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Alternative Designs for Tariffs on Embodied Carbon:

A Global Cost-Effectiveness Analysis

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Alternative Designs for Tariffs on Embodied Carbon: A Global Cost-Effectiveness Analysis

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Abstract: In the absence of effective world-wide cooperation to curb global warming, import tariffs on embodied carbon have been proposed as a potential supplement to unilateral emissions pricing. We consider alternative designs for such tariffs, and analyze their effects on global welfare within a multi-region, multi-sector computable general equilibrium (CGE) model of global trade and energy. Our analysis suggests that the most cost-efficient policy could be region-specific tariffs on all products, based on direct plus electricity emissions. In the end, however, the potential cost savings through carbon tariffs must be weighed against the administrative costs as well as legal issues and political considerations.

Key Words: carbon leakage, embodied carbon, border tariffs

JEL Classification Numbers: Q43, Q54, H2, D61

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1. Introduction

In the absence of effective world-wide cooperation to curb global warming, some economies have introduced national or regional climate policies. However, as the climate problem is global, unilateral action potentially leads to carbon leakage, i.e., the relocation of emissions to countries with no or more lenient climate regulations. Theory suggests that border measures, like import tariffs and export subsidies on the carbon embodied in trade, can be used as a second-best instrument to improve the economic efficiency of unilateral emissions pricing policies (Markusen, 1975; Hoel, 1996; Gros, 2009).

However, desirability and feasibility of border measures depend on legal, practical and political considerations that must be balanced against the scope for efficiency gains. In this paper we use a computable general equilibrium (CGE) model of the world economy to quantify the global economic impacts of alternative tariff systems on embodied carbon (so-called *carbon tariffs*) imposed by a coalition of countries pursuing unilateral climate policy. In our central case simulations, we consider Europe as the coalition. Two further coalitions are also analyzed, one including all Annex-1 regions (except for Russia) and an even larger one adding China.

The carbon tariffs are varied along three dimensions:

(i) embodied carbon coverage: what emissions embodied in the production of imported goods are covered (only direct emissions, direct emissions plus indirect emissions embodied in electricity input, or total input-output embodied emissions),

(ii) sector coverage: which goods are subject to tariffs (only the energy-intensive and trade-exposed sectors or all sectors),

(iii) tariff rate differentiation: whether the carbon content basis is country- and sector-specific or only sector-specific (in which case embodied carbon averages are used of either the coalition regions or the non-coalition regions).

Economic intuition suggests that the most efficient system embodies the total input-output-corrected carbon content of all imported items. On the other hand such a comprehensive and detailed tariff design might also be the most expensive in terms of legal, practical and political obstacles. In our impact assessment we combine the main elements of possible tariff structures in a systematic way, quantify the efficiency costs of departing from the most comprehensive and detailed systems, and discuss the trade-offs involved. In this vein, quantitative analysis of potential global efficiency losses from more pragmatic carbon tariff designs can provide useful policy guidance.

Previous analyses of carbon tariff systems vary with respect to the choices along the dimensions presented above, but few shed light on the relative performance of different choices. Structural path analyses (see, e.g., Babiker et al., 1997; Peters and Hertwich, 2008) seek to grasp the carbon content of traded goods from cradle to grave while the bulk of economic analysis assessing embodied carbon tariffs focuses on direct emissions from fossil fuel inputs and indirect emissions from electricity use only (e.g., Winchester, 2011). The choices of coverage of traded goods likewise tend to vary from analysis to analysis; however, to our knowledge different degrees of coverage have not been compared systematically with respect to efficiency outcomes. Kuik and Hofkes (2010) compare two different carbon content bases for the tariff calculation, one where the (direct) average carbon content of non-abating regions is used and one where that of the abating regions is used. They show that this choice is of vital importance, as the abating regions have significantly lower carbon content in most relevant policy scenarios.

Our numerical results largely confirm the qualitative insights from basic second-best reasoning. Region-specific tariffs are in most cases more cost-efficient for the world than uniform tariffs. Moreover, in most cases it is efficiency improving to impose carbon tariffs on all products, not just energy-intensive and trade-exposed products. Furthermore, tariffs based on direct emissions are inferior to tariffs that also account for emissions from electricity. However, irrespective of coalition size, we find that the most cost-efficient policy imposes tariffs on all products based on direct and electricity emissions only.[1] The result illustrates the difficulty of finding metrics of the carbon content that are both realistic and well-targeted. The total embodied carbon measure we apply still leaves out numerous indirect emissions effects of the tariffs, which can increase leakage to *non-coalition* countries. Furthermore, total embodiment tends to price some emissions in the coalition twice, as parts of the embodied carbon in imports originate from intermediates already taxed and exported from coalition to non-coalition countries. In addition, the CGE model incorporates numerous existing tax and subsidy interventions that could give rise to distortions and thereby affect the welfare effects of the tariffs.

Our numerical simulations reveal substantial differences in global cost savings across alternative tariff designs. In our central case with Europe as the coalition, the global efficiency cost savings of imposing carbon tariffs vis-à-vis emissions pricing stand-alone range between 2% and 16%. These potential savings indicate the cost ceiling of legal, political and administrative obstacles for the system to be worthwhile. Estimates reviewed by Evans (2003) indicate that taxation administration is not very costly. Hence, the hardly quantifiable legal and political costs are left as the main objections against reaping the efficiency gains from carbon tariffs.

The remainder of the paper is structured as follows: Section 2 presents the ideal tariff system from a strictly economic efficiency point of view. These conclusions are challenged when the perspective is broadened, and some practicability issues are scrutinised in Section 3. Section 4 describes our numerical method for assessment and the underlying data. Section 5 lays out the policy scenarios, while Section 6 presents our numerical simulation results. Section 7 concludes.

2. Import tariffs – the basic theoretical reasoning

Unilateral policy targeted towards greenhouse gas emissions involves the risk of so-called carbon leakage. The issue of using trade policy measures to curb carbon leakage from countries that have carbon policies was raised already by Markusen (1975) in a model for two countries and two goods, and further developed by Hoel (1996) in a more general *n*-country, *n*-good model. Both authors show that an optimal unilateral policy is to combine a uniform carbon tax (or auctioned emission quotas) with tariffs on carbon-intensive imports and subsidies on carbon-intensive exports. The import tariffs should mimic the domestic emission price on the carbon content of all goods that are not regulated in the countries of origin.

Hoel (1996) maximizes domestic (or coalition) welfare with respect to a domestic (or coalition) carbon tax and a system of import tariffs (and export subsidies), where welfare consists of the coalition's utility of consumption minus the environmental costs of global emissions. He finds that the optimal tariffs consist of two terms. The first is the *terms of trade effect*: A tariff reduces imports, which in general reduces the import price and improves terms of trade (alike optimal tariffs in the trade policy literature). The second term is the *foreign emission effect*: A tariff reduces emissions abroad by contracting foreign supply. In this study we evaluate the efficiency of different carbon metrics with respect to *global* costs of achieving a global emissions target through unilateral action of a coalition. In this case the strategic terms of trade effect disappears,[2] and the optimal tariff for all traded goods t_j can be expressed by the foreign emission effect (Hoel, 1996, eq. 11):

$$t_j = \theta e_j \,. \qquad (1)$$

θ is the coalition's (uniform) carbon tax and e_j is the marginal effect on foreign emissions of changes in net imports of j, m_j. The vector of foreign emissions, e, depends on net imports via the effects of net imports on the vector of international prices, p:

$$e = e(m) = f(p(m)) \,. \qquad (2)$$

The marginal effect on e of a change in m_j is

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[1] When tariffs are imposed only on energy-intensive and trade-exposed products, using the total embodied carbon content turns out more cost efficient than using the direct and electricity emissions, only.

[2] Gros (2009) maximises global welfare and finds that the optimal tariff depends on the coalition's carbon tax and a foreign emission effect as in Hoel (1996).

(3) $$e_j = \sum_i \frac{\partial f}{\partial p_i} \frac{\partial p_i}{\partial m_j}.$$

The foreign emission effect reflects the marginal change in *all* foreign emissions of increased net imports, accounting for all market adjustments taking place and the respective emission intensities involved. The optimal tariff will be higher the higher is the carbon tax in the coalition and the larger is the reduction in foreign emissions for a given (net) import change. The latter depends on how strongly tariffs affect international prices and thereby change supply and demand in the rest of the world.

