Taxing Carbon along the Value Chain.

A WIOD CGE Application

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Abstract: In this paper we examine global carbon supply chains and assess the effects of tariffs on embodied carbon in a computable general equilibrium framework. Thereby, we take advantage of the comprehensive representation of international trade flows in the new World Input-Output (WIOD) dataset and specifically adjust the value of due embodied carbon tariffs accordingly. Hence we account for a potential overlap in regulation, if intermediate inputs are taxed multiple times along the supply chain of a product due to environmentally motivated trade policy. Carbon is added at numerous stages during the production of a good and even though domestic inputs dominate, especially in energy and trade intensive non-domestic carbon input is significant. Building on this insight, we show that compared to a simplistic Border Tax Adjustment (BTA) approach, taxing all embodied carbon in imports, accounting for the origin of carbon in the production process reduces economic distortions and decreases the social cost of a BTA regime accompanying unilateral climate policy.

Keywords: carbon leakage, embodied carbon, border taxes, global value chains

JEL Classification: Q43, Q54, H2, D61

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1. Introduction

As the outcome of the recent UN conference in Durban on climate change by end of the year 2011 has revealed, the international community has still a long way to go reach a global agreement to reduce greenhouse gas (GHG) emissions. The withdrawal of Canada and Japan from the Kyoto Agreement indicates that even the already established “coalition of the willing” is not stable. This leads to an increasing frustration of countries which take the view that a comprehensive regulation of GHG emissions is urgently necessary.

Therefore, the idea to add trade measures as an additional instrument to the climate policy tool box has gained influential supporters. One rationale can be found in the fact that the regulation of GHG emissions may raise production costs and prices of carbon-intensive goods, endangering international competitiveness of carbon-intensive producers from regulated countries. Furthermore, this price increase might be an incentive for producers of carbon-intensive goods in unregulated countries to extend the production of carbon-intensive goods and hence increase emissions, counteracting the abatement efforts by the regulating countries[2].

Several studies estimated the size of this so called carbon leakage problem *ex ante* with computable general equilibrium (CGE) models. Carbon leakage is typically measured as the emission increase in non-regulated countries relative to the emission reduction in the regulated ones. The fourth assessment report by the IPCC (IPCC, 2007) resumes that the range of these estimation studies is large and uncertainties are high. Most studies conclude that the efforts of Annex B countries, which have committed to reduce GHG emissions under the Kyoto Protocol, cause a carbon leakage of 5% to 20% in Non-Annex B countries. Since the Kyoto Protocol is operational since 2005, enough data is now available to conduct also an *ex post* econometric evaluation of this effect. In a recent study, Aichele and Felbermayr (2011) measure an 8% increase of trade in embodied carbon from countries not committed under the Kyoto Protocol to such with a binding commitment, which gives evidence that indeed Kyoto has led to leakage.

Several studies examined the carbon content of internationally traded goods and showed that almost one-quarter of emitted carbon dioxide is embodied in internationally traded goods and services (e.g. Peters and Hertwich, 2008; Peters and Hertwich, 2009). There is also a clear direction in the flow of embodied carbon: Most industrialized countries where net importers of emissions, whereas most developing countries are net exporters. As shown by a recent study by Peters et al. (2011) the amount of traded carbon emissions embodied in goods and services in increased substantially in the recent

[2] Additionally, abatement policies lead to a decrease in demand for fossil fuels in the regulated countries. This depresses the world market prices of these commodities and thus increases demand in non-regulating countries. *(Most studies indicate that this channel is actually the more important one!! Wird aber auch von BTA nicht addressiert. Dieses Argument müssen wir weiter vorne wieder aufnehmen.)*

past.. Net emission transfers via international trade in goods from developing to developed countries increased from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008. 11% of the growth in global CO_2 emissions can be attributed to the consumption in Annex B countries (while the production of emissions actually decreased in the Annex B countries by 3%).

As an approach to overcome this problem, trade policy instruments such as border tax adjustments (BTA) came into the debate, for example in the European Union (see e.g. Alexeeva-Talebi et al., 2008) . Such a border measure could materialize as a tax on imported carbon-intensive products or a requirement for the exporting country to buy domestic emission permits to offset the carbon emissions coupled with the production of the imported good.

Overall, BTA aims at counteracting the negative competitiveness effects of GHG abatement policies by levelling the playing field between domestic and foreign producers. In his seminal paper, Markusen (1975) studies the use of border measures on environmental problems and shows that import tariffs are part of the optimal policy set for trans-boundary pollution problems. Copeland (1996) generalizes this work for variable abatement technologies. He concludes that the country affected by the negative externality should levy a tariff, which varies with the pollution content of the imports.

Hence, as these studies on trade in embodied carbon indicate, the sole regulation of emissions directly attributed in Annex B regions is not sufficient to tackle the emission problem. Tariffs on embodied carbon may raise the effectiveness of subglobal climate policies and extend the reach of these policies. Böhringer et al. (2011) show with a multi-regional general equilibrium model at hand that the implementation of import tariffs on embodied carbon can reduce emissions in non-abating countries. And in addition, such a policy may lead to dramatic shift in the burden of climate policy from coalition to non-coalition members.

However, the period following World War II did not only go along with more trade in final goods and the respective increasing amount of embodied carbon. In the last several decades an increasing interconnectedness of production processes in a vertical trading chain that stretches across many countries, with each country specializing in particular stares of a good's production sequences, could been observed. Hummels et al. (2001) estimated that vertical specialization[3] accounted for 21% of the exports of OECD and emerging market countries at beginning of the 1990s. International trade based on vertical specialization activities increased by almost 30% between 1970 and 1990.

This complex multi-stage production processes hamper not only the practical assessment of the carbon content of goods, it might also lead to a double taxation of some eventually already regulated carbon

[3] Vertical specialization is just one of the expressions used to describe this phenomenon. It has also been labeled as "slicing up the value chain", "outsourcing", "disintegration of production", "fragmentation", "multi-stage production", and "intra-product specialization".

dioxide. Think for example of a production process over just over two stages: An European steel works - already regulated under the EU Emission Trading Scheme (EU ETS) - exports steel to China. There the steel is assembled together with other goods to the final-good. This final good is then exported to the EU, where the EU will put at its border a tariff, based on the total embodied carbon, on the good and hence double burden steel production in the EU.

In this paper we explore the implications of a BTA regime which accounts for the origin of carbon along the supply chain of products on the basis of a multiregional computable general equilibrium model. Thereby we go beyond earlier work by Böhringer et al. (2011) and apply an import tariff which does not just depend on the overall quantity of embodied carbon of the imported good, but taxes precisely only the carbon outside the scope of any carbon regulation. To this end, we first outline our approach of computing embodied carbon and give an overview of the data we use in Section 2 and Section 3. Subsequently we give in Section 4a brief description of the carbon flows induced by production processes in Europe. In Section 5 we describe our model and in Section 7 we present the results of our counterfactual simulations. We conclude in Section 8 with a short summary and discussion of the results of our analysis.

