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Title: The relevance of process emissions for carbon leakage: A comparison of unilateral climate policy options with and without border carbon adjustment

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The relevance of process emissions for carbon leakage: A comparison of unilateral climate policy options with and without border carbon adjustment

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JEL: Q54, D58, H2, O3

1. Introduction

With the shift of the UNFCCC process from a top-down legally binding climate policy architecture to a bottom-up approach in which countries decide individually on emission reduction targets (“voluntary pledges”), the discussion on carbon leakage and possible compensatory policies has gained prominence. Carbon leakage refers to a partial offset of domestically reduced GHG emissions in countries with less stringent environmental requirements and is hence a measure of reduced environmental effectiveness. Major leakage channels comprise competitiveness and industrial relocation, the international fuel market(s), terms-of-trade impacts and technology diffusion (e.g. Böhringer et al., 2010; Burniaux and Martins, 2011; Fischer and Fox, 2007). To quantify global leakage rates a broad literature has developed, particularly within global Computable General Equilibrium (CGE) models, but resulted generally in comparatively low leakage rates. We argue in this paper, that one reason that led to these low leakage rates is that most of these quantitative analyses are confined to consider combustion emissions only.

While the lion’s share of carbon dioxide emissions arises in fossil fuel combustion, some 10% of global production CO_2 emissions are related to industrial processes (UNFCCC, 2011). While 10% might seem negligible, it is not in the analysis of carbon leakage, because these process emissions originate from basically three economic activities (coke conversion in the iron and steel production, clinker production, and to a smaller extent in the chemical industry) that each are foreign trade intensive and under intense international competition. More specifically, process emissions account for roughly half of sector CO_2emissions in the iron and steel and the cement sectors of many countries, and for about a fifth in the chemical industry (UNFCCC, 2011).

In addition to omitting some 10% of production CO_2 emissions, there is also an important technological difference between process and combustion emissions. While combustion based emissions can be reduced by increasing energy efficiency or fuel switch, mitigation of process emissions can only be achieved by switching the production process, if a low-carbon one is available, or by reducing activity. Thus, reduction of process based emissions basically requires a switch in production technology, often not readily available at reasonable costs.

As a consequence, also the effectiveness of anti-leakage policies, i.e. border carbon measures like tariffs or rebates, depends on whether process emissions are correctly taken into account in their set-up. For this purpose, we develop a multi-sectoral multi-regional CGE model that accounts for process emissions based on UNFCCC data to quantify both the implications of a unilateral EU climate policy on leakage rates across world regions and the relevance and effectiveness of border carbon adjustment measures that have been discussed as options to reduce leakage (e.g. Droege, 2011). By comparison of results with respective model runs in which only combustion based emissions are considered, we conclude on the significance of acknowledging process emissions for both the magnitude of leakage and the effectiveness of border carbon adjustment measures in reducing it.

Methodologically, the present paper contributes to the literature on multi-sectoral multi-regional CGE models analyzing climate policies, competitiveness and carbon leakage (e.g. Böhringer, 2000; Burniaux and Martins, 2000; Paltsev, 2001; Kuik and Gerlagh, 2003; Babiker, 2005; Fischer and Fox, 2007; Fæhn and Bruvoll, 2009). While UNFCCC GHG accounting includes combustion and process emissions and is used for climate agreements and monitoring thereof, most of climate policy analysis modeling is based on the IEA accounting, as comprised for example in the GTAP data base, which, however, excludes process emissions. Since industrial process emissions are crucial in core sectors that are prone of leakage and competitiveness concerns, we expand the analysis by acknowledging industrial process emissions. Comparing results of this model to one without process emissions, we then analyze how the inclusion of process emissions changes affects carbon leakage rates and the degree that border carbon adjustment measures (BCA) can reduce leakage.

The main findings of this paper are the following. First, the correct accounting for process emissions – in addition to combustion emissions – results in quite higher leakage rate of unilateral climate policy. For the example of unilateral EU 20% CO_2 emission reduction, the leakage rate rises from 29% (combustion emissions only) to 38% (combustion and process emissions). Second, this higher leakage rate is due to the fact that (a) process emissions cannot easily be substituted away from, (b) process-emission intensive sectors are particularly trade exposed and (c) are more emission intensive in non-EU world regions. Third, border carbon adjustment measures are significantly more effective to prevent leakage when they adequately account for process emissions as well in their rate. Fourth, this higher effectiveness is due to the fact that their rate tailoring (in terms of level and sectors) is most adequate when it acknowledges the full spectrum of CO_2 emissions, combustion and process emissions as well. Finally, we suggest areas of further analysis: other fractions of emissions not readily considered so far (other non-combustion emissions), and the interaction between border carbon adjustment and dynamic incentives for technological innovation.

The paper is structured as follows. Section 2 addresses the consequences of unilateral climate policy for carbon leakage and options for anti-leakage policies in the form of border carbon measures. Moreover, the relevance of process emissions across sectors and regions is discussed in more detail. A non-technical model summary of our multi-regional multi-sectoral CGE model is provided in Section 3, and a technical one in the Supplementary Material (Appendix C). Section 3 also describes the data bases used for combustion and process carbon emissions (UNFCCC and IEA), as well as for the economic data (GTAP 7) for calibration of our model. We then, in Section 4, compare model simulation results with and without coverage of process emissions for a set of scenarios: (i) when unilateral EU climate policy is implemented, (ii) when this policy is combined with border carbon measures, and (iii) when decomposing the fuel channel from other channels of carbon leakage. Section 5 provides a discussion of our results, focusing also on non-CO_2 emissions, robustness with regard to the size of the policy region, and options for technological innovation to reduce process emissions. Section 6 summarizes our findings and concludes.

2. Unilateral climate policy, carbon leakage and process based emissions

2.1 Carbon leakage

A serious consequence of bottom-up architectures to climate policy with a limited regional scope is reduced environmental effectiveness which has been termed carbon leakage. This phenomenon refers to a partial offset of domestically reduced GHG emissions in countries with less stringent environmental requirements as a result of various mechanisms (see e.g. Burniaux and Martins, 2011; Droege, 2011). First, leakage can be triggered by a relocation of production to regions not facing mitigation policies (the so called competitiveness channel of leakage). Second, reduced demand for fossil fuels in the policy region imposes a downward pressure on world fossil fuel prices, which in turn raises fossil fuel demand in non-policy regions (the so-called energy market channel or fuel channel). Third, any price change of fossil fuels relative to other, especially non-fossil (or GHG) intensive goods implies a shift in the terms-of-trade of fossil fuel exporters (or fossil-fuel intensive goods exporters) versus exporters of non-GHG intensive goods, implying an income effect (the so-called terms-of-trade channel). The effects induced by the energy market channel mentioned before are only one trigger of this latter terms-of-trade channel, which more comprehensively is a result of the full range of macro-economic feedbacks, in particular primary factor prices readjusting as well as balance of trade (and real exchange rate) adjustments. Finally, technological spill over of green technologies from the policy region to other non-policy regions is the leakage channel that works in opposite direction, i.e. this technology channel helps to reduce GHG emissions also in the non-policy region as a consequence of unilateral climate policy in the policy region.

An economic consequence of climate policies implemented in some countries only, which is related to the first of the above leakage channels, is the claimed reduction of competitiveness of trade exposed, energy intensive sectors. Thus, along with the likely emergence of bottom-up policy approaches, both the EU and the US foresee measures to shield themselves from negative consequences for environmental effectiveness and competitiveness (van Asselt and Brewer, 2010). In principal, measures for equalizing carbon prices across countries (and thus help to avoid both leakage along the competitiveness channel as described above and competitiveness concerns) can utilize several leverages: (i) reducing the level of carbon prices in regulated countries (i.e. grandfathering of emission permits); (ii) increasing the level of carbon prices in unregulated countries (e.g. by sectoral agreements among Annex I and non-Annex I countries); and (iii) tax adjustments at the border (according to the grey carbon in international trade; see e.g. Grubb et al., 2009). After the Copenhagen Conference and reconfirmed by subsequent UNFCCC Conferences, however, only the third option of border carbon adjustments (BCA) seems of significant political relevance and that is why it is found in both EU and US documents (Kuik and Hofkes, 2010). An alternative approach to BCA, but with only long-term relevance, is seeking to make carbon prices irrelevant for competitiveness by fostering carbon-free production technology innovation. We will discuss this alternative in section 5.

To assess which sectors might be at risk of carbon leakage, we follow the classification of the EC Directive 2003/87/EC (European Parliament, 2003) for Phase III of the EU Emissions Trading Scheme, according to which a subsector is acknowledged as being exposed to a significant risk of carbon leakage if its estimated direct and indirect cost would increase production cost by at least 5% and if the intensity of trade with non-EU countries make up at least 10% of market size within the EU. In fulfillment of this directive, the EC (2009) has exempted e.g. mining (coal, chemical and fertilizer minerals), coke oven products, refined petroleum, pulp and paper, chemical production, glass and ceramics, iron and steel, and non-ferrous metals. In addition, exemptions apply when a sector has either at least a 30% production cost increase or a 30% intensity to trade, such as e.g. cement and lime production (EC, 2009).

2.2 Industrial process emissions

As argued in the previous section, the three sectors iron and steel, cement, and chemicals are among the leakage prone sectors due to their energy intensity and/or trade exposure. In addition, this section will demonstrate that these three sectors account for almost all of CO_2 process emissions and hence it is essential whether anti-leakage measures are based only on combustion based emissions or consider process emissions as well.

To understand the relevance of process emissions, it is essential to quantify the different sources of GHG emissions. GHG emissions arise in fuel combustion (energy use), industrial processes, non-combustion activities in agriculture (e.g. enteric fermentation of animals), waste (e.g. landfill emissions) and in some other processes. In Annex I countries (for which leakage is primarily discussed), fuel combustion accounts for the dominant share, i.e. in 2010 causing 83.3% of GHG emissions, and 93% thereof are carbon dioxide (UNFCCC 2012). As a consequence, most macroeconomic analyses (of both leakage and GHG policy in general) have focused on combustion emissions in the form of CO_2. However, the remaining (non-combustion related) GHG emissions in Annex I countries are not distributed equally across production sectors and consumptive uses: the majority of non-combustion related GHG emissions arises in agriculture (7.6% of total GHG emissions), followed by industrial processes (6.3%), and by waste (2.7%). Ignoring these emissions may lead to distorted results (e.g. for leakage rates), as this paper demonstrates for industrial process emissions.

Let us take a closer look on the nature of industrial process emissions (see e.g. Cooper and Droege, 2011; Monjon and Quirion, 2011). In iron production, the coke is used as a chemical reductant and hence carbon dioxide process emissions arise. In cement production, carbon dioxide is emitted as a by-product of the intermediate product clinker, in which calcium carbonate ($CaCO_3$) is calcinated and converted to lime (CaO), the primary component of cement. In chemical industry, process emissions include nitrous oxide emissions from the production of nitric acid (largely used in production of ammonium nitrate); carbon dioxide emissions from ammonia production; and methane emissions from the production of organic polymers and other chemicals. Forecasts are that the chemical sector in some countries will exhibit large increases in process emissions over the next decades, due to increased activity level in both existing and new processes (e.g. Australian Government, 2011). Finally, process emissions arise also in production and consumption activities releasing F-gases (halocarbons and SF_6), mainly in refrigeration and air conditioning appliances or as aerosols (UNFCCC, 2012).

Comparing CO_2 to non-CO_2 process emissions, 67% of all industrial process emissions in Annex I countries are CO_2. Non-CO_2 emissions are concentrated in the chemical sector, where mainly N_2O is emitted in nitric and adipic acid production, and in F-gases (UNFCCC 2012). While the problem with F-gases is that the UNFCCC inventory data does not allocate them to specific sectors, the problem with N_2O process emissions is that they substantially differ across years, which can be either due to a change in the production process or due to data problems or definition changes. Not being able to solve these issues, we therefore focus in our subsequent analysis on – among process emissions – CO_2 process emissions only (that account for two thirds of process emissions, however) and will discuss implications of this restriction in section 5.

The three sectors which account for almost all of CO_2 process emissions are iron and steel, cement, and chemicals. At the global level, process emissions amount to 9% of GHG emissions, but in the three sectors mentioned ahead, in many countries they account for the dominant share. Fig. 1 decomposes process and combustion CO_2 emissions as shares of total CO_2 emissions arising in total production (see also Table A.3 in Appendix B). For Europe, 17% of total production CO_2 emissions are caused jointly from iron and steel (I_S), non-metallic mineral products (NMM, including cement) and chemical products (CRP) (almost 5% from I_S and CRP, and almost 8% from NMM). Within each sector's emission in the EU, the contribution of process emissions ranges from 27% for CRP, to 49% for I_S, and even 57% for NMM. At the global level, the share of industrial process emissions in production CO_2 emissions is 9%. This share varies however significantly across world regions: While the U.S. has the lowest share with 3%, for Russia it is 11%, and 15% for India. These differences depend on the relative importance of the three industrial process emissions generating sectors I_S, NMM, and CRP for the total economic output of the respective regions.

< Figure 1 about here >

In the following section, we set out the model structure, taking also account of process emissions as analyzed in this section.

3. Model and data

3.1 Model specification

We construct a static multi-region, multi-sector CGE model of global trade and energy use. In the following we give a non-technical model summary underlying our core assumptions (for a detailed algebraic overview and information on the applied elasticities of substitution see electronic supplementary material and Bednar-Friedl et al., 2012).

On the regional level, we differentiate between nine world regions (see Table 1). On the sectoral level, we differentiate between 14 sectors according to their energy intensity and trade exposure (see Table 2). The sectoral aggregates for which industrial process emissions are relevant are: iron and steel (I_S), cement (non-metallic mineral products; NMM), and chemical products (CRP).

Table 1 Regional dimension of the CGE model

Model region	Model code	GTAP7 regions
EU-27 plus EFTA	EUR	EU-27, Norway, Switzerland, Liechtenstein, Iceland
United States of America	USA	USA
Russian Federation	RUS	Russian Federation
Other Annex 1 except Russian Federation	RA1	Canada, Japan, Belarus, Ukraine, Australia, New Zealand, Turkey
China	CHN	China, Hong Kong
India	IND	India

Energy exporting countries (excluding Mexico)	EEX	Indonesia, Iran, Rest of Western Asia (Iraq, Kuwait, Qatar, Saudi Arabia, Emirates,...), Rest of North Africa (Algeria, Lybia), Nigeria, Rest of South Central Africa, Ecuador, Venezuela, Egypt, Bolivia, Malaysia
Other middle income countries	MIC	Singapore, Korea, Taiwan, Rest of North America (Bermuda, Greenland), Rest of Europe (Bosnia and Herzegovina, Macedonia, Serbia and Montenegro, Faroe Islands, Gibraltar, Monaco, San Marino), Albania, Armenia, Argentina, Azerbaijan, Brazil, Botswana, Chile, Colombia, Costa Rica, Georgia, Guatemala, Croatia, Kazakhstan, Sri Lanka, Morocco, Mauritius, Mexico, Panama, Peru, Philippines, Paraguay, Thailand, Tunisia, Uruguay, South Africa, Rest of Oceania, Rest of South America, Rest of Central America, Caribbean, Rest of South African Customs Union
Other low income countries	LIC	Bangladesh, Ethiopia, Kyrgyzstan, Cambodia, Rest of East Asia (Korea, Mongolia, Macau), Lao People's Democratic Republic, Madagascar, Myanmar, Malawi, Mozambique, Nicaragua, Pakistan, Senegal, Tanzania, Uganda, Vietnam, Zambia, Zimbabwe, Rest of South Asia, Rest of Southeast Asia, Rest of Eastern Europe (Moldova), Rest of former Soviet Union, Rest of West Africa, Rest of Central Africa, Rest of Eastern Africa

Table 2 Sectoral dimension of the CGE model

Sectors	**Code**	**GTAP7 sector description & numbers**
Energy intensive and trade exposed sectors	**EIT**	
Iron and steel	I_S	Ferrous metals (35)

Non-metallic mineral products	NMM	Mineral products nec (34)
Non ferrous metals	NFM	Metals nec (36)
Chemical products	CRP	Chemical, rubber, plastic products (33)
Energy sectors		
Crude oil	CRU	Oil (16)
Coal	COL	Coal (15)
Natural gas	GAS	Gas (17), gas manufacture & distribution (44)
Refined oil products	OIL	Petroleum, coal products (32)
Electricity	ELE	Electricity (43)
Other industries and services		
Other extraction	EXT	Forestry (13), fishing (14)
Transport aggregate	TRN	Transport nec (48), water transport (49), air transport (50)
Other mining	OMN	Minerals nec (18)
All other manufacturing and services	AOG	Agriculture (1-12), food & beverages (19-26), textiles & leather (27-29), wood (30), paper (31), metal products (37), vehicles & machinery (38-42), water (45), construction (46), trade (47), private services (51-55, 57), public services (56)
Capital goods	CGDS	

Note: nec…not elsewhere classified

Fig. 2 illustrates the diagrammatic structure of the model. Following the structure of agents used in the social accounting matrix generated by GTAP, the so-called "Regional Household" is an aggregate of private and public households and thus represents total final demand in each region r. This regional household provides the primary factors capital (K_r), labor (L_r), and natural resources (R_r) for the 14 sectors, and receives total income including various tax revenues. The regional household redistributes this stream of income with a unitary elasticity of substitution between the private household and the government for private and public consumption, respectively. Moreover, labor and capital are cross-sectorally mobile within a region but immobile between regions. The specific resource input is used in the extraction of primary energy (COL, CRU, GAS), other mining (OMN), and other extraction (EXT). There are three types of production activities Y_{ir} which differ slightly in their production functions: (i) resource using (primary energy) extraction sectors, (ii) the oil sector in which fossil inputs are specified such that production cannot substitute away from them and (ii) non-resource using commodity production (comprising all energy intensive, trade exposed sectors and all other industry and service sectors). For all types of production activities, nested constant elasticity of substitution (CES) production functions with several levels are employed, to specify the substitution possibilities in domestic production between the primary inputs (capital, labor, and natural resources), intermediate energy and material inputs as well as substitutability between energy commodities (primary and secondary) (see Fig. 3 as well as Fig. A.1. - A.3. in the Appendix for diagrammatic nesting structures).

< Figure 2 about here >

< Figure 3 about here >

Following the Armington hypothesis (Armington 1969), goods produced in different regions are not perfectly substitutable. The Armington aggregation activity G_{ir} corresponds to a CES composite of domestic output and imported goods IM_{irs} as imperfect substitutes. The resulting Armington supply G_{ir} enters the domestic supply satisfying final demand and intermediate demand in production activities. The domestic output is also exported to satisfy the import demand of other regions EX_{irs} (see Fig. 1). Further, the imports of any particular world region consist of imports from all other model regions, traded off at a constant but sectorally differentiated elasticity of substitution.

Final demand in region r is determined by consumption of the private household and the government. Both the private household and the government (public good supply) maximize utility subject to their disposable income received from the regional household. Consumption of private households in each region is characterized by a constant elasticity of substitution between a material consumption bundle and an energy aggregate. Public consumption is modeled as a Cobb Douglas aggregate of an intermediate material consumption bundle.

3.2. Modeling of carbon emissions and policy

As a prerequisite for our climate policy analysis, we model CO_2 emissions as both arising in combustion and industrial processes.

