EMBODIED CARBON TARIFFS

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First revision: November 2015
Second revision: April 2016

Abstract

Embodied carbon tariffs tax the direct and indirect carbon emissions embodied in trade — an idea popularized by countries seeking to extend the reach of domestic carbon regulations. We investigate their economic and environmental impacts using simulations from an applied general equilibrium model of global trade and energy use. We find that carbon tariffs do reduce foreign emissions, but their ability to improve global cost-effectiveness of unilateral action is quite limited, even when the optimal tariffs for a unilateral climate policy are implemented. Carbon tariffs levied on the full carbon footprint of imports are likely to increase rather than decrease the global cost of emission reduction. The main effect of carbon tariffs is to shift the economic burden of developed-world climate policies to the developing world.

Keywords: carbon tariffs, carbon leakage, computable general equilibrium
JEL classifications: Q58, D58

1. Introduction

In a world where the likelihood of a stringent 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 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 countries without domestic carbon controls 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 unilateral climate policy.

All of these arguments have contributed to the popularity of 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, or the discussion of carbon tariffs in several OECD countries.

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 developed-world climate policies — first, by covering foreign sources of emissions and, second, by covering indirect sources of emissions.

While embodied carbon tariffs have intuitive appeal, the life-cycle analyses that lend them support cannot model a key behavioral response by industries subjected to the tariffs — the incentive to re-direct output to other markets in the world economy. This effect, if found to be quantitatively significant, would cast doubt on the potential of the tariffs as an environmental policy tool. In this paper we use a large-scale computable general equilibrium (CGE) model of global trade and energy use to quantify the economic and environmental performance of carbon tariffs. Our benchmark scenario reflects a situation where OECD countries rely on domestic carbon pricing alone to achieve a 20% reduction in OECD emissions. We then compare the efficiency and equity implications of this scenario with two policy variants that adopt carbon tariffs to target foreign emissions and achieve an identical global emission reduction. First, we build on the embodied carbon metric and apply the OECD carbon price to the full carbon content embodied in imports from Non-OECD countries. Second, we incorporate second-best considerations on the responsiveness of trade flows (Hoel 1996) to approximate "optimal" carbon tariffs.

We find that while carbon tariffs levied on the full carbon content of traded goods can effectively reduce carbon leakage they increase rather than decrease global cost of emission reduction. The cause of this counterproductive outcome is the re-routing of carbon-intensive output to other markets in the world economy to avoid the penalty imposed by the tariffs. Moreover, even when tariff rates are designed to account for such behavioral responses, we find that their potential to improve global cost-effectiveness of unilateral climate policy remains quite limited. The small and potentially adverse efficiency impacts of carbon tariffs contrast with the large redistributive effects they generate. The main welfare effect of carbon tariffs applied by OECD countries is to shift the burden of OECD climate policy to the developing world as OECD regions extract surplus from Non-OECD exporters of emission-intensive goods. The redistributive effects are particularly strong when carbon tariffs are based on the full embodied carbon content: in this case, the economic burden of emission reduction is entirely shifted to Non-OECD countries which are much poorer on a GDP-per-capita base than OECD countries. Carbon 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.

We conclude that the use of carbon tariffs is difficult to justify based on the idea that it would substantially lower the global efficiency cost of unilateral carbon regulation. The tariffs may, however, represent a tempting policy option for countries seeking to reduce their domestic compliance costs under the pretext of eliminating carbon leakage from their unilateral climate policy initiatives.

The remainder of the paper is structured as follows. Section 2 reviews the literature on carbon tariffs. Section 3 lays out the data base underlying our empirical analysis. Section 4 contains a non-technical summary of the CGE model destined for the impact assessment of carbon tariffs. Section 5 describes our simulation analysis. Section 6 concludes.

2. Review

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 with no or more lenient climate regulations (Hoel 1991, Felder and Rutherford 1993). The relocation of emissions undermines global cost-effectiveness of subglobal action. 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 emission-intensive goods, as the cost of producing these goods in the abating countries rise and emission-intensive production will be relocated abroad.

Estimates of carbon leakage from unilateral climate policy are predominantly based on multi-region multi-sector CGE models where prices play a central role in the determination of price-elastic 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. They are used to 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, Fischer and Fox 2009, 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 the existence of initial market imperfections (Babiker 2005).

In order to reduce carbon 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 since export rebates may constitute a subsidy under the WTO's Agreement on Subsidies and Countervailing Measures (Cosbey, Dröge, Fischer, Reinaud, Stephenson,Weischer and Wooders 2012).

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. As a result, optimal tariff rates will typically be lower per unit of embodied carbon in traded goods than the domestic carbon price.

Hoel (1996) generalizes Markusen's analysis and produces a similar intuition for the design of optimal carbon tariffs. Maximizing domestic welfare of unilateral emission regulation with respect to a domestic carbon tax and a system of import tariffs, the optimal tariffs consist of two components. The first is a terms-of-trade effect: a tariff reduces imports, which in general reduces the import price and improves terms of trade. The second term is the foreign emission effect: a tariff reduces emissions abroad by contracting foreign supply. If the objective is to minimize global cost of global emission reduction through unilateral action, the strategic terms-of-trade effect disappears. The optimal tariff on an imported good from some non-regulating region is based on the domestic price of carbon scaled in proportion to the marginal responsiveness of global emissions to a change in the imported good.[1]

We can directly transfer this analytical result to the setting for our quantitative analysis. In case that the import reduction induced by carbon tariffs does not lead to a redirection of output to non-abating regions, the marginal responsiveness equals the full carbon content of one unit of the imported good. Due to redirection, however, the emission effect of reducing imports is less than a 100% and therefore the marginal responsiveness is smaller than the full carbon content. In other words: the effectiveness of tariffs is limited to the extent that countries facing tariffs can find alternative, unregulated markets in which to sell their emission-intensive goods; carbon tariffs accounting for such second-best effects should therefore be lower than suggested by policy proposals based on the embodied carbon content of traded goods.

The quantitative impact assessment of carbon tariffs – see Böhringer, Balistreri and Rutherford (2012) for a meta-analysis of CGE studies on carbon tariffs – has been predominantly based on proposals for embodied carbon.[2] In contrast, our study connects the quantitative literature on carbon tariffs to the theoretical literature on optimal environmental tariffs. In our simulations, we compute tariffs rates that are consistent with the prescription from the theoretical literature as a benchmark against which to judge the performance of tariffs based on "blunt" embodied carbon measures.[3]

A complementary strand of the economic literature adopts a strategic perspective on carbon tariffs. Game-theoretic analyses show that international cooperation on transboundary pollution control may be advanced by the use of trade sanctions as an enforcement tool (Spagnolo 1999, Conconi and Perroni 2002, Ederington 2004, Limao 2005). The burden-shifting effect of carbon tariffs identified by the quantitative literature suggests that carbon tariffs have the potential to confer substantial trade gains to countries that use them and trade losses to those subjected to them. Thus the threat of carbon tariffs — rather than their actual application— could lead to more effective climate policy if unregulated countries prefer to adopt domestic emission controls than to face tariffs (see e.g. Böhringer, Carbone and Rutherford 2016).

Another line of research addresses the role of carbon tariffs in an endogenous growth setting with directed technical change. Hemous (2012) shows analytically and by means of highly stylized numerical simulations that carbon tariffs can be beneficial to the extent that they trigger technological change towards cleaner technologies in carbon-intensive countries without emission controls.

[1] See Gros (2009) or Balistreri, Kaffine and Yonezawa (2012) for similar findings.

[2] In an earlier contribution, Elliot, Foster, Kortum, Munson, Cervantes and Weisbach (2010) use a CGE model to quantify the effect of full border adjustment on leakage. In line with the bulk of CGE analysis, they find that full border adjustment can eliminate leakage but neither do they base tariff design on second-best considerations nor do they provide a global cost-effectiveness and differentiated incidence analysis across alternative climate policy designs. Shapiro (2014) uses a gravity model of international trade and climate damages to show that unilateral carbon taxes can be used by OECD countries as a strategic trade instrument for exploiting terms of trade.

[3] Böhringer, Bye, Faehn and Rosendahl (2012) perform global cost-effectiveness comparisons of alternative designs for carbon tariffs such as different levels of embodied carbon coverage and sector coverage but do not tie their results to the relationship of the tariff rates implied by the embodied carbon logic to optimal tariff rates.

In the real world, implementation of carbon tariffs is subject to various legal, practical and political challenges which call for careful ex-ante assessment. 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 (Pauwelyn 2007, Brewer 2008, Howse and Eliason 2008, Charnowitz, Hufbauer and Kim 2009, Cosbey et al. 2012, McAusland and Najjar 2015).

There are non-trivial 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 environmental 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 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.

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).[4]

3. Data

For our quantitative impact assessment of embodied carbon tariffs we make use of the GTAP 9 dataset, which includes detailed national input-output tables as well as bilateral trade flows and CO_2 emission data for up to 140 regions and 57 sectors for the year 2011 (Narayanan, Aguiar and McDougall 2015). The dataset is aggregated to reflect key dimensions of international climate policy negotiations.

At the country level, there is intense bargaining over appropriate emission reduction pledges by individual states. The minimum consensus goes back to Article 3.1 of the United Nations Framework Convention on Climate Change which states that emission reduction commitments of countries should be based on "equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change." (United Nations 1992). In this vein, we assume that OECD countries are proactive with unilateral climate

[4] 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).

policy whereas developing countries will abstain in the near- to mid-term from stringent emission constraints that could eventually restrict their economic growth. Among developing countries we explicitly include all major emerging nations that are member of the G20 forum (covering the 20 major economies of the world). In order to capture the distributional impacts of climate policies, we aggregate all other countries by income into two composite regions (low- and middle-income) according to the World Bank classification of the world's economies.[5]

Regarding the choice of sectors for the aggregate dataset, we explicitly represent all primary and secondary energy carriers (coal, gas, crude oil, refined oil products, and electricity) to capture differences in CO_2 intensity and the degree of interfuel substitutability. With respect to the application of carbon tariffs, we select those sectors in the GTAP dataset that stand out for a high carbon intensity in terms of embodied carbon and a high share of Non-OECD imports in OECD domestic market supply. All remaining sectors in the original dataset are aggregated to a composite sector "Other manufactures and services". Table 1 provides the list of sectors and regions for the composite dataset underlying our quantitative analysis.

