The relevance of carbon free production processes for carbon leakage and carbon border adjustment

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December 2012

Abstract: Climate policy arrangements of partial regional coverage, as they seem to emerge from the UNFCCC process, might lead to carbon leakage and hence a broad literature has developed to quantify global leakage rates. While most of these analyses, are confined to consider combustion emissions only, Bednar-Friedl et al. (2012b) have pointed out the particular relevance of process emissions for both leakage rates and effectiveness of border carbon adjustment. We use this expanded framework in considering both combustion and process emissions in a multi-sectoral multi-regional Computable General Equilibrium model and analyze the implications of carbon free process innovations. As a medium-term alternative to border carbon adjustment, we find that such a technological switch, for example in the European steel industry towards low-carbon electrowinning, can effectively reduce global carbon leakage. For border carbon adjustment considerations this implies their setting including a phase-out, such that incentives for carbon free innovations are preserved.

Key Words: carbon leakage, embodied carbon, border tariffs, process emissions, carbon free production

JEL: Q54, D58, H2, O3

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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 reduced environmental effectiveness (carbon leakage) and possible compensatory policies has gained prominence. 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 CGE models, but resulted generally in comparatively low leakage rates. We have argued in Bednar-Friedl et al. (2012b), that one reason that led to these low leakage rates is that most of these quantitative analyses are confined to consider combustion emissions only, most often based on International Energy Agency (IEA) data, as comprised for example in the GTAP data base.

However, some of the most simultaneously energy intensive and internationally trade exposed sectors are also subject to substantial process emissions, i.e. non combustion-related emissions. For example, in the steel and cement sectors of many countries process emissions account for roughly half of sector carbon emissions (UNFCCC, 2011). In addition to the substantial role of process emissions particularly in some leakage-prone sectors mitigation of process emissions can only be achieved by switching production process, if low-carbon ones are available, or by reducing activity. Thus, while combustion based emissions can be reduced by increasing energy efficiency, reduction of process based emissions basically requires a switch in production technology, often not readily available at reasonable costs.

As a consequence, for avoiding process emissions, carbon free innovation is crucial. We here test for the implications of successful carbon free innovation on both leakage and carbon border adjustment rates.

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, which, however, excludes process emissions. Since industrial process emissions are crucial in core sectors that are prone of leakage and competitiveness concerns, we use and expanded analysis acknowledging industrial process emissions.

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). Third, any price change of fossil fuels relative to other, especially non-fossil-(or GHG-)intensive goods implies a shift in 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). 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. it 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. 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). In the present paper, we focus on the effectiveness of such border carbon adjustment (BCA) measures and whether a correct accounting of also process emissions in their rate setting is relevant for their effectiveness.

2.2 Process emissions

The three sectors which account for almost all of process emissions (iron and steel, cement and chemicals) are all both energy intensive and trade exposed. At the global level, process emissions account for roughly 10% of GHG emissions, but in the three sectors mentioned ahead, in many countries they account for the dominant share (see Figure 3 below).

Let us first take a closer look on the nature of process emissions in each of these sectors and discuss potential technology switches for within-sector carbon substitution (see e.g. Cooper and Droege, 2011, Monjon and Quirion, 2011; for further details see section 5). 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, which is not available large scale yet and additionally raises the issue of renewable electricity production. In cement production carbon dioxide is emitted as a by-product of the intermediate cement product clinker, in which calcium carbonate ($CaCO_3$) is calcinated and converted to lime (CaCO), the primary component of cement. To date, clinker production partially has already been or is considered to be relocated outside climate policy regions, an alternative is to use clinker substitutes. 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. Substitution of chemical products is the main option for reduction. Forecasts are that the chemical sector in some countries will exhibit large increases in process emissions over the next decades (e.g. Australian Government, 2011).

In the following section, we set out the model structure, taking also account of process emissions as analyzed in this section. In section 3.2, we give a detailed empirical overview of the relevance of process emissions across world regions.

3. Model and data

3.1 Model specification

We construct a 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 Bednar-Friedl et al., 2012a).

