Targeted carbon tariffs:

Export response, leakage and welfare

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Abstract: Climate benefits of unilateral carbon policies are undermined by carbon leakage. To counteract leakage and increase global cost-effectiveness carbon tariffs can be imposed on the emissions embodied in imports from non-regulating regions. We present a stylized model analysis on the economic incentives for emissions abatement of producers subjected to carbon tariffs. The impacts of different carbon tariff designs are, then, quantified by an empirically based multi-sector, multi-region computable general equilibrium model of the global economy. We find that firm-targeted tariffs can deliver considerably stronger leakage reduction and higher gains in global cost-effectiveness than tariff designs operated at the industry level. Moreover, because the exporters are able to reduce their carbon tariffs by adjusting emissions, their competitiveness and the overall welfare of their economies will be less adversely affected than in the case of industry-level carbon tariff regimes.

Keywords: carbon leakage, border carbon adjustment, carbon tariffs, computable general equilibrium (CGE)

JEL classification: Q43, Q54, H2, D61

1. Introduction

The 21st Conference of Parties to the United Nations Framework Convention on Climate Change – held in Paris in December 2015 – agreed to "pursue efforts" to limit global warming to 1.5° Celsius above pre-industrial levels (UNFCC, 2015). The so-called Paris Agreement has been appraised as a historic step forward to global climate action since it constitutes the world's first comprehensive climate agreement, with all countries expected to pitch in. However, greenhouse gas emission reduction targets communicated by more than 190 Parties/States in terms of intended nationally determined contributions (INDCs) are not only very disparate in ambition level but also legally non-binding. As a consequence, international climate policy can be expected to remain quite fragmented with large asymmetries in emission pricing across countries. Such asymmetries will undermine the environmental effectiveness of more ambitious national climate policy initiatives through carbon leakage as domestic emission-intensive and trade-exposed industries (EITE) will relocate to countries without or with only quite lenient emission pricing. Concerns on carbon leakage and competitiveness losses of EITE industries are at the core of the climate policy debate in industrialized countries contemplating stringent domestic carbon pricing.

Seminal theoretical papers by Markusen (1975) and Hoel (1996) suggest that a region should supplement its unilateral carbon pricing with border carbon adjustments (BCAs) to account for adverse international emissions spillovers via trade. BCAs include tariffs designed to tax carbon emissions embodied in imports (carbon tariffs), combined with rebates of emissions payments for exports.[1] If comprehensively applied, BCA effectively works as destination-based carbon pricing

[1] See also Copeland (1996), Jakob et al. (2013), Böhringer et al. (2014) and Balistreri et al. (2015) for analytical contributions on BCAs.

which levels the playing field in international trade while internalizing the cost of climate damage into prices of goods and services.

Although carbon tariffs have not been implemented so far, they are assessed and debated in several OECD countries. In the EU, the USA, and Australia, the discussions have been closely linked to the design of emissions cap-and-trade systems.[2] In the vein of carbon tariffs, the EU has attempted to incorporate all flights to and from EU airports into the EU Emission Trading System (ETS) (Directive 2008/101/EC).[3] BCAs are, however, controversial, and there are diverging views as to whether they are compatible with WTO rules (Horn and Mavroidis, 2011, Böhringer et al., 2012b).

Several empirical studies have quantified the implications of carbon tariffs, considering alternative designs of the coverage of embodied carbon and the range of sectors (goods) subjected to the tariff; see e.g. the EMF 29 model cross-comparison study summarized in Böhringer et al. (2012a), and recent overviews by Branger and Quirion (2014) or Zhang (2012). In general, the studies find that while carbon tariffs can reduce carbon leakage markedly, the global cost-effectiveness of unilateral carbon policies is only slightly increased (see e.g. Mattoo et al. 2009, and Böhringer et al. 2012a, b).

However, the carbon tariffs investigated so far in the numerical literature are almost exclusively (Winchester, 2012, is the only exception) based on some average embodied carbon content and not targeted towards the individual firm or shipment. This average may for instance be calculated for each

[2] In the EU, carbon tariffs have e.g. been put forward in 2015 by a High Level Working Group on Competitiveness and Growth (http://data.consilium.europa.eu/doc/document/ST-8878-2015-INIT/en/pdf). In the USA, carbon tariffs were proposed in The American Clean Energy and Security Act, which was passed by the House of Representatives (2009) but not by the U.S. Senate.

[3] The plan has been put on hold due to fierce opposition from the international aviation community and major non-EU countries such as the USA and China (Ireland, 2012). The ongoing political debate on measures for pricing emission from aviation at a global scale highlights the importance of distributional and legal issues at stake.

exporting region, referred to as region-specific tariffs.[4] Such tariffs do not give individual polluters abroad incentives to reduce the emission-intensity of their production.

The contribution of this paper is to analyze and discuss more thoroughly the possibilities, limitations, and implications of carbon tariff systems designed to target specific emission-intensities of foreign producers. We will refer to this as (firm-)targeted tariffs. We hypothesize that succeeding to design and implement such systems could improve the carbon leakage response and the global cost-effectiveness appeal of BCAs. Furthermore, we assess the distributional implications of targeting carbon tariffs. This research question is crucial as more acceptable distributional outcomes could enhance the legitimacy of carbon tariffs.

To our knowledge, Winchester (2012) is the only previous numerical study analyzing carbon tariffs that incentivize low-carbon production processes abroad. The contribution of our paper relative to Winchester (2012) is fourfold: First, we discuss the feasibility of firm-targeted tariffs and investigate analytically how alternative tariff designs affect firms' incentives for emissions abatement. Second, our numerical simulation model is much more disaggregated at the industry and region level, thereby enhancing the policy relevance of our assessment: Whereas Winchester (2012) uses a highly aggregated model of the global economy with only two regions and one EITE industry, our model divides the world into nine regions and includes five separate EITE industries (and eight non-EITE industries), thus accounting more realistically for reallocations taking place – in fact, our simulation results point to rather substantial sectoral and regional differences in responses to the policies. Third, we cover a different range of alternative tariff designs, such as allowing for carbon tariffs that respond to the embodied carbon in electricity input. Fourth – and most important – we ensure comparability

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[4] Alternatively, the carbon tariff for a certain good could be equal across exporting regions, based on either emission intensities in all exporting regions jointly, the importing region's emission intensities, or best available technology (see e.g. Ismer and Neuhoff, 2007).

across different carbon tariff scenarios by keeping global emissions at identical levels, thus accommodating consistent cost-effectiveness analysis of alternative climate policy designs. The work by Winchester (2012) does not allow drawing conclusions on how alternative carbon tariff designs affect global, nor regional, welfare of unilateral climate policy as also global emissions vary across scenarios and have unquantified welfare effects.

Our analysis is based on numerical simulations with a computable general equilibrium (CGE) model for the world economy (see Section 4 for an introduction). We consider unilateral climate policy action by Europe, which is one of the nine regions in the model. Europe imposes a uniform carbon price, and may in addition implement a carbon tariff on imports of EITE goods. Producers of EITE goods outside Europe can choose to export their goods to Europe, or sell to non-European regions. If they export to Europe, the carbon tariff and how it is designed will matter for the exporters' incentives. With region-specific tariffs, analyzed in most previous studies, the exporters have no incentives to reduce the carbon intensities of their production. On the other hand, with firm-targeted tariffs exporters to Europe are incentivized to reduce their carbon intensity. If the tariff is not only levied on direct emissions of production, but also on indirect emissions (emissions embodied in intermediate non-fossil fuel inputs such as electricity), the exporting firms will also have incentives to look for inputs with low carbon contents, as they would be remunerated with a lower carbon tariff.

Our numerical analysis finds that firm-targeted tariffs for EITE goods can deliver considerably stronger leakage reduction and higher global efficiency gains than region-specific tariffs addressed in previous studies. Furthermore, because exporting regions subjected to firm-targeted tariffs are able to reduce effective tariff payments by adjusting to the implicit carbon taxation, cost shifting is attenuated compared to earlier analyses (including Mattoo et al., 2009; Böhringer et al. ,2012a; Winchester, 2012). This could facilitate a higher degree of legitimacy for BCAs if implemented as firm-targeted tariffs.

We find the largest gains in global cost-effectiveness, and the least pronounced cost-shifting effects, when the tariffs not only respond to a firm's direct emissions but also to its indirect emissions contribution from its use of electricity (e.g., depending on whether the firm buys coal power, gas power or renewable power). The indirect emissions component in the tariffs is not firm-targeted in Winchester (2012) and explains his much smaller effects of firm-targeted tariffs (compared with region-specific). Though the potential is substantial, we will emphasize that benefits from including indirect emissions will be moderated to the extent that already existing renewable electricity is merely reshuffled to the exporting firms. Administrative costs will also moderate the benefits. We discuss these reservations in Section 4.2. and 2, respectively, as well as in the Conclusions.

The remainder of this paper is organized as follows: In Section 2 we discuss practical designs of targeted carbon tariffs. We then investigate these designs analytically in Section 3. In Section 4 we quantify the policy relevance of alternative carbon tariff designs based on numerical CGE simulations for the global economy. In Section 5 we conclude.

2. Feasibility aspects of targeted carbon tariffs

One important feasibility barrier for firm-targeted tariffs is administration (transaction) cost. The more targeted the tariff system, and the more of the indirect emissions content to account for, the more bureaucracy will be involved. Unless a (high) default tariff is accepted by the exporter, the information on emissions content would have to be collected by the producers (exporters) or importers and validated by some external body.

To our knowledge, no calculations have been undertaken so far of costs associated with the governments' administration of, and firms' compliance with, alternative carbon tariff designs. Persson (2010) presents scattered estimates of transaction cost components in international trading and carbon accounting but no overall evaluation. Evans (2003) reviews studies of administrative costs of tax systems. He observes that in cases where individual companies, not only centralized public bodies, bear a substantial part of the paperwork, the administrative costs of tax systems rise substantially. A recent study by Mc Ausland and Najjar (2015) study carbon footprint taxes (CFTs) that tax the lifecycle emissions, including the total carbon content of imports (i.e., *all* indirect emissions, not only electricity). Their study suggests that compliance and administration costs of CFTs are rather negligible. CFTs have similarities with carbon tariffs. However, contrary to firm-targeted systems they are based on average emissions.

Communications and data technologies develop fast and, recently, novel emissions inventories and standards designed for tracking carbon contents have been established that ease the administrative load. One such promising data system is the international standards of carbon footprints (CFPs) launched in 2013 – the ISO standard of carbon footprint (ISO 14067: 2013). Until recently there has been no common operational definition of the CFP of a product. The ISO standard defines CFP as the sum of greenhouse gas (GHG) emissions and removals in a product system expressed as CO_2-equivalents, based on a life-cycle assessment. The product system includes inputs of other products, materials and energy flows, starting from the deployment of the raw material of natural resources (see also ISO 14044:2006). The life-cycle assessment implies that for all products the GHG emissions from both the initial raw material depletion, and the final disposal are included, a feature that makes it less relevant for direct use in carbon tariff calculations. Offsetting impacts as, e.g., investments in new renewable energy technologies, energy efficiency measures, or afforestation/reforestation, are also included.

Further guidance to the calculation of the carbon content embodied in products can be obtained from The Greenhouse Gas Protocol (2010), which specifies carbon accounting standards for companies and organizations preparing a GHG emissions inventory.[5]

[5] The Greenhouse Gas Protocol also includes adjustments for indirect emissions from electricity production.