Combustion CO_2 emissions are linked in fixed proportions to the use of fossil fuels differentiated by the specific CO_2 content of fuels (see Fig. 3). In particular, fossil fuel intermediate inputs in the production process enter as fixed-coefficient composite of a CO_2 permit linked to the combustion of fossil fuels. The combustion of fossil fuels by private households is linked to the generation of CO_2 emissions in a similar way (see Appendix A for the slightly different nesting structure for sectors OIL and other resource-using sectors, and that of household demand).

Regarding process emissions, we include process emissions in the I_S, CRP and the NMM sectors. Following the analysis of process emissions by sector in section 2.2, they are nested in a Leontief style CES function at the top level of the nesting tree with all other inputs in the production process (see Fig. 3). As a consequence of this zero elasticity of substitution, firms can reduce process emissions mainly by reducing the level of production. In contrast, combustion CO_2 emissions can be reduced by exploiting substitution options (fuel switch and/or energy efficiency increases). For the degree of substitution, the magnitude of the elasticities of substitution among energy inputs (fuel switch), as well as between energy and other inputs (energy efficiency), is essential (for the respective values, see the supplementary material).

In the policy region (EU), the price of CO_2 emission permits is endogenously determined in order to achieve an exogenously set global reduction target. Since among coalition countries permit trading is allowed, there is a single carbon price across coalition states (in our case the EU).

Regarding BCA, we model both import tariffs and export rebates. Regarding import tariffs, we assume that the EU imposes tariffs in leakage-prone, i.e. energy intensive and trade exposed sectors (I_S, NMM, NFM, CRP, OIL) to level the playing field with products originating from countries outside the EU. We follow the established literature by applying tariffs which are based on sectoral carbon intensities in the originating countries (Kuik and Hofkes, 2010; Hertel et al., 2008). Thus, the carbon tariffs are calculated as the product of sectoral carbon intensities (carbon emission per value of sectoral output in exporting country) and the carbon price in the importing country. Dividing these values by the respective import prices (c.i.f.) gives the tariff rates for the respective sectors (see Table A.1 in the Appendix). Regarding export rebates, European leakage-prone sectors receive a refund of the carbon costs for goods that are delivered to regions outside the climate policy coalition. The sector-specific export subsidy rate is thus calculated as the product of European sectoral carbon intensity and the European carbon price divided by the respective output price (f.o.b.).

3.3. Process emission data and model calibration

The extension of our multi-regional multi-sectoral CGE model includes carbon emissions only, yet both combustion based (according to the GTAP data base, as in the vast majority of literature) and process based (according to UNFCCC data, as derived in this article). As mentioned in the previous section, we consider process emissions to arise in a fixed sectoral output relation (Leontief) on the top output nesting of the three relevant sectors (see Fig. 3).

For our analysis we use the GTAP database (Narayanan and Walmsley, 2008) which is unique in its sectoral and regional coverage of consistent input output and trade tables (113 countries and 57 commodities for the base year 2004). Furthermore the data base provides information on international energy markets derived from the International Energy Agency's (IEA) energy volume balances, again for the year 2004 (McDougall and Lee, 2006; McDougall and Aguiar, 2007; Rutherford and Paltsev, 2000). GTAP7 relies on updated energy prices for the year 2004 – using price indices and exchange rates from the year 2000 – to add information about the monetary energy input values to the physical energy quantities.

Despite the impressive scope of the database, it has some limitations with regard to emissions, which are solely based on energy generating/transforming combustion processes (Lee, 2008), while process related emissions (which can be substantial for some sectors like iron and steel) are not part of the emissions data in GTAP. Since these CO_2 emissions are derived from the IEA energy balances, they only take account of combustion based CO_2 emissions.

During industrial production processes which physically or chemically transform materials, different GHGs including CO_2, CH_4, N_2O, and PFCs can be released. In the present analysis however we focus solely on CO_2 related industrial process emissions, as argued above. To include also these process related CO_2 emissions, we add CO_2 emissions from industrial processes to the emissions in the sectors I_S, CRP and NMM. We derive the relevant data on industrial process emissions from the UNFCCC GHG inventory data base (UNFCCC, 2011), which covers in a comprehensive way CO_2 emissions related to industrial processes for Annex I as well as non-Annex I countries. However, while data for Annex I countries is available for the GTAP base year 2004, industrial process emissions data for non-Annex I countries is for the most part only available for the year 1994. Therefore we assume for non-Annex I countries the same share of industrial process emissions in total CO_2 emissions is released by the three relevant sectors in 2004 as in 1994. After aggregating industrial process emissions for some 200 single countries to our model regions, we obtain the total amount of industrial process emissions for each model region as presented in Fig. 3. For more details on the estimation of industrial process emissions, see Appendix B.

4. Results

Applying the model presented in section 3 we evaluate unilateral climate policy options, that each have an equivalent impact on the global absolute emission level. We do so for unilateral EU climate policy of reducing *global* emissions by 20%, once with and once without acknowledging process emissions correctly. To avoid any dependence of baseline scenario specification, we report results of a comparative static analysis for the base year the model is calibrated to, i.e. for the year 2004.

4.1 The relevance of process emissions for leakage rates

The first climate policy setting (labeled our “reference case”) is one where the European Union implements climate policy without any border carbon adjustment measures. Thus, leakage prevails, and EU has to choose more stringent reduction levels than 20% within its policy area, to accommodate for the emissions rise in the non-coalition triggered by unilateral EU policy, i.e. to accommodate for carbon leakage. The objective is to reduce *global* emissions by 20% relative to 2004 baseline emissions.

Fig. 4 compares the results on leakage for the two model runs of unilateral EU climate policy, one with and one without accounting correctly for process emissions. We find that accounting for process emissions in the analysis does raise leakage. More specifically, when accounting for process emissions, emissions in non-coalition (i.e. all model regions but EU) rise by 64%, with largest absolute increases of emissions in Russia, China, Other Middle Income Countries and Energy Exporting Countries. To accommodate for this rise, EU has to choose a target more stringent by 23% than it had to when process emissions where not accounted for. Measured in terms of leakage, the leakage rate is 28.9% when process emissions are not accounted for, but 38.4% when they are.

< Figure 4 about here >

The reasons for higher leakage, when accounting for process emissions, are threefold: First, production from sectors with high process emissions is shifted over proportionally to non-coalition countries and hence emissions in these non-coalition countries increase. This is due to the fact that sectors with high process emissions are of high trade exposure and are confronted with the further requirement to reduce process emissions as well. Second, process emissions cannot easily be substituted away from by their very nature, implying a stronger production price implication of any carbon policy for process emissions than for combustion emissions. Third, process emission intensity is higher in non-coalition countries than in the European Union and therefore the shift of production to non-coalition countries is accompanied with a proportionally higher share of process emissions.

Fig. 5 reports the sectoral carbon leakage rates for both cases, with (green/dark bars) and without (grey bars) process emissions accounted for. Not surprisingly, we find that it is those sectors where process emissions occur (I_S, NMM, CRP), where absolute leakage rises significantly, when these process emissions are adequately accounted for in our modeling. Note, that there are two partly counteracting effects relevant for the remaining sectors. First, with process emission intensive sectors now stronger relocating abroad, domestic production shifts to other sectors. In those sectors domestic production tends to increase for reasons of foreign trade (balance) and domestic resource factor availability, and thus leakage in those sectors tends to decrease (less imports of grey carbon emissions). Second, with the emission reduction target (now also covering process emissions) stricter, the policy induced carbon price rises, implying a tendency for stronger leakage in emission intensive sectors. We thus find leakage to increase in sectors such as NFM, OIL, ELE (for which the carbon price effect dominates) and to decrease in sectors such as TRN, OMN and AOG (where the sectoral output shift effect dominates).

< Figure 5 about here >

4.2. The relevance of process emissions for the environmental effectiveness of border carbon adjustment measures

In a climate policy regime of only partial compliance, border carbon adjustment (BCA) measures have been proposed to limit carbon leakage and potential competitiveness disadvantages for energy intensive, trade exposed sectors in the climate policy region. As indicated in Balistreri et al. (2011), a comparison of available models for the effectiveness of BCA measures results in supplying the following range: leakage rates of 5 to 20% can be cut by BCA by 1/10 up to ½.

Regarding BCA, we distinguish that either a carbon tariff is implemented on imports of energy intensive, trade exposed goods from non-coalition countries (scenarios *tariff*) or we assume that both an import tax for carbon intensive products and an export subsidy for carbon intensive products, that are delivered to regions outside the climate policy coalition, apply in order to level the playing field also for domestic producers in their non-policy area export markets (scenarios *btax*). For region specific border carbon adjustment rates both without and with industrial process emissions, see Table A.1 in Appendix A. Regarding the use of revenues from the carbon tariff, we either assume that the exporting region (non-coalition countries) (scenarios *exporter*) or the importing region (coalition, i.e. EU) (scenarios *importer*) collects them. We thus have four BCA policy scenarios, a *tariff* (only import tariffs) and a *btax* scenario (import tariffs and export subsidies), for each of which we distinguish the *exporter* and *importer* variant for revenue allocation. Fig. 6 compares the reference scenario without BCA (scenario *ref*) to the different variants of how BCA can be implemented.

< Figure 6 about here >

As illustrated in Fig. 6, we find that for the EU unilateral climate policy with the 20% global emission reduction objective, BCA does reduce leakage by 24% (in scenario *btax importer*), when process emissions are not accounted for. Morover, the effectiveness of BCA is rising slightly when also exports are subsidized (scenarios *btax*). When process emissions had been accounted for, the effectiveness of BCA turns out to increase, in the most effective case (*btax importer*) up to 63%, with now stronger difference across the options of shaping BCA.

Our first result on BCA is therefore that BCA is more than double as effective in reducing leakage, when process emissions are accounted for. This is due to two, analytically separable causations. First, as had been indicated in section 4.1 above, the amount of absolute leakage rises when we correctly account for process emissions. Thus, the reference amount that BCA measures address to correct is larger. Second, the effect BCA has on reducing absolute leakage is stronger. The latter effect dominates and results from the fact that process emission sectors are particularly trade exposed, so in these sectors domestic production benefits from BCA, when the BCA rate is accordingly higher. When accounting for process emissions in the determination of BCA measure levels (tax rate and/or subsidy rate) the BCA measure is better tailored to the relevant sectors (in both scope and level), and since moreover process emissions cannot easily be substituted away from, absolute leakage is reduced stronger than when process emissions are not accounted for. Thus, the effectiveness of BCA is higher when we account for process emissions in their specification.

Our second result is that there is a remarkable difference in the relevance of the BCA scenario for BCA effectiveness: while the type of BCA measure is hardly relevant when process emissions are not accounted for, it is highly relevant when they are – again due to the very nature of process emissions. When process emissions are not accounted for, inputs linked to emissions can be substituted for, implying less production cost difference to the non-policy area. When process emissions are accounted for, however, the reduction of the now larger overall emissions is more difficult, as part of those emissions (i.e. process emissions) cannot be avoided other than by output reduction. Thus, carbon price increase is both higher and translating stronger to output prices in process emission prone sectors. In that case it does indeed matter, whether it is only import tariffs charged (scenario *tariff*, leveling the playing field for the domestic market only) or also export subsidies granted (scenario *btax*, leveling the playing field for both domestic and export markets) – both being based on the now higher domestic carbon price.

In sectoral terms (see Fig. 7), when process emissions are considered and BCA (here in the form of scenario *tariff importer*) is applied, leakage rates are often similar as when process emissions are not considered, but in chemicals, rubber and plastics (CRP), and iron and steel (I_S) they are significantly lower and in fact turn even negative because emissions in these sectors are actually reduced in non-coalition countries. This divergence in sectoral leakage rates is due to higher process emission intensity in these sectors in the non-coalition area (see also Fig. 3 above).

< Figure 7 about here >

4.3 Effectiveness of BCA and the fuel channel

Finally, we take a look at the relevance of process emissions in determining the effectiveness of BCA on separate leakage channels. In particular, the fuel market channel is often thought to be less manageable by BCA. We thus separate out the fuel channel, first for the unilateral EU climate policy case without any BCA measures, by holding fuel prices constant to their baseline levels. With the results reported in Fig. 8 for the model with process emissions accounted for, we see that the fuel channel contributes about 60% of total carbon leakage for the reference scenario (without BCA, utmost left bars, denoted “ref”).

< Figure 8 about here >

When BCA is applied – see the remaining bars in Fig. 8 – we find the following. The strong positive contribution of the fuel channel to carbon leakage is partly compensated by an even negative carbon leakage effect through the non-fuel channels (competitiveness channel and other channels). In other words, the non-fuel channels cause emissions in non-coalition countries to *fall* as a consequence of unilateral climate policy in the coalition (here the EU). This is due to the fact that pre-policy energy (and more particular emission) intensity is lower in EU. When an export rebate is granted to energy (and carbon) intensive industries, those experience a comparative advantage within EU, which is the higher the higher the fuel price is. Thus, with the fuel channel “switched-off” production would shift to EU, where production with lower emission-intensity is applied, and leakage therefore turns out negative.

Focusing on the case without process emissions, the picture is much different, as can be seen from Fig. 9. Now leakage is much stronger dominated by leakage arising from the fuel channel. Without considering process emissions, BCA measures are effective to just counterbalance the competitiveness channel (and other channels), such that the overall leakage is basically determined by the fuel channel leakage only. Contrary to above, when process emissions were considered in BCA rate setting, the comparative advantage regained by BCA is now less significant and the emission intensive sectors (which are, however, of lower energy intensity than their competitors outside the policy area) cannot relocate production from overseas.

< Figure 9 about here >

5. Discussion

5.1. Process emissions: CO_2 and non-CO_2

In the previous analysis of process emissions, we focused on CO_2 emissions only (i.e. we included CO_2 emissions only, distinguishing for combustion and industrial process emissions). For overall industrial process emissions of GHG, CO_2 constitutes two thirds of them in the EU. One third arises as nitrous oxide or F-gases (UNFCCC, 2012). Looking at the sectoral breakdown of industrial process emissions (see Fig. 10) reveals that non-CO_2 process emissions mainly arise in the chemical industry (included in CRP in our sectoral definition) in nitric acid and adipic acid production in the form of N_2O while the shares in mineral products (mainly cement, NMM) and in metal production (mainly iron and steel, I_S) are negligible. However, while the sectoral volumes of CO_2 emissions follow rather closely sectoral output levels in the respective years, this does not hold for non-CO_2 emissions: the chemical N_2O emissions make up 56% of sectoral GHG emissions in 2004 while the share is only 29% in 2010. Conversely, the level of halocarbons and SF_6 emissions (not sectorally allocated) is much higher in 2010 than in 2004 such that total non-CO_2 process emissions are roughly the same in both years. This leads us to the conclusion that it is much more difficult to assign non-CO_2 emission to specific industrial process (and sectors) than CO_2 emissions and that an in-depth assessment at process level, particularly with respect to F-gases, is needed before non-CO_2 process emissions should be included in a CGE analysis. For the validity of our results, this implies that we cover all relevant process emissions in NMM and I_S sectors, while there is some underestimation of sectoral leakage rates in the CRP and those sectors to be identified where F-gas emissions are to be attributed to.

< Figure 10 about here >

5.2. The relevance of other non-combustion emissions for leakage

Having shown that the inclusion of industrial process emissions into unilateral climate policy analysis significantly increases the leakage rate raises the question, whether the inclusion of the remaining non-combustion GHG emissions, arising basically in agriculture and waste, would have a similar or a counterbalancing effect on the leakage rate.[1] While this is an open question that lacks quantitative analysis, we tend to argue – before such analysis is done – that the implication of covering also the remaining non-combustion GHG emissions will be both much less significant (if relevant at all) and is of unclear direction.

Including non-combustion GHG emissions from agriculture implies significantly higher sectoral emissions and hence higher climate policy costs in EU agriculture due to the binding EU reduction target (see e.g. Vermont and Cara, 2010). Yet, climate policy targets are traded-off with other policy targets, for agriculture especially with food security. Given the relevance of the food security target, relocation of agricultural production to outside the EU (and thus leakage of the respective emissions) will be very limited.[2] Moreover, given the

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[1] We would like to thank one anonymous reviewer for the suggestion to discuss potential implications of extending our analysis to non-combustion emissions arising from other than industrial processes.

[2] There may be a few products, where EU imports might increase, such as beef from the Americas, but given food supply concerns it can be considered as unlikely, that any larger world region such as the EU will allow for a major increase in import dependency in food or agricultural inputs for the food industry on a net basis. What we do expect, and partly even observe today, is an equalization of agricultural carbon intensity across Europe – intensity in animal farming increasing in e.g. Poland, and decreasing in countries such as the

technological limits in the available agricultural mitigation options (such as environmental restrictions on manure management, fertilizer management, or reduced tillage systems), it is unlikely that cost-efficient climate policy will reduce non-combustion agricultural GHG emissions at an equal rate as emissions in other sectors. In other words, including agricultural non-combustion GHG emissions in the analysis is likely to mainly increase the overall reduction target on combustion and process emissions. This, however, will trigger the very leakage effects as analyzed in this article.

In the waste and waste water sector, a significant share of GHG emissions in Annex I countries (and in Europe in particular) has already been reduced by (technological) regulations. Further improvements are likely to be achieved in taking advantage of available technologies, and will be directed mainly at domestic process improvements (such as landfill gas recovery, improved landfill practices, or engineered wastewater management) (see e.g. Bogner et al., 2008). As for agriculture, it seems rather unlikely that significant shares of the waste sector could be relocated to outside Europe. If this presumption is true, and since quite efficient reduction options exist within the sector, the inclusion of waste sector non-combustion emissions could contribute slightly to reduce the overall leakage rate.[3] Overall, waste sector GHG emissions are both small and do not seem likely to have large leakage implications as such either.

In contrast to the important role of industrial process emissions for carbon leakage, we thus conclude that the overall effect on leakage of including further non-combustion emissions is likely to be irrelevant or at most only small. If there were an effect, the net direction is still unclear.

5.3. Size of unilateral policy zone

It is well known that the leakage rate is inversely related to the size of the policy region, with the limiting case that all regions apply equally strong emission restrictions such that no carbon leakage arises. In our analysis in section 4, we focused on the case that the EU only

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Netherlands (primarily for environmental concerns beyond climate) – but not a shift of production abroad (outside of EU).

[3] However, it is the use of waste emissions as a fuel substitute that makes many of those GHG reduction options of the waste sector economically attractive. As such, they are included in many modeling exercises of climate policy in combustion related emissions. It depends on the particular emission accounting chosen, whether the waste sector emission reduction also is implicitly already included in those studies.

implements the emission reduction policy. Expanding the policy region to the Rest of Annex I countries (excluding Russia) reveals that leakage rates are approximately halved in all scenarios compared to the EU only scenarios (see Tab. 3). However, the effectiveness of BCA remains approximately the same: with industrial process emissions correctly accounted for, in case of the Annex I coalition 65% of leakage can be prevented by means of an import tariff and an export rebate (see scenario *btax_exporter*) compared to 63% in the EU only scenario. If the size of the coalition is further increased to China (coalition A1xR_Chn), then leakage is 10% and lower depending on the scenario, but BCA is still able to cut leakage by more than half when process emissions are correctly accounted for. Thus, while the absolute levels of leakage avoided differs for different coalition sizes, our general conclusion remains unaffected: when process emissions are correctly accounted for, BCA are at least twice as effective in reducing leakage rates than otherwise.