2. Computing Embodied Carbon

In contrast to direct CO_2 emissions, the amount of carbon embodied in the output of a particular industry and its sectoral and regional origin is generally not reported directly in input-output datasets. But in order to evaluate regulations targeting on embodied carbon, concepts are necessary to measure the carbon content of a final products. This includes on the one hand direct emissions arising at the final stage of production, but also the emissions incorporated in the intermediate inputs. Peters (2008) provides a comprehensive overview of the two main approaches how direct and indirect emissions can be accounted by using input-output data, namely the emissions embodied in bilateral trade (EEBT) approach and the multi-region input-output (MRIO) approach. Peters stresses that no approach is right or wrong, they simply imply a different treatment emissions embodied from intermediates in the production process. While EEBT allocates emissions from any form of consumption, i.e. intermediate use and final demand, to the region where it takes place, MRIO accounts for the fact that a share of the goods produced using intermediates are exported and final consumption eventually occurs in a different region.

Building on our rich dataset which is described in detail in Section 3 of this paper, we follow Peters (2008) and apply a simplified MRIO approach to compute the amount of carbon embodied in the goods produced in the economy. In the following, *intermed(r,i,s,j)* represents the amount of intermediate input coming from sector *i* in region *r* and which used as an intermediate input in regions *s* sector *j*. Total output of sector *i* in region *r* is given by $TotOutput_{(r,i)}$ and $TotCO2Sec_{(r,i)}$ represents the corresponding direct CO_2 emissions.

In Order to determine how much CO_2 emissions arise along the supply chain of a specific good, first we have to compute the total amount of intermediate inputs employed in the production process. In accordance to Leontief's input-output concept (Leontief, 1970), the input coefficient of good *i* of region *r* for the production of sector *j* in region *s* is given as:

$$a_{(r,i,s,j)} = \frac{intermed_{(r,i,s,j)}}{TotOutput_{(s,j)}}$$

and can be interpreted as the amount of input *i* from region *s* which is necessary to produce one unit of output in region *s* sector *j*. The corresponding input coefficient matrix **A** is thus:

$$\boldsymbol{A} = \begin{pmatrix} a_{(r,i,r,i)} & \cdots & a_{(r,i,s,j)} \\ \vdots & \ddots & \vdots \\ a_{(s,j,r,i)} & \cdots & a_{(s,j,s,j)} \end{pmatrix}$$

The Leontief inverse $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ then provides all necessary information of global intermediate input consumption along the supply chain in the whole economy.

Following Peters (2008), the total amount of embodied CO_2 emissions arising from the production of a unit of final demand is subsequently given by:

$$TotEmCO2 = \boldsymbol{F}'(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{C}$$

where *TotEmCO2* is a scalar representing the total amount of direct and indirect CO_2 emissions from sectoral production, **C** is final demand in form of a column vector and **F** is a column vector containing the direct CO_2 emission intensity of the sectors. So:

$$\boldsymbol{F} = \begin{pmatrix} CO2Intens_{(r,i)} \\ \vdots \\ \vdots \end{pmatrix}$$

where

$$CO2Intens_{(r,i)} = \frac{TotCO2Sec_{(r,i)}}{TotOutput_{(r,i)}}$$

A reduced form of the relationship provided by Peters gives

$$\boldsymbol{G} = \boldsymbol{F}'(\boldsymbol{I} - \boldsymbol{A})^{-1}$$

where **G** is a row vector providing information on the amount of direct and indirect carbon included in one unit of output of sector *i* in region *r* for all sectors of the economy, denoted $g_{(r,i)}$.

$$\boldsymbol{G}' = \begin{pmatrix} g_{(r,i)} \\ \vdots \\ \vdots \end{pmatrix}$$

Furthermore, combining the input coefficient matrix **A** and the direct emission intensities of the sectors $CO2Intens_{(r,i)}$ yields matrix $\mathbf{A_{CO2}}$:

$$\boldsymbol{A_{CO2}} = \begin{pmatrix} a_{(r,i,r,i)}CO2Intens_{(r,i)} & \cdots & a_{(r,i,s,j)}CO2Intens_{(r,i)} \\ \vdots & \ddots & \vdots \\ a_{(s,j,r,i)}CO2Intens_{(s,j)} & \cdots & a_{(s,j,s,j)}CO2Intens_{(s,j)} \end{pmatrix} = \begin{pmatrix} a_{CO2}{}_{(r,i,r,i)} & \cdots & a_{CO2}{}_{(r,i,s,j)} \\ \vdots & \ddots & \vdots \\ a_{CO2}{}_{(s,j,r,i)} & \cdots & a_{CO2}{}_{(s,j,s,j)} \end{pmatrix}$$

which – analogous to **A** – can be interpreted as a CO_2 emission input coefficient matrix. Thus $a_{CO2(r,i,s,j)}$ describes how much CO_2 is implied by using $a_{(r,i,s,j)}$ units of product *i* from region *r* which in turn is necessary to produce on unit of output in sector *j* in region *s*. So $a_{CO2(r,i,s,j)}$ is the amount of CO_2 added by sector *i* in region *r* at a specific production step to the total amount of embodied carbon of good *j* produced in region *s* given by $g_{(s,j)}$. Hence $\mathbf{A_{CO2}}$ provides us with the sectoral and regional origin of CO_2 emissions embodied in goods. This information is crucial to determine the by how much an embodied carbon tariff has to be adjusted when truly accounting for the origin of CO_2 emissions.

TotEmCO2, **G** as well as $\mathbf{A_{CO2}}$ include direct and indirect emissions arising along the whole supply chain of a produced good. That is to say, *TotEmCO2*, **G** and $\mathbf{A_{CO2}}$ do not only consider local intermediate inputs and the CO_2 entailed by them, but also account for internationally interwoven production processes and the associated imported CO_2 emissions. With this we have all information on embodied carbon we require for our analysis.

3. Data

In order to conduct this analysis, data from the WIOD project is used.[4] Within the WIOD project sets of intercountry input-output tables have been developed. The consistent intercountry input-output tables allow to follow precisely the supply chains across different regions and sectors since the data shows the regional and sectoral origin of intermediate inputs. Taken together with extensive satellite

[4] The WIOD database is available at http://www.wiod.org/. We use data from March 2012 in this paper.

accounts with GHG emissions, the WIOD data enables us to detect the sectoral and regional origin of embodied carbon on an industry-level. Thus this rich dataset allows in particular to keep track where imports and hence also indirect carbon originates on every stage along the value chain.

The original database covers the economic linkages within and between 35 sectors in 27 EU countries and 13 other major regions in the world for the period from 1995 to 2009. However, for reasons of clarity and comprehensibility, we aggregated the data to 15 sectors and distinguish between 11 regions. The regional and sectoral aggregation scheme is give in the Appendix. For our analysis we focus on data for the year 2005 in order to avoid drawing conclusions from a period of economic turmoil.

