# The Strategic Value of Embodied Carbon Tariffs

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**Abstract**

Unilateral carbon policies are inefficient due to the fact that they generally mean that abatement takes place in high-cost countries and because they are subject to carbon leakage. In this paper, we ask whether the use of carbon tariffs — tariffs on the carbon embodied in imported goods — might lower the cost of achieving a given reduction in world emissions. Specifically, we explore the role that the tariffs might play as an inducement to unregulated countries to adopt emission controls of their own. We use a computable general equilibrium model to generate the payoffs of a one-shot policy game. In the game, a coalition of countries regulates its own emissions and chooses whether or not to employ carbon tariffs against unregulated countries. Unregulated countries may respond by adopting emission regulations of their own, retaliating against the carbon tariffs by engaging in a trade war, or by pursuing no policy at all. In the unique Nash equilibrium produced by this game, the use of carbon tariffs by coalition countries is credible. China and Russia respond by adopting binding abatement targets to avoid being subjected to them. Other unregulated countries retaliate. Cooperation by China and Russia lowers the global welfare cost of acheiving a 10% reduction in global emissions by half relative to the case where coalition countries undertake all of this abatement on their own.

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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, offsetting increases in emissions in unregulated countries, which increases these costs even further (Hoel 1991, Felder and Rutherford 1993).

In theory, a system of international emission-permit trade could deliver on the demands of the developing world and control world emissions in a cost-effective way. However, there remains considerable skepticism that such a system is practical. The monitoring and enforcement challenges as well as the large and explicit transfers of wealth that unrestricted permit trade would impart to countries with limited institutional capacities make finding the political will to implement such a scheme difficult (McKibbin and Wilcoxen 1997).

Against this background, many policy analysts have noted that developed countries are large net importers of embodied carbon emissions from their developing-world trade partners. This observation has contributed to the popularity of proposals to use trade policies as tools for regulating carbon emissions in countries that currently have no domestic emission regulations of their own. These policies could work directly by stifling demand for carbon-intensive goods produced in developing countries. They could also work indirectly as an environmentally-sanctioned punishment that speeds the adoption of emission controls in those countries.

One popular set of proposals involves the use of embodied carbon tariffs, tariffs levied on the direct and indirect carbon emissions embodied in imported goods. They have support as a form of direct regulation from the theory of second-best environmental taxation (Markusen 1975, Hoel 1996). If foreign governments cannot regulate these emissions at the source, tariffs may be justified from a global efficiency perspective. Nevertheless, there are substantial practical and legal costs that would inevitably come with their use (Brewer 2008, Pauwelyn 2007, Howse and Eliason 2008, Charnowitz, Hufbauer and Kim 2009). Furthermore, quantitative evidence from computable general equilibrium (CGE) models suggests that the use of embodied carbon tariffs is unlikely to result in substantial reductions in the global cost of achieving emission reductions. The main effect of carbon tariffs is to shift the burden of policy to the countries subjected to them (Böhringer, Carbone and Rutherford 2011, Mattoo, Subramanian, Mensbrugghe and He 2009, Babiker and Rutherford 2005, Böhringer and Rutherford 2002).

In this paper, we explore the indirect role carbon tariffs might play as an environmental sanction. Their burden-shifting effect means that they have the potential to confer substantial trade gains to the countries that use them, making them politically attractive there. They also

have the potential to inflict damage on the countries subjected to them. Thus unregulated countries may prefer to adopt emission controls of their own than suffer the effects of the tariffs, a response that could significantly lower the global cost of climate policy. On the other hand, these countries may prefer to adopt countervailing tariffs of their own rather than suffer the cost of emissions regulation, a response that could significantly increase costs.[1]

We ask: which of these regimes is likely to arise from the self-interested policy choices of nations and what does it mean for the prospect of designing effective international responses to climate change? We construct a computable general equilibrium model of the world economy and use it to generate the payoffs of a one-shot policy game. In the game, a coalition of Annex-I countries is commited to reducing global emissions to 10% below business-as-usual levels, a target consistent with their commitments under the Kyoto Protocol. To achieve this, the coalition regulates its own emissions domestically using a uniform carbon tax. In addition, it chooses 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 by engaging in a trade war, or by taking no action and simply leaving their emissions unregulated. Equilibria of the game are policy regimes in which no non-coalition country wishes to change its policy given the policies of others and in which the coalition chooses whether or not to use carbon tariffs to maximize its payoff anticipating the best responses of non-coalition countries.

In the unique Nash equilibrium prediction produced by this game, the use of carbon tariffs by coalition countries is credible. China and Russia respond by adopting binding abatement targets to avoid being subjected to them. All other non-coalition countries retaliate. Cooperation by China and Russia lowers the global welfare cost of acheiving a 10% reduction in global emissions by half relative to the case where coalition countries undertake all of this abatement on their own.

These countries are motivated to cooperate for two main reasons. First, they avoid the punishment of carbon tariffs by doing so. Second, these countries are dependent on the performance of coalition economies, as a destination market for their exports and as the origin of imports. When China and Russia take on abatement, less is required of coalition countries to meet the assumed 10% 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. Russia's gains are concentrated in energy and energy-intensive export markets. China's gains are more generalized. Thus, it is the combination of the punishment of the tariffs and the terms-of-trade advantages that countries experience when the abatement burden shifts to China and Russia

[1]Many policymakers have expressed concern that the specter of the tariffs could disrupt on-going international climate policy negotiations (Houser, Bradley and Childs 2008) or trade relations (ICTSD 2008).

sustains the equilibrium in our simulations.

The rest of the paper proceeds as follows. Section 1 describes the structure of the CGE that we use to generate the payoffs for our policy game. Section 2 describes the GTAP dataset we use to calibrate the CGE model. Section 3 describes the structure of the policy game we study and the details of the specific policy options countries face within the game structure. Section 4 describes the results of our main policy experiments and Section 5 covers the results of sensitivity analysis with respect to some key assumptions in the CGE model and the policy game. Section 6 concludes with a discussion of the policy significance of our results and possible extensions.

# 1 The General Equilibrium Model

We make use of a generic multi-region, multi-sector CGE model of global trade and energy use established for the analysis of greenhouse gas emission control strategies (Böhringer and Rutherford 2010).[2] 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. 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

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

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).[3]

We follow the standard calibration procedure in applied general equilibrium analysis in which the base-year dataset determines the free parameters of the functional forms (i.e., cost and expenditure functions) such that the economic flows represented in the data are consistent with the optimizing behavior of the model agents.[4]

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 (Narayanan and Walmsley 2008). 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).

## 2 Data and Calibration

We make use of the GTAP 7.1 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 112 regions and 57 sectors for the year 2004 (Narayanan and Walmsley 2008).

The economic structure underlying the GTAP dataset is illustrated in Figure 1. Symbols correspond to variables in the economic model. $Y_{ir}$ indicates the production of good $i$ in region $r$. The labels $C_r$, $I_r$ and $G_r$ portray private consumption, investment and public demand,

[3]Revenues from emission regulation accrue either from $CO_2$ taxes or from the auctioning of emission allowances (in the case of a grandfathering regime) and are recycled lump sum to the representative agent in the respective region.

[4]See Shoven and Whalley (1992) for a detailed description of the calibration procedure.

respectively. $M_{jr}$ portrays the import of good $j$ into region $r$. $RA_r$ stands for the representative household in each region.