Imposing updated firm- or even sector-specific import tariffs on total embodied carbon across all traded goods is very data demanding and probably impeded by legal, practical and political constraints, some of which we will discuss in the next section.

3. The feasibility of tariffs on embodied carbon

3.1. Legality

A major concern is how carbon tariffs would comply with the WTO law. Two central GATT (General Agreement on Tariffs and Trade) rules that can be violated by carbon tariffs include (i) the most-favoured nation principle (Article I), which ensures that imports from all parties of WTO be treated similarly in accordance with the most favoured, and (ii) the national treatment principle (Article III), which likewise prevents discrimination between similar imported and domestically produced products.

Crucial for the considerations on discrimination is the question whether GATT rules can consider products as dissimilar if their characteristics are similar, and only their production processes and methods differ. If so, the challenge remains of what is sufficient documentation of the production methods. This brings up the complex issue of carbon-content metrics. The metrics should give relevant information about the production methods of the single products facing border measures, without risking discrimination. At the same time, too complex and costly bureaucracy on the border can also be a case of violation of the articles. Another criterion for non-discrimination is that the border treatment of imports accounts for the carbon-restrictiveness of measures in the countries of origin. Similar treatment implies that only the restrictiveness gap should be taxed. It is a major challenge to compare different designs of carbon emission regulations across countries and quantify gaps in restrictiveness on a bilateral basis.

Possible violations of Articles I and III, including the question of whether measures can be based on production methods, can be overcome by resorting to Article XX of GATT. Production method bases have been accepted in previous disputes (Pauwelyn, 2007). GATT’s Article XX has two clauses that can justify exceptions in the case of carbon tariffs, one on ”*necessary (measures) to protect human,* *animal and plant life or health"* and one on "(*measures) relating the conservation of exhaustible natural resources"*.

The first clause involves an assessment of the necessity of the carbon tariff measure. Assessing the necessity includes balancing the ends in the clause with other concerns, including the free trade objectives of WTO. Previous disputes have put much emphasis on preventing measures from being disguised trade restrictions or arbitrarily discriminatory. Another important concern has been fairness, which in earlier cases has led to favourable treatment of less developed countries (Holzer, 2010). Necessity considerations also relate to whether the measure empirically can help reach the ends and can do so sufficiently more effectively than other, less trade-restrictive measures. In previous cases, negotiations among the partners have been put forward as a prerequisite for trade-restrictive measures to be justifiable. The question remains whether the UNFCCC-framed negotiations fulfil this requirement.

The second clause can apply only if the climate can be regarded as an exhaustible natural resource. It also involves the assessment of means and ends. Previous panels have ruled clean air as an exhaustible natural resource, and climate can probably be covered by the same assessment. Besides, climate change affects other natural resources. The long-term nature of climate change can pave the way for a less restrictive interpretation of the observable evidence needed on the relationship between the means and the ends.

As carbon tariffs are likely to run counter some way or other with the current WTO rules, and as litigations need to be instituted in each case – a procedure which is resource-consuming and short-sighted – more permanent and practical solutions have been suggested. Changing WTO law involves complex procedures. Hoerner and Muller (1996) rather suggest an institution established under the UNFCCC umbrella, which overrides WTO law on trade-related climate measures. It could only be binding for those WTO members that are parties in the UNFCCC. However, whether negotiations on carbon tariffs take place within the UNFCCC or WTO consensus seems to be far-fetched, given the developing countries' opposition to greenhouse gas mitigation burdens and their concern for market access.

A more feasible solution would be to grant a waiver to the WTO. That would need approval by three fourth of the members and apply for a limited time, only (Holzer, 2010). Another approach would be to enter separate multilateral or bilateral carbon tariffs agreements with parts of the WTO members (Hufbauer et al, 2009; Bacchus, 2010). These would, however, bind only members who sign and, thus, involve free-rider problems because of the most-favoured-nation principle of the WTO.

3.2. Practicability

Irrespective of legal problems, the formulation and implementation of rules and procedures for calculating the carbon content of imports constitute complex tasks. Ismer and Neuhoff (2007) suggest to use the carbon content of the best available technology and only include the main basic materials together with electricity as the basis of the tariff calculation. Besides feasibility concerns, this approach would keep the interpretation of non-discrimination in conventional product terms instead of the more troublesome terms of production methods. By law, such a system must allow for lowering tariffs if the foreign producers can document lower emissions. However, the incentive for technology improvement under such a tariff design would be weak. On the other hand, a more accurate approach seems infeasible. If all producers were to demonstrate their true carbon content on the border, the controls would, by law, have to be carried out by the exporting jurisdiction. This would weaken the enforcement power; besides, it would be considerably more costly and involve the difficult production-method interpretation of similarity.

The realistic solutions discussed in the literature will provide hardly any incentive at the firm level to search for less carbon-intensive production methods and deliveries of intermediates. Though input-output information is prepared for most economies, these data are, overall, too aggregate and too infrequently updated for this purpose (Andrew et al., 2009). Even in the most detailed structural path analyses (e.g., Peters and Hertwich, 2008) there are large uncertainties due to data inaccuracies, approximations, and manipulations. Ismer and Neuhoff (2007) argue that bottom-up approaches are more appropriate. For selected businesses such data could be collected on the border. A resembling system exists for food products in many countries.[3]

To our knowledge, no calculations of costs associated with the governments' administration and firms' compliance of alternative carbon tariff designs have been undertaken so far. Corresponding estimates provided for other forms of taxation based on product information indicate compliance costs borne by informants/firms of between 2 and 16% and public administration costs of around 1 % of the tax revenue (Evans, 2003). There are clear indications of regressivity in the surveyed material, i.e. comprehensive systems have economies of scale. Uniform systems are less costly as are operations conducted in more developed economies. As the private compliance costs are relatively high compared to public administration costs, it is reasonable to expect that less precise and less complex systems based on centralised information from national accounts and other official sources will be significantly cheaper than systems based on information collected from traders on the border.

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[3] Prior to the Uruguay round the EU, for instance, applied variable import levies to ensure that the food industry was compensated for cost variations stemming from input prices of agricultural products. Hence, for the border taxes to give the desired effects and incentives, information on the input structure of the production abroad was needed. In principle, also indirect inputs of agricultural products justified compensatory import levies.

3.3. Political considerations

One major political concern that triggered the debate on border measures is the issue of competitiveness of energy-intensive firms in regulating countries. Besides national political (economy) considerations, it can be argued that border measures can incentivise non-coalition countries to commit to and sign international agreements on mitigation. However, even though individual firms or industries might be hit hard, the non-coalition economies as a whole may be little affected as long as exports subjected to tariffs constitute only a small share of domestic production or re-routing of export to non-abating trading partners is relatively easy. The potential for efficiency gains has to be weighed against possible adverse effects such as legal disputes or the deterioration of the political climate for international cooperation. Retaliation from countries like China is also a possible strategic response that must be taken into account. Nothing can prevent non-coalition states from introducing border measures based on their own climate policy principles, e.g. on emissions-per-capita terms. The distributional effects of the tariff system, *per se*, might trigger trade disputes, even in cases where the combined outcome of the carbon tax and tariff systems is still positive for foreign stakeholders. Besides, the distributional impact is an issue in itself, given that the most probable coalitions tend to consist of relatively wealthy countries, while those threatened by carbon tariffs tend to be emerging or less developed economies. The latter on average are net exporters of embodied carbon to industrialized countries and will most likely face terms-of-trade losses from the imposition of carbon tariffs (Böhringer et al., 2011).

4. Model and data

4.1. Computable general equilibrium model of the world economy

For our quantitative economic impact analysis of alternative carbon tariff designs we use a generic multi-region, multi-sector CGE model of global trade and energy established for the analysis of greenhouse gas emission control strategies (see, e.g., Böhringer et al., 2010). CGE models build upon general equilibrium theory that combines behavioural assumptions on rational economic agents with the analysis of equilibrium conditions. They provide 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 in a setting with various, existing public interventions. The simultaneous explanation of the origin and spending of the agents' income makes it possible to address both economy-wide efficiency as well as distributional impacts of policy reforms.

