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CARBON TARIFFS REVISITED

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Abstract

Concerns about adverse impacts on domestic energy-intensive and trade-exposed (EITE) industries are at the fore of the political debate about unilateral climate policies. Tariffs on the carbon embodied in imported goods from countries without emission pricing appeal as a measure to reduce carbon leakage and protect domestic EITE industries. We show that the introduction of carbon tariffs can do more harm than good to domestic EITE industries. Two determinants drive the sign and magnitude of EITE impacts. Firstly, the composition of embodied emissions in goods: if a large share of embodied carbon is imported in intermediate inputs, industries might suffer from carbon tariffs. Secondly, the share of domestic output that is supplied to the export market: while carbon tariffs level the playing field on domestic markets, they increase the cost-disadvantage vis-à-vis competitors from abroad in foreign markets.

Keywords: carbon tariffs, unilateral climate policy, multi-region input-output analysis, CGE

JEL classifications: Q58, D57, D58

1. Introduction

Concerns on the competitiveness of domestic emission-intensive and trade-exposed (EITE) industries are at the fore of the unilateral climate policy debate. Industries where emission-intensive inputs represent a significant share of direct and indirect costs will face negative production and employment effects from unilateral emission pricing. These adverse impacts will be more accentuated for emission-intensive industries which are trade-exposed since they do not only face higher cost vis-à-vis less emission-intensive production sectors at home but also a loss in comparative advantage against competitors abroad.

Prima facie, the losses of EITE industries in competitiveness at the national and international level could be viewed as the logical outcome of structural change towards cleaner production and consumption patterns. At second glance, however, requests for EITE-specific protective measures can be rooted in more general economic efficiency considerations. The reasoning behind is the global nature of the carbon externality. While unilateral carbon pricing will decrease domestic production and emissions of carbon-intensive tradable goods, this may be counteracted by increased production of such goods abroad. Given that only world-wide CO_2 emissions matter for climate change, such carbon leakage can seriously hamper the cost-effectiveness of unilateral emission regulation (see e.g. Hoel, 1991; or Felder and Rutherford, 1993).

Measures to attenuate the loss in competitiveness of domestic EITE industries therefore bear some efficiency rationale and cannot be simply disguised as blunt lobby policy by interest groups.

Principal among anti-leakage measures are carbon tariffs where emissions embodied in imports from non-regulating regions are taxed at the emission price of the regulating region. Carbon tariffs are appealing in various respects. Economists appraise them as a second-best instrument to reduce leakage and improve global cost-effectiveness of unilateral emission regulation (Markusen, 1975; Hoel, 1991).[1] Environmentalists embrace them as a means to capture the carbon footprint of imported products. Stakeholders of EITE industries welcome carbon tariffs as a corrective measure which levels the playing field in international trade of emission-intensive goods. The concordant main findings of previous quantitative studies (see e.g. Caron, 2012; Fischer and Fox, 2012; Balistreri and Rutherford, 2012) are that carbon tariffs reduce carbon leakage, typically increase global cost-effectiveness of unilateral action and – last but not least – attenuate adverse production impacts of unilateral emission pricing for domestic EITE industries.[2]

In this paper we focus on the economic implications of carbon tariffs for EITE industries. Contrary to previous findings, we show that carbon tariffs can worsen rather than ameliorate adverse impacts for unilaterally regulated EITE industries. The key impact drivers are the amount and composition of embodied emissions in EITE production (consisting of direct emissions from fossil fuel inputs, indirect emissions embodied in domestically produced intermediate inputs, and indirect emissions embodied in imported intermediate inputs) and the share of EITE production that is supplied to the export market. If the carbon embodied in an EITE good stems predominantly from imported inputs, then this industry can rather suffer than benefit from the imposition of carbon tariffs. Likewise, industries exporting larger shares of their output suffer more, since carbon tariffs level the playing field only in domestic markets but lead to a further cost-disadvantage in foreign markets. Export-oriented EITE industries that are relatively clean in terms of direct emissions but rather dirty in terms of the imported carbon run the risk to shoot themselves in the foot if they lobby for carbon tariffs. We draw our conclusions from combined multi-region input-output (MRIO) and computable general equilibrium (CGE) analyses. In our numerical simulations we focus on Switzerland and the United States of America as prime examples of how carbon tariffs can affect the performance of EITE industries in opposing ways. While we find that carbon tariffs reduce the adverse EITE production impacts of unilateral emission pricing in the case of the US, they exacerbate the negative EITE production effects in the case of Switzerland.

The remainder of this paper is organized as follows. In Section 2 we describe our benchmark data, provide non-technical summaries of our MRIO and CGE models and lay out our policy scenarios. In Section 3 we present MRIO estimates on embodied carbon and discuss differences in the output supply of EITE

[1] In theory, full border carbon adjustment also includes rebating of emission charges levied on exports to non-regulating countries. However, export rebates may constitute a subsidy under the WTO's Agreement on Subsidies and Countervailing Measures (Cosbey et al., 2012) and therefore are generally omitted in policy proposals.

[2] Böhringer et al. (2012a) provide a summary of a model cross-comparison study on the economic impacts of carbon tariffs.

industries between Switzerland and the US. In Section 4 we interpret CGE simulation results on the economic impacts of carbon tariffs. In section 5 we conclude.

2. Data, Models and Policy Scenarios

Data

We base our analysis on the GTAP 8 dataset, which includes detailed national input-output tables as well as bilateral trade flows and CO_2 emission data for 129 regions and 57 sectors for the year 2007 (Narayanan et al., 2012). For the sake of compactness, the dataset is aggregated to 15 sectors and 19 regions that are relevant to our research topic (see Table 1). As to sectors, we explicitly represent the primary and secondary energy carriers (coal, gas, crude oil, refined oil products and electricity) to capture differences in CO_2 intensity and the degree of fuel substitutability. Furthermore, we treat energy-intensive and trade-exposed non-energy sectors (non-ferrous metals, mineral products, iron and steel, chemical products, as well as paper, pulp and print) separately as these are at the fore of policy concerns on competitiveness.[3] In addition, the aggregate dataset comprises agriculture and three transport sectors (air transport, water transport, and other transport including road and rail). All remaining sectors in the original dataset are aggregated to a composite sector "All other manufactures and services". With respect to regions, we explicitly include industrialized economies as the prime candidates for unilateral emission regulation and emerging economies that are important in international trade.

Table 1: Model sectors and regions

Sectors and commodities	*Countries and regions*
Energy	Switzerland
Coal	USA
Crude oil	European Union (EU 27)
Natural gas	Canada
Refined oil products*	Japan
Electricity	South Korea
*Emission-intensive & trade-exposed sectors**	Norway
Chemical products	New Zealand
Non-metallic minerals	Australia
Iron and steel industry	Russia
Non-ferrous metals	India
Paper, pulp and print	Indonesia
Transport sectors	South Africa
Air transport	China (incl. Hong Kong)
Water transport	Brazil
Other transport	OPEC
Other industries and services	Remaining OECD
Agriculture	Low income countries
All other manufactures and services	Middle income countries

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

[3] Note that refined oil production also forms part of the EITE industries.

Multi-region input-output model

Embodied carbon refers to the total amount of CO_2 that is emitted to produce a certain good. The total carbon content[4] thereby includes direct emissions (those due to the combustion of fossil fuel inputs in the production of the good) as well as indirect emissions (such as emissions created by the generation of electricity used for the production of the good). In order to calculate the region- and sector-specific carbon content of goods we use input-output accounting identities for output, imports and international transport services in each region (see Appendix A for an algebraic description). After solving the occurring linear system of equations, we can decompose the embodied emissions in EITE 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.

Computable general equilibrium model

The virtue of CGE models in applied policy analysis is their micro-consistent and comprehensive representation of market interactions through price-responsive supply and demand reactions. Beyond the assessment of price-induced structural change, CGE models allow for the quantification of efficiency and distributional implications triggered by policy measures. We use a standard multi-region, multi-sector computable general equilibrium (CGE) model of global trade and energy (for an algebraic representation of the core model logic see Appendix B).

Primary factors of production include labor and capital which are assumed to be mobile across sectors within each region but not internationally mobile. In fossil fuel production, part of the capital is treated as a sector-specific resource. Factor markets are perfectly competitive.

The production of goods other than fossil resources is represented through a five-level nested constant-elasticity-of-substitution (CES) function. At the top level, a composite of value added, energy and material intermediate inputs trades off with a transport composite of air transport, water transport and other transport services. On the second level, the value-added composite trades off with an energy aggregate. The third level describes the substitution within value added between labor and capital. At the same level, electricity trades off with a composite of coal, gas and oil to form the energy aggregate. The fourth level describes the trade-off between coal and an aggregate of gas and oil. Substitution possibilities between gas and oil are captured at the fifth level. In fossil resource production (coal, gas and crude oil) the specific resource factor trades off with a Leontief composite of all other inputs at a constant elasticity of substitution.