Table 3 Leakage rates with increasing coalition size: EU only (EU) vs. EU, rest of Annex I excl. Russia (A1xR) vs. EU, rest of Annex I (excl. Russia), and China (A1xR_Chn)

Coalition size	**EU**		**A1xR**		**A1xR_Chn**	
	with	without	with	without	with	without
Scenarios	process emissions		process emissions		process emissions	
Ref	38.4	28.9	19.3	14.3	10.4	7.7
tariff_importer	20.9	23.0	8.8	10.5	5.8	6.1
tariff_exporter	21.3	23.3	9.2	10.8	5.9	6.2
btax_importer	14.2	22.0	6.8	10.1	4.8	5.9
btax_exporter	14.6	22.3	7.2	10.3	5.0	6.0
Reduction in leakage (most effective BCA vs. ref)	**63%**	**24%**	**65%**	**30%**	**54%**	**24%**

5.4. Technological innovation to reduce CO_2 process emissions

A crucial modeling assumption that does drive our results is process emissions being generated under fixed coefficients in the process emission relevant sectors (Leontief production function). This clearly depicts the fact that process emissions can only be avoided by (a) an output level reduction and/or (b) a switch of production process to less-carbon-intensive or carbon-free processes, none of which is available to date at an economically reasonable cost for any of the three relevant sectors. The availability of low-carbon technologies, however, may, or even is likely to become available in the future, in the medium and long run.

In iron production, the use of coke as a chemical reductant (and related carbon process emissions) can be avoided by switching to electrical steel production (to be more precisely: pig iron production), which is not available large scale yet and additionally raises the issue of renewable electricity production. Using cost estimates for solar electricity from Grossmann et al. (2012a, 2012b), one can conclude that carbon-free electric steel production is likely to become competitive with the currently dominating steel production process (BOF, basic oxygen furnace) in the course of the 2030s.

In cement production, carbon dioxide is emitted as a by-product of the intermediate cement product clinker, which is why clinker production partially has already been or is considered to be relocated outside climate policy regions. An alternative to this relocation is to use clinker substitutes. For chemical industry process emissions, substitution of chemical products is the main option for reduction.

Whenever a process emission free production process becomes available at competitive cost (as we indicated for pig iron and thereby steel production to be likely in the 2030s) or whenever consumption or production processes can be switched economically to other than process emission intensive (intermediate input) goods (as we indicated for clinker and chemical products), process emissions of the relevant sector will be eliminated. What does this mean in terms of the analysis of this paper? Basically then we are back to the standard model neglecting process emissions (at least of the relevant sector), but only then this neglect is permissible. For any situation where process emissions cannot be fully avoided, but can only be partially substituted for, the general conclusion of this paper of divergence of results from available analyses neglecting process emissions holds, but obviously then only to a smaller degree, i.e. the degree to that process emissions cannot be avoided.

As most processes in these three sectors are complex, optimized for product quality and costs and subject to legal norms and rules of best practice, none of the options for decreasing emissions of GHGs is easy. Some of these options are profitable but may require considerable upfront investments, e.g. increasing efficiency of energy use by insulation or architectural use of glass elements for zero-energy buildings. Given these hurdles in low-carbon innovation, the (economic) incentive for such innovation is crucial. This does have implications for the use of the BCA instrument.

While climate policy per se provides an incentive for innovation, this incentive is reduced if complemented by BCA measures. As we haven shown, BCA reduces leakage particularly in process emission prone sectors, indicating the reduction in competitiveness loss. Without BCA measures, carbon-free innovation could achieve the same reduction in competitiveness loss, and therefore could become a viable option for the industry. With BCA, this option becomes less attractive which impedes incentives for innovation.

But even if there were an incentive for innovation, those carbon-free technologies are not available yet and will not become available immediately. Therefore BCA measures might well be considered for the immediate future. However, it seems crucial that they are set up in a dynamic way, including their fade out, with the fade out scheme known to industry to sustain the incentive for carbon-free innovation, particularly so for process-emission prone sectors.

6. Conclusions

For the relevance of process emissions in measuring the effectiveness of border carbon adjustment (BCA) measures, we evaluate the EU unilateral policy of reducing its CO_2 emissions by 20% (on a global level). Effects are quantified in a comparative static analysis for 2004 by comparing results to a model without process emissions accounted for. We find the following:

First, leakage of climate policy turns out to be higher when process emissions are correctly accounted for (38% instead of 29% for combustion emissions only, Fig. 6). These higher leakage rates of climate policy, arise as (i) sectors with high process emissions are shifted over proportionally to other world regions, because sectors with high process emissions are more exposed to international trade, (ii) process emissions are harder to substitute for than combustion emissions, and (iii) process emission intensity is higher in other world regions than in the EU (non-OECD, in particular China and India).

Second, BCA has a higher impact on leakage reduction, and is hence more effective when the CO_2 emission allowances and corresponding import tariff and export rebate rates also acknowledge process emissions. Reduction of leakage can reach up to 63% for the unilateral EU policy, when both import tariffs and export rebates are targeted at the respective sectors and tariff revenues are collected by the importing country (EU). In comparison, when taking into account combustion emissions only in setting BCA measures, our analysis shows an effectiveness of BCA of 24% leakage reduction, which is in line with the literature. This second result, i.e. higher impact on leakage reduction, originates from the trade exposure of sectors with considerable process emissions. Thus these sectors benefit over-proportionally from BCA, which reduces leakage rate (relative to otherwise). As a consequence, border carbon adjustment can reduce leakage more, when process emissions are acknowledged. I.e. higher absolute policy leakage is reduced more effectively by BCA.

Third, the consideration of process emissions does not significantly change the relative importance of the fuel channel as a cause for leakage – for the above policy scenarios the fuel channel remains to explain more than half of leakage across coalition scenarios. Yet, with the use of BCA we find that when process emissions are considered, BCA in all scenarios tested reduces leakage by more than the leakage triggered by all non-fuel channels, i.e. BCA overcompensates the competitive leakage channel. This is due to significantly lower energy intensity in trade exposed sectors of the EU before climate policy is taken. This gives the EU (when not considering the fuel channel) a competitive advantage in third country export markets. Thus, BCA levels the playing field for EU production which is of higher emission efficiency than their global competitors, reducing emissions globally, as well as turning leakage negative. In other words, part of EU coalition only emission reduction in this scenario (with BCA) is taken over by non-coalition countries (as their exports shrink). A BCA system based also on process emissions does not only address otherwise given competitiveness disadvantage in sectors due to their fuel use, but also due to non-fuel related – process – emissions. Such a system can therefore reduce leakage more than a BCA system without process emission consideration, where the fuel channel leakage fully remains. With process emission consideration, net leakage remaining under BCA therefore is even smaller than what the fuel leakage channel alone would account for.

Finally, we discuss further extensions of our analysis, and how these changes might affect our results. First, the inclusion of other non-combustion GHG emissions, which occur mainly in agriculture and the waste and waste water sector, are argued to have (if at all) only a minor effect on leakage (and BCA effectiveness), and unclear whether strengthening or partially compensating for the effect that we show in this paper. Second, we enlarge coalition size (i.e. the geographic and thus economic size of the policy zone). While absolute leakage levels decline by these enlargements (as we should expect), the two core results of this paper are robust for all cases: (a) when process emissions are considered, leakage rates are significantly higher, and (b) BCA is more than double as effective when process emissions are correctly accounted for than when they are not. Third, we have discussed core options that exist for a reduction of GHG emissions in process-intensive sectors. But since e.g. technology switches, such as use of electrolysis for steel-making, require substantial upfront investment or the availability of sufficient renewable electricity at competitive prices, BCA might be employed to restore competitiveness until such carbon-free breakthrough technologies become competitive. It is, however, necessary to employ BCA dynamically (i.e. e.g. with decreasing rates) to sustain the incentive for such carbon-free innovation.

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Appendix A

Fig. A.1 depicts the nesting structure of resource using extraction processes, and Fig. A.2 that of the oil sector. The production in sector OIL differs from all other non-resource using sectors, as fossil inputs CRU, COL, and OIL are specified as Leontief type inputs at the top nesting level to all other inputs (i.e. they are characterized by zero elasticity of substitution). Figure A.3 illustrates the nesting structure of final demand.

<Figure A.1 about here>

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Table A.1 Carbon tariff rates for imports to EU with and without process emissions (for scenario *tariff_importer*)

	Without consideration of process emissions					With consideration of process emissions				
	I_S	NMM	NFM	CRP	OIL	I_S	NMM	NFM	CRP	OIL
USA	0.05	0.07	0.02	0.03	0.07	0.15	0.19	0.03	0.04	0.10
RUS	0.16	0.23	0.07	0.13	0.05	0.72	1.08	0.09	0.28	0.07
CHN	0.13	0.42	0.06	0.07	0.00	0.21	1.19	0.08	0.10	0.01
IND	0.14	0.40	0.03	0.07	0.02	0.57	1.40	0.04	0.15	0.03
RA1	0.05	0.05	0.02	0.02	0.04	0.12	0.21	0.03	0.04	0.05
EEX	0.16	0.22	0.05	0.17	0.23	0.48	1.24	0.07	0.30	0.31
MIC	0.07	0.12	0.02	0.04	0.03	0.25	0.42	0.03	0.05	0.05
LIC	0.34	0.37	0.04	0.23	0.09	1.16	0.89	0.06	0.41	0.13

Appendix B. CO_2 process emission data

As absolute fuel combustion emission (FCE) numbers differ between the GTAP 7 CO_2 data set (based on IEA energy data, supplied in Lee, 2008) and UNFCCC inventory data, we apply ratios of sectoral IPE to FCE (instead of absolute numbers), derived from UNFCCC, to GTAP-based FCE. In other words we assume that the share of industrial process emissions (IPE) in total CO_2 emissions can be transferred from the UNFCCC data basis to estimate IPE on top of GTAP FCE. In particular, we proceed in the following steps:

1. Retrieve IPE by process/sector *i* (iron and steel I_S; mineral products NMM; chemical processes CRP) and total energy (fuel combustion, FCE) CO_2 emissions for all countries and all years from UNFCCC GHG inventory database (see Table A.2, columns labeled 'total CBE').
2. Aggregate IPE and energy emissions to respective country aggregates (see Table A.2, columns labeled 'IPE') ; if data is not available for specific years, use data for other base year (for non-Annex I countries, most data is available for 1994)

Table A.2 UNFCCC combustion and process emission data by model region (2004)

	total CBE*	**IPE*** [Mt CO_2]			**IPE as share of total CBE**		
Party	[Mt CO_2]	**I_S**	**NMM**	**CRP**	**I_S**	**NMM**	**CRP**
EUR	4,027	80	148	43	2%	4%	1%
USA	5,901	75	69	22	1%	1%	0%
RUS	1,372	90	45	16	7%	3%	1%
IND**	679	46	39	15	7%	6%	2%
CHN**	2,795	23	251	4	1%	9%	0%
RA1	2,647	86	100	26	3%	4%	1%
EEX**	229	4	14	5	2%	6%	2%
MIC**	1,495	89	82	9	6%	6%	1%
LIC**	299	8	14	5	3%	5%	2%

** Due to lack of data for the base year, data used for 1994.

*Source: UNFCCC (2011)

3. Calculate the following ratio for each region: (sectoral IPE) / (total FCE), as displayed in columns 'IPE as share of total CBE' in Table A.2

4. To estimate sectoral IPEs per region, apply these ratios to total FCE emissions according to GTAP data for the respective year. Results are displayed in Table A.3: columns ‘Estimated IPE’ give the absolute numbers, columns ‘Share of IPE to sectoral total’ give the relative numbers.

Table A.3 Estimated industrial process emissions across regions, absolute and as share of sectoral CO_2 emissions (2004)

	total CBE*	**Estimated IPE**			**Share of IPE to sector total**		
Party		**I_S**	**NMM**	**CRP**	**I_S**	**NMM**	**CRP**
EUR	4,077	81	149	44	49%	57%	27%
USA	6,070	77	71	23	59%	48%	12%
RUS	1,552	102	51	19	69%	71%	35%
IND	1,061	73	60	23	14%	52%	3%
CHN	4,472	36	402	6	65%	61%	36%
RA1	2,586	84	98	26	47%	65%	20%
EEX	2,522	41	159	60	53%	75%	24%
MIC	2,983	178	164	17	62%	60%	10%
LIC	673	18	32	12	60%	42%	24%
global	25,996	691	1,188	230	50%	57%	18%

Source: GTAP (Narayanan and Walmsley, 2008)

Appendix C. Electronic supplementary material

Supplementary data to this article can be found online at <please insert URL>

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Figure Captions

Fig. 1. Combustion based and industrial process CO_2 emissions for sectors I_S, NMM, and CRP (as share of total production CO_2 emissions in 2004).

Source: own calculations based on UNFCCC (2011) and GTAP (Narayanan and Walmsley, 2008).

Note: for definition of sectors and regions, see Tab. 1 and 2.

Fig. 2. Diagrammatic structure of the CGE model

Fig. 3. Nesting structure of combustion and process emissions in production (for non-resource using sectors)

Fig. 4. Carbon leakage (in Mt CO_2) of unilateral EU climate policy across world regions (reference case)

Note: NCOA (non-coalition) aggregates all regions but EUR.

Fig. 5. Sectoral carbon leakage rates (in %) of unilateral EU climate policy (reference case)

Fig. 6. Leakage rates (in %) with and without process emissions accounted for, across EU unilateral climate policy scenarios (reported for the reference year)

Fig. 7. Sectoral carbon leakage rates (in %) for EU unilateral climate policy with BCA (tariff_importer)

Fig. 8. Carbon leakage rate (in %) of different unilateral EU climate policy scenarios, with process emissions accounted for

Fig. 9. Carbon leakage rate (in %) of different unilateral EU climate policy scenarios, without process emissions accounted for

Fig. 10. CO_2 and non-CO_2 emission from industrial processes for EU 27, 2004 and 2010 (source: UNFCCC GHG inventory data 2012)

