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**Abstract:** Carbon-based import tariffs are discussed as policy measures to reduce carbon leakage and increase the global cost-effectiveness of unilateral $CO_2$ emission pricing. We assess how the potential of carbon tariffs to increase cost-effectiveness of unilateral climate policy depends on the magnitude and composition of carbon embodied in trade. For our assessment, we combine multi-region input-output (MRIO) analysis with computable general equilibrium (CGE) analysis based on data from the World Input-Output Database (WIOD) for the period 1995 to 2007. The MRIO analysis confirms that carbon embodied in trade has sharply increased during this period. Yet, the CGE analysis suggests that the effectiveness of carbon tariffs in reducing leakage and improving global-cost effectiveness of unilateral climate policy does not increase over time, whereas the potential to shift the economic burden of $CO_2$ emissions reduction from abating developed regions to non-abating developing regions increases substantially.

**Keywords:** carbon tariffs; unilateral climate policy; computable general equilibrium

**JEL classifications:** Q58; D57; D58

# 1. Introduction

Our interest in the analysis of carbon embodied in trade emerges from two major developments over the last two decades. First, in spite of the more recent global agreement to limit global warming to less than 2 degrees Celsius, there is still no global climate treaty which prescribes legally binding emission caps for individual countries. Second, trade in carbon embodied in goods has increased over time. Against these developments our analysis investigates whether embodied carbon tariffs have become a more potent instrument for avoiding counter-productive emission leakage and for strengthening global cost-effectiveness of unilateral $CO_2$ emission pricing.

With respect to the development of international climate policy, it can be stated that irrespective of the recent Paris agreement, the prospects for globally coordinated stringent emission abatement with harmonized emission pricing remain bleak. The Paris agreement negotiated at the 21st Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change in Paris in December 2015 declares global consensus on keeping the global mean surface temperature increase below 2 degrees Celsius compared to pre-industrial levels (UNFCCC, 2015a). For the first time in climate policy history, developing countries also signaled their willingness to reduce their greenhouse gas (GHG) emissions (in turn for climate finance transfers). In the forerun to Paris, many countries communicated their intended nationally determined contributions (INDCs) to reduce GHG emissions (UNFCCC, 2015b). However – contrary to the previous Kyoto Protocol – there is no legal enforcement mechanism if a set target is not met. It remains to be seen how the voluntary INDCs of countries will be followed up in more detail over the next years and eventually lead to global emission pricing at stringent levels.

To date, the most comprehensive approach for transnational emission pricing is the European Union Emissions Trading Scheme (EU ETS) which entered into force in 2005 setting a cap on carbon emissions from energy-intensive sectors within the EU. A report by the World Bank in 2015 which takes stock of the state and trends of carbon pricing in the world finds that only 12% of global annual GHG emissions are covered by an emission pricing instrument (World Bank, 2015). To conclude: The world community is still far off from a comprehensive GHG emission pricing and it is quite likely that a situation with much more stringent emission regulation in industrialized countries and no or quite lenient emission regulation in the developing world will prevail for quite some time.

A critical drawback of such disparate emission regulation, however, is emission leakage, i.e., the relocation of emissions from regulating countries to parts of the world economy subject to no or weaker regulation (Felder and Rutherford, 1993; Hoel, 1991). Leakage can occur through international energy markets, as the drop in demand for fossil fuels in the abating countries lowers world prices for these goods, which in turn stimulates fossil fuel demand abroad. It can also occur through the markets for emission-intensive goods, as the cost of producing these goods in the abating countries rises and incentivizes the relocation of emission-intensive production abroad.

Given the global nature of the GHG emission externality and the fact that only *global* GHG emissions matter for climate protection, emission leakage reduces the global cost-effectiveness of unilateral policies. Concerns on emission leakage and undue competitiveness losses of emission-intensive and trade-exposed industries have fostered the policy appeal of carbon tariffs in industrialized countries.[1] In order to extend the reach of domestic carbon regulation, carbon tariffs apply the domestic $CO_2$ price as a tax on emissions embodied in imports from countries without (or with very lenient) emission regulation.[2] In theory, supplemental carbon tariffs bear the potential to increase global cost-effectiveness compared to domestic emission pricing only.

The policy appeal of carbon tariff in terms of its impact on leakage and global cost-effectiveness has been examined in a number of empirical studies. Fischer and Fox (2012), for example, investigate anti-leakage measures that could complement unilateral emission pricing and conclude that full border carbon adjustment is likely the most effective anti-leakage policy.[3] Peterson and Schleich (2007) evaluate embodied carbon tariff options for the sectors covered by the EU ETS and find only marginal overall effects in terms of their capability to reduce carbon leakage. Monjon and Quirion (2011) also compare the effectiveness of various designs for border carbon adjustment and output-based allocation in reducing carbon leakage from EU ETS sectors. The authors show that border carbon adjustment is the most effective anti-leakage policy. Böhringer et al. (2014) investigate anti-

[1] Aside the prospects of reducing carbon leakage and hence ameliorating anxieties regarding the loss of competitiveness in domestic industries, advocates of carbon tariffs also point out that unilateral policies geared towards emission abatement solely in domestic production sectors ignore the carbon footprint of imported goods and therefore amount to shirking of polluter-pays responsibilities.

[2] Embodied carbon refers to the entire $CO_2$ that is emitted to produce and supply a certain good to the destination market, i.e., direct $CO_2$ emissions from fossil fuel combustion in the production process as well as indirect $CO_2$ emissions to produce intermediate inputs such as electricity or international transportation services.

[3] Full border carbon adjustment consists of carbon tariffs on the import side and carbon-related rebates to exports.

leakage measures as a function of abatement coalition size. The authors identify full border carbon adjustment as the superior measure to improve the global cost-effectiveness of unilateral emission pricing. A large number of empirical studies also emphasize the potential of carbon tariffs to shift the economic burden to non-abating regions (see e.g., Böhringer et al., 2012; Böhringer et al., 2011; Ghosh et al., 2012; Weitzel et al., 2012).

To summarize: The bulk of empirical analysis on the implications of carbon tariffs comes up with two central findings (for summaries see e.g., Böhringer et al., 2012; Branger and Quirion, 2014): (i) carbon tariffs are potent in reducing emission leakage but gains in global cost-effectiveness remain rather modest, and (ii) carbon tariffs shift the economic burden of emission reductions from regulating developed regions to unregulated developing regions.

Empirical analyses so far have been based on single pointwise assessments for specific base-years without accounting for the fact that embodied carbon in trade has increased significantly over time. While industrialized OECD countries have become large net importers, developing Non-OECD countries are mostly large net exporters of embodied carbon (Caldeira and Davis, 2011; Peters and Hertwich, 2008; Peters et al., 2011). This raises the policy-relevant question on the performance of carbon tariffs if one considers the increasing amount of carbon embodied in trade. Clearly, if there was no carbon embodied in trade at all, the implementation of carbon tariffs would have no effect. In turn, it seems plausible at first glance that the potential of carbon tariffs to reduce leakage and increase global cost-effectiveness of unilateral emission pricing augments as trade in carbon sharply increases. Another policy-relevant question is how the burden shifting potential of carbon tariffs evolves over time – given the commitment of industrialized countries to avoid adverse economic spillover effects of their emission regulation to the developing world.[4]

We address these issues by combining multi-region input-output (MRIO) and computable general equilibrium (CGE) analyses for the period from 1995 to 2007 based on annual data provided by World Input-Output Database (WIOD). Results from our MRIO analysis confirm the increase of embodied carbon in trade. Both imports of embodied carbon in developed countries and exports of embodied carbon from developing countries have gone up substantially between 1995 and 2007. The decomposition of carbon embodied in OECD

[4] As a prominent example, the Kyoto Protocol explicitly reflected concerns on adverse terms-of-trade effects by postulating that developed countries '. . . shall strive to implement policies and measures . . . in such a way as to minimize adverse . . . economic impacts on other Parties, especially developing country Parties. . . ' (UNFCCC, 1997, Article 2, paragraph 3).

production of emission-intensive and trade-exposed goods shows that the share of carbon stemming from imported (non-OECD) intermediate inputs doubled from about 7% in 1995 to 14% in 2007. Contrary to intuitive reasoning, however, our CGE analysis suggests that the increase in carbon trade over time does not go along with an increase in the effectiveness of carbon tariffs to reduce carbon leakage and decrease global cost of emission abatement. The major effect over time is that the burden shifting potential of carbon tariffs from abating industrialized regions to non-abating developing countries – mediated through changes in the terms of trade – increases markedly.[5]

The remainder of our paper is organized as follows. Section 2 describes the data and numerical MRIO and CGE models underlying our empirical analysis on the implications of carbon tariffs. Section 3 lays out the policy scenarios and interprets simulation results. Section 4 concludes.

## 2. Data and numerical models

*2.1 Data*

Our analysis is based on the World Input-Output Database (WIOD) – see Timmer et al. (2015). WIOD provides time series of detailed input-output tables and trade flows as well as socio-economic and $CO_2$ emission data for the time period of 1995 to 2009. We constrain our analysis to data from 1995 to 2007 since figures for the years 2008 and 2009 are strongly impacted through the global economic slow-down triggered by the international financial crisis in early 2008. WIOD features data for 35 sectors and 41 world regions. We aggregate the data to 13 sectors and 9 geopolitical regions reflecting our primary interest in carbon trade between (industrialized) OECD regions and (developing) non-OECD regions. The sectors and regions incorporated in our model-based analysis are listed in Table 1.

We explicitly represent primary and secondary energy carriers: fossil fuels (included in the WIOD sector "mining and quarrying"), refined oil products, and electricity. Furthermore, we explicitly incorporate emission-intensive and trade-exposed (EITE) industries as they are subject to carbon tariffs in most policy proposals for border carbon adjustments. As to regions, we include industrialized OECD economies that have undertaken or are

[5] Note that our analysis does not take into account the strategic power of carbon tariffs (see for e.g., Böhringer et al., 2016). That is, the use of tariffs as a credible and effective threat to pressurize unregulated regions to adopt emission reduction policies.

contemplating unilateral emission pricing as well as the major developing Non-OECD economies that still refrain from stringent emission regulation.

Table 1: Sectors and regions included in the MRIO and CGE analysis

| *Sectors and commodities* | *Countries and regions* |
|---|---|
| *Energy* | *OECD* |
| Mining and quarrying | European Union (EU 27) |
| Refined oil products* | USA |
| Electricity, gas and water supply | Remaining OECD countries |
| *Emission-intensive and trade-exposed sectors** | *Non-OECD* |
| Rubber and Plastics | Russia |
| Basic metals and fabricated metal | India |
| Chemical products | Indonesia |
| Non-metallic minerals | China |
| Paper, pulp and print | Brazil |
| *Transport sectors* | Rest of the world |
| Air transport | |
| Water transport | |
| Other transport | |
| *Other industries and services* | |
| Agriculture | |
| All other manufactures and services | |

* Included in the group of *emission-intensive and trade-exposed industries* (EITE).

### *2.2 Multi-region input-output (MRIO) model*

In order to calculate the region- and sector-specific carbon content of goods we use basic input-output accounting identities – see Appendix B for a detailed description of the multi-region input-output (MRIO) model (see also Böhringer et al. (2011). After solving the associated system of linear equations, we can decompose the embodied emissions in goods according to their origin, i.e., whether they stem from the production process (through fossil fuel inputs) or are embodied in domestic or imported intermediate inputs.

### *2.3 Computable general equilibrium (CGE) model*

Computable general equilibrium (CGE) models are widely used for the economic impact assessment of policy initiatives as they capture price-driven supply and demand responses of economic agents in a comprehensive and consistent manner. Our analysis is based on an established static CGE model of global production, consumption and trade developed by Böhringer and Rutherford (2002) – for a detailed algebraic summary of the model structure, see Appendix C.

Primary factors in the model are labor, capital and fossil resources. Capital and labor are intersectorally mobile. Fossil fuel resources are specific to the mining and quarrying sector in each region. Final consumption in each region is realized through a representative agent who receives income from the primary production factors and maximizes welfare subject to an income constraint.

Production of goods other than fossil fuels is captured through a three-level nested constant-elasticity-of-substitution (CES) function. At the top level, a material composite substitutes with a composite of value added and energy. The second level describes the trade-off between value added and energy. At the third level, labor and capital form the value added composite. At the same level the energy goods – electricity, fossil resources and refined oil products – trade off in the energy aggregate. In the production of fossil fuels, the fuel-specific resource trades off with a Leontief composite of all other inputs. The top-level elasticity is calibrated to match an exogenous supply elasticity for fossil resources.