Table 1: Regions and sectors in quantitative impact analysis

	REGIONS
OECD	Australia (incl. New Zealand); Canada; France; Germany; Italy; Japan; Mexico; Rest of EU; Rest of OECD; South Korea; Turkey; United Kingdom; United States
Non-OECD	Argentina; Brazil; China (incl. Hong Kong); India; Indonesia; Low-Income-Countries; Middle-Income-Countries; OPEC; Russia; South Africa
	SECTORS
Energy sectors	Coal; Crude oil; Natural gas; Refined oil products; Electricity
Emission- and trade-intensive sectors	Chemical, rubber, plastic products; Ferrous metals; Non-metallic minerals; Air transport; Metal products; Plant-based fibers; Minerals; Textiles; Transport equipment; Machinery and equipment; Water transport
Rest of industry and services	Rest of industry and services (composite of all other industries and services)

A central determinant of the effects of carbon tariffs is the amount of embodied carbon in internationally traded goods. Embodied carbon refers to the total amount of CO_2 that is emitted to produce a certain good. The total carbon content therefore includes direct emissions (those due to the combustion of fossil fuel inputs in the production of the good) as well as indirect emissions (such as emissions created by

[5] According to the World Bank income classification for 2011, a country with an annual per-capita income of less than USD 1,025 is assigned to the composite of Low-Income-Countries, whereas developing countries with an income between USD 1,026 and USD 12,475 is assigned to the composite of Middle-Income-Countries (World Bank 2012).

the generation of electricity used for the production of the good). In order to calculate the region- and sector-specific carbon content of goods we use multi-region input-output (MRIO) accounting identities (see Appendix A for an algebraic description of the MRIO model). The GTAP dataset furthermore facilitates the decomposition of embodied carbon into direct emissions from fossil fuel use in the production process and indirect emissions embodied in domestic or imported intermediate inputs.

Table 2 provides a list of GTAP sectors by carbon intensity and trade shares. Sectors that are classified as carbon- and trade-intensive are those industries in Non-OECD regions that range above both the average carbon intensity and the average import share to OECD markets.

Table 2: Emission intensities and trade shares of sectors

	Carbon intensity of Non-OECD sectors (kg of CO_2 per USD)	Share of Non-OECD imports in OECD domestic market (%)	Carbon intensity of OECD sectors (kg of CO2 per USD)
Electricity	8.40	0.33	3.37
Non-metallic minerals	1.96	3.86	0.59
Ferrous metals	1.93	5.99	0.69
Non-ferrous metals	1.50	15.70	0.62
Air transport	1.24	8.57	1.08
Metal products	1.17	4.41	0.32
EITE[*]	*1.11*	*8.24*	*0.40*
Chemical, rubber, plastic products	1.06	6.99	0.35
Water transport	1.00	4.67	0.71
Machinery and equipment	0.93	9.04	0.24
Minerals	0.83	19.43	0.45
Textiles	0.82	19.06	0.30
Transport equipment	0.78	5.57	0.24
Plant-based fibers	0.68	13.64	0.47
Average[**]	*0.67*	*3.66*	*0.23*
Refined oil products	0.50	8.37	0.34
Rest of industry and services	0.48	2.49	0.19

[*] EITE: value-weighted average across all emission- and trade-intensive sectors

[**] Average: value-weighted average across all industries (without electricity)

Figure 1 visualizes the trade patterns of embodied carbon between OECD and Non-OECD economies. Embodied carbon trade is measured as net exports of embodied carbon, i.e. embodied emissions in exports less embodied emissions in imports. Each data point in Figure 1 represents the net exports 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 OECD countries and a point to the right of the y-axis indicates that it is a net exporter to Non-OECD countries.

Figure 1: Net exports of embodied carbon[6]

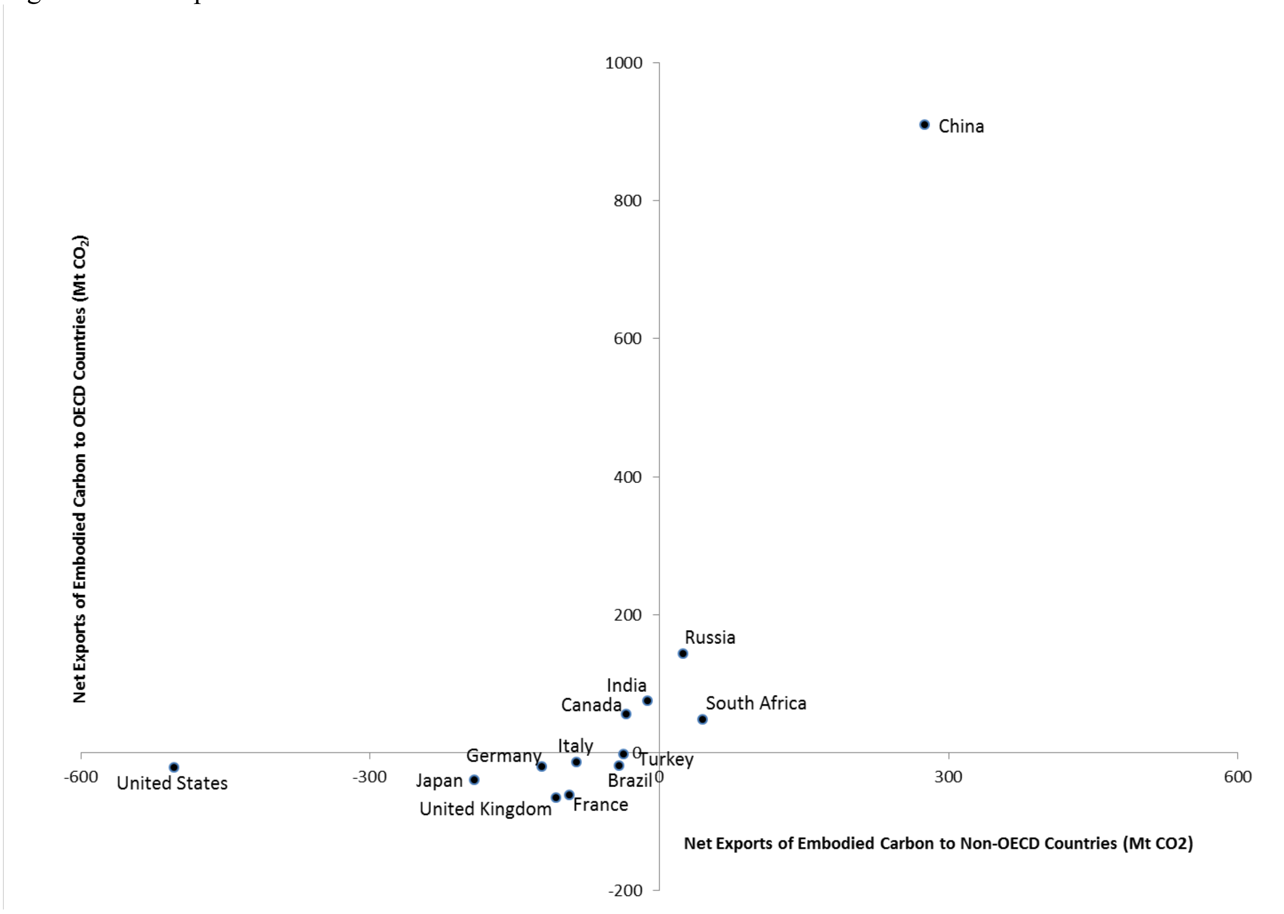
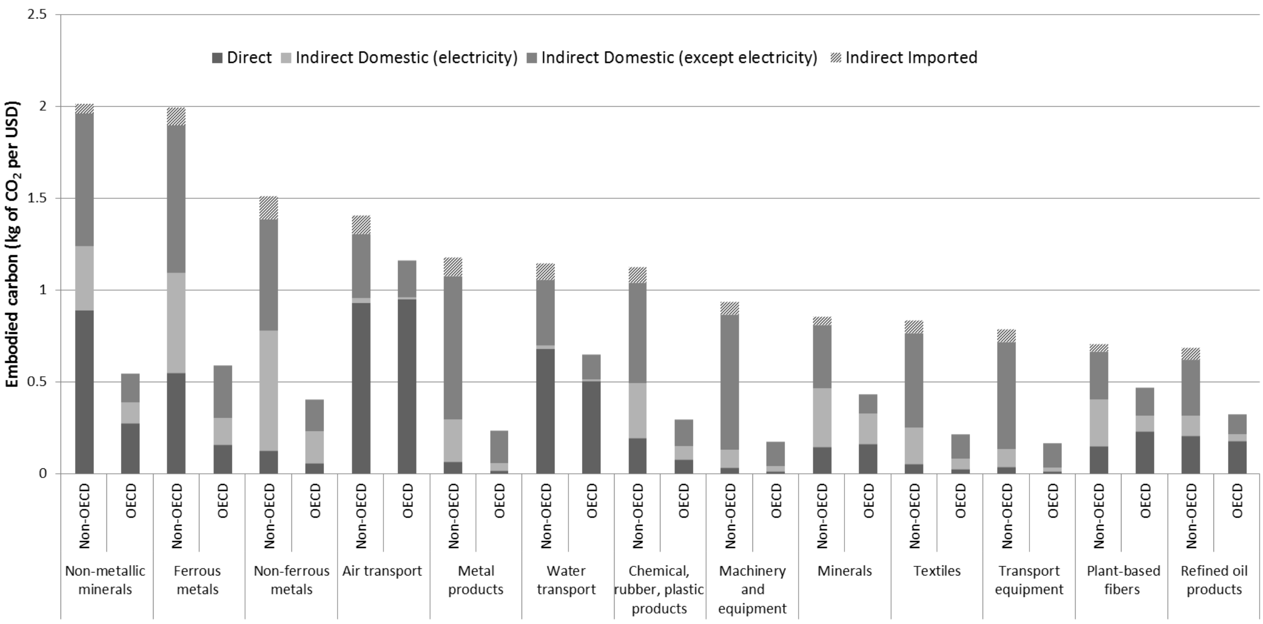


Figure 2: Composition of carbon content across selected sectors



[6] Net exports of countries in Mt CO_2 (to OECD/ to Non-OECD) not displayed in Figure 1 for the sake of readability are: Australia (19.5/-3.5), Mexico (27.7/ -24.4), South Korea (18.3/-17.5), Rest of European Union (117.7/-284.6), Rest of OECD (-13.2/-36.9), Argentina (6.2/-2.3), Indonesia (23.0/-34.8), OPEC (60.4/-75.8), Middle-Income-Countries (285.1/-108.1), and Low-Income-Countries (8.3/-71.1).