4. Carbon Chain – Embodied Carbon along the Supply Chain

As noted in the previous section, the comprehensive CO_2 emissions and international trade data of WIOD, allows for a detailed analysis of the direct and indirect emissions arising along the international supply chain of individual sectors. Thus it is possible to evaluate how much domestic and non-domestic carbon is contained for example in a good produced in the European manufacturing industry. Such detailed information is of particular importance, as today industries have complex supply chains often stretching all around the globe. As a consequence, value – and in this context even more importantly carbon – is added to a good at several stages of the production, each step involving different input- and emission intensities. To which extent modern supply chains are complex can be seen exemplarily from the production of sectors MAN and CPN in Europe presented in Figure 9 and Figure 10 in the Appendix. The figures describe for four steps in the supply chain, how much carbon is added in each production step from the two most carbon intensive non-domestic inputs. They make clear that embodied carbon is not just composed of carbon added in the final production step, but indicate that indirect carbon arising in upstream processes is also of importance. Furthermore, the supply chains – or here rather the carbon chains – show that even though an intermediate input might be declared as non-domestic due to the location where it is produced and consequently will be taxed in case of a standard BTA regime, it may still contain a significant quantity of domestic – potentially already regulated – carbon. Thus, as has been already outlined in the introduction, in case of a simple BTA approach taxing the full carbon content, multi-taxation potentially takes place.

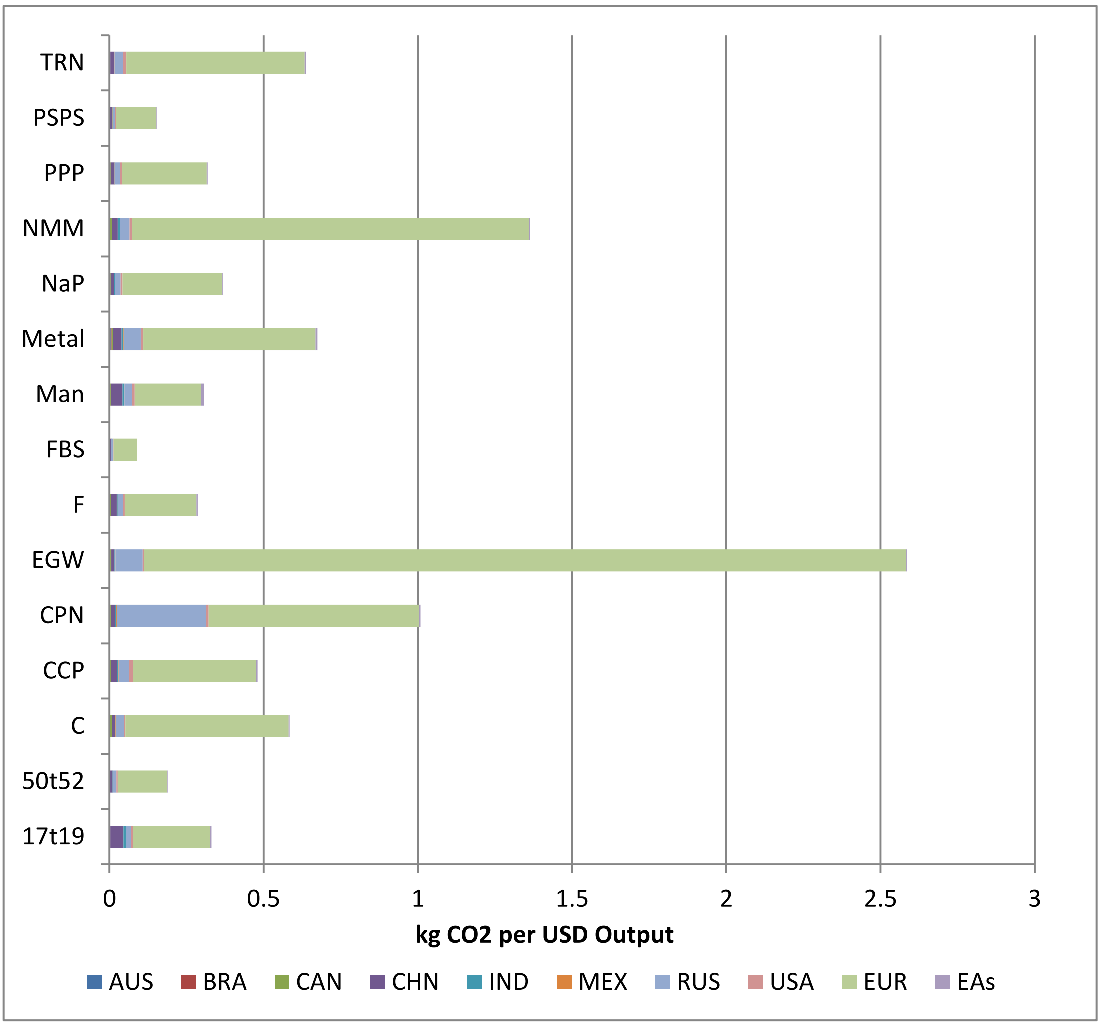

Figure 1: Embodied Carbon in Sectors of the EU in the Year 2005

Figure 1 illustrates for the year 2005 the quantity of carbon embodied in a good produced in Europe and the region of origin of the contained carbon. With respect to the total amount of embodied carbon per output, EGW clearly dominates all other sectors. Compared to other sectors NMM, CPN, METAL and TRN also have highly carbon intensive production processes, but nevertheless fall short of EGW. For all European sectors under investigation, the largest share of embodied carbon arises domestically. This is to be expected for two main reasons. First, in particular in energy intensive sectors such as EGW or METAL, the biggest part of embodied carbon it attributable to direct emissions, hence emission arising in the last production step of a good, which in this case takes place in Europe. Second, European industries source a large part of their inputs from other European industries. Consequently a big share of the indirect emissions can also be allocated to Europe. As potentially a certain share of European indirect emissions consist of emissions reimported to Europe, this part of embodied carbon is also of crucial relevancy in the BTA context as it may be subject to multi-taxation.