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 (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

Aggregated Region	**Model code**
EU-27 plus EFTA	EUR
United States of America	USA
Russian Federation	RUS
Other Annex 1 except Russian Federation	RA1
China	CHN
India	IND
Energy exporting countries (excluding Mexico)	EEX
Other middle income countries	MIC
Other low income countries	LIC

Table 2: Sectoral dimension of the CGE model

Aggregated Sectors	**Model Code**
Energy intensive and trade exposed sectors	**EIT**

Iron and steel	I_S
Non-metallic mineral products	NMM
Non ferrous metals	NFM
Chemical products	CRP
Energy sectors	
Crude oil	CRU
Coal	COL
Natural gas	GAS
Refined oil products	OIL
Electricity	ELE
Other industries and services	
Other extraction	EXT
Transport aggregate (air, water, and other transport)	TRN
Other mining	OMN
All other manufactures and services	AOG
Capital goods	CGDS

Figure 1 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 two types of production activities Y_{ir} which differ slightly in their production functions: (i) resource using (primary energy) extraction sectors, and (ii) non-resource using commodity production (comprising ETS and other non-ETS sectors)[1]. 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 Figure 2 and the Appendix for diagrammatic nesting structures).

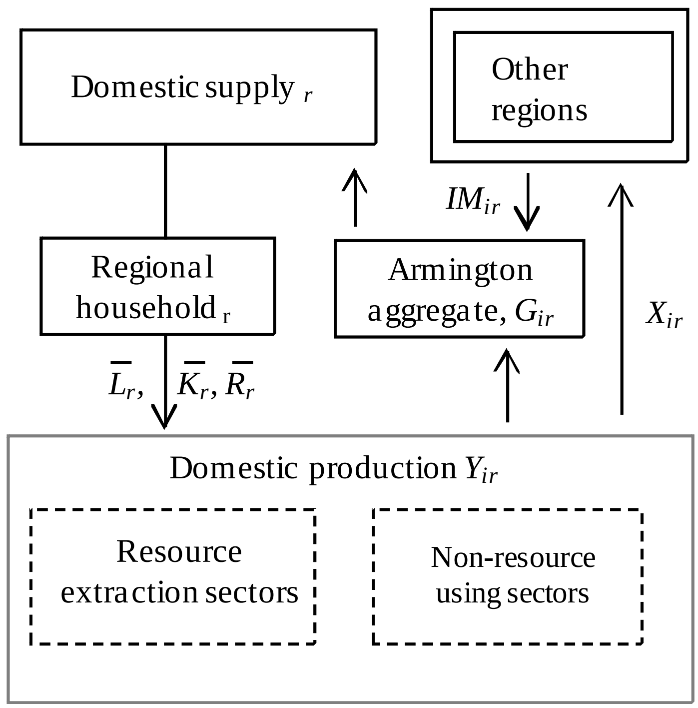


Figure 1: diagrammatic structure of the CGE model

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_{ir} as imperfect substitutes. The

[1] Finally, the production in sector OIL differs from all other non-resource using sectors, such that in this sector fossil inputs CRU, COL, and OIL are Leontief type inputs at the top nesting level to all other inputs (i.e. they are characterized by zero elasticity of substitution) such that production cannot substitute away from energy inputs (see the Appendix for the corresponding diagrammatic nesting structure).

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 X_{ir} (see Figure 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 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.

As a prerequisite for our climate policy analysis, we model CO_2 emissions as both arising in production and consumption. In three production sectors, i.e. in the I_S, CRP and the NMM sectors we also include industrial process emissions. 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 Figure 2).

Combustion CO_2 emissions are linked in fixed proportions to the use of fossil fuels differentiated by the specific carbon content of fuels (see Figure 2). In particular, fossil fuel intermediate inputs in the production process enter as fixed-coefficient composite of a carbon 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 the same way as in the production sectors.

