are both available to coalition and non-coalition players respectively. Yet, a clear ruling from the WTO would likely make one instrument or the other legal but not both. As a result, there would be consequences for the use of an illegal tariff. We do not model these consequences explicitly in our policy game. Instead, we explore different regimes that might be consistent with different outcomes. Our baseline case — in which both instruments may be used — is consistent with an outcome in which the costs of illegal actions are sufficiently small as to leave a player's best responses in the game unaltered.

Alternatively, we consider a restricted version of the game in which the retaliation option is not available to non-coalition regions, modelling the case in which these costs are sufficiently large to rule them out. When carbon tariffs are illegal and the consequences of stepping outside of WTO law, we can explore the best responses of non-coalition regions assuming there is no threat of tariffs.

It is possible that the tariffs would be lucrative for coalition regions to impose even against *cooperating* non-coalition countries all else equal. In this case, the threat of carbon tariffs as a punishment for non-compliance is not credible because non-coalition regions can expect to be subjected to them regardless of their climate policy actions. To address this concern, we compare the payoffs of the Nash equilibrium that arises in our baseline policy experiment to the best responses of non-coalition regions when carbon tariffs are imposed irrespective of their actions. If we find that payoffs to coalition regions are higher in the baseline policy experiment, then this supports the finding that carbon tariffs are a credible threat.

Retaliation in our policy game means raising a uniform tariff on imports from coalition regions equal in value to the carbon tariffs placed on the retaliating region. This assumption is meant to capture the spirit of the retaliatory measures allowable under the WTO when a region is faced with a trade barrier the WTO deems illegal. Similarly, both the carbon tariffs and the countervailing measures are limited to a set of energy-intensive, trade-exposed goods (described in Table 1). It should be acknowledged, however, that alternative designs for the tariffs result in different potency, which could make cooperation from non-coalition regions either more or less likely.

Non-coalition cooperation in our model involves these regions taking on abatement responsibilities equal (as a percentage reduction from base-year emissions) to the abatement undertaken in the coalition in equilibrium. We also assume that non-coalition regions do not have access to trade in emission permits with each other or with coalition regions. While the specific requirement that abatement rates should be equal might appear arbitrary, it represents a strong impediment to sustaining cooperation from non-coalition regions as it assigns far more abatement responsiblity to these regions than current international climate negotiations are pursuing. If non-coalition regions can justify equilibrium abatement at this level, it is likely that cooperation in regimes with more modest commitments would be sustainable as well.

Similarly, prohibiting access to international permit trade for these regions tends to raise the cost of participation. It also responds to concerns in the climate-policy debate regarding the feasibility of including developing-world regions in unrestricted emission trading systems. As we will see in our simulation analysis, if major non-coalition regions can be included without cost in unrestricted emissions trade then the rationale for carbon tariffs largely disappears.

Finally, we have chosen to aggregate a number of the smaller non-coalition countries into larger regions that choose their policy strategies as unitary actors. For example, the countries summarized within the composite Other Energy-Exporting region then act collectively. While this assumption may exaggerate the power of both the decision to adopt emission controls and the decision to use tariffs in retalition against the carbon tariffs used by the coalition, the alternative is to disaggregate these countries and solve for their strategies separately. The difficulty here is that this would increase the dimensionality of the policy game substantially.[14] We show in the discussion of results of our baseline policy experiment as well as in sensitivity analysis presented in Section 5 that these countries do not appear to be key players in determining the character of the Nash equilibrium outcomes.

4 Results from the Baseline Policy Experiment

Table 3 reports the welfare effects of key policy regimes. Welfare impacts are defined as Hicksian equivalent variation in income as a percentage of the pre-policy equilibrium levels. The pre-policy equilibrium is one in which no region pursues climate policy or uses carbon or countervailing

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[14] In the game's current configuration, we must compute payoffs for over 5000 different policy regimes to get the required payoff structure to solve the game. This number increases as an exponential function of the number of regions in the model. Adding more regions to the model also increases the size of the equilibrium system required (as well as the computational complexity) to solve for the payoffs of each policy regime. For example, the GTAP database that we use to calibrate the CGE model would, in principle, allow us to disaggregate the model to as many as 113 world regions. For our baseline coalition structure, this would result in 39 coalition regions and 79 non-coalition regions. Thus, the total number of policy scenarios that would be required to solve the game would be $2^{34} * 3^{79} = 8.4644545 * 10^{47}$.

tariffs. Thus, carbon emissions are at business as usual levels. A positive number in the table represents a welfare loss (i.e. a positive cost) and a negative number a welfare gain.[15]

In the unique Nash equilibrium prediction from the model, all coalition regions find it optimal to use the threat of carbon tariffs. China (CHN) and Russia (RUS) cooperate (C) by adopting emission targets and all other non-coalition regions retaliate (R) against the carbon tariffs with import tariffs imposed on coalition regions. This outcome is listed in column (1).

We compare this outcome to a number of benchmarks. As measure of the potential for the carbon tariffs to benefit coalition regions and punish non-coalition regions, we include the regime in which all non-coalition regions choose to remain unregulated — the "Do Nothing" (D-N) outcome — despite being subjected to carbon tariffs by the coalition (column 2). We compare this with the regime where all non-coalition regions continue to "Do nothing" but where the coalition does not use carbon tariffs (column 3). This outcome also represents the best response of non-coalition regions if the coalition were to choose not to use the tariffs. Therefore, coalition regions use the payoffs associated with this outcome to determine the returns to using the tariffs. As one measure of the potential efficiency gains associated with fully cooperative behavior, we also report the regime in which all non-coalition regions choose to cooperate (column 4). Since cooperating non-coalition regions are assumed to abate domestically without access to international emissions trading the outcome described in (4) does not yield the global least-cost abatement policy. As a second measure of the potential for efficiency gains in abatement, we report the equilibrium outcome in which all world regions face a uniform carbon tax or, equivalently, participate in an system of unrestricted international emission permit trade (column 5). This outcome represents the

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[15] The welfare measures for the aggregated regions are based on a utilitarian social welfare function which is agnostic about the distribution of the costs or benefits within the region.

minimum-cost strategy for meeting the global abatement target. The assumption regarding the burden sharing in this scenario is that regions are allocated emission permits sufficient to cover 80% of their base-year emissions for coalition regions and 100% of their base-year emissions for non-coalition regions. Thus, non-coalition regions are compensated for their direct abatement costs by transfers from coalition regions (note, however, that they may experience other gains or losses due to the general equilibrium adjustments such as terms-of-trade changes).

