Conference Paper - 22nd Annual Conference on Global Economic Analysis

in Warsaw, Poland June 19-21, 2019

Conference Paper

The European Emission Trading System and renewable electricity: Using the GTAP Power Database to analyze the role of carbon prices on the development of renewables in the EU.

Mareike Soeder * mareike.soeder@ifw-kiel.de

Sneha Thube* sneha.thube@ifw-kiel.de

Malte Winkler* (presenting author) malte.winkler@ifw-kiel.de

*** Affiliation: Kiel Institute for the World Economy**

Abstract

About one half of the European greenhouse gas (GHG) emissions are regulated under the EU emission trading system (ETS), the other half is not. Under increasing carbon prices this may lead to intersectoral carbon leakage, since some GHG emissions are burdened with a price, and others are not. Furthermore, increasing carbon prices also aggravate international leakage effects, shifts in electricity production technologies (fossil fuel vs. renewable) and inter-European burden sharing of GHG abatement. Here we use the computable general equilibrium (CGE) model DART-CLIM to analyze these effects under a set of scenarios reflecting different degrees of flexibility on the production and/or consumption side. While in most non-ETS sectors emissions (and, thus, intersectoral carbon leakage) are highest when development of renewables is hampered (low flexibility), emissions in direct fossil fuel consumption increase with higher flexibility, because prices for fossil fuels (mainly gas) drop strongest in these scenarios. International carbon leakage increases with higher allowance price, with China showing especially high emissions under the assumption of reduced renewable installation. In the EU´s electricity sector coal decreases by 75% when an allowance price of 50€ is assumed. When renewables are thwarted, mainly gas and oil increase their electricity production to fill the gap left by coal and renewables, but overall electricity production decreases. Our results indicate that a strong development of renewable electricity production is desirable to restrict intersectoral and international carbon leakage. Strong measures for household GHG emissions should be taken to avoid increasing emissions in this sector when fossil fuel prices decrease due to higher allowance prices.

1. Introduction

The European Emission Trading System (EU-ETS) is the central instrument of the EU´s greenhouse gas (GHG) emission mitigation strategy (Böhringer and Lange 2012; ICAP 2016). The current EU-ETS regulates the GHG emissions of large energy producing facilities (> 20 MW), energy intensive industries and inner-European air traffic. In total, roughly one half of the total European GHG emissions is covered by the EU-ETS (ICAP 2016; EC 2015).

This implies that the second half of European GHG emissions is not covered by the EU-ETS. Among the sectors not covered, road transport and heat production have the highest GHG emissions (UNFCCC 2017). Although not covered by the EU-ETS, these fossil fuel intensive sectors are also affected by the price regime inside the EU-ETS, mainly through prices for electricity and fossil fuels.

When some goods are burdened with a price on emissions (like sectors or regions inside an ETS) and others are not (like sectors outside an ETS), the relative prices of associated goods change: Goods including a price on GHGs become relatively more expensive compared to goods not including such a price, which can lead to carbon leakage. This effect occurs when emissions are reduced in regulated regions or sectors, but the reduction is (over-) compensated by an increase of GHG emissions in unregulated regions or sectors, which gain a competitive advantage by not facing a carbon price (see e.g. Babiker 2005). In this study we differentiate between international and intersectoral carbon leakage. On the one hand, the former has widely been discussed in the literature. Verde (2018) and Martin et al. (2016) provide reviews of this literature with regard to the EU-ETS. Neither finds the EU-ETS to have caused traceable international carbon leakage. This is mainly due to both the low allowance prices in the surveyed period and the free allowance allocation used by the EU to avoid competition disadvantages of European industries (Naegele and Zaklan 2019; Joltreau and Sommerfeld 2018).

On the other hand, we found no publication explicitly broaching the issue of intersectoral carbon leakage. However, we expect it to follow the same pattern as international carbon leakage: When the use of fossil fuels is burdened with a price in sectors inside the EU-ETS (e.g. electricity production), but not in sectors outside the EU-ETS (e.g. road transport or heat production), this implies different prices for the same fuel, depending on the sector it is used in. If prices in ETS sectors increase compared to non-ETS-sectors, emissions abated in ETS-sectors could be (over-) compensated in non-ETS sectors. This paper explores both international and intersectoral carbon leakage effects subject to the EU-ETS.

Furthermore, the allowance price indirectly affects energy production outside the EU-ETS by gains in competitive advantage against energy production inside the EU-ETS. Non-ETS energy production is mainly limited to renewable electricity production, since entities of solar and wind electricity are typically smaller than 20 MW. In contrast, most conventional electricity production based on coal and gas are covered by the EU-ETS and therefore face increasing production cost in the case of higher allowance prices. As a consequence, we expect positive effects on the competitiveness of renewable electricity from increasing prices within the EU-ETS. In many countries renewable electricity production is so far only competitive due to governmental support programs (source). In that way, the EU-ETS can serve as an instrument to foster the use of renewable energy technologies, closing the hitherto existing gap between production costs of fossil versus production costs of renewable energy production. This paper quantifies these effects.

Finally we explore the inter-European burden sharing of emission reduction incentivized by the EU-ETS by analyzing which countries (or groups of countries) participating in the EU-ETS exhibit the highest emission reductions. As such, we identify the regions and sectors with the lowest marginal abatement cost within the participating countries.

All research question raised above require an intersectoral, interregional comparison of effects induced by changing prices in the EU-ETS. Therefore, we implement the EU-ETS into DART ("Dynamic Applied Regional Trade"), a global multi-sectoral, multi-regional computable general equilibrium (CGE) model. In order to be able to represent different renewable and conventional electricity production technologies, we use GTAP9 Power (Peters 2016) as a database for our analysis. GTAP9 Power contains a disaggregated electricity sector. To our best knowledge it is the first time this database is used to analyze the EU-ETS.

The rest of the paper is structured as follows: Section 2 contains a description of the model version used in this study, DART-CLIM, and the implemented scenarios. In section 3 modelling results are described, interpreted and discussed. Section 4 concludes.

2. Materials and Methods

2.1. DART-CLIM

The DART model is a global multi-sectoral, multi-regional recursive-dynamic[1] CGE model. Developed at the Kiel Institute for the World Economy, it has been widely applied to analyze international climate policies, (e.g. Klepper and Peterson 2006a, Springer 2002, Springer 1998), environmental policies (Klepper and Peterson 2006b), energy policies, (e.g. Weitzel et al. 2012), and biofuel policies, (e.g. Calzadilla et al. 2016). The version used in this study, DART-CLIM, is a version of the DART model with a detailed representation of the energy sector. It is designed to analyze climate and energy policies (e.g. in Weitzel et al. 2012, Weitzel 2010).

2.1.1. Model Structure and Theory

In DART, the economy in each region is modelled as a competitive economy. Flexible prices and market clearing are assumed. The economic structure of DART is fully specified for each region and covers production, investment as well as final consumption by consumers and the government (Calzadilla et al. 2016). Electricity is produced as a homogeneous good by renewable (wind, solar, others (incl. biofuels, waste, geothermal, and tidal technologies)), conventional (coal, gas, oil) and nuclear technologies. Consumer demand is modelled with non-unitary income elasticities by using the linear expenditure system (LES) approach (Stone 1954), where a representative consumer is divided into two categories: 'subsistence consumers' who spends fixed parts of their income on a subsistence quantity for each commodity and 'surplus consumers' who allocate their supernumerary income according to income elasticities of demand and relative price changes of consumption goods.