Government and investment demand are fixed at exogenous real levels. Investment is paid by savings of the representative agent while taxes pay for the provision of public goods and services. International trade is modeled following Armington's differentiated goods approach, where goods are distinguished by origin (Armington, 1969). The Armington composite for a traded good is a CES function of an imported composite and domestic production for that sector. The import composite in each country is again a CES function of production from all other countries. A balance of payment constraint fixes the base-year trade deficit or surplus for each region.

$CO_2$ emissions are linked in fixed proportions to the use of fossil fuels. Restrictions to the use of $CO_2$ emissions in production and consumption are implemented through exogenous emission constraints. $CO_2$ emission abatement then takes place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities).

For model parameterization we follow the standard calibration procedure in applied general equilibrium analysis. Base-year input–output data together with exogenous estimates for elasticities determine the free parameters of the cost and expenditure functions such that the economic flows represented in the data are consistent with the optimizing behavior of the economic agents. The responses of agents to price changes are driven by a set of exogenous elasticities, which are taken from the pertinent econometric literature. Sector-specific estimates based on WIOD data for cross-price elasticities of substitution between, capital, labor, energy and (non-energy) material inputs stem from Koesler and Schymura (2015). Trade elasticities are taken from the GTAP 9 database (Narayanan et al., 2015). The elasticities of substitution in fossil fuel production/cost functions are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham et al., 1999; Krichene, 2002; Ringlund et al., 2008).

# 3. Policy scenarios and simulation results

*3.1 Policy scenarios*

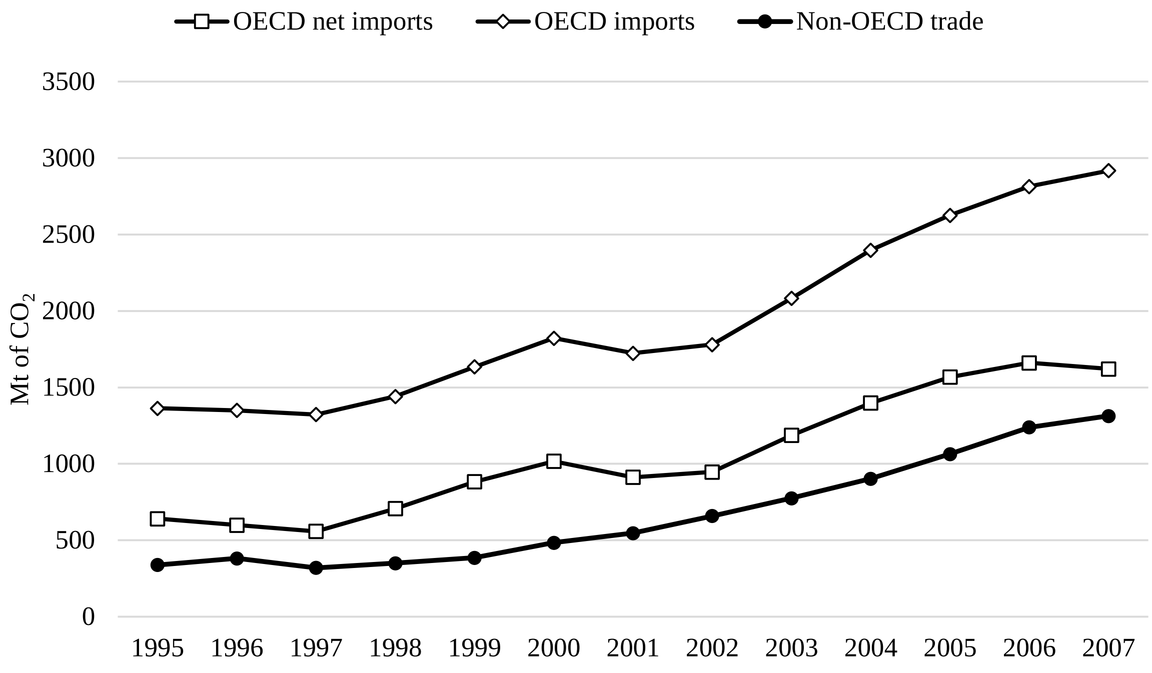
For each year of the time period under consideration (1995 – 2007) we simulate two alternative unilateral climate policy designs in OECD countries. The first climate policy design is captured through the reference scenario *REF* where the OECD countries jointly reduce domestic $CO_2$ emissions by 20% compared to their benchmark emissions in the respective year. This is achieved through a uniform $CO_2$ price within the OECD – implemented either as an OECD-wide emissions trading scheme or equivalently as a uniform OECD-wide $CO_2$ tax. The second OECD climate policy design gets reflected in the scenario *TRF* where the OECD countries additionally introduce a carbon tariff, that is, a tariff on the imported embodied carbon at the OECD $CO_2$ price. In our central case simulations, the carbon tariff is levied on imports of emission-intensive and trade-exposed (EITE) goods. In order to conduct a consistent global cost-effectiveness analysis, we keep the global level of emissions constant across scenarios *REF* and *TRF* for each year. This implies that the exogenous reduction target in the OECD as specified under *REF* must endogenously adjust in scenario *TRF*, such that the same level of global emissions is met as in the respective *REF* case.[6] By holding the level of global emissions constant across scenarios *REF* and *TRF* for each year we circumvent an economic assessment of climate damages acknowledging larger uncertainties in external cost estimates of carbon emissions.

[6] Technically, this is implemented in the CGE model through an endogenous scaling of the OECD emission cap (or likewise the OECD emission price).

*3.2 Multi-region input-output (MRIO) analysis*

We begin our assessment of carbon tariffs by investigating the development of carbon embodied in global trade for the period 1995 to 2007. Figure 1 depicts the evolution of total and net imports of embodied carbon in OECD from Non-OECD countries, as well as total trade in embodied carbon among Non-OECD countries. The MRIO results indicate significant increases in both total imports and net imports of embodied carbon for OECD. Total imports of embodied carbon in OECD countries – which are potentially covered by carbon tariffs – increased by a factor of 2.1 from an initial level of 1363 Mt of $CO_2$ in 1995 to 2919 Mt in 2007, while net imports increased by a factor of 2.5 from 641 Mt to over 1621 Mt.[7]

Figure 1: Trade in embodied carbon



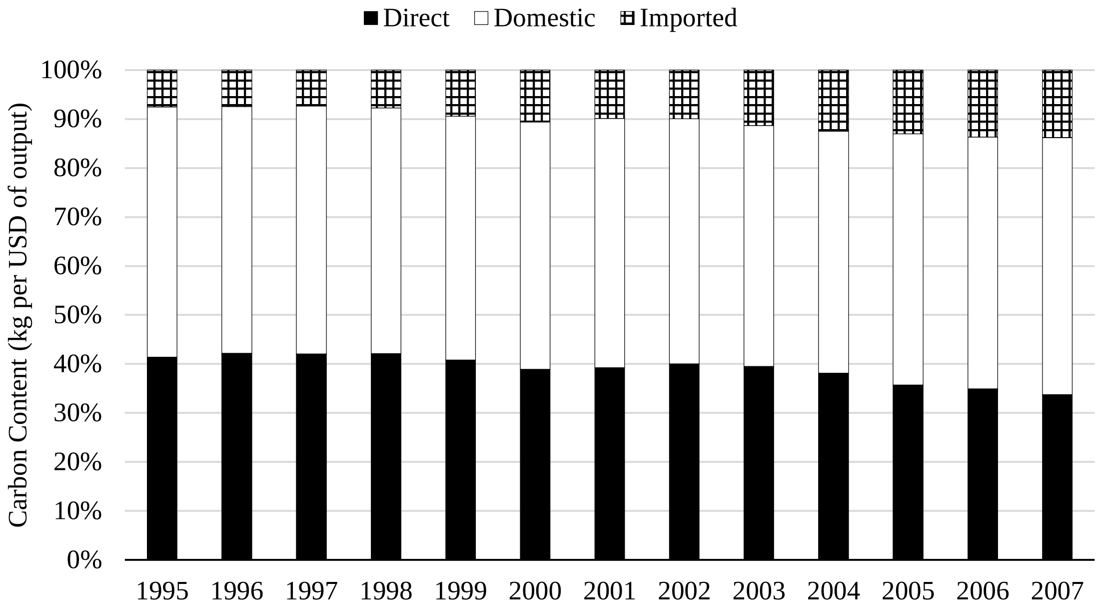

At the same time, trade in embodied carbon not only became more relevant for trade flows from Non-OECD to OECD countries, but also within Non-OECD: intra-Non-OECD trade of embodied carbon increased by a factor of almost 4 from 339 Mt to 1313 Mt between 1995 and 2007. These numbers provide empirical evidence for a substantial increase in carbon

[7] The massive increase in net imports of embodied carbon in OECD is consequently mirrored by a declining OECD-share of global production-based ("direct") $CO_2$ emissions: In 1995, global $CO_2$ emissions from fossil fuel use amounted to 18636 Mt, of which 60% stemmed from OECD countries. In 2007, only 45% of the globally emitted $CO_2$ (25383 Mt) is attributed to OECD.

trade over the last two decades with industrialized OECD countries being large net importers of embodied carbon and developing Non-OECD countries being large net exporters, and likewise a marked increase of carbon trade among developing Non-OECD countries.

Figure 2 decomposes embodied carbon for an average EITE good of OECD in percentage shares. The label "Direct" in Figure 2 refers to direct emissions from fossil fuel combustion in the production process, the label "Domestic" to indirect emissions from carbon embodied in *domestic* intermediate inputs, and the label "Imported" to indirect emissions from carbon embodied in *imported* intermediate inputs from non-OECD countries (including emissions from associated international transport services). It becomes apparent that the share of embodied carbon in the average EITE OECD good stemming from imported non-OECD sources doubles from 7% in 1995 to 14% in 2007. Thus one would expect that OECD carbon tariffs taxing embodied carbon in EITE imports from non-OECD countries become more potent as an instrument to reduce carbon leakage.[8]

Figure 2: Percentage decomposition of the carbon content of an average EITE good in OECD




*3.3 Computable general equilibrium analysis*

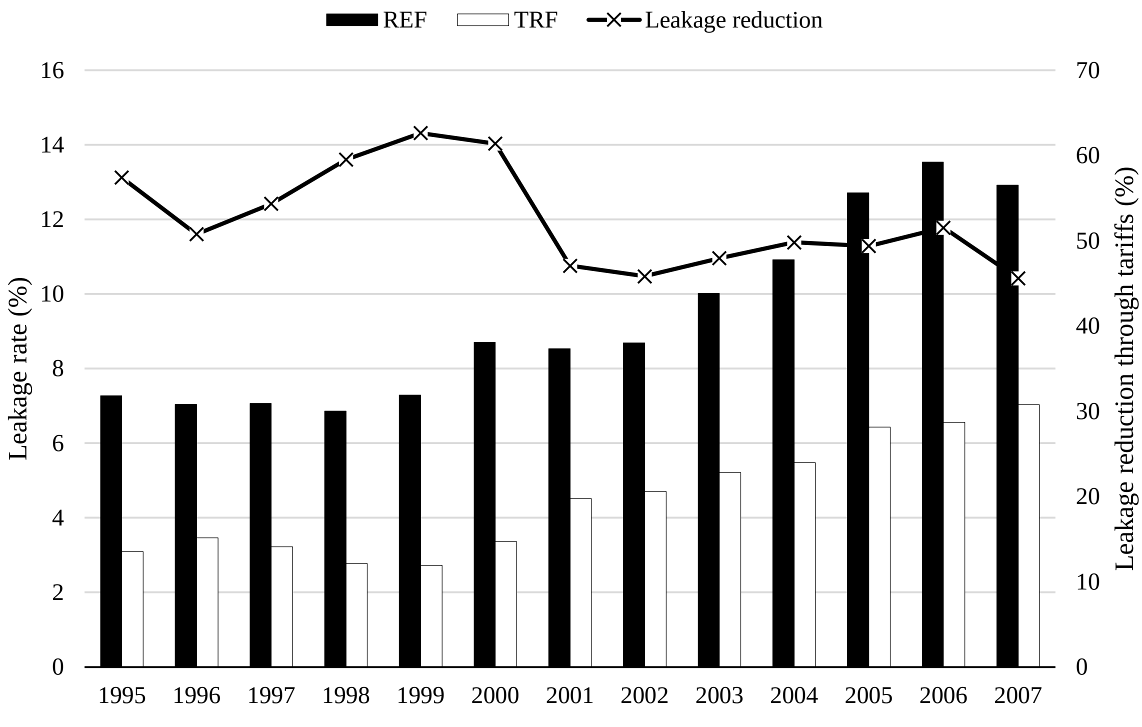
The CGE analysis starts with the quantification of leakage rates triggered by the two alternative climate policy designs for each year between 1995 and 2007 (see Figure 3). The

[8] Note that in absolute terms, the carbon content for the average OECD EITE good decreases from 0.93 kg per USD of EITE output in 2001 to 0.58 in 2007 where the decline in direct emissions and indirect domestic emissions indicates a trend towards "cleaner" domestic EITE production in the OECD.

leakage rate is defined as the increase in $CO_2$ emissions in unregulated regions (here: Non-OECD regions) as a percentage share of the decrease in $CO_2$ emissions in the regulated regions (here: OECD regions).