Fig. A.1. Nesting structure of resource using extraction processes

Fig. A.2. Nesting structure of OIL sector

Fig. A.3. Nesting structure of household demand

Supplementary material Caption

Electronic supplementary material. Algebraic model formulation

Figure1 b&w

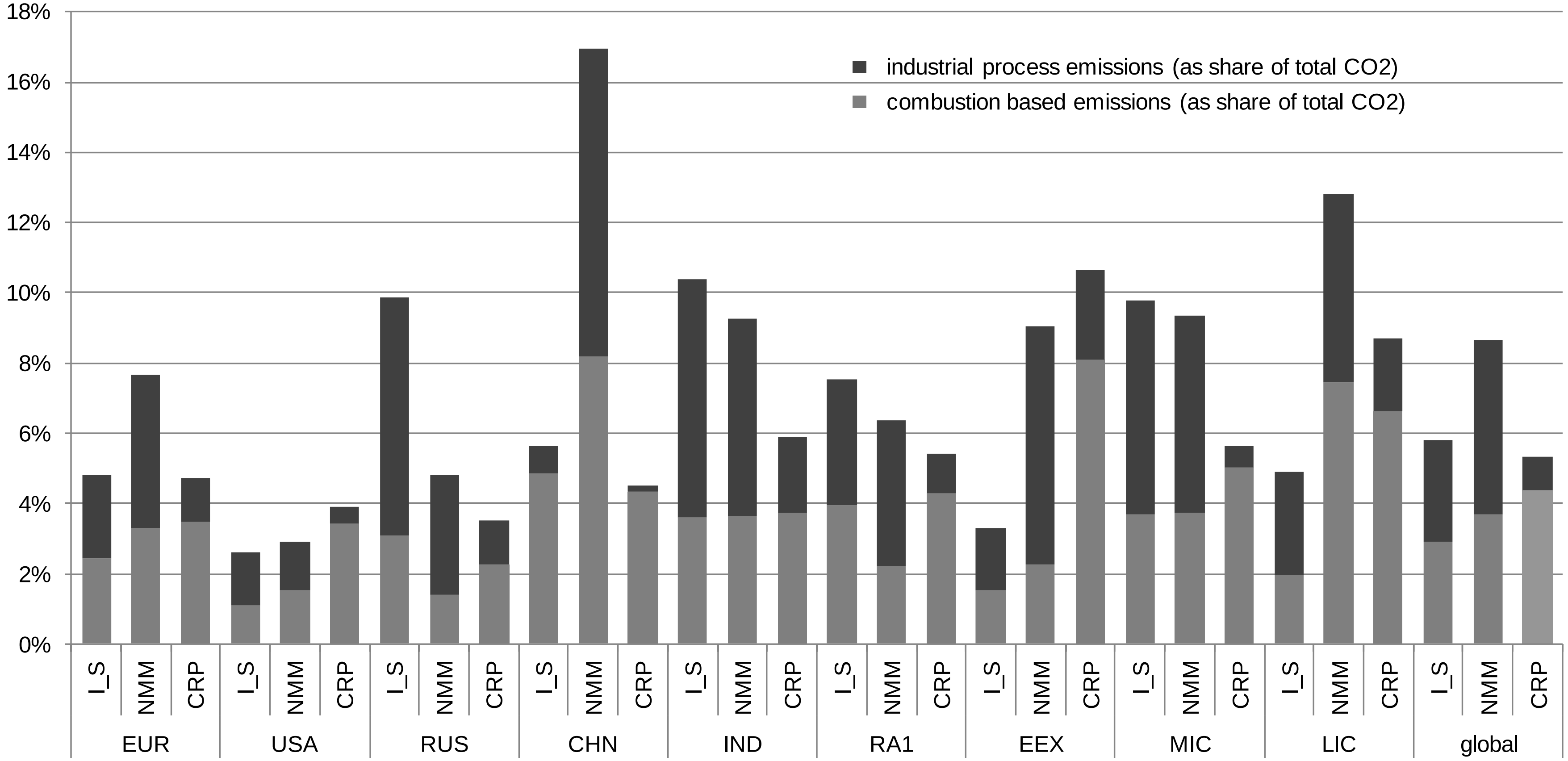

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Figure2 b&w

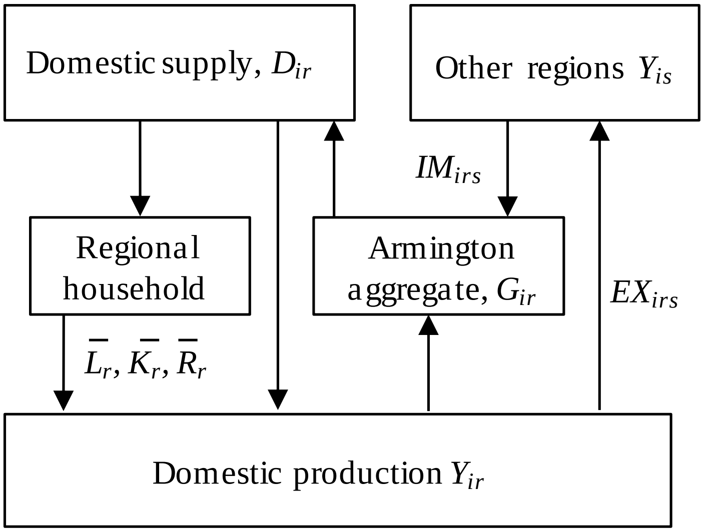

Fig. 2. Diagrammatic structure of the CGE model

Figure3 b&w

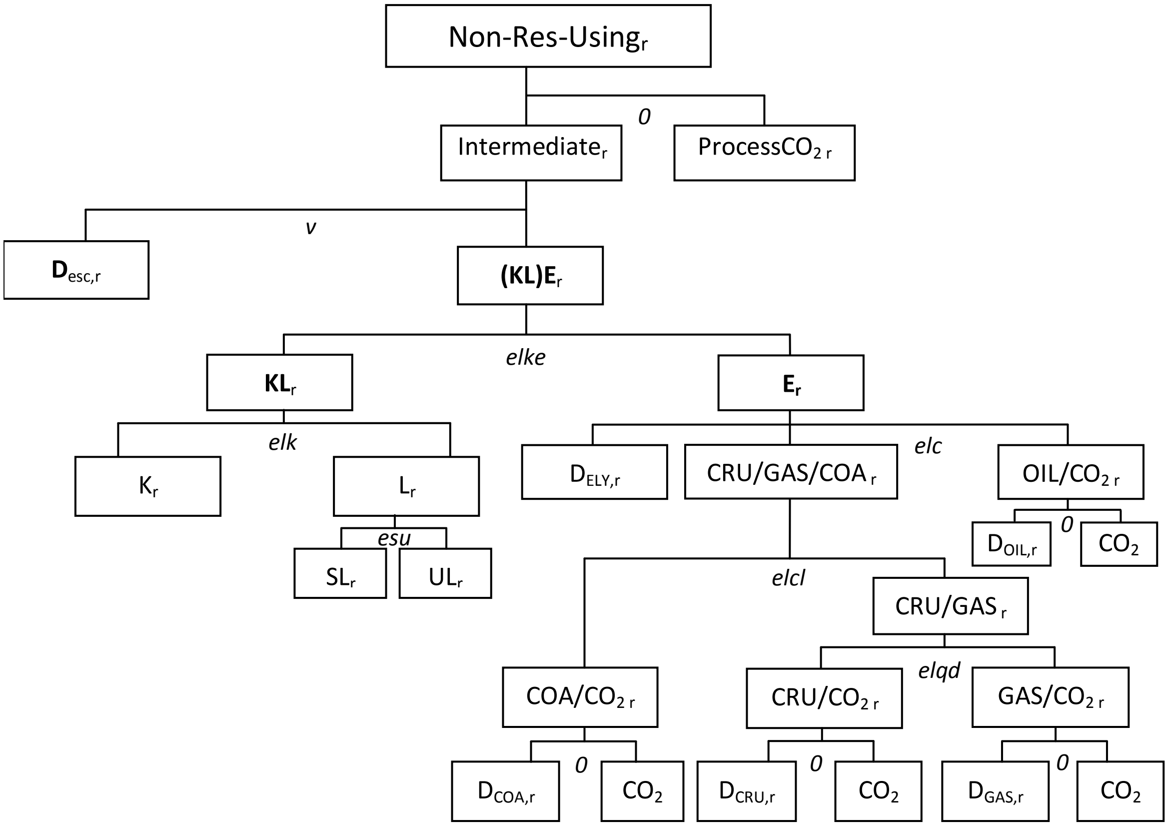

Fig. 3. Nesting structure of combustion and process emissions in production (for non-resource using sectors)

Figure4 b&w

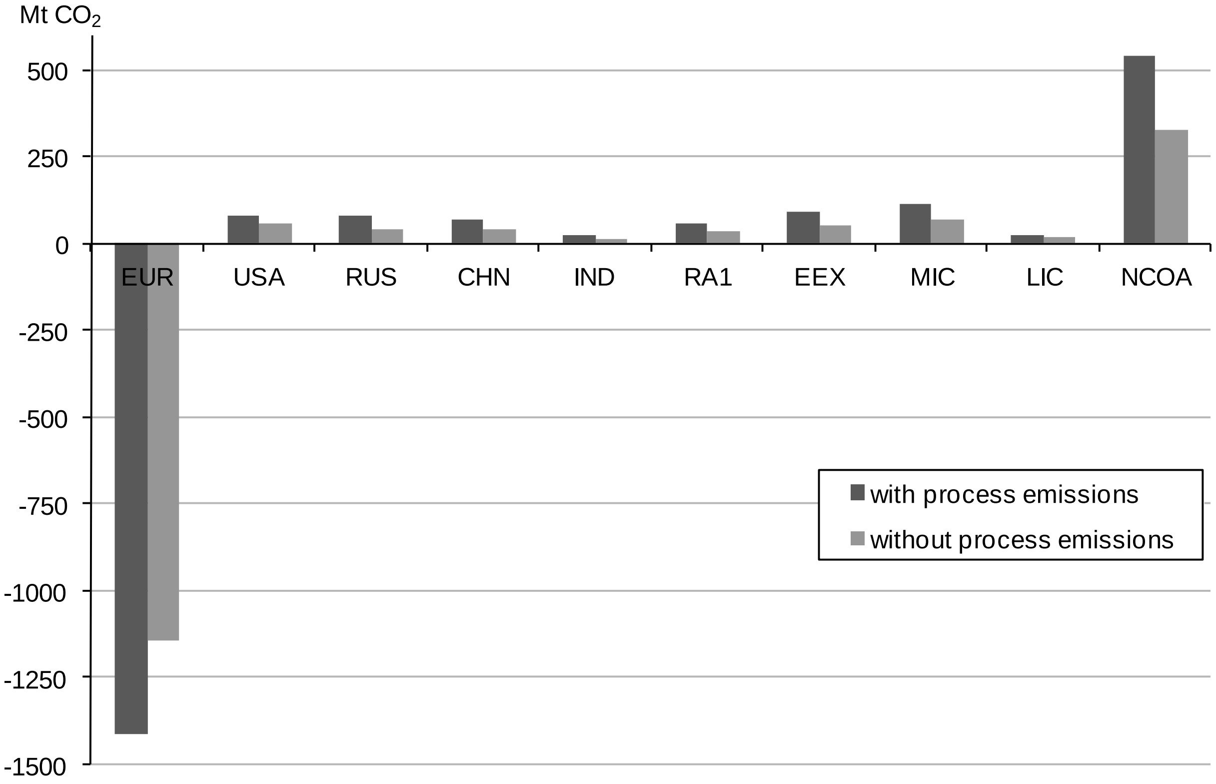

Fig. 1. Carbon leakage (in Mt CO_2) of unilateral EU climate policy across world regions (reference case)

Note: NCOA (non-coalition) aggregates all regions but EUR.

Figure5 b&w

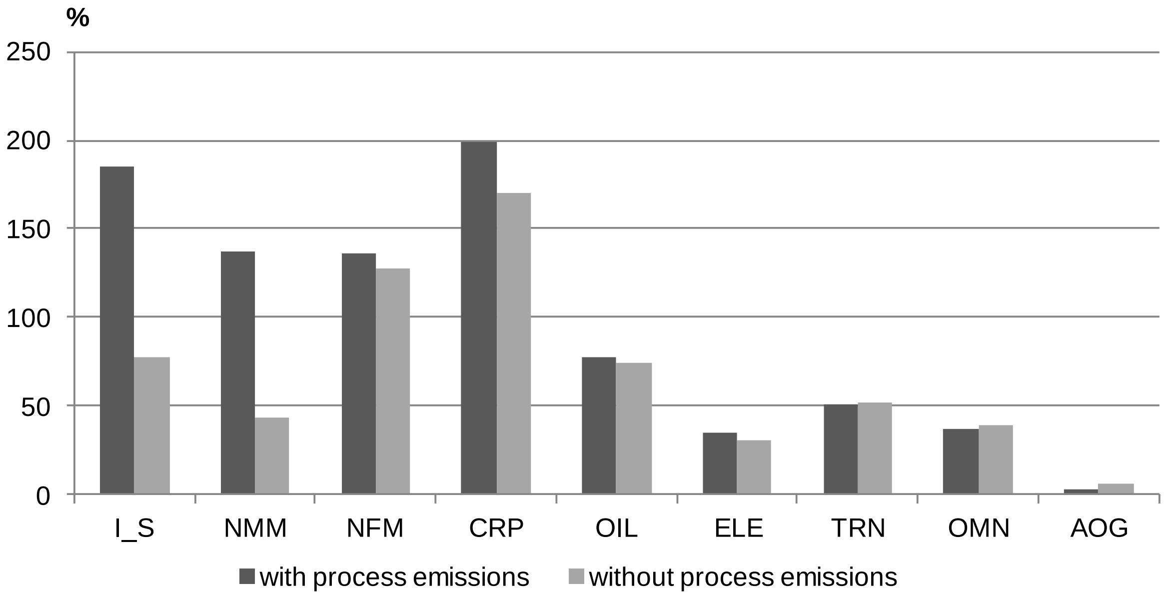

Fig. 5. Sectoral carbon leakage rates (in %) of unilateral EU climate policy (reference case)

Figure6 b&w

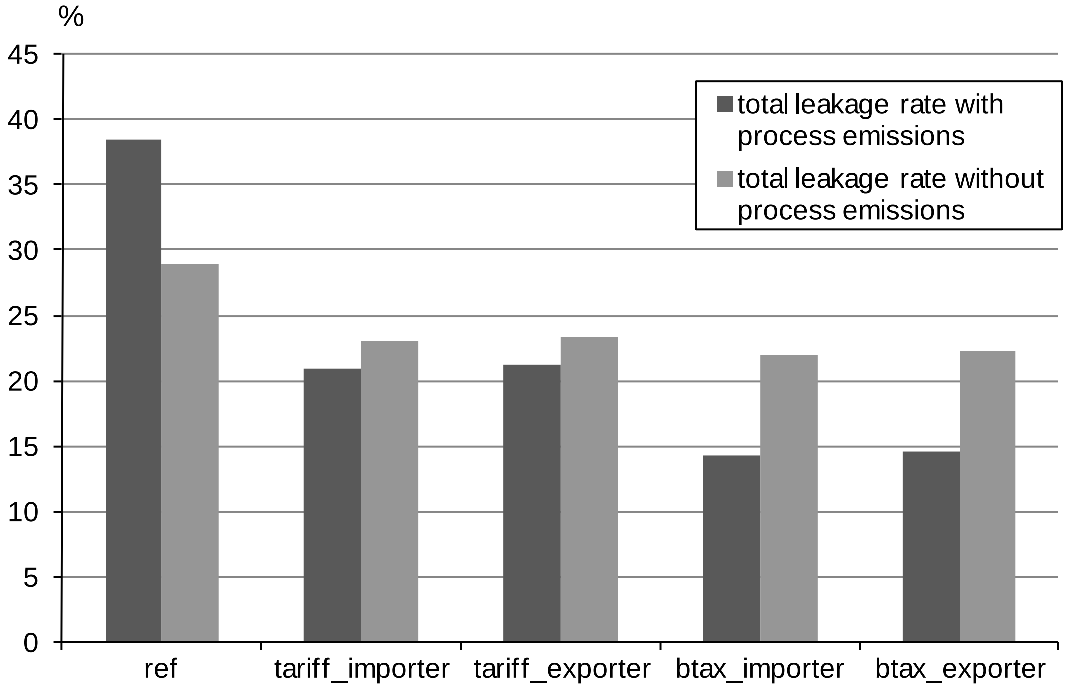

Fig. 6. Leakage rates (in %) with and without process emissions accounted for, across EU unilateral climate policy scenarios (reported for the reference year)

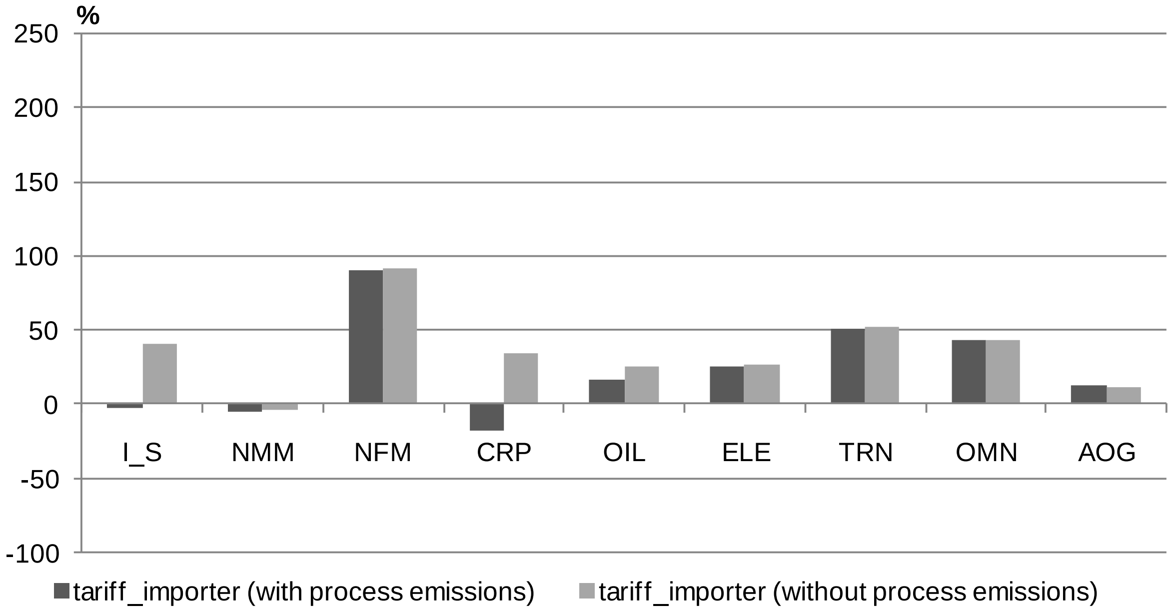

Fig. 7. Sectoral carbon leakage rates (in %) for EU unilateral climate policy with BCA (tariff_importer)

Figure8 b&w

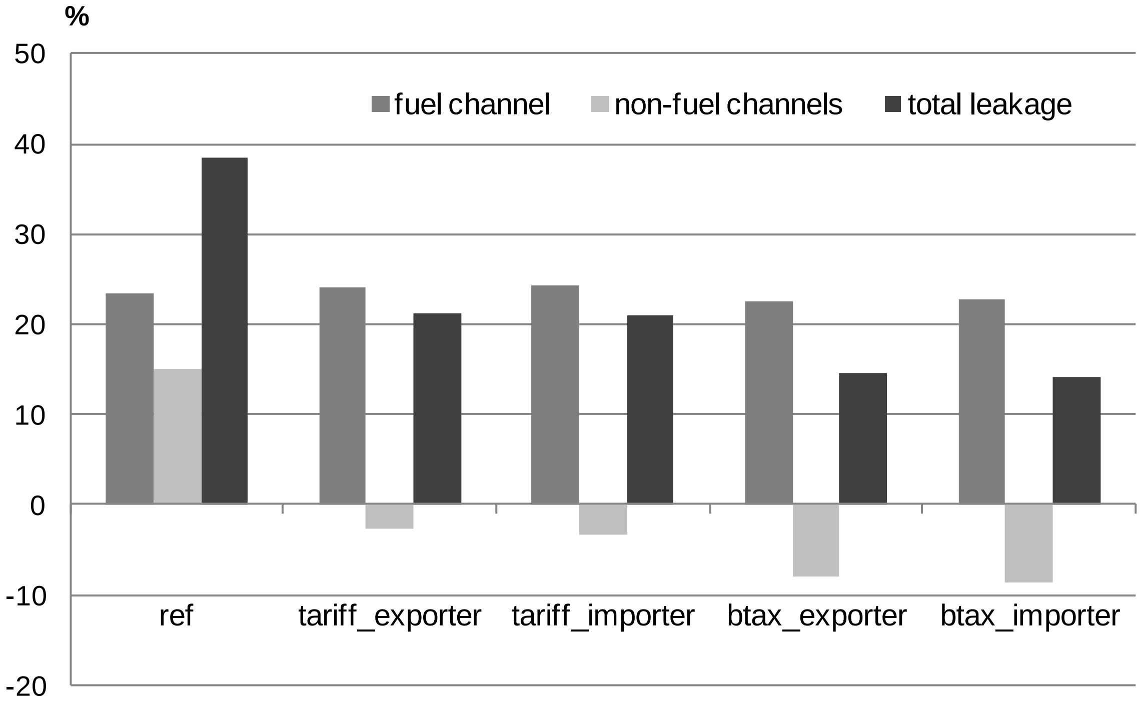

Fig. 8. Carbon leakage rate (in %) of different unilateral EU climate policy scenarios, with process emissions accounted for

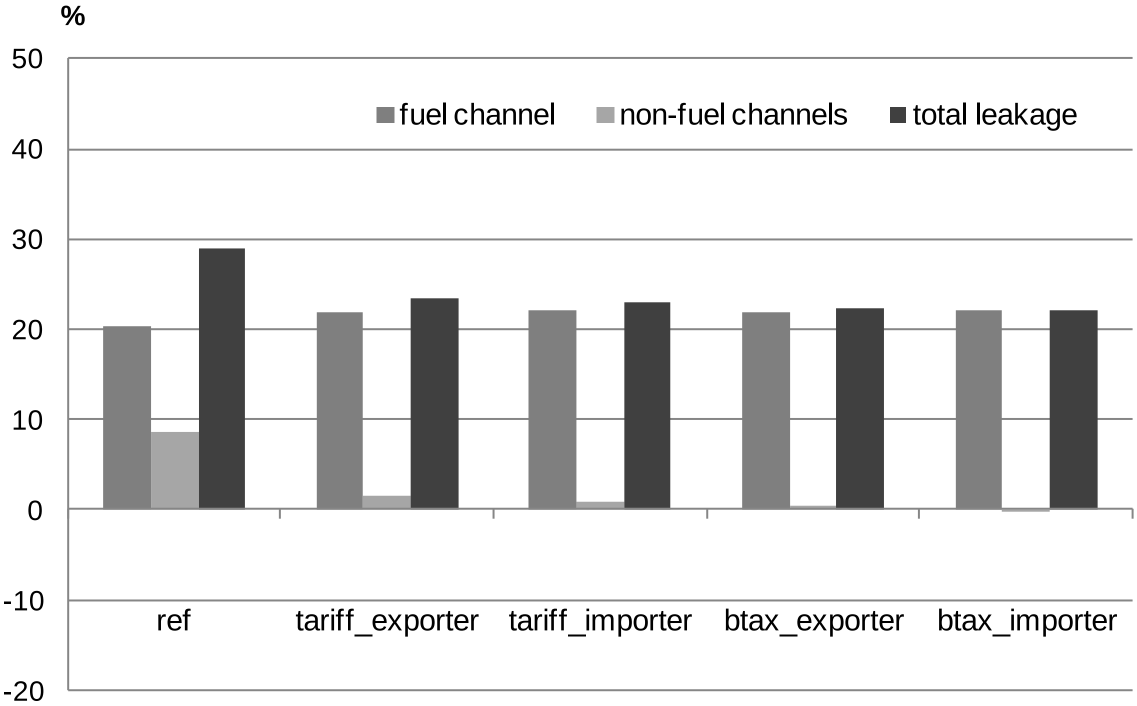

Fig. 9. Carbon leakage rate (in %) of different unilateral EU climate policy scenarios, without process emissions accounted for