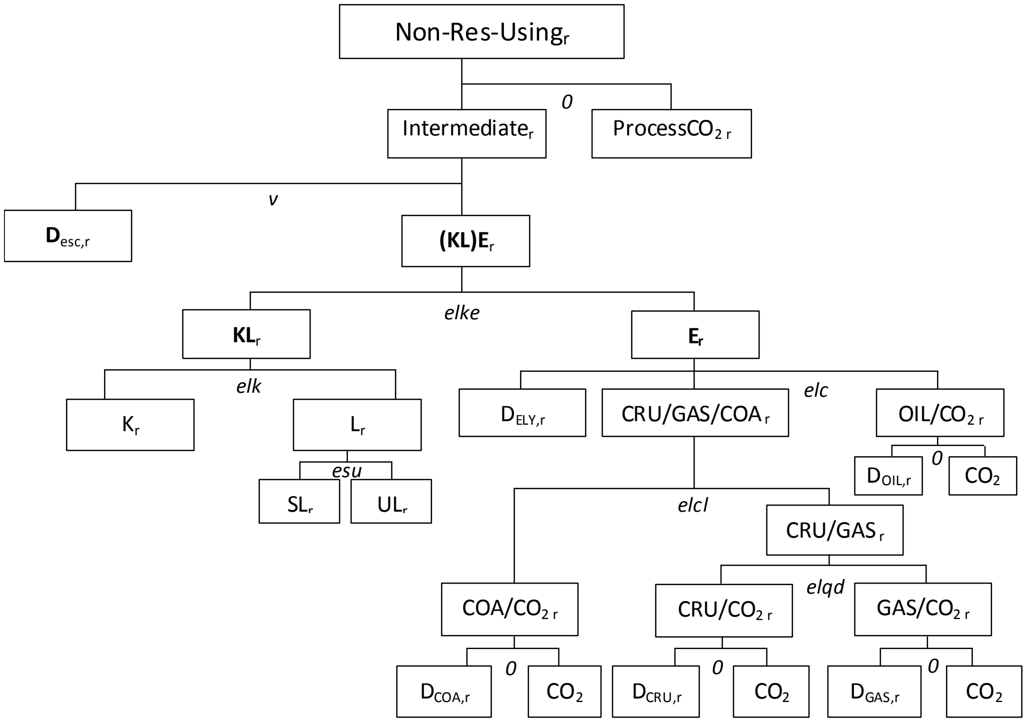


Figure 2: Nesting structure of combustion and process emissions in production

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.

3.2. 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 Figure 2).

For our analysis we use the GTAP database (GTAP 2007) 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. This data therefore is excluding some 10% of global CO_2 emissions which are related to industrial processes[2]. While 10% might seem negligible, it is not in our context of analysis, because it is 10% of global emissions originating 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.

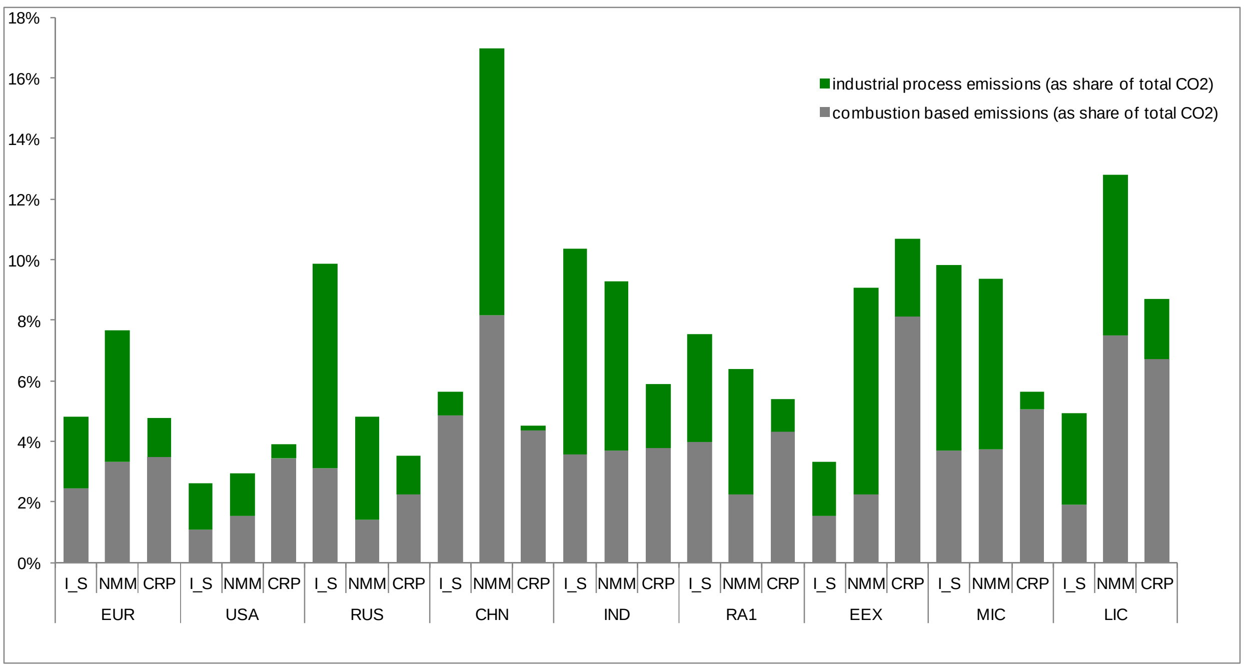
During industrial production processes which physically or chemically transform materials, different GHGs including CO_2, CH_4, N_2O, and PFCs can be released. In the present analysis however we focus solely on CO_2 related industrial process emissions. To include also these process related CO_2 emissions, which are particularly relevant for iron and steel as well as clinker production and somewhat less relevant for the chemical industry, 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 process 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 released by the three relevant sectors in 2004 as in 1994. After aggregating industrial process emissions for some 200 single countries to our model