In Figure 1, commodity and factor market flows appear as solid lines and tax payments associated with various economic activities in production, consumption and trade appear as dotted lines.

Domestic production ($vom_{ir}$) is distributed to exports ($vxmd_{irs}$), international transportation services ($vst_{ir}$), intermediate demand ($vdfm_{ijr}$), household consumption ($vdfm_{iCr}$), investment ($vdfm_{iIr}$) and government consumption ($vdfm_{iGr}$). The accounting identity on the output side thus reads as:

$$\underbrace{vom_{ir}}_{\text{Domestic Production}} = \underbrace{\sum_s vxmd_{irs}}_{\text{Bilateral Exports}} + \underbrace{vst_{ir}}_{\text{Transport Exports}} + \underbrace{\sum_j vdfm_{ijr}}_{\text{Intermediate Demand}} + \underbrace{vdfm_{iCr} + vdfm_{iIr} + vdfm_{iGr}}_{\text{Final Demand (C + I + G)}}$$

The value of output is, in turn, related to the cost of intermediate inputs, value-added, and tax payments (net of production subsidies) $R_{ir}^Y$ by sector $i$ in region $r$:

$$\underbrace{vom_{ir}}_{\text{Value of Output}} = \underbrace{\sum_j vifm_{jir} + vdfm_{jir}}_{\text{Intermediate Inputs}} + \underbrace{\sum_f vfm_{fir}}_{\text{Factor Earnings}} + \underbrace{\mathcal{R}_{ir}^Y}_{\text{Tax Revenue}} \tag{1}$$

Imported goods which have an aggregate value of $vim_{ir}$ enter intermediate demand ($vifm_{jir}$), private consumption ($vifm_{iCr}$) and public consumption ($vifm_{iGr}$). The accounting identity for these flows on the output side reads as:

$$\underbrace{vim_{ir}}_{\text{Value of Imports}} = \underbrace{\sum_j vifm_{ijr}}_{\text{Intermediate Demand}} + \underbrace{vifm_{iCr} + vifm_{iGr}}_{\text{Final Demand (C+G)}}$$

and the accounting identify relating the value of imports to the cost of associated inputs is:

$$\underbrace{vim_{ir}}_{\text{CIF Value of Imports}} = \underbrace{\sum_s vxmd_{isr} + \sum_j vtwr_{jisr}}_{\text{FOB Exports + Transport Cost}} + \underbrace{\mathcal{R}_{ir}^M}_{\text{Tariffs Net Subsidies}} \tag{2}$$

Part of the cost of imports includes the cost of international transportation services. These services are provided with inputs from regions throughout the world, and the supply demand balance in the market for transportation service $j$ requires that the sum across all regions of service exports ($vst_{jr}$) equals the sum across all bilateral trade flows of service inputs ($vtwr_{jisr}$):

$$\underbrace{\sum_{r} vst_{jr}}_{\text{Service Exports for } j} = \underbrace{\sum_{isr} vtwr_{jisr}}_{\text{Transport Demand for } j} \quad (3)$$

Carbon emissions associated with fossil fuels are represented in the GTAP database through a satellite data array ($eco2_{igr}$) constructed on the basis of energy balances from the International Energy Agency (IEA). These emissions are proportional to fossil fuel use. Given detailed emissions associated with fossil fuel inputs, we can calculate direct carbon emissions emerging from the production of good $j$ in region $r$ as:

$$\underbrace{co2e_{jr}}_{\text{Aggregate Carbon}} = \underbrace{\sum_{fe} eco2_{fe,j,r}}_{\text{Sum of Carbon in Fuel Inputs}}$$

where $eco2_{fe,j,r}$ is the IEA-based statistic describing carbon emissions linked to the input of fuel $fe$ in the production of good $j$ in region $r$.

In our analysis, we adopt the 2004 baseline described in the GTAP dataset as the pre-policy equilibrium against which we compare the effects of policy regimes. We aggregate the 57 sectors provided by the GTAP database into 13 sectors that reflect the key differences in sectoral energy and trade intensity. 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 fossil-fuel switching in the price-responsive CGE model. Furthermore, the GTAP dataset includes 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 major 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. The coalition or non-coalition membership is indicated in the table. The carbon tariffs and the retaliatory measures used by non-coalition members that are the subject of the policy scenarios are limited to a set 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 from the fully disaggregate GTAP dataset to our aggregation are described in Appendix B.