Figure10 b&w

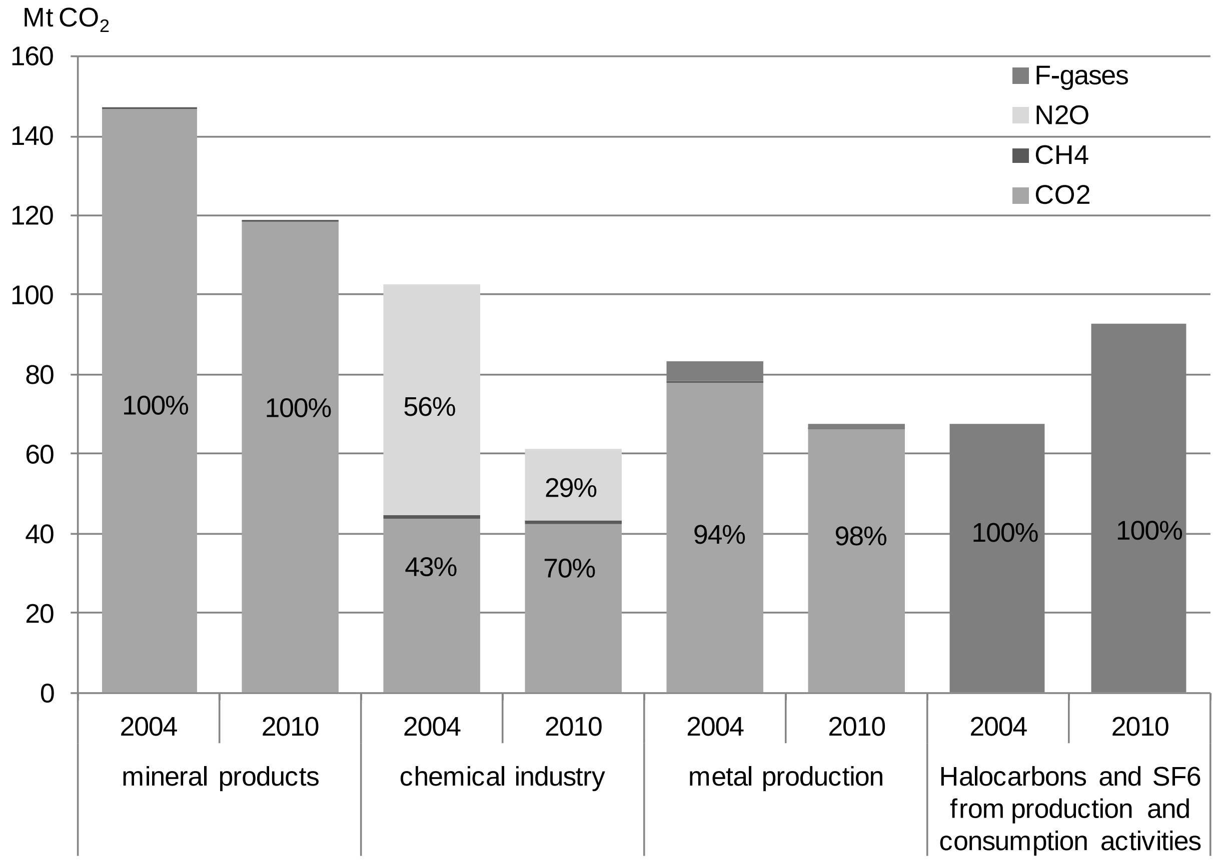

Fig. 10. CO_2 and non-CO_2 emission from industrial processes for EU 27, 2004 and 2010 (source: UNFCCC GHG inventory data 2012)

FigureA1

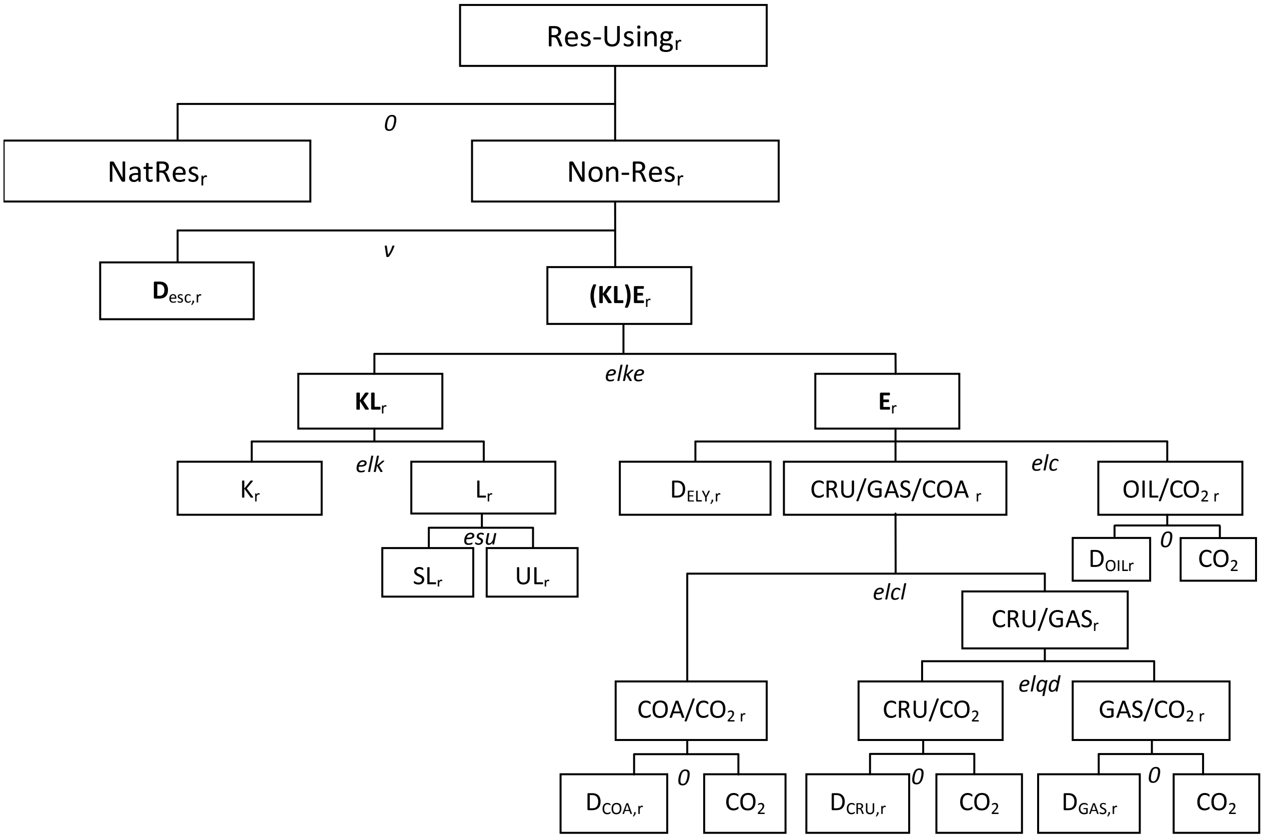

Fig. A.1. Nesting structure of resource using extraction processes

FigureA2

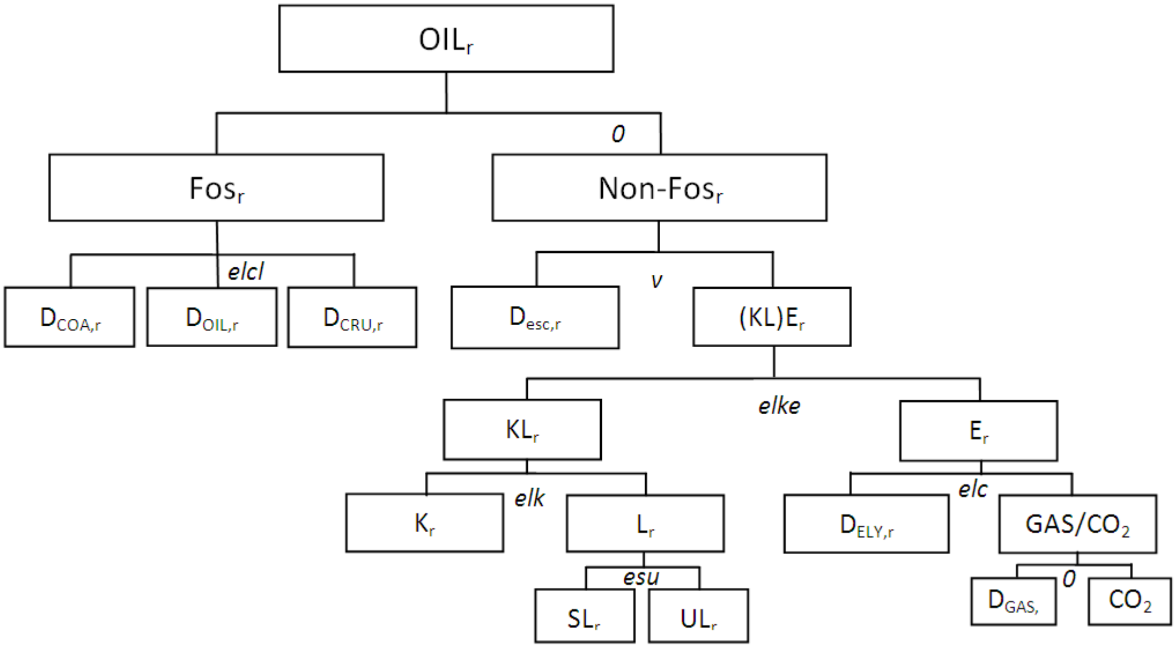

Fig. A.1. Nesting structure of OIL sector

FigureA3

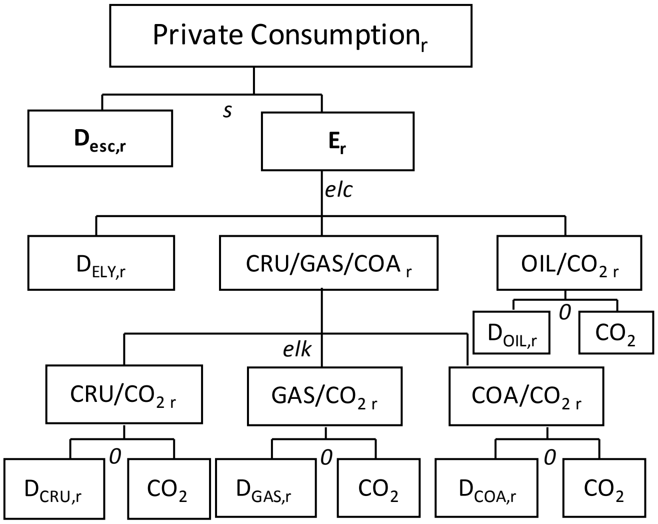

Fig. A.3. Nesting structure of household demand

Figure1 colour

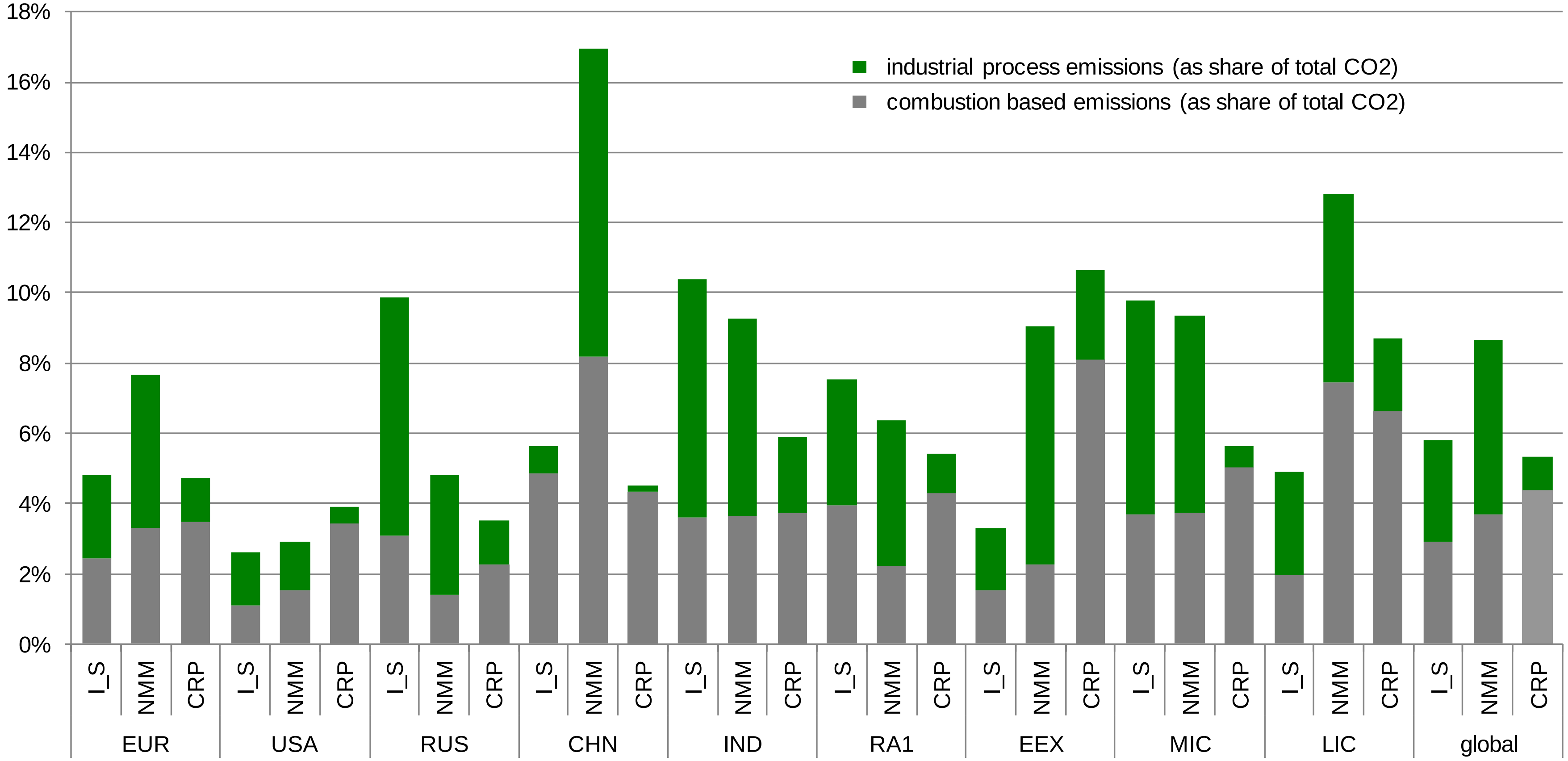

Fig. 1. Combustion based and industrial process CO_2 emissions for sectors I_S, NMM, and CRP (as share of total production CO_2 emissions in 2004).

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Note: for definition of sectors and regions, see Tab. 1 and 2.

Figure4 colour

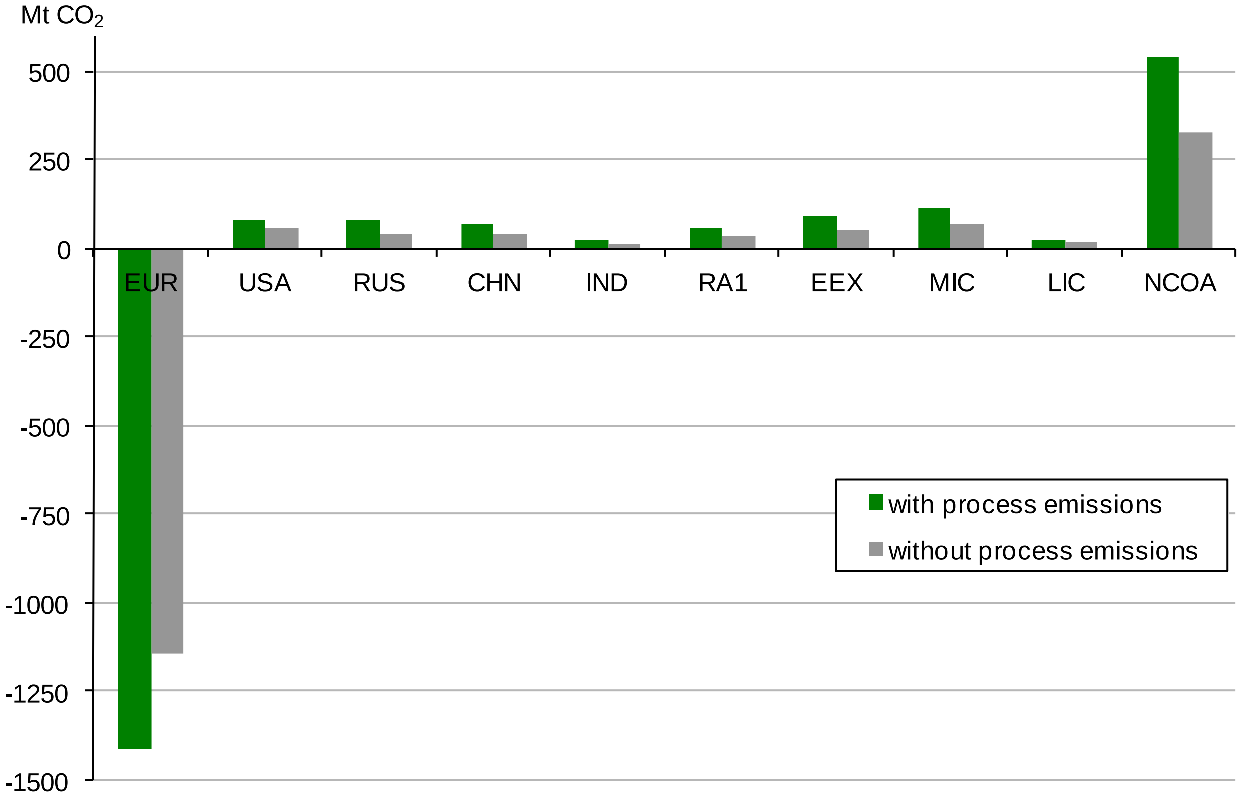

Fig. 4. Carbon leakage (in Mt CO_2) of unilateral EU climate policy across world regions (reference case)

Note: NCOA (non-coalition) aggregates all regions but EUR.