[2] The share of industrial process emissions in total GHG emissions varies significantly across model regions. E.g. for the U.S. this share amounts to 3%, for EUR to 6%, for RUS to 10%, and for IND to 13%. 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 (UNFCCC 2011).

regions, we obtain the total amount of industrial process emissions for each model region as presented in Figure 3 (see also Table A.1 in the Appendix).

Figure 3 decomposes emissions of iron and steel (I_S), non-metallic mineral products (NMM) and chemical products (CRP), as share of total CO_2 emissions arising in total production. For Europe, 17% of total emissions are caused from these three sectors (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.

Figure 3: Combustion based and industrial process emissions for sectors I_S, NMM, and CRP (as share of total production-related emissions in 2004)



Source: own calculations based on UNFCCC (2011) and GTAP (2007).

4. The relevance of technology switches in process-emission prone sectors

In section 2.2 above we gave a first account of potential switches in technology to avoid process emissions. Let us go into more detail here, and let us also quantify within our model framework the relevance such a switch could have for the effectiveness of unilateral climate policy. Does a switch to low-carbon technology (triggered by any other means or policy) even render a BCA superfluous?

To answer this question in our empirical analysis we concentrate in the following on the iron and steel sector, to choose one of the three process-emission-relevant sectors in full detail. The principles applied carry over to the other sectors as well, but not the particular production methods that are discussed.

4.1. Options to reduce carbon process emissions

A gradient of options exists for decreasing emissions in each of the process-emission prone sectors. These are improving energy efficiency, changing of production processes, changing of the product, substitution of the product by a different product and functional replacement of a product. Improvement of energy efficiency usually does not much change the production process. But even if the production process is changed, the product might still very much stay the same, such as exemplified by the partial replacement of coal in steel production by natural gas. On the other hand, a product can be changed by the addition of suitable wastes, e.g. fly ash from the iron and steel industry, to cement. Such changes need great care so that the different product still meets the norms which are set for the established product (e.g. stability or health issues). Examples of substitution of a product are the use of aluminum instead of steel, or replacing transformers in the power sector by electronics. Functional replacement takes many forms; e.g. the replacement of letters by e-mails or more general replacement of printed papers by electronic processes. Obviously, an industrial sector can change its production process and its products but it will usually be opposed to substitution of products by other products or by functional substitution.

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. Decreasing emissions in all three sectors is complicated, as the following section demonstrates for the iron and steel sector.