Our model features a representative agent in each region that receives income from three primary factors: labour, capital, and fossil-fuel resources. Labour 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, labour, energy and materials. At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital, and labour 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 labour and capital. At the third level, capital and labour substitution possibilities within the value-added composite are captured by a CES function whereas different energy inputs (coal, gas, oil, and electricity) enter the energy composite subject to a constant elasticity of substitution. In the production of fossil fuels, all inputs, except for the sector-specific fossil fuel resource, are aggregated in fixed proportions. This aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution.

Final consumption demand in each region is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment (i.e., a given demand for savings) and exogenous government provision of public goods and services. Total income of the representative household consists of net factor income and tax revenues. Consumption demand of the representative agent is given as a CES composite that combines consumption of composite energy and an aggregate of other (non-energy) consumption goods. Substitution patterns within the energy bundle as well as within the non-energy composite are reflected by 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 (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities).

4.2. Data

Our CGE analysis of embodied carbon tariffs is based on the GTAP 7.1 dataset 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 (Badri Narayanan and Walmsley, 2008). GTAP can be flexibly aggregated towards a composite dataset that accounts for the specific requirements of the policy issue under investigation, in our case the global efficiency impacts of alternative carbon tariff schemes. The composite dataset in use includes all major primary and secondary energy carriers: coal, crude oil, natural gas, refined oil products, and electricity. This disaggregation is essential in order to distinguish energy goods by CO_2 intensity and the degree of substitutability. In addition, we separate the main emission-intensive and trade-exposed sectors: chemical products, non-metallic minerals, iron and steel products, and non-ferrous metals, as they will be the most affected by emission control policies and the prime candidates for embodied carbon tariffs. Regarding regional coverage, we explicitly include all major industrialized and developing countries to capture international market responses to unilateral emission regulation. Table 1 summarizes the sectors (commodities) and regions present in our actual impact analysis of alternative carbon tariff schemes.

Table 1: Model sectors and regions

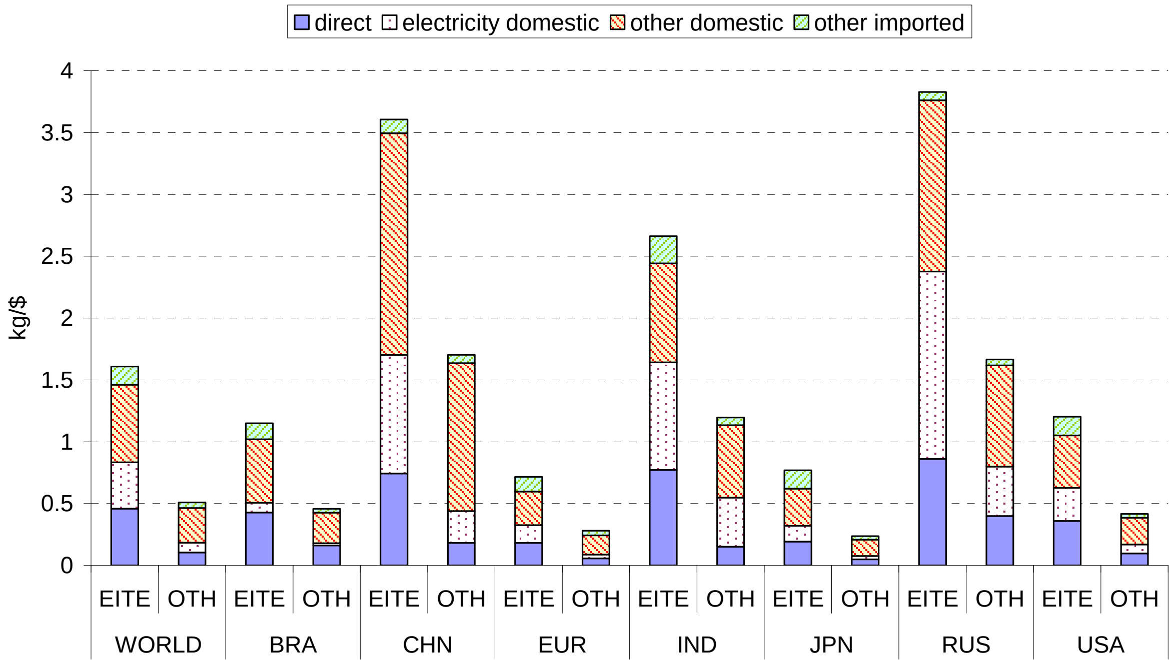
Sectors and commodities	*Countries and regions*
Energy	*Annex 1 (industrialized) regions*
Coal (COL)	Europe – EU-27 plus EFTA (EUR)
Crude oil (CRU)	United States of America (USA)
Natural gas (GAS)	Japan (JPN)
Refined oil products (OIL)*	Canada (CAN)
Electricity (ELE)	Australia and New Zealand (ANZ)
	Russia (RUS)
*Emission-intensive & trade-exposed sectors**	Remaining Annex 1 (RA1)
Chemical products (CRP)	
Non-metallic minerals (NMM)	*Non-Annex1 (developing) regions*
Iron and steel industry (I_S)	Energy exporting countries excl. Mexico (EEX)
Non-ferrous metals (NFM)	Brazil (BRA)
	Mexico (MEX)
*Transport sectors***	China (CHN)
Air transport (ATP)	India (IND)
Water transport (WTP)	Other middle income countries (MIC)
Other transport (OTP)	Other low income countries (LIC)
*Other industries and services***	
Fishery (FSH)	
Agriculture (AGR)	
Paper–pulp–print (PPP)	
All other manufactures and services (AOG)	

*Included in the composite *Energy-intensive, trade-exposed industries* (EITE). ** Included in the composite *Other, non-energy sectors* (OTH).

For model parameterization we follow the standard calibration procedure in applied general equilibrium analysis: the base-year input-output data determines the free parameters of the functional forms (cost and expenditure functions) such that the economic flows represented in the data are consistent with the optimizing behaviour of the model agents. 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 (Armington elasticities) and substitution possibilities in production (between primary factor inputs) are directly provided by the GTAP database. The elasticities of substitution in fossil fuel sectors are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham et al., 1999; Krichene, 2002).

For the design of alternative carbon tariff schemes we need to calculate the different components adding up to the total carbon content embodied in goods. In addition to the direct carbon emissions stemming from the combustion of fossil fuel inputs there are indirect carbon emissions associated with intermediate non-fossil inputs which may be further decomposed into indirect carbon from electricity inputs and indirect carbon from all other (non-electric and non-fossil) inputs. Following Böhringer et al. (2011) we apply simple multi-region input-output calculus on the GTAP dataset to derive the total carbon content of production across sectors and regions. Figure 1 compares cross-country differences in embodied carbon for two production segments of the economy: the composites of *Emission-intensive, trade-exposed* (EITE) sectors, and of *Other, non-energy* (OTH) sectors. We can furthermore distinguish how indirect carbon emissions split up between domestically produced inputs and imported inputs. Our decomposition of embodied carbon gives insights into the relative importance of embodied carbon for imports of EITE and OTH goods (note that grid-based electricity is hardly traded across larger geopolitical regions, and thus embodied carbon of imported electricity is omitted from Figure 1).

Figure 1. Embodied carbon in selected regions[*] for the EITE and OTH goods composites