Figure5 colour

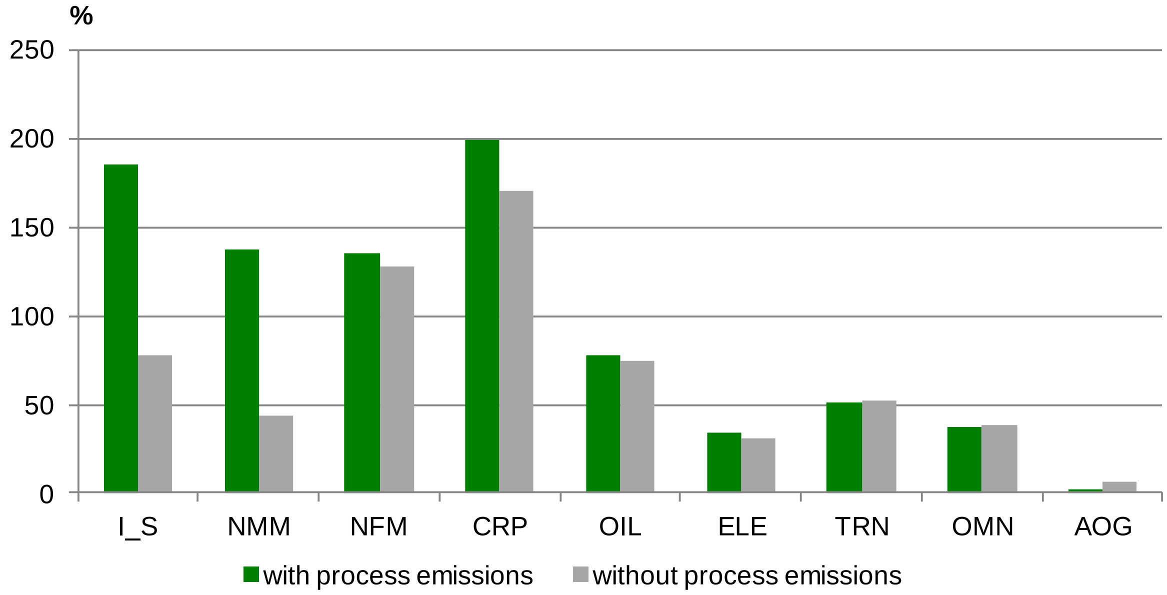

Fig. 5. Sectoral carbon leakage rates (in %) of unilateral EU climate policy (reference case)

Figure6 colour

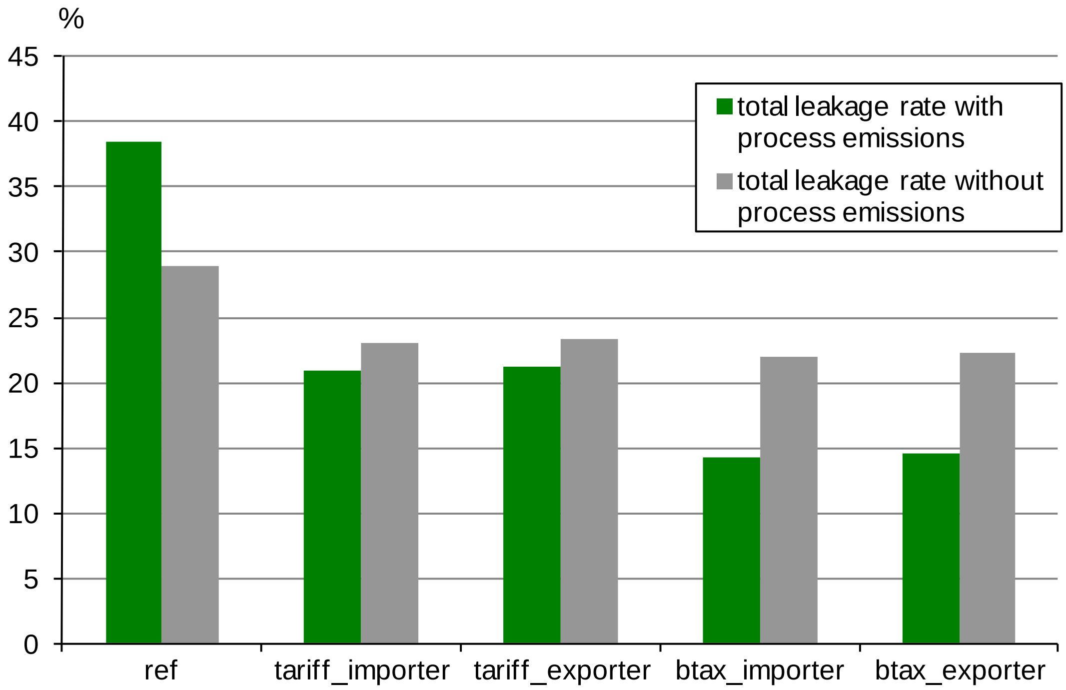

Fig. 6. Leakage rates (in %) with and without process emissions accounted for, across EU unilateral climate policy scenarios (reported for the reference year)

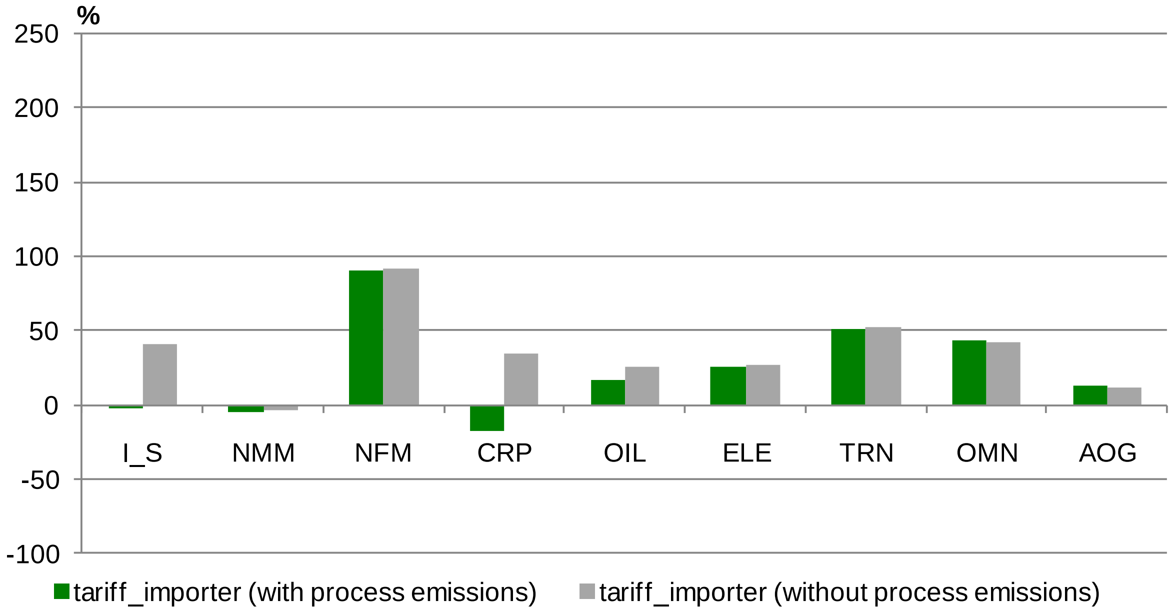

Fig. 7. Sectoral carbon leakage rates (in %) for EU unilateral climate policy with BCA (tariff_importer)

Figure8 colour

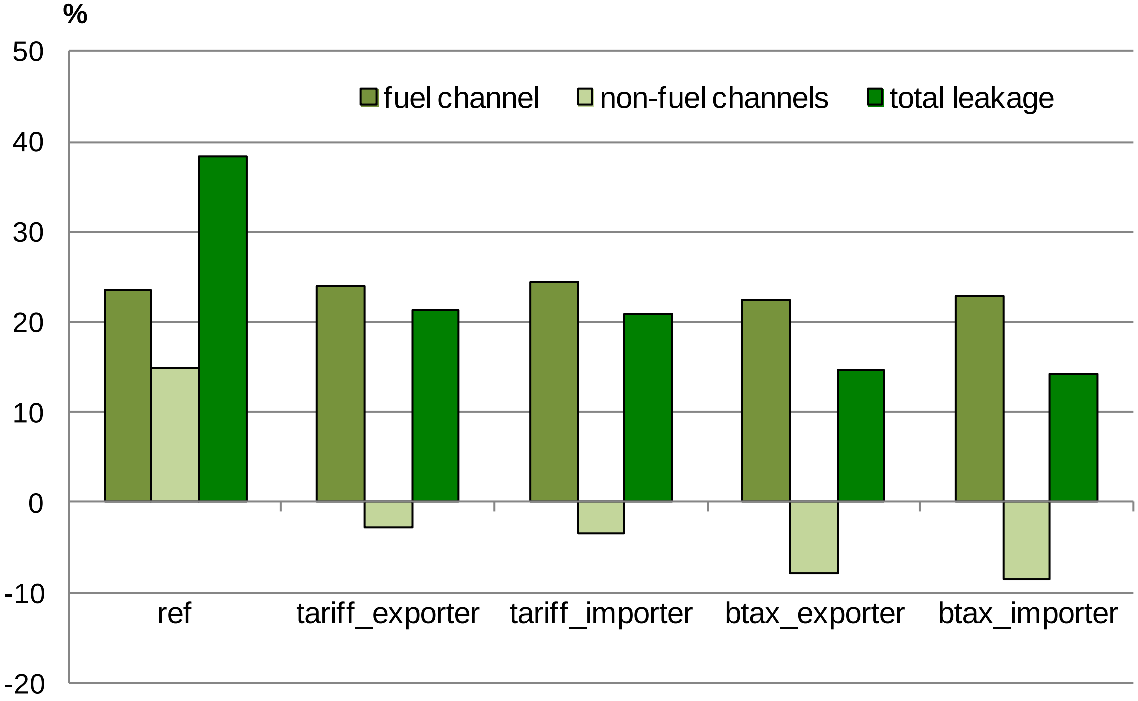

Fig. 8. Carbon leakage rate (in %) of different unilateral EU climate policy scenarios, with process emissions accounted for

Figure9 colour

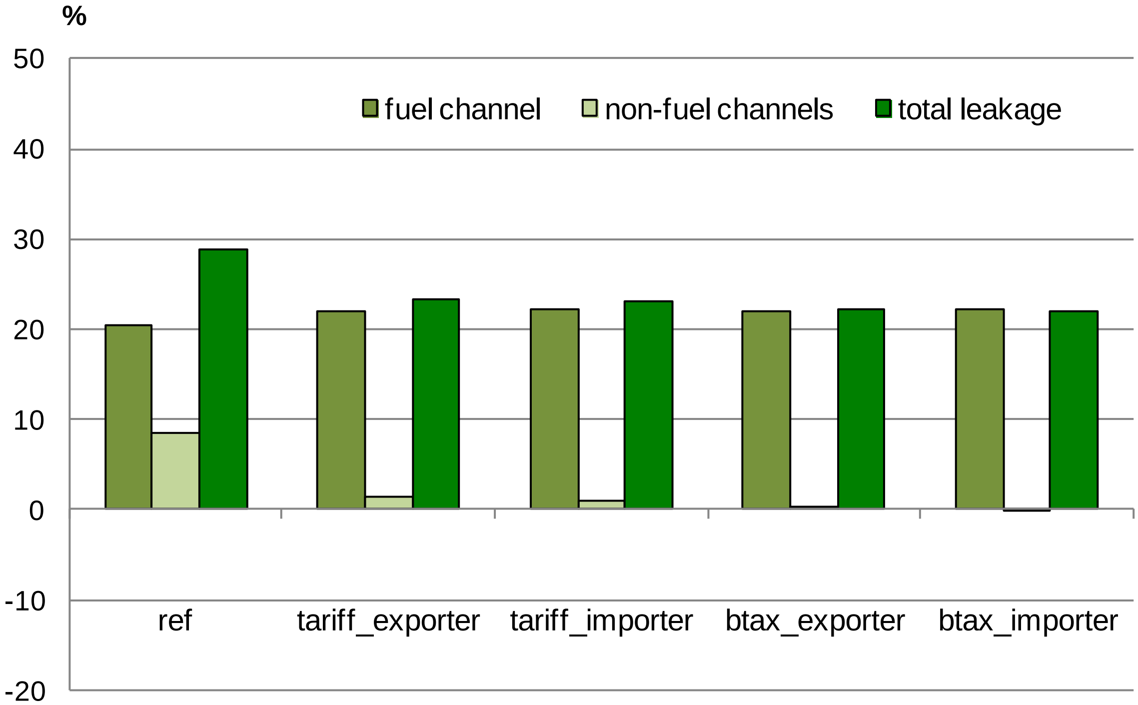

Fig. 9. Carbon leakage rate (in %) of different unilateral EU climate policy scenarios, without process emissions accounted for

Figure10 colour

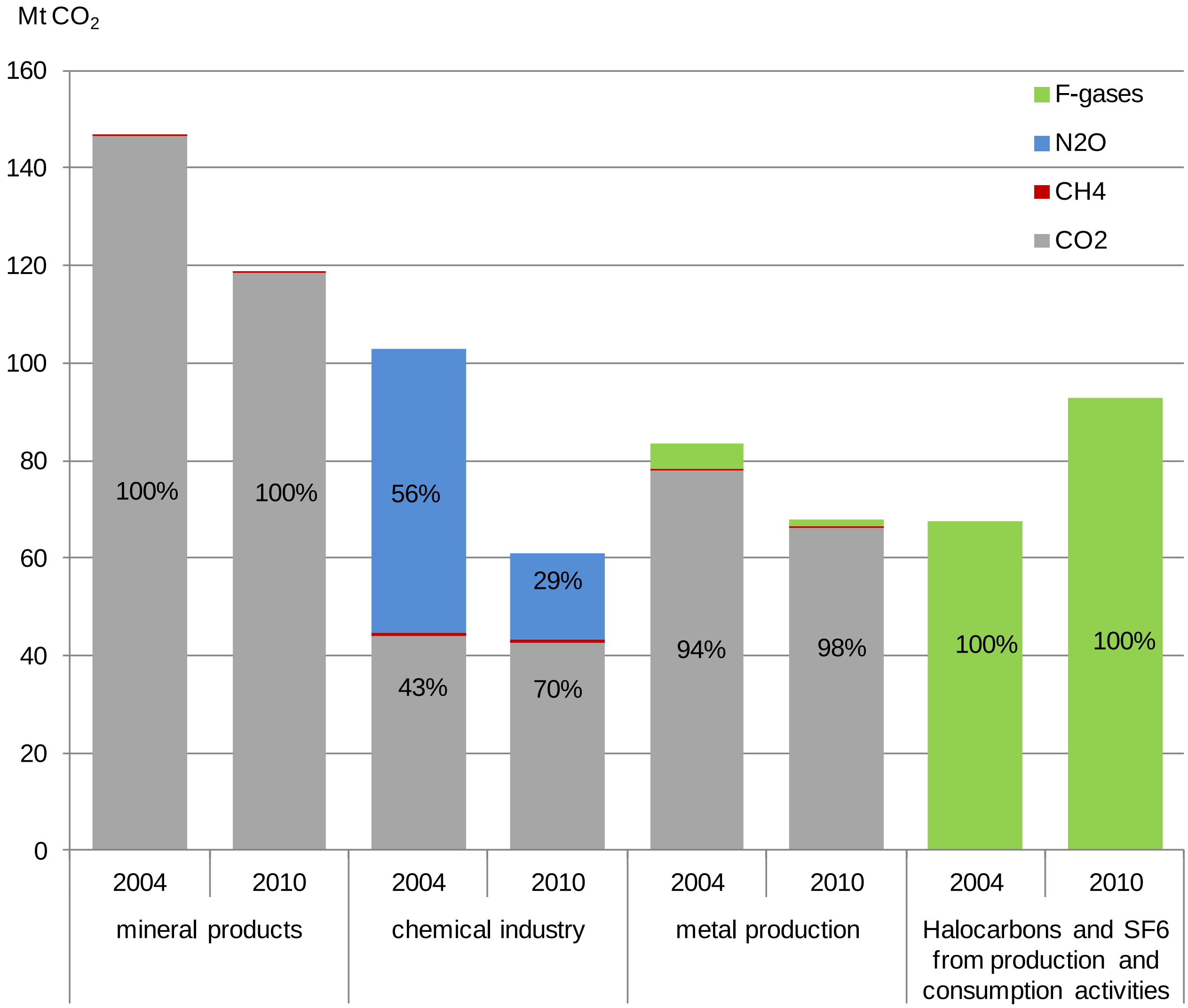

Fig. 10. CO_2 and non-CO_2 emission from industrial processes for EU 27, 2004 and 2010 (source: UNFCCC GHG inventory data 2012)

Supplementary Material to EMF article

The relevance of process emissions for carbon leakage: A comparison of unilateral climate policy options with and without border carbon adjustment

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Algebraic model formulation

The computable general equilibrium is formulated as a system of non-linear inequalities. Three classes of conditions characterize the competitive equilibrium of our model: (i) zero profit conditions, (ii) market clearance conditions and (iii) income balances. The first class is associated with activity levels, the second one with price levels and the third class with income levels.

In our algebraic formulation, the notation of Π_{ir}^{Z} is used to denote the unit profit function of sector *i* in region *r* for the production activity *Z*. In terms of notation we use *i* (aliased with *j*) as an index for commodities (sectors) and *r* (aliased with *s*) as an index for regions. Initial benchmark data refers to the base year 2004. All variables and parameters are defined as given in Tables A-1 to A-10.

Zero profit conditions

The zero profit conditions require that any activity produced at positive values has to earn zero profit. Thus, the value of inputs must be equal or greater than value of outputs. Activity levels are the associated complementarity variables.

1. Production of non resource using domestic goods (i$\notin$ RES and i $\neq$ OIL):

$$\Pi_{ir}^{Y} = p_{ir}^{D}\,(1-\bar{t}_{ir}^{D}) - \frac{\bar{\mathrm{C}}_{ir}^{Y}}{\bar{\mathrm{Y}}_{ir}}\left\{\theta_{ir}^{IPE}\left(\frac{p_{ir}^{CO}}{\bar{p}_{ir}^{CO}}\right) + (1-\theta_{ir}^{IPE})\left[\theta_{ir}^{ME}\left(\theta_{ir}^{ELK}\left(\frac{p_{ir}^{LK}}{\bar{p}_{ir}^{LK}}\right)^{1-\sigma_i^{ELK}} + (1-\theta_{ir}^{ELK})\left(\frac{p_{ir}^{E}}{\bar{p}_{ir}^{E}}\right)^{1-\sigma_i^{ELK}}\right)^{\frac{1-\sigma_i^{ME}}{1-\sigma_i^{ELK}}} + (1-\theta_{ir}^{ME})\left(\frac{p_{ir}^{M}}{\bar{p}_{ir}^{M}}\right)^{1-\sigma_i^{ME}}\right]^{\frac{1}{1-\sigma_i^{ME}}}\right\}$$

$$\leq\ 0 \text{ with } \perp Y_{ir} \text{ for i} \notin \text{ RES and i } \neq \text{ OIL}$$