In the reference scenario (*REF*) where we consider uniform $CO_2$ pricing stand-alone, we observe a steady increase in the leakage rate, from 7% in 1995 to 13% in 2007. The increase in the leakage rate is driven by two factors. First, the declining share of OECD production-based $CO_2$ emissions (see footnote 7). As the share of global $CO_2$ emissions covered by unilateral OECD climate policies declines over time, the leakage rate goes up.[9] Second, the carbon content of EITE goods produced in OECD countries decreases over time (see footnote 8). The lower the benchmark carbon content, the higher must be the $CO_2$ price to effect relative price changes that are sufficient to achieve a given emission reduction target.[10] Along with higher unilateral $CO_2$ prices the leakage rate goes up.[11]

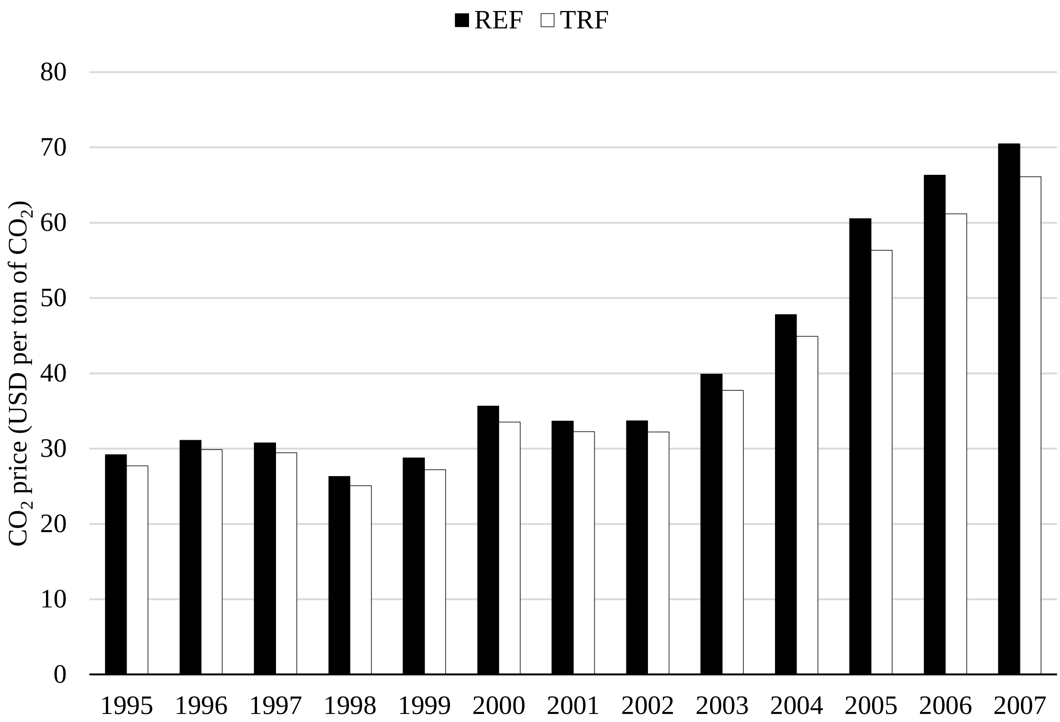
Figure 3: Leakage rates under *REF* and *TRF* (left axis) and percentage leakage reduction through tariffs (right axis)




[9] This result has been established in Böhringer et al. (2014) who show analytically that ceteris paribus emission leakage goes up as the share of base-year emissions in the abatement coalition over global emissions declines.
[10] See Figure 4 where the emission price in scenario *REF* increases from 29 USD to 70 USD per ton of $CO_2$ over time.
[11] In order to disentangle effects from increasing $CO_2$ prices over the time period, we additionally simulated scenarios with fixed (deflated) $CO_2$ prices rather than fixed reduction targets. All of our insights remain robust.

As expected, leakage rates under the carbon tariff regime (*TRF*) are lower in all years relative to the *REF* scenario. Carbon tariffs attenuate the relocation of EITE production (and emissions) from OECD to Non-OECD regions.[12] The reduction in the leakage rates due to carbon-based tariffs on EITE goods falls in the range of 3.6 and 7 percentage points. In relative terms, this is equivalent to a reduction of the *REF* leakage rate between 46% and 63% – with a mean reduction of 53%. Note that there is a decreasing trend in the potency of carbon tariffs to combat leakage such that in 2007 carbon tariffs cut the *REF* leakage rate by just 46%. Thus, despite the increase in carbon embodied in trade, there is no visible improvement of the relative effectiveness of carbon tariffs in reducing leakage over time.

Figure 4: $CO_2$ prices under *REF* and *TRF*

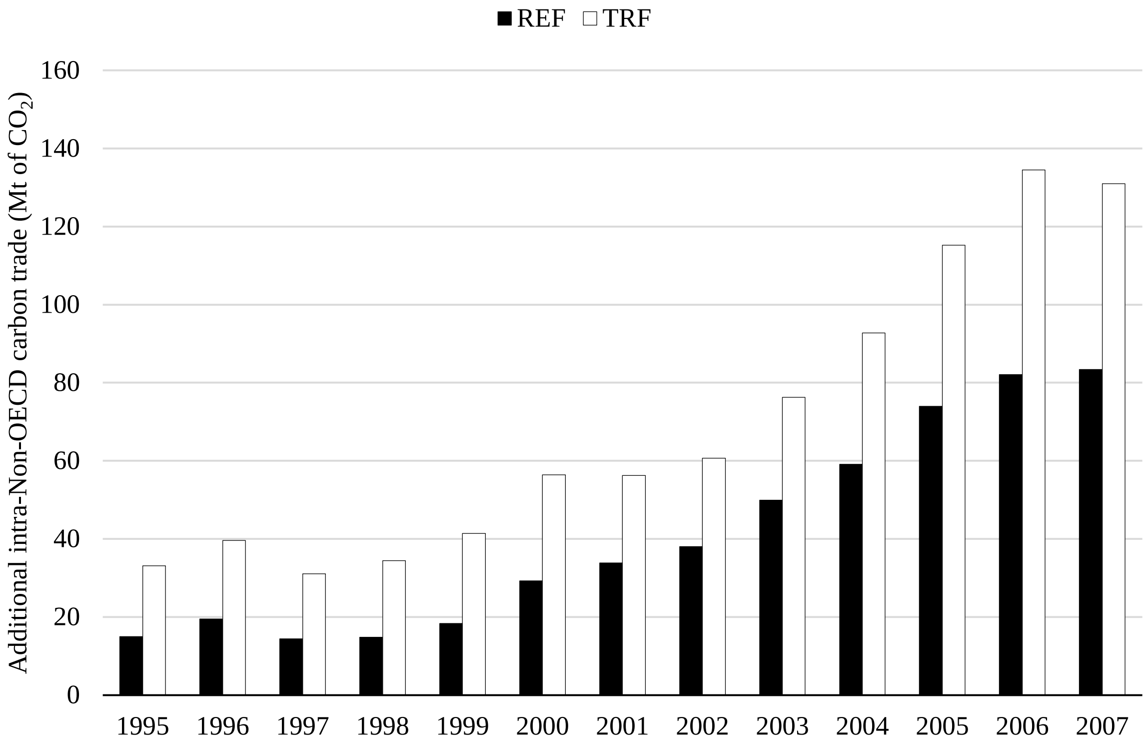



The reasoning behind is that not only do we observe more trade integration between OECD countries and Non-OECD countries over the years, but also more trade integration among Non-OECD economies. As a consequence, supply can more easily be redirected within Non-OECD when a carbon tariff is introduced in OECD countries. This evasion mechanism

[12] As a consequence of leakage reduction, $CO_2$ emission prices in *TRF* are lower than in *REF*. The reason is that lower leakage rates in *TRF* imply a lower effective domestic emission reduction requirement for OECD to achieve the same global emission reduction as in *REF*.

becomes evident from Figure 5, which reports the additional carbon trade in Mt of $CO_2$ among Non-OECD countries as a response to unilateral OECD climate policies. Keeping in mind the sharp increase of business-as-usual intra-Non-OECD carbon trade (see Figure 1), we find that uniform OECD-wide $CO_2$ pricing (*REF*) induces an expansion of intra-Non-OECD carbon trade by about 5% while additional carbon tariffs (*TRF*) lead to an expansion of about 10% compared to business-as-usual. Thus, the relative effectiveness of OECD carbon tariffs to reduce emission leakage to Non-OECD countries does not increase over time.

Figure 5: Additional intra-Non-OECD trade in embodied carbon compared to business-as-usual under *REF* and *TRF*




Global cost-effectiveness of unilateral OECD $CO_2$ emission pricing is only slightly improved when accompanied by additional carbon-based tariffs on EITE imports. Throughout our CGE analysis we measure economic adjustment cost to emission regulation as Hicksian equivalent variation as percentage share of business-as-usual income for the respective year. It should be kept in mind that emission regulation in our cost-effectiveness approach generally induces positive cost since we do not monetize the benefits from emission reductions.

Figure 6 indicates that global economic cost in the *REF* scenario ranges between 0.11% and 0.18% of global business-as-usual income.[13] The development of cost across the different base-years mirrors the development of the carbon content in average EITE products as described in footnote 8. A lower carbon content requires higher $CO_2$ prices (taxes) which – absent from external cost accounting – lead to higher losses in allocative efficiency. The imposition of carbon tariffs reduces global economic adjustment cost by up to 5% – the potential for global cost savings from carbon tariffs is thus quite limited (Böhringer et al., 2012; Branger and Quirion, 2014).[14]