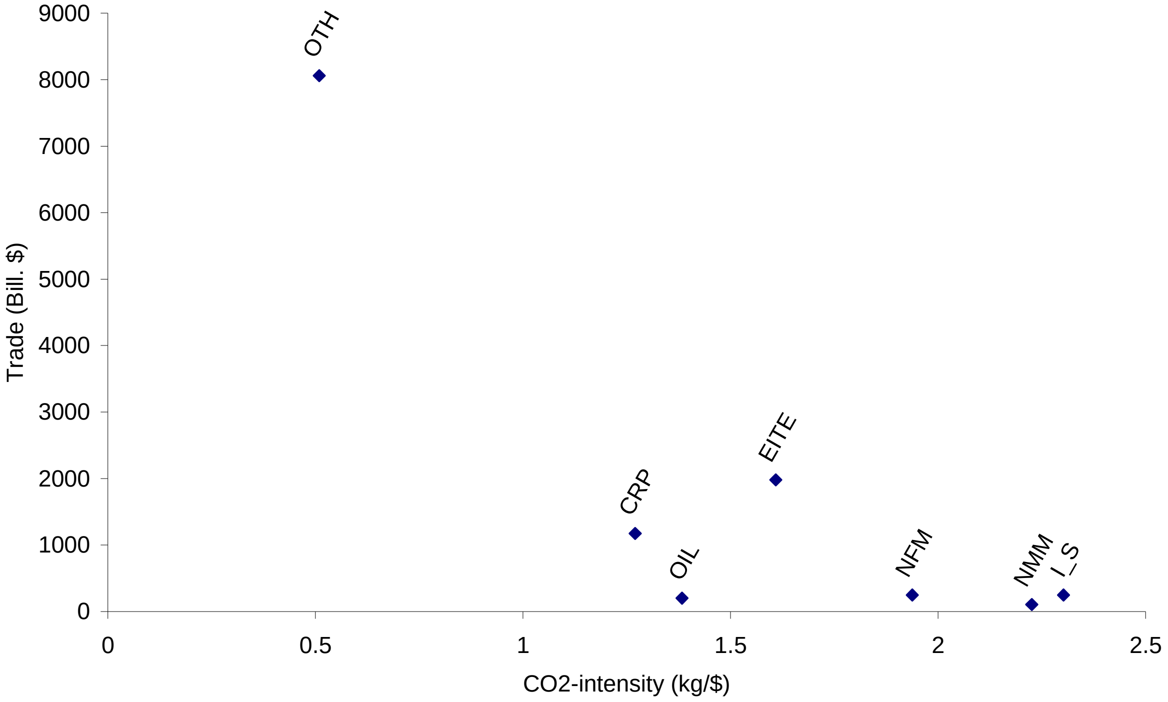


[*] For the abbreviations of regions, see Table 1.

We see that emission intensities vary drastically across regions. Non-OECD regions are generally more emission-intensive than OECD regions, with Brazil being an important exception (due to the massive use of hydropower and biofuels). As expected, embodied carbon in EITE sectors is much higher than that in OTH sectors within each region. Across regions, it is remarkable that the embodied carbon content in OTH sectors of larger non-OECD regions such as China or Russia is higher than the embodied carbon of EITE sectors in most OECD regions including Europe, Japan and USA. Moreover, direct emissions constitute only a modest share of total embodied carbon, both for EITE and OTH products. Indirect emissions from electricity use are on average of approximately the same size as direct emissions, whereas other indirect emissions account for the largest share in most countries. This is particularly the case for OTH goods.

The input-output calculations provide additional information on the carbon embodied in trade across regions. Figure 2 reports global trade values and CO_2-intensities of the two product categories EITE and OTH, as well as the individual EITE sectors.

Figure 2. Global trade value and average CO_2 intensity of selected sectors[*]



* For abbreviations of goods, see Table 1.

The scatter plot shows that the value of global trade in OTH products is several times higher than global trade in all EITE products, together. The emissions intensities on the other hand are lower. Accounting for these differences in trade volume and CO_2 intensity, global trade in carbon is about 30% higher for the OTH sector group than for the EITE group. This observation is important when we consider import tariffs for all sectors, not only for EITE sectors. Among the EITE sectors, chemical products account for the largest share of traded carbon worldwide.

5. Scenarios

We investigate combinations of tariff design variants along the following dimensions:[4]

(i) Embodied carbon coverage:

- DIR: the tariff is levied on direct (fuel) emissions, only.
- INDIR: the tariff is levied on direct (fuel) emissions plus indirect emissions from electricity.
- TOTAL: the tariff is levied on the total embodied carbon.[5]

(ii) Sector coverage:

- EITE: only emission-intensive and trade-exposed sectors are subject to import tariffs.

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[4] The tariffs are always calculated using base-year emission intensities provided by the GTAP dataset for 2004.

- ALL: all sectors are included in the tariff regime.

(iii) Tariff rate differentiation:[6]

- DOMEST: Uniform embodied carbon tariffs are applied to all unregulated countries, based on the average carbon content of the abating coalition.
- FOREIGN: Uniform embodied carbon tariffs are applied to all unregulated countries, based on the average carbon content of the non-coalition (importing) countries.
- REGION: Tariffs are applied specific for each exporting country/region in the model, based on their carbon content.

The scenarios seek to operationalize systems with different emphasis on the economic, legal, political, and practical concerns discussed above. For all the three dimensions (i) to (iii) high coverage and detail will serve efficiency but at the expense of public administration costs. All data used to calculate carbon contents are publicly available from national accounts and other official sources, so that private compliance costs can be disregarded. Legal and political cost implications of detailed systems are less obvious. When *(i) embodied carbon coverage* is high, the legal risk of generating bureaucracy on the border, along with the political risk of trade wars, will be high (because tariffs rise). On the other hand, higher tariffs would be more politically effective, both as coercion tactics to join the coalition and as means to satisfy domestic industry lobbyists. A complete versus a partial *(ii) sector coverage* also has ambiguous political cost implications; while the risk of provoking resistance becomes more widespread, it would avoid the politically delicate task of selecting some sectors. Increasing *(iii) tariff rate differentiation* can either raise or reduce legal costs: it increases border bureaucracy but lowers the risk of illegal, arbitrary discrimination of firms. Low tariff rates would, however, diminish this risk. Legally, using the probably relatively low carbon content of the abating coalition is thus a good alternative to high differentiation, though with the political implications of low tariff rates mentioned above.

We assess the resulting 18 combinations of alternative tariff designs for three different coalition sizes: the case in which Europe goes ahead with unilateral action (EU), the case where other Annex-1 regions except for Russia join an abatement coalition with the EU (A1xR) and finally the case in which China enters the A1 coalition (A1xR_CHN). In total, this leaves us with 54 tariff scenarios. For the sake of brevity and transparency, our results discussion focuses on those scenarios where only Europe adopts an active climate policy and imposes carbon tariffs on the EITE sectors. Yet, we will also briefly refer to the main findings with bigger coalitions and with carbon tariffs on all products.

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[5] Including embodied carbon in imports to the exporting country may imply double regulation of emissions in coalition countries when these emissions come from producing intermediate goods that are exported to non-coalition countries.

[6] Tariffs are sector-specific in all the sub-variants considered here.

The economic impacts of alternative tariff schemes are compared with a reference policy (*ref*) where unilaterally abating regions abstain from the imposition of tariffs and just apply domestic emissions pricing.[7] In order to provide a meaningful cost-effectiveness analysis, global emissions must be kept constant across all policy simulations (for a given size of the abatement coalition). The global emissions level is defined as the sum of the emissions cap adopted by unilaterally abating regions and base-year, business-as-usual (BaU) emissions of unregulated regions. In our central case simulations we assume a unilateral cap at 80 % of the abating regions' BaU emissions.[8]

6. Results

6.1. Carbon leakage and carbon prices

Before discussing the efficiency effects of the different tariff designs, it is instructive to examine how they affect carbon leakage and carbon prices. The leakage effects – depicted in Figure 3 for the cases with EU climate policies – are consistent with our previous theoretical discussion: Leakage declines as more embodied emissions are included, and is lowest when tariffs are country-specific and thus more accurate. Whereas the leakage rate is 17% in the reference scenario (i.e., unilateral emissions pricing stand-alone without carbon tariffs), the leakage rate falls to 14%, 11% and 8% in the scenarios with region-specific tariffs on EITE products (DIR, INDIR, TOTAL).[9] With uniform tariffs based on total embodied carbon in the EU, the leakage rates are slightly closer to the reference leakage rate than to the leakage rates with region-specific tariffs. On the other hand, if the uniform tariffs are based on non-EU emissions, the leakage rates are closer to the non-uniform rates.