2. Production of refined oil products (i = OIL).

$$
\begin{aligned}
\mathit{\Pi}_{i,r}^{Y} = {} & p_{i,r}^{D}(1-\bar{t}_{ir}^{D}) \\
& - \frac{\bar{\mathrm{C}}_{i,r}^{Y}}{\bar{\mathrm{Y}}_{i,r}} \Bigg\{ \Bigg[\theta_{r}^{FOS,1} \left(\theta_{i,r}^{COL} \frac{p_{\{COL,r\}}^{G}}{\bar{p}_{\{COL,r\}}^{G}} (1+\bar{t}_{i,r}^{C,COL}) + \theta_{i,r}^{CO,COL} \frac{p_{r}^{CO}}{\bar{p}_{r}^{CO}} \right)^{1-\sigma^{FOS}} \\
& + \theta_{r}^{FOS,2} \left(\theta_{i,r}^{CRU} \frac{p_{\{CRU,r\}}^{G}}{\bar{p}_{\{CRU,r\}}^{G}} (1+\bar{t}_{i,r}^{C,CRU}) + \theta_{i,r}^{CO,CRU} \frac{p_{r}^{CO}}{\bar{p}_{r}^{CO}} \right)^{1-\sigma^{FOS}} \\
& + \left[(1-\theta_{r}^{FOS,1}-\theta_{r}^{FOS,2}) \right] \Bigg(\theta_{i,r}^{OIL} \frac{p_{\{OIL,r\}}^{G}}{\bar{p}_{\{OIL,r\}}^{G}} (1+\bar{t}_{i,r}^{C,OIL}) \\
& + \theta_{i,r}^{CO,OIL} \frac{p_{r}^{CO}}{\bar{p}_{r}^{CO}} \Bigg)^{1-\sigma^{FOS}} \Bigg]^{\frac{1}{1-\sigma^{FOS}}} \\
& + \Bigg[\theta_{ir}^{ME} \left(\theta_{ir}^{ELK} \left(\frac{p_{ir}^{LK}}{\bar{p}_{ir}^{LK}} \right)^{1-\sigma_{i}^{ELK}} + (1-\theta_{ir}^{ELK}) \left(\frac{p_{ir}^{E}}{\bar{p}_{ir}^{E}} \right)^{1-\sigma_{i}^{ELK}} \right)^{\frac{1-\sigma_{i}^{ME}}{1-\sigma_{i}^{ELK}}} \\
& + (1-\theta_{ir}^{ME}) \left(\frac{p_{ir}^{M}}{\bar{p}_{ir}^{M}} \right)^{1-\sigma_{i}^{ME}} \Bigg]^{\frac{1}{1-\sigma_{i}^{ME}}} \Bigg\}
\end{aligned}
$$

$$\leq 0 \text{ with } \perp Y_{ir} \text{ for i} = \text{OIL}$$

3. Production of resource using domestic goods (i ∈ RES):

$$
\begin{aligned}
\mathit{\Pi}_{ir}^{Y} = {} & p_{ir}^{D}\,(1-\bar{t}_{ir}^{D}) \\
& - \frac{\bar{\mathrm{C}}_{ir}^{Y}}{\bar{\mathrm{Y}}_{ir}} \Bigg\{ \theta_{ir}^{RES} \left(\frac{v_{ir}}{\bar{v}_{ir}} (1-\bar{\mathrm{t}}_{ir}^{F,R}) \right) \\
& + (1-\theta_{ir}^{RES}) \Bigg[\theta_{ir}^{ME} \left(\theta_{ir}^{ELK} \left(\frac{p_{ir}^{LK}}{\bar{p}_{ir}^{LK}} \right)^{1-\sigma_{i}^{ELK}} + (1-\theta_{ir}^{ELK}) \left(\frac{p_{ir}^{E}}{\bar{p}_{ir}^{E}} \right)^{1-\sigma_{i}^{ELK}} \right)^{\frac{1-\sigma_{i}^{ME}}{1-\sigma_{i}^{ELK}}} \\
& + (1-\theta_{ir}^{ME}) \left(\frac{p_{ir}^{M}}{\bar{p}_{ir}^{M}} \right)^{1-\sigma_{i}^{ME}} \Bigg]^{\frac{1}{1-\sigma_{i}^{ME}}} \Bigg\}
\end{aligned}
$$

$$\leq 0 \text{ with } \perp Y_{ir} \text{ for i} \in \text{RES}$$

4. Sector specific capital - labor aggregate:

$$\mathit{\Pi}_{ir}^{KL} = p_{ir}^{LK} - \frac{\bar{\mathrm{C}}_{ir}^{KL}}{\overline{\mathrm{KL}}_{ir}} \left\{ \theta_{ir}^{LK} \left(\frac{\nu_r}{\bar{\nu}_r} \left(1 + \bar{t}_r{}^{F,K}\right) \right)^{1-\sigma_i^{LK}} + \left(1 - \theta_{ir}^{LK}\right) \left(\frac{p_{ir}^{SU}}{\bar{p}_{ir}^{SU}} \right)^{1-\sigma_i^{LK}} \right\}^{\frac{1}{1-\sigma_i^{LK}}}$$

$$\leq \; 0 \text{ with} \perp \; LK_{ir}$$

5. Sector specific skilled and unskilled labor aggregate

$$\mathit{\Pi}_{ir}^{SU} = p_{ir}^{SU} - \frac{\bar{\mathrm{C}}_{ir}^{SU}}{\overline{\mathrm{SU}}_{ir}} \left\{ \theta_{ir}^{SU} \left(\frac{\omega_r^S}{\bar{\omega}_r^S} \left(1 + \bar{t}_r{}^{F,SL}\right) \right)^{1-\sigma_i^{\mathrm{SU}}} + \left(1 - \theta_{ir}^{SU}\right) \left(\frac{\omega_r^U}{\bar{\omega}_r^U} \left(1 + \bar{t}_r{}^{F,UL}\right) \right)^{1-\sigma_i^{SU}} \right\}^{\frac{1}{1-\sigma_i^{SU}}}$$

$$\leq \; 0 \text{ with} \perp \; SU_{ir}$$

6. Sector specific material aggregate

$$\mathit{\Pi}_{ir}^{M} = p_{ir}^{M} - \frac{\bar{\mathrm{C}}_{ir}^{M}}{\bar{\mathrm{M}}_{ir}} \left[\sum_{\mathrm{j \neq NRG}} \theta_{jir}^{M} \left(\frac{p_{jr}^{G}}{\bar{p}_{jr}^{G}} \left(1 + \bar{\mathrm{t}}_{ir}^{C,j}\right) \right)^{1-\sigma_i^{M}} \right]^{\frac{1}{1-\sigma_i^{M}}} \leq \; 0 \text{ with} \perp \; M_{ir}$$

7. Sector specific energy aggregate ($i = OIL$):

$$\mathit{\Pi}_{ir}^{E} = p_{ir}^{E} - \frac{\bar{\mathrm{C}}_{ir}^{E}}{\bar{\mathrm{E}}_{ir}} \left\{ \theta_{ir}^{EN,1} \left(\frac{p_{\{ELY,r\}}^{G}}{\bar{p}_{\{ELY,r\}}^{G}} \left(1 + \bar{t}_{ir}^{C,ELY}\right) \right)^{1-\sigma_i^{ELEC}} \right.$$

$$\left. + \left(1 - \theta_{ir}^{EN,1}\right) \left(\theta_{ir}^{GAS} \frac{p_{\{GAS,r\}}^{G}}{\bar{p}_{\{GAS,r\}}^{G}} \left(1 + \bar{t}_{ir}^{C,GAS}\right) + \theta_{ir}^{CO,GAS} \frac{p_r^{CO}}{\bar{p}_r^{CO}} \right)^{1-\sigma_i^{ELEC}} \right\}^{\frac{1}{1-\sigma_i^{ELEC}}}$$

$$\leq \; 0 \text{ with} \perp \; E_{ir} \text{ for i} = \mathrm{OIL}$$

8. Sector specific energy aggregate ($i \neq OIL$):

$$
\begin{aligned}
\Pi_{ir}^{E} = p_{ir}^{E} - \frac{\bar{\mathrm{C}}_{ir}^{E}}{\bar{\mathrm{E}}_{ir}} \Bigg\{ & \theta_{ir}^{EN,1}\left(\frac{p_{\{ELY,r\}}^{G}}{\bar{p}_{\{ELY,r\}}^{G}}\left(1+\bar{t}_{ir}^{C,ELY}\right)\right)^{1-\sigma_i^{ELEC}} \\
& + \theta_{ir}^{EN,2}\Bigg(\theta_{ir}^{FF}\left[\theta_{ir}^{COL}\frac{p_{\{COL,r\}}^{G}}{\bar{p}_{\{COL,r\}}^{G}}\left(1+\bar{t}_{ir}^{C,COL}\right)+\theta_{ir}^{CO,COL}\frac{p_r^{CO}}{\bar{p}_r^{CO}}\right]^{1-\sigma_i^{ELECL}} \\
& + (1 \\
& - \theta_{ir}^{FF})\Bigg[\theta_{ir}^{OG}\left(\theta_{ir}^{CRU}\frac{p_{\{OIL,r\}}^{G}}{\bar{p}_{\{OIL,r\}}^{G}}\left(1+\bar{t}_{ir}^{C,CRU}\right)+\theta_{ir}^{CO,\mathrm{CRU}}\frac{p_r^{CO}}{\bar{p}_r^{CO}}\right)^{1-\sigma_i^{ELEQD}} \\
& + (1 \\
& - \theta_{ir}^{OG})\left(\theta_{ir}^{GAS}\frac{p_{\{GAS,r\}}^{G}}{\bar{p}_{\{GAS,r\}}^{G}}\left(1+\bar{t}_{ir}^{C,GAS}\right)+\theta_{ir}^{CO,GAS}\frac{p_r^{CO}}{\bar{p}_r^{CO}}\right)^{1-\sigma_i^{ELEQD}}\Bigg]^{\frac{1-\sigma_i^{ELECL}}{1-\sigma_i^{ELEQD}}}\Bigg)^{\frac{1-\sigma_i^{ELEC}}{1-\sigma_i^{ELECL}}} \\
& + \left(1-\theta_{ir}^{EN,1}-\theta_{ir}^{EN,2}\right)\left[\theta_{ir}^{\mathrm{OIL}}\frac{p_{\{PC,r\}}^{G}}{\bar{p}_{\{PC,r\}}^{G}}\left(1+\bar{t}_{ir}^{C,OIL}\right)+\theta_{ir}^{CO,OIL}\frac{p_r^{CO}}{\bar{p}_r^{CO}}\right]^{1-\sigma_i^{ELEC}}\Bigg\}^{\frac{1}{1-\sigma_i^{ELEC}}}
\end{aligned}
$$

$$\leq \ 0 \text{ with} \perp \ E_{ir} \text{ for i} \neq \text{OIL}$$

9. Armington Aggregate:

$$\Pi_{ir}^{G} = p_{ir}^{G} - \frac{\bar{\mathrm{C}}_{ir}^{G}}{\bar{\mathrm{G}}_{ir}}\left\{\theta_{ir}^{A}\frac{p_{ir}^{IM\,1-\sigma_i^{A}}}{\bar{p}_{ir}^{IM}} + (1-\theta_{ir}^{A})\frac{p_{ir}^{D\,1-\sigma_i^{A}}}{\bar{p}_{ir}^{D}}\right\}^{\frac{1}{(1-\sigma_i^{A})}} \leq \ 0 \text{ with} \perp \ G_{ir}$$

10. Aggregate imports across regions for region *r*:

$$\Pi_{\mathrm{ir}}^{IM} = p_{\mathrm{ir}}^{IM} - \frac{\bar{\mathrm{C}}_{ir}^{IM}}{\bar{\mathrm{IM}}_{ir}}\left\{\sum_{s}\theta_{isr}^{IMR}\left(\left[\theta_{isr}^{GROW}\frac{p_{is}^{D}}{\bar{p}_{is}^{D}}\left(1+\bar{t}_{irs}^{EX}\right)\right]\left(1+\bar{t}_{isr}^{IM}\right)+\theta_{isr\}}^{TR}\frac{p^{T}}{\bar{p}^{T}}\right)^{1-\sigma_i^{IMR}}\right\}^{\frac{1}{(1-\sigma_i^{IMR})}}$$

$$\leq \ 0 \text{ with} \perp IM_{ir}$$

11. International transport sector:

$$\Pi^{T} = p^{T} - \frac{\bar{\mathrm{C}}^{T}}{\bar{\mathrm{T}}}\left\{\prod_{\mathrm{r}}\left(\frac{p_{\{TRANS,r\}}^{G}}{\bar{p}_{\{TRANS,r\}}^{G}}\right)^{\theta_r^{T}}\right\} \leq \ 0 \text{ with} \perp \mathrm{T}$$

12. Welfare of regional household:

$$\Pi_r^{WHH} = p_r^{WHH} - \frac{\bar{\mathrm{C}}_r^{WHH}}{\overline{\mathrm{WHH}}_r}\left\{\theta_r^{WHH}\left(\frac{p_r^{MHH}}{\bar{p}_r^{MHH}}\right)^{1-\sigma_r^{WHH}} + (1-\theta_r^{WHH})\left(\frac{p_r^{EHH}}{\bar{p}_r^{EHH}}\right)^{1-\sigma_r^{WHH}}\right\}^{\frac{1}{(1-\sigma_r^{WHH})}}$$

$$\leq\ 0 \text{ with} \perp WHH_r$$

13. Material aggregate in household consumption of region r:

$$\Pi_r^{MHH} = p_r^{MHH} - \frac{\bar{\mathrm{C}}_r^{MHH}}{\overline{\mathrm{MHH}}_r}\left[\sum_{\mathrm{i}\neq\mathrm{NRG}} \theta_{ir}^{MHH}\left(\frac{p_{ir}^{G}}{\bar{p}_{ir}^{G}}\left(1+\bar{\mathrm{t}}_{i,r}^{CHH}\right)\right)^{1-\sigma_r^{MHH}}\right]^{\frac{1}{1-\sigma_r^{MHH}}} \leq\ 0 \text{ with} \perp\ MHH_r$$

14. Household energy consumption:

$$\begin{aligned}
\Pi_{HH,r}^{E} = p_r^{EHH} - \frac{\bar{\mathrm{C}}_r^{EHH}}{\overline{\mathrm{EHH}}_r}&\left\{\theta_{HH,r}^{EHH,1}\left(\frac{p_{\{ELY,r\}}^{G}}{\bar{p}_{\{ELY,r\}}^{G}}\left(1+\bar{t}_{HH,r}^{C,ELY}\right)\right)^{1-\sigma_r^{EHH}}\right. \\
&+ \theta_{HH,r}^{EHH,2}\left(\theta_{HH,r}^{PET,1}\left[\theta_{HH,r}^{COL}\frac{p_{\{COL,r\}}^{G}}{\bar{p}_{\{COL,r\}}^{G}}\left(1+\bar{t}_{HH,r}^{C,COL}\right)+\theta_{HH,r}^{CO,COL}\frac{p_r^{CO}}{\bar{p}_r^{CO}}\right]^{1-\sigma_r^{PETHH}}\right. \\
&+ \theta_{HH,r}^{PET,2}\left[\theta_{HH,r}^{CRU}\frac{p_{\{CRU,r\}}^{G}}{\bar{p}_{\{CRU,r\}}^{G}}\left(1+\bar{t}_{HH,r}^{C,CRU}\right)+\theta_{HH,r}^{CO,CRU}\frac{p_r^{CO}}{\bar{p}_r^{CO}}\right]^{1-\sigma_r^{PETHH}} \\
&+ \left[\left(1-\theta_{HH,r}^{PET,1}-\theta_{HH,r}^{PET,2}\right)\right]\left[\theta_{HH,r}^{GAS}\frac{p_{\{GAS,r\}}^{G}}{\bar{p}_{\{GAS,r\}}^{G}}\left(1+\bar{t}_{HH,r}^{C,GAS}\right)\right. \\
&\left.\left. + \theta_{HH,r}^{CO,GAS}\frac{p_r^{CO}}{\bar{p}_r^{CO}}\right]^{1-\sigma_r^{PETHH}}\right)^{\frac{1-\sigma_r^{EHH}}{1-\sigma_r^{PETHH}}} \\
&+ \left[\left(1-\theta_{HH,r}^{EHH,1}-\theta_{HH,r}^{EHH,2}\right)\right]\left[\theta_{HHr}^{PC}\frac{p_{\{PC,r\}}^{G}}{\bar{p}_{\{PC,r\}}^{G}}\left(1+\bar{t}_{HH,r}^{C,PC}\right)\right. \\
&\left.\left. + \theta_{HH,r}^{CO,OIL}\frac{p_r^{CO}}{\bar{p}_r^{CO}}\right]^{1-\sigma_r^{EHH}}\right\}^{\frac{1}{1-\sigma_r^{EHH}}}
\end{aligned}$$

$$\leq\ 0 \text{ with} \perp\ EHH_r$$

15. Welfare due to public good provision (regional government):

$$\Pi_r^{WGOV} = p_r^{WGOV} - \frac{\bar{\mathrm{C}}_r^{WGOV}}{\overline{\mathrm{WGOV}}_r}\left[\sum\nolimits_{\mathrm{i}} \theta_{ir}^{MGOV}\left(\frac{p_{ir}^{G}}{\bar{p}_{ir}^{G}}\left(1+\bar{\mathrm{t}}_{i,r}^{CGOV}\right)\right)^{1-\sigma_r^{MGOV}}\right]^{\frac{1}{1-\sigma_r^{MGOV}}} \leq\ 0 \text{ with} \perp \mathrm{WGOV_r}$$

Market clearance conditions

Market clearance conditions require that for every commodity with a positive price, supply and demand must be in balance. Thus, any good with excess supply has a price of zero. Differentiation of the unit profit function with respect to the price gives the compensated supply and demand quantities. The price of each quantity is the associated complementarity variable.

16. Skilled labor market:

$$\overline{SL_r} \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial \omega^S_r} \qquad \text{with} \perp \omega^S_r$$

17. Unskilled labor market:

$$\overline{UL_r} \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial \omega^{\mathrm{U}}_r} \qquad \text{with} \perp \omega^U_r$$

18. Capital market:

$$\overline{K_r} \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial \nu_r} \qquad \text{with} \perp \nu_r$$

19. Resource market:

$$\overline{R_{ir}} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial \upsilon_{ir}} \qquad \text{with} \perp \upsilon_{ir}$$

20. Sector specific energy aggregate:

$$E_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^E_{ir}} \qquad \text{with} \perp p^E_{ir}$$

21. Aggregate household energy consumption:

$$EHH_r \geq WHH_r \frac{\partial \Pi^{WHH}_r}{\partial p^{EHH}_r} \qquad \text{with} \perp p^{EHH}_r$$

22. Sector specific capital-labor aggregate

$$LK_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^{LK}_{ir}} \qquad \text{with} \perp p^{LK}_{ir}$$

23. Sector specific skilled-unskilled labor aggregate

$$SU_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^{\mathrm{SU}}_{ir}} \qquad \text{with} \perp p^{SU}_{ir}$$

24. Regional, sectoral output for domestic and export markets:

$$Y_{ir} \geq G_{ir} \frac{\partial \Pi^G_{ir}}{\partial p^D_{ir}} + IM_{is} \frac{\partial \Pi^{IM}_{is}}{\partial p^D_{ir}} \qquad \text{with} \perp p^D_{ir}$$

25. Import aggregate across regions:

$$IM_{ir} \geq G_{ir} \frac{\partial \Pi^A_{ir}}{\partial p^{IM}_{ir}} \qquad \text{with} \perp p^{IM}_{ir}$$

26. Armington aggregate:

$$G_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^G_{ir}} + WHH_r \frac{\partial \Pi^{WHH}_r}{\partial p^G_{ir}} + WGOV_r \frac{\partial \Pi^{WGOV}_r}{\partial p^G_{ir}} \qquad \text{with} \perp p^G_{ir}$$

27. Household material consumption:

$$MHH_r \geq WHH_r \frac{\partial \Pi_r^{WHH}}{\partial p_r^{MHH}} \qquad \text{with} \perp p_r^{MHH}$$

28. Sector specific material consumption:

$$M_{i,r} \geq Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{M}} \qquad \text{with} \perp p_{ir}^{M}$$

29. Welfare of regional Household:

$$WHH_r \geq \frac{I_r}{p_r^{WHH}} \qquad \text{with} \perp p_r^{WHH}$$

30. Public good market (regional government):

$$WGOV_r \geq \frac{I_r}{p_r^{WGOV}} \qquad \text{with} \perp p_r^{WGOV}$$

31. Carbon emissions for region *r*:

$$CO_r \geq \sum_i Y_{\text{ir}} \frac{\partial \Pi_{ir}^{Y}}{\partial p_r^{CO}} \qquad \text{with} \perp p_r^{CO}$$

32. Transport market:

$$T \geq \sum_r \sum_i IM_{ir} \frac{\partial \Pi_{ir}^{IM}}{\partial p^{T}} \qquad \text{with} \perp p^{T}$$

Income balance

The respective income balance conditions require the representative agents' income I_r, which is made up of the receipts from the rental of primary factors and tax income (including carbon market revenue) plus the balance of payment $\overline{B_r}$, to equal final demand plus savings.

