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V – 340 – 11

September 2011

Department of Economics
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NBER WORKING PAPER SERIES

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Working Paper 17376
http://www.nber.org/papers/w17376

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
August 2011

This research has been supported by Environment Canada. Research assistance has been provided by Justin Carron. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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JEL No. F18,H23,Q54,Q56

ABSTRACT

In a world where the prospects of a global agreement to control greenhouse gas emissions are bleak, the idea of using trade policy as an implicit regulation of foreign emission sources has gained many supporters in countries contemplating unilateral climate policies. Embodied carbon tariffs tax the direct and indirect carbon emissions embodied in imported goods. The appeal seems obvious: as OECD countries are, on average, large net importers of embodied emissions from non-OECD countries, carbon tariffs could substantially extend the reach of OECD climate policies. We investigate this claim by simulating the effects of embodied carbon tariffs with a computable general equilibrium model of global trade and energy use. We find that embodied carbon tariffs do effectively reduce carbon leakage. However, the scope for improvements in the global cost-effectiveness of unilateral climate policy is limited. The main welfare effect of the tariffs is to shift the burden of OECD climate policy to the developing world.

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1 Introduction

In a world where the likelihood of a global agreement to control greenhouse gas emissions seems small, the idea of using trade policy as a form of indirect regulation of foreign emission sources has gained many supporters in OECD regions considering unilateral climate policies. One popular proposal involves the taxation of carbon emissions embodied in imported goods — an instrument we refer to in this paper as an "embodied carbon tariff." Under such a scheme, for example, imported steel from non-OECD countries would face a tax based on direct emissions (those due to the combustion of fossil energy in steel production) as well as indirect emissions (such as emissions created by the generation of electricity for use in steel production).

The intuitive appeal of embodied carbon tariffs to those concerned about climate change is clear: when emissions from domestic production activities are priced unilaterally, the global environmental impact will be undermined to the extent that emissions increase elsewhere — an effect known as carbon leakage. Advocates of consumption-based emission policies (including embodied carbon tariffs) argue that regulating emissions in domestic production also fails to account for other emissions a country is "responsible for" if its citizens consume imported goods with embodied emissions. Embodied carbon tariffs may provide a way for climate-concerned nations to reduce carbon leakage and regulate the emissions embodied in imported consumption goods. Taxation of embodied carbon is also attractive from a political economy perspective; embodied carbon tariffs ensure that the production of emission-intensive goods cannot easily avoid regulation by relocating abroad, ameliorating concerns about the loss of competitiveness in domestic industries due to climate policy.

All of these arguments have contributed to the popularity of recent climate policy initiatives that seek to regulate emissions embodied in consumption activities. Examples include California's low-carbon fuel standard (LCFS), the proposed United States federal LCFS, and the discussion of border adjustments (or carbon tariffs) at relatively mature states of the climate policy debate in both the United States and the European Union.

Advocates of embodied carbon policies cite the results of engineering studies based on life-cycle analysis or, more specifically, multi-regional input-output (MRIO) studies, that calculate carbon emissions embodied in production, consumption and trade throughout the world economy. The calculations show that the developed world is, on average, a large net importer of embodied emissions from developing countries and has been becoming more so over time (Weber and Matthews 2007, Peters and Hertwich 2008a, Peters and Hertwich 2008b, Peters and Hertwich 2008c). Furthermore, a substantial amount of the emissions embodied in traded goods is not due to the combustion of fossil energy inputs used directly in their production. For example, much of the emissions embodied in manufactured goods stems from electricity use, where the combustion of fossil fuels in electricity generation is the primary source of the emissions in the supply chain. Supporters of embodied carbon tariffs argue, therefore, that this instrument could substantially extend the reach of unilateral OECD climate policies — first, by covering foreign sources of emissions and, second, by covering indirect sources of emissions.

In this paper we quantify the economic and environmental performance of embodied carbon tariffs. We use a global dataset on economic activity and carbon flows to calculate the carbon embodied in traded goods drawing on standard MRIO methods. We then use a computable general equilibrium (CGE) model that is calibrated to the same dataset to simulate policies based on embodied carbon tariffs. We compare policies in which OECD countries rely solely on a domestic carbon tax to produce abatement to policies in which all OECD countries additionally use embodied carbon tariffs on imports from all non-OECD countries in order to meet the same global abatement target.

Our simulation results indicate that while embodied carbon tariffs do effectively reduce carbon leakage the global cost savings are small compared to the redistributive impacts. The main welfare effect of the tariffs is to shift the burden of OECD climate policy to the developing world. The OECD regions benefit by extracting surplus from non-OECD exporters of emission-intensive goods. The redistributive impacts generated by the tariffs are large; some of the OECD regions implementing the tariffs even experience negative net costs of climate policy, whereas most non-OECD countries suffer from substantial welfare losses due to the imposition of tariffs. China suffers a loss of 4% of GDP when subjected to them. The tariff policies are therefore heavily penalized when we assess their global welfare effects through the lens of social welfare functions that exhibit some degree of inequality aversion.

Compensation of non-OECD countries for tariff-induced welfare losses — either through lump-sum transfers or by returning tariff revenues — can alleviate the burden shifting problem. However, it also tends to offset the global cost savings associated with using the tariffs. This is because part of the effectiveness of tariffs stems from the fact that they are harmful to countries subjected to them: the negative income effect to these countries reduces demand for emission-intensive goods and thereby decreases carbon leakage.

Thus we conclude that the use of embodied carbon tariffs is difficult to justify based on the idea that it would move the world closer to implementing optimal second-best policy. The tariffs may, however, represent a tempting policy option for OECD countries seeking to reduce their domestic compliance costs and eliminate carbon leakage from their unilateral climate policy initiatives. How their use, or the threat of their use, would impact international negotiations on climate change policy remains an important open question.

The remainder of the paper is structured as follows. In section 2 we review the case for and against embodied carbon tariffs as a second-best instrument in unilateral carbon regulation. Section 3 lays out the dataset and the key economic accounting identities which underlie our empirical assessment of embodied carbon tariffs. Section 4 presents the MRIO calculations to determine the full carbon content embodied in traded goods. Section 5 contains a nontechnical summary of the CGE model we use to assess the economic responses of the alternative regulations that we consider. Section 6 describes and interprets our policy scenarios. Section 7 draws policy conclusions. The appendices include technical details on the MRIO calculations and the algebraic structure of the CGE model.

2 Background

A fundamental problem with unilateral climate policy is carbon leakage: policies meant to reduce emissions in one country cause emissions to increase in other countries without emission controls in place (Hoel 1991, Felder and Rutherford 1993). Leakage can occur through international energy markets, as the drop in demand for fossil fuels in the abating countries lowers world prices for these goods which in turn stimulates fossil fuel demand abroad. It can also occur through the markets for energy-intensive goods, as the cost of producing these goods in the abating countries rise and energy-intensive production will be relocated abroad.

In order to reduce leakage and increase cost-effectiveness of unilateral climate policy, various instruments have been considered to complement domestic emission regulation. One prominent policy measure is based on the idea of border carbon adjustments. On the import side, this involves a tariff levied on the embodied carbon of energy-intensive imports from non-abating regions assessed at the prevailing carbon price. On the export side, energy-intensive exports to non-abating countries would get a full refund of carbon payments at the point of shipment. Full border adjustments combine import tariffs with export subsidies, effectively implementing destination-based carbon pricing (Whalley and Lockwood 2010). In practice, the policy debate focuses on the use of import tariffs.

Estimates of carbon leakage are predominantly based on multi-region, multi-sector, computable general equilibrium (CGE) models where prices play a central role in the determination of market supply and demand: trade flows respond to relative prices, and unilateral carbon regulation in large open economies influences carbon emissions in the rest of the world (i.e. carbon leakage). CGE models combine data from input-output tables with assumptions about market structure and elasticities that govern how responsive supply and demand are to price changes. Analysts then compute the outcome of how the economy adjusts to policy interventions.