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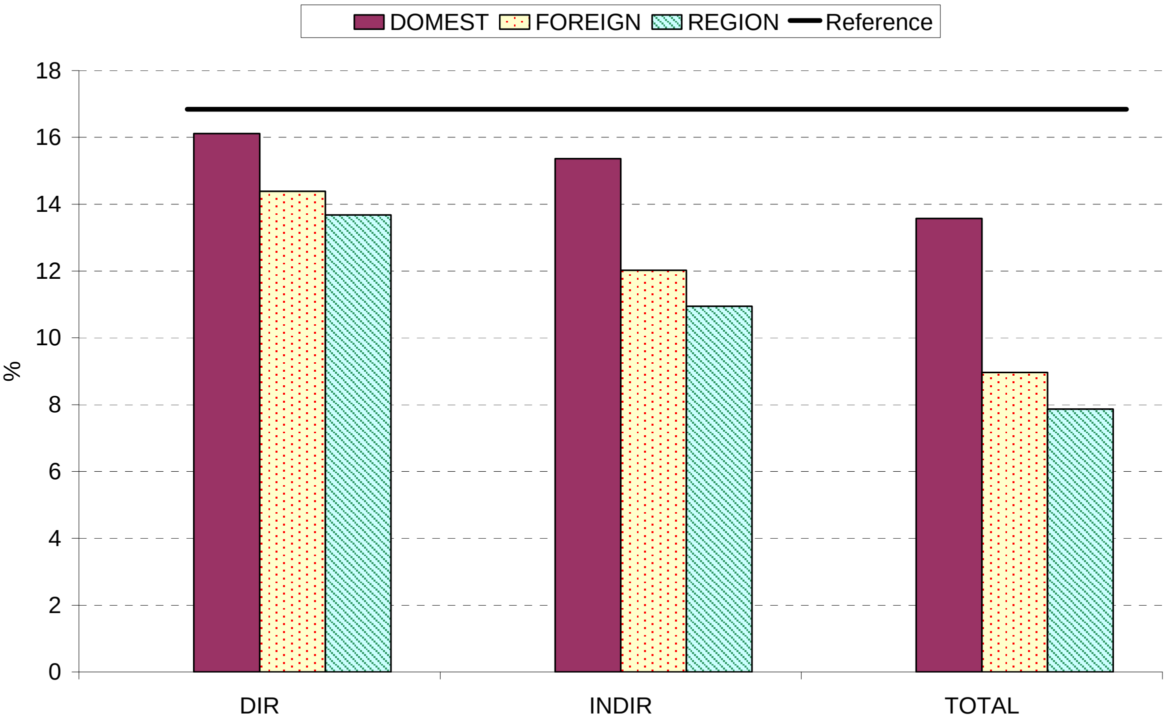
[7] We assume that emissions are reduced efficiently within the abatement coalition through the implementation of a regional emissions trading system.

[8] The global emission constraint requires that the initial emission cap of the abating region is scaled endogenously to "compensate" for emission leakage.

[9] The leakage rate is conventionally measured as the emission increase in non-regulated countries over the emission reduction in regulated countries.

Figure 3. Carbon leakage rates (%)[*] with EU coalition under alternative tariffs on EITE products



* For the definition of the carbon leakage rate, see Footnote 9.

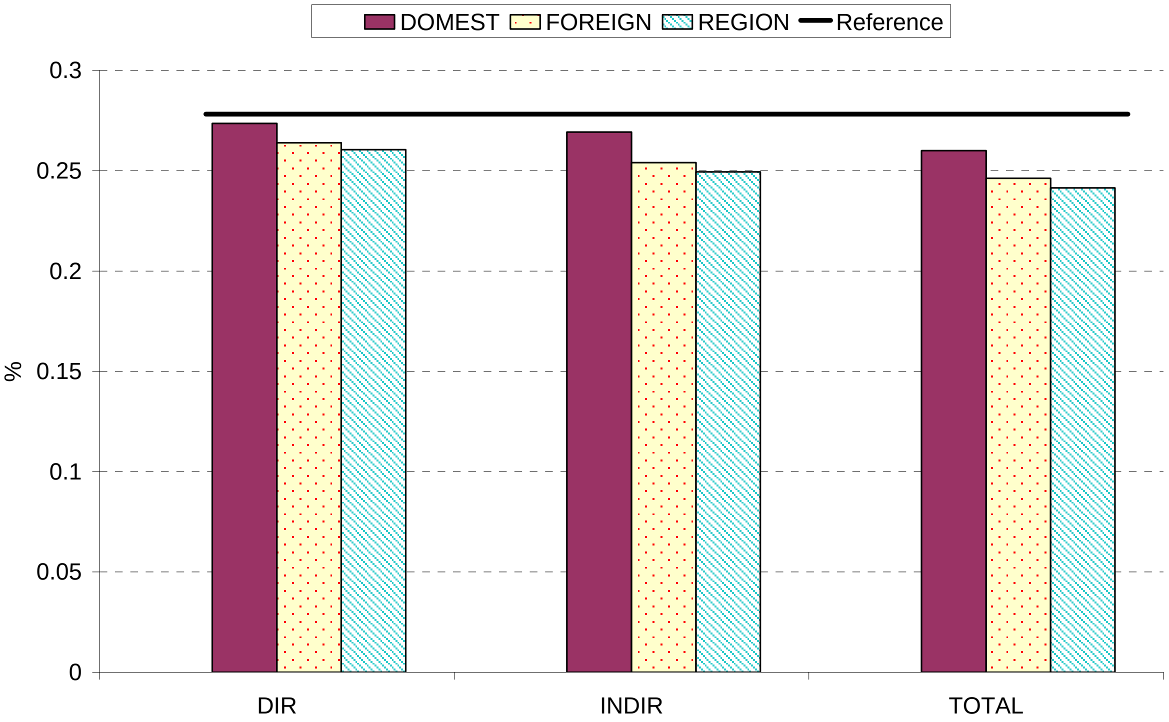
We find similar conclusions for larger coalition sizes where leakage rates are in general much smaller than for the EU coalition. In the reference scenarios they are 7% (coalition A1xR) and 4% (A1xR_CHN). When tariffs are based on total region-specific emissions, the leakage rates fall to 2% and 1%, respectively. If the tariffs are introduced for all goods, not just EITE products, leakage rates decline further.

Given that unilateral abatement policies must comply with an exogenous global emissions level, reduced leakage implies that less emission reductions have to take place within the coalition. Thus, we should expect that the carbon price drops when leakage rates fall. Whereas the carbon price is 57 $/ton of CO_2 in the EU's reference scenario, it falls to 47 $/ton of CO_2 in the scenario with region-specific tariffs based on total embodied carbon. The carbon price reductions are smaller when all Annex 1 countries form the coalition, and much smaller when both Annex 1 and China join the coalition.

6.2. Global welfare effects

We now examine the global welfare effects, and start by looking at the scenarios where the EU imposes carbon tariffs on EITE products. Changes in global welfare are measured from 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 remains agnostic about cost distribution. In the reference scenario without tariffs, the global welfare costs amount to 0.28%, cf. Figure 4. The imposition of carbon tariffs reduces global costs between 2% and 13%. As Figure 4 shows, there is a clear ordering when we focus on two dimensions of tariff design, i.e., embodied carbon coverage and tariff rate differentiation: Global welfare costs are reduced when the embodied carbon metric is changed from only direct emissions to direct plus electricity emissions, and further to total embodied carbon. Moreover, costs are reduced when we move from uniform tariffs (across regions) to country-specific tariffs, and uniform tariffs based on embodied carbon in the EU are more costly than tariffs based on average carbon content in non-EU countries.

Figure 4. Global welfare costs (% of BaU welfare) with EU coalition under alternative tariffs on EITE products



These findings are in line with our basic theoretical propositions: The more emissions we account for, and the more precise the tariff is (region-specific), the lower are the global welfare costs. However, we notice that the difference between region-specific tariffs and uniform tariffs based on non-EU average carbon content is quite small. It is much more important whether the tariff is based on embodied carbon content of EU production or non-EU production. The reason for this is that emission intensities in the EU are significantly lower than the average intensities in other regions (see Figure 1).

The same ordering as in Figure 4 occurs if we extend the coalition by considering climate policies for the larger A1xR coalition (i.e., all Annex 1-countries excluding Russia). One difference, however, is that the costs of uniform tariffs based on average embodied carbon in non-coalition regions are somewhat closer to the costs of tariffs based on average coalition emissions. The explanation is that the differences in emission intensities between coalition and non-coalition regions are reduced when the coalition is extended from EU to A1. For instance, emissions intensities in the USA are much higher than in the EU (see Figure 1). The global cost reductions of imposing carbon tariffs vary between 1% and 7%, i.e., the relative cost savings are approximately halved compared to the corresponding EU scenarios.

In the case where climate policies are imposed in China, too (coalition A1xR_CHN), the ordering is robust with one exception: Uniform tariffs based on total embodied carbon in non-coalition regions are less cost-efficient for the world than tariffs based on total embodied carbon in the coalition. They are also more costly than uniform tariffs based on emissions from only direct fuel use and/or electricity in non-coalition regions. This is due to total embodied carbon in Chinese EITE production being much higher than the global average (see Figure 1). The global cost reductions of imposing carbon tariffs are now merely 0.2-2.5%, reflecting the fact that efficiency losses from unilateral action become less of an issue as the abatement coalition covers the bulk part of global emissions.