In the Nash equilibrium where China and Russia cooperate while the remaining non-coalition regions retaliate, the 10% reduction in global carbon emissions comes at cost of 0.19% of global welfare. Compared to the outcomes where no non-coalition regions participate in abatement, the cooperation from China and Russia reduces the cost of achieving the target from 0.41% when coalition regions do not employ carbon tariffs (3) or 0.39% when they do use the tariffs (2). The cost under full cooperation (4) is 0.12%. Hence, the Nash equilibrium outcome captures approximately three-quarters of the possible efficiency gains measured against our cooperative benchmark or approximately two-thirds of the gains attainable by the cost-minimizing first-best regime in (5).

The overall cost of the policy is lower when non-coalition regions take on abatement responsibility because these regions are the source of low-cost abatement opportunities; shifting abatement to these regions moves the policy toward the first-best outcome with equalized marginal abatement costs across all regions (see Table 2). In the Nash equilibrium, the costs of abatement fall more heavily on the non-coalition regions (0.48%) than the coalition (0.08%). This distribution reflects the fact that China and Russia take on abatement responsibilities. However, comparing this outcome to column (3), in which the coalition is responsible for all abatement, it is clear that abatement is costly for non-coalition regions (0.65%) even when they do not undertake it themselves. This is due primarily to the fact that Russia and Other Energy-Exporting countries suffer from the depressing effect that abatement has on demand and prices for their exports of energy and energy-intensive goods. Other non-coalition regions experience relatively small, negative changes in welfare compared to the pre-policy benchmark equilibrium.[16]

Comparing columns (2) and (3) provides a measure of the impact when coalition regions impose carbon tariffs on non-coalition regions. Coalition regions uniformly benefit from the use of the tariffs as they allow these regions to capture terms-of-trade gains; on the other side, non-coalition regions (except for India) uniformly lose with major energy suppliers (Russia and Other Energy-Exporting) suffering the most in percentage terms. The global welfare cost of abatement declines only from 0.41% to 0.39% when tariffs are used. Thus carbon tariffs are not particularly effective as a means to directly reduce the global cost of abatement.

The regime described in (3) represents the best response for non-coalition regions if the coalition fails to employ the tariffs. Energy-importing non-coalition regions (China, India, Other Middle-Income and Other Low-Income) would prefer this outcome to the Nash equilibrium primarily because energy imports become cheaper, but energy exporters prefer the latter for the same reason. However, coalition regions uniformly prefer to use the tariffs — in part because of the rents they capture from using them and in part because the cooperation it induces from China and Russia relieves them of a substantial share of the abatement burden to meet the global emission reduction target.

The comparison of (2) and (3) makes clear that the tariffs have a measurable punitive effect on many of the non-coalition regions. However, the comparison of (3) and (4) also makes clear that the net effect of changes to the terms of trade plays an important role in shaping the equilibrium out-

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[16] The exception is India which benefits when the coalition takes on more abatement. India experiences a stronger positive terms-of-trade effect in the form of lower prices on fossil energy imports when abatement takes place.

come. China, Russia and the Other Energy-Exporting region all experience welfare gains moving from the unregulated outcome in (3) to the fully cooperative outcome in (4), implying that these sources of economic gains are strong enough to offset the direct costs of abatement in these regions.

Finally, we compare (1) with (5), the case in which there is a global system of international trade in emission permits and non-coalition regions receive compensation via the assumption that their initial holdings of permits are sufficient to cover 100% of their base-year emissions. As noted before, the equilibrium in (5) represents a minimum-cost method of achieving the global abatement target. We would expect it to dominate all other policy regimes in aggregate welfare terms. The aggregate cost of the policy is 0.08% or slightly less than half the cost of the Nash equilibrium policy regime. Both coalition and non-coalition regions benefit with most of the gains going to non-coalition regions.[17] This is because our burden-sharing rule implies large wealth transfers to these regions in exchange for their abatement services.

Table 4 describes the welfare losses non-coalition regions experience when they unilaterally deviate from their Nash equilibrium strategy. Welfare losses are calculated as percentage-point differences from the welfare changes obtained in the Nash equilibrium. China and Russia both cooperate in equilibrium. Retaliating with higher import tariffs of their own benefits China relative to doing nothing. However, both policies would generate moderate welfare losses relative to cooperation. Russia registers a modest welfare loss if it follows either alternative policy. Cooperation appears costly for most of the non-coalition regions that choose to retaliate in equilibrium — particularly energy-exporting and low-income regions. The "Do Nothing" option is less costly, suggesting that these regions choose not to cooperate mainly to avoid abatement costs as opposed to capturing rents from their countervailing tariffs.

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[17] The exception is the United States which is slightly worse off under (5).

Table 5 reports on the emission changes from the same policy scenarios as described in Table 3. Emissions are reported as a percentage of pre-policy base-year levels. The prevailing price of carbon emissions (measured in 2007 US Dollars per ton of CO_2) in each region and policy regime is listed in parentheses directly below the emission entries in the table. As noted before, the coalition's commitment to reducing their domestic emissions by 20% translates into an approximately 9% reduction in global emissions. When all non-coalition regions remain unregulated and the coalition does not employ tariffs (3), non-coalition emissions rise by approximately 2%. This corresponds to a global leakage rate of approximately 9%.[18]

The effect of the carbon tariffs on leakage can be seen from (2). Leakage falls by roughly a third due to the tariffs, an effect that relieves coalition regions of approximately 3% of their abatement responsibility relative to (3). The tariffs are particularly effective at controling leakage to Russia (through their dampening effect on Russia's energy-intensive exports) which goes from increasing its emissions by 2.25% under (3) to 0.54% under (2).

In the Nash equilibrium (1), China and Russia take on approximately 40% of the coalition's abatement responsibilities relative to (3). Leakage to other non-coalition regions falls relative to the carbon-tariff benchmark in (2). The prevailing carbon prices in China, Russia and the coalition in the Nash equilibrium show that marginal abatement costs are significantly lower in China and Russia – particularly in China. These countries reduce their emissions by approximately 14% at a marginal abatement cost of \$7 per ton in China and \$20 per ton in Russia. The same reduction in coalition regions implies a marginal abatement cost of \$27 per ton.