Average leakage rates in CGE studies of comparable climate policy regulations range between 10-30% (Paltsev 2001, Böhringer and Löschel 2002, Babiker and Rutherford 2005, McKibbin and Wilcoxen 2008, Ho, Morgenstern and Shih 2008, Böhringer, Fischer and Rosendahl 2010) but there are “outliers” on both sides of this range depending on key determinants such as the price responsiveness of fossil fuel supply (Burniaux and Martins 1999), the degree of heterogeneity in traded goods (Böhringer, Rutherford and Voss 1998), or market imperfections

(Babiker 2005).[1] In the quantitative impact assessment of carbon tariffs based on direct embodied emissions, CGE studies commonly find a leakage dampening effect accompanied by terms-of-trade changes that can be substantial relative to the direct cost of emission abatement (Böhringer and Rutherford 2002, Mattoo, Subramanian, Mensbrugghe and He 2009).

The literature on the optimal taxation of international environmental externalities provides support for the idea of using trade restrictions as an instrument to reduce leakage and increase economic efficiency of unilateral emission regulation. Markusen (1975) was the first to develop the insight that a sufficiently large country (or group of countries) might be able to discourage foreign production of pollution-intensive goods through the use of import tariffs. Markusen analyzes a simple two-region model in which one region imposes tariffs on the other. Production of dirty goods results in a fixed amount of pollution per unit of output, all pollution is generated by the dirty-goods sector in the model, and there are no indirect emissions embodied in the production of other goods through the use of pollution-intensive intermediate inputs. In this setting, Markusen derives a condition for the optimal tariff on dirty-goods imports as a function of the domestic pollution tax in the country imposing the tariffs as well as the elasticities of supply and demand for dirty goods outside the regulated region. The intuitive result is that the optimal tariff corresponds to the optimal (Pigouvian) domestic pollution tax discounted by the degree to which demand for dirty goods outside the regulated region is stimulated by the tariff-induced reduction in the world price of the good. Hoel (1996) provides a more general theoretical model to derive the conditions for optimal consumption and production in the unilaterally regulating country. He shows that, in the optimum, a uniform carbon tax on all domestic consumers and producers should be complemented with tariffs on the traded goods (i.e. taxes on net imports or subsidies on net exports) in order to account for counterproductive spillovers on foreign emissions via international trade.

While carbon tariffs have support from economic theory as a second-best instrument in unilateral climate policy regulation, they face a number of practical challenges not confronted by the theoretical studies. From a legal perspective, tariffs are generally not permitted according to trade agreements such as GATT or NAFTA and it is not clear whether environmental tariffs are an exception (Brewer 2008, Pauwelyn 2007, Howse and Eliason 2008, Charnowitz, Hufbauer and Kim 2009). There are also practical problems in the calculation and application of appropriate tariff rates. 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, reducing their effectiveness. Furthermore, regulators would ideally trace out the specific supply chains for individual foreign firms and all of their individual upstream partners to calculate individualized tariffs rates but this is a challenging and potentially expensive task. As a consequence, the tariffs rate would most likely need to

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[1] For individual sectors — in particular, for energy-intensive and trade-exposed industries — leakage rates can be much higher than the average leakage rates (Ho et al. 2008, Fischer and Fox 2009).

be calculated based on industry-average measures of embodied carbon in each country. In this situation, the tariffs do not give individual polluters responsible for the upstream emissions included in embodied carbon measures an immediate incentive to adopt less emission-intensive production techniques. Finally, in a world where agents respond to changes in relative prices the effectiveness of unilateral tariffs would be further reduced to the extent that countries can find alternative unregulated markets in which to sell their carbon-intensive products, an effect known as demand-side leakage (Copeland and Taylor 2004).[2]

The legal and technical challenges of calculating and implementing embodied carbon tariffs as well as the potential for re-routing of carbon-intensive demand work against the possibility that tariffs might represent a cost-effective policy instrument. However, abatement cost tend to be significantly lower in the countries subjected to the tariffs (in fact, the pre-policy marginal cost of abatement are zero as long as countries have no emission controls of their own in place) which may make emission reductions in these countries — even when triggered through a relatively blunt instrument — cheaper than equivalent reductions in currently regulated countries.

Policymakers also worry about the wider implications of using carbon tariffs for on-going international climate policy negotiations (Houser, Bradley and Childs 2008) or trade relations (ICTSD 2008). In particular, the United Framework Convention on Climate Change (UNFCCC) guarantees compensation from Annex B to the developing world for induced economic cost under Articles 4.8 and 4.9. In this context, the Kyoto Protocol to the UNFCCC warns of negative impacts for the developing world. The principal concern is that unilateral abatement in industrialized countries may deteriorate the terms of trade for developing countries with adverse effects on their economic well-being (Böhringer and Rutherford 2004).[3] On the other hand, proponents of tariffs view the threat of trade sanctions as a political stick in the drive to commit intransigent countries to adopt emission restrictions.

3 Dataset and Accounting Identities

For our empirical assessment of embodied carbon tariffs 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 (Narayanan and Walmsley 2008).

The economic structure underlying the GTAP dataset is illustrated in Figure 1 and can be readily incorporated in an economic model with either fixed input-output ratios (here, MRIO

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[2] Another more subtle reaction to carbon tariffs is the 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).

[3] The Kyoto Protocol explicitly reflects concerns on adverse terms-of-trade effects by postulating that developed countries '…shall strive to implement policies and measures…in such a way as to minimize adverse…economic impacts on other Parties, especially developing countries Parties…' United Nations (1997), Article 2, paragraph 3.

models) or price-responsive relationships (here, CGE models). 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, 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:

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

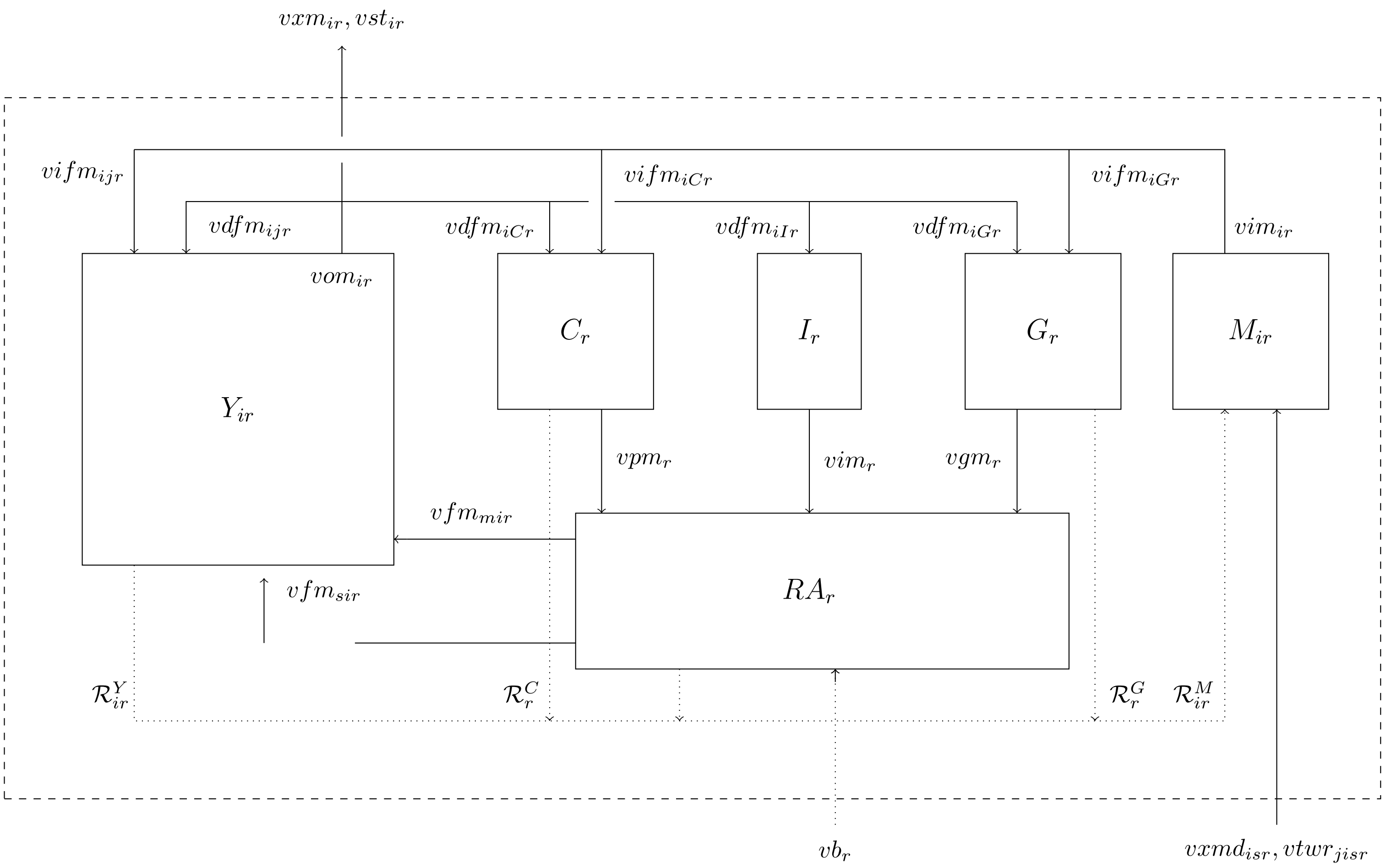

Figure 1: GTAP7 Benchmark Flows

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 ($vtwr_{jisr}$):

$$\underbrace{\sum_r vst_{jr}}_{\text{Service Exports for } j} = \underbrace{\sum_{isr} vtwr_{jisr}}_{\text{Transport Demand for } j} \tag{3}$$

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:

$$\underbrace{co2e_{jr}}_{\text{Aggregate Carbon}} = \underbrace{\sum_i eco2_{ijr}}_{\text{Sum of Carbon in Fuel Inputs}}$$

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

In our quantitative analysis we keep all the 57 sectors provided by the GTAP database to reflect sector-specific differences in energy and trade intensity. The energy goods identified are coal, crude oil, natural gas, refined oil products, and electricity which allows 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 features a variety of energy-and-trade-intensive (non-energy) commodities that are most exposed to unilateral climate policies and therefore are prime candidates for border measures: paper, pulp and print; chemical products; mineral products; iron and steel; non-ferrous metals; machinery and equipment; plant-based fibers; air, land and water transports. At the regional level, the model features explicitly all G20 economies which are the major players in international climate policy negotiations as they collectively account for the bulk of global gross national production, trade, population and CO_2 emissions. We include Ethiopia as the poorest country in the GTAP dataset to test the robustness of policy conclusions when we account for inequality aversion in our impact analysis of carbon tariffs. All remaining countries are subsumed in a composite "Rest of World" region.

Table 1 provides a list of sectors and regions for the composite dataset underlying our quantitative analysis.

REGIONS	
OECD	Australia and New Zealand (ANZ), Canada (CAN), France (FRA), Italy (ITA), Germany (DEU), Japan (JPN), United Kingdom (GBR), United States (USA), Rest of European Union (EUR)
Non-OECD	Argentina (ARG), Brazil (BRA), China and Hong Kong (CHN), India (IND), Indonesia (IDN), Mexico* (MEX), Russian Federation (RUS), South Africa (ZAF), South Korea* (KOR), Turkey* (TUR), OPEC (OPC), Ethiopia (ETH), Rest of World (ROW)
SECTORS	
Energy	Coal (COA), Crude oil (CRU), Natural gas (GAS), Refined petroleum and coal (OIL), Electricity (ELE)
Energy-and trade-intensive	Paper, pulp, print (PPP), Chemical, rubber, plastic products (CRP), Iron and steel (I_S), Non-ferrous metal (NFM), Non-metallic mineral (NMM), Machinery and equipment (OME), Plant-based fibers (PFB), Water transport (WTP), Air transport (ATP), Other transport (OTP)
Rest of industry and services	Paddy rice (PDR), Wheat (WHT), Other cereal grains (GRO), Vegetables, fruit, nuts (V_F), Oil seeds (OSD), Sugar cane, sugar beet (C_B), Other crop (OCR), Bovine cattle, sheep and goats, horses (CTL), Other animal products (OAP), Raw milk (RMK), Wool, silkworm cocoons (WOL), Forestry (FRS), Fishing (FSH), Other minerals (OMN), Bovine meat products (CMT), Other meat products (OMT), Vegetable oils and fats (VOL), Dairy products (MIL), Processed rice (PCR), Sugar (SGR), Other food products (OFD), Beverages and tobacco products (B_T), Textiles (TEX), Wearing apparel (WAP), Leather products (LEA), Wood products (LUM), Metal products (FMP), Motor vehicles and parts (MVH), Other transport equipment (OTN), Electronic equipment (EEQ), Other manufactures (OMF), Water (WTR), Construction (CNS), Trade (TRD), Communication (CMN), Other financial services (OFI), Insurance (ISR), Other business services (OBS), Recreational and other services (ROS), Public administration, defense, education, health (OSG), Dwellings (DWE)

* — These countries are OECD members but are re-assigned to the non-OECD group in our model to better reflect their historical role in international climate policy.

Table 1: Regions and Sectors in the G20 Aggregation

4 MRIO Calculation of Embodied Carbon

To determine the full carbon content embodied in goods we need to account for the indirect carbon emissions associated with intermediate non-fossil inputs in addition to the direct carbon emissions stemming from the combustion of fossil fuel inputs. For this calculation (based on the GTAP dataset) one must define a multi-region input-output (MRIO) model.

Three sets of variables characterize the MRIO model. x^y_{gr} describes the embodied carbon of produced goods, final private demand (C), investment (I) and government demand (G), where g indexes this joint set of activities. x^m_{ir} describes the embodied carbon of imported commodity i defined as a weighted average of imported varieties across trade partners. x^t_j describes the embodied carbon of international trade services. The multi-regional input-output model relates these variables to the accounting identities in the GTAP dataset described in equations (1-3). Thus, the composite carbon embodied in the output, x^y_{gr}, is defined as:

$$\underbrace{x^y_{gr}\ vom_{gr}}_{\text{Total Embodied Carbon}} = \underbrace{co2e_{gr}}_{\text{Direct Carbon}} + \underbrace{\sum_i x^m_{ir}\ vifm_{igr}}_{\text{Indirect Imported}} + \underbrace{\sum_i x^y_{ir}\ vdfm_{igr}}_{\text{Indirect Domestic}} \tag{4}$$

which follows directly from equation (1). Total embodied carbon is composed of the direct emissions generated by production plus indirect emissions produced by the use of domestic and imported intermediate inputs.

The embodied carbon of imports, x^m_{ir}, is defined as:

$$\underbrace{x^m_{ir}\ vim_{ir}}_{\text{Carbon Embodied in Imports}} = \underbrace{\sum_s x^y_{is}\ vxmd_{isr}}_{\text{Carbon in Goods}} + \underbrace{\sum_j x^t_j\ vtwr_{jisr}}_{\text{Carbon in Transport}} \tag{5}$$

which follows from equation (2). The carbon embodied in imports consists of the carbon embodied in the output of the good from the region of origin plus the emissions embodied in transport services consumed to bring the good to the destination market.

Finally, the embodied carbon of international transport, x^t_j, is defined as

$$\underbrace{x^t_j\ vtw_j}_{\text{Embodied Carbon of Transport}} = \underbrace{\sum_r x^y_{jr}\ vst_{jr}}_{\text{Carbon in Inputs}} \tag{6}$$

which follows from equation (3). The carbon embodied in transport consists of the carbon embodied in the inputs required to produce transport services.

Equations (4)-(6) can be represented as a linear system of the form:

$$x = b + Ax$$

which can be formulated and solved directly as a square system of equations or solved recursively using a diagonalization algorithm. We use the latter approach, the details of which are described in Appendix A.