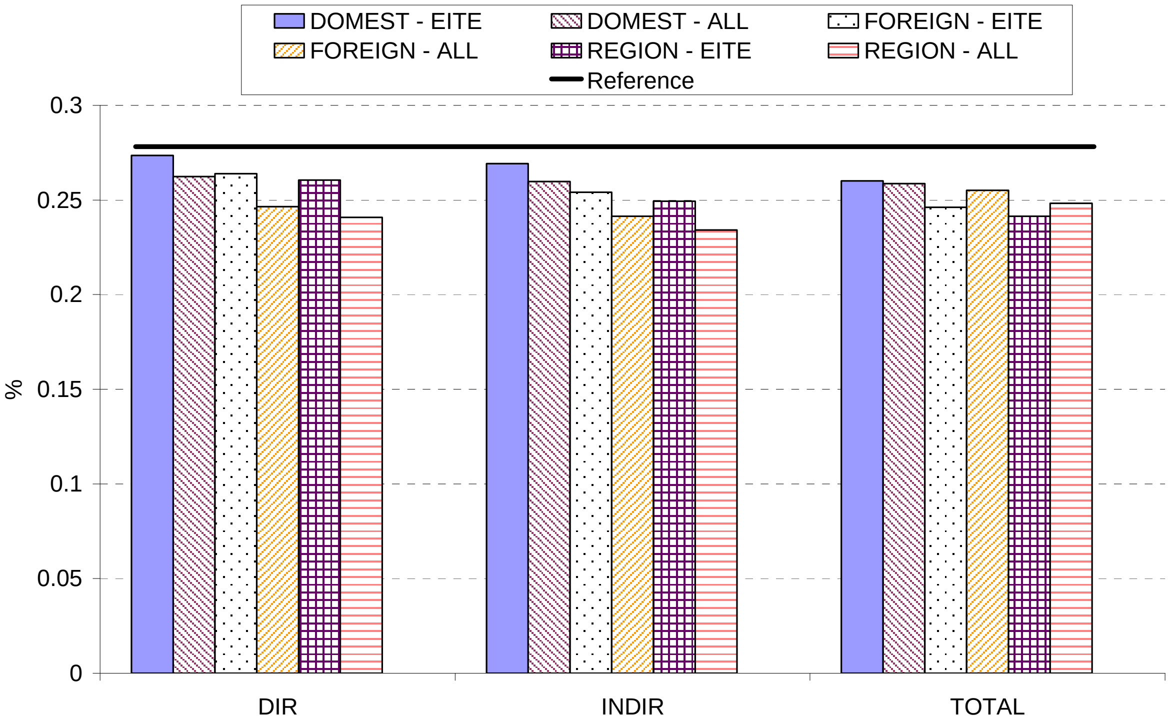
So far carbon tariffs have been discussed mostly with regard to EITE industries, which are the most emission-intensive and trade-exposed segments in the economy. For practical policy conclusions it is interesting also to investigate the impacts of imposing carbon tariffs on *all* products (ALL) to see if there are significant additional efficiency gains from extending the use of tariffs beyond EITE products. Figure 5 compares the global welfare costs of tariffs on ALL versus EITE products for the case of climate policies in the EU under different tariff designs. We notice that the welfare costs are in fact further reduced significantly, at least when tariffs are based on direct emissions or direct emissions plus embodied emissions from electricity use. The global cost reductions (vis-à-vis emission pricing stand-alone) more than double in the three DIR (direct fuel emissions only) scenarios, and increase by 50-100% in the INDIR (direct plus indirect emissions from electricity) scenarios. The reason is that embodied carbon in several trade-intensive non-EITE products is substantial, cf. Figures 1-2. For instance, embodied carbon of AOG goods ("All other manufactures and services", which includes electronics, cars, clothes, etc.) in China is on average comparable to embodied carbon in EITE products in the EU when direct plus electricity emissions are included, and much higher when total embodied carbon are considered.

When tariffs on all products are based on total embodied carbon, the efficiency gains are less clear. There are a number of reasons for this. First of all, it is not necessarily optimal to implement an import tariff that accounts for all embodied carbon, as reduced imports may have positive indirect emissions effects besides the negative direct emissions effects from reduced output. A second reason is that some emissions in the coalition may be priced twice: Parts of the total embodied carbon in non-coalition countries that are subject to tariffs come from emission-intensive intermediates exported from coalition to non-coalition countries, and therefore are already taxed. Both these explanations reflect the trade-off between finding feasible political designs, on the one hand, and targeting the tariffs efficiently, on the other. The most comprehensive carbon content metric in our study falls short of grasping all emissions effects accurately. Third, existing taxes, tariffs and subsidies could give rise to distortions that affect the optimal tariff level. Our simulations do, for instance, not account for export subsidies that could bring global gains by reducing leakages associated with the CO_2-taxes on exported goods. The studied tariff systems vary with respect to how this shortcoming is compensated (or reinforced).

As a consequence, the biggest simulated welfare gain in the case of the EU coalition is seen when all products face region-specific tariffs and when the carbon content is based on direct emissions plus indirect emissions from electricity inputs. The welfare gain then amounts to 16% vis-à-vis emission pricing stand-alone. Offsetting operational costs can be ignored: The carbon metric can be based on already available official data, which avoids compliance costs of firms, and public administration costs, roughly estimated at 1% of revenue (Evans, 2003), will be negligible. The legal and political arguments remain and it is difficult to say whether they weigh towards or against such a system.

The welfare increase of extending the sector coverage is significant also in the cases where all Annex 1 countries except Russia (coalition A1xR) take part in the coalition, and where both Annex 1 excl. Russia and China join the coalition (A1xR_CHN). This suggests that import tariffs, if introduced, should be seriously considered also for other products than EITE products, but not based on total embodied carbon in the non-coalition regions. There is still little risk of triggering high operational costs, as the required information is already collected official data. However, legal and political costs have to be considered.

Figure 5. Global welfare costs (% of BaU welfare) with EU coalition and tariffs on EITE or ALL sectors