2.1.2. Sectors and Regions in DART-CLIM

The version DART-CLIM is calibrated based on the GTAP9 Power database (Peters 2016), which represents the global economy in 2011. In this model version, the world is divided into 20 regions, which are depicted in Table 1.

[1] Note that in this study we use a static version of DART.

Table 1 List of regions modelled in DART-CLIM.

Region code	Countries / regions	Description
Europe		
FRA	France	
GER	Germany	
ITA	Italy	
GBR	United Kingdom, Ireland	
BLX	Belgium, Netherlands, Luxembourg	
SPO	Spain, Portugal	
SCA	Denmark, Finland, Sweden, Norway	
EHC („Europe High Carbon“)	Poland, Czech Republic, Bulgaria, Greece, Slovenia	Other European countries with high share (> 20 %[2]) of coal in the energy sector
ELC („Europe Low Carbon“)	Romania, Hungary, Slovakia, Baltic States, Cyprus, Malta, Croatia Austria, Liechtenstein, Iceland	Other European countries with low share (< 20 %[3]) of coal in the energy sector
Rest of World		
USA	USA	
CAN	Canada	
RAXB	Rest of Annex B: Japan, Australia, New Zealand, Switzerland	
RUS	Russia	
FSU	Rest of former Soviet Union	
CPA	China, Hong Kong	
IND	India	
LAM	Latin America	
PAS	Pacific Asia	
MEA	Middle East, Northern Africa, Turkey	
AFR	Sub-Saharan Africa	

Table 2 List of sectors in DART-CLIM.

Sector Code	Sector description	Sector in EU-ETS
ECoal	Coal based electricity	Yes
EGas	Gas based electricity	Yes
EOil	Oil based electricity	Yes
ESolar	Solar based electricity	No
EWind	Wind based electricity	No
EOther	Electricity based on other inputs: biomass, waste, geothermal, tides	No
ENuclear	Nuclear based electricity	No
EHydro	Hydro based electricity	No
FFP	Fossil fuel production (coal, natural gas,crude oil)	No
Oil	Refining of crude oil to produce oil products	Yes
CRP	Chemical Rubber Products	Yes

[2] basierend auf Daten zur Primärenergieerzeugung von Eurostat
[3] basierend auf Daten zur Primärenergieerzeugung von Eurostat

M_M	Production of metals (iron and non-iron)and minerals (e.g. cement)	Yes
PPP	Pulp, paper and print	Yes
O_I	Other industry	No
AGR	Agriculture (except livestock) and forestry	No
CTL	Livestock	No
WATP	Commercial water and air transport	No
OTP	Commercial road and rail transport[4]	No
SVCS	Services	No
CONS	Direct consumption (e.g. of fossil fuels)	No

2.1.3. Modelling the EU-ETS and Renewable Energy Technologies

In DART the prices of electricity from different technologies is the same and because of this model construction we implement a fixed resource in Solar and Wind technologies (see the Annex for a details in the nesting structure). The fixed resource prevents the flip-flop changes in production of electricity from different technologies. This fixed resource is simply a share of the capital available in the Solar and Wind and after calibrating it is set to 0.1. Since the elasticity of substitution between the fixed resource and KLE nest affects how freely Solar and Wind grow we change in the one of our scenarios to simulate a world where the growth of Solar and Wind is restricted and compare the results to the BAU. Owing to our assumption that the Nuclear and Hydro production is policy driven we don't need the fixed resource in these sectors since their production values are not endogenously determined.

2.1.4. Implementing learning in the renewable electricity sectors in DART

The renewable and nuclear electricity sectors[5] globally and regionally in the European Union as well have undergone tremendous growth between 2011 and 2015(International Energy Agency database). A steady drop in their costs in the past years has been a big factor stimulating the growth in these sectors. To implement this decrease in input cost, in the DART model we introduced a learning curve model within some renewable electricity sectors. This is one of the most commonly used model forms and it associates the unit cost of electricity technology to its generation. The typical characteristic parameter is called the learning rate and it can be understood as the fractional reduction in cost for each doubling of cumulative production (Rubin et al 2015). Formerly, this had been implemented in the dynamic version of DART and a detailed description can be found in Weitzel, 2010.

Mathematically, we use the following transformation to change the progress rates into learning factor for the technologies.

$$Learning\ factor^t = \frac{\sum_r Y_r^t}{\sum_r Y_r^{2011}}^{\frac{\log(progress\ rate)}{\log(2)}}$$

4 Privater Straßenverkehr ist nicht Teil des Sektors „Transp. Straße/Schiene", sondern ist, ebenso wie die private Wärme durch den direkten Konsum fossiler Rohstoffe der Haushalte im Modell integriert.

5 It should be noted that when we talk about renewable electricity sectors we include Solar PV, Wind and Hydro in the definition.

Since we use a static model, progress rate values are determined in a manner such that after calibration the regional electricity production values in 2015 for Solar and Wind match the values reported in the International Energy Agency database. The calibrated progress rate for Wind is 0.42 and Solar is 0.41.

In the next section we will define our different scenarios and then subsequently present our results.

2.2. Implementation and Definition of Scenarios

We define the following scenarios:

Baseline_6: The baseline scenario simulates the electricity sector and carbon markets of 2015. Thus, we calibrate the model to meet the market shares of each type of electricity of 2015 on the European level. Market shares were calculated based on the IEA electricity data. The learning rates of renewable electricity (wind and solar) where calculated based on IEA growth rates as described above. The progress rate was adjusted in order to meet the market share of wind and solar electricity in 2015. Nuclar and Hydroelectricity were calibrated to their 2015 levels and are assumed to maintain this level throughout all scenarios. This is based on the assumption that these types of electricity are mainly policy driven. In addition to the progress rate we calibrate the electricity sector by using the elasticity of substitution for the fixed factor in the production of wind and solar electricity. This elasticity simulates the growth potential of wind and solar electricity which might be limited in the short term due to restrictions in the availability of suitable labor force or locations or long term planning horizons e.g. for offshore wind parks. Since we calibrate the data for a relatively long time step from 2011 to 2015, the baseline scenario includes an elasticity of substitution of 7. Recursive dynamic models with annual time steps typically include and elasticity of 0.6 (EPPA Source Sneha). The baseline scenario includes the EU-ETS including only CO2 Emissions and the currently included sectors. The cap is chosen in order to meet the average price of 6€/tCO2eq

Baseline_50: In this scenario, we reduced the cap of the EU-ETS in order to reach a price of 50€/tCO2 per emission allowances. All other model parameters stay the same as in the Baseline_6 scenario.

Low_Flex: In the Low_Flex scenario we decrease the elasticity of substitution for the fix factor to 0.6 and simulate a world where it is more difficult to realize solar and wind electricity projects and therefore reduce the growth potential of these two electricity sectors. The cap stays the same as in the Baseline_50 scenario.