The output in each production sector is allocated either to the domestic market or the export market according to a constant-elasticity-of-transformation function.

Final consumption stems from a representative agent in each region who receives income from primary factors and maximizes welfare subject to a budget constraint. Substitution patterns within the consumption

[4] The carbon content is defined as the embodied carbon in kg CO_2 per USD of output.

bundle of the representative agent are described through a nested CES function which follows the same structure as the production functions of non-resource goods.

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 is then a CES function of production from all other countries. A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

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

For model parameterization we follow the standard calibration procedure in applied general equilibrium analysis. The base-year input–output data determines the free parameters of the 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 determined by a set of exogenous elasticities taken from the pertinent econometric literature. Elasticities in international trade (Armington elasticities) and substitution possibilities in production (between primary factor inputs) are directly provided by the GTAP database. The elasticities of substitution in fossil fuel sectors are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham et al., 1999; Krichene, 2002; Ringlund et al., 2008).

Policy scenarios

We assess the economic impacts of carbon tariffs with respect to a reference scenario (denoted *REF*), in which a specific country – in our core simulations: Switzerland or the US – undertakes unilateral pricing of domestic CO_2 emissions. Alternatively to this reference scenario, the unilaterally acting country can complement domestic emission pricing with carbon tariffs on imported goods (scenario *TRF*). In both scenarios, the unilaterally abating country reduces domestic CO_2 emissions by 20% compared to business-as-usual reflecting mid-term emission reduction pledges of industrialized countries in domestic climate policy strategies. To effect the targeted emission reduction, the country either levies a uniform emission tax or equivalently implements a domestic emission trading system.

Carbon tariffs can be designed in various ways reflecting alternative legal, practical, and political considerations (see Böhringer et al., 2012b). In our core simulations, we apply carbon tariffs to the full carbon content embodied in imported goods as calculated from the base-year statistics using the MRIO model. From the perspective of the unilaterally abating region the entire carbon embodied in imports is then taxed at the domestic CO_2 price when crossing the border.[5]

3. Multi-region input-output analysis

Central to the effects of carbon tariffs is the amount and the composition of embodied carbon in internationally traded goods as well as the export supply share of production.

Table 2 presents summary statistics on the trade patterns of embodied carbon at the economy-wide level for Switzerland and the US. The first four columns report the amounts of production-based, consumption-based[6], imported and exported CO_2. The last two columns show the so-called balance of emissions embodied in trade (BEET), i.e., the net exports of embodied carbon in Mt of CO_2 and as a percentage share of the production-based emissions.

For the 2007 base-year the US produces 5583.3 Mt CO_2, which is more than a hundred times the Swiss production-based emissions (43.5 Mt CO_2) and consumes about seventy times as much emissions as Switzerland (6160.3 compared to 88.2 Mt CO_2). In relative terms, however, Switzerland has a much higher intensity in embodied carbon trade than the US: Switzerland imports more than twice the amount of its production-based emissions while exporting almost one and a half times its production-based emissions. The US, in contrast, imports less than one quarter and exports just around 13% of production-based emissions. The BEET shows that both regions are net importers of embodied carbon. Yet, while the US net imports only amount to about 10% of domestically produced embodied carbon, Switzerland's net imports amount to roughly 100% of domestically produced embodied carbon.

Table 2: Carbon in production and trade for Switzerland and the USA

	Production (Mt CO_2)	Consumption (Mt CO_2)	Exports (Mt CO_2)	Imports (Mt CO_2)	BEET* (Mt CO_2)	BEET* (%)
Switzerland	43.5	88.2	60.8	105.4	-44.7	-102.6
USA	5583.3	6160.3	709.8	1286.8	-577.0	-10.3

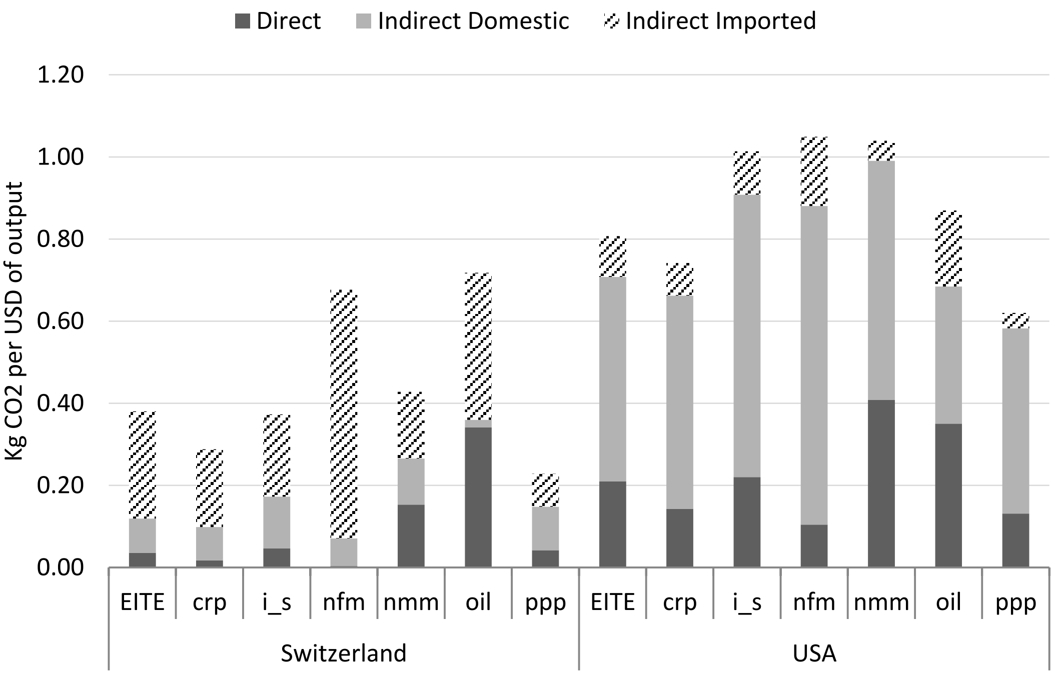
*BEET: Balance of emissions embodied in trade (either in Mt CO_2 or in % of production-based emissions)

Figure 1 shows the specific carbon content for individual EITE industries in Switzerland and the US with a decomposition into direct emissions from fossil fuel inputs ("Direct") and indirect emissions embodied in intermediate inputs. The indirect carbon content is further split down into embodied carbon of domestically produced intermediate inputs ("Indirect Domestic") and imported intermediate inputs ("Indirect Imported").[7] Figure 2 shows the same decomposition in percentage shares rather than absolute levels.

[5] We discuss results for alternative designs of carbon tariffs in our sensitivity analysis in Section 4.
[6] Production-based emissions comprise all emissions from fossil fuel burning in domestic production, whereas consumption-based emissions comprise all the embodied carbon in final consumption.
[7] "Indirect Imported" emissions include those of international transport services.

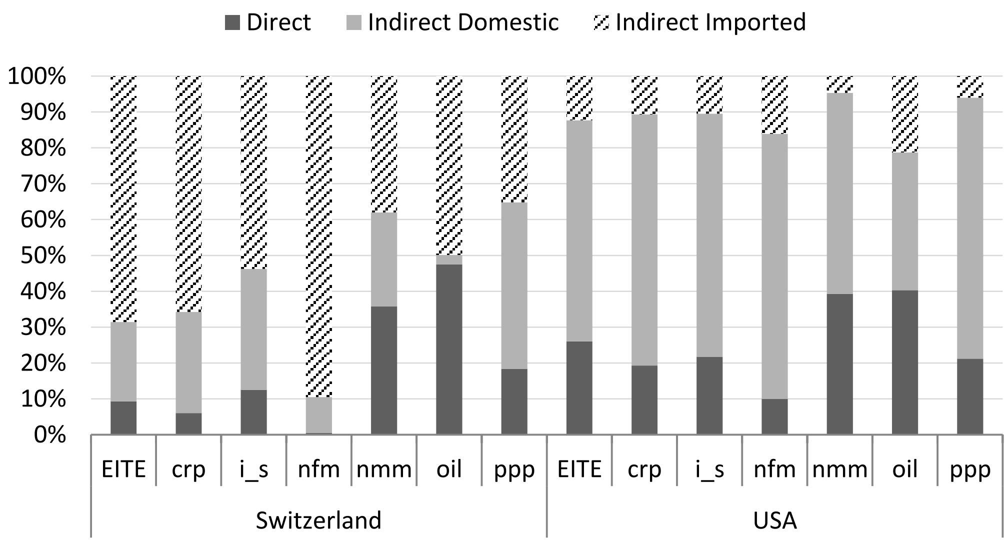
We see that in each individual EITE sector, the share of imported carbon content is substantially larger in Switzerland than in the US. For the EITE industry as a whole, this share amounts to about 68% in Switzerland and roughly 12% in the US.