To summarize our main results, we find that the non-cooperative equi-

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[18] The leakage rate is defined as the ratio of the emission change in non-coalition regions over the emission change in coalition regions.

librium in our policy game supports cooperation from China and Russia. These countries are large enough sources of relatively low-cost abatement that this results in substantial global cost savings to achieve the global abatement target. Their cooperation is supported by a combination of two effects. First, facing carbon tariffs is damaging to these countries. Second, the improvement in the performance of world economy when abatement shifts from high-abatement-cost coalition regions to these comparatively low-cost countries benefits them as well. Both factors lower the opportunity cost of cooperation. Other non-coalition regions generally find abatement too expensive to justify cooperation — particularly given that they can free ride on the efforts of China and Russia.

5 Sensitivity Analysis

5.1 Trade and Fuel-Supply Elasticities

There are two sets of parameter values to which the results of CGE analyses of unilateral carbon policies consistently prove sensitive. First, the trade elasticities that govern the ease of substitution between varieties of the same good produced in different countries are important. The trade elasticities affect the degree to which consumers can look elsewhere for emission-intensive goods when the varieties they would have purchased from coalition regions become more expensive under the carbon policy. They also impact the potential terms-of-trade advantage a region can expect to gain by using tariffs. When these elasticities take on smaller values, export supply of a given region's product is less elastic, implying a higher optimal tariff.

Second, the values of the supply elasticities of fossil energy goods will affect the uptake in energy demand in unregulated regions when carbon policies come into place. A lower elasticity value implies a larger drop in the price of an energy good when its demand in regulated regions falls under the carbon policy. This leads to larger welfare losses for energy-exporting regions.

We have conducted sensitivity runs in which we double and halve the central-case values of these elasticities. Our finding that China cooperates in equilibrium is robust to the alternative elasticity assumptions. Russia also continues to cooperate in most cases. However, when fuel-supply elasticities are doubled Russia no longer chooses to cooperate. The intuition for this result is that when fuel supply is more elastic, Russia no longer stands to lose as much revenue from depressed fuel prices under unilateral abatement by the coalition. Therefore, its gains from cooperation are smaller.

However, between China and Russia, it is China's decision to cooperate that is critical to sustaining equilibrium efficiency gains to climate policy — the global cost rises by only two tenths of a percentage point when Russia drops out.

When trade elasticities are halved, Middle-Income countries and, in some cases, countries in the Other Energy-Exporting region join China and Russia in taking on abatement responsibilities. When the trade elasticities are low, the carbon tariffs have a more punishing effect, which promotes cooperation. When trade elasticities are doubled, India no longer retaliates and simply remains unregulated.

5.2 Abatement Target

A less stringent abatement target will attenuate the global economic adjustment to emission constraints and also affect the cost incidence across countries. It is possible that the tariffs then may no longer represent a credible threat for coalition members in this scenario. The effects of the tariffs and coalition abatement on non-coalition regions may also no longer be sufficient to induce cooperation. On the other hand, the costs of cooperation to non-coalition regions will fall as well, so it is not obvious how policy stringency and propensity for cooperation should be related. Here we explore how the equilibrium in our game changes with different target stringencies.

Our baseline policy experiment assumed a 20% reduction in coalition emissions. We have also run our simulation model for targets that are both less stringent (5% and 10%) and more stringent (30% and 40%) than in the baseline case. In all of these sensitivity runs, we maintain the assumption that cooperating non-coalition regions must match the abatement rate adopted by the coalition.

At a 5% target, China and Russia continue to cooperate and Middle-Income countries join them while the remainder retaliate. All coalition regions find it optimal to use carbon tariffs. When the target is set at a 10% reduction in coalition emissions, we find that the equilibrium actions of non-coalition players are unchanged — China and Russia cooperate and all other non-coalition regions retaliate. There are multiple equilibria in which Europe and either United States or Other Annex-I regions (but not both) use tariffs. At the 30% and 40% targets, Russia no longer finds it optimal to cooperate and retaliates instead. China continues to cooperate and the efficiency gains from equilibrium cooperation are largely preserved relative to the baseline policy experiment. Europe and the United States find it optimal to use tariffs while the Other Annex-I region does not. For the targets below 40% that we consider, the cooperation induced by the threat of tariffs cuts the global efficiency cost of meeting the target by 50-60% relative to the case where tariffs are not used and the coalition shoulders all of the abatement load.

At the 40% target, the gains fall to approximately 35% of this same benchmark because China has an incentive to cooperate even when there is no threat of tariffs. Thus the terms-of-trade shift in the world economy when abatement allocation moves to China is alone sufficient to induce cooperation in this case.

5.3 Coalition Size

Our main results rely on the assumption that all Annex-I countries are committed to reducing CO_2 emissions. The struggles of Australia, the United States and other Annex-I countries to adopt and execute the stringent emission constraints specified under the Kyoto Protocol are well documented however. Therefore, we examine the results of an alternative coalition structure where Europe (EU-27 plus EFTA) is the only coalition member. The United States and Other Annex-I countries join the group of non-coalition regions. Thus Europe is now the only source of carbon tariffs and the United States and Other Annex-I countries are potentially on the receiving end of these tariffs.

The Nash equilibrium prediction, once again, involves China and Russia adopting abatement targets while other non-coalition regions retaliate against the carbon tariffs from Europe. The exception is India, which chooses not to retaliate. The United States and Other Annex-I countries generally benefit from Europe's abatement, so they are not inclined to adopt abatement targets of their own.

The best response from non-coalition regions when Europe chooses not to employ carbon tariffs differs from our earlier experiments. China continues to find it in its best interest to cooperate in spite of the fact that it faces no threat of the tariffs. Because of this, the gains from using the tariffs are smaller. By design, the reduction in world emissions (a 20% reduction in Europe's emissions translates into roughly a 3% reduction in world emissions) is smaller in this experiment than in our core simulations, so all of the welfare differences between the policy regimes appear smaller. In conclusion, cooperation is still sustainable with a smaller coalition of commited countries, but the stakes for cooperation are lower.

