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Working Paper

Mission Impossible!? On the Harmonization of National Allocation Plans under the EU Emissions Trading Directive

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Nontechnical Summary

Starting in 2005, the EU will introduce an EU-wide carbon emissions trading system to promote cost-efficiency of aggregate EU emission abatement (EU 2003). By implementing the EU Directive, the first multi-national trading scheme will become operative. It covers energy-intensive installations in five downstream sectors that account for the larger part of the overall EU carbon emissions: power, heat and steam generation, oil refineries, coke ovens in iron and steel production, mineral industries (e.g. glass, cement) as well as pulp and paper plants. Member States must allocate 95 % of emission allowances for free until 2008 and can auction at most 10 per cent of the allowances in the second period 2008-2012 (Article 10, EU 2003).

In this paper we show that it is generally impossible to retain overall economic efficiency when requiring free allocation of allowances *and* non-discrimination of firms across countries. In general, the assignment of allowances is endogenous and differs widely across countries, thereby substantiating concerns for implicit state aid and competitive distortions. Thus, the stated objectives of the European Directive – efficiency, harmonization ("rule neutrality" and "competition neutrality"), and free allocation of allowances – are incompatible.

An efficient way out of the current regulation dilemma posed by the multiple objectives of the EU Directive could be to relax the requirement of free allocation. Then, the minimal fraction of allowances which must be allocated is given by the minimum of assignment factors across EU Member States. As a mean to heading towards a more harmonized allocation of allowances, a continuous increase of the auctioned ratio of tradable allowances may prove a realistic policy option.

Mission Impossible !?

On the Harmonization of National Allocation Plans under the EU Emissions Trading Directive

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Abstract. Starting in 2005, the EU will implement a CO_2 emissions trading scheme. In this paper we show that the outspoken goals of economic efficiency and free allocation of allowances are incompatible with harmonized allocation rules. In general, the assignment of allowances is endogenous and differs widely across countries, thereby substantiating concerns for implicit state aid and competitive distortions. We discuss potential adjustments to the Directive in order to allow for harmonization, i.e. for identical assignment factors to similar firms located in different EU countries.

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1. Introduction

Starting in 2005, the EU will introduce an EU-wide carbon emissions trading system to promote cost-efficiency of aggregate EU emission abatement (EU 2003). By implementing the EU Directive, the first multi-national trading scheme will become operative. The envisaged trading scheme represents part of the EU efforts to cut its greenhouse gas emissions by 8 % by 2008-2012 (as committed to under the Kyoto Protocol) and 70 % in the longer term (as stated in the preamble of the Directive) compared to 1990 emission levels.[1] It covers energy-intensive installations in five downstream sectors that account for the larger part of the overall EU carbon emissions: power, heat and steam generation, oil refineries, coke ovens in iron and steel production, mineral industries (e.g. glass, cement) as well as pulp and paper plants. Member States must allocate 95 % of emission allowances for free until 2008 and can auction at most 10 per cent of the allowances in the second period 2008-2012 (Article 10, EU 2003).

We show that these provisions of the Directive, namely efficiency and the free allocation of allowances, are in conflict with the goal of harmonized allowance allocation rules. Each Member State is required by the EU Directive to lay down these rules in National Allocation Plans. Within the National Allocation Plans, each Member State (i) fixes the quantity of allowances it intends to allocate to installations covered by the Directive (allocation budget), and (ii) states rules to assign these allowances to the respective installations (allocation mechanism). Complementary abatement policies must be pursued in the sectors not covered by the Directive to balance the countries' emissions budgets which are given by the EU burden sharing agreement (EU 1999). The National Allocation Plans will be scrutinized by the Commission with respect to "common criteria" such as competitive distortions (Annex III, EU 2003). However, as there is no explicit harmonization of allocation plans across countries, concerns persist that differences in the assignment of free emission allowances to firms could distort competition.

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[1] Note that the EU Directive will become effective independent of the enactment of the Kyoto Protocol which still requires the (rather uncertain) ratification by Russia.