Figure 1: Decomposition of carbon content in EITE industries into direct emissions and indirect emissions from domestic or imported goods



Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

Figure 2: Percentage decomposition of carbon content in EITE industries into direct emissions and indirect emissions from domestic or imported goods



Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

In particular, the Swiss industries for chemical products (crp), iron and steel (i_s) and non-ferrous metals (nfm) stand out with high shares of indirect imported emissions. For chemical products the carbon content stems to roughly 65% from imported emissions, in iron and steel production to around 53%, and in the production of non-ferrous metals to almost 90%. We can already deduce from Figures 1 and 2 that the Swiss non-ferrous metals industry will not be severely affected – at least compared to other EITE industries – if only domestic emissions are priced. However, if carbon tariffs are imposed having domestic industries pay for the embodied carbon of imported inputs, the production of non-ferrous metals in Switzerland will face a substantial cost increase.

The EITE sectors in Switzerland on average are "cleaner" with respect to embodied carbon than in the US since their total embodied carbon content is lower. In a multilateral perspective, both Swiss and US EITE production is rather clean compared to other world regions. The average carbon content (in kg CO_2 per USD of output) of an EITE product is 0.38 and 0.81 in Switzerland and the US, respectively, compared to 1.1 for the global average. For the BRIC countries the MRIO calculations yield an average EITE carbon content of 2.1 kg per USD of output, for China 2.4.[8]

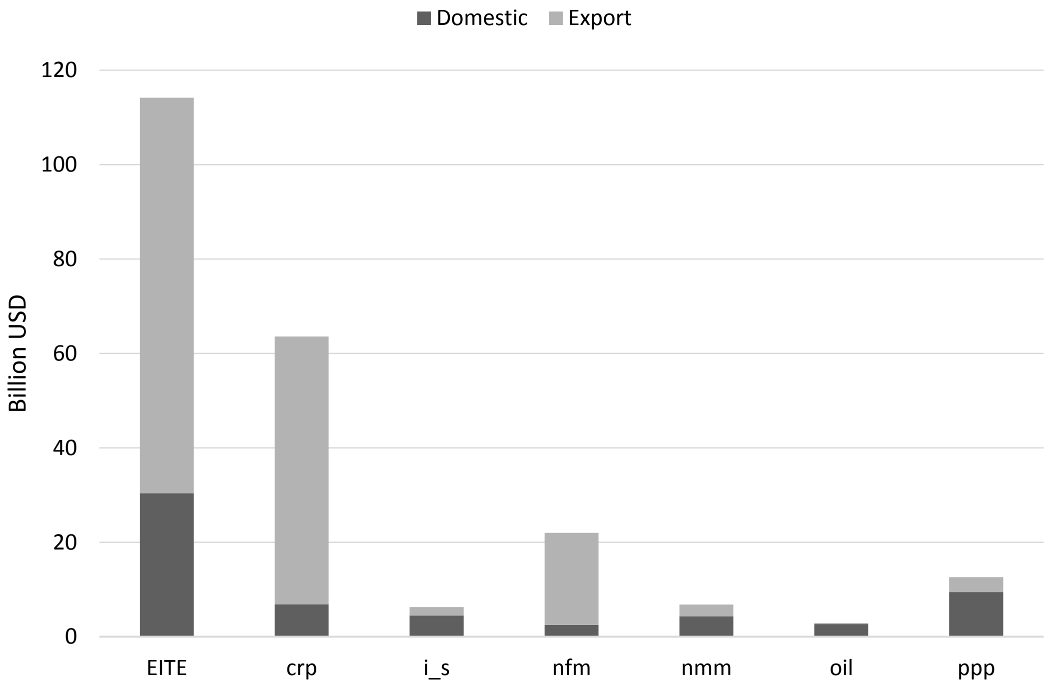
EITE industries compete on domestic and international markets with foreign industries producing the same good. Additionally, on each market they compete with domestic and foreign goods of other industries that are close substitutes. Our climate policies under consideration – unilateral emission pricing stand-alone versus unilateral emission pricing complemented with tariffs on the embodied carbon in imported goods – affect the competitiveness of domestic EITE industries on domestic and export markets differently. Accounting for domestic and export supply separately is therefore relevant in order to deduce the overall production impact for a specific industry.

Figure 3 shows the total output for the Swiss EITE industries decomposed into supply to the domestic market and supply to the export market. Switzerland supplies almost three thirds of total EITE output to foreign markets. In particular, the largest EITE industries – chemical products (crp) and non-ferrous metals (nfm), which together account for three quarters of overall output – export around 90% of their output. The remaining EITE industries depend more on the domestic market with export supply shares of 36% for non-metallic minerals, 28% for iron and steel, and 7% for refined oil products.

Figure 4 shows the same statistics for US EITE industries. The largest industries with respect to output are chemical products (crp) and refined oil products (oil), which together account for about 60% of total EITE output. As opposed to Switzerland, all of the US EITE industries supply large shares of the output to the domestic market. Inversely, the US EITE industry as a whole supplies only roughly 15% of its output to foreign markets with chemical products and non-ferrous metals (nfm) having the largest shares of export supply (but still less than 25%).

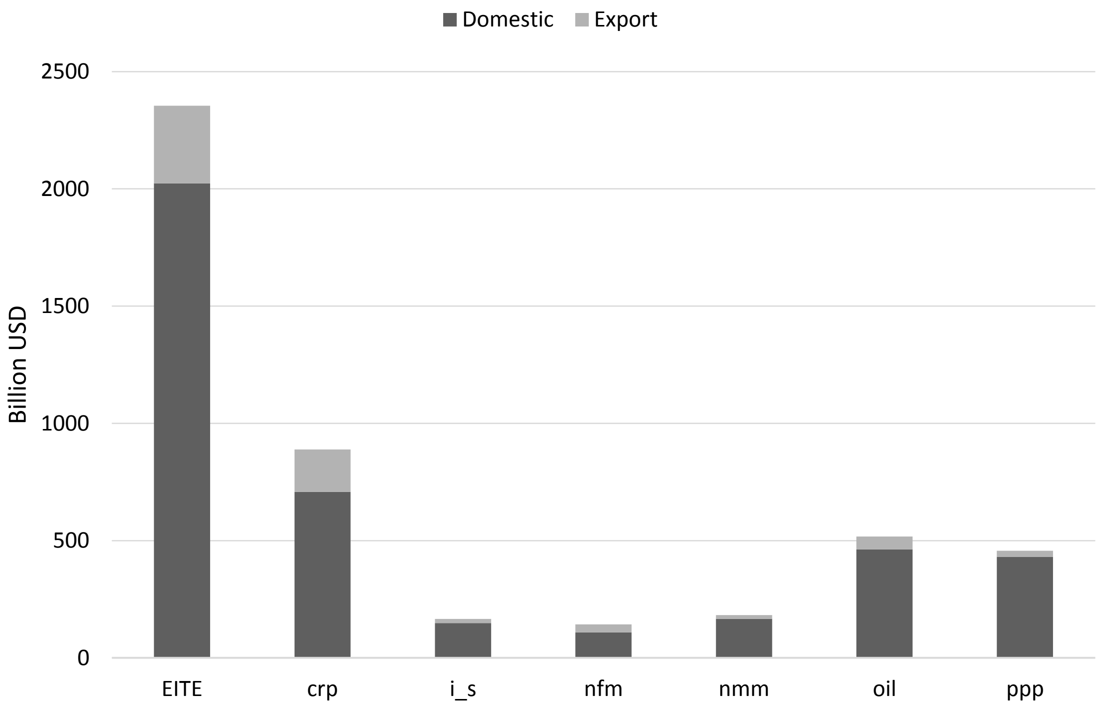
[8] Note that as a first-round effect, carbon tariffs will improve competitiveness of domestic industries on domestic markets against "dirtier" competitors from abroad.