Medium_Flex: Instead of restricting the growth of wind and solar electricity, in the medium flex scenario, we run a version without any fixed factor in the production function. This scenario simulates a world without any external restrictions to the growth of solar and wind electricity. The cap stays the same as in the Baseline_50 scenario.

High_Flex: In addition to the Medium_Flex scenario without fixed factors for renewable electricity, the High_Flex scenario simulates a world with more flexibility in the final consumption of energy goods. Thus, in this scenario we increase the elasticity of substitution between electricity and all fossil fuels from Cobb-Douglas to 2. Thus, this scenario simulates a world, where consumers can more easily substitute their heating based on fossil oil by a heating system e.g. based on electricity or coal. In addition, they can substitute fossil fuels used for private transport e.g. by electricity for electric mobility. Since these type of consumption decisions are normally related to a long term investments into a certain heating system or type of car, consumption of energy goods is very inflexible in the short term. Thus, this scenario simulates long term effects in final consumption of energy goods of higher prices for emission allowances. The cap stays the same as in the Baseline_50 scenario.

3. Results

Figure 1: Baseline_6 CO2 and Non-CO2 emissions within the EU

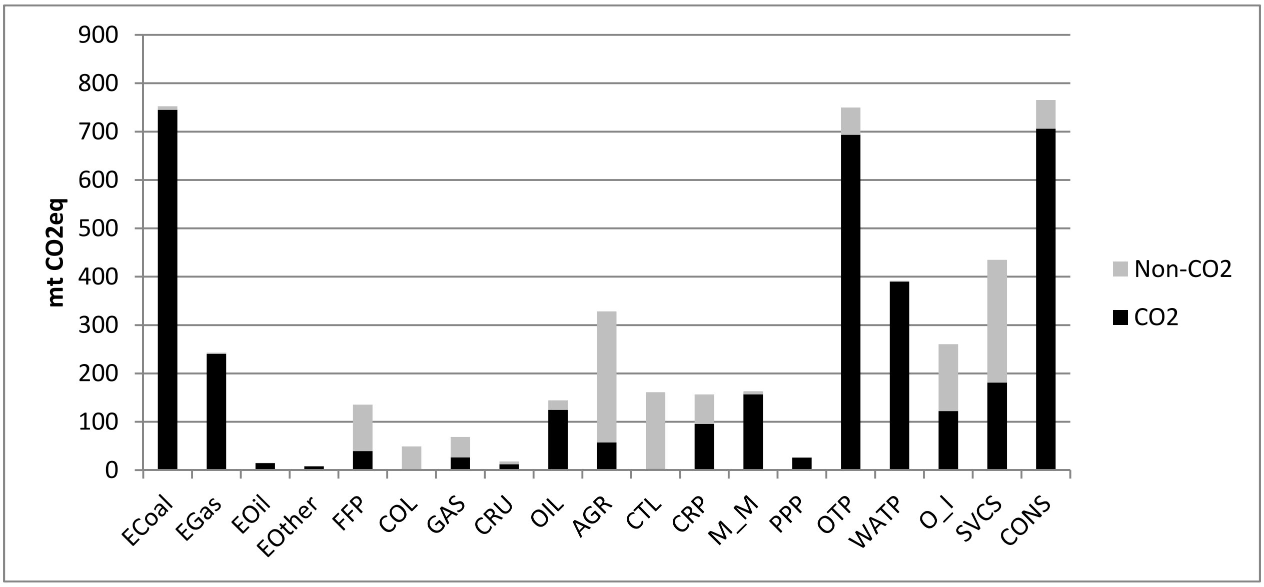


Figure 1 illustrates the sectoral CO_2 and Non-CO_2 emissions within the EU in the Baseline_6 scenario. All other scenarios will be compared to this scenario. In the Baseline_6 scenario electricity production from coal exhibits the highest greenhouse gas (GHG) emissions of all production sectors. However, other transport including road and rail transport and final consumption exhibit similar amounts of GHG emissions. Final household consumption includes consumption of fossil fuels for heating purposes as well as fossil fuels for private transport. Sectors with the highest Non-CO_2 emissions are agricultural production and cattle production as well as public services including e.g. GHG emissions from waste combustion.

Within the EU-ETS electricity production from coal and gas are the sectors with the highest CO_2 emissions. Among other industries, production of metals and minerals as well as chemical and rubber products exhibit the highest CO_2 within the current EU-ETS.

Table 1 gives an overview of the scenario results. We keep the cap constant in all scenarios. Thus the CO_2 emissions covered and the emissions reduced within the EU-ETS stay constant as well across scenarios. However, we can observe differences in prices for emission allowances across the scenarios. In particular we observe a strong price increase two 65 €/tCO_2 when we decrease the elasticity of substitution for the fixed factor in renewable electricity production in the Low-Flex Scenario. Thus, constraining the potential in capacity growth of solar and wind electricity increases prices for emission allowances within the EU. Increasing the flexibility even further by excluding the fixed factor from the production function of wind and solar electricity in the Medium-Flex scenario does not significantly affect prices for emission allowances nor does it substantially affect the overall emission reduction within the EU. For all scenarios we observe a lower emission reduction for the EU as a whole compared to the emission reduction within the EU-ETS resulting from decreasing the cap. Thus, the higher prices within the EU-ETS cause higher GHG emissions outside the EU-ETS, which we call sectoral leakage of the EU-ETS. Across scenarios, this sectoral leakage becomes substantial (around 12% of the emission reduction within the EU-ETS) once we adapt a higher substitutability between energy goods (electricity and fossil fuels) within households energy consumption in the High-Flex scenario.

Table 1: Overview of scenario results

Scenario	Price for Emission allowances in €/tCO_2	GHG Emissions covered by the EU-ETS (CO2 Emissions within EU-ETS sectors)	Emission reduction within EU-ETS sectors (compared to Baseline_6)	Total GHG Emissions within the EU	Emission reduction within EU-ETS sectors (compared to Baseline_6)
Baseline_6	6	1412		4736	
Baseline_50	50	747	665	4116	620
Low-Flex	65	747	665	4115	621
Medium-Flex	50	747	665	4113	623
High-Flex	48	747	665	4151	585

As a next step, we analyze the details of the sectoral effects within the EU. We first analyze changes within the electricity production portfolio since they give rise to the changes in GHG emission from electricity production. Figure 2 illustrates these changes by showing the terra watt hours (twh) of each production technology. Since we hold nuclear and hydroelectricity constant across scenarios, they are only displayed for illustrative reasons.

Compared to the Basline_6 scenario, electricity production from coal reduces to by almost ¾ of its former production. Given lower CO2 emission factors per energy unit, electricity production from gas reduces less than coal across scenarios. Across scenarios, the reduction of the growth potential of renewables in the Low-Flex scenario causes the largest differences. The higher price of 65€/tCO_2 causes coal electricity to further decrease. Due to growth restrictions wind electricity growths less compared to other the scenarios. Due to a lower competitiveness compared to wind electricity, solar electricity even falls back under the Baseline_6 level. In order to meet the demand for electricity nonetheless, we observe increases in electricity production mainly from gas and oil in the Low-Flex scenario. The elimination of the fixed factor in the Medium_Flex and High_Flex scenario almost does not affect the amount of wind electricity production. Only solar electricity production increases slightly. Thus, the elasticity of substitution of 7 for the fixed factor does already give a high freedom of growth for wind based electricity. The higher capital share in production for solar electricity (72% for solar compared to 56% for wind for global average) explains this difference since we implement the fixed factor by taking 10% of capital input.