Another possibility for documenting the carbon content of products could be to apply procedures similar to those practiced for the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change (UNFCCC, 2012, 2014). The CDM certificates are based on reports from a Designated National Authority (DNA), validation by an external validator, and a final decision by the CDM Executive Board (nominated by the UNFCCC) on whether the project qualifies as a CDM project. A main issue in the CDM procedure is the assessment of the project's additionality, which is not relevant when settling carbon tariff rates; furthermore, only direct emissions are measured in CDM projects. The CDM standards appear less transparent than the ISO standards, and the procedures are labor-consuming since the DNA, the external validator as well as the CDM Executive Board have to approve the assessments.

From the discussion above, it seems that the new ISO certification procedure would be the most accurate and easiest to take advantage of. Experiences from existing and previous border procedures for food products are highly relevant for a firm-targeted practicing of an ISO carbon footprint system.[6] However, handling the reshuffling problem in the electricity markets will still be an issue. One way out would be to establish a market for emissions from the electricity production in the exporting country, e.g., a green certificate market; see the discussion in Section 4.2.

Along with the practical obstacles of implementing and operating firm-targeted carbon tariffs come several legal and political hindrances. Böhringer et al. (2012b) discuss these issues in more detail. The main legal challenge is to comply with the World Trade Organization (WTO) law. Discrimination of equal goods based on their production methods is not legal. Though in principle it may be legal to take

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[6] The ISO 22000 standards are established for the purpose of food safety management. A previous system in the EU regulated food imports for the purpose of applying variable input levies to protect agricultural production. These two systems have in common with an information system for targeted carbon tariffs that inputs of the imported goods have to be mapped on a detailed level.

action based on environmental considerations, the specific procedures for the implementation of carbon tariffs are rather strict. Allowing exporters to affect their tariff rate by adjusting their carbon input could be more acceptable than fixing average tariff rates. On the other hand, comprehensive documentation requirements can be regarded as non-tariff trade barriers.

The international political implications of carbon tariffs are also a critical issue. Carbon tariffs against countries without or with lax emissions regulation can negatively affect their willingness to contribute to more stringent action against climate change in the wake of the Paris Agreement (UNFCCC, 2015). There is also the non-negligible risk of retaliation from large countries leading into potentially detrimental trade wars. Previous studies of carbon tariffs have shown that the distributional effects are in disfavor of countries subjected to carbon tariffs (Branger and Quirion, 2014, Böhringer et al., 2016). In this vein, distributional aspects could strengthen the case for firm-targeted tariffs, since these allow countries to reduce their tariff costs and ameliorate competitiveness losses of their EITE industries.

Based on the discussion above, we conclude that firm-targeted tariffs do not necessarily increase the political, legal and practical barriers significantly relative to less targeted tariff systems. Some aspects of firm-targeted tariffs can actually be politically and legally superior because they have distributional advantages and can be regarded as more fair. Furthermore, practical barriers have diminished during recent years as complex electronic data bases are developed and border registration procedures established.

3. Stylized model analysis

In this section we show analytically, by using a stylized partial model, how different tariff designs may affect the incentives for firms in non-regulating countries that export to a region that has a carbon price t and imposes carbon tariffs τ_j per unit of imports of goods j from non-regulating regions. We assume that each exporting firm in non-regulating regions either only exports to the regulating region *or* only sells to non-regulating regions (including its domestic market). In this section we focus on firms that export to the regulating region. However, we will point to how the incentives differ compared to the firms that only sell to non-regulating regions. The stylized model corresponds to the modeling of export behavior in the numerical CGE model.[7]

3.1 Region-specific tariffs on direct emissions

A firm *i* producing good *j* in the non-regulating region and only selling to the regulating (emission-abating) region has the following profit function (we omit indices for regions throughout this section):

(1) $$\pi_{ij} = p_j^y y_{ij} - p_j^x x_{ij} - \tau_j y_{ij} \qquad \text{s.t.} \qquad y_{ij} = f_{ij}(x_{ij}, e_{ij})$$

where:

p_j^y is the product price of good *j* in the market of the regulating region,

y_{ij} is exported quantity,

e_{ij} denotes carbon emissions,

τ_j is the level of the carbon tariff, which is generally given by the product of the carbon price t and some emission-intensity ε_j for good *j* ($\tau_j = t\varepsilon_j$),

x_{ij} is the level of input (to simplify notation and without loss of generality for tariffs on direct emissions, only, we consider only one input),

p_j^x is the price of the input, and

[7] For further details on the CGE model see Section 4 and the Appendix. Strictly speaking, as the CGE model assumes one representative agent in each sector of the non-regulated regions, the representative producer in sector *j* in a region disposes of one production line for each market, including one production line for exports to the regulating region and production lines for sales to the non-regulating regions and to the domestic market. In the stylized model, we interpret the production lines as firms, aggregate the production lines for sales to the non-regulating regions, and disregard deliveries domestically.

f_{ij} is the production function, which is assumed to be concave and increasing in both x_{ij} and e_{ij} ($\partial f_{ij} / \partial x_{ij} > 0$, $\partial^2 f_{ij} / \partial (x_{ij})^2 < 0$, $\partial f_{ij} / \partial e_{ij} > 0$, $\partial^2 f_{ij} / \partial (e_{ij})^2 < 0$).

The crucial parameter here is the emission-intensity component in the tariff, ε_j, which can be either firm-targeted or region-specific, and which can be based on direct emissions only or also indirect emissions.

To start with, we assume that ε_j only embraces direct emissions. Region-specific tariffs imply the conventional assumption in the literature that ε_j facing the firm i is determined by the average emission-intensity, $\hat{\varepsilon}_j$, of producing good j in the region in which the firm operates. Hence, assuming that each firm is too small to have a notable influence on $\hat{\varepsilon}_j$, the tariff τ_j is considered exogenous for the individual firm. This is how carbon tariffs are modelled in almost all numerical studies so far.[8] The first-order conditions for the exporting firm i in the non-regulating region are then:

(2) $$\partial \pi_{ij} / \partial y_{ij} = p_j^y - \tau_j - \mu_{ij} = 0$$

(3) $$\partial \pi_{ij} / \partial x_{ij} = -p_j^x + \mu_{ij} \left(\partial f_{ij} / \partial x_{ij} \right) = 0$$

(4) $$\partial \pi_{ij} / \partial e_{ij} = \mu_{ij} \left(\partial f_{ij} / \partial e_{ij} \right) = 0$$

[8] Alternatively, the tariffs can be based on average emission intensities over exporting regions. They can also be based on emission intensities in the regulating countries. Further, $\hat{\varepsilon}_j$ can be determined either exogenously using base-year emission intensities, or endogenously using emission intensities in the new equilibrium. The tariff payments are usually allocated to the import country, but they could alternatively be allocated to the export country. The important thing here is that the tariff is considered exogenous for the individual firm.

μ_{ij} denotes the shadow price on the production constraint $y_{ij} = f_{ij}(x_{ij}, e_{ij})$, which can also be interpreted as the marginal costs of production. Equation (2) states that the firm will expand production until the price minus the (exogenous) tariff equals the marginal costs of production. The higher is the tariff, the less will be produced and exported to the regulating region. Equation (3) is the standard first-order condition for choice of input level, whereas equation (4) says that the firm will not make any efforts to reduce its emission-intensity, as it will not pay off in terms of lower tariff payments. A firm selling to non-regulating regions will have the same first-order conditions, except that there will be no tariff τ_j and the output prices p_j^y will typically differ. In case of no tariff, the optimal combination of inputs is, obviously, independent of in which market the product is sold.

3.2 Firm-targeted tariffs on direct emissions

As opposed to region-specific carbon tariffs, the tariff aimed at direct emissions can be firm-targeted, i.e., based on the firm's own emissions.[9] A firm-targeted tariff will give the following profit function:

(5) $$\pi_{ij} = p_j^y y_{ij} - p_j^x x_{ij} - t\frac{e_{ij}}{y_{ij}} y_{ij} = p_j^y y_{ij} - p_j^x x_{ij} - te_{ij} \qquad \text{s.t.} \qquad y_{ij} = f_{ij}(x_{ij}, e_{ij})$$

The first-order conditions for the exporting firm are (equation (3) is unchanged):

(6) $$\partial\pi_{ij} / \partial y_{ij} = p_j^y - \mu_{ij} = 0$$

(7) $$\partial\pi_{ij} / \partial e_{ij} = -t + \mu_{ij}\left(\partial f_{ij} / \partial e_{ij}\right) = 0$$

[9] In policy practise, this could be implemented as an option for exporting firms, where the default tariff is the country-specific tariff.

We see from equation (6) that the firm now will expand production (export) until price equals marginal production costs. Further, equation (7) shows that the firm will decrease emissions until the marginal costs of reducing emissions, $\mu_{ij}^{y}\left(\partial f_{ij} / \partial e_{ij}\right)$, equal the carbon price *t*.[10]

By comparing the first-order conditions in equations (2) and (4) with equations (6)-(7) it becomes clear that the first-order effect of changing from a region-specific tariff to a firm-targeted carbon tariff is to lower emissions and increase exports to the regulating region. When comparing with a firm that sells to non-regulating regions, the main difference is that there is no tariff (i.e. no carbon price *t* in equation (7)) for the latter firm, which therefore has no incentive to reduce its emissions. The optimal producer behavior is, thus, different depending on which market the firm serves.

3.3 Region-specific tariffs on direct and indirect emissions

So far we have only considered emissions at the production plant, and disregarded indirect emissions from generating electricity or other inputs that are used in producing good *j*. For many goods, electricity is an important input into production, accounting for a significant share of the total carbon footprint of producing these goods. To increase the outreach and effectiveness, proposals of carbon tariffs often include indirect emissions from electricity production when calculating the tariff. Again, the conventional assumption in the literature is that the tariff gets an additional term which is determined based on average emission-intensities in the electricity sector and the average use of electricity per unit production of good *j*. In this case equations (1)-(4) are unchanged, except that the value of the tariff has increased, which dampens export to the regulating region further.

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[10] Note that this first-order condition is similar to that of a firm inside the regulating region facing either a carbon tax or a quota price equal to *t*.

3.4 Firm-targeted tariffs on direct and region-specific on indirect emissions

The next case we consider is a hybrid case, which represents the most firm-targeted scenario in Winchester (2012). It assumes that both direct emissions and indirect emissions from electricity generation are embodied in the tariff. However, while the tariff is firm-targeted with respect to its direct emissions component (as in equation (5)), the indirect emissions component from use of electricity (denoted x_{ij}^{E}, with price p_j^{E}) is based on the average emission-intensity in the electricity sector, $\hat{\varepsilon}_E$. This emission factor is then multiplied with firm *i*'s use of electricity per produced unit, x_{ij}^{E} / y_{ij}. Hence, the tariff for firm *i* equals $t(\varepsilon_{ij} + (x_{ij}^{E} / y_{ij})\hat{\varepsilon}_E)$. The profit function of the firm then becomes:

(8) $$\pi_{ij} = p_j^{y} y_{ij} - p_j^{x} x_{ij} - p_j^{E} x_{ij}^{E} - t\left(\frac{e_{ij}}{y_{ij}} + \frac{x_{ij}^{E}}{y_{ij}}\hat{\varepsilon}_E\right) y_{ij} = p_j^{y} y_{ij} - p_j^{x} x_{ij} - p_j^{E} x_{ij}^{E} - t\left(e_{ij} + x_{ij}^{E}\hat{\varepsilon}_E\right)$$

$$\text{s.t. } y_{ij} = f_{ij}(x_{ij}, x_{ij}^{E}, e_{ij})$$

Without the tariff (and for firms selling to non-regulating regions) the optimal use of electricity is given by the standard first-order condition in equation (3). With the tariff, however, the first-order condition for electricity use becomes:

(9) $$\partial \pi_{ij} / \partial x_{ij}^{E} = -p_j^{E} - t\hat{\varepsilon}_E + \mu_{ij}\left(\partial f_{ij} / \partial x_{ij}^{E}\right) = 0$$

The first-order conditions with respect to output and emissions are the same as in equations (6) and-(7).