We now discuss the results of our MRIO calculations. Figure 2 compares embodied carbon for the ten most carbon-intensive sectors in the dataset across three countries of production — China, the United States, Japan — together with the composites for non-OECD countries and OECD countries.[4]

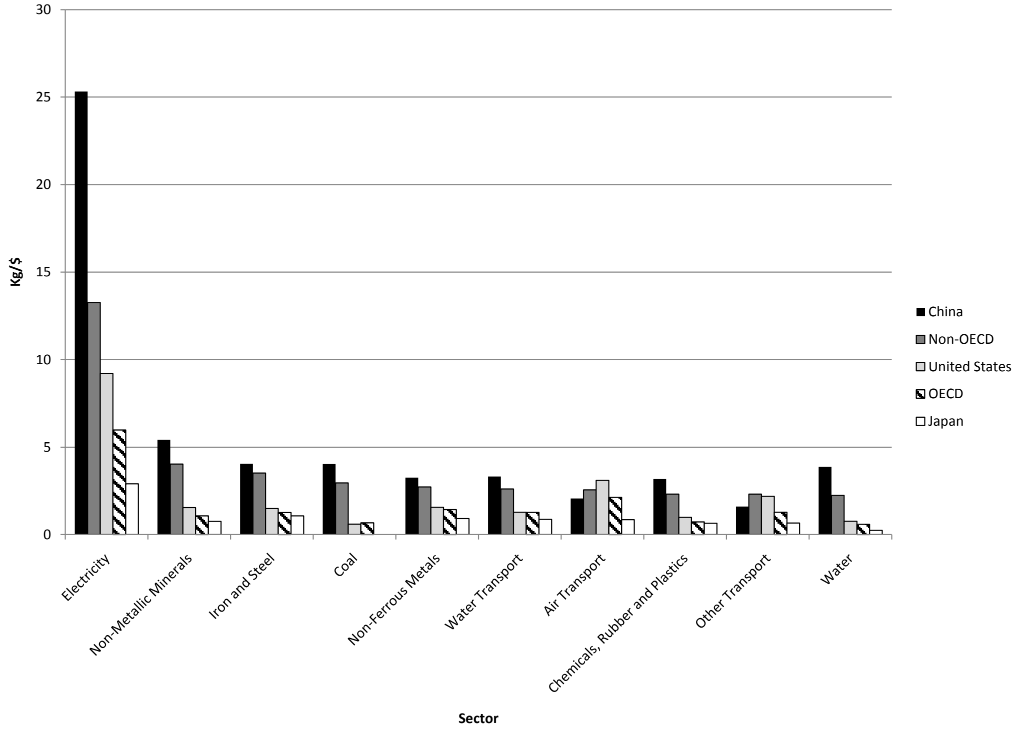

Figure 2: Embodied Carbon in Production by Region and Sector

The most carbon-intensive commodities are electricity, metal and mineral products, transportation services, and chemical products.[5] Looking across regions, it becomes obvious that

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[4] Note again that in our analysis of unilateral OECD climate policies we assume that Mexico, South Korea and Turkey will not adopt unilateral emission pledges. Thus, these three regions are accounted for within the composite of non-OECD regions described in the figure rather than the composite of OECD regions.

[5] Note that the carbon intensity of the fossil fuels coal, gas and oil only includes the embodied carbon associated with refining and mining operations, not the carbon associated with burning of these fuels.

non-OECD production is significantly more carbon-intensive than OECD production. Most striking is the carbon intensity of (mainly coal-based) electricity produced in China, with a value which is nearly twice that of the average value in all non-OECD countries, almost five times the average value in OECD countries, and roughly ten times the carbon intensity of (mainly nuclear-based) electricity produced in Japan.

Figure 3 provides a decomposition of the average embodied carbon of goods produced in OECD and non-OECD countries. Elements of the decomposition include:

Direct ($co2e$) Carbon associated with fossil fuels employed directly in production of this commodity,

Indirect Domestic ($vdfm$) Carbon embodied in domestic intermediate inputs, generally representing electricity inputs,

Indirect Imported ($vifm$) Carbon embodied in imported intermediate inputs, and

Transport ($vtwr$) Average carbon embodied in international transport of exports.

Figure 3 omits electricity from the sectors listed on the x-axis of the diagram in order to improve resolution for goods which are more widely traded. While the pairwise comparison between OECD and non-OECD embodied carbon is highly variable, it is generally the case that domestic indirect emissions are responsible for a large share of embodied emissions and for the differences in carbon intensity across regions. Carbon tariffs based on direct embodied emissions alone would therefore substantially underestimate the full emissions embodied in the most carbon-intensive goods. Indirect emissions stem largely from electricity use: while electricity itself is not a widely traded commodity its indirect effect on emissions embodied in trade appears to be sizable.

Figure 4 compares carbon embodied in net exports for OECD and non-OECD regions. The embodied carbon of exports is defined as:

$$C_r^X = \sum_{i,s} \left(x_{ir}^y vxmd_{irs} + \sum_j x_j^t vtwr_{jirs} \right),$$

and the embodied carbon of imports is defined as:

$$C_r^M = \sum_{i,s} \left(x_{is}^y vxmd_{isr} + \sum_j x_j^t vtwr_{jisr} \right).$$

Each data point in the figure represents the net exports ($C_r^X - C_r^M$) between a given region and its OECD (y-axis) or its non-OECD (x-axis) trade partners. Thus a point above the x-axis indicates that the region listed next to the point is a net exporter of embodied emissions to

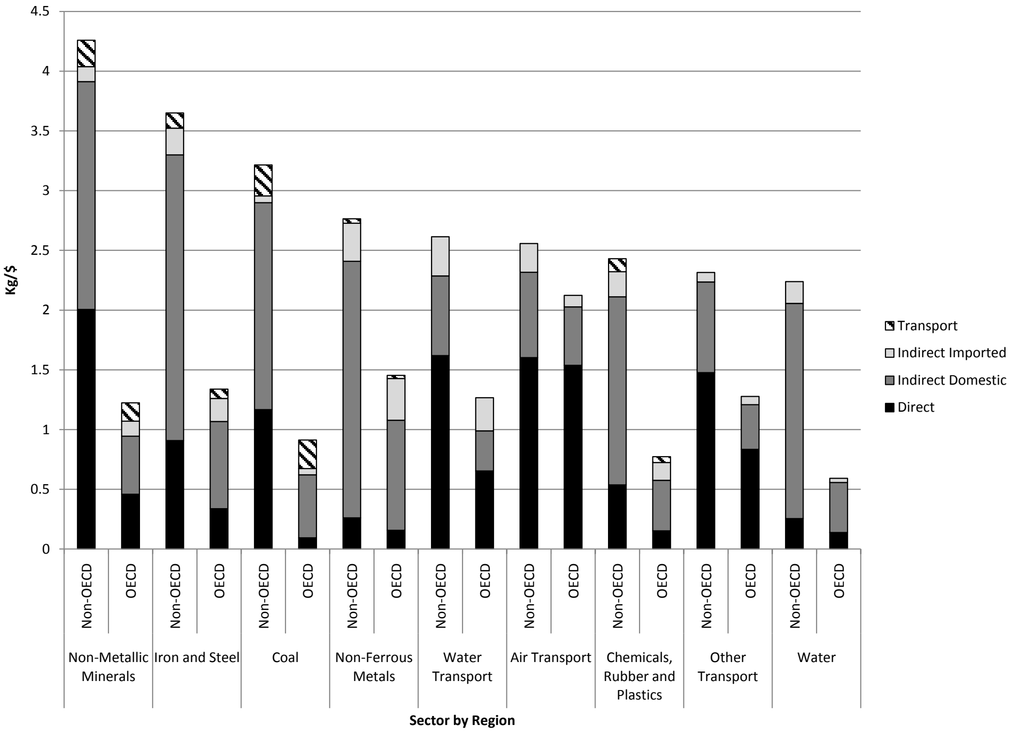

Figure 3: Direct and Indirect Sources of Embodied Carbon by Region and Sector

OECD countries and a point to the right of the y-axis indicates that it is a net exporter to non-OECD countries.