5.4 Coalition Crowding-Out Effects

Our main results are obtained under the assumption that the coalition of Annex-I countries reduce their abatement one-for-one when non-coalition regions take on more of the responsibility in the Nash equilibrium. This assumption could be important in supporting the equilibrium cooperation we find because part of the motivation for China and Russia to cooperate is to improve markets for their exports in coalition regions by relieving them of some abatement responsibility. Here we explore the consequences of assuming that no crowding out takes place. That is, we assume that the level of abatement that takes place within the coalition is constant across the different policy scenarios we consider.[19]

We model this scenario by assuming that the coalition reduces its emissions by 20% below base-year levels regardless of what changes in emission levels take place outside of the coalition. We have run experiments in which we raised the abatement commitment for cooperation by non-coalition regions from 0% to 20% of base-year emissions at intervals of five percentage points. The maximum level of commitment at which cooperation is sustainable as an equilibrium outcome is when non-coalition regions are required to reduce their base-year emission levels by 10%. Once again, the Nash equilibrium involves China and Russia adopting abatement targets. India also chooses to cooperate. All other regions retaliate. This raises global abatement from approximately 9% when only the coalition abates to approximately 15%. China and Russia still register significant gains relative to the case where they are subjected to the tariffs. However, the benefits the coalition experiences are nearly exhausted relative to the case where they decide not to use the tariffs. (This is, of course,

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[19] The welfare effects of these policies are not comparable to those described in our main experiments without parameterizing marginal benefits of abatement curves for the regions in our model because the global abatement levels will differ. We can, however, explore how much additional abatement the coalition can elicit from non-coalition regions through the punishment of the carbon tariffs.

ignoring the environmental benefits of the abatement they receive). Thus, it is the coalition's willingness to use the tariffs that is the limiting factor in sustaining the equilibrium.

5.5 Retaliation Option

We have assumed throughout that the retaliation option available to non-coalition regions is to impose comparable increases in tariffs on imports from coalition regions, where comparable is defined as increases in import-tariff rates on the same categories of goods that yield the same amount of tariff revenue as the carbon tariffs imposed on them by the coalition. This response is unlikely to represent an optimal response by non-coalition regions. First, a general pattern that emerges from the data is that non-coalition regions are sizable net exporters of embodied carbon emissions to coalition regions (Peters et al. 2011). Thus, the design of the retaliatory tariff in our central case experiments is such that it targets categories of goods that are not among those most heavily imported by these regions. Second, as a general rule higher optimal import tariffs should be placed on goods with more inelastic export supply (Limao 2008).

To explore the consequences of varying our assumptions on the design of retaliating tariffs, we have run two alternative specifications. In both cases, we assume that retaliatory tariffs are raised against all categories of imported goods (instead of just against EITE goods) and scaled inversely proportional to the trade elasticities, consistent with the intersectoral pattern of optimal tariffs. In one case, we maintain the assumption that the imposition of retaliating tariffs just raises as much revenue as the carbon tariffs themselves. In the other case, we assume that the increases in the tariffs rates are twice as large.

The results of the first experiment show very little difference from the results of the baseline experiments. That is, the unique Nash equilibrium remains the one in which the coalition employs carbon tariffs, China and

Russia adopt domestic emission controls, and all other non-coalition regions choose to retaliate. The effects on welfare and emission levels are similar as well. In the experiments where the retaliatory tariffs raise twice as much revenue, Russia no longer finds it in its best interest to cooperate. As a result, the Nash equilibrium outcome in this scenario involves all coalition regions employing the carbon tariffs, China adopting domestic emission controls, and all other regions — including Russia — choosing to retaliate. As we observed in some of the other sensitivity runs, the efficiency gains to the use of carbon tariffs are largely preserved here despite Russia's defection.

5.6 Strategic Influence of Aggregated Regions

To limit the dimensionality of our simulation model, we have aggregated a number of countries into larger world regions. Among coalition members, Canada, Japan, Belarus, Ukraine, Australia, New Zealand, and Turkey are all part of the Other Annex-I region while the US and Western Europe (EU-27 plus EFTA) are each treated as a single player. Among non-coalition countries, all but China, India and Russia are aggregated into three regions (Middle-Income, Low-Income and Other Energy Exporters). Western Europe has coordinated climate and economic policies and is largely integrated, so there is a justification for grouping these countries in our analysis. The assumption is far less defensible for the other aggregate regions.

Treating these aggregated regions as unitary actors in our policy game clearly has the potential to exaggerate the degree of market power their constituent countries hold. This could bias our results if the actions of these aggregated regions are driven primarily by this artifact. That is, it may drive countries to use carbon tariffs or retaliate based on an unrealistic ability to extract rents. It may also drive countries to cooperate based on an unrealistic ability take on a large share of the global abatement burden and improve global economic performance.

To address these concerns, we have conducted sensitivity runs in which the actions of aggregated regions are restricted. Specifically, we eliminate the option for aggregated non-coalition regions to retaliate and for the Other Annex-I region to apply carbon tariffs. We do allow for the possibility that non-coalition regions that chose to retaliate in the baseline experiments may find that cooperation is optimal when retaliation is no longer an option. This is important because aggregation may also affect a region's propensity to cooperate. If we find that these regions cooperate when retaliation is not possible, further investigation would be required to determine if this cooperation is genuine or artificial.

We find that carbon tariffs remain a credible threat for the United States and Europe (the remaining strategic coalition members in this experiment). China and Russia continue to cooperate. India retaliates and all other non-coalition regions do nothing.

Thus, to the extent that the aggregated non-coalition regions hold an artificial degree of market power, it is not sufficiently strong as to bias the model toward cooperation. Moreover, our main result — that China and Russia engage in cooperation in the equilibrium — remains unaffected in this restricted version of the model. Neither the retaliation of the non-coalition regions nor the use of tariffs by the aggregate coalition region in our baseline experiment is critical to supporting this result. This result is also corroborated by the finding that non-coalition regions which choose not to cooperate in equilibrium are driven primarily by the desire to avoid the costs of abatement instead of the gains from retaliation.[20]

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[20] See the discussion of Table 4 in Section 4.

5.7 Consequences of Different Legal Regimes

In our baseline policy game, the use of carbon tariffs and retaliatory tariffs are both available to coalition and non-coalition players respectively. Yet, a clear ruling from the WTO would likely make only one of these two responses legal. Here we explore scenarios in which the legal regime makes one or the other of these policy options unprofitable for countries.

If carbon tariffs are illegal and the costs to flouting WTO law (beyond the retaliation measures modelled in our game) are severe enough to discourage their use by coalition regions, the equilibrium in our model would correspond to the best response of non-coalition regions on the "No Tariff" branch of the game tree. As discussed in the previous section, all non-coalition regions choose not to cooperate in this case and all of the abatement responsibility is shouldered by the coalition.

If retaliation by non-coalition regions is deemed illegal and the costs of illegal action are sufficiently high as to make it unprofitable, then we should examine the equilibrium arises when the retaliation option is removed from the action set. We find that the coalition still threatens the use of carbon tariffs, China and Russia choose to cooperate, and all other regions choose to do nothing in the equilibrium of this restricted game.