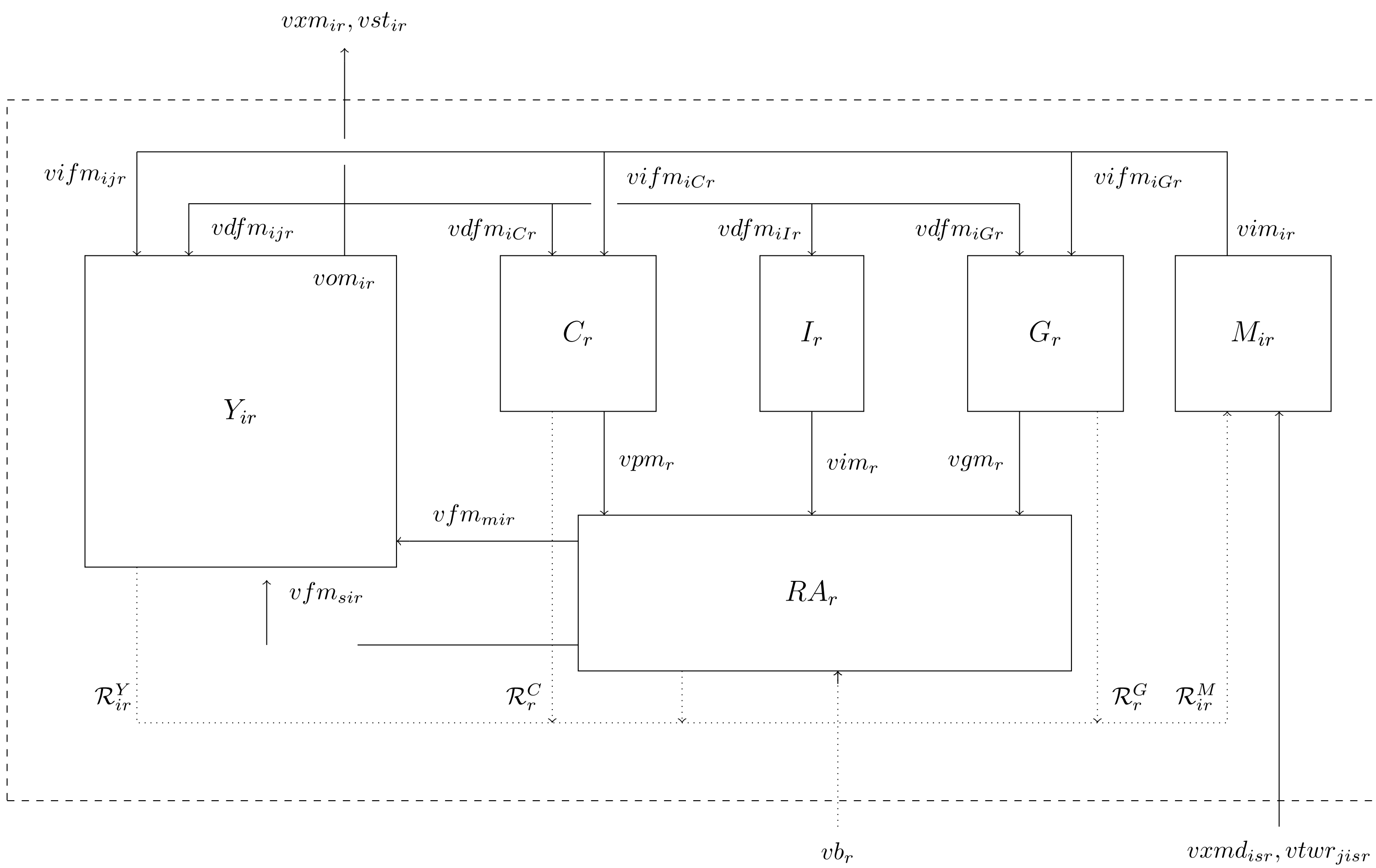


Figure 1: GTAP7 Benchmark Flows

| | |
|---|---|
| | REGIONS |
| *Coalition* | United States (USA), EU-27 plus European Free Trade Area (EUR), Other Annex I minus Russia (RA1) |
| *Non-Coalition* | China and Hong Kong (CHN), India (IND), Russian Federation (RUS), Other Energy-Exporting Countries (EEX), Other Middle-Income Countries (MIC), Other Low-Income Countries (LIC) |
| | SECTORS |
| *Energy* | Coal (COL), Crude Oil (CRU), Natural Gas (GAS), Refined Petroleum and Coal (OIL)*, Electricity (ELE) |
| *Energy-intensive* | Chemical, Rubber, Plastic Products (CRP)*, Iron and Steel (I_S)*, Non-Ferrous Metal (NFM)*, Non-Metallic Mineral (NMM)*, Water Transport (WTP), Air Transport (ATP), Other Transport (OTP) |
| *Other* | All Other Goods (AOG) |

* — 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

## 3 Policy Game

We assume that — in the absence of any emission or policy response from non-coalition countries — coalition countries collectively agree to reduce their emissions by 20% using a uniform carbon tax (or a system of tradable emission permits) across all sectors and regions within the coalition. This translates into a global abatement rate of approximately 10%. Across the different policy regimes described below, the coalition adjusts its domestic abatement target such that global emissions remain constant.

Figure 2 depicts the game tree for the one-shot policy game under consideration in our experiments. The coalition chooses either to use carbon tariffs against unregulated non-coalition countries (Tariff) or not (No Tariff). With knowledge of the coalition's choice, all non-coalition regions simultaneously choose a policy. On the No Tariff branch of the tree, non-coalition regions may choose either to cooperate and adopt regional emission restrictions or do nothing and leave their emission unregulated. On the Tariff branch of the tree, non-coalition regions may choose between the two options just described as well as the option to retaliate by raising

its import tariffs against coalition members and leaving its emission unregulated. On the Tariff branch of the tree, a non-coalition country is subject to carbon tariffs unless they choose cooperation, in which case the tariffs are removed. The policy responses available to non-coalition countries are described in more detail below.

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

**Retaliate** (R) — non-coalition region raises a uniform import tariff on EITE goods from all coalition countries 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) — non-coalition region operates with unrestricted emissions.

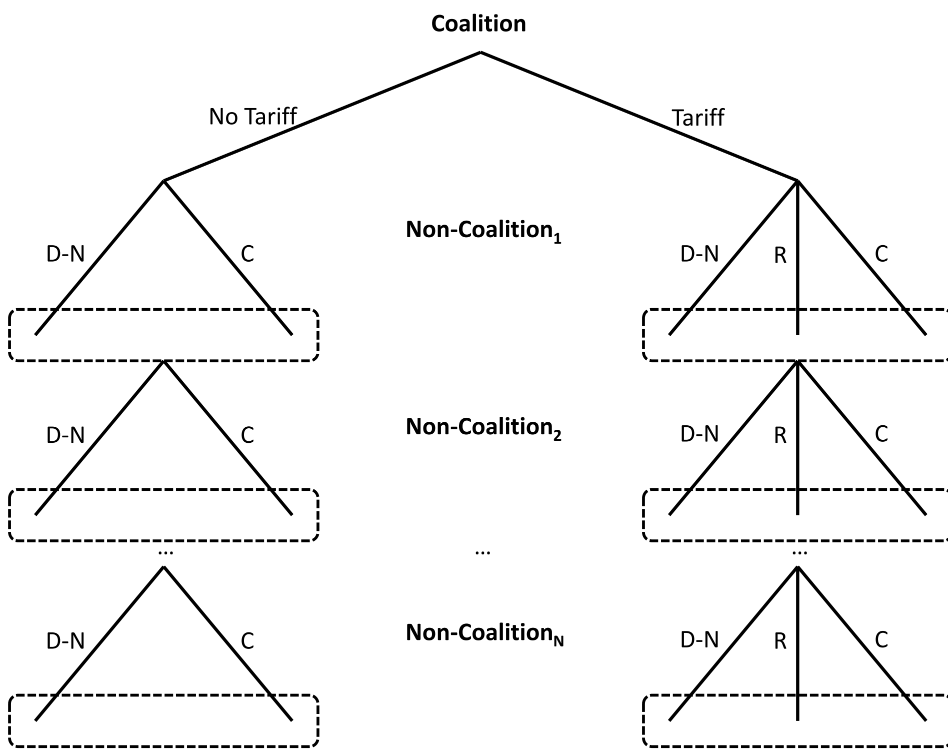


Figure 2: Structure of the Policy Game

When coalition countries employ carbon tariffs, the tariff rates are calculated as follows.

The benchmark gross-of-tax value of intermediate inputs, $vafm_{jir}$, is defined as

$$vafm_{j,i,r} = vdfm_{j,i,r}(1 + rtfd0_{j,i,r}) + vifm_{j,i,r}(1 + rtfi0_{j,i,r})$$

where $rtfd0_{jir}$ and $rtfi0_{jir}$ represent respectively the benchmark tax rates on domestic and imported varieties of input $j$ used in the produce of good $i$ in region $r$. Based on this, embodied carbon intensity of good $i$ from directly burning of fossil energy in production, $\theta_{ir}^{CO_2}$, is defined as

$$\theta_{ir}^{CO_2} = \sum_{fe} eco2_{fe,i,r} * vafm_{fe,i,r}/vom_{i,r}$$

where $fe$ indexes the set of fossil energy goods in the model.

The carbon tariff rate on good $i$ imported from region $r$ to region $s$, $\tau_{irs}$, is constructed from the prevailing carbon price in region $s$, $p_s^{CO_2}$, the direct carbon intensity of the imported good due to fuel combustion in production, and the indirect carbon intensity due to the use of electricity in production.

$$\tau_{irs} = p_s^{CO_2}\left[\theta_{ir}^{CO_2} + \theta_{ele,r}^{CO_2}(vafm_{ele,i,r}/vom_{ir})\right], \;\; i \in EITE,\; s \in \mathcal{C},\; r \in \mathcal{U}$$

where $EITE$ is the set of energy-intensive and trade-exposed goods in the model (see Table 1), $\mathcal{C}$ is the set of coalition countries and $\mathcal{U}$ is the set of unregulated non-coalition countries in the current policy regime (i.e. those countries which choose policies R or D-N).