We notice that the tariff enhances incentives for firms to cut back on electricity use, as the shadow price of electricity is equal to the electricity price *plus* the extra tariff payments per unit of electricity use. Thus, firms exporting to the regulating region will tend to use less electricity per produced unit than firms selling to non-regulating regions if this tariff design is chosen.

3.5 Firm-targeted tariffs on direct and indirect emissions

Finally, we consider the case where the firm can reduce its tariff payments further if it can demonstrate that its electricity use comes from electricity plants with lower than average emission-intensities. The tariff then becomes $t(\varepsilon_{ij} + (x_{ij}^E / y_{ij})\varepsilon_{iE})$, where $\varepsilon_{iE} = e_{ij}^E / x_{ij}^E$ denotes the emission-intensity of the electricity bought by firm *i*. The firm now has an incentive to pay electricity generators an additional amount if they can deliver cleaner than average electricity. To what degree this is possible to realize without reshuffling of already existing low-carbon electricity is discussed in Section 4.2. A reduction in the emission-intensity ε_{iE} will lower the tariff payment by t for every unit of electricity used. Hence, the firm will be willing to pay up to $t\,x_{ij}^E$ for every unit reduction in ε_{iE}.

To investigate the outcome of such a tariff, we first assume, for the sake of simplicity, that the firm owns the electricity plant delivering electricity to the firm (in other words: the firm produces its own electricity). In this case, the firm internalizes all costs and benefits from electricity generation. Its profit function becomes:

(10)
$$\begin{aligned}\pi_{ij} &= p_j^y y_{ij} - p_j^x x_{ij} - p_j^E x_{ij}^E - t\left(\left(e_{ij} / y_{ij}\right) + \left(x_{ij}^E / y_{ij}\right)\left(e_{ij}^E / x_{ij}^E\right)\right) y_{ij} + p_j^E x_{ij}^E - p_E^x x_{iE}^E \\ &= p_j^y y_{ij} - p_j^x x_{ij} - p_j^E x_{ij}^E - t\left(e_{ij} + e_{ij}^E\right) + p_j^E x_{ij}^E - p_E^x x_{iE}^E\end{aligned}$$

s.t. $\quad y_{ij} = f_{ij}(x_{ij}, x_{ij}^E, e_{ij})$ and $x_{ij}^E = f_{iE}(x_{iE}, e_{iE})$

where f_{iE} is the production function for electricity generation, and x_{iE} denotes input into this production. Note that we keep $-p_j^E x_{ij}^E$ and $+p_j^E x_{ij}^E$ in the expression to explicitly state the (internal) payment for electricity.

The first-order conditions are now given by equations (6), (7) and the following:

(11)
$$\partial\pi_{ij} / \partial x_{ij}^E = \mu_{ij}\left(\partial f_{ij} / \partial x_{ij}^E\right) - \mu_{ij}^E = 0$$

(12) $$\partial \pi_{ij} / \partial e_{ij}^{E} = -t + \mu_{ij}^{E} \left(\partial f_{iE} / \partial e_{ij}^{E} \right) = 0$$

where μ_{ij}^{E} denotes the shadow price on the electricity production constraint $x_{ij}^{E} = f_{iE}(x_{iE}, e_{iE})$, which can be interpreted as the marginal costs of generating electricity. Equation (11) simply states that the marginal costs of generating electricity should equal the marginal benefits through its impact on firm output. This would look the same for a corresponding firm that is selling to non-regulating regions. Equation (12) states that the marginal costs of reducing emissions in electricity generation should equal the carbon price *t*, i.e., similar to equation (7) for direct emissions. Hence, the electricity generation used to supply the firms exporting to the regulating region faces the same incentives as electricity producers inside the regulating region. This is different from all previous tariff designs discussed above, where there are no incentives to reduce emissions from electricity generation. In those cases, as well as for firms selling to non-regulating regions, the implicit carbon price *t* in equation (12) is equal to zero.

Finally, we drop the assumption that the firm produces its own electricity, assuming instead that electricity generation is “outsourced”. One possibility could then be that the firm makes an agreement with an electricity producer. A likely outcome is that the two firms will come to an agreement that optimizes their joint profit, in which case the first-order conditions above still hold. Another possible outcome is that a market for low-carbon electricity production is established. We return to this issue in Section 4.2.

4. Numerical analysis

Our stylized partial analysis in Section 3 clarifies the economic incentives for firms outside the regulating region when exporting to the regulating region. The numerical CGE analysis incorporates these incentives within an economy-wide setting that accounts for supply and demand reactions of economic agents in a comprehensive manner and based on empirical data. Particularly important in our context are the price-responsive input-output relationships among firms that transmit cost effects across industries and countries. While our stylized analysis shows first-order impacts of carbon tariffs on exporting firms' output and emissions choices, the multi-sector, multi-region CGE framework enables us to address policy impacts on global emissions and carbon leakage, industry-specific competitiveness and trade patterns, as well as global cost-effectiveness and economic incidence of unilateral emissions regulation.[11]

Section 4.1 provides a non-technical summary of key model features. Section 4.2 details the implementation of firm-targeted tariffs. Section 4.3 lays out the data used for model parametrization. Section 4.4 describes our policy scenarios to study the effects of alternative carbon tariff designs. Section 4.5 is devoted to the presentation and discussion of simulation results.

4.1 Non-technical CGE model summary

For our quantitative economic impact analysis of targeted border carbon tariffs we use a multi-region, multi-sector CGE model of global trade and energy designed for the analysis of carbon emissions control strategies (see the Appendix for a detailed algebraic description).

Factor and commodity markets within each region are characterized by perfect competition. Primary factors of production include labor, capital and fossil fuel resources. Labor and capital are intersectorally mobile within a region but immobile between regions. Fossil fuel resources are specific to fossil fuel production sectors in each region.

Production in each industry and each region is represented by a representative firm using an "average" technology (see Figures A1-A2 in the Appendix). Firms producing commodities other than primary

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[11] Jakob et al. (2014) review the literature on consumption vs. production-based instruments and conclude that in order to assess the full effects of the policies, it is necessary to assess the global general equilibrium effects.

fossil fuels are modelled with three-level constant elasticity of substitution (CES) cost functions describing the price-dependent use of capital, labor, energy and materials. At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital and labor. At the second level, a CES function describes the substitution possibilities between intermediate demand for the energy aggregate and a value-added composite of labor and capital. At the third level, capital and labor substitution possibilities within the value-added composite are captured by a CES function whereas different energy inputs (coal, gas, oil, and electricity) enter the energy composite subject. 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 agent consists of net factor income and tax revenues net of subsidies. 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). Prices on traded goods may then develop differently among regions. 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 a CO_2 tax or (in the sensitivity analysis) as an (equivalent) exogenous emissions constraint. CO_2 emissions abatement 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 consumption activities).

4.2 Implementation of firm-targeted tariffs

The CGE model differentiates trade flows at the bilateral level. Each representative firm of each EITE-industry (sector) in each region disposes of production lines distinguished by destination.[12] When firm-targeted tariffs are introduced on bilateral trade flows, the export production lines that are subject to tariffs will have incentives to change the input mix as shown in the stylized model, Section 3.

We consider tariffs based on both direct emissions and indirect emissions from electricity use. When the latter part of the tariff is based on average emission-intensities in the region, electricity will become more expensive for exporters inducing them to use less electricity than before. When the tariff is based on the individual firm's indirect emissions, i.e., emissions from the electricity used by the individual firm, the firm has a direct incentive to buy less emission-intensive electricity. To represent this mechanism, we allow for differentiating electricity generation serving the different production lines of EITE-production.

Obviously, with a national electricity grid, it is not possible to know where exactly the electricity comes from (unless it is produced within the firm itself). Our setting can be interpreted as if a market will emerge for some labelling or green-certificate system, providing firms with credible documentation on the carbon content of their electricity input. To the extent that exporting to the

[12] All production lines within a sector share the same CES production technology. For the base-year calibration we assume that production across the different lines is split proportionally to base-year supply shares.

regulating region is a profitable option, one can expect a demand for such documentation to emerge. A certificate system could resemble systems already existing in several OECD countries, including several US states, the UK and the common Swedish-Norwegian green certificate market.[13] These markets are designed to support and increase electricity generation from renewables, partly for climate concern reasons, and could, therefore, be expected to reduce overall emissions and not only reshuffle the same, clean electricity volume among production lines.[14] The newly launched Chinese green certificate scheme illustrates that such schemes are relevant also for Non-OECD countries.[15] This might partly be a response to the potential threat of carbon tariffs. The firms exporting to the coalition could also initiate themselves a separate green certificate market as a response to such a tariff scheme.

It should be noted that our implementation of tariffs in the model still keeps the assumption that firms within each industry and region have homogenous technologies. This assumption is due to the lack of more specific data. The simplification comes at some loss in real-world heterogeneity. Even before introducing carbon tariffs emission intensities will likely vary across firms within the same sector. Carbon tariffs could, thus, lead to sorting where the least emission-intensive firms export to the regulating region, while the most emission-intensive firms supply to the other regions. Although the least emission-intensive firms may still find it profitable to reduce emissions further when tariffs are firm-targeted rather than region-specific, our model setting will probably overestimate the difference. This is also the case when we consider emissions from electricity generation. The representative firm

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[13] See http://www.cleanpowermarkets.com/green_certificates.php for states in the USA, http://www.greenenergyscheme.org/ for the UK, and http://www.nve.no/en/Electricity-market/Electricity-certificates/ for Norway-Sweden.

[14] If the green certificate scheme only leads to trade in certificates and no new renewable production, or if the scheme would have been implemented in any case, there will be 100% reshuffling.

[15] China has launched a green certificate system starting in July 2017, http://www.reuters.com/article/us-china-economy-renewables-idUSKBN15I0AK

in the electricity industry in each region represents an “average” technology over fossil and renewable technologies. Abatement can be interpreted as if the clean technology share in the composite increases. However, in reality instead of reducing emission-intensities in some plants, the exporters may switch to electricity plants with relatively low emissions. Thus, the options could be more discrete than our modelling implicitly assumes and, again, the firm-targeting will have smaller impacts than in a setting where agents are representative. However, as argued above a 100% reshuffling, i.e., no impact of firm-targeting indirect emissions, is less likely.

4.3 Data

Our CGE analysis is based on empirical data from the Global Trade, Assistance and Production (GTAP9) project, which provides detailed national accounts on production and consumption (input–output tables) together with bilateral trade flows and CO_2 emissions for the year 2011 (Narayanan et al., 2015). The GTAP9 dataset can be flexibly aggregated thereby reflecting specific requirements of the policy issue under investigation. As to sectoral disaggregation our composite dataset explicitly includes different primary and secondary energy carriers: *Coal*, *Crude Oil*, *Natural Gas*, *Refined Oil* 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 (EITE) industries (*Chemical Products*, *Non-Metallic Minerals*, *Iron & Steel*, *Non-Ferrous Metals*, and *Refined Oil*), which are regarded as sectors at risk of carbon leakage and therefore constitute prime candidates for the application of carbon tariffs. The remaining industries covered in our dataset include three transport sectors (air transport, water transport, and other transport), as well as a composite sector of all remaining manufacturers and services. Regarding regional coverage, we include major industrialized and developing regions that are important geopolitical players in the climate policy debate. Table 1 summarizes the sectors (commodities) and regions present in our actual impact analysis of alternative carbon tariff schemes.