5.8 Credibility of Carbon Tariffs

It is possible that the tariffs would be lucrative for coalition regions to impose even against *cooperating* non-coalition regions all else equal. In this case, the threat of carbon tariffs as a punishment for non-compliance is not credible because non-coalition regions can expect to be subjected to them regardless of their climate policy actions. To address this concern, we compare the payoffs of the Nash equilibrium that arises in our baseline policy experiment to the best responses of non-coalition regions when carbon tariffs are imposed irrespective of their actions.

We find that payoffs to coalition regions are higher in the baseline policy experiment than in this counterfactual, supporting our finding that carbon tariffs are a credible threat. If China and Russia are to be subjected to carbon tariffs even under cooperation, this strategy becomes unprofitable for them. Thus, the best response of non-coalition regions in this case is for all to retaliate except for India which does nothing. This results in an average welfare loss to coalition regions of 0.30%, substantially larger than their loss in our baseline policy experiment (0.08%). (The welfare losses of the individual members of the coalition are all substantially lower as well.) This suggests that the threat of carbon tariffs is credible in the sense that the coalition has incentives both to use them when outsiders do not cooperate and to revoke them when they do.

6 Concluding Remarks

The issue of how to control emissions in large developing countries is central to the future of global warming policy. Without the participation of these countries, the cost of controling global emissions at levels consistent with avoiding "dangerous" climate interference will be high if not prohibitively so. An assumption that seems to underlie much economic analysis of international climate policy is that the level of compensation required by developing countries to gain their participation in the near term is a political non-starter in countries that would be doing the compensation. In our analysis, the combined influence of carbon tariffs and international trade linkages in the global economy produces a different picture. Key developing countries are already disadvantaged when Annex-I countries abate even if they undertake no abatement of their own. This is primarily because they depend on the economic performance of Annex-I countries as destinations for their exports. In our analysis, this fact combined with the threat of the tariffs is enough to bring China and Russia into the fold.

The result is striking not only because the global cost savings from equilibrium cooperation are substantial but also because it is the cooperation of China alone that is primarily responsible for this outcome. China's size and abundance of low-cost abatement opportunities would allow it to absorb a large fraction of the global abatement burden. Its trade orientation would also make carbon tariffs a costly prospect. These characteristics contribute to our finding that China's participation is a constant across an array of robustness checks.

This suggests that the benefits of carbon tariffs may be attainable without confronting many of the difficult challenges associated with the actual implementation of carbon tariffs — the credible threat of their use is enough. Very little of the cost savings in our equilibrium come from actually imposing the tariffs on the regions that remain out of compliance. Thus, a coalition might reasonably pursue an agreement with China alone and forego task of imposing sanctions on other countries.

Figures and Tables

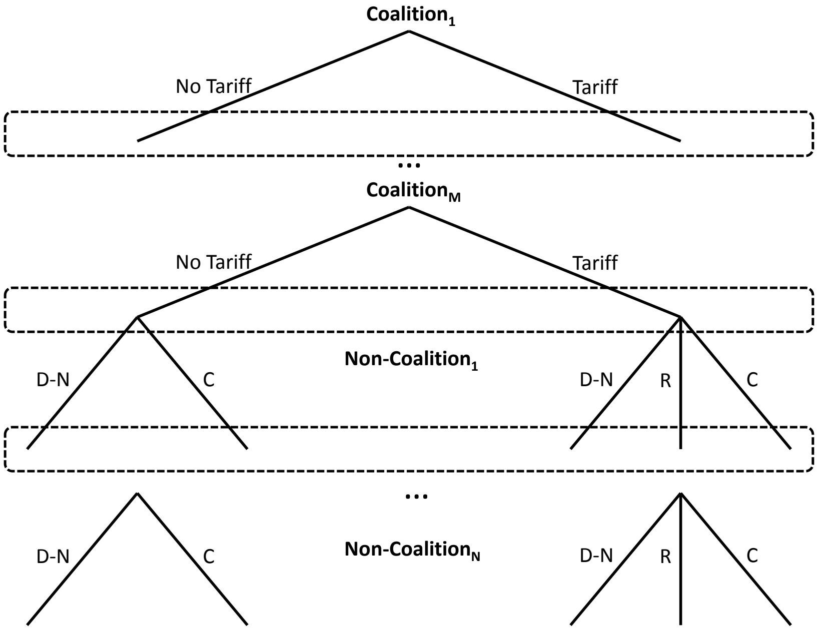

Figure 1: Structure of the Policy Game

	REGIONS
Coalition	United States; EU-27 plus European Free Trade Area; Other Annex I without Russia (Canada, Japan, Belarus, Ukraine, Australia, New Zealand, Turkey)
Non-Coalition	China and Hong Kong; India; Russia; Other Energy-Exporting Countries; Other Middle-Income Countries; Other Low-Income Countries
	SECTORS
Energy	Coal; Crude Oil; Natural Gas; Refined Petroleum*; Electricity
Energy-intensive	Chemical, Rubber and Plastic Products*; Iron and Steel*; Non-Ferrous Metal*; Non-Metallic Mineral*; Water Transport; Air Transport; Other Transport
Other	All Other Goods

* — Indicates energy-intensive and trade-exposed (EITE) sectors that are the subject of the carbon tariffs and countervailing measures.

Table 1: Regions and Sectors in the Aggregated Dataset

	CO_2	GDP	CO_2 Intensity
	Coalition		
United States	5.58	14060.93	0.39
Other Annex-I	2.59	7631.75	0.34
Europe	4.15	17846.81	0.23
	Non-Coalition		
China	5.18	3696.53	1.39
Russia	1.42	1299.67	1.09
India	1.30	1232.35	1.05
Other Low-Income	0.65	733.82	0.88
Other Energy-Exporting	1.92	2414.06	0.80
Other Middle-Income	3.45	6879.37	0.50

* — CO_2 measured in billions of metric tons; GDP measured in billions of US dollars 2007; CO_2 intensity measured in metric tons per thousand dollars.