Figure 3: Domestic and export supply of EITE industries in Switzerland



Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

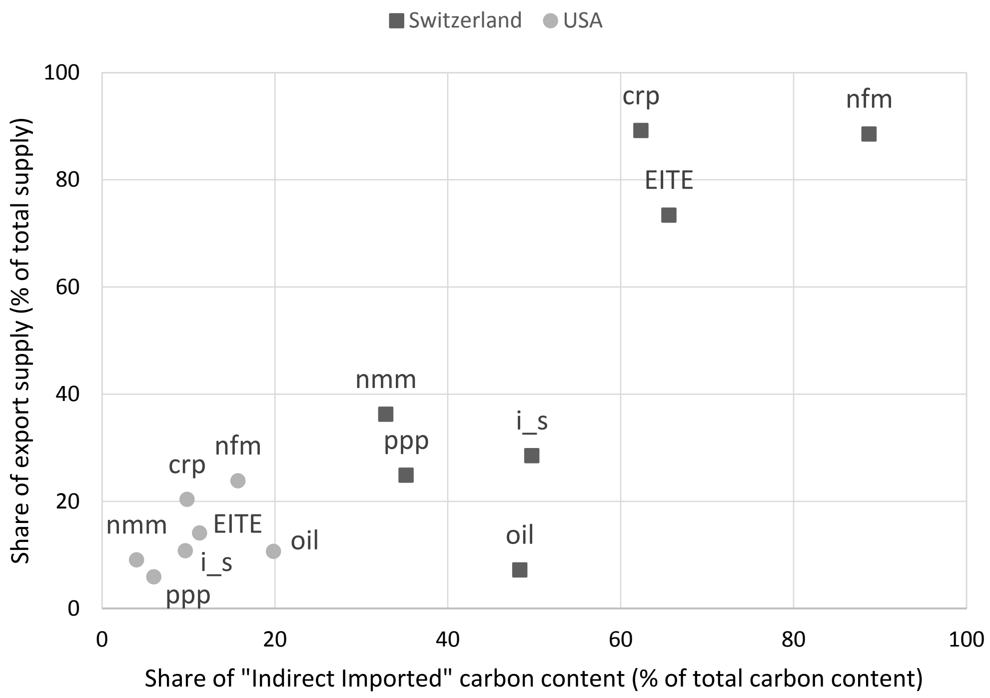
Figure 4: Domestic and export supply of EITE industries in the USA



Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

The scatter diagram in Figure 5 provides a comparison of the share of imported carbon content and the share of export supply in each EITE industry for Switzerland and the US. The further to the right and to the top an industry is located, the worse is the expected output impact from the introduction of carbon tariffs. Thus, in particular the Swiss chemical industry and non-ferrous metals industry are likely to suffer from carbon tariffs.

Figure 5: Share of "Indirect Imported" carbon content and share of export supply of EITE industries in Switzerland and the USA



Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

4. Computable general equilibrium analysis

We use our multi-sector multi-region CGE model to quantify the economic impacts of emission regulation. If not stated otherwise, all results are reported as percentage changes from the base-year equilibrium which constitutes our business-as-usual without policy interference. We begin with a brief discussion of emission changes and macroeconomic effects to relate our assessment with previous analysis on the impacts of unilateral climate policies. Our main focus is then on the production impacts for EITE industries which are at the center of attention in unilateral climate policy design. Finally, we present sensitivity analysis to investigate how robust our findings are with respect to changes in key parameters and assumptions.

Emissions and macroeconomic impacts

Table 3 reports the impacts of unilateral emission regulation in Switzerland and the US on emissions and welfare. The leakage rate is defined as the change in unregulated emissions abroad as a share of the domestic emission reduction. A leakage rate of 50%, for example, means that half of the domestic emission reduction is offset by increases in emissions abroad. Welfare changes are reported in Hicksian equivalent income variation. This measure denotes the amount which is necessary to add to (or subtract from) the business-as-usual income of the household so that she enjoys a utility level equal to the one in the counterfactual policy scenario on the basis of ex-ante relative prices.[9] One difficulty, however, in comparing welfare impacts between *REF* and *TRF* is that the amount of global emissions differs between the two regulatory regimes, as the abating country keeps with a fixed 20% reduction target in domestic base-year emissions irrespective of the emissions in the rest of the world. To accommodate a coherent global cost-effectiveness analysis between the *REF* and *TRF* scenarios, we would need to keep global carbon emissions constant. In this vein, we implement an additional scenario – denoted *TRF** – where we adjust the domestic emission reduction target of the unilateral abating region in the case of carbon tariffs to match the same global emissions as triggered in the *REF* scenario.[10]

Table 3: Leakage rates (%), emission changes (%) and welfare effects (in % Hicksian equivalent variation in income)

	Switzerland			USA		
	REF	*TRF*	*TRF**	*REF*	*TRF*	*TRF**
Leakage (%)	31.93	1.36	-4.04	4.46	2.41	2.40
Domestic emissions (%)	-20.00	-20.00	-13.09	-20.00	-20.00	-19.58
Foreign emissions (%)	0.0106	0.0005	-0.0009	0.241	0.130	0.127
Global emissions (%)	-0.023	-0.033	-0.023	-4.07	-4.15	-4.07
Domestic welfare (%)	-0.33	0.23	0.33	-0.17	-0.12	-0.11
Foreign welfare (%)	-0.002	-0.011	-0.007	-0.027	-0.069	-0.067
Global welfare (%)	-0.0049	-0.0094	-0.0043	-0.069	-0.084	-0.080

We see that leakage rates are reduced effectively through tariffs that are levied on the full carbon content of imported goods. For Switzerland, carbon tariffs almost eliminate leakage (if Switzerland adjusts its domestic reduction target to meet the same amount of global emissions as in *REF*, leakage becomes even negative). In the US, carbon tariffs halve the leakage rate compared to domestic CO_2 pricing only.

For both Switzerland and the US, carbon tariffs reduce the cost of domestic climate policy compared to *REF*. This is due to terms-of-trade effects: Carbon tariffs implicitly work as a substitute for strategic tariffs shifting the economic burden of emission reduction from abating countries to non-abating countries. For

[9] Global welfare accounting is based on a utilitarian (Benthamite) perspective on efficiency where welfare changes of individual regions are perfectly substitutable.
[10] In this framework, leakage reduction through carbon tariffs implies that the unilaterally abating region must cut back domestic emissions to a lesser extent than in the reference scenario in order to achieve the same global emission reduction.

Switzerland the terms-of-trade effects emerging from the imposition of carbon tariffs even leads to a net welfare gain compared to the business-as-usual.[11]

With respect to global cost-effectiveness, the leakage-adjusted scenario *TRF** where we keep global emissions at the *REF* level, indicates only small changes from the imposition of carbon tariffs. The limited potential for global cost savings from carbon tariffs can be traced back to the fact that import tariffs applied to the industry-average of embodied carbon do not incentivize polluters in unregulated countries to adopt less emission-intensive production techniques (see Böhringer et al., 2012a). It may even happen – as is the case for US action – that carbon tariffs are not efficiency improving since it is not necessarily optimal to tax the entire embodied carbon crossing the border.[12]

Production impacts in EITE industries

We now turn to the impact assessment of unilateral emission pricing on EITE industries where we can build on the insights from the multi-region input-output analysis in Section 3.

Unilateral CO_2 emission pricing leads to a cost increase for domestic EITE goods where emission-intensive goods – either in terms of fossil fuels or in terms of other dirty non-energy intermediate goods – represent a significant share of inputs. The cost increase reduces competitiveness vis-à-vis producers from unregulated regions both on the domestic market as well as on international markets. A complementary carbon tariff affects the competitiveness of domestic EITE production differently on the domestic and international markets. In first place, the tariff leads to a further cost increase since the domestic emission price has to be paid additionally on the carbon embodied in imported inputs. Domestic EITE industries then face an even bigger cost disadvantage on international markets than under uniform emission pricing only. In contrast, the tariff levels the playing field in domestic markets, since it effects that the entire embodied carbon of a good has to be paid for – independent of whether it is produced domestically or abroad. In fact, since the EITE industries in Switzerland and the US are “cleaner” from the outset compared to other world regions (see Section 3), unilateral emission pricing complemented with carbon import tariffs may even establish a cost advantage on domestic markets against at least some foreign competitors.[13]

We first look at the EITE production impacts for the US as these results are qualitatively in line with the findings of former studies (for a summary see Böhringer et al., 2012a). Then we turn to the production impacts for Swiss EITE industries which run counter to the common expectation that carbon tariffs protect domestic EITE production.