When non-coalition countries choose to retaliate, they calculate their countervailing tariff rates as follows.

$$\tau_{irs} = \frac{\sum_{j \in EITE}\sum_{t \in \mathcal{C}} \text{Exports}_{jst} p_{js} \tau_{jst}}{\sum_{j \in EITE}\sum_{t \in \mathcal{C}} \text{Exports}_{jts} p_{jt}}, \;\; i \in EITE,\; r \in \mathcal{C},\; s \in \mathcal{R} \tag{4}$$

where $\text{Exports}_{jrt}$ is the volume of exports of good $j$ from region $r$ to region $t$, $p_{js}$ is the domestic price of good $j$ in region $s$, and $\mathcal{R}$ is the set of retaliating countries.[5] In words, a retaliating country chooses a tariff rate (uniform across sectors and coalition countries) such that the value of the tariff revenues equal the value of the revenues by the carbon tariffs imposed by coalition countries on them.

A number of assumptions underlying the policy scenarios deserve further discussion. First, we hold global emissions constant across all of the policy scenarios. There are two main reasons for this modeling choice. From an analytical perspective, holding the emission reduction constant allows us to make welfare comparisons across the different policy options. In the ab-

[5] $\text{Exports}_{jst}$ is calculated based on the equilibrium in which coalition countries implement the carbon tariffs and non-coalition countries which do not choose to retaliate implement their chosen policies (either C or D-N), but prior to retaliating countries implementing the countervailing tariffs. In other words, $\text{Exports}_{jrt}$ is not updated endogenously after the countervailing tariffs come into effect to ensure that (4) holds in equilibrium.

sence of this assumption, different policies would lead to higher or lower environmental benefits from reducing the impacts of climate change. Quantifying the benefits of these changes, as would be required to produce estimates of the net benefits of the policy, would require making an assumption about the willingness to pay for climate services for all of the different world regions represented in the model. While there are estimates in the empirical literature for some of the elements that would go into such a measure, to our knowledge a comprehensive willingness-to-pay measures do not currently exist. Furthermore, not even partial estimates exist for most regions of the world outside of the North America and Europe.

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 of 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. In our context, the rational response of coalition countries to increased levels of abatement in non-coalition countries is to curtail their effort. Our assumption that global emissions are held constant amounts to assuming that there is full crowding out of Annex-I contributions to the public good when non-Annex-I countries increase their contributions.[6] An alternative would be to specify formal preferences for climate services and to calculate the endogenous policy responses within the numerical model, a feature that would add significantly to the computational complexity of the analysis.

Second, coalition countries 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 a variety of assumptions represented in the literature on border carbon adjustments ranging from the use of just direct emissions (Mattoo et al. 2009), to the use of direct emissions plus electricity emissions (Babiker and Rutherford 2005) as we have done here, to the use of measures based on input-output models that calculate the full direct and indirect emissions embodied in goods (Böhringer et al. 2011). The measure we use here is a compromise. It is significantly more comprehensive than using just direct emissions as electricity is an important, carbon-intensive input to many traded goods. However, it is also simple enough to calculate that one could imagine actual policies based on this metric (as opposed to those based on the full input-output measures).

Third, retaliation means raising a uniform tariff on imports from coalition countries equal in value to the carbon tariffs placed on the retaliating country. This assumption is meant to capture the spirit of the retaliatory measures allowable under the World Trade Organization (WTO) when a country 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-

[6] 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 the world and regional economies.

exposed goods (described in Table 1). It should be acknowledged, however, that alternative designs for the tariffs might give them more potency in their assigned roles in our experiments, which could make cooperation from non-coalition countries either more or less likely.

Fourth, cooperation from non-coalition countries means taking on abatement responsibilities equal (as a percentage reduction from baseline emissions) to the abatement undertaken in coalition countries in equilibrium. We also assume that non-coalition regions do not have access to trade in emission permits with each other or with coalition countries. While the specific requirement that abatement rates should be equal is arbitrary, we model the abatement requirement this way because it would appear to represent a strong impediment to sustaining cooperation from non-coalition countries. It assigns far more abatement responsiblity to these countries than current international climate negotiations are pursuing. If non-coalition countries can justify abatement at this level, it seems likely that cooperation in regimes where more modest actions were expected of these countries would be sustainable as well. Similarly, prohibiting access to international permit trade for these countries 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 following section, if major non-coalition countries can be included without cost in unrestricted emissions trade then the rationale for carbon tariffs largely disappears.

## 4 Results

We begin by analyzing the welfare effects of key policy regimes. Table 2 describes welfare losses by region and policy regime. They are measured as a percentage of levels in the pre-policy equilibrium represented by the GTAP data. A positive number in the table represents a welfare loss (i.e. a positive cost) and a negative number a welfare gain.

In the unique Nash equilibrium prediction from the model, China and Russia cooperate (C) by adopting emission targets and all other non-coalition regions retaliate (R) against the carbon tariffs with import tariffs imposed on coalition countries. 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 states and punish non-coalition states, we include the regime in which all non-coalition states 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 same regime but where the coalition does not use the carbon tariffs (column 3). This outcome also represents the best response of non-coalition countries if the coalition were to choose not to use the tariffs. Therefore, coalition countries 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 cooperation, we also report the regime in which all non-coalition countries choose to cooperate (column 4). The cooperative outcome described in (4) will not,

| | Tariff | | No Tariff | | Unrestricted |
|---|---|---|---|---|---|
| | CHN,RUS=C Others=R* | All D-N | All D-N* | All C | Int'l Permit Trade |
| | (1) | (2) | (3) | (4) | (5) |
| All | 0.19 | 0.35 | 0.37 | 0.13 | 0.09 |
| Coalition | 0.10 | 0.22 | 0.31 | 0.01 | 0.07 |
| Non-Coalition | 0.51 | 0.89 | 0.62 | 0.59 | 0.16 |
| | *Coalition* | | | | |
| Europe | 0.13 | 0.26 | 0.39 | 0.01 | 0.05 |
| United States | 0.06 | 0.13 | 0.19 | – | 0.09 |
| Other Annex-I | 0.15 | 0.30 | 0.40 | 0.04 | 0.09 |
| | *Non-Coalition* | | | | |
| China | 0.25 | 0.35 | 0.23 | 0.19 | -0.59 |
| Russia | 2.77 | 4.71 | 3.21 | 2.60 | 1.38 |
| India | -0.20 | -0.26 | -0.37 | -0.12 | -0.26 |
| Other Energy-Exporting | 1.75 | 2.80 | 2.28 | 1.81 | 1.07 |
| Other Middle-Income | 0.03 | 0.17 | 0.06 | 0.16 | 0.00 |
| Other Low-Income | 0.34 | 0.48 | 0.31 | 0.63 | 0.33 |

* — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime.

Table 2: % Welfare Loss by Region and Policy Regime

in general, produce the minimum-cost method of reaching the abatement target and, therefore, underestimates the full efficiency gains that could theoretically be obtained from cooperation. 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 minimum-cost method of meeting the global abatement target. The assumption regarding the burden sharing in this scenario is that countries are allocated emission permits sufficient to cover 80% of their benchmark emissions for coalition countries and 100% of their benchmark emissions for non-coalition countries. Thus non-coalition countries are fully compensated for their abatement by transfers from coalition countries for the direct costs of the abatement they undertake (although they may experience other gains or losses due to the adjustments that take place in the world economy under the abatement regime).