The slightly higher coal electricity production and slightly lower gas electricity production can be explained by the lower price for emission allowances of 48€ in the High_Flex scenario.

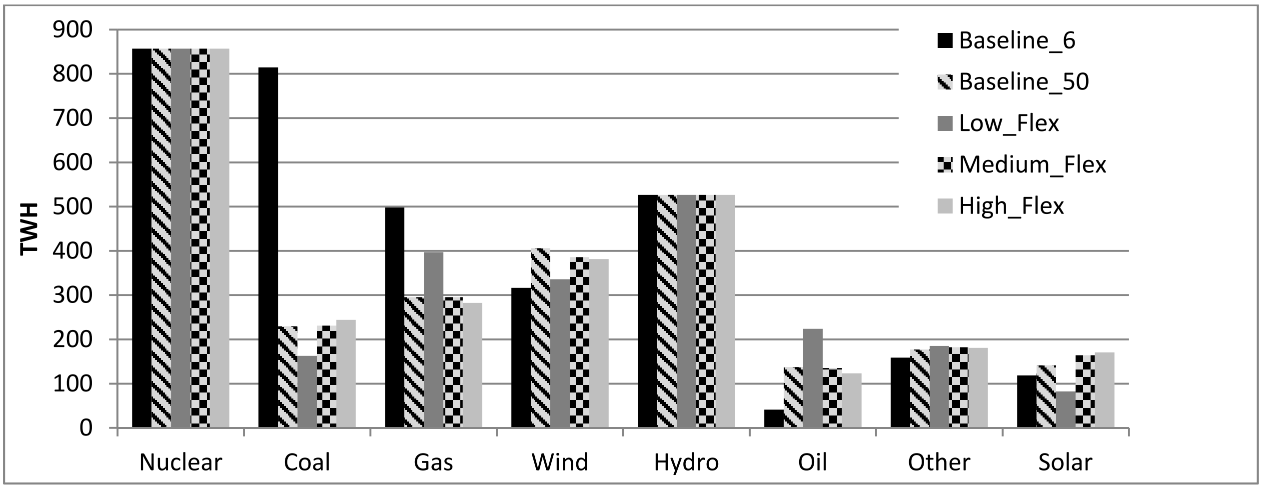


Figure 2: Electricity production per technology within the EU.

Figure 3 illustrates the changes in GHG emissions (values in $mtCO_2$ equivalents) within the EU-ETS sectors compared to the Baseline_6 scenario. Overall it is evident that high prices for emission allowances within the EU-ETS causes the highest emission reduction within the electricity production from coal which mirrors the results of changes in TWH produced by different technologies. Due to increases in electricity production based on oil, Eoil is the only sector within the EU-ETS with rising CO_2 emissions. Among the non-electricity sectors, mining and minerals exhibits the highest reduction in CO_2 emissions, however, the overall reduction is small compared to the electricity sector. Thus, marginal abatement costs are higher compared to the electricity sector. Reduction in CO_2 emissions is even lower in the chemical and rubber industry. However, this sector contains relatively high non-CO2 emissions which are not covered by the current EU-ETS.

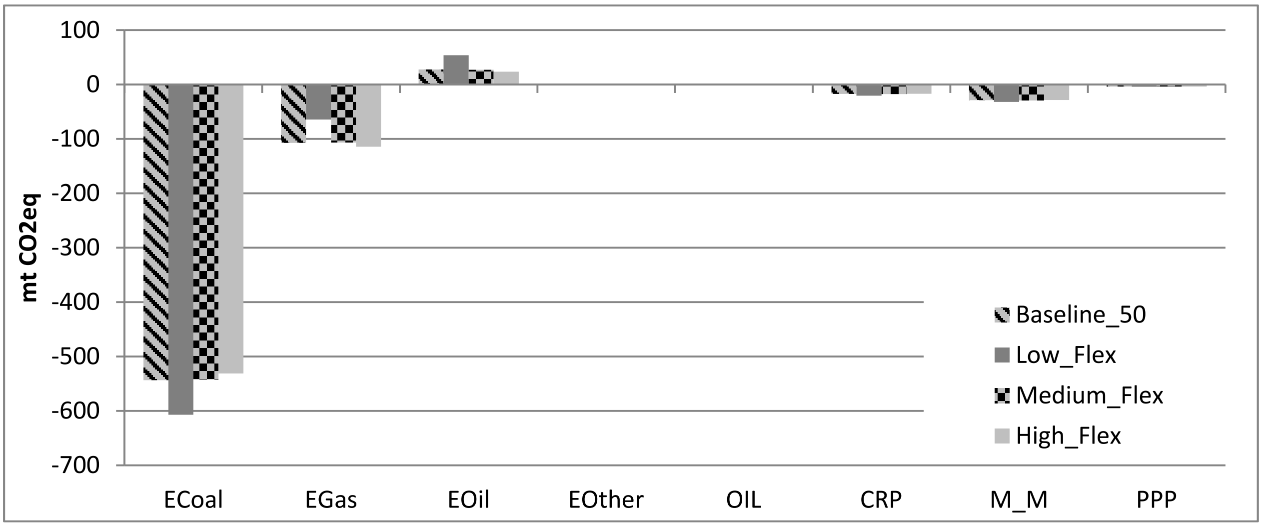


Figure 3: Changes in Emissions per EU-ETS sector for the EU

As a next step we analyze changes in GHG emissions outside the EU-ETS and illustrate the causes of these effects. These changes are illustrated in figure 4. Industries outside the EU-ETS react differently to increasing prices within the EU-ETS. Overall results show the highest decreases in the emissions of fossil fuel production. In addition, emissions decrease in the water and air transport sector. Increases in GHG emissions are the highest in the service sector followed by other industries and the agricultural sector. The effect are the highest in the Low-Flex scenario, where electricity production from coal reduces the most due to high prices for emission allowances. In order to illustrate the causes of emissions we show in figure 6 the changes in prices for the different energy goods for intermediated consumption in industries and for final household consumptions. Here we show results for Germany, a country with a high share of coal electricity in its production portfolio, and France, a country with a relatively low share. Results for all countries are available upon request. We observe that in Germany price changes for coal for industry intermediate consumption decrease between 25 and 30 in the Low-Flex scenario. Prices for Electricity on the other hand increase by up to 25% and oil prices up to 4% in the Low-Flex scenario. Since the model allows a substitution between energy goods of 1.5 between fossil fuels in non-energy sectors and of 0.75 between fossil fuels and electricity, results show increases in GHG emissions due to a substitution of electricity and oil with coal. Thus, part of the emission reduction within the EU-ETS due to decreases in coal electricity is eliminated due to increase in coal consumption in the non-EU-ETS sectors which is caused by decreases in coal prices.