For model parameterization, we follow the standard calibration procedure in applied general equilibrium analysis: base-year input-output data together with elasticities determine 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 behavior of the model agents. Beyond base-year cost and expenditure shares, the responses of agents to price changes are driven by a set of exogenous elasticities taken from the pertinent econometric literature. Elasticities in international trade (so-called Armington elasticities) indicate the substitutability between domestically produced goods and imported goods of the same variety. These Armington elasticities are taken from the GTAP database which also provides estimates for substitution elasticities among factor inputs to production. 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).

Table 1: Sectors and regions in the CGE model

Sectors and commodities	*Countries and regions*
Primary Energy	Europe – EU-28 plus EFTA (EUR)
Coal (COA)	United States of America (USA)
Crude Oil (CRU)	Russia (RUS)
Natural Gas (GAS)	Remaining Annex 1** (RA1)
*Emission-intensive & trade-exposed sectors**	Energy-Exporting Countries (EEX)
Chemical Products (CRP)	China (CHN)
Non-Metallic Minerals (NMM)	India (IND)
Iron & Steel (I_S)	Other Middle-Income Countries (MIC)
Non-Ferrous Metals (NFM)	Other Low-Income Countries (LIC)
Refined Oil (OIL)	
Other emission-intensive sectors	
Air Transport (ATP)	
Water Transport (WTP)	
Other Transport (OTP)	
Electricity (ELE)	
Other sectors	
All Other Manufactures and Services (AOG)	

*The EITE sectors that are subject to tariffs in the simulations.

**Includes Canada, Japan, Belarus, Ukraine, Australia, New Zealand, and Turkey.

4.4 Policy scenarios

For our impact assessment of alternative carbon tariff designs we consider six different carbon policy scenarios, which we compare with the business-as-usual (*BaU*) without carbon policy regulation (in our case: the base-year economic situation). In the first carbon policy scenario – the *benchmark* scenario (*Bench*) – we introduce a domestic cap-and-trade regime in the unilaterally regulating region (in our core case: Europe). The five remaining scenarios combine carbon pricing with tariffs for EITE products based on embodied carbon. The combinations are in line with the five systems analyzed in our stylized model analysis in Sections 3.1-3.5. They represent different combinations of two dimensions: (i) the embodiment of emissions, and (ii) the degree of targeting. When it comes to (i) we look at systems including direct emissions from the combustion of fossil fuels (*Dir*), and systems including both direct emissions and indirect emissions embodied in use of electricity (*Indir*). In terms of (ii) we study region-specific (*Reg*) and firm-targeted *(Firm)* tariffs. Beyond the four scenarios representing all combinations of the dimensions (i) and (ii), we include a system combining firm-targeting of direct emissions with embodiment of indirect emissions from electricity in a region-specific manner (*FirmDirRegIndir*).[16] Table 2 provides a summary of scenario characteristics.

Table 2: Overview of scenarios

Scenario	*Description*	*Theoretical analysis*
Bench	Uniform carbon price in EUR	
RegDir	Uniform carbon price + tariffs based on a *region*'s average *direct* emissions in the industry	See section 3.1
FirmDir	Uniform carbon price + tariffs based on *firm*-specific *direct* emissions	See section 3.2

[16] Winchester (2012) considers *RegIndir* and *FirmDirRegIndir*, but not the other three tariff scenarios.

RegIndir	Uniform carbon price + tariffs based on a *region*'s average *direct* emissions per industry and *indirect* emissions from electricity	See section 3.3
FirmDirRegIndir	Uniform carbon price + tariffs based on *firm*-specific *direct* emissions and region-specific *indirect* emissions from electricity	See section 3.4
FirmIndir	Uniform carbon price + tariffs based on *firm*-specific *direct* emissions and *indirect* emissions from electricity	See section 3.5

Our core simulations refer to unilateral emissions regulation in Europe. The *Bench* scenario involves a 20% reduction from *BaU* levels of domestic CO_2 emissions for Europe. The remaining five climate policy scenarios achieve the same *global* emissions reduction as *Bench* for alternative assumptions on the design of supplemental carbon tariffs applied to EITE goods. [17] This ensures that the six policy scenarios have the same changes from *BaU* of the global emissions and the subsequent welfare evaluation of the curbed climate change. Hence, our welfare measure does not suffer from excluding these contributions. Thus, welfare outcomes can be compared across scenarios irrespective of the evaluation of emissions, and we can readily quantify how alternative tariff designs affect the global cost-effectiveness of unilateral climate policy. If not stated otherwise, the effects of policy regulation are reported as percentage change from the *BaU* situation. In our exposition below, we use the acronym EUR to refer to Europe and the acronym non-EUR to denote all other regions.

[17] Technically, we adjust the emissions cap of the regulating region endogenously such that the carbon price in the regulating region ensures the global emissions to be ceiled at the emissions level of the *Bench* scenario.

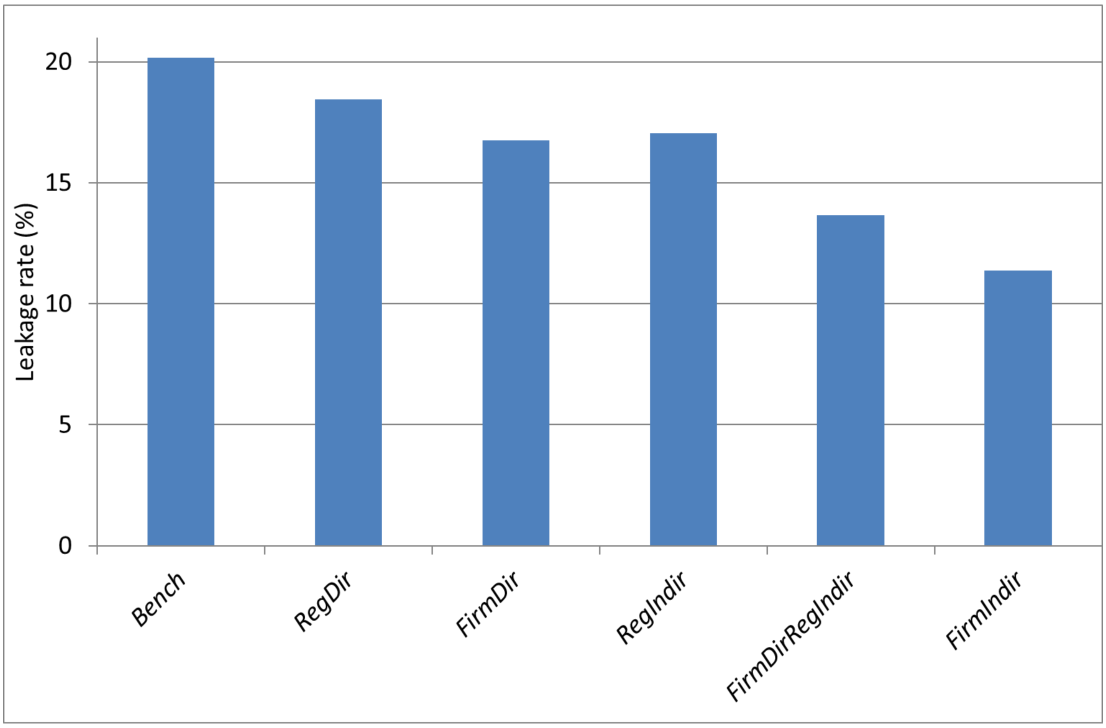
4.5 Simulation results

Carbon leakage

Figure 1 shows the carbon leakage rates across the policy scenarios, i.e., the increase in emissions in the non-EUR regions divided by the emissions reduction in EUR resulting from its policy. The CGE model computes leakage effects originating from both fossil fuel market changes and competitiveness impacts in the markets for energy-intensive goods. In *Bench*, the scenario without carbon tariffs, the leakage rate is 20.2.%. In line with previous studies (see e.g. Fischer and Fox, 2012, and the EMF study summarized by Böhringer et al., 2012a), we see that tariffs based on average regional embodied emissions reduce the leakage rates, and particularly so if they also take into account indirect emissions from electricity production. The resulting leakage rates in the *RegDir* and *RegIndir* scenarios are 18.5% and 17.0%, respectively.

Our analysis of firm-targeted tariffs adds new insight to the existing literature. As Figure 1 shows, carbon leakage declines further as the exporting firms face incentives to abate. Moving from *RegDir* to *FirmDir*, when the tariffs are based on direct embodied emissions, only, yields a modest reduction in the leakage rate, from 18.5% to 16.8%. The drop is considerably larger when the tariffs are based on indirect emissions from electricity use, too. The hybrid *FirmDirRegIndir* scenario, where the embodied emissions that the tariff accounts for are the firm-specific direct emissions and the region-specific indirect emissions from electricity, yields a carbon leakage rate of 13.7%, i.e., a reduction of one third from the benchmark level (*Bench*). With a tariff design that furthermore effectively targets the specific indirect emissions from the firm's use of electricity (*FirmIndir*) the leakage rate drops to 11.4% – i.e., around one half of the *Bench* rate. This is significant compared to earlier studies mentioned above.

Figure 1: Leakage rates (in %)



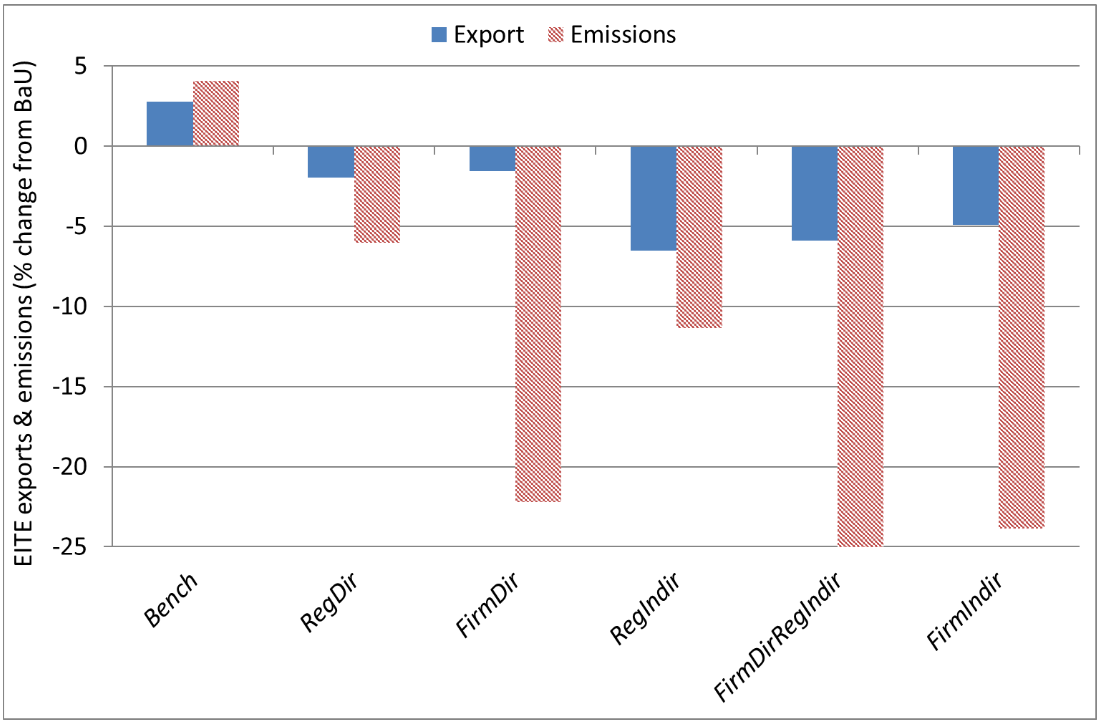
EITE exports, emissions and tariff payments

The variation in the carbon leakage effects is first of all explained by the different responses of EITE exporters to the tariff systems. Figure 2 shows how EITE exports from non-EUR regions to EUR are affected in the five policy scenarios compared with *BaU*. It also shows the impact on direct emissions (i.e., not including changes in indirect emissions from electricity generation) from this export activity. In the *Bench* scenario where carbon pricing is introduced we notice that export increases, which is as expected as EITE competitiveness in EUR deteriorates. (See also Figure 5 below.) We also see that emissions increase slightly more than output – increased emission intensities are due to a drop in relative fossil fuel prices caused by reduced consumption of these fuels in EUR.