The first three rows of the table report aggregated welfare changes for all world regions, all coalition regions and all non-coalition regions respectively. In the Nash equilibrium, the 10% reduction in carbon emissions we assume in our experiments costs 0.19% of global wel-

fare. 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 0.37% when coalition countries do not employ carbon tariffs (3) or 0.35% when they do use the tariffs (2). The cost in fully cooperative regime (4) is 0.13%. Thus the Nash equilibrium outcome captures 75% of the possible efficiency gains measured against our cooperative benchmark. The overall cost of the policy is lower when non-coalition countries take on abatement responsibility because these countries are the source of low-cost abatement opportunities. Thus shifting abatement to these countries moves the policy toward the first-best outcome.

In equilibrium, the costs of abatement fall more heavily on the non-coalition countries (0.51%) than the coalition (0.1%). This distribution reflects the fact that China and Russia take on abatement responsibilities in this policy regime. 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 countries (0.62%) even when they do not undertake it themselves. This is due primarily to the fact Russia and Other Energy-Exporting countries suffer from the depressing effect abatement has on demand for their energy and energy-intensive exports. Other non-coalition regions register little change in welfare when we compare (1) with (3). The exception is India which generally benefits when the coalition takes on more abatement.

Comparing columns (2) and (3) provides a measure of the impact when coalition countries impose carbon tariffs on non-coalition countries. Coalition regions uniformly benefit from the use of the tariffs as they allow these countries to capture terms-of-trade gains and, on the other side, non-coalition countries uniformly lose with major energy suppliers (Russia and Other Energy-Exporting) suffering the most in percentage terms. However, the global welfare cost of abatement decline only from 0.37% to 0.35% when the tariffs are used. Thus the tariffs are not effective as a means to (directly) reduce the global cost of meeting the abatement target.

The regime described in (3) represents the best response for non-coalition countries if the coalition fails to employ the tariffs. Energy-importing non-coalition countries (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 countries 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.

The comparison of (2) and (3) makes clear that the tariffs have a measurable punative effect on many of the non-coalition countries. However, the comparison of (3) and (4) also makes clear that the net effect of changes to the terms of trade also plays an important role in shaping the equilibrium outcome. 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 benchmark calculation in which there is a global system of international emission-permit trade and non-coalition countries receive compensation via the assumption that their initial holdings of permits are sufficient to cover 100% of their baseline emissions. The equilibrium in (5) represents a minimum-cost method of achieving the abatement target in the model. As a result, we would expect it to dominate all other policy regimes depicted in the table in aggregate welfare terms. The aggregate cost of the policy is 0.09% or roughly half the cost of the Nash equilibrium policy regime. Both coalition and non-coalition regions benefit although most of the gains go to non-coalition countries. This is because the burden-sharing rule assumed implies large wealth transfers to these countries in exchange for their abatement services. The exception is the United States which is slightly worse off under (5).

| | Deviation | Welfare Change |
|---|---|---|
| China | Retaliate | 0.34 |
| | Do Nothing | 0.52 |
| Russia | Retaliate | 1.06 |
| | Do Nothing | 1.06 |
| Other Energy-Exporters | Cooperate | 2.30 |
| | Do Nothing | 0.16 |
| India | Cooperate | 0.70 |
| | Do Nothing | 0.03 |
| Other Low-Income | Cooperate | 1.13 |
| | Do Nothing | 0.02 |
| Other Middle-Income | Cooperate | 4.67 |
| | Do Nothing | 1.15 |

Table 3: % Welfare Cost of Deviation from Nash Equilibrium

Table 3 describes the welfare losses non-coalition countries experience when they unilaterally deviate from their Nash equilibrium strategy. Once again, welfare losses are calculated as a percentage of pre-policy baseline welfare levels. 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 a third to a half of a percent welfare loss relative to cooperation. Russia also strongly prefers cooperation to other actions, registering an approximately 1% welfare loss if they follow either alternative policy. Cooperation appears quite costly for most of the non-coalition regions that choose to retaliate in equilibrium. The "Do Nothing" option, on the other hand is only modestly more costly, suggesting that these

countries choose not to cooperate mainly to avoid abatement costs as opposed to capturing rents from their countervailing tariffs.

Table 4 provides further evidence on the incentives driving the cooperation from China and Russia. Following on the experiments described in Table 3, the table reports the benchmark value of sectoral net exports (in billions of 2004 US Dollars) and changes in domestic sectoral prices (as a percentage of benchmark price levels) for China and Russia when each country unilaterally switches from retaliation to cooperation, assuming all other countries play their Nash equilibrium strategies. (Therefore the comparision for China is the Nash equilibrium versus the regime in which Russia cooperates and all others retaliate, and the comparision for Russia is the Nash equilibrium versus the regime in which China cooperates and all others retaliate.) Thus a positive entry in a "Price Chg." column indicates that domestic prices rise when it switches to its Nash equilibrium strategy. These two pieces of information combine to give an approximate indicator of change in the terms-of-trade a country experiences under the switch, as price increases benefit countries which are net exporters and hurt countries that are net importers in a given industry. This is described in columns labelled "T-o-T". A "+" entry in one of these columns indicates a terms-of-trade gain and a "-" entry a loss for that country.

| | *China* | | | *Russia* | | |
|---|---|---|---|---|---|---|
| | Net Exports | Price Chg. | T-o-T | Net Exports | Price Chg. | T-o-T |
| All Other Goods | 161.23 | 0.23 | + | -62.28 | 0.45 | - |
| Water Transport | 18.74 | 1.29 | + | 2.69 | 2.41 | + |
| Air Transport | 6.22 | 0.62 | + | 1.77 | 4.02 | + |
| Other Transport | 6.06 | 0.34 | + | -0.20 | 4.32 | - |
| Coal | 1.95 | -1.76 | - | 1.42 | -0.46 | - |
| Natural Gas | -0.22 | 3.50 | - | 4.96 | -3.33 | - |
| Electricity | -0.26 | 11.29 | - | -0.35 | 18.24 | - |
| Non-Ferrous Metals | -6.45 | 1.08 | - | 12.60 | 4.64 | + |
| Refined Oil | -7.21 | 1.08 | - | 12.02 | 1.39 | + |
| Non-Metallic Minerals | -9.22 | 1.38 | - | 0.02 | 2.44 | + |
| Iron and Steel | -9.58 | 1.48 | - | 12.16 | 4.67 | + |
| Crude Oil | -28.30 | 1.23 | - | 47.27 | 0.32 | + |
| Chemicals, Rubber,... | -56.27 | 0.82 | - | -2.16 | 5.11 | + |

Table 4: Net Exports, Price Changes and Terms of Trade by Region and Sector

The rows are sorted with China's largest net exports at the top and largest net imports at the bottom of the table. China is a large net exporter of non-energy-intensive manufactured goods that fall into the "All Other Goods" category in our aggregation and a net importer of most of the other commodities described in our aggregation of the GTAP data. Most domestic prices rise when China decides to take abatement (the exception is the price of coal). Thus they experience terms-of-trade gains for their manufacturing industries and losses associated with

their imports.[7] Russia is a major exporter of crude oil as well as energy-intensive goods (non-ferrous metals, iron and steel) and a large net importer of non-energy-intensive manufactured goods (All Other Goods). Once again, most domestic price rise in Russia in the switch to the Nash equilibrium. Thus Russia experiences terms-of-trade gains in energy-intensive sectors (particularly in the non-ferrous metals and iron and steel industries) and, to a lesser extent in energy sectors (gains in crude and refined oil and losses in natural gas) and losses in the cost of acquiring manufactured goods from abroad.