Figure 6: Global economic cost under *REF* and *TRF*

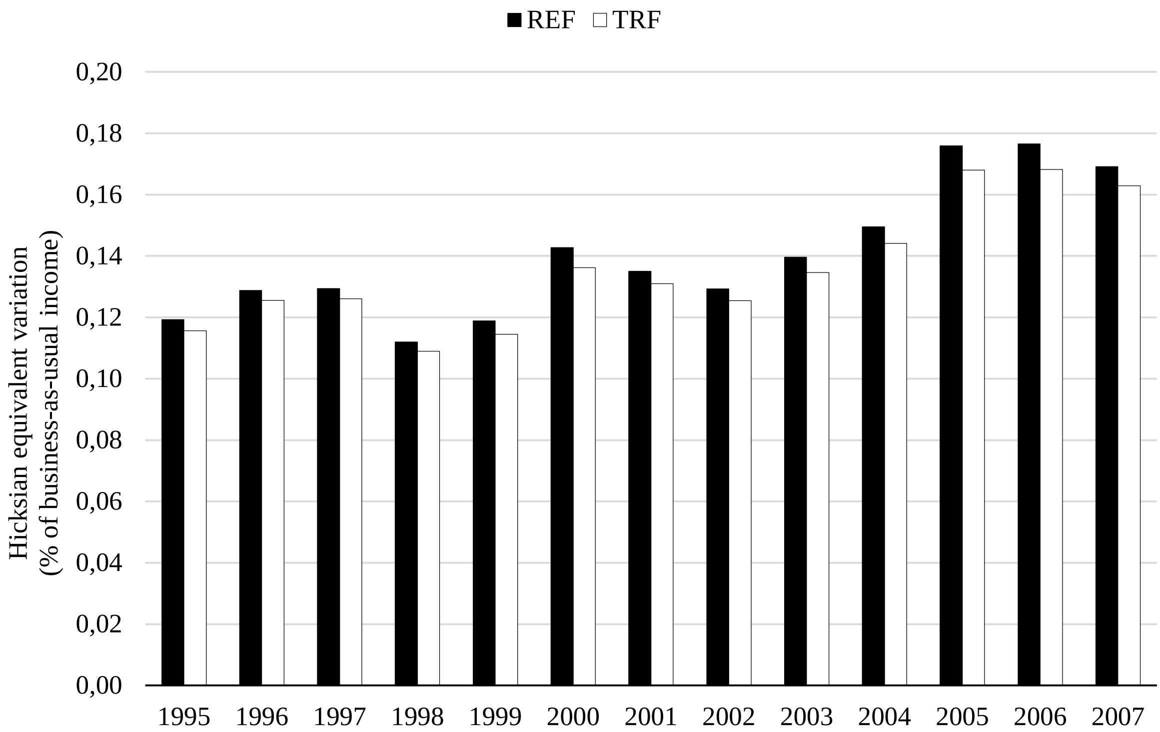


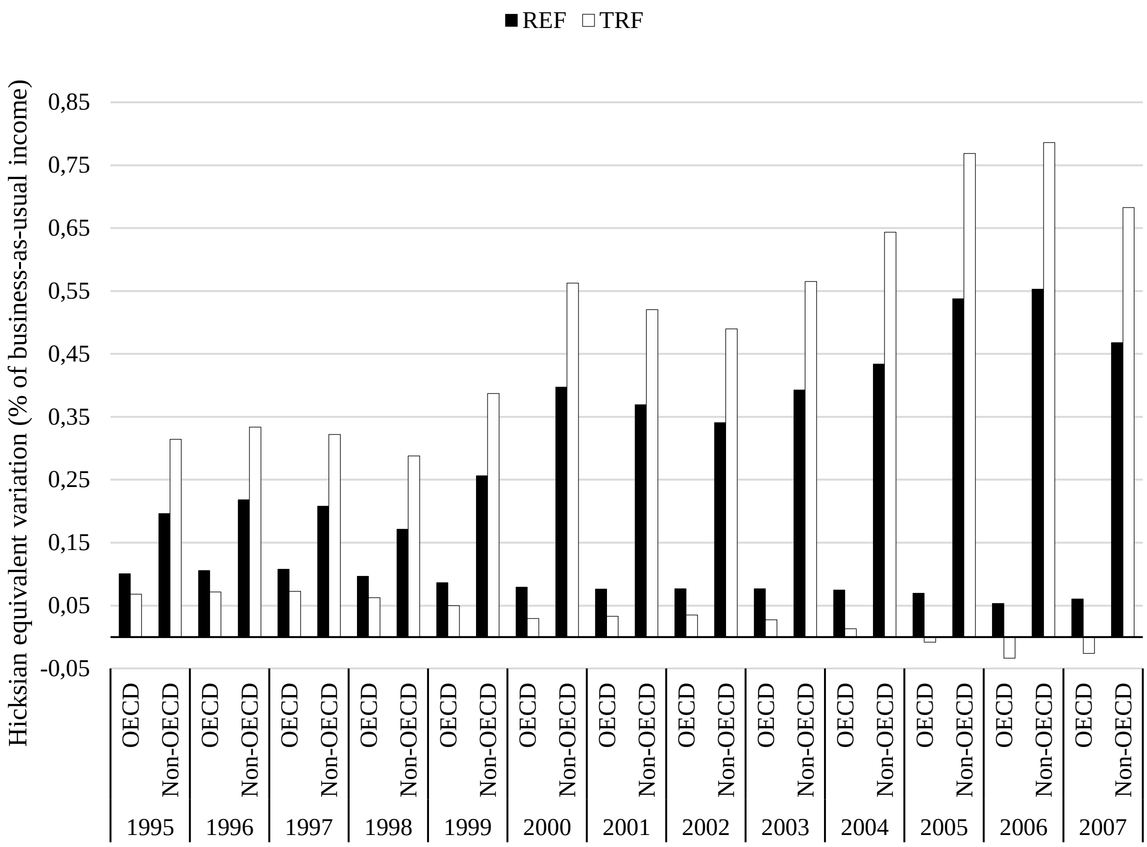

Figure 7 shows the distributional effects on both OECD and Non-OECD countries. In the reference scenario (*REF*), unilateral OECD emission pricing to cut OECD $CO_2$ emissions by 20% induces a substantial burden to Non-OECD countries. Supplementary carbon tariffs on EITE goods amplify this incidence of OECD emission abatement further at the expense of

[13] Global welfare accounting is based on a utilitarian (Benthamite) perspective.

[14] The limited scope of carbon tariffs for improving global cost-effectiveness of unilateral emission pricing echoes caveats on carbon-based import tariff applied at the industry-average which does not reflect firm-specific heterogeneities and hence fails to incentivize the deployment of less emission-intensive technologies in unregulated regions (Böhringer et al., 2015).

Non-OECD countries. With a carbon tariff in place, we observe a clear downward trend in income losses for the OECD – turning even into welfare gains for the years 2005-2007, mirrored by a sharp cost increase for Non-OECD countries. The burden shifting effect of carbon tariffs has been highlighted in previous research (e.g., Böhringer et al., 2012). However, to our best knowledge, we are the first to show that the re-distributional impact of carbon tariffs increases over time. Given the missing evidence on increased cost-effectiveness over time, our finding seems to weaken rather than strengthen the case for carbon tariffs.

Figure 7: Economic adjustment cost in OECD and Non-OECD under *REF* and *TRF*




The rationale behind the burden shifting effect of unilateral OECD emission pricing is as follows. Emission pricing affects the terms of trade, i.e., the ratio of export prices to import prices for OECD and Non-OECD countries. The heterogeneous nature (imperfect substitutability) of traded commodities makes it possible for an open economy to pass on a fraction of domestic abatement cost via higher prices to trading partners. In this vein, carbon tariffs may work as a strategic substitute for "optimal" tariffs (where "optimal" is defined from the perspective of the tariff imposing country which seeks to exploit terms of trade). As a matter of fact, the adverse terms-of-trade effects for Non-OECD countries become more pronounced with carbon-based import tariffs to the extent that the effective price increase is still below an optimal tariff rate. Our simulation analysis demonstrates that the potential of carbon tariffs to change the terms of trade in favor of OECD countries and to the disadvantage of Non-OECD countries increases during the period 1995-2007. The decline in cheaper abatement options within OECD over time (reflected through the lower carbon intensity of OECD production) implies higher $CO_2$ prices to attain the targeted level of emission reduction but the associated increase in effective carbon tariffs thereby still figures below an "optimal" tariff rate. In fact, the terms-of-trade gains from carbon tariffs can even more than offset the direct emission abatement cost in OECD countries and make them better off than without emission regulation.

Figure 8: Terms of trade for OECD and Non-OECD under *REF* and *TRF*

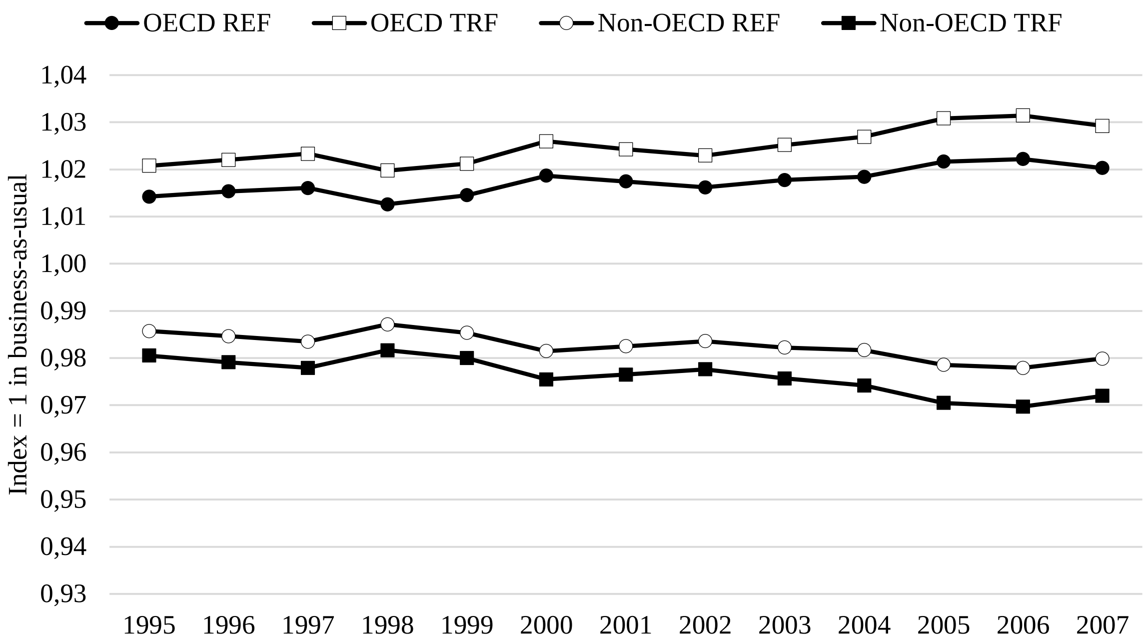



Figure 8 visualizes the development of the terms-of-trade effect as the ratio of the Fisher price indexes for exports and imports in OECD and Non-OECD.[15] The changes in terms of trade mirror the development of trade in embodied carbon (see Figure 1) as well as the composition of the carbon content (see Figure 2), which consequentially lead to the regional pattern of cost incidence depicted in Figure 7: A higher domestic OECD $CO_2$ price induces

[15] The Fisher index is the geometric mean of the Laspeyres index and Paasche index. The Laspeyres index uses benchmark quantities whereas the Paasche index uses counterfactual quantities to calculate aggregate price changes. Both indexes entail substitution-biases which the Fisher index overcomes (Reinsdorf, 2010).

stronger terms-of-trade effects that work in favor of OECD and to the disadvantage of Non-OECD countries. The terms-of-trade effects are amplified through carbon-based tariffs rising with the amount of embodied carbon that is taxed at the border (Figure 1). To summarize: Higher $CO_2$ prices joint with increasing imports of embodied carbon from Non-OECD to OECD regions imply that the re-distributional impact of carbon tariffs becomes stronger over the years.

*3.4 Sensitivity analysis*

We conduct sensitivity analysis to assess the robustness of results with respect to key assumptions underlying our core simulations. Firstly, we vary the design of unilateral climate policy along three dimensions: the stringency of the reduction target, the size of the abatement coalition, and the introduction of carbon-based rebates to exports in addition to carbon-based tariffs on imports. Secondly, we investigate the influence of trade elasticities and fossil fuel supply elasticities, which are known as critical parameters in the impact assessment of climate policy.

We find that all of our results remain robust to these changes in the parametrization space: Over time (i.e., the period of 1995-2007) carbon-based tariffs do not become more effective in combating leakage or improving global cost-effectiveness; instead, their potency for shifting the burden of abatement from regulating OECD countries to Non-OECD trading partners without emission regulation via changes in the terms-of-trade increases over time. Details of the sensitivity analysis can be found in Appendix A.

## 4. Conclusions

At the 21st Conference of Parties to the United Framework Convention on Climate Change in Paris, 195 countries agreed to reduce their carbon output "as soon as possible" and to do their best to keep global warming "to well below 2 degrees Celsius" (UNFCCC, 2015a). Despite this Paris Agreement, the world community is still far off from comprehensive emission pricing. In the mid-run, it seems likely that industrialized countries will go ahead with stringent emission pricing, whereas developing countries adopt rather lenient regulations. Major discrepancies in the stringency of emission pricing across trading partners raise concerns on carbon leakage and the global cost-effectiveness of more ambitious climate action in OECD countries.

Against this background, carbon tariffs are discussed as a complementary instrument to unilateral emission pricing. Carbon tariffs tax the carbon emissions embodied in imported goods and thereby extend the reach of domestic emission pricing. Previous empirical analysis on the impacts of carbon tariffs has identified that carbon tariffs can substantially reduce leakage but deliver only small gains in global cost-effectiveness while amplifying the burden shifting effect of carbon pricing from developed OECD countries to developing non-OECD countries. However, such analysis has been based on a single observation of global economic activity in time.

In this paper, we have investigated the implications of carbon tariffs based on data from the World Input-Output Database (WIOD) for the period 1995 to 2007. The motivation for our approach stems from the fact that trade in carbon has sharply increased over the last two decades. One therefore might expect that the potency of carbon tariffs to cut leakage and improve global cost-effectiveness of unilateral emission pricing would go up substantially over time. In other words, as the world economy gets more and more integrated via trade, carbon tariffs can gain a more prominent role than asserted by previous analysis.

Our assessment of carbon tariffs, however, shows that the increase in carbon trade over time does not go along with an increase in the effectiveness of carbon tariffs to reduce carbon leakage and decrease global cost of unilateral climate policy. The major change over time is that the burden shifting potential of carbon tariffs from abating industrialized OECD regions to developing Non-OECD countries increases markedly due to enforced terms-of-trade effects. The main reasoning behind these insights is that along with the increase in imports of carbon from Non-OECD to OECD there is a strong increase in trade in embodied carbon between Non-OECD countries. In addition, the carbon intensity of OECD regions declined over time such that $CO_2$ prices must be higher to effect an identical relative emission reduction over time – the higher $CO_2$ prices together with increased imports of carbon-intensive goods from Non-OECD countries increase the burden-shifting potential of carbon tariffs.