Table 2: Base-Year Economic and Emission Statistics by Region

COALITION ACTIONS:	All = Tariff		All = No Tariff		
NON-COALITION ACTIONS:	China, Russia = C Others = R*	All D-N	All D-N*	All C	Unrestricted Int'l Permit Trade
	(1)	(2)	(3)	(4)	(5)
All	0.19	0.39	0.41	0.12	0.08
Coalition	0.08	0.23	0.33	-0.01	0.06
Non-Coalition	0.48	0.87	0.65	0.49	0.14
	Coalition				
Europe	0.10	0.28	0.41	-0.02	0.03
United States	0.02	0.08	0.14	-0.02	0.08
Other Annex-I	0.20	0.45	0.57	0.04	0.11
	Non-Coalition				
China	0.25	0.44	0.16	0.12	-0.41
Russia	1.66	2.83	2.08	1.59	0.83
India	-0.21	-0.31	-0.44	-0.22	-0.34
Other Energy-Exporting	1.89	3.32	2.91	2.02	1.20
Other Middle-Income	0.09	0.23	0.15	0.10	-0.02
Other Low-Income	0.37	0.56	0.43	0.63	0.33

Notes: * — Indicates policy regime that represents a best response for all non-coalition regions for a given carbon tariff regime; C=Cooperate, D-N=Do Nothing, R=Retaliate.

Table 3: % Welfare Loss by Region and Policy Regime

	Deviation	Welfare Change
China	Retaliate	0.06
	Do Nothing	0.08
Russia	Retaliate	0.01
	Do Nothing	0.01
India	Cooperate	0.06
	Do Nothing	—
Other Energy-Exporters	Cooperate	0.34
	Do Nothing	0.02
Other Middle-Income	Cooperate	0.06
	Do Nothing	0.03
Other Low-Income	Cooperate	0.33
	Do Nothing	—

Table 4: Percentage-Point Welfare Cost of Deviation from Nash Equilibrium

Coalition Actions:	All = Tariff		All = No Tariff		
Non-Coalition Actions:	China, Russia = C Others = R*	All D-N	All D-N*	All C	Unrestricted Int'l Permit Trade
	(1)	(2)	(3)	(4)	(5)
All	9.39	9.39	9.39	9.39	9.39
Coalition	13.58	21.37	22.01	9.39	6.22
Non-Coalition	5.68	-1.21	-1.78	9.39	12.20
	Coalition				
Europe	10.32	16.80	17.43	6.75	4.37
United States	16.41	25.26	25.88	11.75	7.91
Other Annex-I	12.71	20.30	20.99	8.53	5.52
	(27.39)	(55.82)	(57.66)	(17.61)	(10.58)
	Non-Coalition				
China	13.58	-0.23	-0.75	9.39	18.85
	(6.89)	—	—	(4.51)	(10.58)
Russia	13.58	-0.54	-2.25	9.39	7.98
	(20.29)	—	—	(13.06)	(10.58)
India	-0.90	-1.07	-1.47	9.39	17.09
	—	—	—	(5.20)	(10.58)
Other Energy-Exporting	-1.06	-1.45	-2.01	9.39	5.25
	—	—	—	(20.20)	(10.58)
Other Middle-Income	-1.80	-2.69	-2.93	9.39	7.01
	—	—	—	(15.37)	(10.58)
Other Low-Income	-1.68	-2.29	-2.84	9.39	6.65
	—	—	—	(15.91)	(10.58)

Notes: * — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime; C=Cooperate, D-N=Do Nothing, R=Retaliate.

Table 5: % Emission Reduction by Region and Policy Regime

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A Algebraic Description of the CGE Model

The applied general equilibrium model is formulated as a system of nonlinear inequalities. The inequalities correspond to the two classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for constant-returns-to-scale producers; and (ii) market clearance for all goods and factors. The former class determines activity levels and the latter determines price levels. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint and a commodity price to a market clearance condition.

In our algebraic exposition, the notation is used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for constant-returns-to-scale production of sector i in region r where z is the name assigned to the associated production activity. Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's Lemma), which appear subsequently in the market clearance conditions. We use g as an index comprising all sectors/commodities i ($g = i$), the final consumption composite ($g = C$), the public good composite ($g = G$), and aggregate investment ($g = I$). The index r (aliased with s) denotes regions. The index EG represents the subset of all energy goods (here: coal, oil, gas, electricity) and the label FF denotes the subset of fossil fuels (here: coal, oil, gas). Tables 6 - 11 explain the notation for variables and parameters employed within our algebraic exposition. Figures 2 - 4 provide a graphical exposition of the production structure. Numerically, the model is implemented in GAMS (Brooke, Kendrick and Meeraus 1996) and solved using PATH (Dirkse and Ferris 1995).

Zero-profit conditions:

- Production of goods except fossil fuels ($g \notin FF$):

$$\Pi^{Y}_{gr} = p_{gr} - \left[\theta^{M}_{gr} p_{gr}^{M(1-\sigma^{KLEM}_{gr})} + (1-\theta^{M}_{gr}) p_{gr}^{KLE(1-\sigma^{KLEM}_{gr})}\right]^{1/(1-\sigma^{KLEM}_{gr})} \leq 0$$

- Sector-specific energy-value-added aggregate:

$$\Pi^{KLE}_{gr} = p^{KLE}_{gr} - \left[\theta^{E}_{gr} p_{gr}^{E(1-\sigma^{KLE}_{gr})} + (1-\theta^{E}_{gr}) p_{gr}^{KL(1-\sigma^{KLE}_{gr})}\right]^{1/(1-\sigma^{KLE}_{gr})} \leq 0$$

- Sector-specific material aggregate:

$$\Pi^{M}_{gr} = p^{M}_{gr} - \left[\sum_{i \notin EG} \theta^{MN}_{igr} p_{igr}^{A(1-\sigma^{M}_{gr})}\right]^{1/(1-\sigma^{M}_{gr})} \leq 0$$

- Sector-specific energy aggregate:

$$\Pi^{E}_{gr} = p^{E}_{gr} - \left[\sum_{i \in EG} \theta^{EN}_{igr} (p^{A}_{igr} + p^{CO_2}_{r} a^{CO_2}_{igr})^{(1-\sigma^{E}_{gr})}\right]^{1/(1-\sigma^{E}_{gr})} \leq 0$$

- Sector-specific value-added aggregate:

$$\Pi^{KL}_{gr} = p^{KL}_{gr} - \left[\theta^{K}_{gr} v_{gr}^{(1-\sigma^{KL}_{gr})} + (1-\theta^{K}_{gr}) w_{r}^{(1-\sigma^{KL}_{gr})}\right]^{1/(1-\sigma^{KL}_{gr})} \leq 0$$