As such, the representative agents' income is defined as follows:

$$I_r \equiv \omega_r^S \overline{SL_r} + \omega_r^U \overline{UL_r} + \nu_r \overline{K_r} + \sum_i \upsilon_{ir} \overline{R_{ir}} + p_r^{CO} CO_r + \overline{B_r} + TAX_r \ ,$$

with the following tax income:

$$\begin{aligned} TAX_r = \ & \omega_r^S \overline{SL_r} \bar{t}_r^{F,SL} + \omega_r^U \overline{UL_r} \bar{t}_r^{F,UL} + \nu_r \overline{K_r} \, \bar{t}_r^{F,K} + \sum_i \upsilon_{ir} \overline{R_{ir}} \, \bar{t}_r^{F,R} + \sum_i p_{ir}^D Y_{ir} \bar{t}_{ir}^D \\ & + \sum_i p_{ir}^D \sum_s (IM_{is} \bar{t}_{irs}^X) + \sum_i p_{ir}^{IM} \, IM_{ir} \sum_s \bar{t}_{isr}^{\mathrm{IM}} + \sum_i p_{ir}^G \, G_{ir} \bar{t}_{ir}^C \ , \end{aligned}$$

and the balance of payment ($\overline{B_r}$), fixed at initial benchmark level is as follows:

$$\overline{B_r} = \ p_{\{CGDS,r\}}^G \ \sum_i (Y_{ir} - G_{ir}) \ + p^T T,$$

and has to equal the value of savings plus final demand:

$$I_r = \ p_{\{CGDS,r\}}^G G_{\{CGDS,r\}+} p_r^{WHH} \mathrm{WHH_r} + p_r^{WHH} \mathrm{WHH_r}$$

Definitions

Table A- 1 Sets

*i (*alias *j)*	Sectors
*r (*alias *s)*	Regions
RES	Resource using extraction sectors: coal (COL), crude oil (CRU), gas (GAS), other extraction (EXT), other minerals (OMN)
NRG	Energy goods: coal (COL), crude oil (CRU), gas (GAS), refined oil products (OIL), and electricity (ELE)
F	Factors: skilled (SL) and unskilled (UL) labor, capital (K) and resource (R)
IPE	Sectors with industrial process emissions: I_S, CRP and NMM
HH	Private household
GOV	Government

Table A- 2 Activity Variables

Y_{ir}	Production of sector *i* in region *r*
G_{ir}	Armington aggregate of good *i* in region *r*
M_{ir}	Material composite for good *i* in region *r*
IM_{ir}	Aggregate imports of good *i* in region *r*
T	International transport
E_{ir}	Energy aggregate for good *i* in region *r*
LK_{ir}	Labor-capital aggregate for good *i* in region *r*
SU_{ir}	Skilled-unskilled labor aggregatefor good *i* in region *r*
WHH_r	Welfare of household in region *r*
EHH_r	Energy composite in household consumption in region *r*
MHH_{ir}	Material composite for private consumption in region *r*
$WGOV_r$	Welfare due to public goods provision in region *r*

Table A- 3 Benchmark activity variables

$\overline{\mathrm{Y}}_{ir}$	Benchmark production of sector *i* in region *r*
$\overline{\mathrm{G}}_{ir}$	Benchmark Armington aggregate of good *i* in region *r*
$\overline{\mathrm{M}}_{ir}$	Benchmark material composite for good *i* in region *r*
$\overline{\mathrm{IM}}_{ir}$	Benchmark aggregate imports of good *i* in region *r*
$\overline{\mathrm{T}}$	Benchmark international transport
$\overline{\mathrm{E}}_{ir}$	Benchmark energy aggregate for good *i* in region *r*
$\overline{\mathrm{LK}}_{ir}$	Benchmark labor-capital aggregate for good *i* in region *r*
$\overline{\mathrm{SU}}_{ir}$	Benchmark Skilled-unskilled labor aggregatefor good *i* in region *r*
$\overline{\mathrm{WHH}}_r$	Benchmark welfare of household in region *r*
$\overline{\mathrm{EHH}}_r$	Benchmark aggregate energy household consumption in region *r*
$\overline{\mathrm{MHH}}_{ir}$	Benchmark material composite for private consumption in region *r*
$\overline{\mathrm{WGOV}}_r$	Benchmark welfare due to public goods provision in region *r*

Table A- 4 Benchmark cost

$\bar{\mathrm{C}}^{\mathrm{Y}}_{\mathrm{ir}}$	Benchmark cost of item *i* in production activity Y_{ir} in region *r*
$\bar{\mathrm{C}}^{\mathrm{G}}_{\mathrm{ir}}$	Benchmark cost of item *i* in production activity G_{ir} in region *r*
$\bar{\mathrm{C}}^{\mathrm{M}}_{\mathrm{ir}}$	Benchmark cost of item *i* in production activity M_{ir} in region *r*
$\bar{\mathrm{C}}^{\mathrm{IM}}_{\mathrm{ir}}$	Benchmark cost of item *i* in production activity IM_{ir} in region *r*
$\bar{\mathrm{C}}^{\mathrm{T}}$	Benchmark cost of international transport
$\bar{\mathrm{C}}^{\mathrm{E}}_{\mathrm{ir}}$	Benchmark cost of item *i* in production activity E_{ir} in region *r*
$\bar{\mathrm{C}}^{\mathrm{LK}}_{\mathrm{ir}}$	Benchmark cost of item *i* in production activity LK_{ir} in region *r*
$\bar{\mathrm{C}}^{\mathrm{SU}}_{\mathrm{ir}}$	Benchmark cost of item *i* in production activity SU_{ir} in region *r*
$\bar{\mathrm{C}}^{\mathrm{WHH}}_{\mathrm{r}}$	Benchmark cost of WHH_r in region *r*
$\bar{\mathrm{C}}^{\mathrm{WGOV}}_{\mathrm{r}}$	Benchmark cost of $WGOV_r$ in region *r*
$\bar{\mathrm{C}}^{\mathrm{EHH}}_{\mathrm{r}}$	Benchmark cost of EHH_r in region *r*
$\bar{\mathrm{C}}^{MHH}_{r}$	Benchmark cost of MHH_r in region *r*

Table A- 5 Price variables

p^{D}_{ir}	Price of domestic goods of item *i* in region *r*
p^{G}_{ir}	Price of Armington good *i* in region *r*
p^{M}_{ir}	Price of material composite for good *i* in region *r*
p^{IM}_{ir}	Price of imports of item *i* in region *r*
p^{CO}_{r}	Carbon value in region *r*
p^{E}_{ir}	Price of energy composite of item *i* in region *r*
p^{LK}_{ir}	Price of value-added aggregate of item *i* in region *r*
p^{SU}_{ir}	Price of skilled-unskilled labor aggregate of item *i* in region *r*
p^{T}	Price of international transport services
p^{WHH}_{r}	Price of households' welfare in region *r*
p^{EHH}_{r}	Price of aggregate energy household consumption in region *r*
p^{MHH}_{r}	Price of material aggregate in household consumption in region *r*
p^{WGOV}_{r}	Price of public goods provision in region *r*
ω^{S}_{r}	Wage rate for skilled labor in region *r*
ω^{U}_{r}	Wage rate for unskilled labor in region *r*
υ_{ir}	Rent of resources in region *r* ($i \in FF$)
ν_{r}	Rental rate (price of capital services) region *r*

Table A- 6 Benchmark price variables

$\bar{p}_{ir}^{D}$	Benchmark price of domestic goods of item *i* in region *r*
$\bar{p}_{ir}^{G}$	Benchmark price of Armington good *i* in region *r*
$\bar{p}_{ir}^{M}$	Benchmark price of material composite for good *i* in region *r*
$\bar{p}_{ir}^{IM}$	Benchmark price of imports of item *i* in region *r*
$\bar{p}_{r}^{CO}$	Benchmark carbon value in region *r*
$\bar{p}_{ir}^{E}$	Benchmark price of energy composite of item *i* in region *r*
$\bar{p}_{ir}^{LK}$	Benchmark price of value-added aggregate of item *i* in region *r*
$\bar{p}_{ir}^{SU}$	Benchmark price of skilled-unskilled labor aggregate of item *i* in region *r*
$\bar{p}^{T}$	Benchmark price of international transport services
$\bar{p}_{r}^{WHH}$	Benchmark price of households' welfare in region *r*
$\bar{p}_{r}^{EHH}$	Benchmark price of aggregate energy household consumption in region *r*
$\bar{p}_{r}^{MHH}$	Benchmark price of material aggregate in household consumption in region *r*
$\bar{p}_{r}^{WGOV}$	Benchmark price of public goods provision in region *r*
$\bar{\omega}_{r}^{S}$	Benchmark wage rate for skilled labor in region *r*
$\bar{\omega}_{r}^{U}$	Benchmark wage rate for unskilled labor in region *r*
$\bar{\upsilon}_{ir}$	Benchmark rent of resources in region *r* (*i* $\in$ *FF*)
$\bar{\nu}_{r}$	Benchmark rental rate (price of capital services) region *r*

Table A- 7 Endowments

$\overline{SL_r}$	Aggregate skilled labor endowment for region *r*
$\overline{UL_r}$	Aggregate unskilled labor endowment for region *r*
$\overline{K_r}$	Aggregate capital endowment for region *r*
$\overline{R_{ir}}$	Endowment of resource *i* for region *r* (i $\in$ FF)
$\overline{CO_r}$	Carbon emission allowances in region *r*
$\overline{B_r}$	Initial balance of payment surplus or deficit (note: $\sum_r B_r = 0$)

Table A- 8 Taxes

$\bar{t}_{r}^{F}$	Exogenous factor tax in region *r*; F $\in$ {SL, UL, K, R}
$\bar{t}_{ir}^{C,j}$	Exogenous commodity tax on item *j* in production of good *i* in region r
$\bar{t}_{ir}^{CHH}$	Exogenous commodity tax on item *i* in private consumption in region r
$\bar{t}_{ir}^{CGOV}$	Exogenous commodity tax on item *i* in public consumption in region r
$\bar{t}_{isr}^{IM}$	Exogenous import tax on item *i* from region *s* to region *r*
$\bar{t}_{irs}^{X}$	Exogenous export tax on item *i* from region *r* to region *s*
$\bar{t}_{ir}^{D}$	Exogenous domestic output tax on item *i* in region *r*

Table A- 9 Cost and output shares

θ_{ir}^{ME}	Cost share of energy composite in production of item *i* in region *r*
θ_{jir}^{M}	Cost share of material input *j* in the material composite for item *i* in region *r*
θ_{ir}^{ELK}	Cost share of value added in the aggregate of energy and value added of item *i* in region *r*
θ_{ir}^{LK}	Cost share of capital within the value added of good *i* in region *r*
θ_{ir}^{SU}	Cost share of skilled labor within the labor value added of good *i* in region *r*
$\theta_{ir}^{EN,1}$	Cost share of electricity in the energy aggregate of good *i* in region *r*
$\theta_{ir}^{EN,2}$	Cost share of the composite of oil and gas in the energy aggregate of good *i* in region *r*
θ_{ir}^{FF}	Cost share of coal in the aggregate of coal and oil and gas of good *i* in region *r*
θ_{ir}^{OG}	Cost share of oil within the composite of oil and gas of good *i* in region *r*
$\theta_{r}^{FOS,1}$	Cost share of coal within the composite of coal-crude oil-refined oil products in the production of refined oil products (OIL) in region *r*
$\theta_{r}^{FOS,2}$	Cost share of crude oil within the composite of coal-crude oil-refined oil products in the production of refined oil products (OIL) in region *r*
θ_{ir}^{IPE}	Cost share of industrial process CO_2 emissions in the production of good *i* (i $\in$ IPE) in region *r*
θ_{ir}^{COL}	Cost share of *coal* intermediate input within the coal – CO2 composite of good *i* in region *r*
θ_{ir}^{CRU}	Cost share of *crude oil* intermediate input within the coal – CO2 composite of good *i* in region *r*
θ_{ir}^{GAS}	Cost share of *gas* intermediate input within the coal – CO2 composite of good *i* in region *r*
θ_{ir}^{OIL}	Cost share of *petroleum and oil products* in the energy aggregate of good *i* in region *r*
$\theta_{ir}^{CO,COL}$	Cost share of *CO2 emission* within the coal – CO2 composite of good *i* in region *r*
$\theta_{ir}^{CO,CRU}$	Cost share of *CO2 emission* within the crude oil – CO2 composite of good *i* in region *r*
$\theta_{ir}^{CO,GAS}$	Cost share of *CO2 emission* input within the gas – CO2 composite of good *i* in region *r*
$\theta_{ir}^{CO,OIL}$	Cost share of *CO2 emission* input within the petroleum and oil products – CO2 composite of good *i* in region *r*
θ_{ir}^{RES}	Cost share of resources in the resource using production of of good *i* in region *r*
θ_{ir}^{A}	Cost share of imports in the Armington item *i* in region *r*
θ_{isr}^{IMR}	Cost share of import and transport composite of good i from region s to region r
θ_{isr}^{GROW}	Cost share of imports in the import and transport composite of good *i* from region s to region *r*

θ^{TR}_{isr}	Cost share of transport in the import and transport composite of good *i* from region *s* to region $r \in ROW$
θ^{T}_{r}	Cost share of transport services of region *r* within the interregional transport composite
θ^{WHH}_{r}	Cost share of material aggregate in demand of households in region *r*
θ^{MHH}_{ir}	Cost share of material input *i* in the material composite for household consumption in region *r*
$\theta^{EHH,1}_{HH,r}$	Cost share of electricity in the household energy consumption aggregate in region *r*
$\theta^{EHH,2}_{HH,r}$	Cost share of the gas-oil-coal composite in the household energy consumption aggregate in region *r*
$\theta^{PET,1}_{HH,r}$	Cost share of coal in the gas-oil-coal composite within the household energy consumption aggregate in region *r*
$\theta^{PET,2}_{HH,r}$	Cost share of oil in the gas-oil-coal composite within the household energy consumption aggregate in region *r*
$\theta^{COL}_{HH,r}$	Cost share of *coal* intermediate input within the coal – CO_2 composite of household energy consumption in region *r*
$\theta^{CRU}_{HH,r}$	Cost share of *crude oil* intermediate input within the coal – CO_2 composite of household energy consumption in region *r*
$\theta^{CRU}_{HH,r}$	Cost share of *crude oil* intermediate input within the coal – CO_2 composite of household energy consumption in region *r*
$\theta^{OIL}_{HH,r}$	Cost share of *refined oil products* intermediate input within the coal – CO_2 composite of household energy consumption in region *r*
$\theta^{CO,COL}_{HH,r}$	Cost share of *CO_2 emission* within the coal – CO_2 composite of household energy consumption in region *r*
$\theta^{CO,CRU}_{HH,r}$	Cost share of *CO_2 emission* within the crude oil – CO_2 composite of household energy consumption in region *r*
$\theta^{CO,GAS}_{HH,r}$	Cost share of *CO_2 emission* input within the gas – CO_2 composite of household energy consumption in region *r*
$\theta^{CO,OIL}_{HH,r}$	Cost share of *CO_2 emission* within the refined oil products – CO_2 composite of household energy consumption in region *r*
θ^{MGOV}_{ir}	Cost share of material input *i* in the material composite for public consumption in region *r*

Table A- 10 Elasticities

σ_i^{LK}	Substitution between labor and capital in the value added nest in the production of item *i*
σ_i^{SU}	Substitution between skilled and unskilled labor in the labor value added nest in the production of item *i*
σ_i^{ELK}	Substitution between energy composite and value added nest in the production of item *i*
σ_i^{ME}	Substitution between energy and value added composite and intermediate material aggregate in the production of item *i*
σ_i^{M}	Substitution between material inputs *j* (with $j \neq NRG$) within the material composite in the production of item *i*
σ_i^{ELEC}	Substitution at the top nesting level of the energy aggregate between electricity – coal, crude oil, and gas – petroleum and oil products in the production of item *i*
σ_i^{ELECL}	Substitution between coal and oil and gas nesting within the energy aggregate in the production of item *i*
σ_i^{ELEQD}	Substitution between oil and gas within the energy aggregate in the production of item *i*
σ^{FOS}	Substitution between oil, crude oil, and refined oil products in the production of refined oil products (OIL)
σ_i^{A}	Armington elasticity: Substitution between the import composite and the domestic production of good *i*
σ_i^{IMR}	Substitution between imports from different regions within the import composite for item *i* in region $r \in ROW$
σ_r^{WHH}	Substitution between material aggregate and energy composite in the consumption of households in region *r*
σ_r^{MHH}	Substitution between material inputs *i* (with $i \neq NRG$) within the material composite in household consumption in region *r*
σ_r^{EHH}	Substitution between electricity, and the coal-oil-gas composite in the energy consumption of households in region *r*
σ_r^{MGOV}	Substitution between inputs *i* in public consumption in region *r*
σ_r^{PETHH}	Substitution between coal, oil and gas within the coal-oil-gas composite in the energy consumption of households in region *r*

Table A- 11 Value of elasticities in production of domestic goods

Sector	σ_i^{ME}	σ_i^{M}	σ_i^{ELK}	σ_i^{LK}	$\sigma_i^{ELEC}*$	$\sigma_i^{ELECL}*$	$\sigma_i^{ELEQD}*$
CRU	0.73	0.31	0.55	0.14	0.16	0.07	0.25
COL	0.73	0.31	0.55	0.14	0.16	0.07	0.25
GAS	0.73	0.31	0.55	0.14	0.16	0.07	0.25
EXT	0.73	0.31	0.55	0.14	0.16	0.07	0.25
OMN	0.73	0.31	0.55	0.14	0.16	0.07	0.25
OIL	0.00	0.39	0.26	0.46	0.16	0.07	0.25
ELE	0.00	0.39	0.26	0.46	0.16	0.07	0.25
NFM	1.17	0.25	0.66	0.22	0.16	0.07	0.25
I_S	1.17	0.25	0.66	0.22	0.16	0.07	0.25
NMM	0.31	0.19	0.41	0.36	0.16	0.07	0.25
CRP	0.85	0.08	0.00	0.33	0.16	0.07	0.25
TRN	0.35	0.33	0.28	0.30	0.16	0.07	0.25
AOG	0.58	0.11	0.48	0.21	0.16	0.07	0.25
Final Demand	1.00	1.00	-	-	0.50	1.00	-

Source: Okagawa and Ban (2008), *Beckman and Hertel (2009); ** Narayanan and Walmsley (2008)

Table A- 12 Armington elasticities and elasticities between imports from different regions of origin

Sector	σ_i^A	σ_i^{IMR}
CRU	5.2	10.4
COL	3.1	6.1
GAS	10.8	32.4
EXT	1.9	3.6
OMN	0.9	1.8
OIL	2.1	4.2
ELE	0[1]	5.6
NFM	4.2	8.4
I_S	3.0	5.9
NMM	2.9	5.8
CRP	3.3	6.6
TRN	1.9	3.8
AOG	2.4	6.5

Source: Narayanan and Walmsley (2008)

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[1] For sector ELE we deviate from the GTAP elasticities and set the value to zero in order to rule out unrealistic trade relationships in the electricity sector.