From a policy perspective, our assessment weakens the case for carbon tariffs. The efficiency argument in favor of carbon tariffs, which has already been questioned in former analysis, does not gain weight as the world becomes more integrated through trade. The redistributive caveat against carbon tariffs on the other hand, gets more severe over time. On these grounds, we conclude that the appeal of carbon tariffs for practical climate policy is rather weak.

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## Appendix A: Sensitivity analysis

The sensitivity analysis is organized in two part. In the first part (A.1), we alter assumptions on the design of unilateral climate policy, specifically regarding the emission reduction target, the size of the abatement coalition, and the comprehensiveness of border carbon adjustments. In the second part (A.2), we assess the implications of changes in trade and fossil fuel supply elasticities which stand out for their critical importance to the magnitude of carbon leakage and terms-of-trade effects.

We find that while altering these assumptions affects the magnitude of policy impacts, all of our qualitative findings remain robust: Carbon tariffs do not become more effective over time both with respect to leakage reduction and global cost savings; yet, the potential to shift the economic burden of emission reduction from regulating to non-regulating regions increases markedly.

For the sake of brevity and compactness, our results representation focuses on carbon leakage and burden shifting – we skip reporting on global cost which remain very similar to the results of the core setting throughout the sensitivity analysis.

### *A.1 Reduction target, abatement coalition, and carbon-based rebates to exports*

To test how the stringency of unilateral climate policy affects our main findings, we consider alternative emission reduction targets of 10% (denoted *REF_t10* and *TRF_t10*) and 30% (denoted *REF_t30* and *TRF_t30*). Regarding leakage (see Figure A.1), we again observe that relocation of emissions from regulating OECD countries to non-regulating Non-OECD countries becomes more important over time. As in the central case simulations, the effectiveness of carbon tariffs to reduce leakage, however, does not increase over time. The main difference when moving from lower to more stringent reduction targets is the cost distribution between OECD and Non-OECD countries under stand-alone emission pricing in the OECD (*REF_t10* and *REF_t30*), depicted in Figure A.2. For the 10% reduction target (*REF_t10*) Non-OECD countries almost entirely bear the cost of abatement. From 2000 onwards OECD countries even face negative cost under *REF*. For the 30% target (*REF_t30*) on the other hand, OECD bears the larger part of the cost under *REF* at least until 1999. For lower reduction targets which entail lower $CO_2$ prices, OECD countries can almost entirely pass through increased production cost to Non-OECD trading partners.

Figure A.1: Leakage rates under *REF* and *TRF* with 10% (*REF_t10* and *TRF_t10*) and 30% (*REF_t30* and *TRF_t30*) reduction target

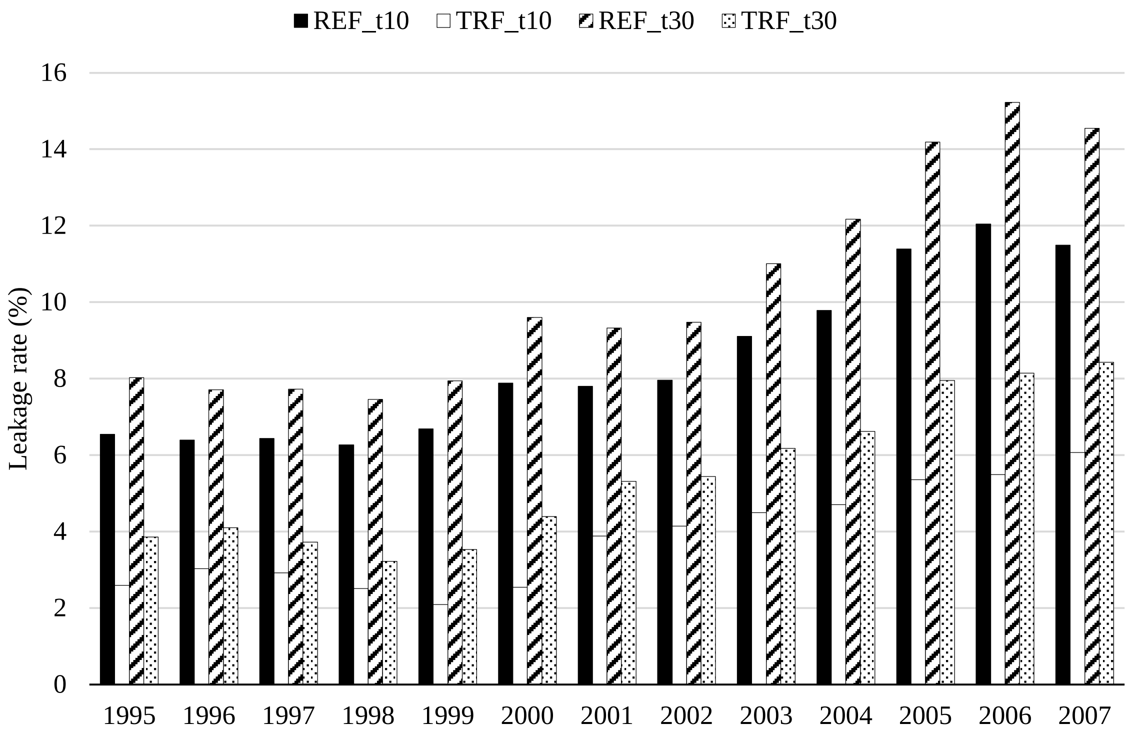
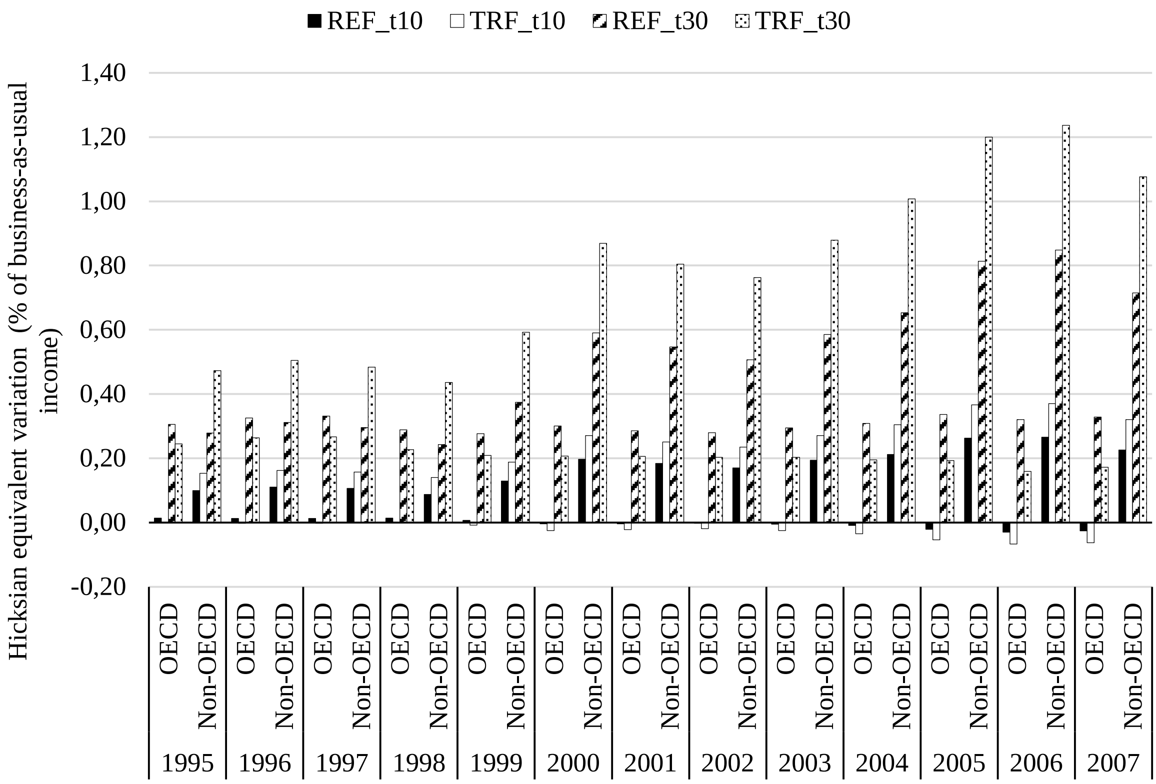



Figure A.2: Adjustment cost in OECD and Non-OECD countries under a 10% (*REF_t10 and TRF_t10*) and 30% (*REF_t30* and *TRF_t30*) emission reduction target



As $CO_2$ emission prices for the 30% target get high, the terms-of-trade changes are no longer sufficient to offset the increasing cost of emission abatement – OECD countries are then left with a substantial share of the overall policy burden. Note that our key insight on the burden shifting potential remains robust across different levels of stringency in emission abatement: Over time, the potency of carbon tariffs to shift the burden of abatement from OECD to Non-OECD countries increases markedly

With respect to regional coverage of the unilateral climate policy, we test the sensitivity of our main findings by considering the European Union (EU) as a smaller coalition and OECD plus China as a larger abating coalition while maintaining the reduction target of 20% of the respective regions' benchmark emissions. The policy scenarios are denoted *REF_EU* and *TRF_EU* for EU action, as well as *REF_OECDxCHN* and *TRF_OECDxCHN* for joint action of OECD countries and China, respectively.

In Figure A.3, we illustrate the evolution of the leakage rate over time for emission pricing stand-alone (*REF_EU* and *REF_OECDxCHN*) and for emission pricing complemented with carbon tariffs (*TRF_EU* and *TRF_OECDxCHN*).  Figure A.4 depicts the burden shifting towards non-abating regions over time. As expected leakage rates are decreasing in the coalition size. The leakage rate for EU action ranges from 13.4% in 1998 to 24.7% in 2006, while emission pricing in OECD plus China causes leakage rates between 3.1% in 1996 and 4.6% in 2005. As in the core scenarios, the potential of carbon tariffs to attenuate leakage does not increase over time. Changes in the coalition size affect the cost incidence under emission pricing stand-alone (*REF_EU* and *REF_OECDxCHN*). The EU bears a larger share of global cost than Non-EU throughout the whole time period, while OECD plus China is better able to pass cost through. The reason for this differential impact is that the EU requires higher domestic $CO_2$ prices to achieve the 20% reduction target. The burden shifting potential of carbon-based tariffs, however, is again huge for each of the considered coalitions.

Again our key insights that – (i) carbon tariffs are less effective in reducing leakage over time despite the increasing amount of emissions embodied in trade, and (ii) that the burden shifting tendency of carbon tariffs to non-abating regions increases sharply over time – remain robust even when the regional coverage of the abating coalition is reduced or expanded.