As can be seen in Figure 4, the United States, Germany, Italy, Japan and Rest of EU import more carbon in trade with non-OECD states whereas they all engage in roughly balanced carbon trade with other OECD states. The United Kingdom and France import carbon from both OECD and non-OECD states while Canada imports from non-OECD states and exports to OECD states.

Among the non-OECD states, China, India, and Indonesia all export more carbon than they import in trade with OECD states but run relatively balanced carbon trade with non-OECD partners. Russia, OPEC and South Africa are net carbon exporters to OECD and non-OECD states alike. Mexico imports a relatively small amount of carbon from non-OECD states and runs a roughly balanced carbon trade with the OECD.

To summarize, our embodied carbon calculations indicate that the amount of carbon em-

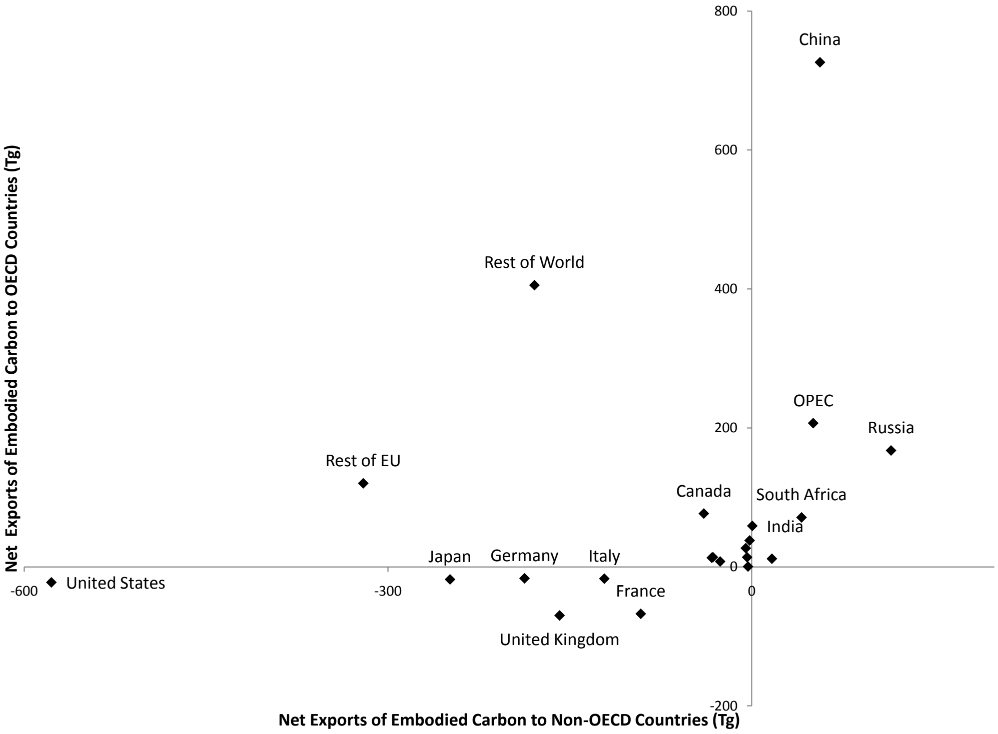

Figure 4: Embodied Carbon Trade

bodied in trade is substantial. Non-OECD countries, in general, are net exporters of embodied carbon to OECD countries — non-OECD exports to OECD are equivalent to 14.5% of all OECD emissions or 13% of all non-OECD emissions. Indirect emissions are a significant component of embodied carbon in production and the largest contribution to indirect emissions is from electricity usage. Non-OECD countries (particularly China) generate distinctly higher emissions in electricity production than OECD countries. Thus, to the extent that embodied carbon tariffs reduce emissions in tandem with demand for carbon-intensive imports, the MRIO results suggest that the tariffs imposed by OECD countries on non-OECD countries could represent an effective environmental policy.

5 The General Equilibrium Model

The MRIO framework is necessary to calculate the total (direct and indirect) embodied carbon of traded goods as a prerequisite for modeling the effects of the embodied carbon tariffs. However, the fixed input-output relationships cannot reflect economic responses in production and consumption triggered by policy interventions. To do this, we employ a computable general equilibrium (CGE) model, the standard tool for assessing the economy-wide impacts of counterfactual policies (Shoven and Whalley 1992). CGE models build upon general equilibrium theory that combines assumptions regarding the optimizing behavior of economic agents with the analysis of equilibrium conditions: producers combine primary factors and intermediate inputs at least cost subject to technological constraints; given preferences consumers maximize their well-being subject to budget constraints. CGE analysis provides counterfactual ex-ante comparisons, assessing the outcomes with a reform in place with what would have happened had it not been undertaken. The main virtue of the CGE approach is its comprehensive micro-consistent representation of price-dependent market interactions. The simultaneous explanation of the origin and spending of the agents' incomes makes it possible to address both economy-wide efficiency as well as distributional impacts of policy interventions.

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).[6] 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

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[6] A detailed algebraic model summary is provided in Appendix B.

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 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). 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).[7]

The CGE model is calibrated using the same GTAP dataset used in the MRIO calculations. 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.[8]

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).

6 Policy Scenarios and Simulation Results

Our main objective is to assess the potential of embodied carbon tariffs as a viable instrument for improving the global cost-effectiveness of unilateral emission policies. Addressing this issue first requires that we establish a reference policy without embodied carbon tariffs

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[7] 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.

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

against which we measure the changes induced when embodied carbon tariffs are used. For our central-case simulations we define this reference scenario (REF) as a 20% uniform emission reduction across all OECD countries relative to their base-year emission levels. The magnitude of emission reduction reflects the unilateral abatement pledges of major industrialized countries such as the U.S., the EU or Canada. Emission abatement within the OECD takes place in a cost-minimizing manner — at equalized marginal abatement cost (implemented through OECD-wide emissions trading). We can then quantify the extent to which the application of the tariffs on embodied carbon reduces leakage and overall economic cost of global emission reduction. The principal comparison reported in our core simulation results is between the regional cost and emissions produced by REF and their respective levels when OECD countries impose embodied carbon tariffs on non-OECD countries. The tariff rates are calculated by taking the MRIO numbers for carbon embodied in imported goods (x_{ir}^{m} from equation (5)) multiplied by the prevailing domestic carbon price in OECD countries. We make the assumption that carbon tariffs cover all sectors and can be levied without transaction costs on all sources of embodied carbon. In the discussion that follows, we refer to this scenario as the border tax adjustment (BTA) scenario.

It is worth noting that the tariff simulations presented here are not intended to provide a detailed analysis of any particular policy that has been put forward in recent debates. They are designed to provide a performance benchmark for this class of policy instruments. Based on this, our strategy is to simulate policies that are broadly consistent with the international climate policy context and use a set of optimistic (in terms of the potential effectiveness of the instrument) assumptions regarding the implementation of the tariffs to evaluate their performance. If we find that the tariffs are not effective in this setting then it is unlikely that experiments based on more realistic implementations would overturn our main results.

In addition to reporting on emission responses and regional welfare effects, we also report on global welfare impacts of the different counterfactual policies. The simplest metric for measuring global welfare effects is based on a utilitarian perspective where we add up money-metric utility with equal weights across all regions. While this measure is a standard metric to quantify global welfare changes it is agnostic about the distribution of cost. In policy practice, the appeal of carbon tariffs will not only hinge on the magnitude of aggregate cost savings but also on how the cost are distributed across regions. If the market outcome does not deliver a Pareto improvement but makes some countries worse off, then the issue of unfair burden shifting arises. This is a problem that has been at the core of the international climate policy debate from the very beginning.