4.2 Management Options for the iron and steel sector

Production of steel is usually a combined process that begins with production of pig iron, and the resulting “hot metal” (liquid iron) is immediately afterwards processed into steel in Europe mostly with the BOF, basic oxygen furnace. While production of pig iron is an endogenous process in terms of energy, the further processing of iron into steel is exogenous because here excess carbon in the pig iron is burned with oxygen. Hence, 90%-97% of CO_2 emissions result from the production of iron so that improvements in the production of steel cannot much decrease emissions of CO_2. Both IEA (IEA ETSAP 2010) and the ULCOS (Ultra Low CO_2 Steelmaking) project (Birat et al. 2008) describe production processes that allow to decrease emissions of CO_2 slightly, e.g. by use of pure oxygen instead of air or oxygen-enriched air in the prevailing "Blast Furnace" process for production of pig iron, or by the use of natural gas (minus 25% CO_2). Hence, the emphasis in the iron and steel sector is on changing processes in the production of iron. The ULCOS project has also shown that emissions of CO_2 might be decreased by up to 50% if the blast furnace process is done with pure oxygen as that allows using a method of carbon-capture-and-storage that is specific for this sector.

But even a reduction of 50% is not sufficient to meet the longer-term requirements of the EU. To achieve close to zero process emissions in iron production, three production methods have become known, the "plasma blast furnaces" which could recycle the carbon from the carbon dioxide, electrolysis, and the use of hydrogen as a reductant instead of coal (Birat et al. 2008). However, despite plasma being used already in several branches of metallurgy, it is so intensive in electricity use that its cost are much too high.

Regarding electrolysis, several groups have proven the feasibility of producing iron through electrolysis of iron oxides (Kim et al., 2011; Licht and Wang, 2010). For instance, a group around Licht proved the feasibility of electrowinning of iron oxides at 800°C where the iron oxide is dissolved in lithium carbonate (Licht and Wang, 2010). Electrowinning uses an electrolysis cell for production of the metal, here of iron, from its oxides, or chlorides or respective substances. The ULCOS group (Birat et al. 2008) has produced small amounts of iron with alkaline electrowinning, which turned out to be superior to pyroelectrolysis.

When applying the third option, using hydrogen in iron production, CO_2 results from the conversion of methane into hydrogen unless combined with carbon-capture and storage (OECD/IEA, 2006) or produced from water through electrolysis. Instead of using the electricity for production of hydrogen it seems more economical to use it for direct production of iron from its ores (electrowinning), according to results from Bossel (2006).

As a consequence, we give calculations for electrowinning in the following. If hydrogen becomes more economic it has to fall below the costs anticipated here.

4.3 Electrowinning in pig iron production

Table 3 illustrates the cost structures of electrowinning (EW) versus BOF. Whereas BOF needs iron ore, coking coal and steel scrap, the EW needs iron ore and electricity (for the reduction of the iron ore). According to Lavelaine and Allanore (2009), 2.05 MWh are necessary for electrolysis to produce 1 t of iron. The most efficient steel-making (with coal) needs 14.5 GJ per ton, or 4 MWh (Beer et al. 1998); the present value is at 18 GJ/t steel (Birat et al. 2008). EW will not be able to achieve the theoretical minimum of 2.05 MWh, but if it operates at 120°C instead of the ~1500° of the BOF process it will operate more efficient than the BOF. For EW, we thus calculate costs with 3 MWh/ t steel or an efficiency of 68%. With electricity costs of $100/MWh (Steel Industry News, 2012) $300 /t of steel for electricity costs arise for EW. We assume that all other costs, for depreciation, capital, labor etc. are the same for both processes and that costs of operation of both processes are also the same, with the exception of revenues from thermal energy and by-products which emerge in BOF but not in EW.