| | **Tariff** | | **No Tariff** | | Unrestricted |
|---|---|---|---|---|---|
| | CHN,RUS=C Others=R* | All D-N | All D-N* | All C | Int'l Permit Trade |
| | (1) | (2) | (3) | (4) | (5) |
| All | 9.88 | 9.88 | 9.88 | 9.88 | 9.88 |
| Coalition | 14.31 | 21.04 | 22.00 | 9.88 | 6.85 |
| Non-Coalition | 5.55 | -1.01 | -1.95 | 9.88 | 12.84 |
| | *Coalition* | | | | |
| Europe | 11.60 | 17.47 | 18.47 | 7.64 | 5.16 |
| United States | 16.11 | 23.45 | 24.37 | 11.43 | 8.04 |
| Other Annex-I | 14.37 | 21.01 | 21.99 | 9.77 | 6.72 |
| | (20.14) | (35.86) | (37.78) | (13.07) | (8.43) |
| | *Non-Coalition* | | | | |
| China | 14.31 | -0.42 | -0.84 | 9.88 | 20.18 |
| | (5.34) | – | – | (3.48) | (8.43) |
| Russia | 14.31 | 0.97 | -2.33 | 9.88 | 10.00 |
| | (12.78) | – | – | (8.47) | (8.43) |
| India | -0.86 | -0.77 | -1.35 | 9.88 | 18.55 |
| | – | – | – | (3.84) | (8.43) |
| Other Energy-Exporting | -1.29 | -1.32 | -2.57 | 9.88 | 6.30 |
| | – | – | – | (13.39) | (8.43) |
| Other Middle-Income | -2.11 | -2.57 | -2.92 | 9.88 | 8.17 |
| | – | – | – | (10.78) | (8.43) |
| Other Low-Income | -1.58 | -1.81 | -2.67 | 9.88 | 7.95 |
| | – | – | – | (10.91) | (8.43) |

* — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime.

Table 5: % Emission Reduction by Region and Policy Regime

[7] The GTAP 7.1 dataset we use is a description of the world economy in 2004. At the time, China was among the world's largest net importers of iron and steel. Since that time it has become the world's largest net exporter. Thus a simple extrapolation of this fact would suggest that a model calibrated based on more recent data would produce more favorable terms of trade changes in the move to the Nash equilibrium for China.

Table 5 reports on the emission changes associated with the same policy regimes described in Table 2. Emission changes are reported as a percentage of pre-policy baseline levels. The prevailing price of carbon emissions (measured in 2004 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. The coalition's commitment to controlling emissions translates into an approximately 10% reduction in global emissions. When all non-coalition countries 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%.

The effect of the carbon tariffs on leakage can seen from (2). Leakage is cut roughly in half by the tariffs, an effect that relieves coalition countries of approximately 5% of their abatement responsibility relative to (3). The tariffs are particularly effective at controling leakage to Russia (through their effect on that country's energy-intensive exports) which goes from increasing its emissions by 2.33% under (3) to reducing its emission by 0.97% under (2).

In the Nash equilibrium (1), China and Russia take on approximately a third of the coalition's abatement responsibilities relative to (3). Leakage to other non-coalition countries in this scenario is roughly the same as in the carbon-tariff benchmark (2). The prevailing carbon prices in China, Russia and the coalition in the Nash equilibrium show that abatement costs are significantly lower in China and Russia – particularly in China. These countries reduce their emissions by over 14% at a marginal abatement cost of $5 per ton in China and $13 per ton in Russia. The same reduction in coalition countries leaves them with a marginal abatement cost of $20 per ton.

To summarize our main results, we find that the non-cooperative equilibrium 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 for our assumed abatement target. Their cooperation is supported by a combination of two effects. First, facing carbon tariffs is damaging to to these countries. Second, the improvement in the performance of world economy when abatement shifts from high-abatement-cost coalition countries 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 off of the efforts of China and Russia.

# 5 Sensitivity Analysis

There are two sets of parameter values to which the results of CGE analyses of unilateral carbon policies consistently prove sensitive. First, the Armington elasticities that govern the degree to which consumers can substitute between varieties of the same good produced in different countries are important because they determine, in part, how easily the world economy can adjust in response to the introduction of climate policy. For example, the Armington elasticities

affect the degree to which the world's consumers can look elsewhere for emission-intensive goods when the varieties they would have purchased from coalition countries become more expensive under the carbon policy. They also impact the terms-of-trade advantage a country can expect to gain by using tariffs. When these elasticities take on smaller values, demand for a given country'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 countries when carbon policies come into place. A lower elasticity value implies a larger drop in the price of an energy good when its demand falls under the carbon policy, which produces a stronger stimulus for demand in unregulated regions of the world. Lower elasticitiy values also imply larger welfare losses to energy-exporting regions when demand for their energy goods falls.

Table 6 describes the results of sensitivity analysis in which we double and halve the Armington and energy-supply elasticities. In each case the elasticity values are changed simultaneously for all regions and goods. Thus a row entry in the table labelled "2x" in the Armington elasticity column is interpreted as doubling all of the Armington elasticities from the reference levels that were the basis of the experiments described in the previous section. Similarly, supply elasticities for coal, natural gas and crude oil are doubled or halved for all three goods in all regions in the model simultaneously. The first two columns of the table describe the elasticity assumptions. Columns 3-8 indicate the Nash equilibrium strategy chosen by each non-coalition country in a particular experiment. The final three columns report the welfare effects associated with the Nash equilibrium.

| Armington | Energy | | | **Regional Strategy** | | | | | **Welfare Change** | |
|---|---|---|---|---|---|---|---|---|---|---|
| Elasticity | Elasticity | CHN | RUS | EEX | IND | MIC | LIC | All | Coalition | Non-Coalition |
| 1/2x | 2x | C | C | C | R | R | R | 0.18 | 0.09 | 0.57 |
| | 1x | C | C | R | R | R | R | 0.18 | 0.06 | 0.68 |
| | 1/2x | C | C | R | R | R | R | 0.18 | 0.02 | 0.83 |
| 1x | 2x | C | C | R | R | R | R | 0.19 | 0.12 | 0.43 |
| | 1x | C | C | R | R | R | R | 0.19 | 0.10 | 0.51 |
| | 1/2x | C | C | R | R | R | R | 0.19 | 0.08 | 0.62 |
| 2x | 2x | C | C | R | D-N | R | R | 0.19 | 0.15 | 0.36 |
| | 1x | C | C | R | D-N | R | R | 0.19 | 0.13 | 0.42 |
| | 1/2x | C | C | R | D-N | R | R | 0.19 | 0.11 | 0.51 |

Table 6: Equilibrium Outcome and Welfare Change Sensitivity Analysis

Our finding that China and Russia cooperate in equilibrium is robust to the alternative elasticity assumptions. The global welfare implications of the equilibrium outcome are also stable. When Armington elasticities are halved and energy-supply elasticities are doubled, the Other Energy-Exporting region joins China and Russia in taking on abatement responsibilities. When

Armington elasticities are doubled, India no longer retaliates and simply remains unregulated.