The effects of introducing carbon tariffs on non-EUR EITE exports and emissions can be directly related to the theoretical analysis in Section 3. We see that EITE exports from non-EUR regions to EUR are reduced for all tariff scenarios, in accordance with the theoretical findings. More surprising at first glance is that for *all* carbon tariff systems, including the region-specific systems, the related emissions decrease even more than the export levels, i.e., emission intensities of non-EUR export production decline. Recall that the analytical model predicted unaltered emission intensities for region-specific tariffs. This happens in spite of a fall in relative fossil fuel prices, as also seen in the *Bench* scenario, which, in isolation, has the contrary effect of substituting fossil fuels for other inputs. The explanation is that the composition of EITE export changes towards less emission-intensive EITE goods and regions. Neither our simple theoretical analysis, nor aggregate numerical approaches like Winchester (2012), account for heterogeneity with respect to EITE goods or exporting regions. By means of our disaggregate numerical model we capture that export from regions with high emissions intensities is partly replaced by export from regions with lower emissions per output, as the tariffs are based on the average emissions intensities in the particular region. Regional and sectoral flexibility extends the latitude for agents' adaptations. It is, therefore, important to account for realistic heterogeneity. When moving to firm-targeted tariffs, two important effects are observable from Figure 2. Comparing, e.g., *RegDir* with *FirmDir* yields, first of all, that emissions related to EITE exports from non-EUR to EUR are drastically reduced,, due to a significant decline in average emission intensities. This suggests that firms' emission intensities have fallen as a response to the incentives that firm-targeted tariffs create for reducing emission intensities, thereby avoiding parts of the tariff burdens. This effect is also predicted by our theoretical analysis. Also, compositional changes of the export add to the emission reductions, however, by studying the emission intensities region by region and sector by sector we find that the former explanation is, indeed, the dominant.

The second observed effect when moving from *RegDir* to *FirmDir* in Figure 2 is that the tariffs in *FirmDir* lead to smaller cutbacks in exports from non-EUR regions to EUR than do *RegDir* tariffs. This is consistent with our theoretical analysis and the observation of emission intensities above: As long as firms find it profitable to reduce their emission intensity, their tariffs are reduced and, hence, it becomes more profitable to export to EUR.

Figure 2: EITE exports from non-EUR regions to EUR and associated direct emissions (% change from *BaU*)

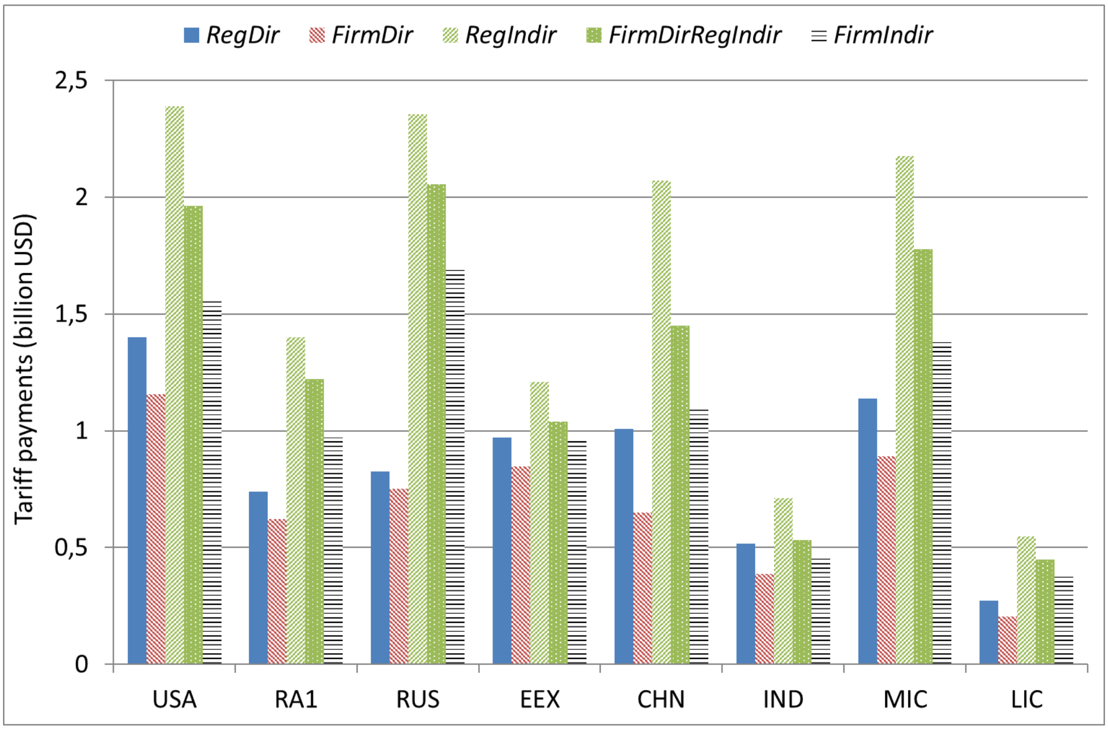


When comparing the *RegDir* and *FirmDir* scenarios with the corresponding scenarios where indirect emissions from electricity are accounted for (*RegIndir* and *FirmIndir*) we observe, as expected from theory, that the EITE export to EUR declines as the tariffs are increased and include more embodied carbon (see Figure 2). The hybrid case *FirmDirRegIndir* also has smaller exports than the two *Dir-*scenarios, and also lower (direct) emissions associated with this export production. However, we notice that emissions do not decline as much as exports when moving from *FirmDir* to *FirmIndir*, i.e., average emission intensities at the EITE plants increase. This counters the theoretical analysis and is due to effects not captured in the stylized partial equilibrium setting. One reason is that the CO_2 price in EUR is lowered (see Figure 4). Lower carbon leakage and, thus, reduced abatement efforts in EUR to keep global emissions unchanged, explains the drop in the CO_2 price. This is carried over to the carbon tariff, which then gives a weaker incentive to reduce emissions for non-EUR EITE firms. An additional explanation for the increased emission intensity is that when the tariff also includes indirect emissions from electricity, the EITE firms have incentives to switch away from the use of electricity towards other inputs such as fossil fuels (in the *FirmIndir* and *FirmDirRegIndir* scenarios). The *economy-wide* emission responses of including indirect emissions are, however, far larger in the *Firm* than in the *Reg* cases, because of the lower electricity input and additional abatement incentives in the electricity sector of the former. This is apparent from the theoretical results above.

The carbon tariff payments of different non-EUR regions are illustrated in Figure 3. We see that for all regions, the tariff payments decrease when moving from *RegDir* to *FirmDir*. This comes despite larger exports from the non-EUR regions to EUR in *FirmDir* and reflects the drop in the tariff rates. The main explanation is that the embodied emissions in the exports fall when the firms have the incentive to reduce their emission intensities.

The reduction in tariff payments of the non-EUR regions is even stronger when moving from *RegIndir* to *FirmIndir*. There are two mechanisms driving this result. First, emissions from the electricity generating plants that supply the EITE producers exporting to EUR, decline by 16%. This is due to a combination of lower emission intensity among these plants, and the reduction in electricity use for the EITE producers. These behavioral changes illustrate the potential benefits of additionally targeting indirect emissions from electricity generation when firm-targeted tariffs are used.

Figure 3: Carbon tariff payments by non-EUR regions (billion USD_{2011})

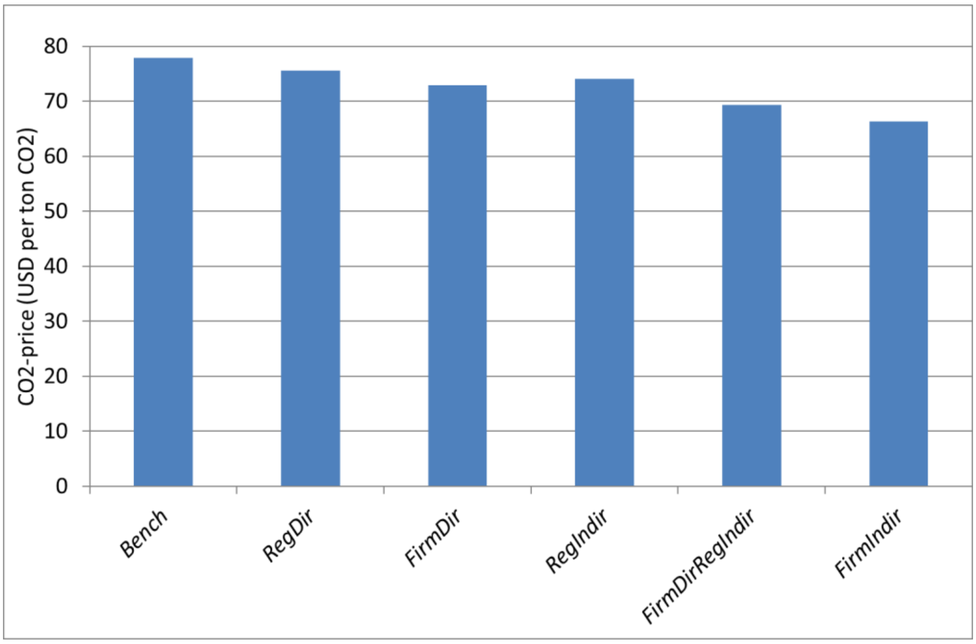


Key: USA - United States of America, RA1 - Remaining Annex 1), RUS – Russia, EEX - Energy exporting countries, CHN - China, IND – India, MIC - Other middle income countries, LIC - Other low income countries,

The second explanation is that the necessary CO_2 price to reach the global emission reduction target is reduced by 10% in the *FirmIndir* case compared with *RegIndir* (see Figure 4). As explained above, reduced carbon leakage allows for a drop in the domestic EUR emission price while keeping global emissions constant at the *Bench* level.

The hybrid regime *FirmDirRegIndir* provides incentives in EITE industries to use less electricity than in the *FirmDir* case. However, as for *RegIndir*, the emission intensities of power generators do not respond directly. This case, thus, reduces tariff payments for all non-EUR regions relative to *RegIndir*, but not as much as is seen for the *FirmIndir* case.