We address the normative issue of equity in two different ways. First, we define three additional scenarios in which non-OECD regions are compensated at specific levels for their losses under the tariffs. Scenarios CMP_BAU and CMP_REF include explicit compensating lump-sum transfers from OECD to non-OECD countries that leave the latter at least as well off as at their pre-policy welfare levels (CMP_BAU) or their welfare levels in the REF scenario (CMP_REF) without tariffs.[9] The two direct compensation variants reflect different normative equity perspectives that might be pursued in the policy debate: under CMP_BAU non-OECD countries claim full compensation for adverse spillovers of unilateral OECD emission abatement; under CMP_REF non-OECD countries are only compensated for potentially adverse effects of border tariffs. The third compensation scenario CMP_VER mimics an implicit transfer — it hands back the revenues from embodied carbon tariffs to non-OECD countries. This scenario is equivalent to a voluntary export restraint where non-OECD countries agree to impose tariffs on their exports to OECD countries based on embodied carbon.

Second, as an alternative to the hypothetical compensation scenarios, we report global economic welfare based on social welfare metrics that exhibit differing degrees of inequality aversion ranging from an Benthamite utilitarian perspective, which is agnostic about the distribution of cost, to the Rawlsian perspective, where only the welfare of the least-well-off region determines global welfare.

Table 2 summarizes the differences across the alternative unilateral climate policy scenarios.

Scenario	*Embodied carbon tariffs*	*Compensation to non-OECD regions*
REF	No	No
BTA	Yes	No
CMP_BAU	Yes	Yes (at the level of BaU welfare)
CMP_REF	Yes	Yes (at the level of REF welfare)
CMP_VER	Yes	Yes (through transfer of tariff revenues)

Table 2: Differences between key policy scenarios

The benchmark equilibrium against which we measure the impacts of policy intervention is defined by the business-as-usual (BAU) economic patterns in 2004 — the most recent base-year provided by the GTAP dataset. Note that this was before the Kyoto Protocol entered into force — climate policies are thus almost absent internationally (and from our dataset) which provides a coherent starting point for our analysis.

Given that we do not attempt to measure the benefits from emission abatement, we must hold global emissions constant across all of the policy scenarios to assure consistency of our cost-effectiveness comparison.[10] The exogenous global emission cap is defined as the world-wide emissions that arise in the REF scenario where OECD regions reduce their business-as-

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[9] In our model implementation, the endogenous lump-sum transfers are split across OECD regions proportional to their initial OECD income shares.

[10] We furthermore need to assume separability between utility obtained from emission abatement as a global public good and utility derived from private good consumption.

usual emissions by 20%. If carbon tariffs reduce leakage then the effective reduction requirement of OECD regions will be lower than 20%. Technically, the global emission constraint requires an endogenous scaling of the initial 20% OECD emission pledge to match the worldwide emissions emerging from the reference scenario (REF). The costs of the emission constraints are measured in terms of the Hicksian equivalent variation (EV) in income.

We begin our discussion of simulation results by examining how emission levels respond to alternative climate policy designs. Columns (1) and (2) of Table 3 report abatement rates by region for the reference scenario (REF) and the uncompensated tariff scenario (BTA) relative to pre-policy baseline emissions.

Because global emissions are held constant across these scenarios, the change in OECD emissions across the scenarios gives an indication of the shift in abatement responsibility between OECD and non-OECD regions implied by the imposition of the tariffs in BTA. In our central case simulations, the use of the tariffs relieves OECD countries on average of more than 10% of their domestic abatement requirements.

Region	*% Δ Emissions*		*Leakage Rate*	
	REF (1)	BTA (2)	REF (3)	BTA (4)
Global	-7.76	-7.76	15.30	3.19
OECD	-20.00	-17.58	-	-
Non-OECD	2.59	0.54	-	-
Rest of World	4.19	1.49	4.77	1.70
China	1.22	0.06	2.54	0.13
Russia	3.28	-0.06	1.89	-0.04
OPEC	2.87	-0.15	1.88	-0.09
South Africa	6.91	0.38	1.20	0.07
India	1.81	0.87	0.93	0.44
South Korea	2.85	2.28	0.55	0.44
Indonesia	3.13	1.27	0.45	0.18
Mexico	2.20	-0.09	0.36	-0.01
Brazil	2.25	0.78	0.29	0.10
Turkey	3.00	2.08	0.28	0.20
Argentina	2.66	1.75	0.13	0.08
Ethiopia	5.24	-2.58	0.01	-0.01

Table 3: Emission Responses by Region and Scenario

Looking across non-OECD regions, we see evidence of carbon leakage under REF with non-

OECD emissions increasing on average by 2.6% (emissions of individual non-OECD regions increase 1-7%) in response to the externally imposed 20% emission reduction by OECD. Tariffs on embodied carbon under BTA uniformly dampen the emission increase in non-OECD regions and thus reduce the effective abatement burden for the OECD.

Columns (3) and (4) of Table 3 describe the same emissions responses in terms of average leakage rates — the change in each non-OECD region's emission level divided by the cumulative change in emissions in OECD countries relative to the pre-policy baseline. The reduction in the leakage rates induced by the carbon tariffs is substantial. The average leakage rate for all non-OECD countries decreases from just over 15% under REF to around 3% under BTA. Thus leakage is to a large extent eliminated by the tariffs. China, OPEC and Russia, all major contributors to global emissions, see their leakage rates fall to approximately zero under BTA.

Table 4 reveals the differences in regional welfare costs as we move from the reference scenario without embodied carbon tariffs (REF) to the BTA scenario with embodied carbon tariffs (regions are ranked in descending order of their welfare losses under BTA). The top of the table summarizes the global efficiency cost of the different policies as well as the average cost to OECD and non-OECD regions when we are agnostic on cost distribution. In the reference scenario, the biggest economic losses are experienced by the energy-exporting regions, Russia and OPEC, despite the fact that they are not subject to emission regulation. These welfare cost, corresponding to around 3% of base-year consumption, are a direct consequence of terms-of-trade changes. Carbon abatement lowers demands for fossil fuels, and this depresses the international price of oil, coal and natural gas — products which represent a substantial share of export earnings and GDP for Russia and OPEC. Beyond terms-of-trade changes on international fuel markets, OECD countries can pass on part of their cost increase in domestic energy-intensive production to trading partners. We see that the welfare impacts for remaining non-OECD countries (other than energy exporters Russia and OPEC) are in a similar order of magnitude as those experienced by abating OECD regions with India and Turkey experiencing modest welfare gains relative to business-as-usual.

Implementation of embodied carbon tariffs without compensation as captured by scenario BTA induces a substantial cost shifting from OECD countries to non-OECD countries. Among the most heavily impacted non-OECD regions are, once again, Russia and OPEC (6-7% losses). China goes from experiencing negligible welfare effects under REF to almost a 4% welfare loss under BTA. The tariffs have a pronounced impact on relative prices, essentially operating as a monopsony markup on exports from the unregulated non-OECD countries. As a result, the indirect terms-of-trade benefits realized by OECD regions more than offset direct abatement cost for major industrialized regions such as Germany, Rest of EU, the United States and Japan. The carbon tariffs function as a sort of "back-door" trade policy for these countries, substituting for optimal tariffs that would be illegal under free trade agreements. These effects are large enough that OECD countries *on average* experience net gains from climate policy relative

	% Δ *Welfare (EV)*	
	REF	BTA
Global	-0.32	-0.32
OECD	-0.25	0.30
Non-OECD	-0.58	-2.48
Russia	-3.28	-7.04
OPEC	-2.91	-6.28
China	-0.20	-3.85
South Africa	-0.20	-2.30
Rest of World	-0.26	-1.96
Argentina	-0.28	-1.83
Indonesia	-0.65	-1.80
Mexico	-0.34	-1.04
Brazil	0.01	-0.72
South Korea	0.24	-0.49
Canada	-1.00	-0.47
Australia/NZ	-0.59	-0.26
India	0.28	-0.26
Turkey	0.40	-0.05
France	-0.41	0.02
United Kingdom	-0.40	0.06
Italy	-0.44	0.16
Japan	-0.26	0.22
United States	-0.15	0.29
Germany	-0.13	0.68
Rest of EU	-0.19	0.79
Ethiopia	0.31	0.89

Table 4: Welfare Effects by Region and Scenario

to business-as-usual for our central case simulation. Non-OECD regions are on average negatively impacted by unilateral OECD climate policy. However, the welfare losses become much more pronounced with the carbon tariffs. We see clear evidence for the concerns of developing countries that the developed world could enact carbon tariffs as a trade policy instrument to change terms of trade in their favor. The comparison of the global efficiency cost under REF and BTA shows that the tariffs do yield global cost savings relative to REF but their magnitude is very small in our central case. We return to this issue in our discussion of the sensitivity analysis below.