Whereas such distortions from a more narrow economic perspective, i.e. in terms of overall efficiency losses, can be prevented by relying on lump-sum allocation mechanisms,[2] Woerdman (2001, 2003) identifies different implicit financial (lump-sum) transfers to similar firms and the resulting distortion of the `level playing field' as a competitive distortion from the legal point of view.

Utilizing this definition, we illustrate by means of a simple partial analytical model that distortions are inherent to the setup of the European emissions trading system as envisaged under the EU Directive. Different from one-jurisdictional trading schemes like the U.S. SO_2 market, reaching efficiency with free allowances implies that identical firms operating in different countries will generally receive different emission assignments. That is, the assignment factor - for example in an emissions-based (grandfathering) allocation scheme - is endogenous in *each* country. Due to this endogeneity, any harmonization of assignment factors to preserve "competition neutrality" has to go along with country-specific adjustments in the allocation rules. Concretely, we illustrate that uniform assignment factors can be reached without affecting economic efficiency through changes in the prescription of free allocation. As an alternative, country-specific allocation budgets could be adjusted. However, such an adjustment will typically induce inefficient emission levels in at least some sectors.

2. The Endogeneity Problem

We use a simple partial two-sector, multi-region model to illustrate the problem of endogeneity and competitive distortions within the multi-jurisdictional setting of the EU Directive. Each region *r* can allocate an overall exogenous emission budget $\overline{E}_r$[3] to either installations in the sectors covered by the Directive or to the remaining sectors of the region.[4] Whereas the former are eligible for international emissions trading (*TRD*), the latter will not

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[2] The allowance allocation may not be affected by (upcoming) firms' decisions - see Böhringer and Lange (2003a, b) for a recent discussion of dynamic allocation rules and the implicit trade-off between economic efficiency and compensation.

[3] In the EU case, the aggregate emission targets are given by the EU burden sharing agreement which distributes the EU-wide Kyoto emission target across individual Member States (EU 1999).

[4] Note that *sector* is used as a more general term of a certain grouping of installations or firms that have similar characteristics and access to similar technologies.

be trading at the international level (*NTR*), i.e. these sectors are subject to complementary domestic regulation (such as e.g. a domestic carbon tax).

Sectors are represented by aggregate abatement cost functions $C_{r,s}(e_{r,s})$ (decreasing, convex, differentiable) where $s \in \{TRD, NTR\}$.[5] The historic emission levels prior to the establishment of the (partial) emissions trading system are denoted by $e_{r,s}^0$ yielding aggregate emission levels $E_r^0 = e_{r,TRD}^0 + e_{r,NTR}^0$.

Reflecting the requirements of National Allocation Plans, each regional government must decide on (i) the allocation budget, i.e. the number of allowances $\bar{e}_{r,TRD}$ it allocates to the sectors covered by the Directive, and (ii) the allocation mechanism, i.e. a specific allocation metric, $g_r(\cdot)$,[6] of free allowances to sectors eligible for international emissions trading; the allocation mechanism maps firm-specific data like (historic) emissions into emissions-assignments. At the national level, the choice of the allocation budget $\bar{e}_{r,TRD}$ must be consistent with the overall exogenous emission budget $\bar{E}_r$, i.e. $\bar{e}_{r,TRD} = \bar{E}_r - e_{r,NTR}$, where $e_{r,NTR}$ denotes the implicit upper bound on emissions for the non-trading sectors outside the EU Directive.

It is obvious that balancing a given choice for $\bar{e}_{r,TRD}$ and the allocation metric $g_r(\cdot)$ requires some endogenous assignment factor: $\bar{e}_{r,TRD} = \lambda_r g_r(\cdot)$. Therefore, even if countries use the same allocation metric $g_r(\cdot) = g(\cdot)$, there is an obvious "trade-off" between the choice of the allocation budget and the implementation of identical assignment factors.