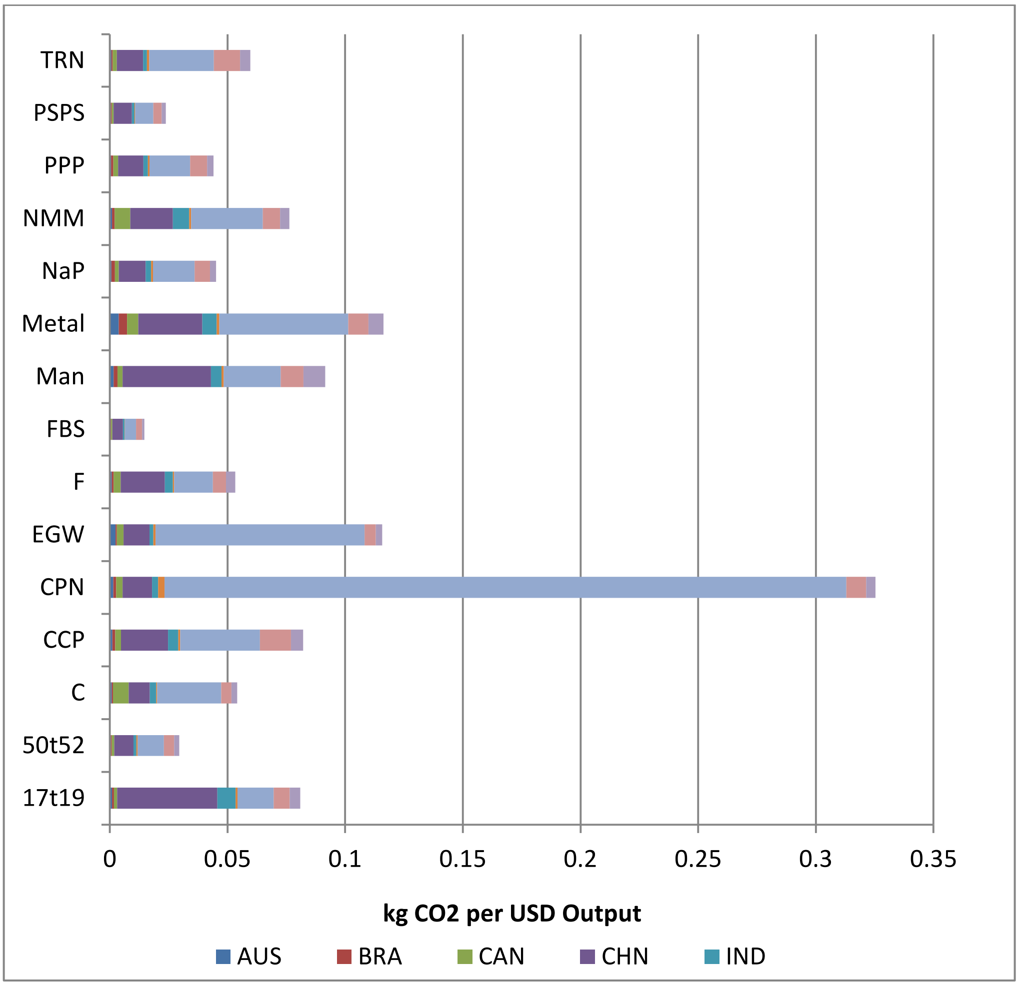

Figure 2: Non-domestic Embodied Carbon in Sectors of the European Union in the Year 2005

Besides carbon arising within Europe, non-domestic carbon plays an important role in several emission intensive sectors such as EGW, CPN, CCP or METAL. Figure 2 takes a closer look at the source of non-domestic embodied carbon. Large parts of all imported carbon for production processes originate from Russia. This holds particularly true for those sectors that have a high demand for natural resources such as CPN, EGW and METAL. The second most important source of indirect CO_2 is China and whose imports play a dominant role in particular in the sectors 17t19, MAN, METAL and F. But although Russia and China are responsible for the majority of carbon imported in production inputs, Figure 2 also shows that all regions of the world contribute to the amount of carbon embodied in European products. This stresses the importance of accounting for international trade when designing environmental policy.

5. The Multiregional Computable General Equilibrium Model

In modern applied economic research, quantitative simulations, in particular computable general equilibrium (CGE) models, are one of the key instruments in order to evaluate alternative policy measures. In particular the *ex-ante* evaluation of climate policy measures has a long tradition in using CGE models (see e.g. Felder and Rutherford (1993), Perroni and Rutherford (1993), for more recent contributions, see Babiker (2005), Elliott et al. (2010)).

We also rely on a CGE model to examine the consequences of a taxation of embodied carbon along the value chain. We use a static multi-regional CGE model based on the WIOD data. Production can be characterized by production function with constant elasticities of substitution (CES) and constant returns to scale. Hence, we are assuming perfect competition in all markets. The model distinguishes between two groups of commodities: energy commodities and non-energy commodities. Nested CES functions with 5 levels are employed to specify the substitution possibilities between labour, capital, energy inputs, non-energy intermediate inputs. Figure 7 shows a graphical representation of the production process.

The output in the respective sectors can be used for intermediate use and/or final consumption domestically and/or exported to other regions. We abstract from any trade distortions, but apply an Armington (1968) formulation, which means that imports and domestic products are imperfect substitutes. The import aggregate is a CES composite of all imports of a commodity composed in the second level of the Armington production function. Figure 8 shows the structure of the Armington aggregation.

Each region is represented by a representative agent who maximizes utility by purchasing a bundle of consumption goods. Final demand of the representative agent is given as a CES composite combining energy with a non-energy Armington bundle. The budget constraint is determined from factor and tax income. Value added or labour and capital are mobile across sectors within regions but not across regions.

Emissions are incorporated as a fictive necessary input into the production of commodities and the respective consumption good. In our context, this input can be interpreted as a form of emission permit. While the fictive input is supplied by the representative agent, it is assumed that the supply of the fictive input outnumbers demand as long as no regulation constrains emissions. Hence, if emissions are not restrained, the production costs induced by the usage of the fictive input are zero.

The implementation of climate policies is then straight forward. As long as the supply of emission permits is greater than its demand the price of the permits is zero. When now capping the supply of permits the price of emission allowances becomes positive. These permits can then be traded among a certain set of sectors and regions.

As in the descriptive analysis, we use data of the WIOD project in order to calibrate the CGE model. We distinguish between 11 different regions and 15 different production sectors, whereas an overview of the regional and sectoral aggregation is given in the Appendix. The model is calibrated to the year 2005.

6. Scenarios

In order to examine the role tariffs on embodied carbon can play in climate policy and how the structure and composition of the value chain affects the efficiency of this measure, we evaluate three policy scenarios in which a coalition of regions and countries introduce unilaterally a CO_2 emission reduction by 20 percent compared to baseline emissions. Thereby we assume that the required domestic emission reductions are granted by a coalition-wide emission trading scheme. Depending on the scenario, the coalition members then extend their climate policy to include a tariff on imported embodied carbon. All other non-coalition countries are not confronted with a restriction in emitting CO_2.

The climate policy coalition is formed by the European Union (EUR), Australia (AUS) and the developed East Asian economies Japan, Republic of Korea and Taiwan (EAS). The European Union has committed itself to extensive emission reductions (XY) and is signalling frequently at international climate negotiations that it is willing to work with other regions to fight global warming. Australia is also engaging itself in combating climate change and has recently set up a carbon pricing mechanism which will eventually evolve into an emission trading scheme which can be linked to international carbon markets (Commonwealth of Australia, 2011). In contrast to Europe or Australia, the developed East Asian economies have not yet established mandatory carbon pricing mechanisms, yet they have committed themselves to implementing emission reductions and are active to this regard. Japan for instance has introduced a voluntary cap-and-trade system in 2005 (XY) and the Republic of Korea is considering to introduce a carbon pricing mechanism in the near future (XY). All this makes the European Union, Australia as well as Japan, the Republic of Korea and Taiwan to suitable candidates for a country overreaching climate coalition conceivable in context studied in this paper.

The first policy scenario (S1) is the reference scenario and assumes that no border measures are implemented in addition to the coalition-wide emission trading scheme. The second scenario (S2) introduces a tariff on embodied carbon on imports of the coalition members from goods produced in non-coalition countries. Imported embodied carbon is priced according to the prevailing price of carbon in the emission trading scheme of the coalition. The tariff is added to the whole carbon content of an imported good, regardless of its origin. Hence, it might be the case that CO_2 emissions are subject to an emission regulation multiple times. This is the case, if a good originated in a coalition country, implying that its emissions have already been settled by purchasing the respective amount of emission permits from the coalition cap-and-trade scheme, is exported to a non-coalition member for further processing and eventually imported again at a later stage by a coalition country.