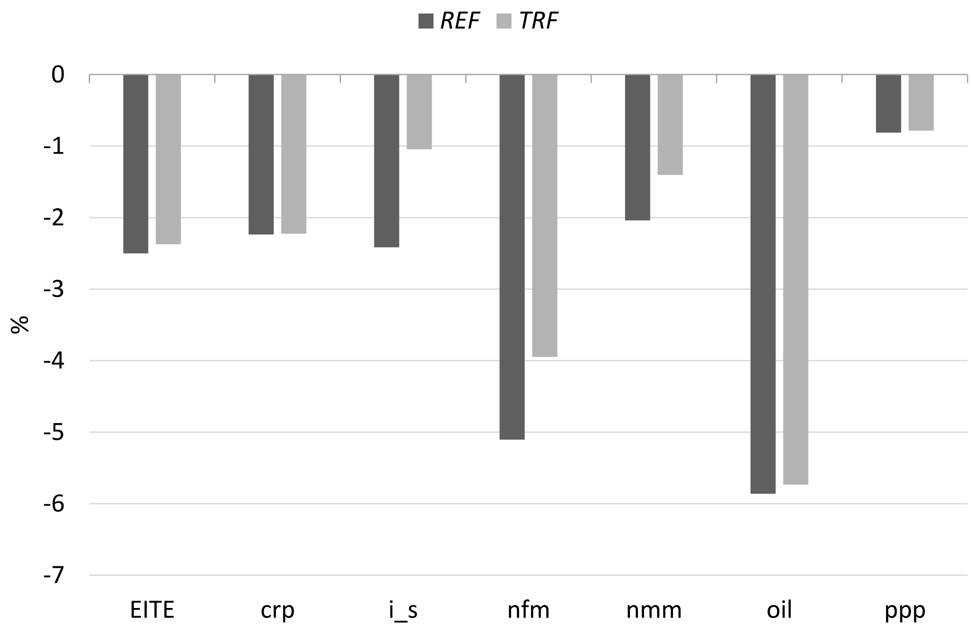
Figure 6 reports the production impacts on US EITE industries for our alternative unilateral climate policy designs. In the case of unilateral emission pricing only (scenario *REF*) output decreases in each EITE

[11] With leakage adjustment, carbon tariffs further decrease the economic cost for unilateral abating regions (scenario *TRF**) since leakage reduction lowers the domestic emission reduction requirement to meet the global emission level prescribed by scenario *REF*.
[12] Reduced export from non-abating countries to the abating country may lead to some redirection of output to non-abating countries, so that the emission effects of reduced export is less than 100%. Furthermore, some of the imported embodied emissions are in fact re-imports and are thus priced twice (see Böhringer et al., 2012b).
[13] Obviously, buyers can still substitute to goods from “cleaner” industries.

sector – ranging from a 0.8% decrease in the paper, pulp and print industry (ppp) to a 5.9% decline in refined oil products (oil). The EITE industry as a whole decreases output by 2.5%.[14] It is not possible to conclude from the magnitude of the specific carbon content directly to a ranking of output effects. For example, the non-metallic minerals industry (nmm) shows the smallest output decrease across all EITE industries, although it exhibits the highest direct and indirect domestic carbon content. The reasoning behind is that goods of this sector cannot be well substituted compared to other EITE commodities.

Implementation of carbon import tariffs alleviates the adverse output effects for each EITE sector. Most notably, production losses in the iron and steel industry (i_s) are more than halved under *TRF*.[15]

Figure 6: Percentage output change in EITE industries for the USA



Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

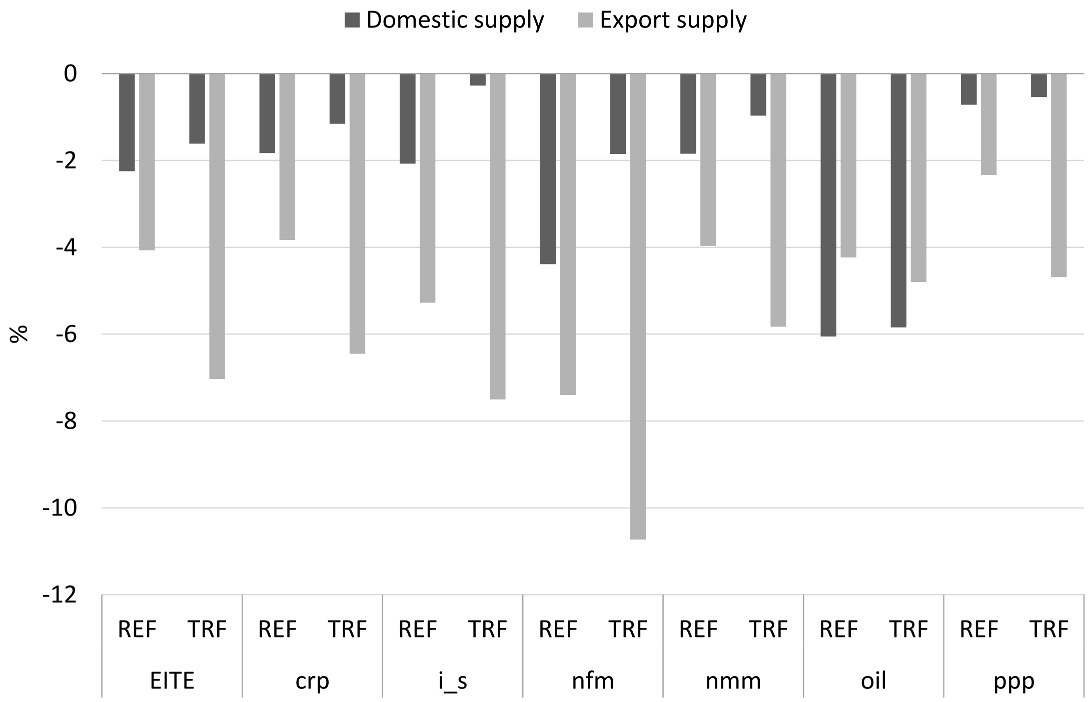
Figure 7 shows percentage changes of supply to the domestic market and to the export market of EITE goods revealing how the imposition of carbon tariffs affect competitiveness on the different markets. With carbon tariffs in place, industries unambiguously supply less to the export market than under *REF*. While EITE as whole decreases export supply by 4% for the *REF* case, supply drops by 7% for the *TRF* case. This result is not surprising as the tariff further increases production costs in EITE industries thereby worsening their competitive situation on international markets against industries from unregulated regions. At the same time, industries unambiguously supply more to the domestic market under *TRF* than under *REF*. This is because with a tariff in place, foreign producers lose their cost advantage on the domestic market of the

[14] The percentage change for the single sectors refers to a change in output quantities. The change in the EITE industry as a whole refers to a change in USD of output, because we cannot add up quantities in the different sectors in a meaningful way.
[15] The CO_2 emission price for the US in line with the 20% domestic emission reduction amounts to 34 USD per ton of CO_2 in the *REF* scenario, and 35 USD per ton of CO_2 for the *TRF* scenario respectively.

unilaterally abating country: compared to *REF* all the embodied carbon crossing the border is taxed at the domestic CO_2 price. Because the US EITE industries supply large shares of their output to the domestic market (see Figure 3), the overall effect of complementary carbon tariffs is positive in all of the sectors.

We conclude that for the US tariffs on the carbon embodied in imported goods constitute an effective measure to protect the domestic EITE industry.

Figure 7: Percentage change in domestic supply and export supply of EITE goods in the USA



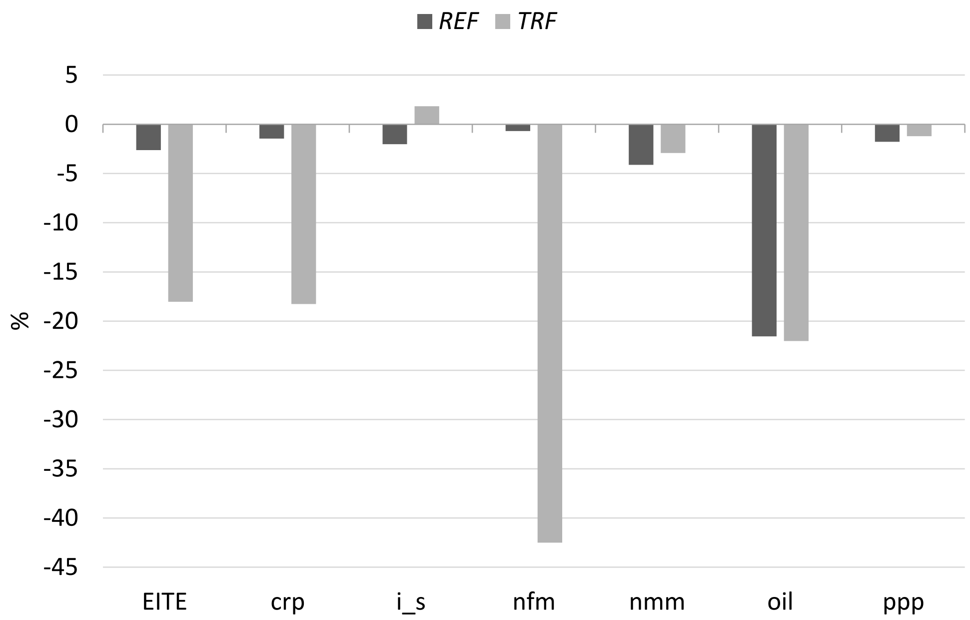
Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

Turning to the results for Switzerland – reported in Figure 8 – yields a very different picture. The Swiss EITE industry as whole decreases in output by 2.6% for the case of domestic emission pricing only, but shrinks by 18% for the case of additional carbon import tariffs.[16] The non-ferrous metals industry stands out for the differential impacts between *REF* and *TRF*: while it is barely affected by domestic emission pricing only (*REF*) – its output declines by less than 1% – the imposition of tariffs leads to a dramatic output loss of more than 40%. The MRIO analysis of Section 2 provides the reasoning behind this initially surprising result as the Swiss non-ferrous metals industry exhibits the most disadvantageous characteristics. Firstly, almost 90% of the embodied carbon stems from imported sources (Figure 2), which gets additionally priced under *TRF*. Secondly, almost 90% of the output is supplied to the export market (Figure 4), where the carbon import tariffs constitute an additional cost-disadvantage compared to unregulated competitors. Among Swiss EITE industries the iron and steel (i_s), non-metallic minerals (nmm), as well as paper, pulp and print (ppp)

[16] The CO_2 emission price for Switzerland in line with the 20% domestic emission reduction amounts to 146 USD per ton of CO_2 in the *REF* scenario, and 157 USD per ton of CO_2 for the *TRF* scenario, respectively.