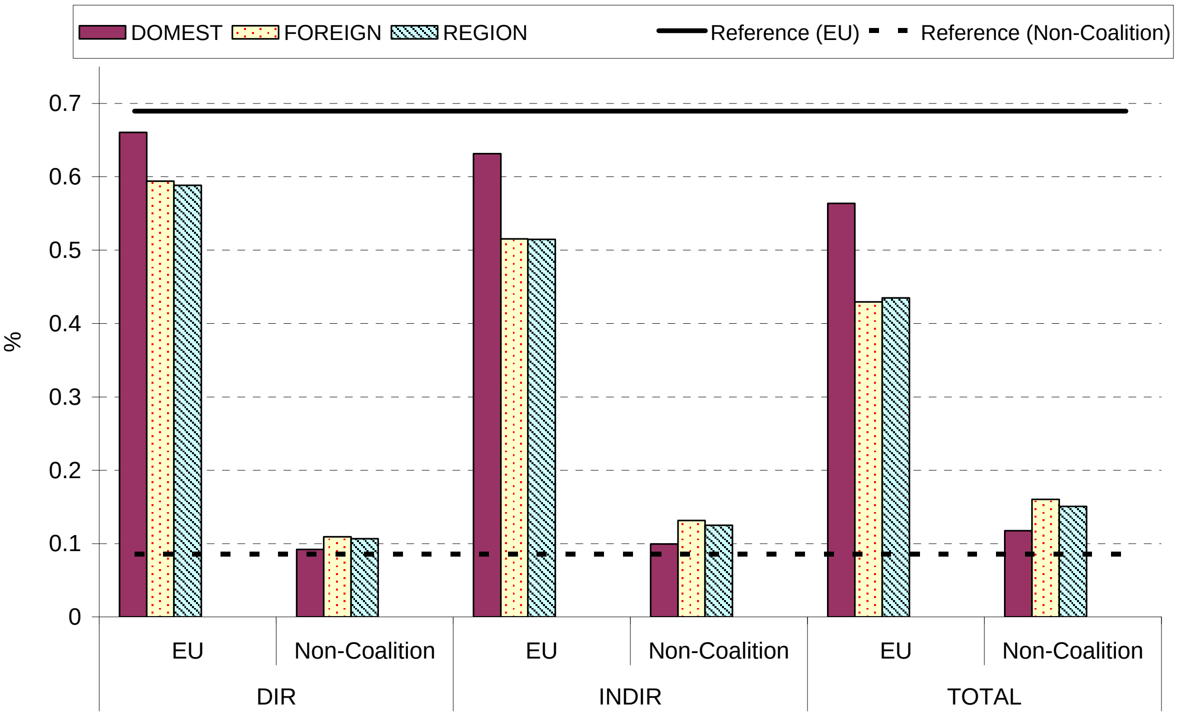


6.3. Distributional effects

Although our main focus is on *global* efficiency gains, political and legal concerns call for analyzing the distributional impacts between coalition and non-coalition regions (both at the total welfare level as well as at the production level of EITE industries). Figure 6 shows the effects on welfare costs of different tariff designs for EITE products under EU climate policies for the EU coalition and for the non-coalition, comprising the rest of the world. We see that the ranking between policies from the perspective of the EU abatement coalition is almost the same as for global costs, with one slight exception: Region-specific tariffs are marginally more costly for the EU than uniform tariffs based on non-EU emissions when all emissions are embodied. We also notice that the relative benefits for the EU of imposing carbon tariffs are bigger than for the whole world – the EU costs of reducing CO_2 emissions are reduced by 4-37% (vis-à-vis emissions pricing stand-alone). Thus, the EU has considerable incentives to impose carbon tariffs. This effect is even stronger if tariffs are imposed on all products – welfare costs in the EU could then be reduced by more than 80%.

For the composite of non-coalition regions, the conclusions are turned around. That is, non-abating regions on average prefer no tariffs at all.[10] Moreover, if a tariff is levied, non-abating countries are better off the lower the tariff is, i.e., with the tariff based on direct emissions, only. For most countries, however, the differences between the policy scenarios are rather small.[11] Regions with particularly emission-intensive EITE production obviously prefer uniform tariffs, which are calculated based on average emission intensities. This explains why non-OECD regions mainly prefer uniform tariffs, whereas OECD regions mainly prefer country-specific tariffs (with EU climate policies), cf. the regional embodied carbon in Figure 1.[12]

Figure 6. EU welfare costs (% of BaU welfare) with EU coalition under alternative tariffs on EITE products



What happens to the EITE industries in the different scenarios? If import tariffs lead to a significant reduction in EITE exports from non-coalition countries relative to exports from the coalition, the risk of trade disputes can evolve. This risk would be even more imminent if non-coalition's (likely) deterioration of competitiveness in the EITE markets from carbon tariffs dominates the (likely) improvement in competitiveness from the coalition's CO_2 pricing, so that they face reduced

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[10] China, however, is slightly better off with EU tariff, unless the tariff is based on direct plus indirect or total embodied carbon emissions in China.

[11] This holds for e.g. China, the USA and India. One exception is Russia, where welfare costs increase from 2% to 3% when going from no-tariff to tariff based on country-specific total embodied carbon.

[12] The welfare difference for China between uniform (based on non-coalition regions) and non-uniform tariffs is 0.1 percentage points when total embodied carbon are used to calculate tariffs. The USA unambiguously prefer non-uniform tariffs.

competitiveness also relative to the BaU scenario without any climate policies. We find that in the case with EU climate policies and import tariffs on EITE goods, total output of EITE goods in the EU falls in all scenarios except if tariffs are based on total embodied carbon, and on either region-specific or uniform carbon content based on non-coalition emissions. The same is true when it comes to total exports of EITE products from the EU. If we consider EITE exports from individual non-coalition countries, exports always increase (vis-à-vis BaU) if the EU introduces uniform tariffs based on own direct emissions. On the other hand, in the cases where EU exports increase as mentioned above, exports from most non-coalition countries decrease. Exports also decrease in some other policy scenarios for most non-coalition countries.[13] Thus, the most cost-efficient unilateral climate policy designs could very well trigger a trade dispute.

A similar picture is seen if the coalition is extended to coalitions A1xR or A1xR_CHN. However, in the latter case with the largest coalition, the coalition as a whole decreases both output and exports of EITE goods in all scenarios. The same holds for the USA and China. On the other hand, the EU increases its EITE exports in all but one of the tariff scenarios with this large coalition.

7. Conclusions

Given that an effective global agreement on emission reductions remains elusive, individual countries go ahead or at least consider unilateral action. Carbon tariffs to counteract emission leakage and thereby increase global cost-effectiveness play an important role in the policy debate on the appropriate design of unilateral emission abatement strategies. Basic economic efficiency concerns call for border measures like the carbon tariff structures discussed in this paper. We have assessed the economic impacts of alternative systems to gain insights into the pending trade-offs between more narrowly defined economic efficiency gains and the potential costs from legal, practical, and political perspectives.

Our efficiency results mostly support the expectations that more complex and detailed systems yield more efficient outcomes. Grasping as much as possible of the embodied carbon content and covering more goods is important in efficiency terms. It is essential to use non-coalition technologies as the basis for carbon content calculations. However, the quantitative differences between systems based on region-specific carbon information and on the regional averages are small, at least for the smaller coalition comprising only the EU. This indicates one possibility for economising administration and compliance costs without very large efficiency losses.

Even though the operationalized systems closest to the ideal cost-efficient system mainly are ranked according to theoretical expectations, we find that, irrespective of coalition size, the most cost-efficient

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[13] For instance, U.S. EITE exports are reduced vis-à-vis BaU in six out of nine tariff scenarios.

simulated policy is not based on total embodied carbon, but includes indirect electricity emissions, only. The result first of all reflects the challenge of finding operationalized metrics of the carbon content that are both realistically feasible and well-targeted in an efficiency sense. Tax-interaction effects of the tariffs also contribute to alter the ranking of the tariff design compared to the expected second-best optimal.

For small coalition sizes, the global cost reductions through carbon tariffs can be significant. Without further quantitative research, it is difficult to assess whether the global cost savings from alternative carbon tariff schemes justify other, less quantifiable costs. We consider administration costs as a minor challenge to the studied systems. However, a call for more accurate data than presumed here would have to involve compliance costs of firms in the non-abating regions, and this could increase operational costs manyfold. No quantifications of legal and political implications are available. Not even the signs are easy to identify, as arguments pull in both directions.

Distributional aspects are important for how stakeholders at the national and international policy level will embrace or reject climate policies. We find that non-coalition regions suffer from carbon tariffs, and mostly so when the tariffs are high and cover all goods. From a political economy perspective, the impacts for influential emission-intensive and trade-exposed industries are important, as well, since they drive lobbying activities and the probability of trade disputes. To what extent carbon tariffs could provide a credible threat for enhancing international cooperation or bear the risk of causing detrimental trade wars is an open issue which we leave for future research.

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Appendix: Algebraic Model Summary

The CGE 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 producers with constant returns to scale; and (ii) market clearance for all goods and factors. The former class determines activity levels, and the latter determines price levels. In equilibrium, each variable 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 Π_{ir}^{z} is used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for production with constant returns to scale 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 investment composite (*g*=*I*). The index *r* (aliased with *s*) denotes regions. The index *EG* represents the subset of energy goods coal, oil, gas, electricity, and the label *FF* denotes the subset of fossil fuels coal, oil, gas. Tables B1–B6 explain the notations for variables and parameters employed within our algebraic exposition. Figures B1–B3 provide a graphical exposition of the production structure. Numerically, the model is implemented in GAMS (Brooke et al., 1996) and solved using PATH (Dirkse and Ferris, 1995).