Instead of the standard border tax on embodied carbon, the third scenario (S3) implements a more sophisticated tariff. Here the tariff prices explicitly just embodied carbon arising along the value chain descending from non-coalition countries. Thereby it corrects for the multi-regulation of carbon at different production stages of a good.

7. Simulation Results

The consequences of those policies within our model framework are presented in the following. The reduction of emissions by 20 percent leads within the coalition to an unequal reduction of CO_2 emissions. In Australia emissions are reduced in the "*Reduction only*" scenario by 45 percent compared to baseline. In Europe and the East Asian region is the reduction around 20 percent. Main reason for the large reduction in Australia can be found in the EGW sector (containing electricity, water and gas). This sector reduces its emissions by almost 60 percent, while emissions in the same sector in Europe are decreasing by 25 percent. Figure 3 shows the emissions for all countries.

The unilateral emission reduction in the coalition may increase emission in non-coalition countries ("carbon leakage"). The carbon leakage rate, defined as the emission increase in non-regulated countries over the emission reduction in regulated countries, is 10 percent. This is a rather average value of carbon leakage comparing with literature, which normally sector leakage rates in the range of 5 to 20 percent (IPCC, 2007).Our calculations show that implementing a tariff on embodied carbon is indeed an effective instrument to reduce carbon leakage to 2 percent. Implementing such as tariff reduces carbon leakage almost totally. However, there is almost no difference between the two different tax bases. Figure 3 shows the leakage rates for the different scenarios.

The sectoral effects are rather mixed. Having a closer look on some specific sectors and the consequences of the different policy scenarios shows more mixed results. In the EGW sector the tariff has, regardless of its tax base, almost no effect. The main reason is that there is almost no cross border trade in this sector. Just in Russia we see a 3 percent reduction of output due to the tariff implementation, while the in the case without border measures its output is increasing by 1 percent. Since this sector is important as input to other carbon-intensive sectors output reductions in these sectors cause then also output reductions further down in the value chain. For focusing more closely on a carbon-intensive sector more at the beginning of in the value chain, the Metal sector shows some interesting results: In Russia and China, we see significant leakage, but also that the embodied carbon tariff is an effective instrument to combat this effect. The tariff reduces the output in Russia and China, but leads to a partly compensation of the reduction induced by the reduction policy in the coalition member states East Asia, Australia, and Europe. Figure 5 shows the changes in output for this sector.

If we study a sector placed more at the end of the value chain, the manufacturing sector, which is based to a relatively large extent on intermediate goods, the evidence is mixed. While in Australia the tariff has large positive effects and even overcompensates for the reduction policy, it leads in East Asia and Europe to a reduction of competitiveness since the necessary intermediates become more expensive for the producers in this part of the coalition. Figure 6 shows the changes in output for this sector.

Changing again the perspective from individual sectors to regional welfare effects we see, as already denoted by Böhringer et al. (2011), that tariffs on embodied carbon are able to shift substantially the burden of climate policy from coalition countries to the main trading partners of the coalition. Figure 7 shows the Hicksian Equivalent Variation in percent of income. Whereas under the *Reduction only* regime the main burden is lying on the coalition countries (which is, however, relatively minor), the implementation of tariffs on embodied carbon shifts the burden mainly to China and Russia, two of the main trading partners of the coalition countries in terms of carbon-intensive goods. In particularly Russia depends to a large extent on access to the European market.

As the regional differentiated changes in sectoral output indicate, climate policy has also an effect on the composition of global value chains. In Figure 8 we plotted the change in embodied imports in a country's total exports. Hummels et al. (2001) propose this indicator as a measurement to what extent a country is vertically specialized. The implementation of an emission regulation policy leads to ambiguous results: On the one hand, the coalition regions located more at the end of the global value chains such as East Asia and Europe get more specialized towards the final assembling and service activities and "outsource" some of their carbon intensive production activities. This leads to an increased share of embodied imports in exports. On the other hand we observe that China could overtake some of the production activities which took before place in Europe and East Asia and gets hence a more integrated supplier in the global value chain, which is accompanied with a smaller fraction of embodied imports in China's exports.

The effect of BTA then on vertical specialization is rather obvious. As shown by Yi (2003), trade barriers affect vertical specialization over proportionally. So it is rather clear that additional trade barriers such as BTA hamper vertical specialization. The differentiation of the tariff regarding the origin of the embodied carbon leads to less pronounced decrease in East Asia, the EU and Australia. These regions can strengthen their trade network within the coalition due to a differentiated tariff relative to a tariff, which doesn't take into account the origin of the embodied carbon.

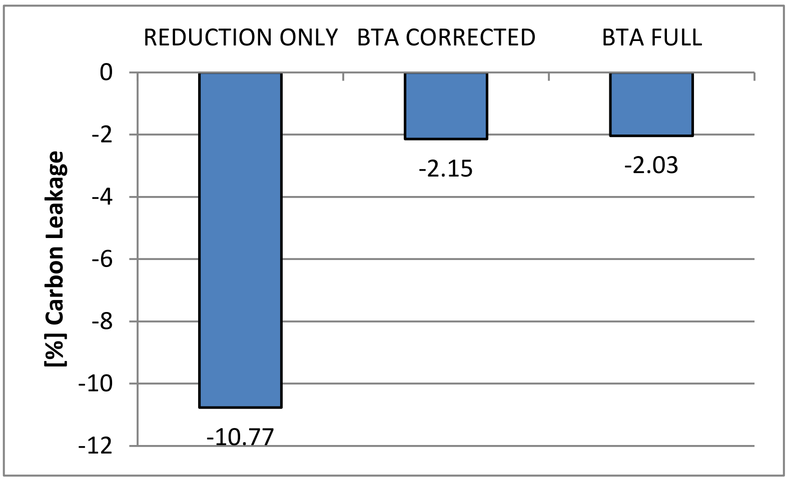

Figure 3: Carbon leakage rates measured as the change in emissions in unregulated countries relative to the change to the emissions decrease in regulated countries.

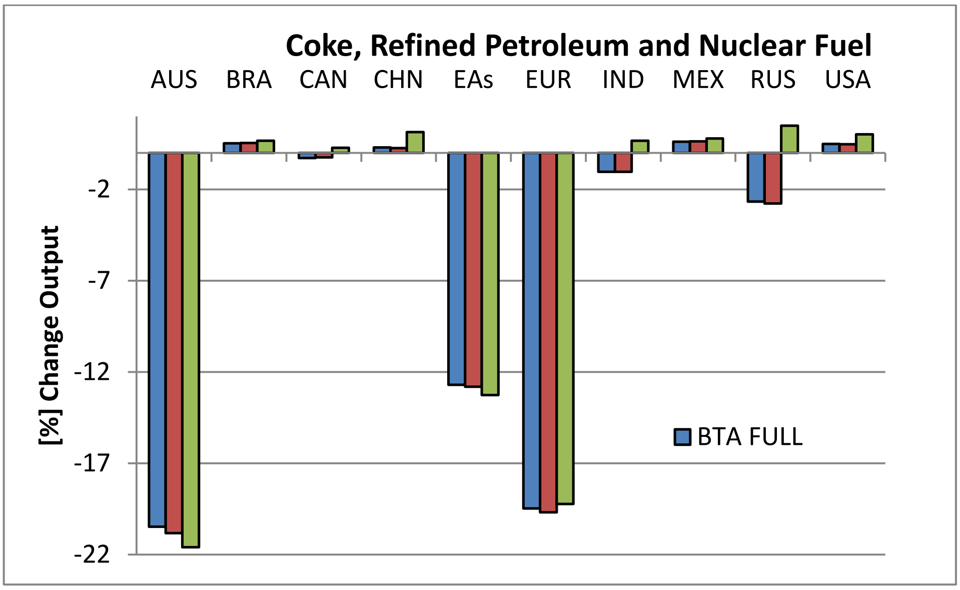

Figure 4: Change in sectoral output in sectoral output of the coke, refined petroleum and nuclear fuel sector relative to the benchmark, a scenario without emission regulation.