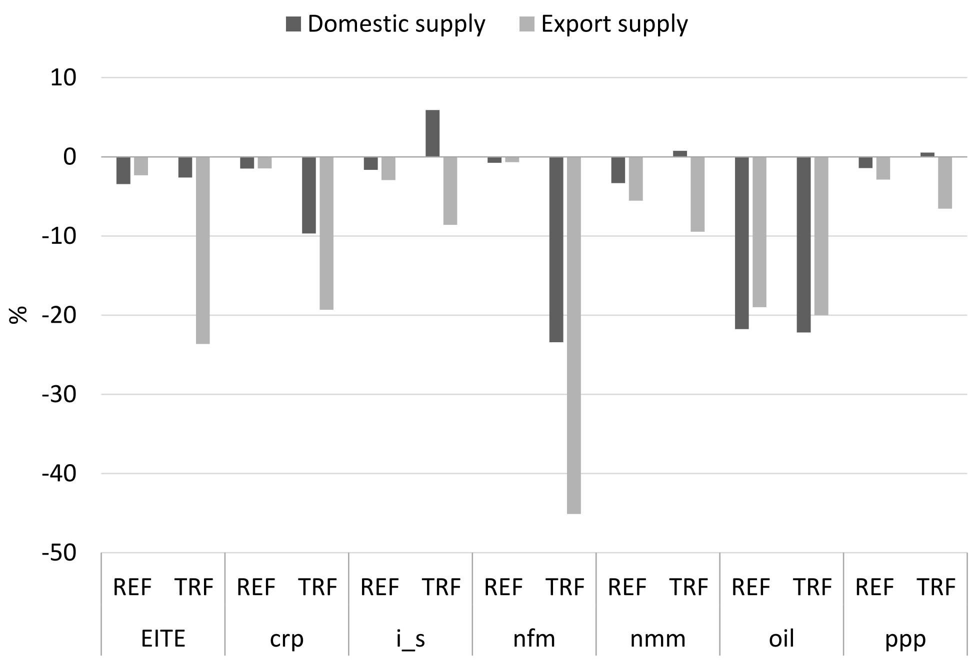
sectors are better off with carbon tariffs as compared to domestic emission pricing only. Iron and steel even increases output by 1.8% above business-as-usual levels when carbon tariffs are imposed. Figure 9 provides the percentage change in supply to the domestic market and to the export market for Swiss EITE sectors.

Figure 8: Percentage output change in EITE industries for Switzerland



Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

Figure 9: Percentage change in domestic supply and export supply of EITE goods for Switzerland



Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

In each EITE industry the supply to the export market is lower with tariffs imposed compared to domestic emission pricing only.[17] The EITE industry as whole decreases export supply by 2.3% under *REF* compared to 23.6% under *TRF*. The impacts for the domestic market supply are mixed. The iron and steel, non-metallic minerals, as well as paper, pulp and print industries are more reliant on the domestic market in their supply structure (see Figure 4) and benefit from the imposition of carbon tariffs – their domestic supply even exceeds business-as-usual levels. On the other hand, chemical products and non-ferrous metals decrease domestic supply drastically – by 9.7% and 23.4%, respectively. The reason is that – although the tariffs level the playing field against international competitors – the price increase induces substantial substitution in the Swiss economy towards other products. Note that along with a decrease of domestic supply also the imports decline markedly for chemical products (14%) and non-ferrous metals products (24%), respectively. The EITE industry as a whole supplies slightly more to the domestic market with carbon tariffs in place compared to domestic emission pricing only.

We conclude that for Switzerland carbon tariffs are rather ineffective in protecting domestic EITE industries. To the opposite, tariffs on embodied carbon drastically acerbate adverse production impacts of unilateral emission pricing for those EITE industries that have a strong export market orientation and import a large share of embodied carbon.

Sensitivity analysis

In order to test the robustness of our results, we perform sensitivity analysis with respect to key assumptions underlying our core simulations. The first part – reported in Table 4 (Switzerland) and Table 5 (USA) – focuses on changes in domestic emission reduction targets, trade (Armington) elasticities, the design of carbon tariffs and the introduction of export rebates on embodied carbon. The second part – reported in Table 6 – expands our analysis to additional industrialized countries that may go ahead with unilateral climate policy. Our finding that the impacts of carbon tariffs primarily hinge on the composition of embodied carbon in EITE goods and the export supply share is robust throughout the sensitivity analysis.

As to the stringency of unilateral climate policy, we consider alternative emission reduction targets of 10% and 30% (denoted *t10* and *t30*) compared to the core assumption of 20%. The qualitative effects are identical to those of the core simulations, only the magnitude varies as a function of the target.

As to alternative degrees in trade responsiveness to policy interference, we either halve (*arm_lo*) or double (*arm_hi*) the Armington elasticities that are adopted from the GTAP database for the core simulations. With domestic CO_2 pricing only (*REF*), lower elasticities reduce the negative output effect for EITE industries. The reason is that goods cannot be substituted as good as in the core parameterization on both the domestic as well as the foreign markets. With carbon tariffs in place (*TRF*), the implications of lower Armington elasticities are different between Switzerland and the US. Reduced trade responsiveness dampens the principal impacts of carbon tariffs on the competitiveness in domestic and export markets: the

[17] Again, the non-ferrous metals industry stands out with a decrease in export supply by more than 45% when tariffs are levied compared to only 0.7% for the *REF* scenario.

adverse impacts of unilateral emission pricing on domestic markets are less attenuated while the negative implications of carbon tariffs on export markets are less pronounced. Overall, lower Armington elasticities then imply that the US chemical products industry as a major EITE industry suffers from the introduction of carbon tariffs which had been beneficial in the core simulations. Since chemical production is the largest EITE industry in the US, EITE production as a whole slightly decreases compared *REF*. For Switzerland, lower Armington elasticities reduce the adverse effects of carbon tariffs since the industries do not lose as much market share on export markets as in the core setting. Higher Armington elasticities work the other way around.

Table 4: Percentage output changes in EITE industries in Switzerland for different reduction targets, Armington elasticities and carbon tariff designs

	EITE		crp		i_s		nfm		nmm		oil		ppp	
	REF	*TRF*	*REF*	*TRF*	*REF*	*TRF*	*REF*	*TRF*	*REF*	*TRF*	*REF*	*TRF*	*REF*	*TRF*
core	-2.6	-18.0	-1.5	-18.3	-2.0	1.8	-0.7	-42.5	-4.1	-2.9	-21.6	-22.0	-1.8	-1.2
t10	-1.2	-8.6	-0.7	-8.3	-0.9	0.6	-0.3	-21.7	-1.9	-1.5	-10.4	-10.6	-0.8	-0.6
t30	-4.3	-28.0	-2.4	-30.0	-3.3	4.1	-1.1	-60.7	-6.7	-4.2	-33.2	-34.0	-3.0	-1.8
arm_lo	-2.0	-11.8	-0.9	-11.9	-1.2	-1.8	-0.5	-27.5	-2.4	-3.5	-18.9	-19.2	-1.1	-2.3
arm_hi	-3.4	-25.0	-2.1	-26.0	-3.2	11.1	-0.6	-60.2	-6.8	0.0	-26.4	-27.0	-2.8	2.5
trf_eite	-2.6	-11.6	-1.5	-11.6	-2.0	5.7	-0.7	-36.9	-4.1	0.6	-21.6	-21.5	-1.8	2.4
trf_elec	-2.6	-9.5	-1.5	-8.5	-2.0	-0.4	-0.7	-21.6	-4.1	-3.2	-21.6	-21.9	-1.8	-2.0
full_bca	-2.6	-0.6	-1.5	-5.2	-2.0	4.8	-0.7	6.5	-4.1	1.5	-21.6	-20.8	-1.8	-2.0

Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

Table 5: Percentage output changes in EITE industries in the USA for different reduction targets, Armington elasticities and carbon tariff designs