Table 3: Production costs of steel: electrowinning versus BOF process

	Actual Costs (2010)		Scenario (higher coal price, solar electricity for electrolysis)	
	BOF	Electro-winning	BOF	Electro-winning
Iron ore	178	178	178	178
Coking coal	104		**114**	
Steel scrap	53		53	
Transport (iron ore, coking coal, scrap delivery)	40	29	40	29
Electricity	12	300	12	**134**
Other operating costs (chemicals, revenues from by-products and thermal energy)	23	80	23	80
Labour	18	18	18	18
Capital expenses	106	106	106	106
Total	534	710	544	544

Source: Steel Industry News (2012); IEA ETSAP (2010)

Clearly, in this calculation at current prices, steel from EW would cost $710/t whereas steel from BOF, according to Steel Industry News (2012) costs $534/t. However, at lower electricity costs for EW, around $40/MWh, costs of the two processes would be almost the same ($534 vs $530 per t).

Regarding the feasibility of lower electricity costs, we investigate the cost of solar electricity since a necessary precondition for electrolysis leading to close to zero emissions in pig iron production is that electricity is produced from renewables. Due to the continuing very rapid decrease of costs for photovoltaic panels, electricity from solar has achieved grid parity in some countries (in Italy (Pew Charitable Trusts, 2011), in parts of California, Hawaii and Spain (Breyer et al. 2009, 2010; Zaman and Lockman, 2011). Using cost estimates for solar electricity from Grossmann et al. (2012a, 2012b), yields cost ranges of US$ 59 to 73 per MWh in 2030 and US$ 34 to 42 in 2040. For our scenario analysis, we furthermore assume slightly higher coal prices (+10%) which increases costs for BOF. As a final step, we calculate the decrease in the electricity price used in EW which is necessary to achieve cost equality across BOF and EW (see the two last columns in Table 3). This price is $ 44.6/MWh.

4.4 Overall implications for a switch to electrowinning production in EU iron and steel production

We employ the electrowinning technology for pig iron production in the EU (but not in other countries) in our CGE model framework to test for the implications of such a technology switch for leakage and economic impacts. This is a cautious estimate as EW would give iron without carbon so that it does not need further processing with the BOF or EAF processes but can instead immediately be alloyed to become steel. Avoiding these common processes for making steel would further decrease costs so that our analysis is conservative. We remain with the comparative static analysis for the year of model calibration, i.e. 2004, thus assuming an equivalent production cost between the current (BOF) and EW production process, with renewable electricity production (solar) for the EW process within EU. As a consequence, EW has relatively higher costs in electricity, non-ferrous metal products (NFM), chemical products (CRP), transport (TRN) and lower ones in all other goods (AOG) and labor (for details on sectoral cost structures , see Table A.2 in the Appendix).

When iron becomes available at equivalent production costs from electrowinning, unilateral climate policy indeed has different implications. Note, that we do assume availability of a carbon-free production process in only one of the emission intensive sectors, iron and steel, and only in the EU since other regions have lower incentives to switch to a low carbon technology. Nevertheless, with results shown in Table 4, the overall leakage rate of unilateral EU policy (i.e. the above reference scenario of 20% global emission reduction, without BCA) declines from the earlier 38% to 29%. In the iron and steel sector itself, the sectoral leakage rate declines from 185% (emission intensity in iron and steel is significantly higher in non-coalition) to only 13%. Reduced emission from iron and steel production are also reflected in a sharp decline in the carbon permit price, from 157 US$/t to 97$.

Table 4: Environmental and economic indicators for unilateral EU policy both reference and with BCA (tariff with revenues collected by importers), with and without electrowinning production process in iron and steel, results for EU

	ref	ref_with EW	BCA (tariff_importer)	BCA (tariff_importer)_with EW
environmental indicators for EU				
CO_2 permit price (US$/t)	156.60	96.55	107.45	71.65
Leakage rate (%)	38.42	29.0	20.94	15.8
Sector leakage rate (I_S) (%)	185.0	13.26	-2.8	-12.14
welfare indicators in EU relative to BAU				
Hicksian Equivalent Variation (%)	-1.71%	-0.94%	-0.99%	-0.63%
change in GDP (%)	-1.54%	-0.89%	-1.01%	-0.58%
sectoral output change in EU relative to BAU (%)				
EITE	-9.93%	-5.57%	-3.65%	-1.89%
EIT	-8.32%	-4.36%	-2.33%	-0.89%
AOG	-0.35%	-0.16%	-0.43%	-0.28%

We find, that even without BCA measures, the simple availability of low-carbon technology in one emission intensive and trade exposed sector of the EU, implies a reduction in welfare burden (the Hicksian equivalent variation is 0.94%, rather than 1.71% without this technology available). Sectoral output losses in the energy intensive sectors (the aggregate of all of them) are roughly half, when electrowinning has become available.