Figure 4: CO_2 price (USD_{2011} per ton CO_2)



Domestic EITE output

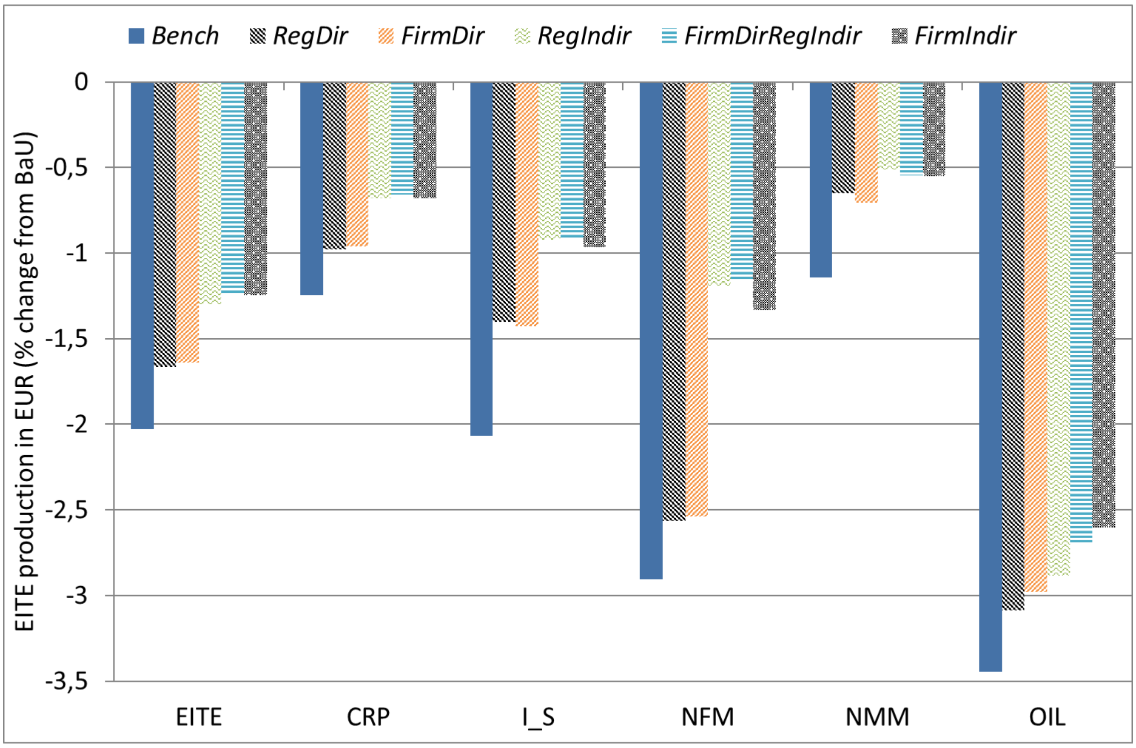
The introduction of carbon pricing in EUR (the *Bench* scenario) leads to lower output of EITE goods; see Figure 5. EITE goods are emission-intensive such that carbon pricing induces a non-negligible increase in production costs. Even in a closed market we should expect reduced EITE output as a consequence of structural change towards a less carbon intensive economy. In an open economy, unilateral emissions pricing will decrease international competitiveness of domestic EITE production with a relocation of EITE production to non-EUR regions, as seen in Figure 2. Figure 5 reveals differences across the EITE sectors, which are due to differences in emission intensities and trade exposure, the latter being reflected in initial trade shares and trade (Armington) elasticities.

Supplementing the carbon pricing with carbon tariffs attenuates the EITE output losses in EUR. This is consistent with the dampening effect on non-EUR EITE exports of introducing tariffs seen in Figure 2. This is in line with the findings of previous BCA studies; see the overview in Section 1; we find this in all the tariff scenarios and across all EITE sectors (cf. Figure 5).

Comparing *RegDir* with *FirmDir* reveals mixed results across industries. As EITE exports from the non-EUR regions to EUR slightly increase when moving from *RegDir* to *FirmDir* (Figure 2), one might expect the EUR output to move in the opposite direction, as a competitiveness effect. However, we see this only for two of the EITE industries (see Figure 5): *Iron & Steel* and *Non-Metal Minerals*. For the remainder we find that *FirmDir* results in a smaller fall from *BaU* in the EUR outputs than *RegDir*,which is also the case for the EITE as an aggregate. The explanation for these mixed results on output is that there are two driving forces that go in different directions: One is the increased competition from imports, which is due to lower tariffs for non-EUR firms under *FirmDir* than under *RegDir.* The other is lower production costs due to lower CO_2 and energy prices in *FirmDir* than in *RegDir* (see e.g. Figure 4), which tends to stimulate domestic output.

In the same vein, we can explain the sector-specific output effects of moving from region-specific to firm-targeted tariffs when indirect emissions from electricity are accounted for (from *RegIndir* to *FirmIndir*). In this case, the competition effect dominates the effects of lower production costs for all EITE industries except *Refined Oil* and *Chemical Products*, and thus output is lower. Aggregate EITE output also drops, though marginally.

Figure 5: EITE production in EUR (% change from *BaU*)



Key: EITE: composite of Emission-Intensive, Trade-Exposed Goods: CRP: Chemical Products, I_S: Iron & Steel, NFM: Non-Ferrous Metals, NMM: Non-Metallic Minerals: OIL: Refined Oil.

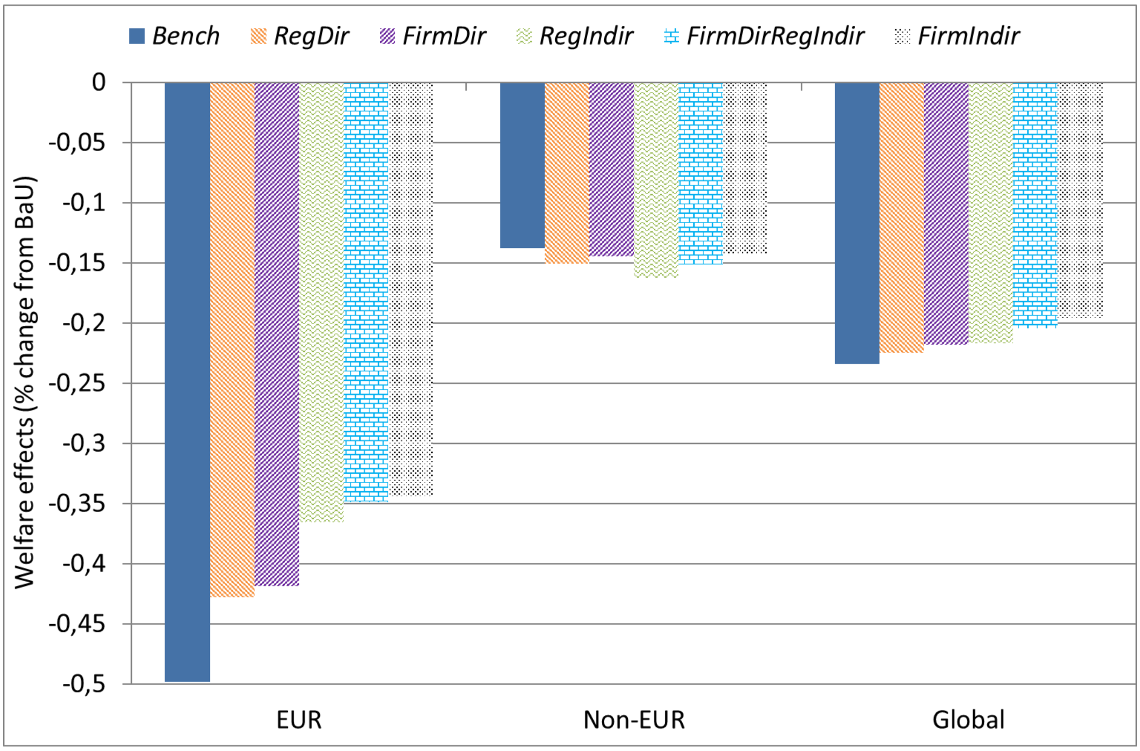
Welfare effects

Previous studies have shown that carbon tariffs are likely to reduce the welfare costs of climate policies, both for the unilaterally abating region and for the world as a whole, while non-abating regions suffer from the imposition of tariffs (Böhringer et al., 2012a; Fischer and Fox, 2012; Mattoo et al., 2009). Figure 6 confirms these findings. Welfare effects are stated in Hicksian equivalent variation in income and are comparable across scenarios since the changes in the excluded value of global emissions are equal.[18] We see that carbon tariffs moderate the welfare costs of unilateral action for EUR, while the costs for non-EUR rise.

[18] For welfare across countries, the equivalent variations are unweighted sums of each region's EV.

For EUR, moving to more targeted systems either by including indirect emissions and/or by giving non-EUR firms incentives to reduce emissions is beneficial. The most targeted system (*FirmIndir*) reduces the welfare costs of EUR by as much as 31% compared with *Bench*. The gain reflects both attenuated losses in comparative advantage vis-à-vis non-EUR exporters (see Figure 2 and 5), and lower carbon leakage which allows for higher emissions along with lower CO_2 prices in EUR (see Figure 2 and 4). The less targeted but potentially more feasible scenario *FirmDirRegIndir* reduces welfare costs of EUR by 30% compared with *Bench*, i.e., almost as much as the most targeted scenario.

Figure 6: Regional welfare effects (% change from *BaU*)



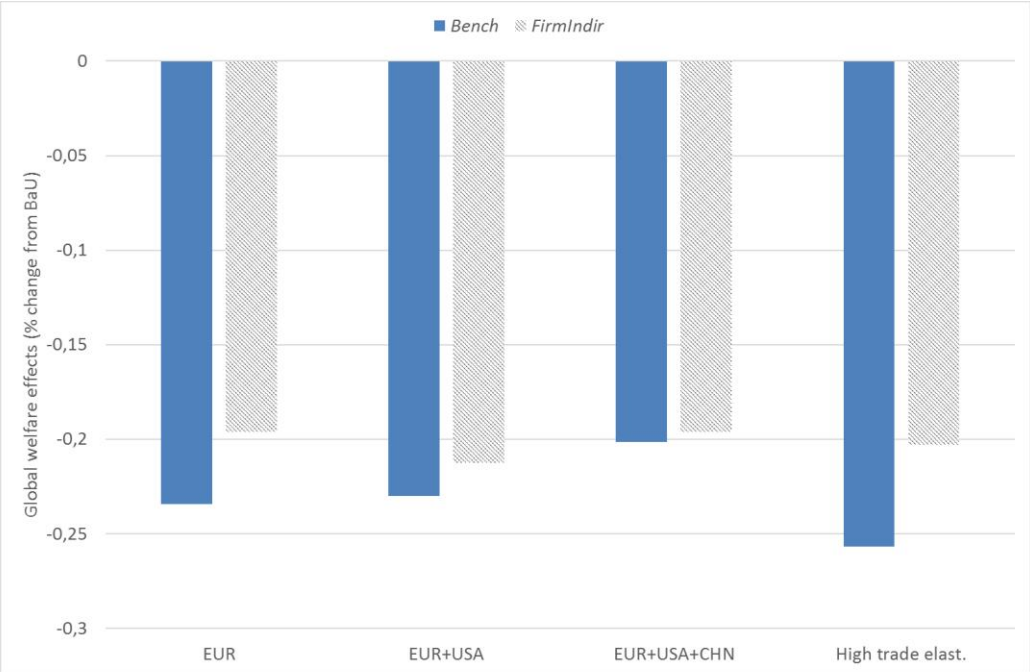
A main observation from Figure 6 is that trade-offs between the welfare effects for EUR and non-EUR are not severe. In particular, we notice that firm-targeted tariffs are better than region-specific tariffs for both EUR and non-EUR. This is true whether the tariffs are based on direct emissions only, or on both direct and indirect. Furthermore, including indirect emissions in firm-targeted tariffs (*FirmIndir* vs. *FirmDir*) benefits EUR without increasing the costs for non-EUR, because firm-targeted tariffs ensure non-EUR firms the opportunity to reduce their tariff rates by reducing emission intensities both in own production and their electricity input. This possibility is absent when tariffs on similar goods are common for all firms in a non-EUR region. Then, including indirect embodied emissions in the basis for the tariff rates (*RegIndir* vs. *RegDir*) will increase the rates, and as a consequence the costs for the non-EUR regions increase by 8%. Interestingly, the most targeted system, where firms exporting to EUR are tariffed according to their direct and indirect emissions (*FirmIndir*) is slightly less costly for the non-EUR regions than the least targeted (*RegDir*). Moreover, welfare costs for EUR are 20% lower. *FirmIndir*, the cheapest carbon policy regime for the world as an entity is, thus, not riddled by severe distributional dilemmas.