As can be seen, all OECD countries are net importers of carbon from Non-OECD countries with the United States ranging at the top end. China, Russia, and South Africa are net carbon exporters both to OECD and Non-OECD states with China ranking far by first.

Figure 2 provides a pairwise comparison between OECD and Non-OECD of embodied carbon for emission-intensive and trade-intensive industries. 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 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.

To summarize, our embodied carbon calculations indicate that the amount of carbon embodied in trade is substantial. Non-OECD countries, in general, are net exporters of embodied carbon to OECD countries: Non-OECD net exports to OECD are equivalent to approximately 12.6% of all OECD emissions or 9.4% 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.[7] Thus, to the extent that embodied carbon tariffs reduce emissions in tandem with demand for carbon-intensive imports, the MRIO results suggest that tariffs imposed by OECD countries on Non-OECD countries could represent an effective environmental policy.

4. Model

To quantify the economic and environmental effects of carbon tariffs we draw on computable general equilibrium (CGE) analysis – a standard numerical approach for the economic impact assessment of policy reforms (Shoven and Whalley 1992). CGE analysis provides counterfactual ex-ante comparisons, assessing the outcomes with a policy reform in place with what would have happened had it not been undertaken. CGE models are rooted in general equilibrium theory combining assumptions on the optimizing behavior of economic agents with the analysis of equilibrium conditions: producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers with given preferences maximize their well-being subject to budget constraints. The simultaneous explanation of the origin and spending of the agents' incomes makes it possible to address both economy-wide efficiency effects as well as the incidence of policy interventions.

For our simulation analysis of unilateral climate policies, we adopt a generic multi-region, multi-sector CGE model of global trade and energy use developed by Böhringer and Rutherford (2002) with the following basic features:

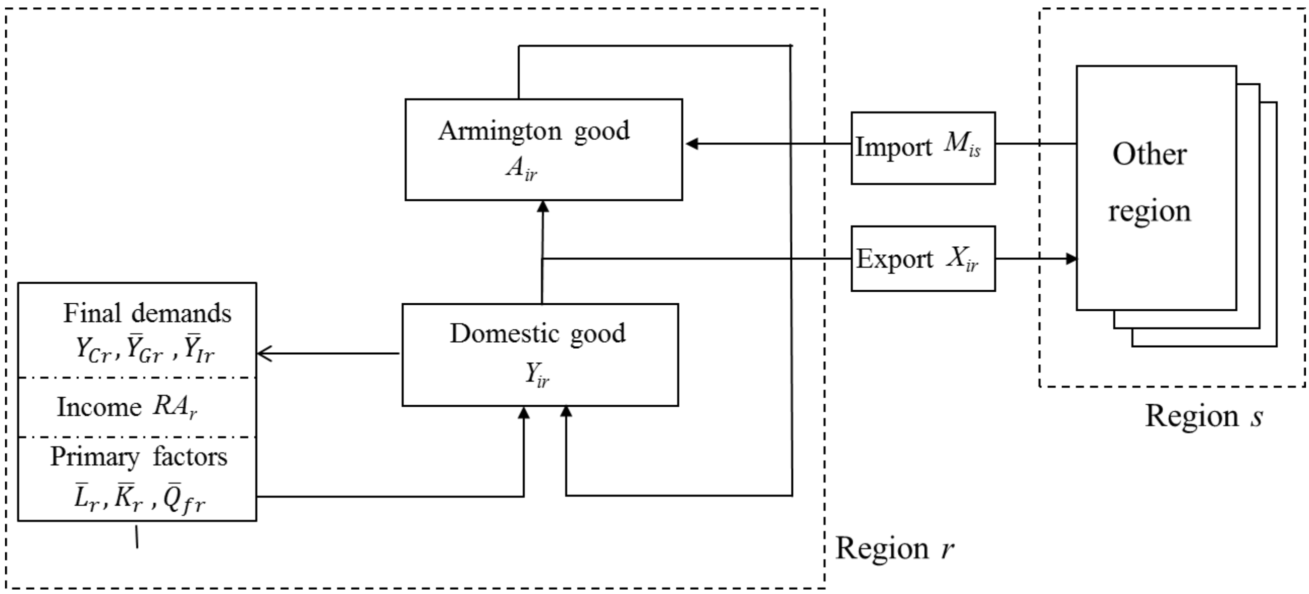
[7] Non-OECD countries (particularly China) generate distinctly higher emissions in electricity production than OECD countries.

- There is one representative consumer for each region that receives income from primary factors: labor, capital, and fossil-fuel resources (specific to the production of crude oil, natural gas and coal).
- Labor and capital are mobile across sectors within a region. Fossil-fuel resources are specific to fossil-fuel production sectors in each region.[8]
- Output and factor prices are fully flexible and markets are perfectly competitive.
- Regions are linked through bilateral trade flows with traded goods being differentiated by region of origin (Armington 1969).
- Government demand, investment demand, and the balance of payment surplus are fixed at the base-year level.
- Preferences and technological constraints are described through nested constant-elasticity-of-substitution (CES) functions that capture demand and supply responses to changes in relative prices.

Three classes of conditions characterize the economic equilibrium for our model: zero-profit conditions for constant-returns-to-scale producers, market-clearance conditions for all goods (incl. factors), and income-balance conditions for the representative agent in each region. An equilibrium allocation determines the three fundamental classes of economic variables: zero-profit conditions pin down the activity levels of production, market-clearance conditions determine prices for goods (incl. factors), and income-balance conditions identify the income levels of the representative agents.

Below we focus on a non-technical model summary. The algebraic model formulation with the detailed specification of functional forms is provided in Appendix B. Figure 3 depicts the fundamental accounting identities of economic flows that can be directly associated with the three classes of equilibrium conditions.

Figure 3: Economic flow chart of the multi-region multi-sector CGE model



[8] Fossil fuel resources refer to natural resources such as coal mines, gas reservoirs, or oil fields that are used in the production of the respective fossil fuels.

The representative agent in each model region r receives income RA_r from primary factors – labor $\bar{L}_r$, capital $\bar{K}_r$ and specific resources $\bar{Q}_{fr}$ in the production of fossil fuels f.[9] The representative agent spends income on aggregate private consumption Y_{Cr}, exogenous investment (savings) demand $\bar{Y}_{Ir}$, and exogenous government demand $\bar{Y}_{Gr}$.

Production Y_{ir} of commodity i in each region r is given as a nested constant-elasticity-of-substitution function which captures price-responsive substitution possibilities between factor and intermediate inputs.[10] Production output enters final demand of the representative agent (Y_{Cr}, $\bar{Y}_{Ir}$, $\bar{Y}_{Gr}$), export demand X_{ir} and input demand for Armington production A_{ir}. Armington production for each good i in region r is based on a CES technology that combines the domestically produced good and imports M_{is} from other regions s. Armington outputs A_{ir} serve as intermediate inputs to the production Y_{ir} of all commodities including final demands.

CO_2 emissions are linked in fixed proportions to the use of fuels, with CO_2 coefficients differentiated by the specific carbon content of fuels (coal, gas, and refined oil). Economy-wide restrictions to the use of CO_2 emissions in production and consumption are implemented through explicit emission pricing of the carbon associated with fuel combustion either via CO_2 taxes or the auctioning of CO_2 emission rights. CO_2 emission abatement then takes place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities). In equilibrium, the direct carbon content of production Y_{ir} is determined by the price-responsive demands for fuel inputs. Likewise, the indirect carbon content from intermediate non fossil-fuel inputs (either domestic or imported) is determined through the equilibrium allocation. In our policy simulations of unilateral OECD climate policies we impose carbon prices on the direct carbon content of fuels that enter intermediate and final demands in OECD regions. In case of unilateral OECD emission regulation that seeks to outreach for foreign CO_2 emissions in Non-OECD countries, carbon tariffs are additionally applied to the carbon content embodied in imports from Non-OECD countries to OECD countries.

To determine the free parameters of functional forms that characterize production technologies and consumer preferences one requires a coherent observation of economic transactions for a particular base year. In line with the MRIO calculations of section 3 we use GTAP 9 data for the base-year 2011. The base-year data together with exogenous elasticity values calibrate the functional forms such that the GTAP dataset is consistent with market structure assumptions and optimizing behavior of economic agents (see Shoven and Whalley 1992 for a detailed description of the calibration procedure). Elasticities which determine the responses of agents to price changes are taken from the pertinent econometric literature. Elasticities in international trade come from the estimates included in the GTAP database ((Narayanan et al. 2015). Substitution elasticities between factors of production are taken from Okagawa and Ban (2008) as well as

[9] For the sake of simplicity, we omit the explicit representation of tax revenues in our exposition of the generic model structure. The budget constraint of the representative agent furthermore includes a balance of payment constraint which captures the base-year trade deficit or surplus for each region.

[10] Note that the index i compromises all sector outputs as well as the final consumption composite (i = C), the public good composite (i = G), and the investment composite (i = I).

Steinbuks and Narayanan (2014). 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).

5. Analysis

Policy scenarios

Our main objective is to assess the potential of embodied carbon tariffs as potential 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 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 in 2011. The magnitude of emission reduction reflects the unilateral abatement pledges of major industrialized countries such as the U.S., the EU or Canada based on national communications to the Copenhagen Accord (United Nations 2011). 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.