	EITE		crp		i_s		nfm		nmm		oil		ppp	
	REF	*TRF*	*REF*	*TRF*	*REF*	*TRF*	*REF*	*TRF*	*REF*	*TRF*	*REF*	*TRF*	*REF*	*TRF*
core	-2.5	-2.4	-2.2	-2.2	-2.4	-1.0	-5.1	-3.9	-2.0	-1.4	-5.9	-5.7	-0.8	-0.8
t10	-1.0	-0.9	-0.9	-0.9	-0.9	-0.4	-2.0	-1.6	-0.8	-0.6	-2.2	-2.2	-0.3	-0.3
t30	-4.8	-4.6	-4.4	-4.3	-4.6	-1.9	-9.5	-7.0	-3.9	-2.6	-11.5	-11.4	-1.6	-1.6
arm_lo	-1.9	-2.0	-1.5	-1.7	-1.7	-1.2	-3.1	-2.9	-1.5	-1.3	-5.4	-5.3	-0.7	-0.7
arm_hi	-3.3	-2.8	-3.1	-2.8	-3.5	-0.5	-8.2	-5.3	-2.9	-1.4	-6.4	-6.4	-1.0	-0.8
trf_eite	-2.5	-1.6	-2.2	-1.3	-2.4	-0.4	-5.1	-2.3	-2.0	-0.9	-5.9	-5.8	-0.8	-0.5
trf_elec	-2.5	-2.3	-2.2	-2.1	-2.4	-1.6	-5.1	-4.4	-2.0	-1.6	-5.9	-5.8	-0.8	-0.8
full_bca	-2.5	-1.3	-2.2	-0.9	-2.4	-0.2	-5.1	-0.5	-2.0	-0.8	-5.9	-4.7	-0.8	-0.6

Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

With respect to carbon tariff design, we consider two variants to our core setting (where the unilateral emission price is applied to all imported goods at their full carbon content). In the variant *elec* the carbon content only accounts for direct emissions from fuel combustion and indirect emissions embodied in electricity (note that the carbon tariff is still applied to all imported goods). In the variant *eite* we keep with the full carbon content as in the core setting but apply the tariff only to EITE imports. While results for the *elec* variant are very similar to the core setting, the *eite* variant shows more favorable output impacts. Here, goods of the domestic EITE industries are still protected through the tariff on the domestic markets, but intermediate inputs from non-EITE industries that may contain substantial amounts of embodied carbon are no longer taxed at the border. Thus, the cost increase in production is lower than under full sector coverage.

One measure to cure the drawback of carbon tariffs for export-oriented EITE industries with a large share of imported embodied carbon is the introduction of rebates on the embodied carbon of exports at the domestic CO_2 price. If we consider such a full border carbon adjustment (variant *full_bca*), EITE industries in Switzerland and in the USA are better off – compared to carbon tariffs only – throughout.[18] The Swiss non-ferrous metals industry then even increases output vis-à-vis business-as-usual. However, given the unclear legal status of export rebates, export rebates are generally omitted in policy (see footnote 1).[19]

Table 6 summarizes EITE production impacts as we apply the core settings of our simulation analysis to other industrialized countries or regions: the European Union (EU 27), Norway, Canada, Australia, Japan and South Korea.

Table 6: Output impacts of carbon tariffs in EITE industries for selected countries

	EU 27		Norway		Canada	
	REF	*TRF*	*REF*	*TRF*	*REF*	*TRF*
EITE	-2.9	-2.1	-6.2	-13.7	-5.2	-6.7
crp	-2.3	-1.8	-7.5	-9.0	-3.0	-3.9
i_s	-4.3	-0.6	-17.9	-22.9	-5.8	-4.2
nfm	-6.4	-0.8	-0.8	-50.2	-12.2	-21.3
nmm	-2.3	-0.6	-4.0	-1.5	-7.4	-8.2
oil	-7.1	-6.7	-15.6	-16.8	-9.6	-9.7
ppp	-0.9	-1.0	0.1	0.0	-2.2	-2.8

	Australia		Japan		South Korea	
	REF	*TRF*	*REF*	*TRF*	*REF*	*TRF*
EITE	-4.4	-4.9	-3.2	-3.0	-3.3	-3.0
crp	-0.4	0.3	-3.7	-3.9	-3.4	-3.4
i_s	-1.7	-1.0	-4.1	-4.6	-4.3	-3.6
nfm	-15.5	-17.9	-5.9	-4.3	-4.1	-7.0
nmm	-4.4	-5.4	-5.6	-1.9	-5.6	-3.7
oil	-5.2	-5.1	-7.6	-7.4	-4.5	-4.3
ppp	-0.1	0.2	-1.2	-1.2	-1.5	-1.3

Key: EITE – average of all emission-intensive and trade-exposed industries; crp – chemical products; i_s – iron and steel; nfm – non-ferrous metals; nmm – non-metallic minerals; oil – refined oil products; ppp – paper, pulp and print

EITE industries in Norway share the same characteristics as the Swiss EITE industries, hence we observe similar results. In particular, the Norwegian non-ferrous metals sector suffers tremendously from the introduction of carbon tariffs. Even in Canada and Australia, carbon tariffs do more harm than good to

[18] Note, however, that welfare in the abating region is lower with rebates in place than with carbon tariffs only due to disadvantageous terms-of-trade effects.

[19] A potentially less controversial rebate scheme under WTO law could be to only rebate payments for direct emissions from the production process rather than the entire embodied carbon of exported goods. In this case, EITE output effects are very similar to the *TRF* case. While US industries are slightly better off throughout, the Swiss chemical (crp) and non-ferrous metals (nfm) sectors even slightly cut back supply compared to *TRF*. Since there are almost no direct emissions in these two industries (see Figure 1), the other competing Swiss industries benefit more from rebates on direct emissions. Hence, there is more substitution away from Swiss chemical and non-ferrous metals goods on foreign markets than in the *TRF* case.

overall EITE production compared to domestic emission pricing stand-alone. In Japan and South Korea the overall effect is slightly positive, but single sectors still reduce output more under *TRF* than under *REF*. Only in Europe carbon tariffs work as a protective measure across all EITE industries – like before in the case of the US.

5. Conclusions

Emission constraints affect comparative advantage, in particular for trade-exposed industries where emission-intensive inputs represent a significant share of direct and indirect costs. When regulatory measures to global emission externalities such as CO_2 are only undertaken unilaterally, the effectiveness of domestic abatement action may be seriously hampered through emission increases abroad. Concerns about leakage and excessive structural change at the disadvantage of domestic emission-intensive and trade-exposed (EITE) industries are central to the policy debate on unilateral emission pricing. In response to such concerns, carbon tariffs appear as an attractive policy option for countries that intend to move forward with unilateral climate policies. Previous studies have highlighted that carbon tariffs constitute an effective instrument to reduce leakage and attenuate the production losses for domestic EITE industries as compared to unilateral emission pricing only. In this paper we dispute the general notion that carbon tariffs will unambiguously work as a protective instrument for EITE industries. We show that the application carbon tariffs can do more harm than good to EITE industries. Two determinants drive the sign and magnitude of EITE impacts. Firstly, the composition of embodied emissions in goods: if a large share of embodied carbon is imported in intermediate inputs, industries might suffer from carbon tariffs. Secondly, the share of domestic output that is supplied to the export market: while carbon tariffs level the playing field on domestic markets, they increase the cost-disadvantage vis-à-vis competitors from abroad in foreign markets.

Our quantitative analysis highlights that tariffs on embodied carbon can drastically acerbate adverse production impacts of unilateral emission pricing for those EITE industries that have a strong export market orientation and import a large share of embodied carbon.

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

The total carbon content of a good is composed of the CO_2 emitted in the production of the good itself as well as of the CO_2 that is emitted to produce intermediate inputs and international transport services. To caculate the full carbon content (per USD of output) we use input-output accounting identities and solve the associated linear system of equations below for the carbon content of production activities cc_{gr}^{Y}, the carbon content of imports cc_{ir}^{M} and the carbon content of international transport services cc_{j}^{T}.[20] 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 plus the carbon embodied in international transport services, see equation.

The third set of equations (3) postulates that the embodied carbon $cc_{j}^{T} \sum_{r \in R} T_{jr}$ of international transport service j must be equal to the sum of the embodied carbon in the production the international transport service across countries.

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

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

$$\forall j \in J: \qquad cc_{j}^{T} \sum_{r \in R} T_{jr} = \sum_{r \in R} cc_{jr}^{Y} T_{jr} \tag{3}$$

We obtain a system of $(card(G) + card(I)) \times card(R) + card(J)$ unknowns and linear equations. The MRIO model can be solved directly as a square system of equations or solved recursively using a diagonalization algorithm. The data for the parameters are provided by the GTAP8 database.

Table A.1: Denotations used in the MRIO calculations

Sets and Indices	
R	Set of regions (with *r* denoting the set index)
I	Set of 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)
J	Set of international transport services (with *j* 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
T_{jr}	International transport service j produced in region r

[20] See Table A.1 for the denotations used in the MRIO calculations.