This substitution effect and the effect model assumptions have on the size of the effect become more evident when analyzing effects on final consumption. Figure 5 illustrates the amount of household´s fossil fuel consumption in mtoe. Figure 5 includes also the amount of consumption in the Baseline_6 scenario in order to appraise the importance of each fossil fuel in final household consumption. Refined oil products are by far the most important energy good since it includes consumption of gasoline and diesel for private transport and oil used for heating. Gas and some coal are mainly used for heating and sometimes cooking. Within the Low_Flex scenario, we observe a decrease in GHG emissions in final household consumption caused by a decrease in the consumption of refined oil products. Since electricity from oil production fills part of the gap in electricity production due to reduced electricity production from coal caused by high prices for emission allowances and restricted growth of electricity production from renewables due to the fixed factor, prices for refined oil products increases the most in the Low_Flex scenario.

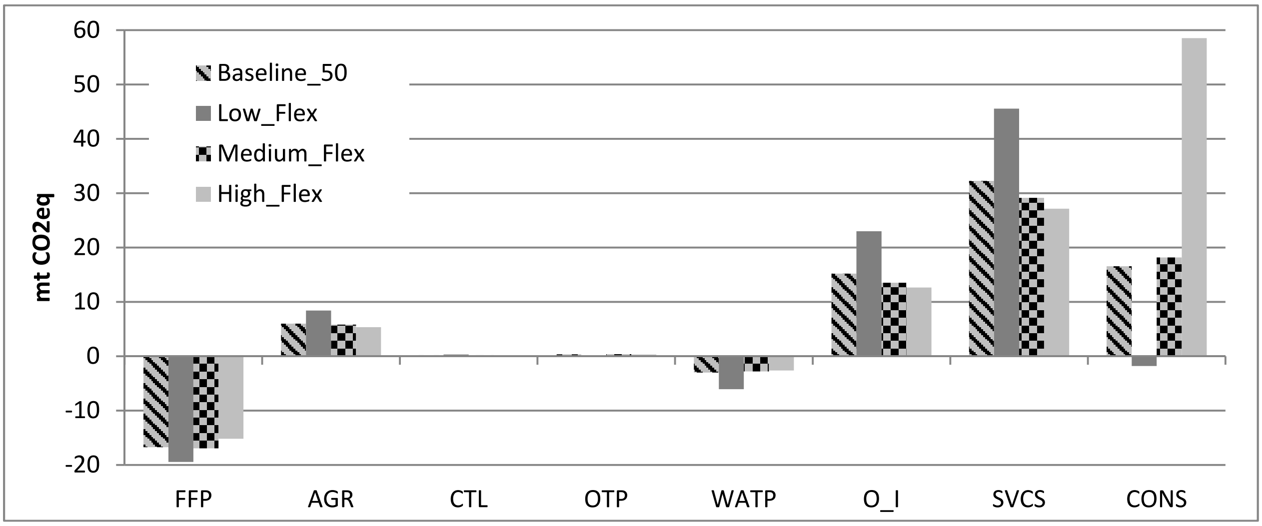


Figure 4: Changes in Emissions per EU-ETS sector for the EU

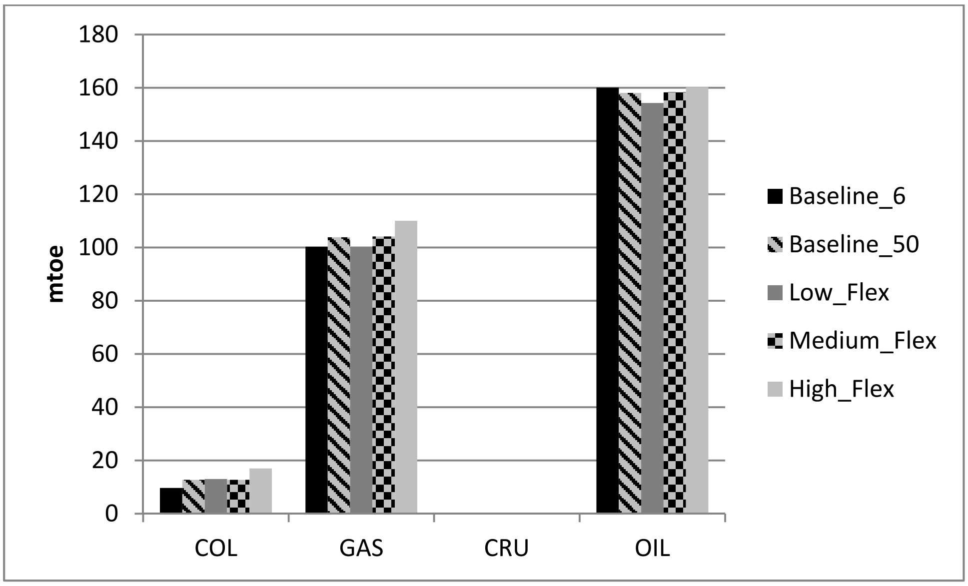


Figure 5: Final households consumption of fossil fuels (in mtoe) EU

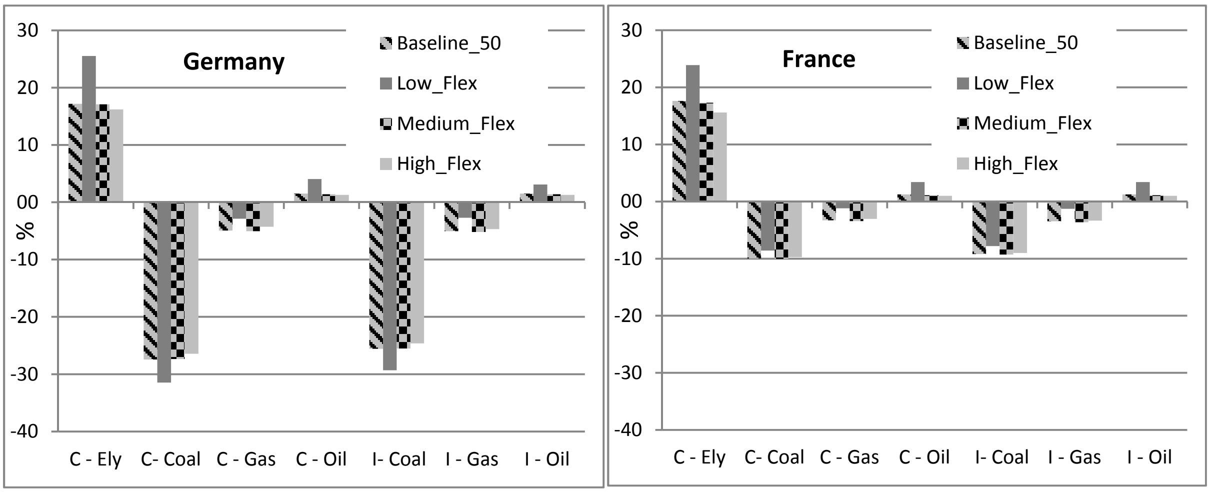
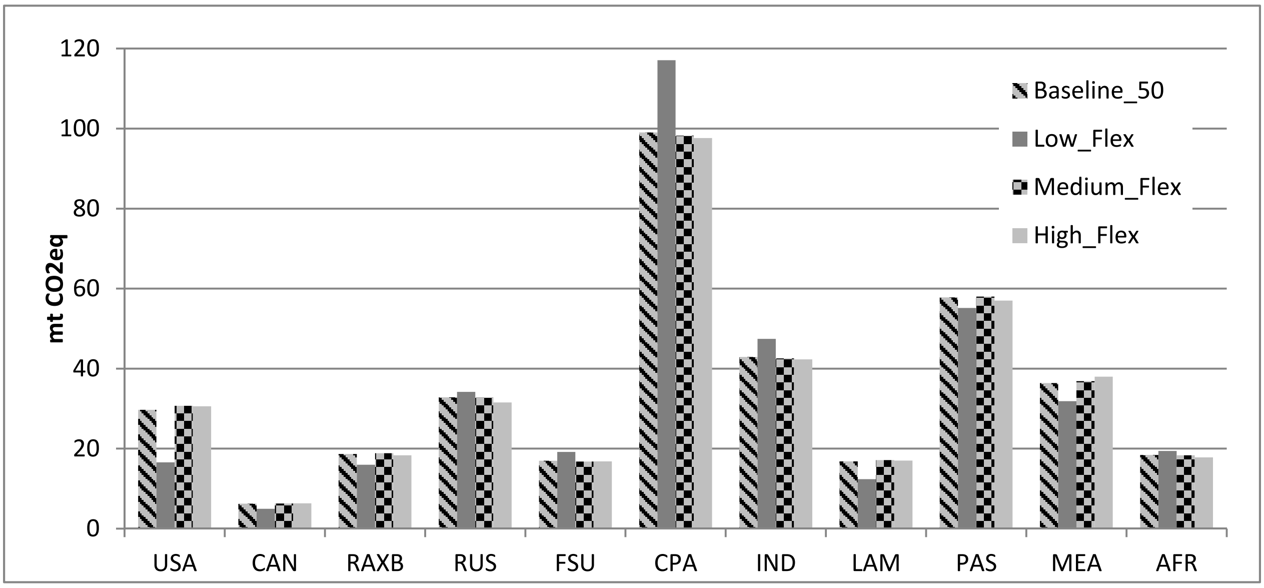