Regarding tariff design we consider four variants that differ in the base to which the OECD emission price applies. The first variant (scenario FULL) reflects proposals to tax the full embodied carbon content of traded goods. As noted before, the embodied carbon metric neglects potentially important trade responses and thus is doomed to set carbon tariffs inefficiently high. We therefore contrast the outcome of scenario FULL with a second variant OPTIMAL in which the choice of tariff rates reflect the theoretical findings of second-best environmental regulation as laid out by Hoel (1996).

Hoel demonstrates analytically that it is optimal (from the perspective of achieving world-wide emission reduction at minimum global cost) to base the tariff rates on the domestic price of carbon, scaled in proportion to the marginal responsiveness of global emissions to a change in imports in a given sector. The intuition for this logic is that goods that produce larger reductions in global emissions per unit of imports should be taxed at higher rates.

To capture Hoel's logic, we numerically evaluate marginal global emission responses at the REF equilibrium and then use them to set the approximately optimal carbon tariff rates. Note that we do not compute exactly optimal rates since this would require the endogenous evaluation of the marginal emission responses at the optimal-tariff equilibrium – a computationally very demanding process which calls for an explicit optimal taxation modeling framework which is beyond the scope of our current analysis.

The third and fourth tariff variants build again on the embodied carbon metric but instead of taxing the full input-output embodied carbon we only price embodied carbon at the level of direct emissions (scenario DIRECT) or at the level of direct emissions plus indirect emissions embodied in electricity input (scenario DIRECT+ELE). The practical policy appeal of the latter two variants is that tariffs are based on more limited definitions of embodied carbon which reduces the regulatory complexity of implementation.[11] At the same time, the theoretical second-best literature suggests carbon metrics that do not capture the full carbon content. Against this background, it is interesting to see how simple practical metrics with reduced carbon content perform against more sophisticated metrics based either on the full embodied carbon content or second-best considerations of optimal taxation. Table 3 summarizes the key features of our core scenarios with respect to the design of carbon tariffs. Note that for reasons of practicability, tariffs are applied to industries in average rather than specific firms such that there are no direct incentives to reduce upstream emissions in Non-OECD countries. Across all scenarios, OECD exports to Non-OECD countries are not exempted from emission pricing, i.e., there are no export rebates.

The benchmark equilibrium against which we measure the impacts of policy intervention is defined by the business-as-usual economic patterns in 2011 — the most recent base-year provided by the GTAP 9 dataset.

Table 3: Tariff design in policy scenarios

	Carbon tariff design
REF	No carbon tariff
FULL	Carbon tariff levied on the full embodied carbon content of imports
OPTIMAL	Carbon tariff based on second-best consideration of optimal taxation
DIRECT	Carbon tariff levied on embodied carbon from direct emissions only
DIRECT+ELE	Carbon tariffs levied on embodied carbon from direct emissions plus indirect emissions embodied in electricity inputs

We do not attempt to measure the benefits from emission abatement. Across our central case scenarios, we therefore hold global emissions constant and compare the cost-effectiveness of the different policies considered.[12] 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-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 world-wide emissions emerging from the reference scenario (REF).

Emission leakage

We begin our discussion of simulation results by examining how effective alternative tariff designs are in mitigating emission leakage. The leakage rate is defined as the change in Non-OECD emissions over OECD emission reduction. Table 4 reports leakage rates for Non-OECD as a whole as well as for individual

[11] As laid out in section 3, indirect embodied emissions from electricity use make up a substantial fraction of total embodied emissions in many sectors.

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

Non-OECD regions. In the REF scenario without carbon tariffs the leakage rate amounts to 14.1% with China being the major source of leakage, followed by Middle-Income-Countries and India. Applying carbon tariffs on full embodied carbon decreases the average leakage rate for all Non-OECD countries drastically – by roughly two thirds from 14.1% under REF to 5.2% under FULL. Leakage reduction is particularly pronounced for China which is by far the largest net exporter of embodied carbon to OECD countries. For alternative tariff designs, leakage reduction is significantly smaller – either because second-best considerations call for lower effective tax rates (scenario OPTIMAL) than applied under FULL or because we only tax a fraction of embodied emissions (scenarios DIRECT or DIRECT+ELE).

Table 4: Leakage (%)

	REF	FULL	OPTIMAL	DIRECT	DIRECT+ELE
Non-OECD	14.1	5.2	9.6	10.9	8.9
Argentina	0.1	0.0	0.1	0.1	0.1
Brazil	0.2	0.2	0.2	0.2	0.2
China	4.1	0.9	2.5	3.5	2.8
India	2.0	1.0	1.3	1.5	1.4
Indonesia	0.3	0.2	0.3	0.3	0.3
Low-Income-Countries	0.1	0.1	0.1	0.1	0.1
Middle-Income-Countries	4.0	2.0	2.9	2.9	2.8
OPEC	0.7	-0.3	0.3	0.1	0.1
Russia	1.5	0.3	1.2	1.3	0.7
South Africa	1.0	0.6	0.9	0.9	0.7

Welfare effects

Table 5 indicates welfare effects as we move from the reference scenario (REF) to the alternative tariff scenarios. Welfare effects are expressed in terms of percentage changes in Hicksian equivalent variation (HEV) of income.[13] The top of Table 5 provides welfare changes for the world as a whole ("Global") as well as for the average of OECD and Non-OECD regions. The common metric for measuring composite welfare effects is based on a Benthamite utilitarian perspective where we add up money-metric utility with equal weights across the respective regions. Benthamite social preferences are indifferent to cost distribution across regions and, therefore, produce a measure of the global efficiency of different policy options.

A striking insight is that carbon tariffs which are based on the full embodied carbon metric worsen rather than improve global cost-effectiveness compared to the REF scenario. The initially appealing notion that taxation of the full carbon footprint is a good idea must therefore be rejected from an efficiency perspective. Global cost-effectiveness of carbon tariffs call for taxation of Non-OECD imports to OECD

[13] Note again that our welfare metric does not include economic benefits from emission reduction. We deliberately focus on the cost-effectiveness comparison for alternative unilateral climate policy designs to achieve an identical level of global emission reduction.

countries at lower effective rates than suggested by the full embodied carbon metric – either based on more sophisticated second-best considerations (scenario OPTIMAL) or less comprehensive embodied carbon metrics (scenarios DIRECT and DIRECT+ELE). Tariffs based on more sophisticated second-best considerations, in which the tariff rates account for how responsive global emissions are to changes in the level of trade in each sector between trade partners, produce roughly a 5% reduction in the global cost of the emission reduction relative to the REF case.

Table 5: Welfare (in % Hicksian equivalent variation of income)

	REF	FULL	OPTIMAL	DIRECT	DIRECT+ELE
Global	-0.553	-0.588	-0.526	-0.532	-0.528
OECD	-0.497	0.144	-0.349	-0.342	-0.216
Non-OECD	-0.689	-2.340	-0.950	-0.987	-1.273
OECD regions					
Australia	-1.368	-1.089	-1.282	-1.273	-1.211
Canada	-0.767	-0.358	-0.667	-0.676	-0.582
France	-0.372	0.318	-0.208	-0.198	-0.063
Germany	-0.790	0.034	-0.576	-0.590	-0.416
Italy	-0.799	0.017	-0.597	-0.604	-0.430
Japan	-0.409	0.232	-0.249	-0.249	-0.122
Mexico	-2.158	-1.665	-2.016	-2.059	-1.961
Rest of EU	-0.592	0.453	-0.352	-0.320	-0.110
Rest of OECD	-1.036	-0.754	-0.922	-0.935	-0.864
South Korea	0.329	1.341	0.533	0.635	0.843
Turkey	-0.328	0.352	-0.171	-0.154	-0.020
United Kingdom	-0.466	0.159	-0.328	-0.298	-0.193
USA	-0.224	0.280	-0.123	-0.122	-0.030
Non-OECD regions					
Argentina	-0.165	-0.485	-0.210	-0.298	-0.325
Brazil	-0.041	-0.165	-0.084	-0.124	-0.101
China	-0.165	-3.793	-0.663	-0.428	-0.945
India	0.474	-0.180	0.170	0.295	0.118
Indonesia	-0.826	-1.307	-0.813	-0.944	-0.997
Low Income	0.349	0.940	0.219	0.346	0.464
Middle Income	-0.248	-1.448	-0.399	-0.583	-0.742
OPEC	-3.019	-5.238	-3.428	-3.704	-4.164
Russia	-2.740	-4.512	-2.974	-3.119	-3.655
South Africa	0.043	-1.287	-0.133	-0.174	-0.998

In our simulations, most of efficiency gains achievable from using carbon tariffs (as measured by the optimal tariff case) can be captured by less comprehensive (and at the same time more practical) embodied carbon tariff designs DIRECT-ELE or DIRECT.[14] Overall, the scope for efficiency gains from carbon tariffs that are operated at the industry level is quite limited. On the other hand, the scope for burden shifting is dramatic: implementation of carbon tariffs induces a substantial cost shifting from OECD countries to Non-OECD countries.

The economic reasoning behind cost shifting of regulatory policies in OECD countries to Non-OECD trading partners resides in policy-induced changes in international prices, the so-called terms of trade. As with carbon leakage, there are two major channels for international price spillovers. First, carbon abatement in OECD countries lowers demands for fossil fuels, and this depresses international fossil fuel prices. As a consequence, fuel exporters will suffer from a decline in export revenues whereas fuel importers benefit from reduced expenditures.