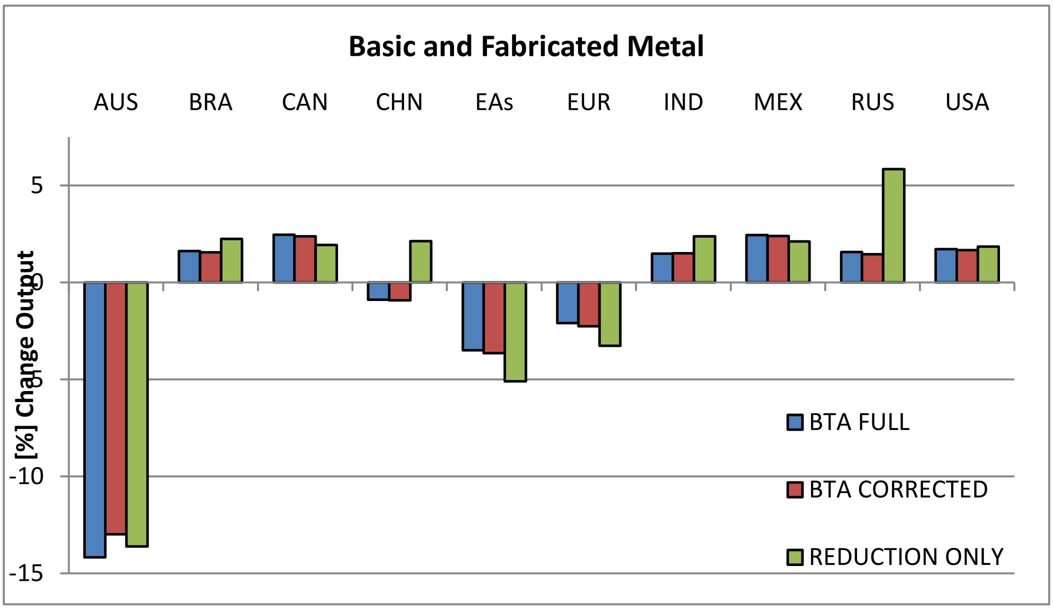

Figure 5: Change in sectoral output of the basic and fabricated metal sector relative to the benchmark, a scenario without emission regulation.

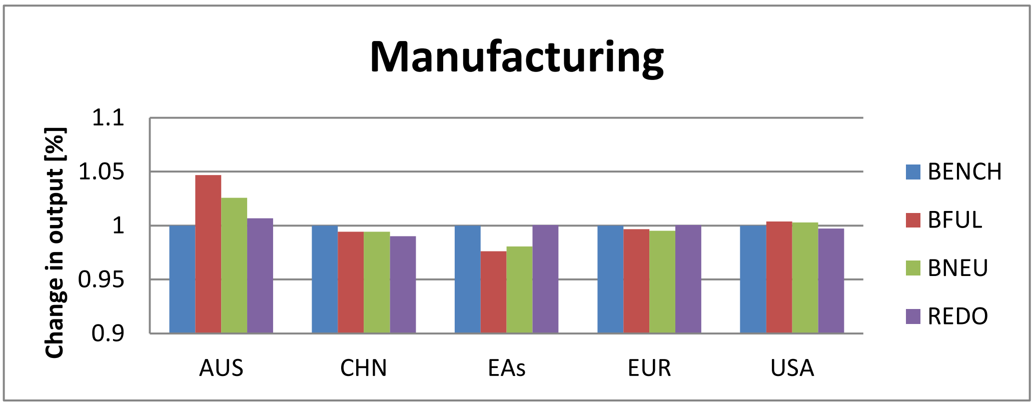

Figure 6: Change in sectoral output

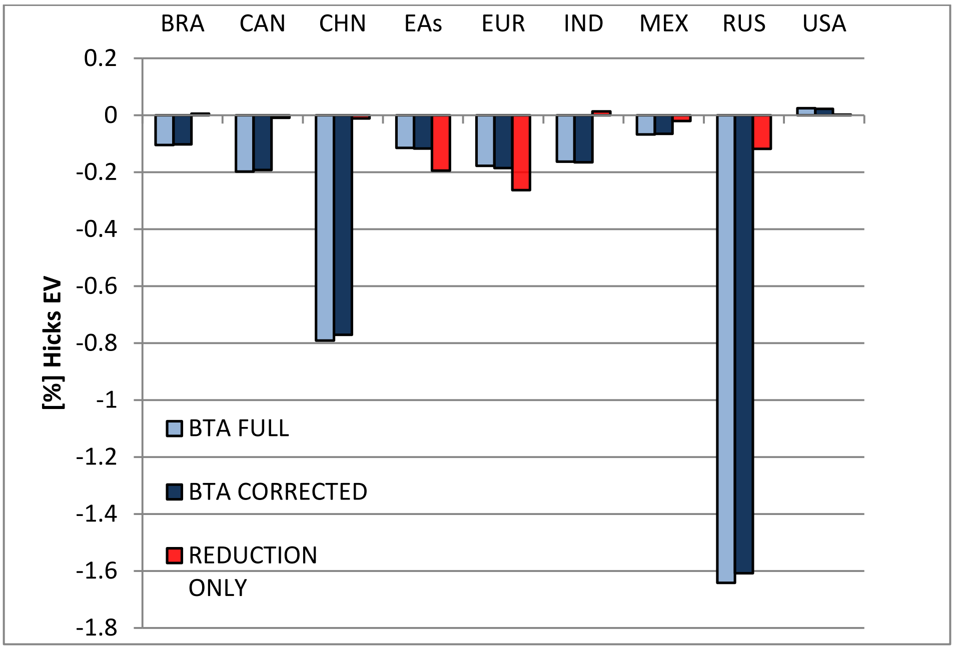

Figure 7: Hicksian Equivalent Variation as percent of regional income.