Figure 6: Price changes of energy goods in % for final consumption and intermediated consumption in industries for Germany and France (Armington composite price final household demand of electricity, coal gas and refined oil products and Armington composite price demand of industries coal, gas and refined oil products)

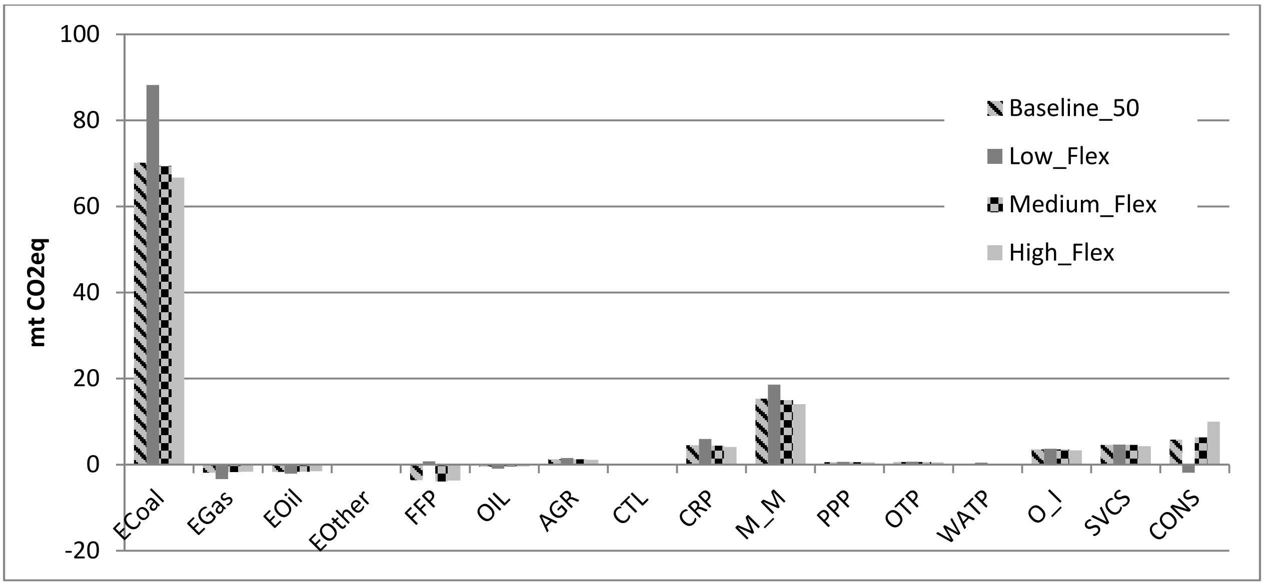
Once me allow for a more flexible substitution between energy goods in final household´s consumption by increasing the elasticity of substitution between energy goods from 1 to 2 in the High-Flex Scenario, GHG emissions of final consumption strongly increase. Compared to the Baseline_6 scenario we observe increases in coal and gas consumption. Since price effects of refined oil products are rather small in this scenario, consumption of this energy good remains almost constant. Thus, we observe a substitution of electricity by coal and gas in final consumption.

Change in Emissions outside the EU (global leakage)



- Baseline_50:
- Low_flex:
- Medium_Flex:
- High_Flex:

Change in emissions in China



4. Discussion and Conclusions

Literature

Babiker, Mustafa H. (2005): Climate change policy, market structure, and carbon leakage. In *Journal of International Economics* 65 (2), pp. 421–445. DOI: 10.1016/j.jinteco.2004.01.003.

Böhringer, Christoph; Lange, Andreas (2012): Der europäische Emissionszertifikatehandel. Bestandsaufnahme und Perspektiven. In *Wirtschaftsdienst* 92 (S1), pp. 12–16. DOI: 10.1007/s10273-012-1344-9.

Calzadilla, A.; Delzeit, R.; Klepper, G. (2016): Assessing the Effects of Biofuel Quotas on Agricultural Markets. In Tony Bryant (Ed.): The WSPC Reference on Natural Resources and Environmental Policy in the Era of Global Change. Volume 3: Computable General Equilibrium Models. 4 volumes. World Scientific, pp. 399–442.

EC (2015): EU ETS Handbook. European Commission (EC). Available online at https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf, checked on 7/11/2018.

ICAP (2016): Emissions Trading Worldwide. Status Report 2016. With assistance of Marissa Santikarn, Alexander Eden, Lina Li, William Acworth, Iurii Banshchikov, Aki Kachi et al. Edited by International Carbon Action Partnership (ICAP). International Carbon Action Partnership (ICAP). Berlin. Available online at https://icapcarbonaction.com/images/StatusReport2016/ICAP_Status_Report_2016_Online.pdf, checked on 7/11/2018.

Joltreau, Eugénie; Sommerfeld, Katrin (2018): Why does emissions trading under the EU Emissions Trading System (ETS) not affect firms' competitiveness? Empirical findings from the literature. In *Climate Policy* 19 (4), pp. 453–471. DOI: 10.1080/14693062.2018.1502145.