Figure A.3: Leakage rates under EU action (*REF_EU* and *TRF_EU*) as well as joint action by OECD and China (*REF_OECDxCHN* and *TRF_OECDxCHN*)

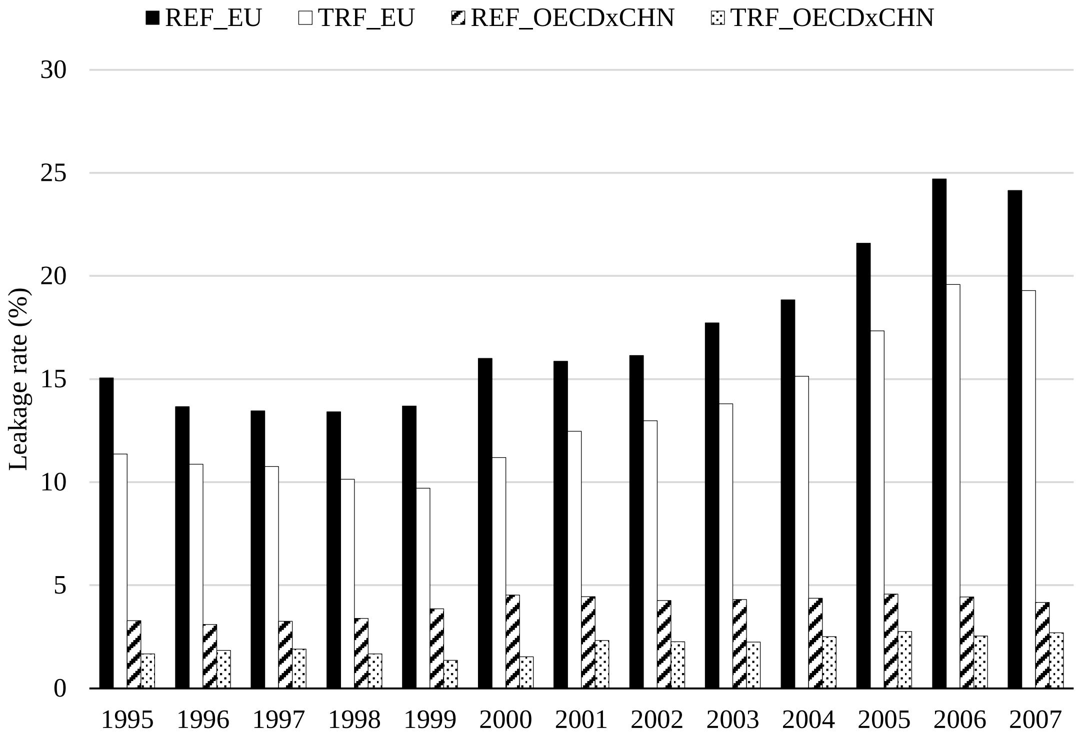



Figure A.4: Economic adjustment cost in the EU (*REF_EU* and *TRF_EU*) and OECD plus China (*REF_OECDxCHN* and *TRF_OECDxCHN*)

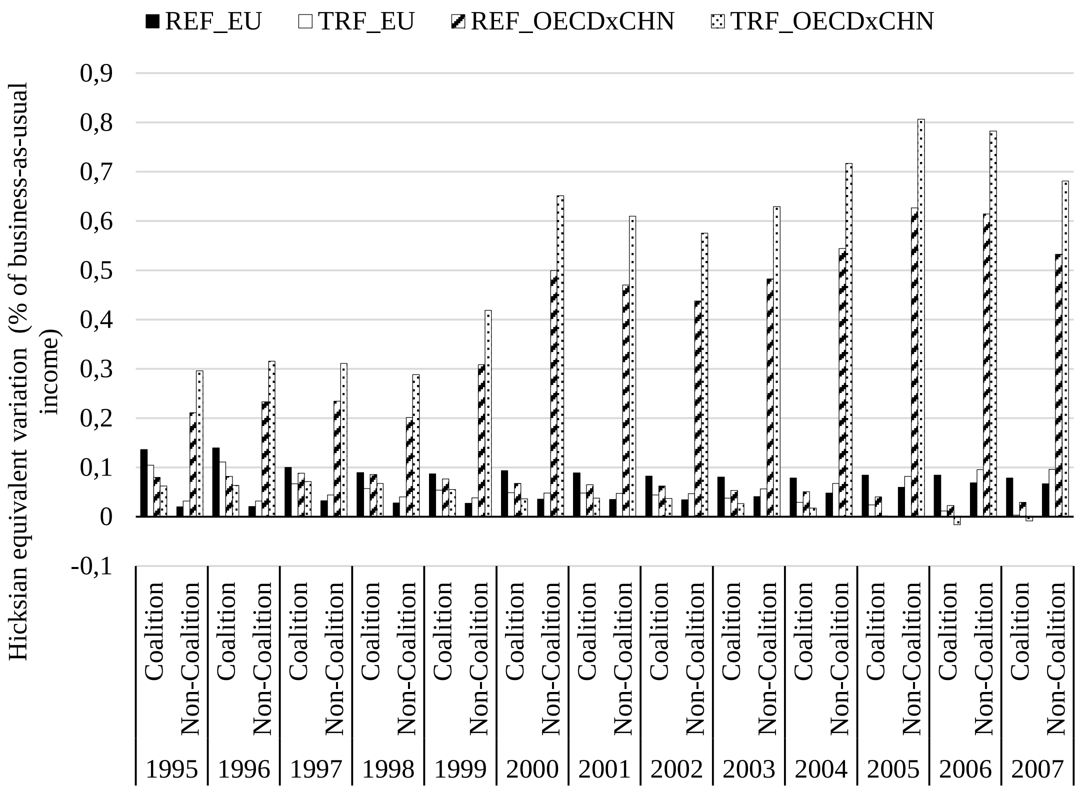


Figure A.5: Leakage rates under *REF*, *TRF*, *REB* and *BCA*

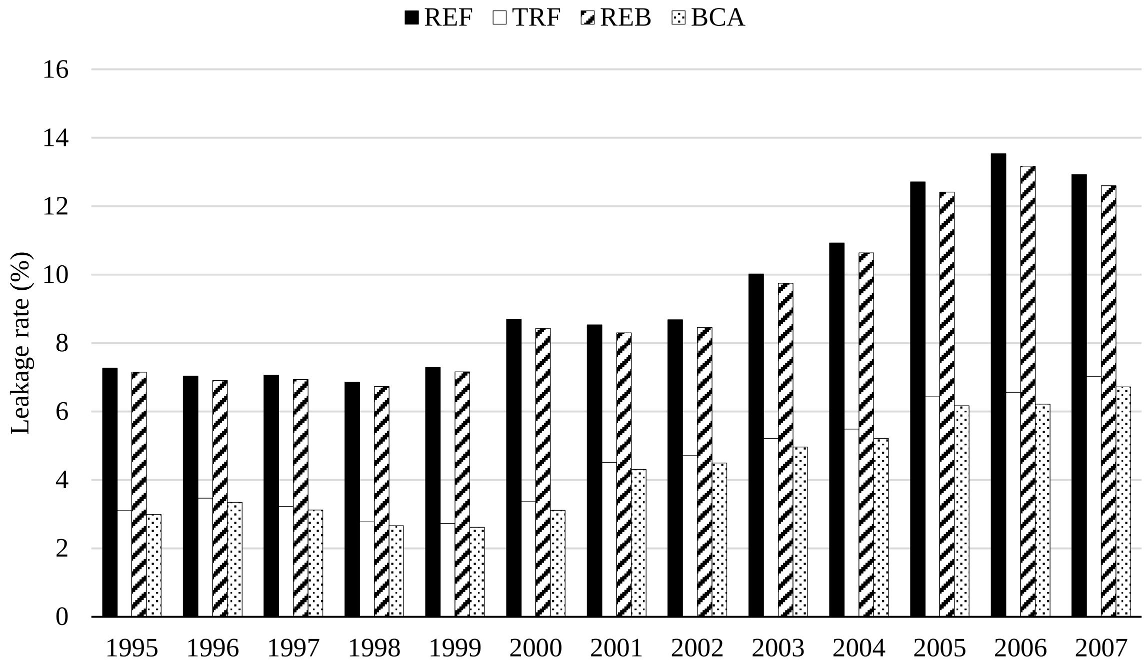
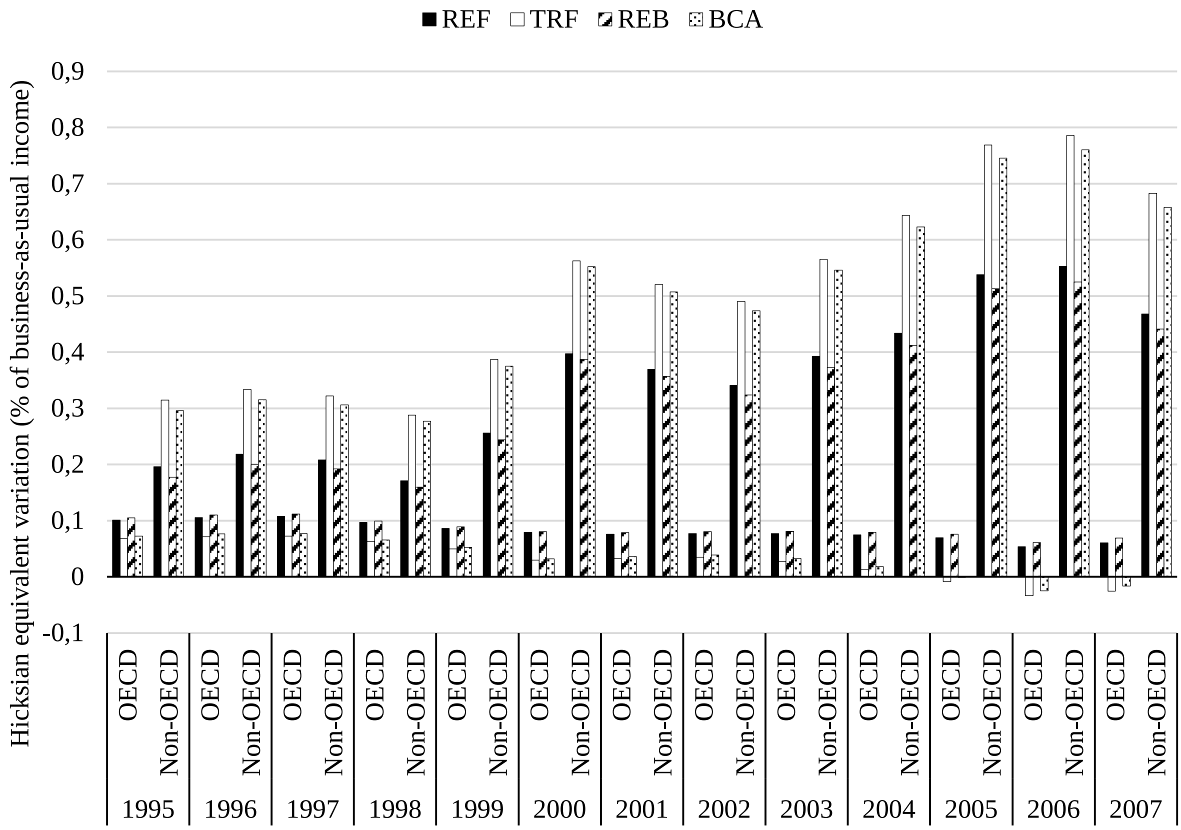



Figure A.6: Economic adjustment cost in OECD and Non-OECD countries under *REF*, *TRF*, *REB* and *BCA*



To account for alternative designs of border carbon adjustments we introduce two additional scenarios. In the variant *REB* we use carbon-based rebates on the direct carbon content of EITE exports as a supplemental instrument to uniform $CO_2$ emission pricing. In the scenario *BCA* we include both carbon-based import tariffs and export rebates in addition to $CO_2$ pricing – that is, the variant *BCA* considers a comprehensive border carbon adjustment scheme. We show leakage results in Figure A.5 and regional cost implications in Figure A.6. The results of the *REB* variant are very similar to *REF*, while *BCA* results are similar to *TRF*. The reason is that only 8% of output for EITE industries in OECD countries are exported to Non-OECD countries. Thus, direct carbon emissions embodied in exports to Non-OECD countries play only a minor role for OECD countries.

### *A.2 Trade elasticities and fossil fuel supply elasticities*

We test the sensitivity of our results with respect to the degree of price-responsiveness of trade flows and fossil fuel supply, which are key drivers of the leakage rate and the cost incidence of unilateral emission pricing. We consider the cases where we either halve or double the Armington elasticities (denoted *REF_arm-lo*, *TRF_arm-lo*, *REF_arm-hi*, and *TRF_arm-hi*) or the fossil fuel supply elasticities (denoted *REF_ffs-lo*, *TRF_ffs-lo*, *REF_ffs-hi*, and *TRF_ffs-hi*, respectively) compared to our core setting. As illustrated in Figure A.7, lowering the Armington elasticities under both *REF* and *TRF* scenarios reduces the leakage rate. This effect is due to the lower substitutability between domestic and foreign goods, dis-incentivizing shifts in production and redirection of trade flows. On the other hand, doubling the Armington elasticities increases relocation and emission leakage. The effectiveness of the tariff in terms of leakage reduction remains largely similar in most years and does not increase over time. In terms of the abatement burden, halving the Armington elasticities substantially increases the share of the economic burden on Non-OECD countries under unilateral emission pricing stand-alone (*REF_arm-lo*) and also the tendency of the carbon-based tariffs to shift the abatement burden (*TRF_arm-lo*), see Figure A.8. With reduced trade-responsiveness to price changes the ability to pass through cost increases for OECD countries. In contrast, increasing trade responsiveness leads to a pronounced increase in the share of cost of the policy borne by OECD under emission pricing stand-alone (*REF_arm-hi*).