T_{jisr}	Input of international transport service j to imports in sector i from region s to region r
$co2e_{gr}$	Direct CO_2 emissions in activity g in region r
Variables	
cc^{Y}_{gr}	Carbon content in activity g in region r
cc^{M}_{ir}	Carbon content of imported commodities i in region r
cc^{T}_{j}	Carbon content of international transport service j

Appendix B: Computable general equilibrium (CGE) model

Three classes of conditions characterize the competitive equilibrium for our model: zero profit conditions, market clearance conditions and income balance. The first class determines activity levels and the second determines price levels. In our algebraic exposition, the notation Π^{u}_{ir} is used to denote the profit function of sector i in region r where u is the name assigned to the associated production activity. Differentiating the 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 and j as indexes for commodities (including a composite public good G and a composite investment good I) and we use 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 B.1 – B.6 explain the notations for variables and parameters employed within our algebraic exposition.

B.1 Zero Profit Conditions

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

$$\Pi^{Y}_{ir} = \left[\theta^{D}_{ir}\, {p^{D}_{ir}}^{1-\eta_{ir}} + \left(1-\theta^{D}_{ir}\right) {p^{EX}_{ir}}^{1-\eta_{ir}}\right]^{\frac{1}{1-\eta_{ir}}} - \left[\theta^{TRN}_{ir}\, {p^{TRN}_{ir}}^{1-\sigma^{TKLEM}_{ir}} + \left(1-\theta^{KLEM}_{ir}\right) {p^{KLEM}_{ir}}^{1-\sigma^{TKLEM}_{ir}}\right]^{\frac{1}{1-\sigma^{TKLEM}_{ir}}} \le 0$$

2. Sector- and region-specific transport aggregate $(i \notin FF)$:

$$\Pi^{TRN}_{ir} = p^{TRN}_{ir} - \left[\sum_{j \in TP} \theta^{TR}_{jir}\, {p^{A}_{jr}}^{1-\sigma^{TR}_{ir}}\right]^{\frac{1}{1-\sigma^{TR}_{ir}}} \le 0$$

3. Sector- and region-specific aggregate of value-added, labor, energy and non-energy inputs $(i \notin FF)$:

$$\Pi^{KLEM}_{ir} = p^{KLEM}_{ir} - \left[\theta^{KLE}_{ir}\left[\theta^{KL}_{ir}\, {p^{KL}_{ir}}^{1-\sigma^{KLE}_{ir}} + \left(1-\theta^{KL}_{ir}\right)\left({p^{E}_{ir}}^{1-\sigma^{KLE}_{ir}}\right)\right]^{\frac{1-\sigma^{KLEM}_{ir}}{1-\sigma^{KLE}_{ir}}} + \left(1-\theta^{KLE}_{ir}\right)\left(\sum_{j \notin EG,\, j \notin TR} \theta^{NE}_{jir}\, {p^{A}_{jr}}^{1-\sigma^{NE}_{ir}}\right)^{\frac{1-\sigma^{KLEM}_{ir}}{1-\sigma^{NE}_{ir}}}\right]^{\frac{1}{1-\sigma^{KLEM}_{ir}}} \le 0$$

4. Sector- and region-specific value-added aggregate $(i \notin FF)$:

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

5. Sector- and region-specific energy aggregate $(i \notin FF)$:

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

6. Production of fossil fuels $(i \in FF)$:

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

7. Armington aggregate:

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

8. Aggregate imports across import regions:

$$\Pi_{ir}^{M} = p_{ir}^{M} - \left[\sum_s \theta_{isr}^{M}\, {p_{is}^{EX}}^{1-\sigma_{ir}^{M}}\right]^{\frac{1}{1-\sigma_{ir}^{M}}} \leq 0$$

9. Household consumption demand:

$$\Pi_{r}^{C} = p_{r}^{C} - \left[\theta_{Cr}^{TRN}\, {p_{Cr}^{TRN}}^{1-\sigma_{Cr}^{TEM}} + \left(1-\theta_{Cr}^{TRN}\right)\left(\theta_{Cr}^{E}\, {p_{Cr}^{E}}^{1-\sigma_{Cr}^{EM}} + \left(1-\theta_{Cr}^{E}\right)\left(\sum_{j\notin EG,\, j\notin TR}\theta_{jCr}^{NE}\, {p_{jr}^{A}}^{1-\sigma_{Cr}^{NE}}\right)^{\frac{1-\sigma_{Cr}^{EM}}{1-\sigma_{Cr}^{NE}}}\right)^{\frac{1-\sigma_{Cr}^{TEM}}{1-\sigma_{Cr}^{EM}}}\right]^{\frac{1}{1-\sigma_{Cr}^{TEM}}} \leq 0$$

B.2 Market Clearance Conditions

10. Labor:

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

11. Capital:

$$\bar{K}_r \geq \sum_j Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial v_r}$$

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

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

13. Output:

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

14. Armington aggregate:

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

15. Import aggregate:

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

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

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

17. Investment ($i=I$):

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

18. Carbon emissions:

$$CO2_r \geq \sum_i A_{ir} a_i^{CO_2}$$

<u>B.3 Income Balance</u>

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

Table B.1: Sets and indexes

i ,j	Indexes for sectors and goods
r,s	Indexes for regions
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas
LQ	Liquid fuels: Crude oil and gas

Table B.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 B.3: Price variables

p_{ir}^{D}	Domestic supply price of good *i* produced in region *r*
p_{ir}^{EX}	Export supply price of good *i* produced in region *r*
p_{ir}^{TRN}	Price of aggregate transport in sector *i* and region *r*
p_{ir}^{KLEM}	Price of aggregate value-added, energy and non-energy in sector *i* and region *r*
p_{ir}^{KL}	Price of aggregate value-added in sector *i* and region *r*
p_{ir}^{E}	Price of aggregate energy in sector *i* and region *r*
p_{ir}^{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 B.4: Cost shares

θ_{ir}^{D}	Share of domestic supply in sector *i* and region *r*
θ_{ir}^{TRN}	Cost share of the TRN aggregate in sector *i* and region *r*
θ_{jir}^{TR}	Cost share of transport service *j* in the TRN aggregate in sector *i* and region *r*
θ_{ir}^{KLEM}	Cost share of KLEM aggregate in sector *i* and region *r*
θ_{ir}^{KLE}	Cost share of value-added and energy in the KLEM aggregate in sector *i* and region *r*
θ_{ir}^{KL}	Cost share of value-added in the KLE aggregate in sector *i* and region *r*
θ_{jir}^{NE}	Cost share of non-energy input *j* in the non-energy aggregate in sector *i* and region *r*
θ_{ir}^{K}	Cost share of capital in value-added composite of sector *i* and region *r*
θ_{ir}^{E}	Cost share of energy composite in the KLE 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 *i* (*T*=*i*) or labor (*T*=*L*) or capital (*T*=*K*) in sector *i* and region *r* $(i \in FF)$
θ_{ir}^{ELE}	Cost share of electricity in energy composite in sector *i* in region *r* $(i \notin FF)$
θ_{ir}^{COA}	Cost share of coal in fossil fuel composite in sector *i* in region *r* $(i \notin FF)$
θ_{jir}^{LQ}	Cost share of liquid fossil fuel *j* in liquid energy aggregate in sector *i* in region *r* $(i \notin FF), (j \in LQ)$

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; TRN – transport

Table B.5: Elasticities

η_{ir}	Transformation between domestic and export supply	4
σ_{ir}^{TKLEM}	Substitution between TRN and KLEM composites	0.1
σ_{ir}^{KLEM}	Substitution between KLE aggregate and material inputs	0.5
σ_{ir}^{KLE}	Substitution between energy and value-added in production	0.5
σ_{ir}^{KL}	Substitution between labor and capital in value-added composite	Narayanan et al. (2012)
σ_{ir}^{TR}	Substitution between air, water and other transport services	0.1
σ_{jir}^{NE}	Substitution between material	0.25
σ_{ir}^{Q}	Substitution between natural resources and other inputs in fossil fuel production calibrated to exogenous supply elasticities μ_{FF}	μ_{COA}=4.0, μ_{CRU}=1.0 μ_{GAS} =1.0
σ_{ir}^{ELE}	Substitution between electricity and the fossil fuel aggregate	0.5
σ_{ir}^{COA}	Substitution between coal and the liquid fossil fuel composite	0.15 (0.75 for *i*=*ELE*)
σ_{ir}^{LQ}	Substitution between gas and oil in the liquid fossil fuel composite	0.5 (1 for *i*=*ELE*)
σ_{ir}^{A}	Substitution between the import aggregate and the domestic input	Narayanan et al. (2012)
σ_{ir}^{M}	Substitution between imports from different regions	Narayanan et al. (2012)
σ_{Cr}^{E}	Substitution between energy and material inputs in consumption	0.5
σ_{Cr}^{TEM}	Substitution between TRN and energy-material aggregate in consumption	0.1

Table B.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* $(i \in FF)$
$\overline{G}_r$	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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