By pricing carbon in exports, abating countries can pass on part of their cost increase in domestic energy-intensive production to trading partners. The terms-of-trade effects are already present in the REF scenario where on average Non-OECD countries without carbon constraints face negative spillover effects that are in the range of average economic cost to OECD countries. With carbon tariffs, however, the losses for Non-OECD countries are accentuated. Carbon tariffs function as a sort of "back-door" trade policy for the OECD, substituting for optimal tariffs that would be illegal under free trade agreements. Most remarkable, again, is the case where tariffs are applied to the full embodied carbon in traded goods: terms-of-trade effects are then large enough that OECD countries on average experience net gains from climate policy relative to business-as-usual whereas Non-OECD welfare goes down on average by more than 2% which is three times the induced cost Non-OECD countries would face for OECD's REF policy (i.e., domestic emission pricing without carbon tariffs). The full embodied carbon metric thus stands out not only for global efficiency losses compared to REF but also for the most pronounced burden shifting where OECD countries can free ride on their abatement efforts at the expense of the developing world. Adopting less comprehensive metrics for embodied carbon (DIRECT or DIRECT+ELE) or following second-best considerations on optimal tariff setting (OPTIMAL) limits the degree of cost-shifting but still places the bulk of global cost (in HEV terms) on the developing world.

Table 5 reports the incidence of alternative OECD climate policy designs for individual OECD and Non-OECD countries. In the REF 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. For the same reason, India and the composite of Middle-Income-Countries experience welfare gains relative to business-as-usual — mainly benefitting from reduced expenditures for fossil fuel imports. The depression of fuel prices also explains why OECD countries such as Mexico or Australia which are exporters of fossil fuels

[14] The fact that the welfare impacts delivered by the DIRECT-ELE tariff design are so similar to the impacts produced by the OPTIMAL design is a remarkable coincidence. It likely indicates that the reduction in the magnitude of the carbon coefficients under the less comprehensive design are approximately equal in magnitude to the amount one reduces the optimal tariffs rates to account for the redirection effects.

suffer distinctly more from OECD emission regulation than the OECD average. The imposition of tariffs is uniformly beneficial for OECD countries while it is welfare decreasing for almost all Non-OECD countries (the one outlier is the composite of Low-Income-Countries)[15] – providing 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.

As noted above, tariffs based on the full carbon content are most detrimental for Non-OECD regions. Among the most heavily impacted Non-OECD regions are, once again, Russia and OPEC (4-5% losses). China goes from experiencing negligible welfare effects under REF to almost a 4% welfare loss under FULL. 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 most industrialized regions such as France, Germany, Italy, Japan, South Korea, Germany, the Rest of EU, South Korea, Turkey, and the United States. The adverse terms-of-trade effects of carbon tariffs for Non-OECD regions get attenuated as we move to lower effective tariff rates – either prescribed by second-best considerations (OPTIMAL) or by a smaller base for embodied carbon, i.e., direct emissions only (DIRECT) or direct emissions plus indirect emission from electricity (DIRECT+ELE).

Tariff rates

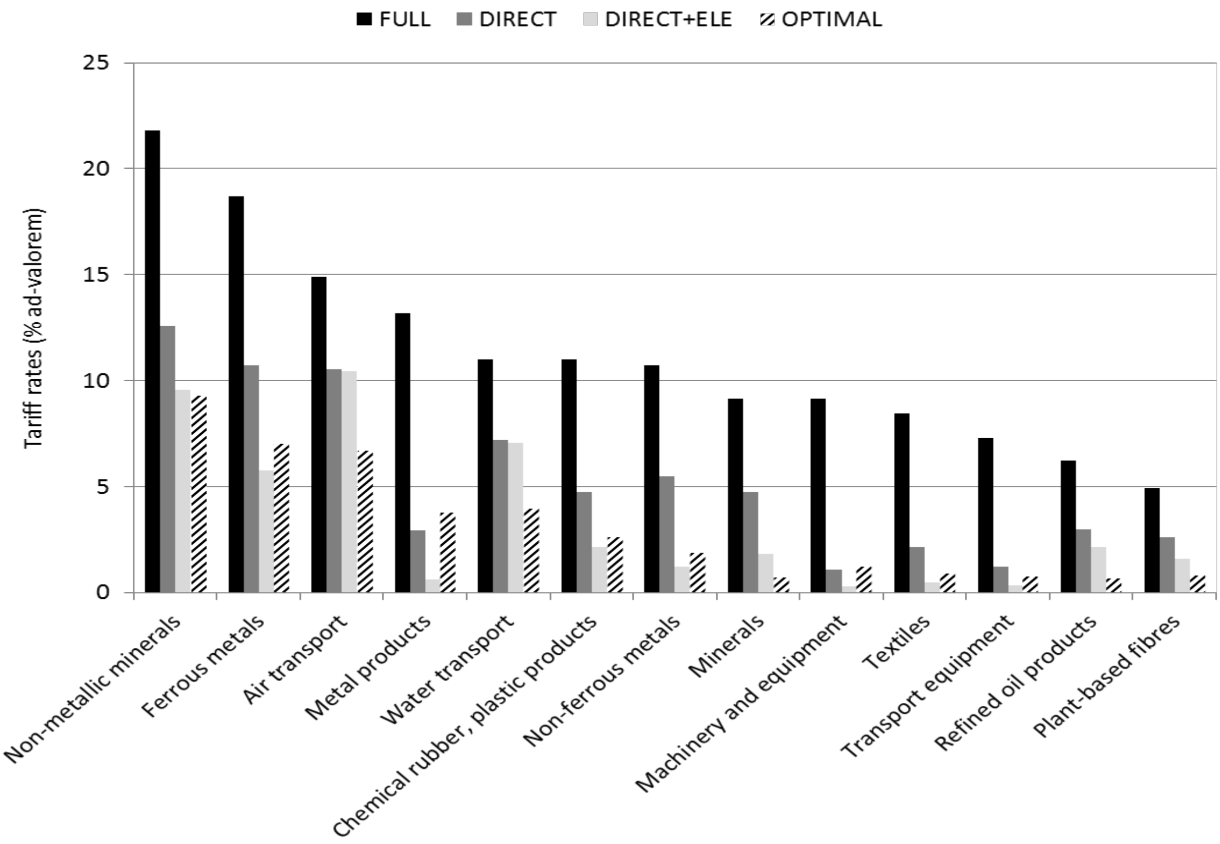
Figure 4 summarizes the average tariff rates (in percentage ad-valorem terms) implied by the different carbon tariff designs on emission- and trade-intensive imports from Non-OECD to OECD regions.[16]

Rates based on the full MRIO measures of embodied carbon (FULL) are markedly higher than the rates implied by the alternative specifications of the tariffs. Obviously, the more comprehensive the embodied carbon metric is, the higher are the tariff rates across sectors. Compared to the OPTIMAL tariff rates implied by second-best considerations, a tariff applied to the full embodied carbon (FULL) produces significantly higher rates in all sectors. Less comprehensive embodied carbon designs (DIRECT+ELE or DIRECT) show a more complex correspondence to the pattern of optimal rates across sectors —with higher rates in some cases and lower rates in others. The pattern of optimal tariffs (OPTIMAL) should reflect, in part, the level of embodied carbon in production – all else being equal, changes in the level of production in sectors with higher embodied carbon will produce larger changes in global emissions. As a result, we would expect the rates based on more comprehensive measures of embodied carbon to be more closely in line with the optimal tariffs than the less comprehensive designs. However, the pattern of the optimal tariffs will also reflect the elasticity of the foreign supply responses – accounting for the ability of the world economy to re-route carbon-intensive products from Non-OECD countries to new markets in response to the tariffs.

[15] Low Income countries benefit from OECD tariffs since they have very little trade with OECD countries while they benefit from depressed export prices of their main Non-OECD trading partners.

[16] The tariff rates in our simulations are specific to each pair of trading countries. As a summary of this information, Figure 4 reports the industry-specific average of the rates employed by all OECD countries to imports from all Non-OECD countries.

Figure 4: Tariff rates (% ad-valorem)



Inequality aversion

Our discussion of global welfare effects triggered by alternative OECD tariff designs so far has been based on a more narrow efficiency perspective. In policy practice, the appeal of carbon tariffs will not only hinge on the magnitude of aggregate cost savings but also on how cost changes are distributed across regions. If carbon tariffs do not deliver a Pareto improvement but make some countries worse off, then the thorny issue of unfair burden shifting arises. To account for differentiated normative views, we report global economic welfare based on social welfare metrics that exhibit differing degrees of inequality aversion ranging from a Benthamite utilitarian perspective, which is agnostic about the distribution of cost, to a Rawlsian perspective, where only the welfare of the poorest region determines global welfare.

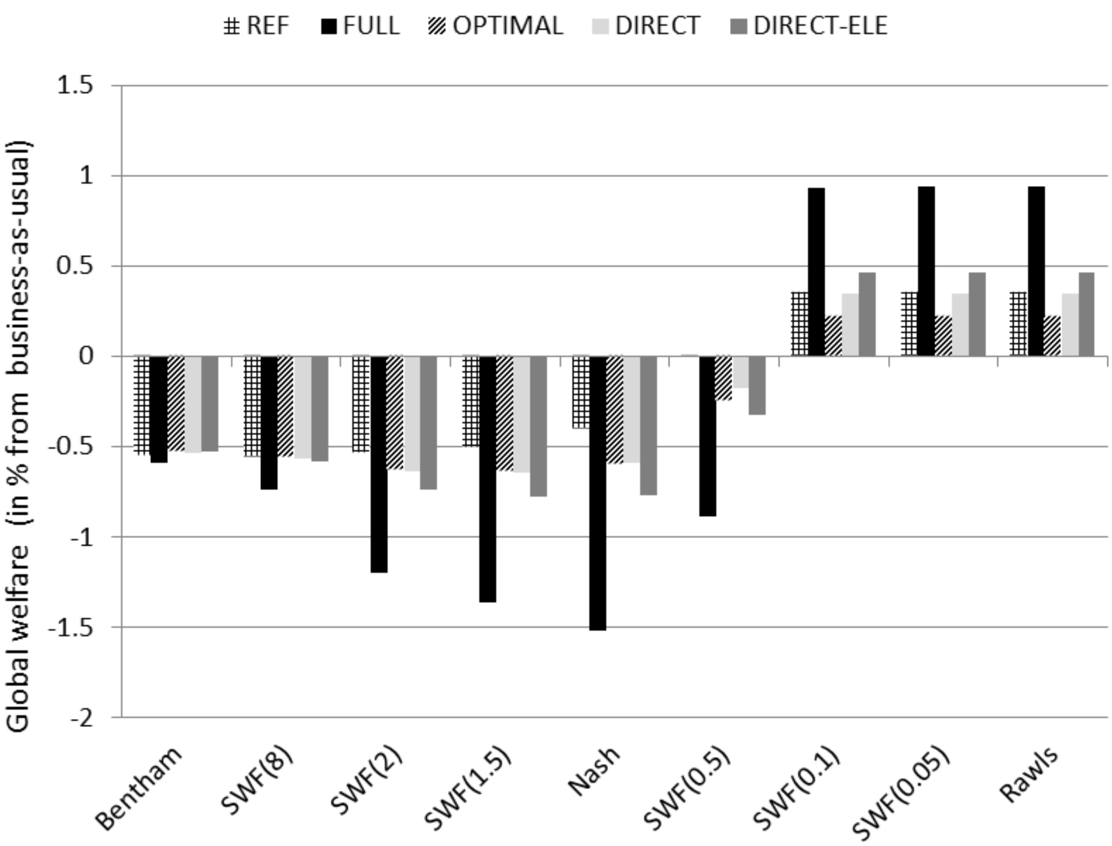
The general form of the social welfare function is (Atkinson 1970):