Figure A.7: Leakage rates under halved (*REF_arm-lo* and *TRF_arm-lo*) and doubled (*REF_arm-hi* and *TRF_arm-hi*) Armington elasticities

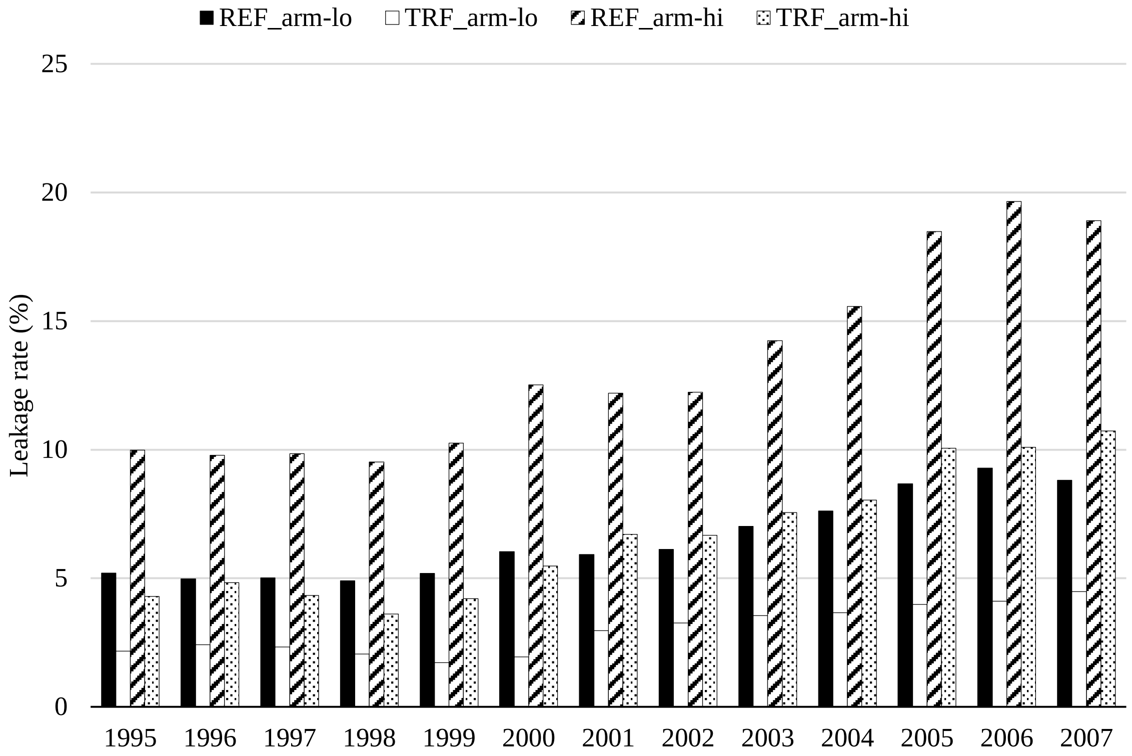



Figure A.8: Adjustment cost in OECD and Non-OECD with halved (*REF_arm-lo* and *TRF_arm-lo*) and doubled (*REF_arm-hi* and *TRF_arm-hi*) trade elasticities

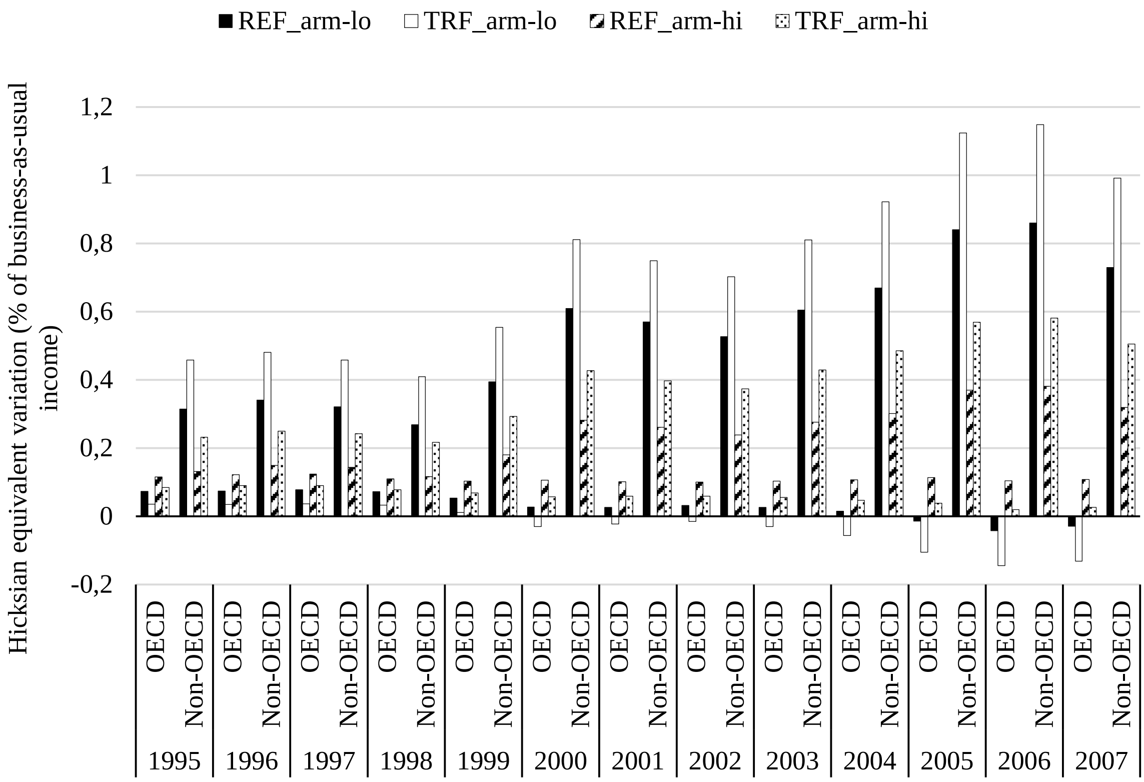


Figure A.9: Leakage rates under halved (*REF_ffs-lo* and *TRF_ffs-lo*) and doubled (*REF_ffs-hi* and *TRF_ffs-hi*) fossil fuel supply elasticities

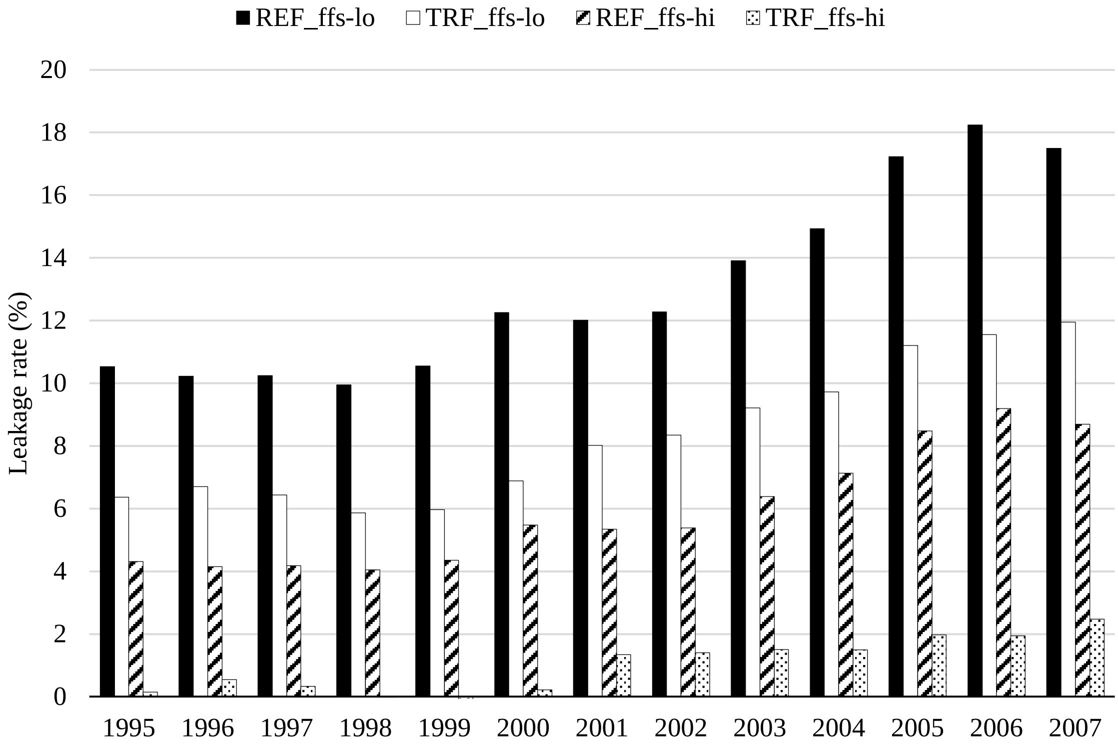
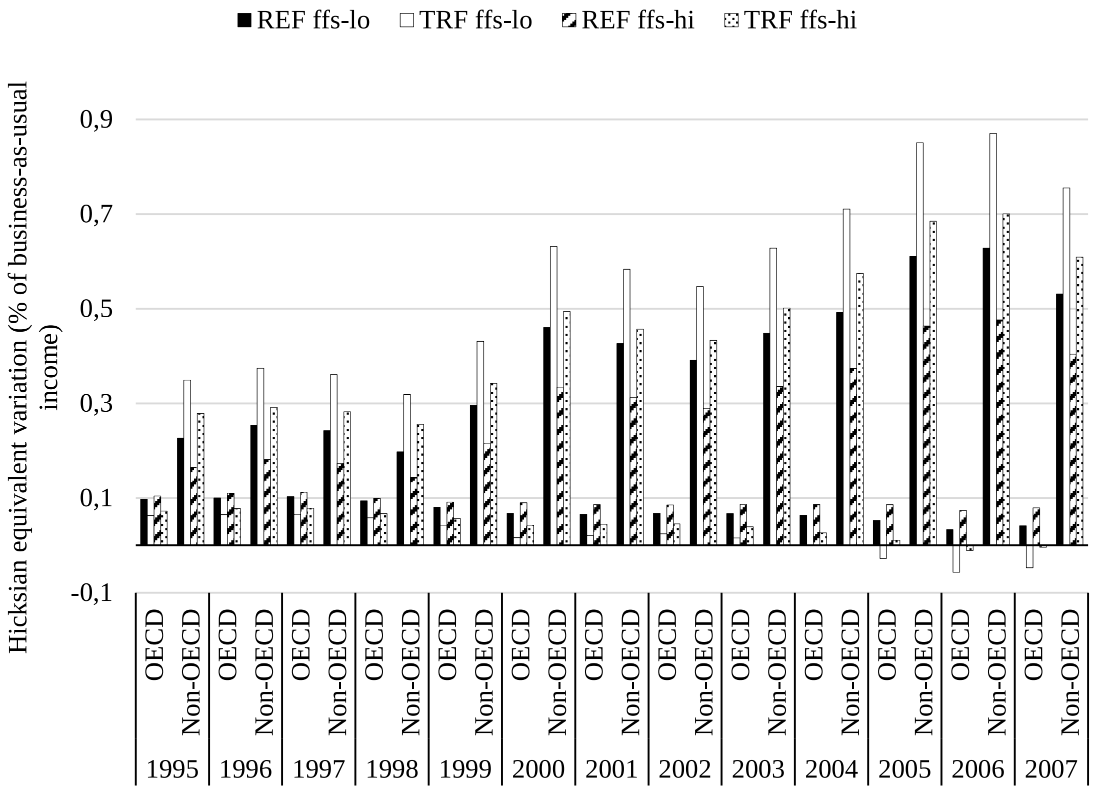



Figure A.10: Adjustment cost in OECD and Non-OECD under halved (*REF_ffs-lo* and *TRF_ffs-lo*) and doubled (*REF_ffs-hi* and *TRF_ffs-hi*) fossil fuel elasticities



The burden shifting potential of tariffs declines towards higher Armington elasticities because of stronger trade diversion by Non-OECD countries away from the OECD to other Non-OECD countries (*TRF_arm-hi*). Yet, the burden shifting potential of carbon tariffs remains substantial and increases over time.

Doubling the fossil fuel supply elasticities leads to a reduction of the benchmark leakage rate within the range of 32%-41% under emission pricing stand-alone (*REF_ffs-hi*) while the leakage reduction ranges from 65% to even negative leakage rates in 1998 and 1999 under carbon tariffs (*TRF_ffs-hi*), see Figure A.9. In contrast, halving the fossil fuel supply elasticities increases the benchmark leakage rate on the average by 40% and 89% under *REF_ffs-lo* and *TRF_ffs-lo*, respectively. That is, a reduced sensitivity of fuel supply to the fall in the OECD fossil fuel demand triggers a more pronounced depression of international fuel prices and hence higher consumption of fossil fuels in Non-OECD countries.

Across alternative choices of fossil fuel supply elasticities, the potential to shift the abatement burden to non-abating countries remains qualitatively identical to the core simulations (Figure A.10).

## Appendix B: Multi-region input-output model

For our MRIO calculation of carbon embodied in trade flows and final products we use the denotations listed in Table B1. The calculation is identical for each year in our analysis (1995-2007), so we omit an index to indicate the year.