Table 7 examines in more detail how the incentives for China and Russia to cooperate are altered in the sensitivity analysis. The table reports the welfare cost for each country of deviating from its equilibrium strategy, the same metric explored in Table 3. Note that we report here only the sensitivity cases in which we vary one set of parameters (either Armington or energy-supply elasticities) while holding the other at its reference levels.

| | | Do Nothing | Retaliate |
|---|---|---|---|
| | | *Armington Elasticity* | |
| China | 2x | 0.54 | 0.65 |
| | 1x | 0.52 | 0.34 |
| | 1/2x | 0.87 | 0.45 |
| Russia | 2x | 1.54 | 1.63 |
| | 1x | 1.06 | 1.06 |
| | 1/2x | 1.19 | 1.12 |
| | | *Energy Elasticity* | |
| China | 2x | 0.67 | 0.50 |
| | 1x | 0.52 | 0.34 |
| | 1/2x | 0.21 | 0.02 |
| Russia | 2x | 0.66 | 0.66 |
| | 1x | 1.06 | 1.06 |
| | 1/2x | 1.38 | 1.37 |

Table 7: % Welfare Cost of Deviation from Nash Equilibrium Sensitivity Analysis

While there is variability in the payoffs across scenarios, overall China and Russia both face substantial penalties if they deviate. This suggests that the insight that these countries will cooperate is fairly robust. Changing the energy-supply elasticities generates more variation in payoffs than changing the Armington elasticities, and a clear pattern in the payoffs to cooperation emerges from this analysis. Russia tends to face stronger incentives to cooperate when energy-supply elasticities take on smaller values. The logic is that lower values imply larger welfare losses to Russia when coalition countries take on abatement because Russia is a major energy exporter.

The results for China, a large net energy importer, show the opposite trend. Cooperation tends to be less valuable to them when energy supply elasticities are low. The intuition is that China benefits from the lower price of energy imports when the coalition abatement depresses world energy markets. The model results show some sensitivity to this effect in particular. The penalty China experiences for retaliating instead of cooperating falls to just 0.02 (as a percentage of per-policy baseline welfare levels) when fuel elasticities are halved. Thus if this effect

were strong enough, China might prefer to leave abatement in the hands of coalition countries. In this case it would lose the terms-of-trade benefits it gets from stronger demand for its exports in coalition countries but it would gain the benefits of cheap energy imports.

Finally, our main results rely on the assumption that all Annex-I countries are committed to reducing at a level roughly consistent with their Kyoto-Protocol targets. To explore the implications of relaxing this assumption, we examine the results of an alternative coalition structure where Europe (EU-27 plus EFTA) is the only coalition member in Table 8. The United States and Other Annex-I countries join the group of non-coalition countries. 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 table reports the key policy regimes and welfare effects in the same manner as Table 2.

| | **Tariff** | | **No Tariff** | |
|---|---|---|---|---|
| | CHN,RUS=C Others=R* (1) | CHN=C Others=D-N (2) | CHN=C Others=D-N* (3) | All C (4) |
| All | 0.06 | 0.07 | 0.07 | 0.03 |
| | *Coalition* | | | |
| Europe | 0.10 | 0.11 | 0.15 | 0.00 |
| | *Non-Coalition* | | | |
| China | 0.07 | 0.09 | 0.12 | 0.04 |
| Russia | 0.92 | 1.14 | 0.75 | 0.75 |
| United States | -0.01 | -0.00 | -0.00 | -0.01 |
| Other Annex-I | -0.02 | -0.01 | -0.01 | -0.00 |
| India | -0.01 | 0.01 | -0.02 | -0.04 |
| Other Energy-Exporting | 0.42 | 0.43 | 0.30 | 0.48 |
| Other Middle-Income | 0.01 | 0.02 | 0.01 | 0.03 |
| Other Low-Income | 0.14 | 0.14 | 0.07 | 0.17 |

* — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime.

Table 8: % Welfare Loss by Region and Policy Regime: Europe-Alone Coalition

The Nash equilibrium prediction, once again, involves China and Russia adopting abatement targets while all other non-coalition countries retaliate against the carbon tariffs from Europe. 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 countries when Europe chooses not to employ carbon tariffs differs from our earlier experiments however. China continues to find it in its best interest to cooperate in spite of

the fact that it faces no threat of the tariffs. Thus the terms-of-trade shift in the world economy when abatement allocation moves to China appears to be strong enough to justify cooperation on its own. 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 experiments, 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 here as well.

## 6 Discussion

The issue of how to control developing-world emissions is central to the future of global warming policy. Without the participation of these countries, the costs of controling global emissions at levels consistent with avoiding "dangerous" climate interference will be very 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 compensating. In our analysis, the combined influence of carbon tariffs and the interconnectedness of the global economy produce a somewhat different picture. Key developing-world countries already lose out when Annex-I countries abate even if they do no abatement of their own. This is primarily because they depend on the strong 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.

There are a number of extensions of this analysis that would be useful to pursue in future research. It would be interesting to decompose the welfare effects experienced by non-coalition countries under the different policy regimes to get a more precise understanding of the linkages in the world economy that are driving the incentives to cooperate. For Russia, it seems clear that the outcomes in markets for energy and energy-intensive goods are of central importance but for China the gains appear to be less concentrated.

Our analysis assumes that retaliation in response to the carbon tariffs involves raising a uniform tariff against all EITE imports from coalition countries. The welfare-maximizing countervailing policy might a more potent tool than the one we have designed — either conferring a greater ability to extract rents from trade partners or to damage them. Both options might make cooperation less attractive. The carbon tariffs in our analysis are also not designed optimally.

We assume that the global abatement target is held constant across policy regimes in our analysis. We do this, in part, to facilitate welfare comparisons across regimes and, in part, to mimic the idea that voluntary effort to control climate change by coalition countries should be crowded out by increased non-coalition effort in a non-cooperative equilibrium. Alternatively,

we could have specified formal preferences for climate services. For example, a common assumption in the trade and environment literature is that environmental quality is a normal good. In this case, the abatement that takes place in each policy regime would be endogenous to the changes they induce in the world economy. It is possible this could change the incentive for countries to cooperate. It would also be interesting to explore extensions of the model in which the share of abatement cooperating countries take on is endogenously determined within the model.

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## A Algebraic Description of the CGE Model

The computable 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 9 - 14 explain the notation for variables and parameters employed within our algebraic exposition. Figures 3 - 5 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 ($g \notin FF$):

$$\Pi^Y_{gr} = p_{gr} - \left[ \theta^M_{gr} p_{gr}^{M(1-\sigma^{KLEM}_{gr})} + (1-\theta^M_{gr}) \left[ \theta^E_{gr} p_{gr}^{E(1-\sigma^{KLE}_{gr})} + (1-\theta^E_{gr}) p_{gr}^{KL(1-\sigma^{KLE}_{gr})} \right]^{\frac{(1-\sigma^{KLEM}_{gr})}{(1-\sigma^{KLE}_{gr})}} \right]^{1/(1-\sigma^{KLEM}_{gr})} \leq 0$$

- 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:

$$\Pi_{gr}^{KL} = p_{gr}^{KL} - \left[\theta_{gr}^{K} v_{gr}^{(1-\sigma_{gr}^{KL})} + (1-\theta_{gr}^{K}) w_r^{(1-\sigma_{gr}^{KL})}\right]^{1/(1-\sigma_{gr}^{KL})} \leq 0$$