6. Conclusions

We find that any breakthrough in the development of carbon-free (or low-carbon) technologies in process-intensive sectors, such as electrowinning for the iron and steel sector, allows for unilateral climate policy with a significantly lower overall leakage rate. For the example of just the electrowinning technology available for the iron and steel sector leakage for unilateral EU climate policy is reduced from 38% to 29%, rendering BCA less relevant.

Political pressure as well as pressure from the general public have created an atmosphere that facilitates and promotes change for decreasing emissions of GHGs. The iron and steel sector – as we have exemplified our analysis of technological switches for – might benefit in developed countries from such pathways, although it requires breakthrough changes, which sound good in theory but are often blocked at some level in companies (there is a long list of examples which is outside the scope of this article). Disruptive innovation, such as use of electrolysis for steel-making, if it becomes possible through solar electricity at competitive rates, even if enforced by law, might benefit the industry, as the use of electricity has been increasing anyway and for a long time throughout most branches of metallurgy, because processes that use electricity often allow a far superior quality of products. Such breakthrough in technological development – as we show in quantitative terms – renders BCA significantly less relevant.

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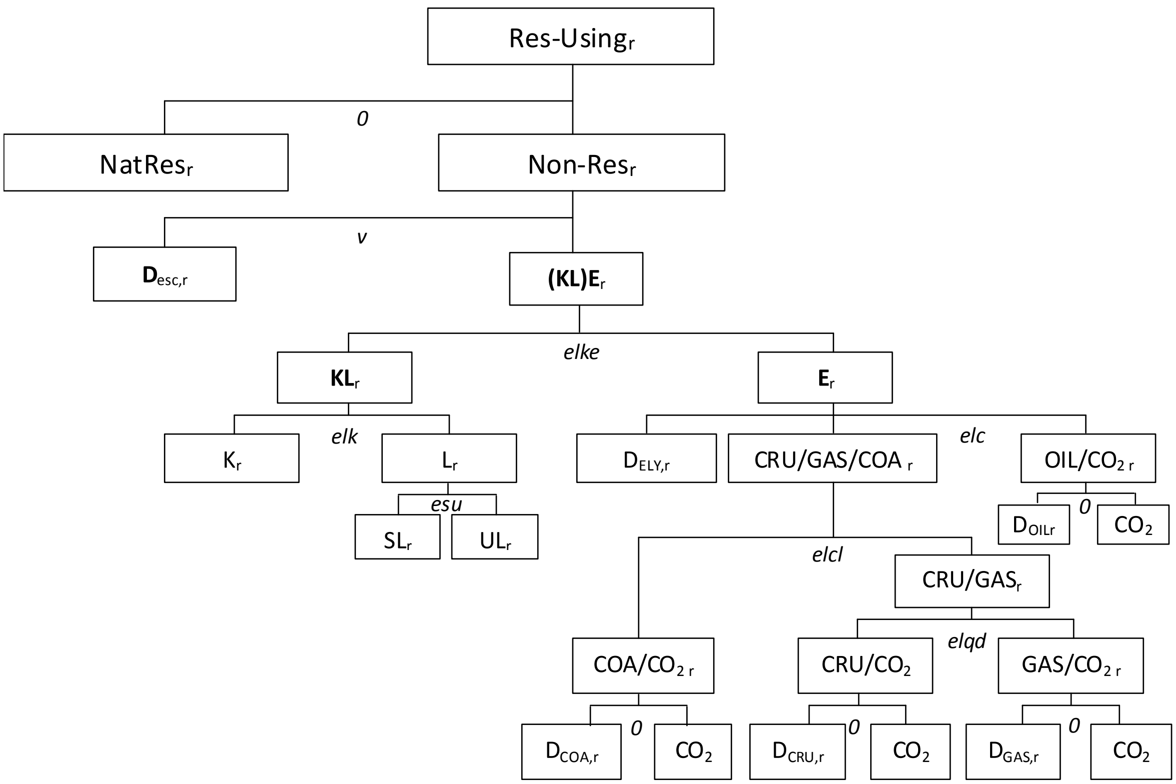
Appendix