All the tariff regimes reduce *global* welfare costs of EUR's carbon policies relative to *Bench*; the most effective, *FirmIndir*, by as much as 16%. This is a larger gain in global cost-effectiveness brought about by carbon tariffs than in previous studies cited above. The reason is that this carbon tariff regime is based on firm-specific information. As shown in the theoretical section, such carbon tariffs are more targeted than previously investigated designs, because they motivate unit emission reductions in the firms (both directly and indirectly) involved in exporting to EUR. The reduction in the global welfare loss in Figure 6 by adding region-specific tariffs based on the direct emissions (*RegDir*) to the carbon price in *Bench* is merely 4%. Going from *RegDir* to *FirmDir* implies an additional 3 percentage points reduction in welfare costs. Further, also including indirect emissions in *FirmDirRegIndir* and *FirmIndir* saves another 6 and 9 percentage points of the welfare costs – in total a 13% and 16% welfare gain compared with *Bench*.

Sensitivity analysis

To investigate the robustness of our insights we perform sensitivity analysis with respect to two key drivers of economic impacts: the regional coverage of 20% unilateral abatement on the one hand (jointly achieved by the abating regions by trading carbon permits at a common CO_2 price) and the trade responsiveness, captured by the Armington elasticities of substitution between domestic and foreign products. We focus, hereby, on the most targeted tariff alternative with firm-targeted tariffs including emissions from the electricity input – *FirmIndir*.

Figure 7: Global welfare effects with different coalitions and trade (Armington) elasticities (% change from *BaU*)



Key: EUR – Europe, USA - United States of America, CHN - China

Figure 7 shows that as we expand unilateral emission regulation from EUR to include also the United States (EUR+USA) and both the USA and China (EUR+USA+CHN) there are gradually less global benefits from supplementing carbon pricing with firm-targeted tariffs. This observation, which is relevant for the eventual outcome of the Paris Agreement, is as expected: when the coalition becomes larger, the non-regulating region becomes smaller and carbon leakage less severe. Both under *Bench* and *FirmIndir* the leakage rate drops by more than 50% when the USA joins EUR in the coalition and an additional 50% when China enters.

We also observe from Figure 7 that including the USA in the coalition slightly decreases global welfare costs, even though the global climate policy ambitions increase. This is also the case when China is included. That is, total costs are dampened in spite of the cost effects of larger emission reductions. The reason is that when first USA and then China enter, costs are lowered by cheaper abatement options available for EUR.[19]

Compared to the effects of regional expansion the benefits from targeted tariffs are less sensitive to the choice of trade (Armington) elasticities. Still, the welfare benefits of firm-targeted tariffs increase somewhat with higher trade elasticities (the elasticities are doubled from the core scenarios setting). This is seen by comparing the first and last pair of columns in Figure 7, which both depicts the case for the EUR coalition. This is also as expected – the larger the trade sensitivity the larger is the leakage rates and, thus, the higher are the benefits of targeting carbon tariffs.

In our main scenarios above it is assumed that non-coalition countries are able to adapt to the carbon tariffs by specializing production lines to serve the coalition markets. Our third sensitivity is an alternative scenario, considered in Winchester (2012), where non-coalition producers have to keep to only one production line. In this case, the producers can only reduce the incidence of the tariff by reducing the carbon intensity of their aggregate production. However, since they only have one production line, it becomes costlier to reduce the emission intensity of their export production, since they then have to reduce the emission intensity of their total production. On the other hand, any reduction of emission intensity will have a bigger impact on overall emissions.

In this sensitivity, we find that the latter effect dominates the former when it comes to carbon leakage. With tariffs based on direct emissions only, the leakage rate becomes 13.3% (compared to 16.8% in

[19] Global emissions reductions are 2.2% with the EUR coalition, 5.8% with the EU+US and 10.8% with EU+US+China. The CO_2 price in the coalition declines from 78 USD per ton in the EUR coalition to 51 USD in the EUR+USA coalition and 29 USD in the EUR+USA+CHN coalition.

the *FirmDir* case), whereas the leakage rate drops to 9.9% when also indirect emissions are accounted for (compared to 11.4% in the *FirmIndir* case). Welfare costs for EUR are also reduced in this case, i.e., from 0.42% to 0.35% in the *Dir* case and from 0.34% to 0.24% in the *Indir* case. Welfare costs for the non-EUR is, as expected, slightly increased, but global welfare costs are marginally reduced. Compared to our main case with specialized production lines, the restriction makes the non-EUR worse off, indicating that specialized production lines will be established if possible. In a real world setting, we believe that firms are able to specialize in shipping to specific markets and typically do so.

5. Conclusions

The climate effect of unilateral carbon pricing is undermined by carbon leakage. To mitigate leakage and increase global cost-effectiveness of unilateral abatement action the literature suggests supplementing unilateral carbon pricing with carbon tariffs designed so as to tax all the carbon emissions directly and indirectly embodied in net imports equally to domestic emissions. In this paper we both theoretically and numerically analyze and discuss the possibilities, limitations, and implications of alternative carbon tariff systems designed to limit increases in the carbon footprint of producers in non-regulating countries.

Our main contribution is to scrutinize practical tariff systems that are more targeted and, thus, give exporting firms more incentives to respond to the tariffs than systems previously studied, with Winchester (2012) representing the current research frontier. We find the largest gains in cost-effectiveness both globally and for the regulating coalition when the tariffs not only respond to a non-coalition firm's direct emissions but also to its indirect embodied emissions from electricity use. Furthermore, the exporters' competitiveness and the overall welfare in the non-coalition will be less randomly and less adversely affected in these systems. This beneficial distributional impact of a more targeted approach could facilitate a higher degree of legitimacy and legality of carbon tariffs as a supplemental instrument in unilateral climate policy. The disaggregated industrial and regional description of our analysis compared to, e.g. Winchester (2012), captures a large variety of relevant reallocations. In general, the more flexible are the responses to carbon tariffs, the less adversely affected will exporters be and the more politically feasible will carbon tariff schemes appear. Also, the effectiveness of the carbon tariffs in reducing leakage improves as a result of more flexibility.

Besides the legal and political feasibility, we also discuss the practicality and administrative burden of such systems. We argue that administration and compliance costs are steadily falling along with the advances in information and communication technologies. A precondition for obtaining the potential global climate benefits of targeted tariffs, policies must succeed to actually reduce over-all emissions outside the coalition, not just redirect the deliveries of already less emission-intensive output to the coalition. This is ensured in our numerical model, as producers are modeled as sector-specific representative agents that deliver both to the coalition and to other markets, though in different production lines. In the real world, where firms within the same industry can differ with respect to emission-intensities, mere reshuffling will dampen the carbon leakage and global welfare benefits of targeted tariffs compared to our results. In the numerical analysis, we differentiate the EITE industry both with respect to goods and location to partly account for such compositional responses. The effects are, nevertheless, considerably stronger than in previous carbon tariff studies.

The carbon tariff system that also targets the emissions from electricity use is more vulnerable to the reshuffling caveat, since some policy arrangement, for instance a green certificate system, would be necessary to ensure that indirect emissions reductions within power generation occur. To what extent this will be realistic will depend on the possibility of reshuffling the existing generation from relatively clean power to exporters facing firm-specific tariffs. The larger such reshuffling, the more likely that the indirect emission reductions computed in our study will overestimate obtainable effects.

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Appendix: Algebraic Model Summary

Below we provide an algebraic description for the multi-region multi-sector CGE model underlying our quantitative simulation analysis. Tables A.1 – A.5 contain the notations for variables and parameters employed within our algebraic exposition. 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.

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.[20] Differentiating the unit

[20] 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} then denotes the zero-profit condition of value-added production in sector *i* and region *r*.

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 i as an index comprising all sectors including the final consumption (i=C), public good provision (i=G), and investment (i=I). Figures A1–A3 complement our algebraic description with 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).

Table A.1: Indices and sets

i (alias j)	Index for all sectors (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 A.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* destined for domestic supply
X_{irs}	Production in sector *i* and region *r* destined for export to region *s*
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 value-added composite in sector *i* and region *r*
p_{ir}^{E}	Price of energy composite in sector *i* and region *r*
p_{ir}^{Y}	Output price of good *i* produced in region *r* for domestic supply
p_{irs}^{X}	Output price of good *i* produced in region *r* for export supply to region *s*

p_{ir}^{M}	Price of import composite 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

Table A.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* ($i \in FF$)
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 A.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 the 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	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 A.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*
$a_i^{CO_2}$	CO_2 emissions coefficient for fuel *i* (coal, gas, refined oil)
$\varepsilon_{ir}^{CO_2}$	Embodied CO_2 content of good *i* produced in region *r*

Zero-profit conditions

1. Production of goods (except fossil fuels) supplied to the domestic market

Production of commodities (except primary fossil fuels - $i \notin FF$) supplied to the domestic market 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.[21] 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

[21] 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.

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:

(A1) $$\Pi_{ir}^{KL} = p_{ir}^{KL} - \left[\theta_{ir}^{K} v_r^{1-\sigma_{ir}^{KL}} + \left(1-\theta_{ir}^{K}\right) w_r^{1-\sigma_{ir}^{KL}}\right]^{\frac{1}{1-\sigma_{ir}^{KL}}} \leq 0$$

The unit-profit function for the energy composite is:

(A2) $$\Pi_{ir}^{E} = p_{ir}^{E} - \left[\theta_{ir}^{ELE} p_{ELE,r}^{A\;1-\sigma_{ir}^{ELE}} + \left(1-\theta_{ir}^{ELE}\right)\left(\sum_{j\in CGO}\theta_{jir}^{CGO}\left(p_{jr}^{A} + p_r^{CO_2} a_j^{CO_2}\right)^{1-\sigma_{ir}^{CGO}}\right)^{\frac{1-\sigma_{ir}^{ELE}}{1-\sigma_{ir}^{CGO}}}\right]^{\frac{1}{1-\sigma_{ir}^{ELE}}} \leq 0$$

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:

(A3) $$\Pi_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{KLE}\left[\theta_{ir}^{KL} p_{ir}^{KL\;1-\sigma_{ir}^{KLE}} + \left(1-\theta_{ir}^{KL}\right) p_{ir}^{E\;1-\sigma_{ir}^{KLE}}\right]^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{KLE}}} + \left(1-\theta_{ir}^{KLE}\right)\left(\sum_{j\notin NE}\theta_{jir}^{NE} p_{jr}^{A\;1-\sigma_{ir}^{NE}}\right)^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{NE}}}\right]^{\frac{1}{1-\sigma_{ir}^{KLEM}}} \leq 0$$

<u>2. Production of fossil fuels supplied to the domestic market</u>

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 aggregate. The unit-profit function for primary fossil fuel production is:

(A4) $$\Pi_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{Q} q_{ir}^{1-\sigma_{ir}^{Q}} + \left(1-\theta_{ir}^{Q}\right)\left(\theta_{Lir}^{FF} w_r + \theta_{Kir}^{FF} v_r + \sum_{j}\theta_{jir}^{FF}\left(p_{ir}^{A} + p_r^{CO_2} a_j^{CO_2}\right)\right)^{1-\sigma_{ir}^{Q}}\right]^{\frac{1}{1-\sigma_{ir}^{Q}}} \leq 0$$

The associated variable is the activity level Y_{ir} of producing good *i* in region *r* for the domestic market.