- Production of fossil fuels ($g \in FF$):

$$\Pi^{Y}_{gr} = p_{gr} - \left[\theta^{Q}_{gr} q_{gr}^{(1-\sigma^{Q}_{gr})} + (1-\theta^{Q}_{gr}) \left(\theta^{L}_{gr} w_{r} + \theta^{K}_{gr} v_{gr} + \sum_{i \notin FF} \theta^{FF}_{igr} p^{A}_{igr}\right)^{(1-\sigma^{Q}_{gr})}\right]^{1/(1-\sigma^{Q}_{gr})} \leq 0$$

- Armington aggregate:

$$\Pi^{A}_{igr} = p^{A}_{igr} - \left(\theta^{A}_{igr} p_{ir}^{(1-\sigma^{A}_{ir})} + (1-\theta^{A}_{igr}) p_{ir}^{IM(1-\sigma^{A}_{ir})}\right)^{1/(1-\sigma^{A}_{ir})} \leq 0$$

- Aggregagte imports across import regions:

$$\Pi^{IM}_{ir} = p^{IM}_{ir} - \left[\sum_{s} \theta^{IM}_{isr} (1+\tau_{isr}) p_{is}^{(1-\sigma^{IM}_{ir})}\right]^{1/(1-\sigma^{IM}_{ir})} \leq 0$$

Market-clearance conditions:

- Labor:

$$\bar{L}_r \geq \sum_g Y^{KL}_{gr} \frac{\partial \Pi^{KL}_{gr}}{\partial w_r}$$

- Capital:

$$\bar{K}_{gr} \geq Y^{KL}_{gr} \frac{\partial \Pi^{KL}_{gr}}{\partial v_{gr}}$$

- Fossil fuel resources ($g \in FF$):

$$\bar{Q}_{gr} \geq Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial q_{gr}}$$

- Material composite:

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial p^{M}_{gr}}$$

- Energy composite:

$$E_{gr} \geq Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial p^{E}_{gr}}$$

- Value-added composite:

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial p^{KL}_{gr}}$$

- Import composite:

$$IM_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi^{A}_{igr}}{\partial p^{IM}_{ir}}$$

- Armington aggregate:

$$A_{igr} \geq Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial p^{A}_{igr}}$$

- Commodities ($g = i$):

$$Y_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi^{A}_{igr}}{\partial p_{ir}} + \sum_{s \neq r} IM_{is} \frac{\partial \Pi^{IM}_{is}}{\partial p_{ir}}$$

- Private consumption ($g = C$):

$$Y_{Cr} p_{Cr} \geq w_r \bar{L}_r + \sum_{g} v_{gr} \bar{K}_{gr} + \sum_{i \in FF} q_{ir} \bar{Q}_{ir} + p^{CO_2}_{r} C\bar{O}_{2r} + \bar{B}_r$$

- Public consumption ($g = G$):

$$Y_{Gr} \geq \bar{G}_r$$

- Investment ($g = I$):

$$Y_{Ir} \geq \bar{I}_r$$

- Carbon emissions:

$$C\bar{O}_{2r} \geq \sum_{g} \sum_{i \in FF} E_{gr} \frac{\partial \Pi^{E}_{gr}}{\partial (p^{A}_{igr} + p^{CO_2}_{r} a^{CO_2}_{igr})} a^{CO_2}_{igr}$$

i, j	Sectors and goods
g	The union of produced goods i, private consumption C, public demand G and investment I
r, s, t	Regions
EG	Energy goods; coal, crude oil, refined oil, natural gas and electricity
FF	Fossil fuels; coal, crude oil and natural gas.

Table 6: Indices & Sets

Y_{gr}	Production of item g in region r
E_{gr}	Energy composite for item g in region r
KL_{gr}	Value-added composite for item g in region r
KLE_{gr}	Energy-value-added composite for item g in region r
A_{igr}	Armington aggregate for commodity i for demand category (item) g in region r
IM_{ir}	Aggregate imports of commodity i in region r

Table 7: Activity Levels

p_{gr}	Price of item g in region r
p_{gr}^{M}	Price of material composite for item g in region r
p_{gr}^{E}	Price of energy composite for item g in region r
p_{gr}^{KL}	Price of value-added composite for item g in region r
p_{gr}^{KLE}	Price of energy-value-added composite for item g in region r
p_{igr}^{A}	Price of Armington good i for demand category g in region r
p_{ir}^{IM}	Price of import composite for good i in region r
τ_{isr}	Tariff rate good i imported from region s to region r
w_r	Wage rate in region r
v_{ir}	Capital rental rate in sector i in region r
q_{ir}	Rent to fossil fuel resources in region r ($i \in FF$)
$p_r^{CO_2}$	Implicit price of carbon in region r

Table 8: Prices

$\bar{L}_r$	Aggregate labor endowment for region r
$\bar{K}_{ir}$	Capital endowment for sector i in region r
$\bar{Q}_{ir}$	Endowment of fossil energy resource i in region r ($i \in FF$)
$\bar{B}_r$	Initial balance for payment deficit or surplus in region r (note: $\sum_r \bar{B}_r = 0$)
$C\bar{O}_{2r}$	Aggregate carbon emission cap in region r
$a_{igr}^{CO_2}$	Carbon emission coefficient for fossil fuel i in demand category g in region r ($i \in FF$)

Table 9: Endowments and Carbon Emissions Specification

θ_{gr}^{M}	Cost share of material composite in production of item g in region r
θ_{gr}^{E}	Cost share of energy composite in the aggregate of energy and value added of item g in region r
θ_{igr}^{MN}	Cost share of material input i in the material composite of item g in region r
θ_{igr}^{EN}	Cost share of energy input in the energy composite of item g in region r
θ_{gr}^{K}	Cost share of capital within the value-added composite of item g in region r
θ_{gr}^{Q}	Cost share of fossil fuel resource in fossil fuel production ($g \in FF$) in region r
θ_{gr}^{L}	Cost share of labor in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ_{gr}^{K}	Cost share of capital in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ_{igr}^{FF}	Cost share of good i in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ_{igr}^{A}	Cost share of domestic output i within the Armington item g in region r
θ_{isr}^{M}	Cost share of exports of good i from region s in the import composite of good i in region r

Table 10: Cost Share Parameters

σ_{gr}^{KLEM}	Substitution between the material composite and the energy-value-added aggregate in the production of item g in region r*
σ_{gr}^{KLE}	Substitution between energy and the value-added composite in the production of item g in region r*
σ_{gr}^{M}	Substitution between material inputs within the energy composite in the production of item g in region r*
σ_{gr}^{KL}	Substitution between capital and labor within the value-added composite in the production of item g in region r*
σ_{gr}^{E}	Substitution between energy inputs within the energy composite in the production of item g in region r (by default $= 0.5$)
σ_{gr}^{Q}	Substitution between natural resource input and the composite of other inputs in the fossil fuel production ($g \in FF$) of region r***
σ_{ir}^{A}	Substitution between domestic variety and the composite of imported varieties from different regions for good i in region r**
σ_{ir}^{IM}	Substitution between imports from different regions within the import composite for good i in region r**

* — Calibrated based on estimates from Okagawa and Ban (2008).