Zero Profit Conditions:

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

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{M} p_{gr}^{M(1-\sigma_{gr}^{KLEM})} + \left(1-\theta_{gr}^{M}\right) \left[\theta_{gr}^{E} p_{gr}^{E\,(1-\sigma_{gr}^{KLE})} + \left(1-\theta_{gr}^{E}\right) p_{gr}^{KL(1-\sigma_{gr}^{KLE})} \right]^{(1-\sigma_{gr}^{KLEM})/(1-\sigma_{gr}^{KLE})} \right]^{1/(1-\sigma_{gr}^{KLEM})} \leq 0.$$

2. Sector-specific material aggregate:

$$\Pi_{gr}^{M} = p_{gr}^{M} - \left[\sum_{i \notin EG} \theta_{igr}^{MN} p_{igr}^{A\;1-\sigma_{gr}^{M}} \right]^{1/(1-\sigma_{gr}^{M})} \leq 0.$$

3. Sector-specific energy aggregate:

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

4. Sector-specific value-added aggregate:

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

5. Production of fossil fuels (*g*∈*FF*):

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

6. Armington aggregate:

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

7. Aggregate imports across import regions:

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

Market Clearance Conditions:

8. Labor:

$$\overline{L}_r \geq \sum_{g} Y^{KL}_{gr} \frac{\partial \Pi^{KL}_{gr}}{\partial w_r}.$$

9. Capital:

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

10. Fossil-fuel resources (g∈*FF*):

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

11. Material composite:

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

12. Energy composite:

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

13. Value-added composite:

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

14. Import composite:

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

15. Armington aggregate:

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

16. Commodities (*g*=*i*):

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

17. Private consumption composite (*g*=*C*):

$$Y_{Cr} p_{Cr} \geq w_{r} \overline{L}_{r} + \sum_{g} v_{gr} \overline{K}_{gr} + \sum_{i \in FF} q_{ir} \overline{Q}_{ir} + p^{CO_2}_{r} \overline{CO}_{2r} + \overline{B}_{r} .$$

18. Public consumption composite (*g*=*G*):

$$Y_{Gr} \geq \overline{G}_{r} .$$

19. Investment composite (*g*=*I*):

$$Y_{Ir} \geq \overline{I}_{r} .$$

20. Carbon emissions:

$$\overline{CO}_{2r} \geq \sum_{g} \sum_{i \in FF} E_{gr} \frac{\partial \Pi^{E}_{gr}}{\partial \left(p^{A}_{igr} + p^{CO_2}_{r} a^{CO_2}_{igr} \right)} a^{CO_2}_{igr} .$$

Table A1. Indices (sets)

G	Sectors and commodities (*g*=*i*), final consumption composite (*g*=*C*), public good composite (*g*=*G*), investment composite (*g*=*I*)
I	Sectors and commodities
r (alias *s*)	Regions
EG	Energy goods: coal, crude oil, refined oil, gas, and electricity
FF	Fossil fuels: coal, crude oil, and gas

Table A2. Activity Variables

Y_{gr}	Production of item *g* in region *r*
M_{gr}	Material composite for item *g* in region *r*
E_{gr}	Energy composite for item *g* in region *r*
$\mathrm{KL}_{\mathrm{gr}}$	Value-added composite for item *g* in region *r*
$\mathrm{A}_{\mathrm{igr}}$	Armington aggregate of commodity *i* for demand category (item) *g* in region *r*
$\mathrm{IM}_{\mathrm{ir}}$	Aggregate imports of commodity *i* and region *r*

Table A3. Price Variables

p_{gr}	Price of item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{M}}$	Price of material composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{E}}$	Price of energy composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{KL}}$	Price of value-added composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{igr}}^{\mathrm{A}}$	Price of Armington good *i* for demand category (item) *g* in region *r*
$\mathrm{p}_{\mathrm{ir}}^{\mathrm{IM}}$	Price of import composite for good *i* in region *r*
w_{r}	Price of labor (wage rate) in region *r*
v_{ir}	Price of capital services (rental rate) in sector *i* and region *r*
q_{ir}	Rent to fossil-fuel resources in region *r* ($i \in$ FF)
$\mathrm{p}_{\mathrm{r}}^{\mathrm{CO_2}}$	Carbon value in region *r*

Table B4. Endowments and Emissions Coefficients

$\overline{L}_r$	Aggregate labor endowment for region *r*
$\overline{\mathrm{K}}_{\mathrm{ir}}$	Capital endowment of sector *i* in region *r*
$\overline{Q}_{ir}$	Endowment of fossil-fuel resource *i* for region *r* ($i \in$ FF)
$\overline{B}_r$	Initial balance of payment deficit or surplus in region *r* (note: $\sum_r \overline{B}_r = 0$)
$\overline{\mathrm{CO}}_{2\mathrm{r}}$	Endowment of carbon emissions rights in region *r*
$\mathrm{a}_{\mathrm{igr}}^{\mathrm{CO}_2}$	Carbon emissions coefficient for fossil fuel *i* in demand category *g* of region *r* ($i \in FF$)

Table B5. Cost Shares

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

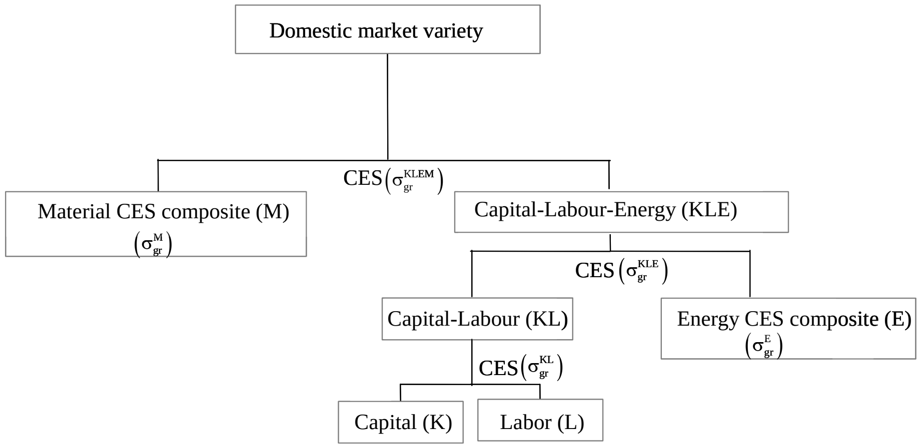
Table B6. Elasticities

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 nest of 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 fossil-fuel production ($g \in$ FF) of region *r* (calibrated consistently to exogenous supply elasticities)
σ_{ir}^{A}	Substitution between the import composite and the domestic input to Armington production of good *i* in region r^{**}
σ_{ir}^{IM}	Substitution between imports from different regions within the import composite for good *i* in region r^{**}

*See Okagawa and Ban (2008).

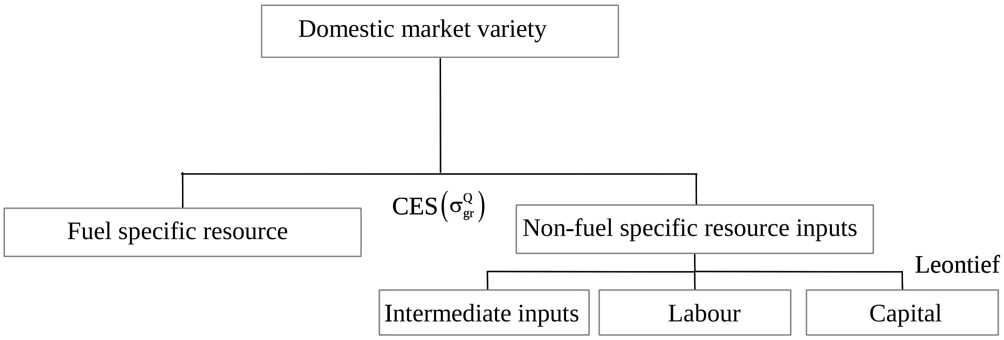
**See Badri Narayanan and Walmsley (2008).

Figure B1. Nesting in Nonfossil-Fuel Production



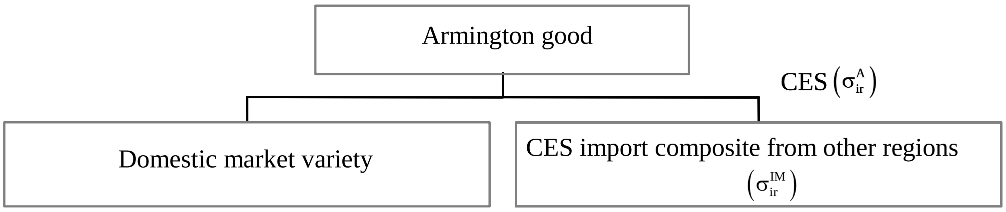
Note: CES=constant elasticity of substitution.

Figure B2. Nesting in Fossil-Fuel Production



Note: CES=constant elasticity of substitution.

Figure B3. Nesting in Armington Production



Note: CES=constant elasticity of substitution.