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

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

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. A value of $\sigma = \infty$ ("Bentham" in Figure 5) 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 Figure 5) 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. In our dataset the composite of Low-Income-Countries is the poorest region. Entries listed in between these two extreme cases on the x-axis of the figure describe results based on intermediate values of σ.

Figure 5: Change in global welfare by social welfare metric



When we compare the alternative policies from a utilitarian perspective ("Bentham") we replicate the global cost results shown in Table 5 – illustrating that the full embodied carbon tariffs (FULL) increase global cost slightly whereas optimally designed carbon tariffs (OPTIMAL) or carbon tariffs levied on a fraction of embodied carbon (DIRECT or DIRECT+ELE) provide small efficiency gains. When inequality aversion is taken into account, the limited potential for global cost savings provided by carbon tariffs evaporates. 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, the composite of Low-Income-Countries, actually benefits from terms-of-trade gains — mainly through reduced export prices of their main Non-OECD trading partners.

Sensitivity analysis

We have performed piece-meal sensitivity analysis to test the robustness of our results with respect to changes in two key elasticities that drive the magnitude of emission leakage and economic cost: Armington trade elasticities and fossil fuel supply elasticities. Table 6 summarizes the results for leakage rates and (Benthamite) welfare effects at the global level as well as for the composite of OECD and Non-OECD regions. We find that all our key insights remain robust.

Table 6: Sensitivity analysis

	REF	FULL	OPTIMAL	DIRECT	DIRECT+ELE
	Leakage (in %)				
Core parametrization	14.1	5.2	9.6	10.9	8.9
Armington trade elasticities halved	9.4	1.8	5.9	7.3	5.7
Armington trade elasticities doubled	22.5	11.0	15.6	17.1	14.4
Fuel supply elasticity halved	18.6	9.4	14.3	15.4	13.4
Fuel supply elasticity doubled	10.6	2.0	5.9	7.5	5.4
	Global welfare (in % Hicksian equivalent variation in income)				
Core parametrization	-0.553	-0.588	-0.526	-0.532	-0.528
Armington trade elasticities halved	-0.555	-0.567	-0.537	-0.542	-0.537
Armington trade elasticities doubled	-0.545	-0.610	-0.502	-0.508	-0.507
Fuel supply elasticity halved	-0.553	-0.587	-0.528	-0.531	-0.528
Fuel supply elasticity doubled	-0.553	-0.588	-0.523	-0.532	-0.527
	OECD welfare (in % Hicksian equivalent variation in income)				
Core parametrization	-0.497	0.144	-0.349	-0.342	-0.216
Armington trade elasticities halved	-0.324	0.529	-0.104	-0.159	0.000
Armington trade elasticities doubled	-0.582	-0.065	-0.435	-0.408	-0.301
Fuel supply elasticity halved	-0.455	0.201	-0.312	-0.297	-0.168
Fuel supply elasticity doubled	-0.534	0.092	-0.381	-0.383	-0.260
	Non-OECD welfare (in % Hicksian equivalent variation in income)				
Core parametrization	-0.689	-2.340	-0.950	-0.987	-1.273
Armington trade elasticities halved	-1.109	-3.189	-1.572	-1.458	-1.819
Armington trade elasticities doubled	-0.457	-1.914	-0.664	-0.748	-1.000

Fuel supply elasticity halved	-0.786	-2.472	-1.044	-1.092	-1.390
Fuel supply elasticity doubled	-0.599	-2.213	-0.864	-0.889	-1.164

The higher are the Armington elasticities that determine how substitutable varieties of 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. The lower are the fossil fuel supply elasticities, 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.

Across all variations, taxing imports at the full embodied carbon content yields the highest leakage reduction effect. Tariff rates based on second-best considerations (OPTIMAL) or metrics with partial coverage of embodied carbon (DIRECT, DIRECT+ELE) are significantly less effective in reducing carbon leakage.

From a global efficiency (utilitarian) perspective, taxing the full carbon content of imports is not a good idea as it neglects important trade responses and thereby induces efficiency losses rather than efficiency gains as compared to unilateral climate policy with domestic emission pricing only. Yet, the scope for efficiency gains from more subtle tariffs based on second-best considerations remain quite limited and can be almost achieved via more practical approaches that levy carbon tariffs on embodied carbon from direct emission plus indirect emissions embodied in electricity inputs.

Changes in Armington trade elasticities and fossil fuel supply elasticities determine the scope of burden shifting between OECD and Non-OECD countries. In the REF scenario without carbon tariffs, lower Armington elasticities provide higher implicit market power to OECD countries for passing through higher product prices to Non-OECD trading partners. Likewise, with lower fossil fuel supply elasticities OECD countries in aggregate (as fuel importers) benefit from a stronger decline in international fuel prices induced by OECD emission reduction. Across all variants, the principal effect of carbon tariffs is to shift the burden of developed-world climate policies to the developing world. The burden shifting effect is most pronounced for the case of levying carbon tariffs on the full embodied carbon content of imports.

6. Conclusions

In the international climate policy debate, the idea of imposing tariffs on embodied carbon has attracted significant attention in 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, carbon tariffs could serve as a second-best instrument to improve cost-effectiveness of unilateral climate policies. In our quantitative experiments, we find that carbon tariffs applied to the full carbon content of imported goods are in fact quite effective in reducing carbon leakage from unilateral OECD policies. However, taxing the full carbon footprint of imports at the domestic carbon price reduces rather than improves global cost-effectiveness of unilateral climate policy. These tariffs are too high from the perspective of optimal environmental policy because they fail to acknowledge a key behavioral response by industries subjected to the tariffs — the incentive to re-direct output to other markets in the world economy. We show that this effect is quantitatively important. However, even if carbon tariffs are set at lower effective rates – either based on second-best considerations of optimal taxation or adopting less comprehensive carbon metrics – their potential for efficiency gains is very limited because they do not set direct incentives to individual polluters abroad for adopting less emission-intensive production techniques.

From a distributional perspective, carbon tariffs exacerbate pre-existing income inequalities as (wealthier) OECD countries shift the burden of emission abatement to (poorer) Non-OECD countries. The burden shifting effect becomes particularly evident for tariffs that tax the full carbon content of imports: in this case a reduction in global cost-effectiveness goes along with a drastic burden shifting where OECD countries can free ride on their climate policy at the expense of the developing world.

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 have argued that they cannot accept binding emissions targets under any equitable climate policy regime. Major developed countries, notably the United States, have argued that they cannot accept stringent 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.

Acknowledgments

Research funding is gratefully acknowledged from Environment Canada and the Stiftung Mercator (ZentraClim). We would like to thank Matti Liski and two anonymous referees for helpful comments. The ideas expressed here remain those of the authors who remain solely responsible for errors and omissions.

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Appendix A: Multi-region input-output (MRIO) calculations

For our MRIO calcuations of embodied carbon we use the denotations listed in Table A.1.

Table A.1: Denotations used in the MRIO calculations

Sets and Indices	
R	Set of regions (with r denoting the set index)
I	Set of production activities including production of final private consumption composite, the public good composite, and the investment composite (with i – alias j – denoting the set index)
U	Set of international transport services (with u denoting the set index)
Parameters	
Y_{ir}	Output of sector i in region r
X_{isr}	Exports of commodity i from region s to region r
M_{ir}	Composite imports of commodity i to region r
Z^{D}_{jir}	Domestic intermediate inputs of commodity j in activity i in region r
Z^{M}_{jir}	Imported intermediate inputs of commodity j in activity i in region r
T_{ur}	International transport service u produced in region r
T_{uisr}	Input of international transport service u to imports in sector i from region s to region r
$co2e_{ir}$	Direct CO_2 emissions in activity i in region r
Variables	
cc^{Y}_{ir}	Carbon content in activity i in region r
cc^{M}_{ir}	Carbon content of imported commodity i in region r
cc^{T}_{u}	Carbon content of international transport service u

The total carbon content of a good is composed of the CO_2 emitted in the production of the good itself as well as of the CO_2 that is emitted to produce intermediate inputs and international transport services. To caculate the full carbon content (per USD of output) we use input-output accounting identities and solve the associated linear system of equations below for the carbon content of production activities cc_{ir}^{Y}, the carbon content of imports cc_{ir}^{M} and the carbon content of international transport services cc_{u}^{T}. The first set of equations (1) states that the total embodied carbon in output $cc_{ir}^{Y}Y_{ir}$ of activity i in region r must be equal to the sum of direct emissions, the embodied carbon in domestic intermediate inputs and the embodied carbon in imported intermediate inputs. The second set of equations (2) demands total embodied carbon in imports $cc_{ir}^{M}M_{ir}$ of commodity i in region r to equal the sum of the embodied carbon of all exports from regions s to r plus the carbon embodied in international transport services. The third set of equations (3) postulates that the embodied carbon $cc_{u}^{T}\sum_{r\in R}T_{ur}$ of international transport service u must be equal to the sum of the embodied carbon in the production of the international transport service across countries.

$$\forall i \in I \;\; \forall r \in R: \qquad cc_{ir}^{Y}Y_{ir} = co2e_{ir} + \sum_{j} cc_{jr}^{M} Z_{jir}^{M} + \sum_{j} cc_{jr}^{Y} Z_{jir}^{D} \tag{1}$$

$$\forall i \in I \;\; \forall r \in R: \qquad cc_{ir}^{M}M_{ir} = \sum_{s\in R}\left(cc_{is}^{Y}X_{isr} + \sum_{u\in U} cc_{u}^{T}T_{uisr}\right) \tag{2}$$

$$\forall u \in U: \qquad cc_{u}^{T}\sum_{r\in R}T_{ur} = \sum_{r\in R} cc_{ur}^{Y}T_{ur} \tag{3}$$

We obtain a system of $(card(I)+card(I))\times card(R)+card(U)$ unknowns and linear equations. The MRIO model can be solved directly as a square system of equations or solved recursively using a diagonalization algorithm. The data for the parameters are provided by the GTAP 9 database.