Klepper, G.; Peterson, S. (2006a): Emissions Trading, CDM, JI and More—The Climate Strategy of the EU. In *Energy Journal* 27 (2), pp. 1–26. DOI: 10.5547/ISSN0195-6574-EJ-Vol27-No2-1.

Klepper, G.; Peterson, S. (2006b): Marginal Abatement Cost Curves in General Equilibrium, The Influence of World Energy Prices. In *Resource and Energy Economics* 28 (1), pp. 1–23.

Martin, Ralf; Muûls, Mirabelle; Wagner, Ulrich J. (2016): The Impact of the European Union Emissions Trading Scheme on Regulated Firms. What Is the Evidence after Ten Years? In *Rev Environ Econ Policy* 10 (1), pp. 129–148. DOI: 10.1093/reep/rev016.

Naegele, Helene; Zaklan, Aleksandar (2019): Does the EU ETS cause carbon leakage in European manufacturing? In *Journal of Environmental Economics and Management* 93, pp. 125–147. DOI: 10.1016/j.jeem.2018.11.004.

Peters, J. C. (2016): The GTAP-power data base: disaggregating the electricity sector in the GTAP data base. In *Journal of Global Economic Analysis* 1 (1), pp. 209–250, checked on 1/30/2019.

Springer, K. (1998): The DART General Equilibrium Model: A Technical Description. In *Kiel Working Paper* (883).

Springer, K. (2002): Climate Policy in a Globalizing World: A CGE Model with Capital Mobility and Trade. Berlin: Springer (Kieler Studien).

Stone, Richard (1954): Linear Expenditure Systems and Demand Analysis: An Application to the Pattern of British Demand. In *The Economic Journal* 64 (2555), pp. 511–527. Available online at https://www.jstor.org/stable/2227743, checked on 3/21/2019.

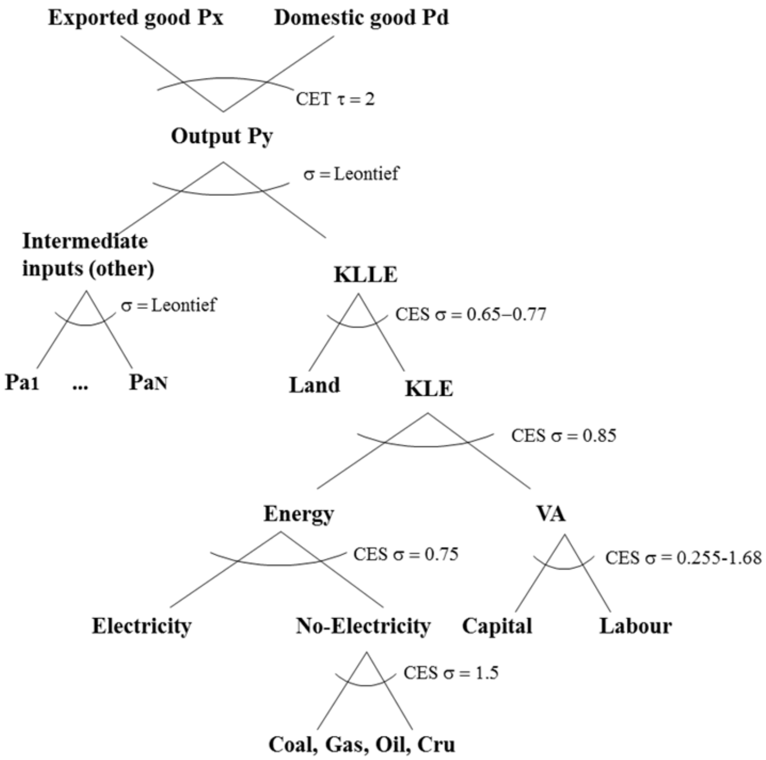
UNFCCC (2017): National Inventory Submissions 2017: EU28. UNFCCC. Available online at http://unfccc.int/national_reports/annex_i_THG_inventories/national_inventories_submissions/items/10116.php, checked on 10/10/2018.

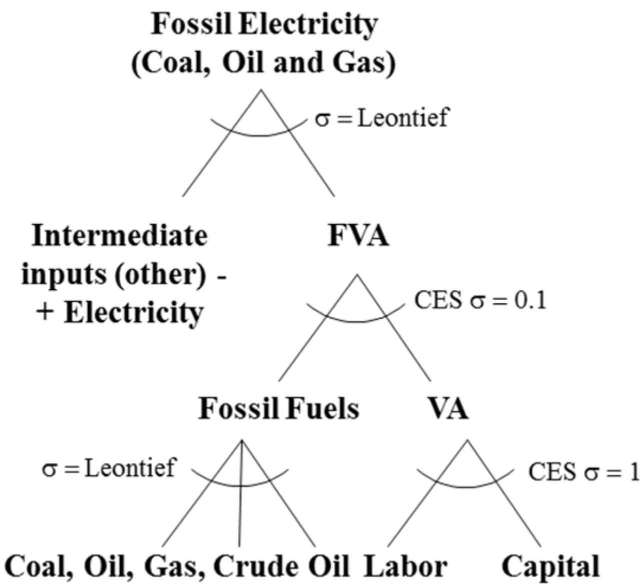
Verde, Stefano F. (2018): The impact of the EU Emissions Trading System on competitiveness and carbon leakage. European University Institute; Robert Schuman Centre for Advanced Studies (EUI Working Paper RSCAS, 2018/53). Available online at http://cadmus.eui.eu/bitstream/handle/1814/59564/RSCAS_2018_53rev.pdf?sequence=4&isAllowed=y, checked on 4/6/2019.

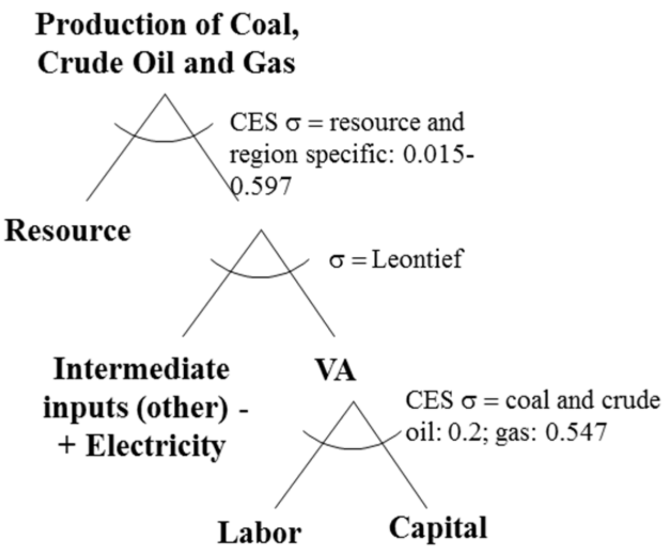
Weitzel, M. (2010): Including renewable electricity generation and CCS into. Kiel, Germany. Available online at https://www.ifw-kiel.de/fileadmin/Dateiverwaltung/IfW-Publications/Matthias_Weitzel/including-renewable-electricity-generation-and-ccs-into-the-dart-model/DART-renewables-ccs.pdf, checked on 4/8/2019.