The total carbon content of a good is composed of the $CO_2$ emitted in the production of the good itself as well as $CO_2$ that is emitted to produce intermediate inputs and international transport services. To calculate the full carbon content (per USD of output) we use input-output accounting identities and solve the associated linear system of equations below for the carbon content of production activities $cc_{gr}^{Y}$ and the carbon content of imports $cc_{ir}^{M}$. The first set of equations (1) states that the total embodied carbon in output $cc_{gr}^{Y} Y_{gr}$ of activity $g$ in region $r$ must be equal to the sum of direct emissions, the embodied carbon in domestic intermediate inputs and the embodied carbon in imported intermediate inputs. The second set of equations (2) demands total embodied carbon in imports $cc_{ir}^{M} M_{ir}$ of commodity $i$ in region

$r$ to equal the sum of the embodied carbon of all exports from regions $s$ to $r$ of commodity $i$.

$$\forall g \in G \forall r \in R: \qquad cc_{gr}^{Y} Y_{gr} = co2e_{gr} + \sum_{i \in I} cc_{ir}^{Y} Z_{igr}^{D} + \sum_{i \in I} cc_{ir}^{M} Z_{igr}^{M} \tag{1}$$

$$\forall i \in I \forall r \in R: \qquad cc_{ir}^{M} M_{ir} = \sum_{s \in R} cc_{is}^{Y} X_{isr} \tag{2}$$

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

Table B1: Denotations used in the MRIO calculations

| | |
|---|---|
| Sets and Indices | |
| $R$ | Set of regions (with *r* denoting the set index) |
| $I$ | Set of producing sectors, or equivalently, set of commodities (with *i* denoting the set index) |
| $G$ | Set of activities, consisting of the producing sectors, public expenditure (G), investment (I) and final consumption (C) (with *g* denoting the set index) |
| Parameters | |
| $Y_{gr}$ | Output in the producing sectors (for $g \in I$) and level of public expenditure, investment and final consumption (for $g \in \{G, I, C\}$) in region $r$ |
| $X_{isr}$ | Exports of commodity $i$ from in region $s$ to region $r$ |
| $M_{ir}$ | Imports of commodity $i$ in region $r$ |
| $Z_{igr}^{D}$ | Domestic intermediate inputs of commodity $i$ in activity $g$ in region $r$ |
| $Z_{igr}^{M}$ | Imported intermediate inputs of commodity $i$ in activity $g$ in region $r$ |
| $co2e_{gr}$ | Direct $CO_2$ emissions in activity $g$ in region $r$ |
| Variables | |
| $cc_{gr}^{Y}$ | Carbon content in activity $g$ in region $r$ |
| $cc_{ir}^{M}$ | Carbon content of imported commodities $i$ in region $r$ |

## Appendix C: Computable general equilibrium model

Three classes of conditions describe the competitive equilibrium for our model: (1) zero profit conditions, determining activity levels; (2) market clearance conditions, determining price levels; and (3) income balances. In our exposition, the notation $\Pi_{ir}^{u}$ is used to denote the profit function of sector *i* in region *r* where *u* is the name assigned to the associated activity. Differentiating the profit function with respect to input and output prices provide compensated demand and supply coefficients (Hotelling's lemma), which appear subsequently in the market clearance conditions. We use *i* and *j* as indexes for commodities (including a composite public good $i$=$G$ and a composite investment good $i$=$I$) and $r$ and $s$ as indexes for regions. The label $EG$ represents the set of energy goods and the label $FF$ denotes the subset of fossil fuels. Tables C.1 – C.6 explain the notations for variables and parameters employed within our algebraic exposition.

## C.1 Zero Profit Conditions

1. Production of goods except fossil fuels $\left(i \notin FF\right)$:

$$\prod_{ir}^{Y} = p_{ir} - \left\{ \left( \sum_{j \notin EG} \theta_{jir}\, p_{jr}^{A} \right)^{1-\sigma_{ir}^{KLEM}} - \theta_{ir}^{KLE} \left[ \theta_{ir}^{E}\, p_{ir}^{E\,1-\sigma_{ir}^{KLE}} + (1-\theta_{ir}^{E}) \left( \theta_{ir}^{L} w_{r}^{1-\sigma_{ir}^{KL}} + (1-\theta_{ir}^{L}) v_{r}^{1-\sigma_{ir}^{KL}} \right)^{\frac{1-\sigma_{ir}^{KLE}}{1-\sigma_{ir}^{KL}}} \right]^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{KLE}}} \right\}^{\frac{1}{1-\sigma_{ir}^{KLEM}}} \leq 0$$

2. Production of fossil fuels $\left(i \in FF\right)$:

$$\prod_{ir}^{Y} = p_{ir} - \left[ \theta_{ir}^{Q} q_{ir}^{1-\sigma_{i}^{Q}} + \left(1-\theta_{ir}^{Q}\right) \left( \theta_{Lir}^{FF} w_{r} + \theta_{Kir}^{FF} v_{r} + \sum_{j} \theta_{jir}^{FF} \left( p_{jr}^{A} + p_{r}^{CO_2} a_{j}^{CO_2} \right) \right)^{1-\sigma_{i}^{Q}} \right]^{\frac{1}{1-\sigma_{i}^{Q}}} \leq 0$$

3. Sector-specific energy aggregate $\left(i \notin FF\right)$:

$$\prod_{ir}^{E} = p_{ir}^{E} - \left( \sum_{j \in EG} \theta_{jir}^{EG} \left( p_{jr}^{A} + p_{r}^{CO_2} a_{j}^{CO_2} \right)^{1-\sigma_{ir}^{EG}} \right)^{\frac{1}{1-\sigma_{ir}^{EG}}} \leq 0$$

4. Armington aggregate:

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

5. Aggregate imports across import regions:

$$\prod_{ir}^{M} = p_{ir}^{M} - \left( \sum_{s} \theta_{isr}^{M}\, p_{is}^{1-\sigma_{ir}^{M}} \right)^{\frac{1}{1-\sigma_{ir}^{M}}} \leq 0$$

6. Household consumption demand:

$$\prod_{r}^{C} = p_{r}^{C} - \left( \theta_{Cr}^{E}\, p_{Cr}^{E\;1-\sigma_{Cr}^{E}} + (1-\theta_{Cr}^{E}) \left[ \prod_{i \notin EG} \left( p_{ir}^{A} \right)^{\gamma_{ir}} \right]^{1-\sigma_{Cr}^{E}} \right)^{\frac{1}{1-\sigma_{Cr}^{E}}} \leq 0$$

## C.2 Market Clearance Conditions

7. Labor:

$$\overline{L}_r \geq \sum_j Y_{jr} \frac{\partial \Pi_{jr}^Y}{\partial w_r}$$

8. Capital:

$$\overline{K}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial v_r}$$

9. Natural resources $(i \in FF)$:

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

10. Output:

$$Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}} \geq \sum_j A_{jr} \frac{\partial \Pi_{jr}^A}{\partial p_{ir}} + \sum_s M_{is} \frac{\partial \Pi_{is}^M}{\partial p_{ir}}$$

11. Armington aggregate:

$$A_{ir} \geq \sum_j Y_{jr} \frac{\partial \Pi_{jr}^Y}{\partial p_{ir}^A} + C_r \frac{\partial \Pi_r^C}{\partial p_{ir}^A}$$

12. Import aggregate:

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

13. Sector-specific energy aggregate:

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

14. Public consumption ($i=G$):

$$Y_{Gr} \geq \overline{G}_r$$

15. Investment ($i=I$):

$$Y_{Ir} \geq \overline{I}_r$$

16. Carbon emissions:

$$\overline{CO2}_r \geq \sum_i A_{ir} a_i^{CO_2}$$

## C.3 Income-expenditure Balance

17. Household consumption:

$$C_r p_r^C = w_r \overline{L}_r + v_r \overline{K}_r + \sum_{j \in FF} q_{jr} \overline{Q}_{jr} + p_{Ir} \overline{Y}_{Ir} + p_{Gr} \overline{Y}_{Gr} + \overline{B}_r + p_r^{CO_2} \overline{CO2}_r$$

Table C.1: Sets

| | |
|---|---|
| I | Sectors and goods (indexed with $i$, $j$) |
| R | Regions (indexed with $r$, $s$) |
| EG | All energy goods: Coal, crude oil, natural gas (aggregated in one sector), refined oil, and electricity |
| FF | Primary fossil fuels: Coal, crude oil and natural gas (aggregated in the sector) |

Table C.2: Activity variables

| | |
|---|---|
| $Y_{ir}$ | Production in sector $i$ and region $r$ |
| $E_{ir}$ | Aggregate energy input in sector $i$ and region $r$ |
| $M_{ir}$ | Aggregate imports of good $i$ and region $r$ |
| $A_{ir}$ | Armington aggregate for good $i$ in region $r$ |
| $C_r$ | Aggregate household consumption in region $r$ |

Table C.3: Price variables

| | |
|---|---|
| $p_{ir}$ | Output price of good *i* produced in region *r* |
| $p_{ir}^{E}$ | Price of aggregate energy in sector *i* and region *r* |
| $p_{ir}^{M}$ | Import price aggregate for good *i* imported to region *r* |
| $p_{ir}^{A}$ | Price of Armington good *i* in region *r* |
| $p_{r}^{C}$ | Price of aggregate household consumption 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* |

Table C.4: Cost shares

| | |
|---|---|
| $\theta_{jir}$ | Cost share of intermediate good *j* in sector *i* and region *r* (i$\notin$FF) |
| $\theta_{ir}^{KLE}$ | Cost share of KLE aggregate in sector *i* and region *r* (i$\notin$FF) |
| $\theta_{ir}^{E}$ | Cost share of energy composite in the KLE aggregate in sector *i* and region *r* (i$\notin$FF) |
| $\theta_{ir}^{L}$ | Cost share of labor in value-added composite of sector *i* and region *r* (i$\notin$FF) |
| $\theta_{ir}^{Q}$ | Cost share of natural resources in sector *i* and region *r* (i$\in$FF) |
| $\theta_{Tir}^{FF}$ | Cost share of good *i* ($T=i$) or labor ($T=L$) or capital ($T=K$) in the non-resource aggregate in sector *i* and region *r* ($i \in FF$) |
| $\theta_{jir}^{EG}$ | Cost share of energy good *j* in the energy composite in sector *i* in region *r* (i$\notin$FF) |
| $\theta_{isr}^{M}$ | Cost share of imports of good *i* from region *s* to region *r* |
| $\theta_{ir}^{A}$ | Cost share of domestic variety in Armington good *i* of region *r* |
| $\theta_{Cr}^{E}$ | Cost share of composite energy demand in household consumption in region *r* |
| $\gamma_{ir}$ | Cost share of non-energy good *i* in non-energy household consumption demand in region *r* |

Table C.5: Elasticities

| | | |
|---|---|---|
| $\sigma_{ir}^{KLEM}$ | Substitution between KLE composite and material inputs in production | Koesler and Schymura (2014) |
| $\sigma_{ir}^{KLE}$ | Substitution between energy and value-added in production | Koesler and Schymura (2014) |
| $\sigma_{ir}^{KL}$ | Substitution between labor and capital in value-added composite | Koesler and Schymura (2014) |
| $\sigma_{ir}^{Q}$ | Substitution between natural resources and other inputs in fossil fuel production calibrated to exogenous supply elasticities | $\mu_{OMN}$=1.0 |
| $\sigma_{ir}^{EG}$ | Substitution between energy goods in the energy aggregate | 0.5 |
| $\sigma_{ir}^{A}$ | Substitution between the import aggregate and the domestic input | Narayanan et al. (2015) |
| $\sigma_{ir}^{M}$ | Substitution between imports from different regions | Narayanan et al. (2015) |
| $\sigma_{Cr}^{E}$ | Substitution between energy and non-energy inputs in consumption | 0.3 |

Table C.6: Endowments and emissions coefficients

| | |
|---|---|
| $\overline{L}_r$ | Aggregate labor endowment in region *r* |
| $\overline{K}_r$ | Aggregate capital endowment in region *r* |
| $\overline{Q}_{ir}$ | Endowment of natural resource *i* in region *r* (i∈FF) |
| $\overline{G}_r$ | Public good provision in region *r* |
| $\overline{I}_r$ | Investment demand in region *r* |
| $\overline{B}_r$ | Balance of payment deficit or surplus in region *r* |
| $\overline{CO2}_r$ | $CO_2$ emission constraint for region *r* |
| $a_i^{CO_2}$ | $CO_2$ emissions coefficient for fossil fuel *i* ($i \in FF$) |

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