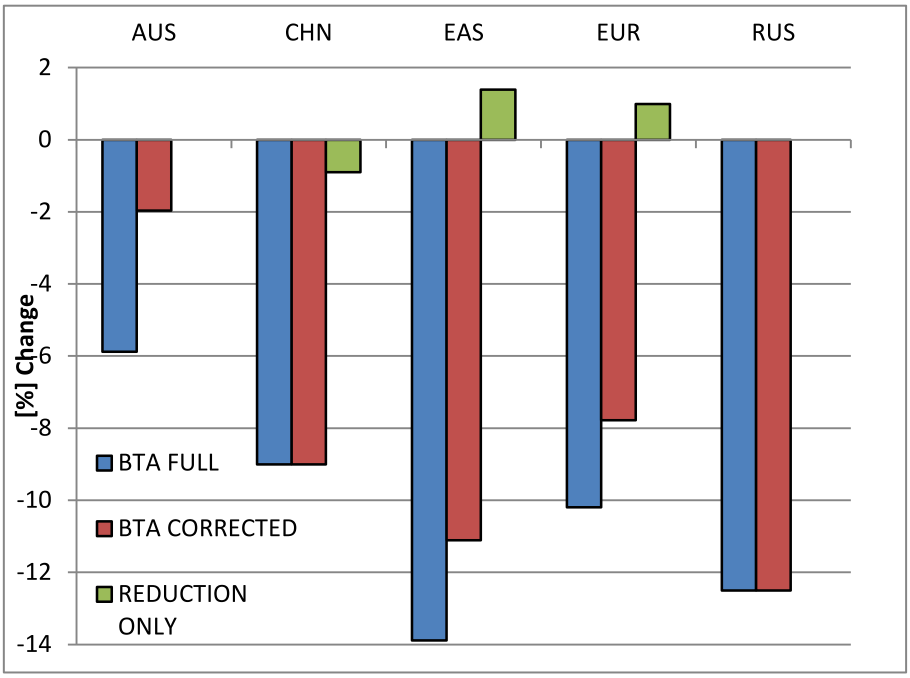

Figure 8: Change in the vertical specialization share of total exports.

8. Concluding Remarks

We used the WIOD database, a new developed set of multiregional input-output tables, in order to calibrate a computable general equilibrium model. The purpose was to examine the consequences of a tariff on embodied carbon as measure to counteract carbon leakage and competitiveness concerns in general and the difference if a more elaborated tariff, which takes into account that some of the embodied carbon in imported goods has its origin in already regulated regions. Add additionally a border tax on this carbon would lead to a double regulation for producers exporting intermediates to non-coalition producers which assemble the intermediates and export the assembled products back into the coalition.

Our results show that a tariff on embodied carbon is very effective to combat carbon leakage. While a domestic carbon reduction target of 20 percent in a coalition including the European Union, East Asian Countries such as Japan and South Korea, and Australia causes a carbon leakage rate of 10 percent, reduces a border tax on embodied carbon leakage to 2 percent. However, while highly effective as a regulation instrument, such a tariff shifts the burden from climate policy to a large extent to non-coalition countries, in particular Russia and China. Therefore, from a political perspective it will be very controversial to operate with such a border tax.

We show that climate policy instruments also affect the degree of vertical specialization. Using the embodied import content of exports as a measure on how strongly a country is vertically specialized along the global value chain shows that an implementation of only domestic instruments leads to a stronger vertical specialization in the implementing coalition of countries. The additional trade barriers from border taxes reduce vertical specialization among all countries.

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Appendix

Regional and Sectoral Aggregation

Region	Countries
AUS	Australia
BRA	Brazil
CAN	Canada
CHN	China
IND	India
MEX	Mexico
RUS	Russia
USA	USA
ROW	Rest of the World, Indonesia, Turkey
EUR	EU-27
EAS	Japan, Republic of Korea, Taiwan

Table 1: Regional Aggregation

Model Sector	WIOD Sector
C	Mining and Quarrying
PPP	Pulp, Paper, Printing, and Publishing
NMM	Other Non-Metallic Mineral
MAN	Machinery; Electrical and Optical Equipment; Transport Equipment; Manufacturing, Nec., Recycling
METAL	Basic Metal and Fabricated Metal
CCP	Chemicals and Chemical Products; Rubber and Plastics
CPN	Coke, Refined Petroleum and Nuclear Fuel

F	Construction
PSPS	Hotels and Restaurants, Post and Telecommunication; Public Admin, Defense and Compulsory Social Security; Education; Health and Social Work; Other Community, Social and Personal Services; Private Households with Employed Persons
FBS	Financial Intermediation; Real Estate Activities; Renting of M&E and other Business Activities
17t19	Textiles and Textile Products, Leather, Leather and Footwear
50t52	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel; Wholesale Trade and Commission Trade Except of Motor Vehicles and Motorcycles; Retail Trade Except of Motor Vehicles and Motorcycles, Repair of Household Goods
TRN	Other Inland Transport; Other Water Transport; Other Air Transport; Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
NAP	Agriculture, Hunting, Forestry and Fishing; Food, Beverages and Tobacco; Wood and Products of Wood and Cork

Production Structures

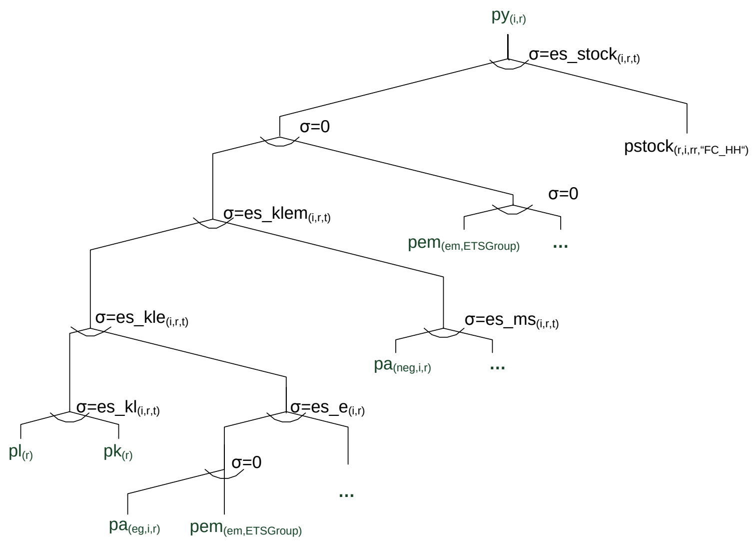

Figure 9: Commodity production.