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

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{Q} q_{gr}^{(1-\sigma_{gr}^{Q})} + (1-\theta_{gr}^{Q}) \left(\theta_{gr}^{L} w_r + \theta_{gr}^{K} v_{gr} + \sum_{i \notin FF} \theta_{igr}^{FF} p_{igr}^{A}\right)^{(1-\sigma_{gr}^{Q})}\right]^{1/(1-\sigma_{gr}^{Q})} \leq 0$$

- Armington aggregate:

$$\Pi_{igr}^{A} = p_{igr}^{A} - \left(\theta_{igr}^{A} p_{ir}^{(1-\sigma_{ir}^{A})} + (1-\theta_{igr}^{A}) p_{ir}^{IM(1-\sigma_{ir}^{A})}\right)^{1/(1-\sigma_{ir}^{A})} \leq 0$$

- Aggregagte imports across import regions:

$$\Pi_{ir}^{IM} = p_{ir}^{IM} - \left[\sum_{s} \theta_{isr}^{IM} (1+\tau_{isr}) p_{is}^{(1-\sigma_{ir}^{IM})}\right]^{1/(1-\sigma_{ir}^{IM})} \leq 0$$

## Market-clearance conditions:

- Labor:

$$\bar{L}_r \geq \sum_{g} Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial w_r}$$

- Capital:

$$\bar{K}_{gr} \geq Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial v_{gr}}$$

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

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

- Material composite:

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{M}}$$

- Energy composite:

$$E_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{E}}$$

- Value-added composite:

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{KL}}$$

- 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 9: 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 $r$ |
| $A_{igr}$ | Armington aggregate for commodity $i$ for demand category (item) $g$ in region $r$ |
| $IM_{ir}$ | Aggregate imports of commodity $i$ in region $r$ |

Table 10: 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 $r$ |
| $p_{igr}^{A}$ | Price of Armington good $i$ for demand category $g$ in region $r$ |
| $p_{ir}^{IM}$ | Price of import composite for good $i$ in region $r$ |
| $\tau_{isr}$ | 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 11: 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 12: Endowments and Carbon Emissions Specification

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

Table 13: Cost Share Parameters

| | |
|---|---|
| $\sigma_{gr}^{KLEM}$ | Substitution between the material composite and the energy-value-added aggregate in the production of item $g$ in region $r$* |
| $\sigma_{gr}^{KLE}$ | Substitution between energy and the value-added composite in the production of item $g$ in region $r$* |
| $\sigma_{gr}^{M}$ | Substitution between material inputs within the energy composite in the production of item $g$ in region $r$* |
| $\sigma_{gr}^{KL}$ | Substitution between capital and labor within the value-added composite in the production of item $g$ in region $r$* |
| $\sigma_{gr}^{E}$ | Substitution between energy inputs within the energy composite in the production of item $g$ in region $r$ (by default $= 0.5$) |
| $\sigma_{gr}^{Q}$ | Substitution between natural resource input and the composite of other inputs in the fossil fuel production ($g \in FF$) of region $r$*** |
| $\sigma_{ir}^{A}$ | Substitution between domestic variety and the composite of imported varieties from different regions for good $i$ in region $r$** |
| $\sigma_{ir}^{IM}$ | 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 and Walmsley (2008) 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 14: Elasticity Parameters

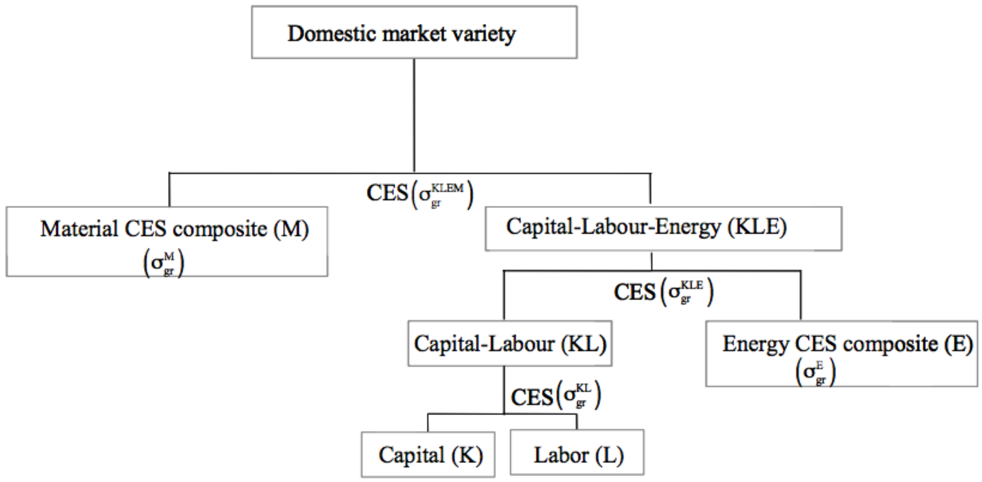


Figure 3: Nesting in Non-Fossil-Fuel Production

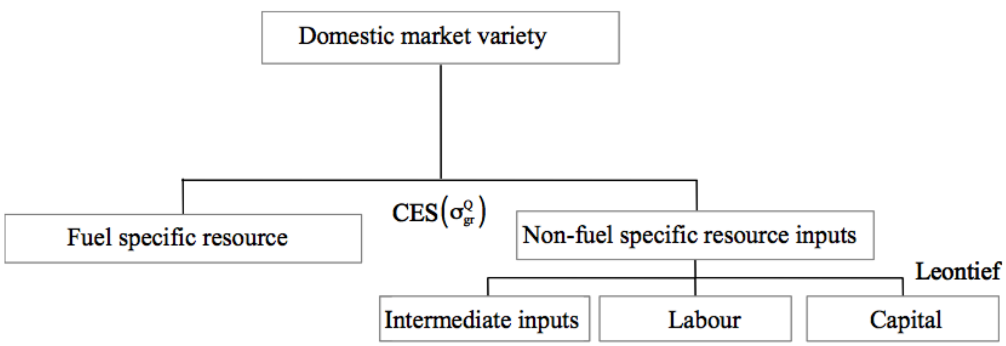


Figure 4: Nesting in Fossil-Fuel Production

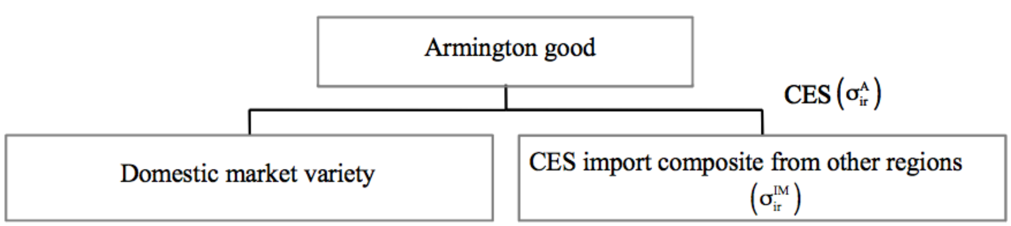


Figure 5: Nesting in Armington Composite Production

# 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 15: Mapping of Regions from the GTAP 7.1 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 16: Mapping of Sectors from GTAP 7.1 Dataset

| | |
|---|---|
| *Physical Capital* | Physical Capital |
| *Labor* | Unskilled Labor, Skilled Labor |
| *Natural Resources* | Natural Resources |

Table 17: Mapping of Factors from GTAP 7.1 Dataset