Figure 5 formalizes the assessment of the distributional effects of the different policies by comparing global welfare changes using social welfare functions that exhibit different degrees of inequality aversion. The general form of the social welfare function is

$$SWF = \left[\sum_r \gamma_r W_r^{(1-1/\sigma)} \right]^{1/(1-1/\sigma)}$$

where W_r represents the money-metric per capita welfare level in model region r, σ is the inequality aversion parameter, and γ_r is region r's share of world population.

Figure 5 reports percentage changes in SWF from pre-policy baseline levels under different assumption about the value that σ takes on. A value of $\sigma = +\infty$ ("Bentham" in the figure) corresponds to the change in aggregate economic surplus, a measure of global welfare change that is agnostic about the regional distribution of cost. A value of $\sigma = 0$ ("Rawls" in the figure) corresponds to the social welfare function

$$SWF = \min_r (W_r)$$

where it is the welfare level of the poorest region that determines global welfare. (Ethopia is the poorest country represented in the GTAP 7.1 dataset.) Entries listed in between these two extreme cases on the x-axis of the figure describe results based on intermediate values of σ.

When we compare the alternative policies from a utilitarian perspective ("Bentham") we find that embodied carbon tariffs increase global cost-effectiveness of unilateral climate policy. Under the Benthamite welfare metric, introducing the carbon tariffs (BTA) is cheaper than relying on domestic OECD abatement alone (REF) but only modestly so.

Assessing the tariff scenarios which involve explicit compensation to non-OECD regions (CMP_BAU, CMP_REF and COMP_VER) we see that compensation tilts the results based on the Benthamite welfare function back in favor of REF. Compensation increases income levels in non-OECD countries. This positive income effect raises demand for fossil energy and emission-intensive goods which results in higher leakage rates. Holding global emissions constant at the REF level requires more domestic abatement efforts on the part of OECD regions, raising the overall cost of these policies.

Finally, we evaluate the welfare impacts of alternative unilateral climate policy designs for different forms of the social welfare function. We find that the welfare cost of BTA rises substantially as inequality aversion becomes a more important element of the welfare criteria. This reflects the finding that OECD tariffs shift emission abatement cost to non-OECD countries via a deterioration of the terms of trade. As non-OECD countries represent the poorer part in the global economy, the burden shifting of unilateral climate policy towards these regions exacerbates pre-existing inequalities. Interestingly, this pattern is interrupted as σ approaches zero in the social welfare function because the poorest region in the model, Ethiopia, actually

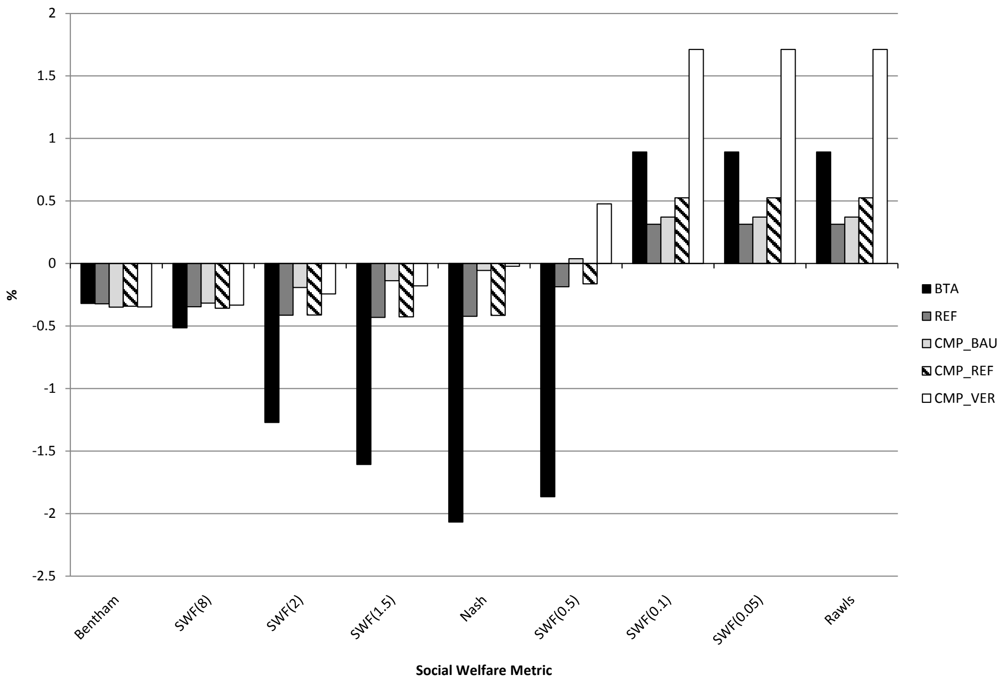

Figure 5: % Change in Global Welfare by Social Welfare Function and Scenario

benefits from terms-of-trade gains — mainly through reduced expenditures for energy imports.

Naturally, the various compensation scenarios fare better than BTA as inequality aversion become important. CMP_REF yields similar welfare changes to REF because non-OECD countries are, by definition, compensated to REF welfare levels. CMP_BAU and CMP_VER do even better because the scope for compensation to non-OECD countries increases. Note, however, that these results are more of a statement about the potential for improving standards of living in non-OECD countries through wealth transfers than they are evidence of the effectiveness of embodied carbon tariffs.

Past studies of carbon leakage based on CGE simulations show that magnitude of leakage is sensitive to a few key model assumptions. First, the larger is the unilateral cutback in emissions that is assumed in the model, the stronger is the leakage effect as abating regions move to increasingly inelastic portions of the demand curve for emission-intensive goods. Second, the higher are the Armington elasticities that determine how substitutable varieties of emission-intensive goods from different countries are, the stronger is the leakage effect as regions may more easily substitute to new sources for these goods in response to the changes induced by the climate policy regime. Finally, the lower are the fossil-fuel supply elasticities that are assumed in the model, the stronger is the leakage effect as the decreased demand for fossil fuels in abating regions produces larger reductions in the price of these goods on world markets, stimulating demand abroad.

We have performed comprehensive sensitivity analysis with respect to all three of these assumptions to test how they alter our conclusions regarding the effectiveness of the carbon tariffs. Table 5 summarizes our main findings. The table depicts the average leakage rate produced by the model under the REF scenario ("REF Leakage Rate" in the table) and the difference in the global cost of the REF and the BTA scenarios as a percentage of global consumption ("BTA-REF Cost Savings" in the table) for three alternative leakage scenarios. The first three columns of the table describe the alternative assumptions underlying the leakage scenarios we model. The table shows the percentage cutback assumed and the values that the Armington and fossil fuel supply elasticities take on relative to their values in the central case that our discussion has focused on up to this point.