3. Imports aggregate across regions

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

$$\text{(A5)}\quad \Pi_{ir}^{M} = p_{ir}^{M} - \left[\sum_{s} \theta_{isr}^{M} \left(p_{isr}^{X} + \varepsilon_{is}^{CO_2} p_{r}^{CO_2} \right)^{1-\sigma_{ir}^{M}} \right]^{\frac{1}{1-\sigma_{ir}^{M}}} \leq 0$$

The associated variable is the activity level M_{ir} of forming the import composite for good *i* in region *r*. With region-specific carbon tariffs, the specific CO_2 emission content $\varepsilon_{is}^{CO_2}$ of good *i* exported from region *s* will be subjected to the carbon price prevailing in the importing region *r*. For example, steel exported from countries without domestic carbon controls would face the carbon price of the importing regulated country on direct emissions (those due to the combustion of fossil energy in steel production) and – with an extended coverage of emissions – also on indirect emissions. The model accounts for indirect emissions created by the generation of electricity for use in production of the respective good (for example electricity used in the steel production). Note that with region-specific tariffs, where the carbon content of exports is typically taxed at the industry average, tariffs do not give individual polluters responsible for the upstream emissions an immediate incentive to adopt less emission-intensive production techniques. This is different from firm-targeted carbon tariffs, which provide immediate cost incentives for domestically unregulated exporting firms to reduce CO_2 emissions in export production to countries with carbon pricing. The modelling of firm-targeted carbon tariffs is explained in the section on export production; see 5. below.

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 region-specific imported varieties of the same good. The unit-profit function for the Armington aggregate is:

(A6) $\prod_{ir}^{A} = p_{ir}^{A} - \left[\theta_{ir}^{A} p_{ir}^{Y\,1-\sigma_{ir}^{A}} + \left(1-\theta_{ir}^{A}\right) p_{ir}^{M\,1-\sigma_{ir}^{A}} \right]^{\frac{1}{1-\sigma_{ir}^{A}}} \leq 0$

The associated variable is the activity level A_{ir} of forming the Armington composite for good *i* in region *r*.

5. Export production of goods

Exports of commodity *i* from region *r* to regions *s* are captured by bilateral export production lines. Export production on each line follows the same nested CES structure as production for the domestic market with identical cross-price substitution elasticities and base-year cost shares. For the sake of brevity, we refer to the composite cost function in capital (K), labor (L), energy (E) and material (M) inputs as c_{irs}^{KLEM} within the unit-profit function:

(A7) $\prod_{irs}^{X} = p_{irs}^{X} - c_{irs}^{KLEM} \leq 0$

The associated variable is the activity level X_{irs} of producing good *i* for exports from region *r* to region *s*.

As with production for the domestic market (see 1. and 2. above), CO_2 emissions from fuel combustion in export production lines are subject to domestic CO_2 emission prices for regions with a domestic emissions cap-and-trade regime. Firm-targeted carbon tariffs come into play on bilateral export production lines of countries *r* without emission regulation to countries *s* with emission regulation. In this case, the carbon content $\varepsilon_{jr}^{CO_2}$ of intermediate fossil fuel inputs *j* in export production of good *i* will be directly subjected to the carbon price of the importing country *s*, leading to an effective user price $p_{jr}^{A} + \varepsilon_{jr}^{CO_2} p_{s}^{CO_2}$. When firm-targeted tariffs are also levied on the indirect emissions from electricity, we furthermore differentiate electricity entering as intermediate input into export production lines. Exporters then have an additional incentive to reduce their indirect emissions contribution from the use of electricity (e.g., depending on whether the firm buys coal power, gas power or renewable power).

Market-clearance conditions

6. Labor

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

$$\text{(A8)} \quad \bar{L}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial w_r} + \sum_{i,s} X_{irs} \frac{\partial \Pi_{irs}^X}{\partial w_r}$$

The associated variable is the wage rate w_r in region r.

7. Capital

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

$$\text{(A9)} \quad \bar{K}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial v_r} + \sum_{is} X_{irs} \frac{\partial \Pi_{irs}^X}{\partial v_r}$$

The associated variable is the price of capital services v_r in region r.

8. 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:

$$\text{(A10)} \quad \bar{Q}_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial q_{ir}} + \sum_{is} X_{irs} \frac{\partial \Pi_{irs}^X}{\partial q_{ir}}$$

The associated variable is the rent q_{ir} to the natural resource *i* in region *r*.

9. Energy composite

The market-clearance condition for the energy composite is:

$$\text{(A11)}\quad E_{ir} \geq Y_{ir}\frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{E}} + \sum_{is} X_{irs}\frac{\partial \Pi_{irs}^{X}}{\partial p_{ir}^{E}}$$

The associated variable is the price of the energy composite p_{ir}^{E} to sector *i* in region *r*.

10. Value-added composite

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

$$\text{(A12)}\quad KL_{ir} \geq Y_{ir}\frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{KL}} + \sum_{is} X_{irs}\frac{\partial \Pi_{irs}^{X}}{\partial p_{ir}^{KL}}$$

The associated variable is the price of the value-added composite p_{ir}^{KL} to sector *i* in region *r*.

11. Output for domestic supply

Output destined for the domestic intermediate markets enters Armington demand. The market-clearance condition for domestic output entering intermediate Armington demand is:

$$\text{(A13)}\quad Y_{ir} \geq \sum_{j} A_{jr}\frac{\partial \Pi_{jr}^{A}}{\partial p_{ir}^{Y}}$$

The associated variable is the price p_{ir}^{Y} of the commodity *i* produced in region *r* and destined for domestic intermediate demand.

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

$$\text{(A14)}\quad Y_{Gr} \geq \overline{G}_{r}$$

The associated variable is the price p_{Gr}^{Y} of the composite public good in region *r*.

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

(A15) $Y_{Ir} \geq \bar{I}_r$

The associated variable is the price p^Y_{Ir} of the composite investment good in region r.

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

(A16) $Y_{Cr} \geq \dfrac{INC_r}{p^Y_{Cr}}$

The associated variable is the price p^Y_{Cr} of the composite final consumption good in region r.

12. Output for export supply

Output destined for exports must satisfy the import demand by other regions. The bilateral market-clearance conditions are:

(A17) $X_{irs} \geq M_{is} \dfrac{\partial \Pi^M_{is}}{\partial p^X_{irs}}$

The associated variable is the price p^X_{irs} of the commodity i produced in region r and destined for export supply to region s.

13. Armington aggregate

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

(A18) $A_{ir} \geq \sum_j Y_{jr} \frac{\partial \Pi^Y_{jr}}{\partial p^A_{ir}}$

The associated variable is the price p^A_{ir} of the Armington good *i* in region *r*.

14. Import aggregate

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

(A19) $M_{ir} \geq A_{ir} \frac{\partial \Pi^A_{ir}}{\partial p^M_{ir}}$

The associated variable is the price p^M_{ir} of the import composite *i* in region *r*.

15. Carbon emissions

A fixed supply of CO_2 emissions limits demand for CO_2 emissions in region *r*, effectively establishing a domestic emissions cap-and-trade system. The market-clearance condition for CO_2 emissions is[22]:

(A20) $\overline{CO2}_r \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^{CO_2}_r} + \sum_{is} X_{irs} \frac{\partial \Pi^X_{irs}}{\partial p^{CO_2}_r}$

Income-balance conditions

16. 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

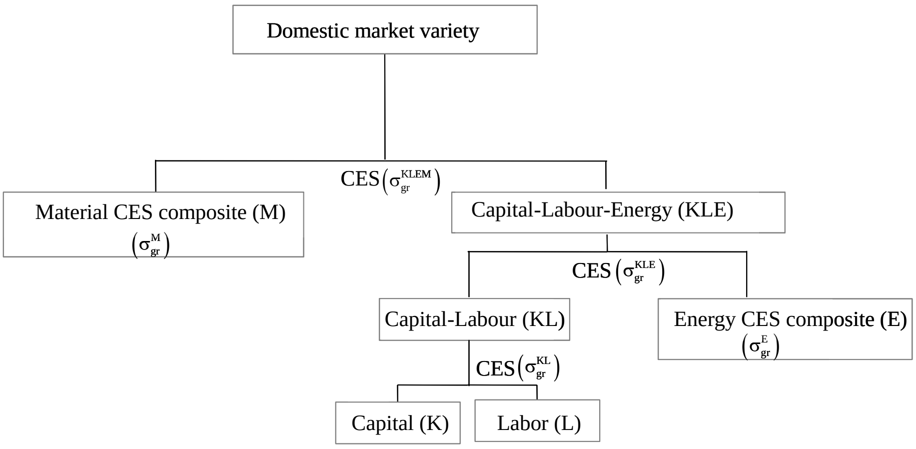
[22] In scenarios where we impose a global emission constraint to accommodate the coherent global cost-effectiveness analysis of unilateral carbon pricing policies the regional carbon emission constraint for countries with unilateral emission regulation is scaled uniformly such that emissions across all regions do not exceed the (exogenous) global emission constraint.

balance of payment. The income-balance condition for the representative agent is:

(A21)

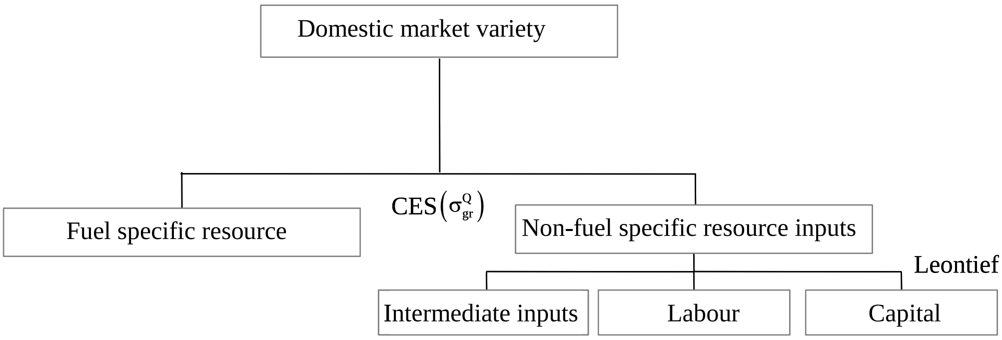
$$
\begin{aligned}
INC_r = \ & w_r \overline{L}_r + v_r \overline{K}_r - p_{Ir}^{Y} \overline{Y}_{Ir} - p_{Gr}^{Y} \overline{Y}_{Gr} + \overline{B}_r \\
& + \sum_{i \in FF} q_{ir} \overline{Q}_{ir} + p_r^{CO_2} \overline{CO2}_r + \sum_{ijs} X_{isr} \frac{\partial \Pi_{isr}^{X}}{\partial \left(p_{js}^{A} + \varepsilon_{js}^{CO_2} p_r^{CO_2} \right)} \varepsilon_{js}^{CO_2} p_r^{CO_2} + \sum_{is} M_{ir} \frac{\partial \Pi_{ir}^{M}}{\partial \left(p_{isr}^{X} + \varepsilon_{is}^{CO_2} p_r^{CO_2} \right)} \varepsilon_{is}^{CO_2} p_r^{CO_2}
\end{aligned}
$$

Figure A1. Nesting in Non-Fossil-Fuel Production



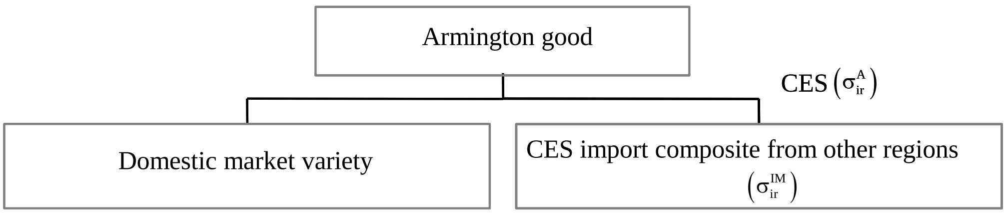
Note: CES=constant elasticity of substitution.

Figure A2. Nesting in Fossil-Fuel Production



Note: CES=constant elasticity of substitution.

Figure A3. Nesting in Armington Production



Note: CES=constant elasticity of substitution.