** — Calibrated based on estimates from Narayanan et al. (2012) with the exception for elasticities in the market for crude oil which are assumed equal to $+\infty$.

*** — Calibrated based on estimates from Graham et al. (1999) and Krichene (2002).

Table 11: Elasticity Parameters

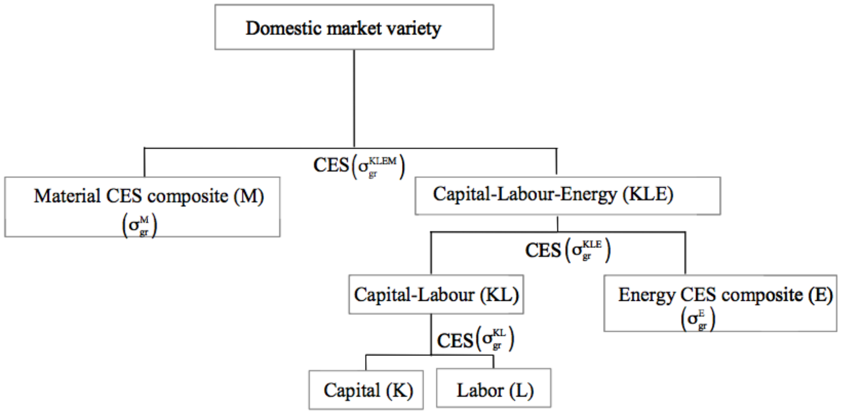

Figure 2: Nesting in Non-Fossil-Fuel Production

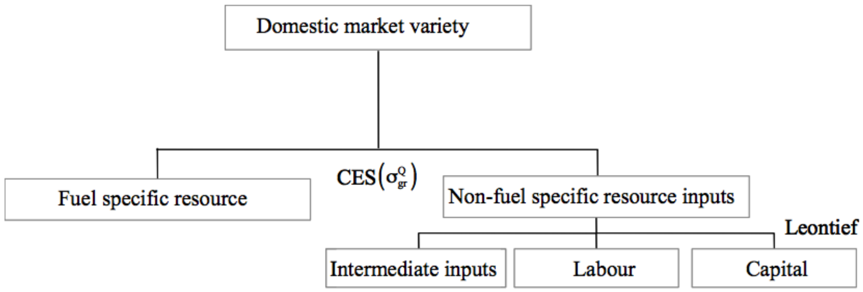

Figure 3: Nesting in Fossil-Fuel Production

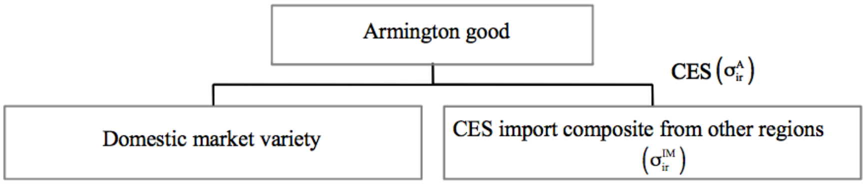

Figure 4: Nesting in Armington Composite Production

B Region and Sector Mappings

United States	United States
EU-27 plus European Free Trade Area	France, Germany, Italy, United Kingdom, Austria, Belgium, Denmark, Finland, Greece, Ireland, Luxembourg, Netherlands, Portugal, Spain, Sweden, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Bulgaria, Cyprus, Switzerland, Norway, Rest of EFTA
Other Annex I minus Russia	Canada, Japan, Belarus, Ukraine, Australia, New Zealand, Turkey
China and Hong Kong	China, Hong Kong
India	India
Russian Federation	Russian Federation
Other Energy-Exporting Countries	Indonesia, Rest of North Africa, Nigeria, Rest of South Central Africa, Ecuador, Venezuela, Islamic Republic of Iran, Rest of Western Asia, Egypt, Bolivia, Malaysia
Other Middle-Income Countries	Albania, Armenia, Argentina, Azerbaijan, Bulgaria, Brazil, Botswana, Chile, Columbia, Costa Rica, Georgia, Guatemala, Kazakhstan, Sri Lanka, Morocco, Mauritius, Mexico, Panama, Peru, Philippines, Paraguay, Thailand, Tunisia, Uruguay, South Africa, Rest of Oceania, Rest of South America, Caribbean, Rest of North Africa, Rest of South African Customs Union
Other Low-Income Countries	Banglandesh, Ethiopia, Kyrgyzstan, Cambodia, Rest of East Asia, Lao People's Democratic Republic, Madagascar, Myanmar, Malawi, Mozambique, Nicaragua, Pakistan, Senegal, Tanzania, Uganda, Vietnam, Zambia, Zimbabwe, Rest of South Asia, Rest of Southeast Asia, Rest of Eastern Europe, Rest of Former Soviet Union, Rest of Western Africa, West of Central Africa, Rest of South Central Africa, Rest of Eastern Africa

Table 12: Mapping of Regions from the GTAP 8 Dataset

Coal	Coal
Crude Oil	Crude Oil
Natural Gas	Natural Gas
Refined Petroleum and Coal	Refined Petroleum and Coal
Electricity	Electricity
Chemical, Rubber, Plastic Products	Chemical, Rubber, Plastic Products
Iron and Steel	Iron and steel
Non-Ferrous Metals	Non-Ferrous Metal
Non-Metallic Minerals	Non-Metallic Mineral, Other Minerals
Water Transport	Water Transport
Air Transport	Air Transport
Other Transport	Other Transport
All Other Goods	All Other Goods

Table 13: Mapping of Sectors from GTAP 8 Dataset

Physical Capital	Physical Capital
Labor	Unskilled Labor, Skilled Labor
Natural Resources	Natural Resources

Table 14: Mapping of Factors from GTAP 8 Dataset