Cutback	*Armington Elasticities*	*Supply Elasticities*	REF *Leakage Rate*	BTA-REF *Cost Savings*
10%	1/2x	2x	6.86	0.011
20%	1x	1x	15.30	0.004
30%	2x	1/2x	30.64	0.097

Table 5: Leakage Sensitivity Analysis

The leakage rate produced by the model is increasing as we move down the rows of the table. The leakage rates produced by the model are approximately 7% and 15% in the low and medium-leakage scenarios, respectively. The cost savings are close to zero in both of these scenarios — less than 0.02 percent of world consumption and approximately 1 percent of the total REF policy cost. The leakage rate increases to approximately 30% in the high-leakage scenario and the cost savings are larger in this case — approximately 0.1 percent of world consumption or 12% of the total cost of the REF policy. Thus, we find that there may be measurable efficiency gains from the tariffs for policy scenarios that produce higher levels of leakage than those reported in our central case. It is worth noting, however, that when we repeat the exercise with the social welfare functions described in Figure 5 using the assumptions of the high-leakage scenario, the efficiency gains produced by the use of the tariffs are not sufficient to overturn the ranking of the policies we established for the central case. That is, the BTA scenario produces larger global welfare losses than the reference policy for all of the welfare metrics that exhibit inequality aversion.

7 Conclusions

In the international climate policy debate, the idea of imposing tariffs on embodied carbon has attracted significant attention in OECD countries contemplating unilateral emission reductions. The basic idea is to combine domestic carbon taxes or cap-and-trade systems that cover direct emissions in production with tariffs on the embodied carbon of goods imported from non-abating trade partners. From a theoretical perspective, the measures could serve as a second-best instrument to improve cost-effectiveness of unilateral climate policies.

In our quantitative experiments, we find that the carbon tariffs are quite effective in reducing carbon leakage from unilateral OECD policies. However, the efficiency gains from carbon tariffs are modest even under our optimistic assumption that the tariffs cover all sectors and can be levied on the full embodied carbon content without transaction costs.

The tariffs are a clear winner from the perspective of those countries implementing them and quite damaging to many of the countries subject to them. Many major OECD members experience net gains from implementing climate policy when tariffs are used but, from an distributional perspective, the tariffs exacerbate pre-existing income inequality, and the modest global cost savings provided by border tariffs quickly evaporate as inequality aversion is taken into account.

It would be difficult to overstate the influence that the divide between the perspectives of developed and developing-world nations has exerted on the international climate policy process to date. Developing countries argue that they cannot accept binding emissions targets under any equitable climate policy regime. Major developed countries, notably the United States, argue that they cannot accept binding targets for fear that their abatement efforts will be undermined by carbon leakage if their developing-world partners are not subject to comparable restrictions.

In light of this tension, the decision to use embodied carbon tariffs — by punishing the developing-world countries subjected to them — could be quite destructive to the existing policy process. In the extreme, it could even result in a tariff war. A different view is that tariffs might function as a political stick in the drive to commit intransigent countries to adopt emission restrictions. They have the appeal of (*i*) being a credible threat, since OECD members benefit from their use while being very damaging to those countries subject to them, and (*ii*) carrying a certain moral stamp of approval because they are being used in the name of environmental policy and appear to have the potential to reduce carbon leakage.

A logical next step in the analysis we have carried out here would be to consider how countries subjected to embodied carbon tariffs might respond and what actions they would be willing to undertake to avoid the tariffs in the first place.

Acknowledgements

This research has been supported by Environment Canada. Research assistance has been provided by Justin Carron. The views expressed here and any errors are our own.

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A MRIO Recursive Solution Algorithm

The estimate in iteration $k+1$ is a simple refinement of the estimate in iteration k

$$x_{k+1} = b + Ax_k$$

Iterative solution of the MRIO model involves the following steps:

Initialize:

$$x^y_{gr} = co2e_{gr}/vom_{gr}$$

Repeat: i. Refine estimates of the embodied carbon of international trade services:

$$x^t_j = \frac{\sum_r vst_{jr} x^y_{jr}}{vtw_j}$$

ii. Refine estimates of the embodied carbon of bilateral imports:

$$x^m_{ir} = \frac{\sum_s \left(vxmd_{isr} x^y_{is} + \sum_j x^t_j vtwr_{jisr} \right)}{vim_{ir}}$$

iii. Update embodied carbon estimates:

$$x^y_{gr} = \frac{co2_{gr} + \sum_i x^m_{ir} vifm_{igr} + \sum_i x^y_{ir} vdfm_{igr}}{vom_{gr}}$$

B 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 6 - 11 explain the notation for variables and parameters employed within our algebraic exposition. Figures 6 - 8 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 ($g \notin FF$):

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

- Sector-specific material aggregate:

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

- 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:

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

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

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

Table 11: Elasticity Parameters

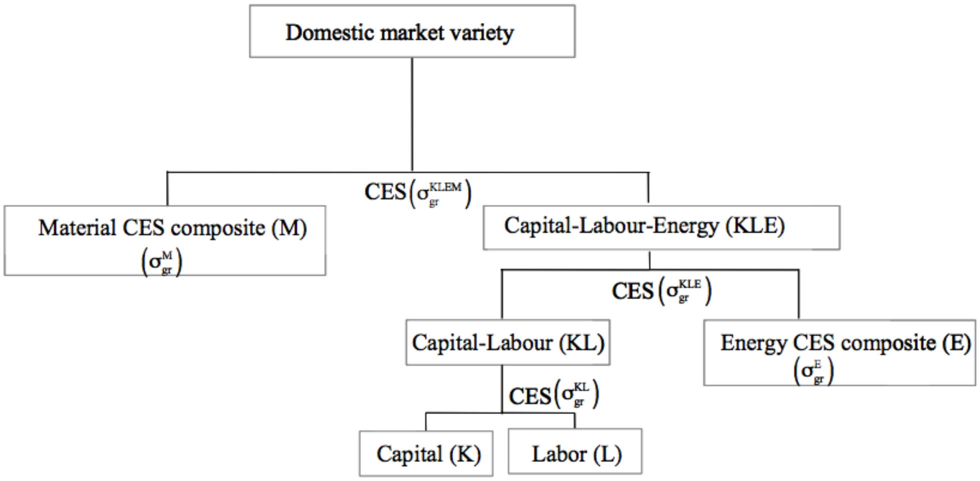

Figure 6: Nesting in Non-Fossil-Fuel Production

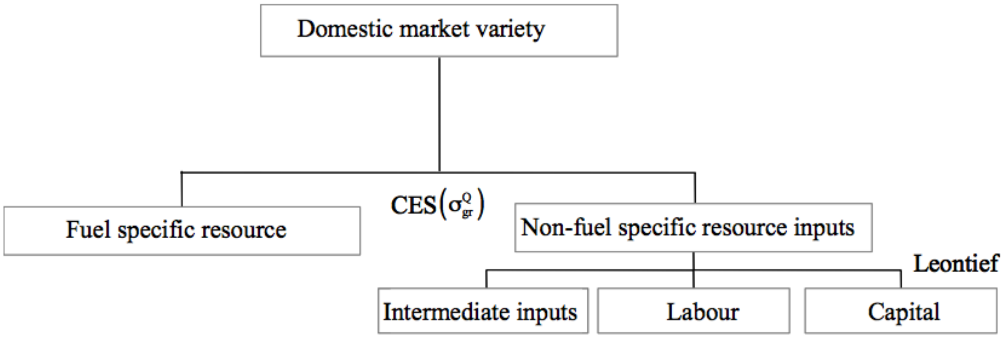

Figure 7: Nesting in Fossil-Fuel Production

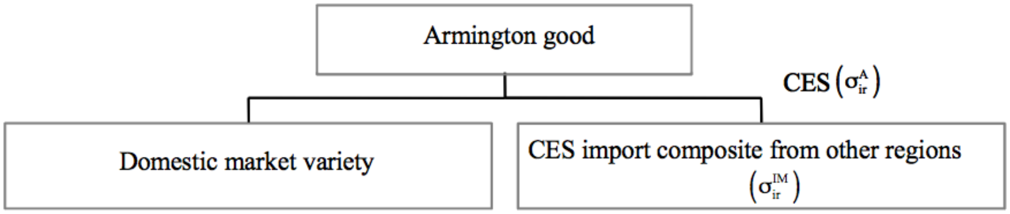

Figure 8: Nesting in Armington Composite Production

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[*] Die vollständige Liste der seit 1985 erschienenen Diskussionspapiere ist unter http://www.vwl.uni-oldenburg.de/51615.html zu finden.