Appendix B: Algebraic summary of computable general equilibrium (CGE) model

We provide a compact algebraic description for the generic multi-region multi-sector CGE model underlying our quantitative simulation analysis. Tables B.1 – B.5 explain the notations for variables and parameters employed within our algebraic exposition. Table B.6 provides an overview of key elasticity values Figures B.1 – B.3 illustrate the nesting structure in production. The algebraic summary is organized in three sections that state the three classes of economic equilibrium conditions constituting a competitive market outcome: zero-profit conditions for constant-returns-to-scale producers, market-clearance conditions for commodities and factors, and income balances for consumers. In equilibrium, these conditions determine the variables of the economic system: zero-profit conditions determine activity levels of production, market-clearance conditions determine the prices of goods and factors, and income-balance conditions determine the income levels of consumers. We use the notation Π_{ir}^{X} to denote the unit-profit function of production activity

i in region r where X is the name assigned to the associated production activity.[17] For a condensed representation of market equilibrium conditions, we can differentiate the unit-profit functions with respect to input and output prices in order to obtain compensated demand and supply coefficients (Hotelling's lemma) which then enter the market equilibrium conditions. Numerically, the model is implemented in GAMS.[18]

Table B.1: Indices and sets

i (alias j)	Index for sectors and goods - including the composite private consumption good (i=C), the composite public consumption good (i=G), and the composite investment good (i=I)
r (alias s)	Index for regions
NE	Set of non-energy goods
FF	Set of primary fossil fuels: Coal, crude oil, gas
CGO	Set of fuels with CO_2 emissions: Coal, gas, refined oil

Table B.2: Variables

Activity levels	
KL_{ir}	Value-added composite in sector i and region r
E_{ir}	Energy composite in sector i and region r
Y_{ir}	Production in sector i and region r
M_{ir}	Import composite for good i and region r
A_{ir}	Armington composite for good i in region r
Price levels	
p_{ir}^{KL}	Price of aggregate value-added in sector i and region r
p_{ir}^{E}	Price of aggregate energy in sector i and region r
p_{ir}^{Y}	Output price of good i produced in region r
p_{ir}^{M}	Import price aggregate for good i imported to region r
p_{ir}^{A}	Price of Armington good i in region r
w_r	Wage rate in region r
v_r	Price of capital services in region r
q_{ir}	Rent to natural resources in region r ($i \in FF$)
$p_r^{CO_2}$	CO_2 emission price in region r
Income levels	
INC_r	Income level of representative household in region r

[17] Note that we can decompose production in multiple stages (nests) and refer to each nest as a separate sub-production activity. In our exposition below, we specify for example the choice of capital-labor inputs as a price-responsive sub-production: Π_{ir}^{KL} (X=KL) then denotes the zero-profit condition of value-added production in sector i and region r.

[18] The model code and data to replicate simulation results are readily available upon request.

Table B.3: Cost shares

θ_{ir}^{K}	Cost share of capital in value-added composite of sector *i* and region *r* ($i \notin FF$)
θ_{ir}^{ELE}	Cost share of electricity in energy composite in sector *i* in region *r* ($i \notin FF$)
θ_{jir}^{CGO}	Cost share of fuel *j* in the fuel composite of sector *i* in region *r*($i \notin FF$), (j $\in CGO$)
θ_{ir}^{KLE}	Cost share of value-added and energy in the KLEM aggregate in sector *i* and region *r* ($i \notin FF$)
θ_{ir}^{KL}	Cost share of value-added in the KLE aggregate in sector *i* and region *r* ($i \notin FF$)
θ_{jir}^{NE}	Cost share of non-energy input *j* in the non-energy aggregate in sector *i* and region *r* ($i \notin FF$)
θ_{ir}^{Q}	Cost share of natural resources in sector *i* and region *r* ($i \notin FF$)
θ_{Tir}^{FF}	Cost share of good *j* (*T=j*) or labor (*T=L*) or capital (*T=K*) in sector *i* and region *r* ($i \in FF$)
θ_{isr}^{M}	Cost share of imports of good *i* from region *s* to region *r*
θ_{ir}^{A}	Cost share of domestic variety in Armington good *i* of region *r*

Key: KLEM – value-added, energy and non-energy; KLE – value-added and energy

Table B.4: Elasticities

σ_{ir}^{KL}	Substitution between labor and capital in value-added composite	Okagawa and Ban (2008)
σ_{ir}^{ELE}	Substitution between electricity and the fuel composite	Narayanan and Steinbuks (2014)
σ_{ir}^{CGO}	Substitution between coal, gas and refined oil in the fuel composite	Narayanan and Steinbuks (2014)
σ_{ir}^{KLE}	Substitution between energy and value-added in production	Okagawa and Ban (2008)
σ_{ir}^{KLEM}	Substitution between material and the KLE composite in production	Okagawa and Ban (2008)
σ_{jir}^{NE}	Substitution between material inputs into material composite	Okagawa and Ban (2008)
σ_{ir}^{Q}	Substitution between natural resources and other inputs in fossil fuel production calibrated to exogenous supply elasticities μ_i: $\mu_{Coal} = 1;\ \mu_{Gas} = 0.5;\ \mu_{Crude Oil} = 0.5$	Graham et al. (1999), Krichene 2002):
σ_{ir}^{M}	Substitution between imports from different regions	Narayanan et al. (2012)
σ_{ir}^{A}	Substitution between the import aggregate and the domestic input	Narayanan et al. (2012)

Table B.5: Endowments and emissions coefficients

$\overline{L}_r$	Base-year aggregate labor endowment in region *r*
$\overline{K}_r$	Base-year aggregate capital endowment in region *r*
$\overline{Q}_{ir}$	Base-year endowment of natural resource *i* in region *r* ($i \in FF$)
$\overline{G}_r$	Base-year public good provision in region *r*
$\overline{I}_r$	Base-year investment demand in region *r*
$\overline{B}_r$	Base-year balance of payment deficit or surplus in region *r*
$\overline{CO2}_r$	CO_2 emission endowment for region *r*
$a_{jir}^{CO_2}$	CO_2 emissions coefficient for fuel j (coal, gas, refined oil) in sector *i* and region *r*

Table B.6: Key elasticities (see Table B.4 for notations and references)

	σ_{ir}^{KL}	σ_{ir}^{KLE}	σ_{jir}^{NE}	σ_{ir}^{KLEM}	σ_{ir}^{ELE}	σ_{ir}^{CGO}	σ_{ir}^{A}	σ_{ir}^{M}
Refined oil products	0.334	0.000	0.082	0.848	0.500	0.500	2.100	4.200
Electricity	0.460	0.256	0.391	0.000	0.500	0.500	2.800	5.600
Chemical, rubber, plastic products	0.334	0.000	0.082	0.848	0.500	0.500	3.300	6.600
Ferrous metals	0.220	0.644	0.253	1.173	0.500	0.500	2.950	5.900
Non-ferrous metals	0.358	0.411	0.191	0.306	0.500	0.500	4.200	8.400
Non-metallic minerals	0.358	0.411	0.191	0.306	0.500	0.500	2.900	5.800
Metal products	0.046	0.529	0.309	0.406	0.500	0.500	3.750	7.500
Minerals	0.358	0.411	0.191	0.306	0.500	0.500	0.900	1.800
Machinery and equipment	0.295	0.292	0.459	0.130	0.500	0.500	4.050	8.100
Transport equipment	0.144	0.519	1.087	0.548	0.500	0.500	4.300	8.600
Textiles	0.161	0.637	0.597	0.722	0.500	0.500	3.750	7.500
Plant-based fibres	0.023	0.516	0.000	0.392	0.500	0.500	2.500	5.000
Air transport	0.310	0.281	0.331	0.352	0.500	0.500	1.900	3.800
Water transport	0.310	0.281	0.331	0.352	0.500	0.500	1.900	3.800
Rest of industry and services	0.264	0.320	0.000	0.492	0.500	0.500	2.280	5.688

Zero-profit conditions

1. Production of goods except fossil fuels

Production of commodities other than primary fossil fuels ($i \notin FF$) is captured by four-level constant elasticity of substitution (CES) cost functions describing the price-dependent use of capital, labor, energy, and material in production. At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital, and labor subject to a CES. 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, a CES function captures capital and labor substitution possibilities within the value-added composite, and likewise the energy composite is a CES function of electricity and a fuel aggregate. At the fourth level, coal, gas, and (refined) oil enter the fuel aggregate at a CES.