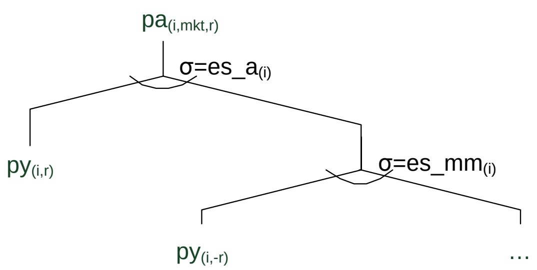

Figure 10: Armington composite structure

Carbon Chains

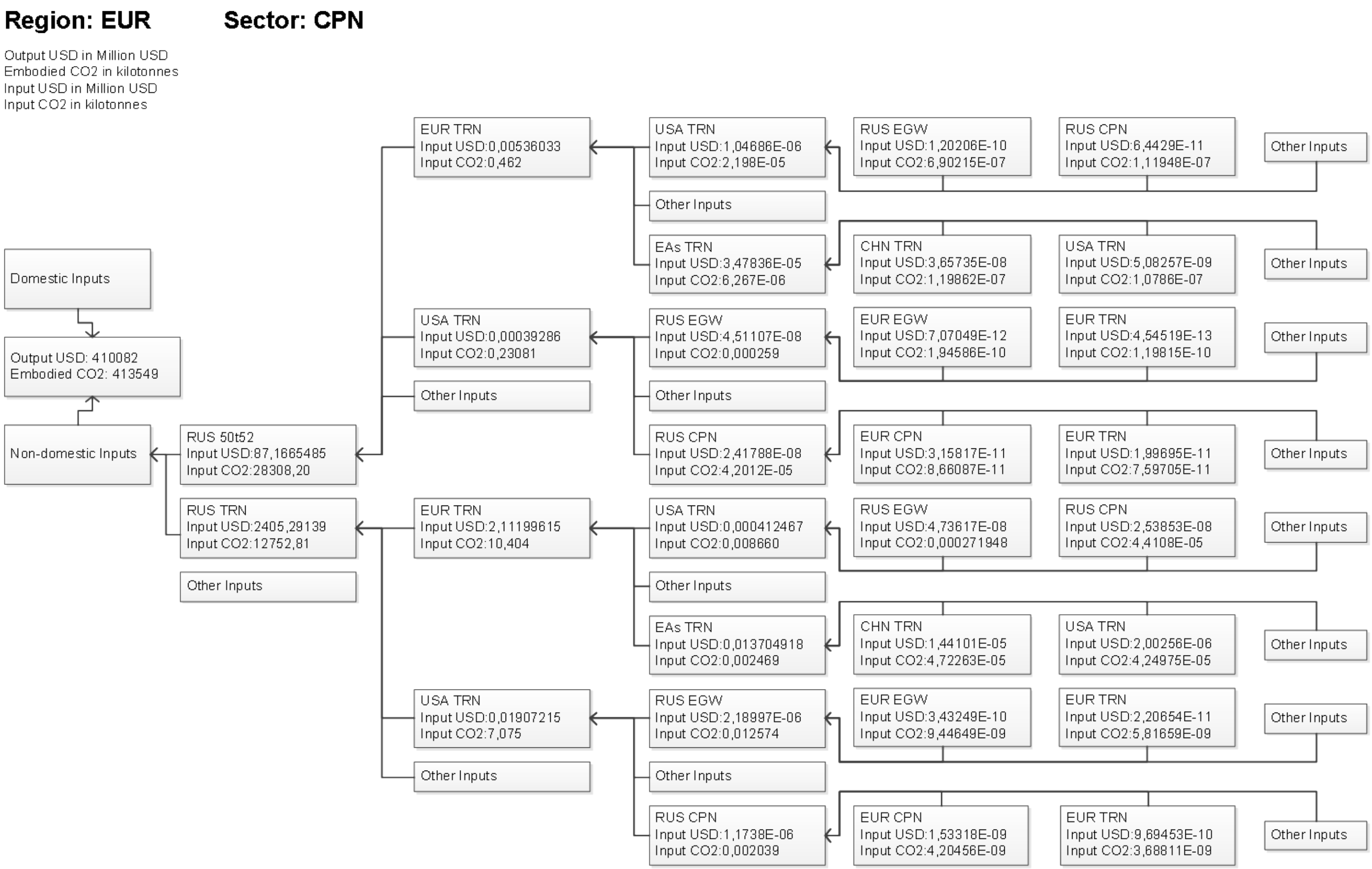

Figure 11: Carbon Chain of European CPN Sector

Region: EU-27 **Sector: Manufacturing**

Output USD in Million USD
Embodied CO2 in kilotonnes
Input USD in Million USD
Input CO2 in kilotonnes

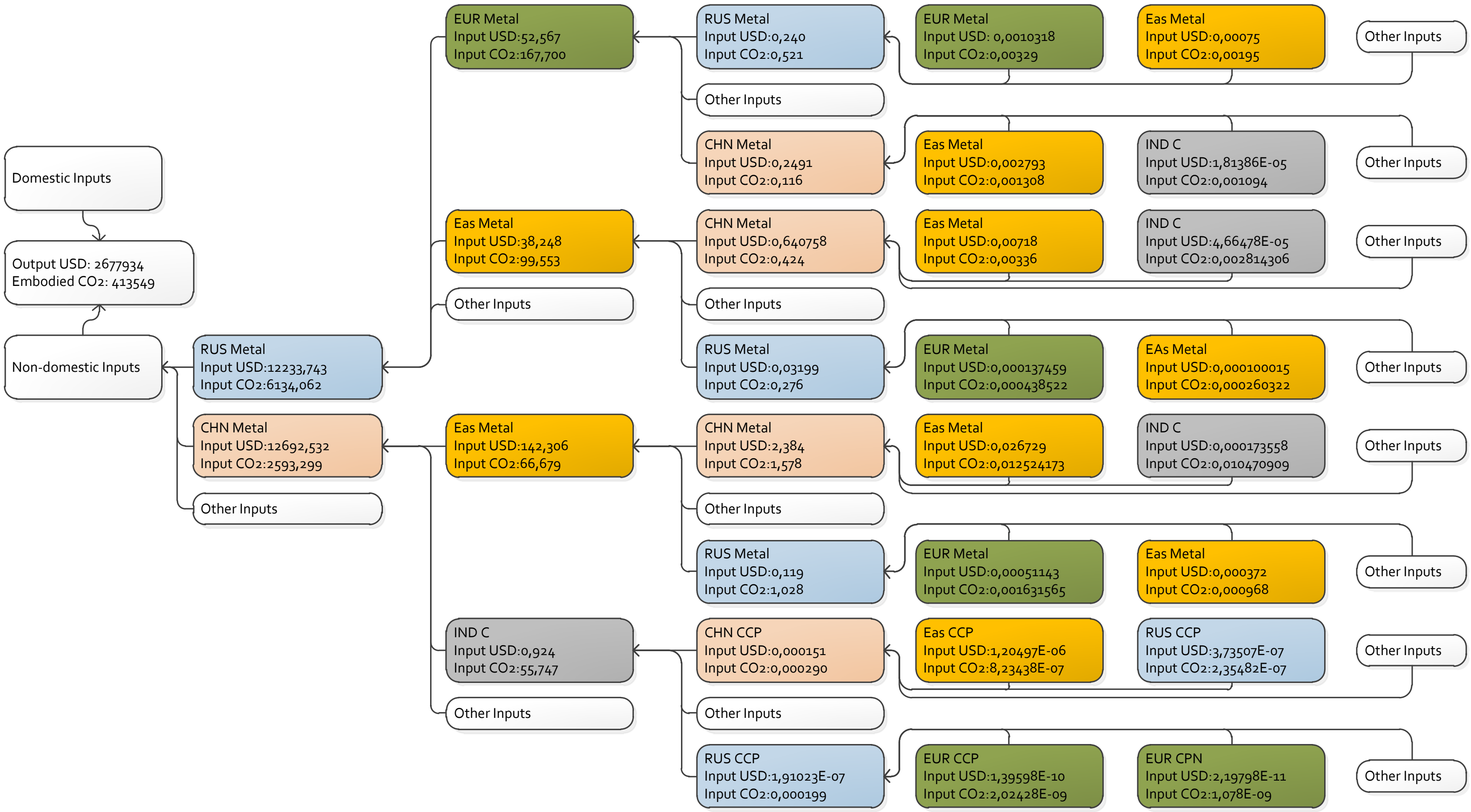

Figure 12: Carbon Chain of European MAN Sector