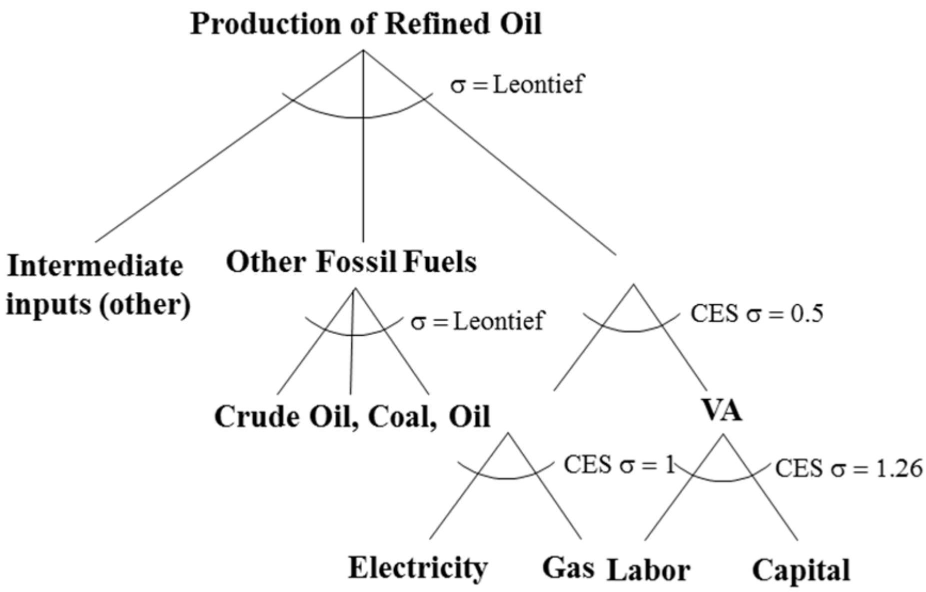
Weitzel, M.; Hübler, M.; Peterson, S. (2012): Fair, Optimal or Detrimental? Environmental vs. Strategic Use of Carbon-Based Border Measures. In *Energy Economics* 34 (Supplement 2), S198-S207. DOI: 10.1016/j.eneco.2012.08.023.

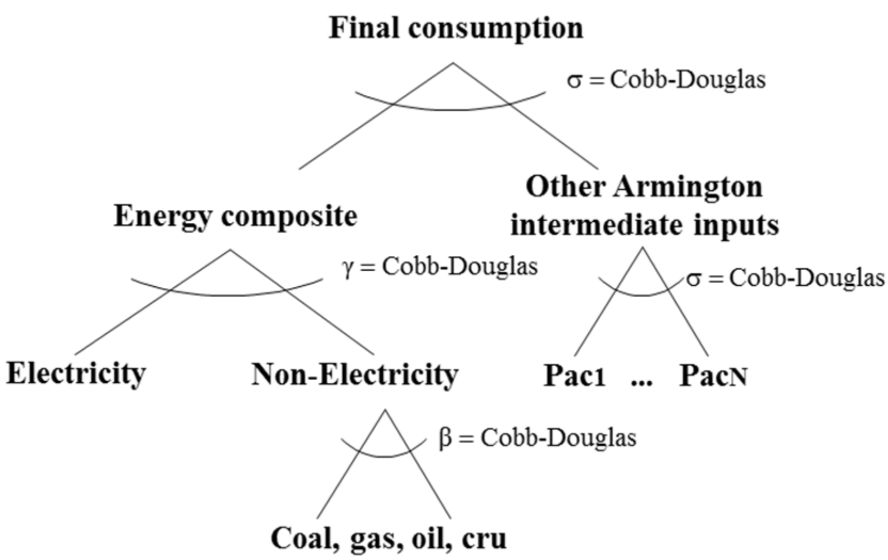
Annex 1: Nesting in Dart-Clim

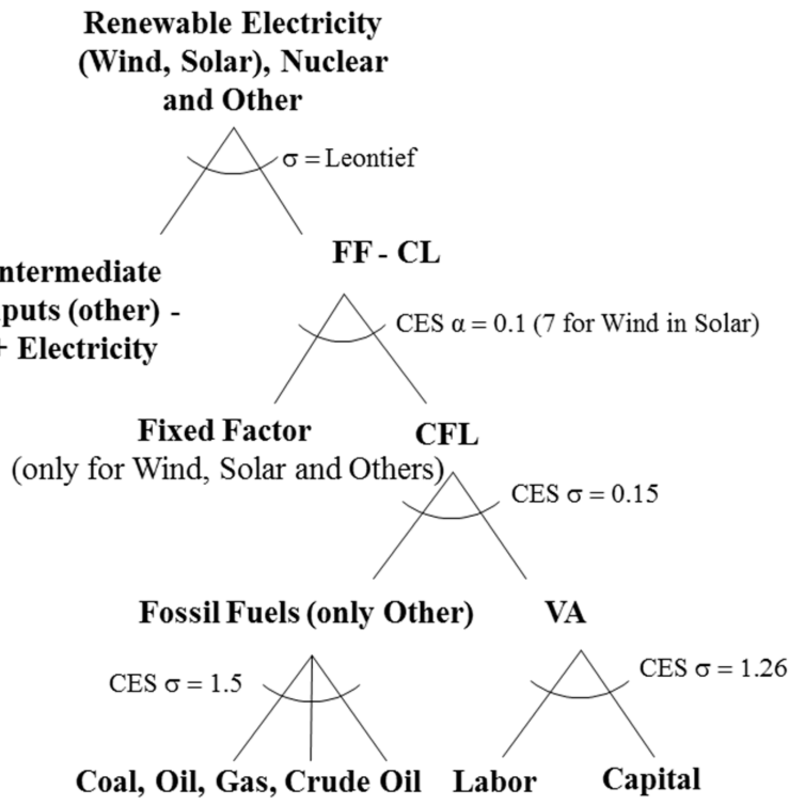





Production of Coal, Crude Oil and Gas
CES σ = resource and region specific: 0.015-0.597
Resource
σ = Leontief
Intermediate inputs (other) - + Electricity
VA
CES σ = coal and crude oil: 0.2; gas: 0.547
Labor
Capital


Production of Refined Oil
σ = Leontief
Intermediate inputs (other)
Other Fossil Fuels
σ = Leontief
Crude Oil, Coal, Oil
CES σ = 0.5
VA
CES σ = 1
Electricity
Gas
CES σ = 1.26
Labor
Capital


Final consumption
σ = Cobb-Douglas
Energy composite
γ = Cobb-Douglas
Electricity
Non-Electricity
β = Cobb-Douglas
Coal, gas, oil, cru
Other Armington intermediate inputs
σ = Cobb-Douglas
Pac1 ... PacN


Renewable Electricity (Wind, Solar), Nuclear and Other
σ = Leontief
Intermediate inputs (other) - + Electricity
FF - CL
CES α = 0.1 (7 for Wind in Solar)
Fixed Factor (only for Wind, Solar and Others)
CFL
CES σ = 0.15
Fossil Fuels (only Other)
VA
CES σ = 1.5
CES σ = 1.26
Coal, Oil, Gas, Crude Oil
Labor
Capital