Nesting structure of resource using extraction processes



Nesting structure of OIL sector

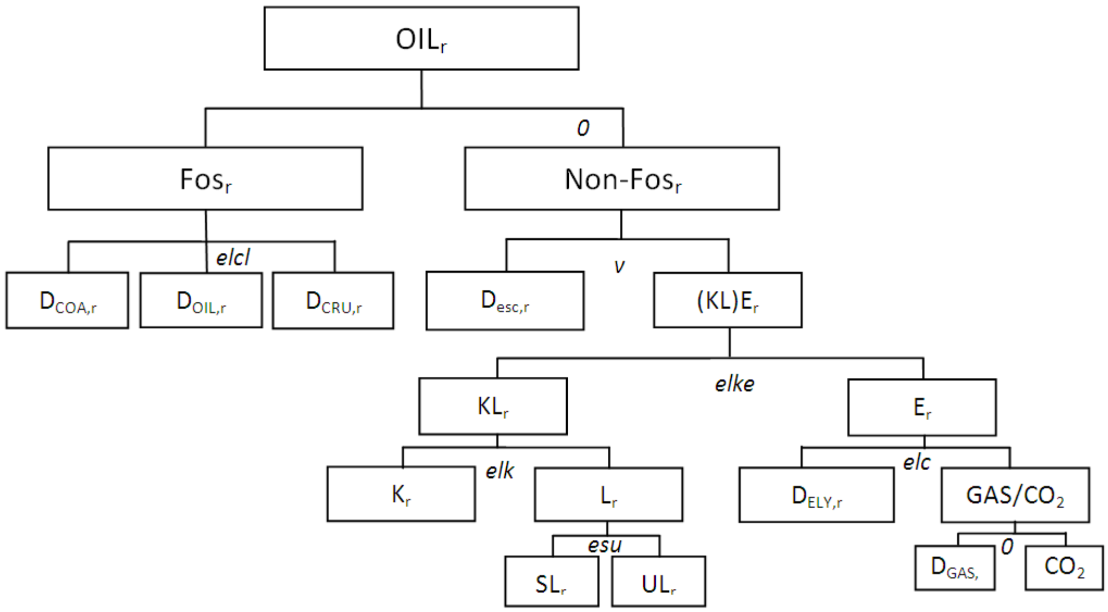


Table A.1: Industrial process emissions as share of sectoral CO_2 emissions across regions (2004)

	IPE as share of sectoral CO_2		
	I_S	NMM	CRP
EUR	49%	57%	27%
USA	58%	48%	12%
RUS	69%	70%	36%
CHN	14%	52%	3%
IND	65%	60%	36%
RA1	47%	65%	20%
EEX	53%	75%	24%
MIC	62%	60%	10%
LIC	61%	42%	23%

Source: UNFCCC (2011) and GTAP (2008)

Table A.2: Relative cost structures for electrowinning and electricity production (solar vs. conventional)

	I_S_EUR (GTAP)	I_S_EUR_Ewin	ELE_EUR (GTAP)	ELE_EUR_PV
CRU	0%	0%	0%	0%
COL	0%	0%	6%	0%
GAS	1%	0%	5%	0%
EXT	0%	0%	0%	0%
OMN	3%	0%	1%	1%
OIL	4%	0%	4%	0%
ELE	6%	26%	5%	5%
NFM	2%	4%	0%	0%
I_S	25%	31%	0%	0%
NMM	2%	0%	0%	3%
CRP	3%	10%	1%	4%
TRN	4%	5%	2%	2%
AOG	29%	0%	24%	24%
CGDS	0%	0%	0%	0%
Unskilled Labor	10%	3%	9%	13%
Skilled Labor	4%	1%	11%	15%
Capital (depreciation)	7%	19%	31%	33%
Total costs	100%	100%	100%	100%