The unit-profit function for the value-added composite is:

$$\prod_{ir}^{KL} = p_{ir}^{KL} - \left[\theta_{ir}^{K} v_r^{1-\sigma_{ir}^{KL}} + \left(1-\theta_{ir}^{K}\right) w_r^{1-\sigma_{ir}^{KL}}\right]^{\frac{1}{1-\sigma_{ir}^{KL}}} \leq 0 \tag{4}$$

The unit-profit function for the energy composite is:

$$\prod_{ir}^{E} = p_{ir}^{E} - \left[\theta_{ir}^{ELE} {p_{ELE,r}^{A}}^{1-\sigma_{ir}^{ELE}} + \left(1-\theta_{ir}^{ELE}\right)\left(\sum_{j\in CGO} \theta_{jir}^{CGO}\left(p_{jr}^{A} + p_r^{CO_2} a_{jir}^{CO_2}\right)^{1-\sigma_{ir}^{CGO}}\right)^{\frac{1-\sigma_{ir}^{ELE}}{1-\sigma_{ir}^{CGO}}}\right]^{\frac{1}{1-\sigma_{ir}^{ELE}}} \leq 0 \tag{5}$$

The value-added composite and the energy composite enter the unit-profit function at the top level together with a CES composite of non-energy (material) intermediate input:[19]

$$\prod_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{KLE}\left[\theta_{ir}^{KL} {p_{ir}^{KL}}^{1-\sigma_{ir}^{KLE}} + \left(1-\theta_{ir}^{KL}\right) {p_{ir}^{E}}^{1-\sigma_{ir}^{KLE}}\right]^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{KLE}}} + \left(1-\theta_{ir}^{KLE}\right)\left(\sum_{j\notin NE} \theta_{jir}^{NE} {p_{jr}^{A}}^{1-\sigma_{ir}^{NE}}\right)^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{NE}}}\right]^{\frac{1}{1-\sigma_{ir}^{KLEM}}} \leq 0 \tag{6}$$

2. Production of fossil fuels

In the production of primary fossil fuels ($i \in FF$) 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 CES. The unit-profit function for primary fossil fuel production is:

$$\prod_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{Q} q_{ir}^{1-\sigma_{ir}^{Q}} + \left(1-\theta_{ir}^{Q}\right)\left(\theta_{Lir}^{FF} w_r + \theta_{Kir}^{FF} v_r + \sum_{j} \theta_{jir}^{FF}\left(p_{ir}^{A} + p_r^{CO_2} a_{jir}^{CO_2}\right)\right)^{1-\sigma_{ir}^{Q}}\right]^{\frac{1}{1-\sigma_{ir}^{Q}}} \leq 0 \tag{7}$$

3. Imports aggregate across regions

Imports of the same variety from different regions enter the import composite subject to a CES. The unit-profit function for the import composite is:

[19] Note that the specification of the unit-profit function also includes the production of final demand components for private consumption (*i=C*), public consumption (*i=G*), and composite investment (*i=I*). In these cases, entries in the value-added nest are zero.

$$\prod_{ir}^{M} = p_{ir}^{M} - \left[\sum_{s} \theta_{isr}^{M} p_{is}^{Y\,1-\sigma_{ir}^{M}}\right]^{\frac{1}{1-\sigma_{ir}^{M}}} \leq 0 \tag{8}$$

4. Armington aggregate

All goods used on the domestic market in intermediate and final demand correspond to a (Armington) CES composite that combines the domestically produced good and a composite of imported goods of the same variety. The unit-profit function for the Armington aggregate is:

$$\prod_{ir}^{A} = p_{ir}^{A} - \left[\theta_{ir}^{A} p_{ir}^{Y\,1-\sigma_{ir}^{A}} + \left(1-\theta_{ir}^{A}\right) p_{ir}^{M\,1-\sigma_{ir}^{A}}\right]^{\frac{1}{1-\sigma_{ir}^{A}}} \leq 0 \tag{9}$$

Market-clearance conditions

5. Labor

Labor is in fixed supply. The market-clearance condition for labor is:

$$\overline{L}_{r} \geq \sum_{i} Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial w_{r}} \tag{10}$$

6. Capital

Capital is in fixed supply. The market-clearance condition for capital is:

$$\overline{K}_{r} \geq \sum_{i} Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial v_{r}} \tag{11}$$

7. Natural resources

Natural resources for the production of primary fossil fuels ($i \in FF$) are in fixed supply. The market-clearance condition for the natural resource is:

$$\overline{Q}_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial q_{ir}} \tag{12}$$

8. Energy composite

The market-clearance condition for the energy composite is:

$$E_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{E}} \tag{13}$$

9. Value-added composite

The market-clearance condition for the value-added composite is:

$$KL_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{KL}} \tag{14}$$

10. Output

Domestic output enters Armington demand and import demand by other regions. The market-clearance condition for domestic output is:

$$Y_{ir} \geq \sum_{j} A_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ir}^{Y}} + \sum_{s} M_{is} \frac{\partial \Pi_{js}^{Y}}{\partial p_{ir}^{Y}} \tag{15}$$

11. Armington aggregate

Armington supply enters all intermediate and final demands. The market-clearance condition for domestic output is:

$$A_{ir} \geq \sum_{j} Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ir}^{A}} \tag{16}$$

12. Import aggregate

Import supply enters Armington demand. The market-clearance condition for the import composite is:

$$M_{ir} \geq A_{ir} \frac{\partial \Pi_{ir}^{A}}{\partial p_{ir}^{M}} \tag{17}$$

13. Public consumption

Production of the public good composite (i=G) covers fixed government demand. The market-clearance condition for the public good composite is:

$$Y_{Gr} \geq \overline{G}_{r} \tag{18}$$

14. Investment

Production of the investment good composite (i=I) covers fixed investment demand. The market-clearance condition for composite investment is:

$$Y_{Ir} \geq \overline{I}_{r} \tag{19}$$

15. Private consumption

Production of the composite private consumption good (i=C) covers private consumption demand. The market-clearance condition for composite private consumption is:

$$Y_{Cr} \geq \frac{INC_r}{p_{Cr}^Y} \tag{20}$$

16. Carbon emissions

A fixed supply of CO_2 emissions limits demand for CO_2 emissions. The market-clearance condition for CO_2 emissions is:

$$\overline{CO2}_r \geq \sum_j \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial (p_{jr}^A + a_{jir}^{CO_2} p_r^{CO_2})} a_{jir}^{CO_2} \tag{21}$$

Income-balance conditions

17. Income balance

Net income of the representative agent consists of factor income and revenues from CO_2 emission regulation adjusted for expenditure to finance fixed government and investment demand and the base-year balance of payment. The income-balance condition for the representative agent is:

$$INC_r = w_r \overline{L}_r + v_r \overline{K}_r + \sum_{i \in FF} q_{ir} \overline{Q}_{ir} + p_r^{CO_2} \overline{CO2}_r - p_{Ir}^Y \overline{Y}_{Ir} - p_{Gr}^Y \overline{Y}_{Gr} + \overline{B}_r \tag{22}$$

Figure B.1: Domestic production except for fossil fuels

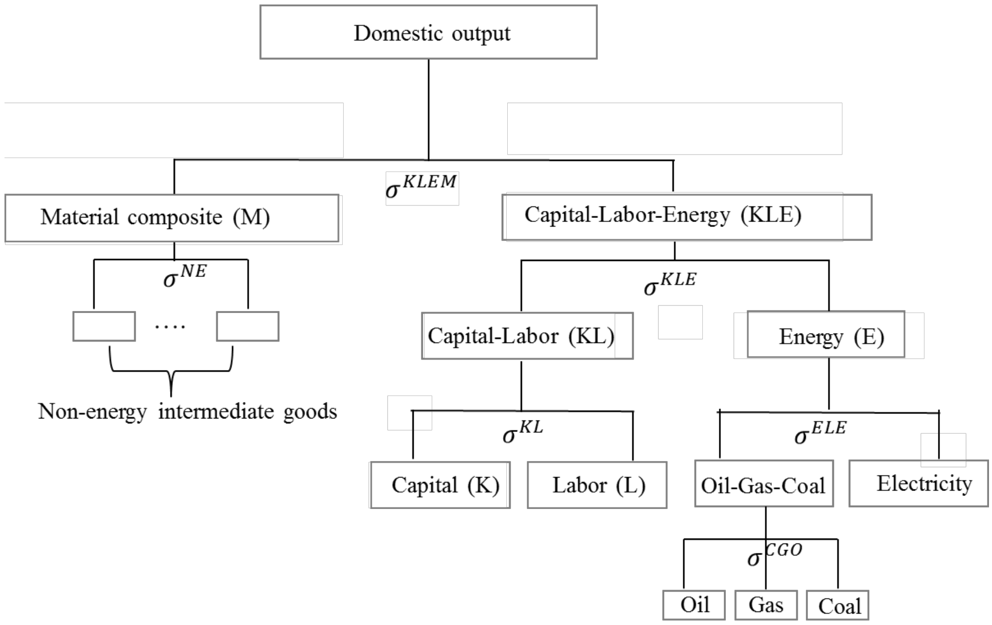

Figure B.2: Domestic fossil fuel production

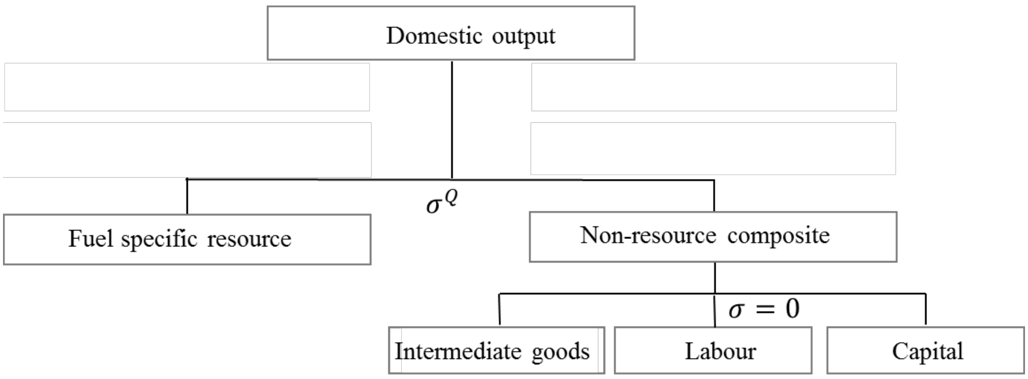

Figure B.3: Armington production