To illustrate this point in more detail, we consider allocations based on grandfathering. Here, the metric $g_r(\cdot)$ is given by historic emissions $e_{r,TRD}^0$. Provided that all allowances are allocated for free, the assignment factor under such a lump-sum emissions-based allocation

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[5] Note that with such a representation of abatement costs, we implicitly assume that the emission target is distributed efficiently across installations inside TRD and inside NTR ,respectively.

[6] $g_r(\cdot)$ captures the functional relationships for the allocation metric, that could include updated or historic emission levels, emission intensities, etc.

rule is endogenously given by $\lambda_r = \frac{\overline{e}_{r,TRD}}{e^0_{r,TRD}} = \frac{\overline{E}_r - e_{r,NTR}}{e^0_{r,TRD}}$.[7] Obviously, we obtain the

following (region-specific) determinants for the assignment factor:

- The larger the overall emission target $\overline{E}_r$, the larger the assignment factor will be.

- The larger the emission budget for the *NTR* sectors, the smaller the allocation budget for the *TRD* sectors and, hence, the smaller the assignment factor will be.

- The smaller the historic level $e^0_{r,TRD}$ of emissions in trading sectors, the larger the assignment factor will be.[8]

Following the `level playing field' argument by Woerdman (2002), allocation schemes should not discriminate between firms having the same characteristics but operating in different countries. In other words: The assignment factors should not differ across regions, i.e. $\lambda_r = \lambda_{r'}$ for all r, r'. Unless regions were to be fully symmetric, this poses a trade-off between "rule neutrality" and "competition neutrality" since the adaptation of the same rules for determining the allocation budget and the allocation metric generally imposes different assignment factors for identical firms in different regions.

3.   Cost-efficient Design of National Allocation Plans

According to the EU Directive, Member States – in setting up the National Allocation Plans – first have to decide on the allocation budget, i.e. the aggregate number of (free) allowances they set aside for the trading sectors. The simplest proposal (see e.g. DIW et al. 2003) involves a uniform reduction in percental emissions across trading and non-trading sectors based on historic emission levels. In this case, the assignment factor to trading sectors in

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[7] For an analysis of distortionary output- and emission-based allocation in a dynamic setting see Böhringer and Lange (2003a,b) and Fischer (2001). In the German debate on the National allocation plan, some more sophisticated non-uniform emission-based allocation schemes have been proposed which account for sector-specific characteristics and early action. By requiring more sector-specific information, however, differentiated rates lead to more possibilities for lobbying by sector-specific interest groups (Stavins 1998, p.79). The resulting sector-specific assignment factors cannot prevent the described endogeneity problem.

[8] In particular, this implies that firms in regions that had faced a stricter historic regulation (or early action etc.) will be partly compensated by higher transfers compared to other regions.

region r would be given by $\lambda_r = \dfrac{\overline{E}_r}{E_r^0}$ where E_r^0 denotes a historic aggregate emission level

for region r. Apart from conflicting with the `level-playing-field' objective, such a proposal

induces potentially large efficiency losses since marginal abatement costs between the trading

and non-trading sectors will generally fall apart. A cost-efficient design of National

Allocation Plans across the European Union (as explicitly pursued under Article 1 of the EU

Directive) implies that aggregate abatement costs $\sum_{r,s} C(e_{r,s})$ should be minimized subject

to the aggregate emission target $\sum_{r,s} e_{r,s} = \sum_r \overline{E}_r$ which leads to $\sigma^* = -C'_{r,s}(e_{r,s}^*)$ for all s

$\in$ {*TRD, NTR*} and r, i.e. equalized marginal abatement costs across all regions and sectors.

If we assume the implementation of the cost-efficient emission level $e_{r,NTR}^*$ in the non-

trading sectors[9], the regulator in region r can issue at most $\overline{E}_r - e_{r,NTR}^*$ allowances to the

trading sectors. As the uniform emissions-based allocation of $\overline{e}_{r,TRD}$ is lump-sum, efficiency

can be reached and the country-specific assignment factors are endogenously determined

by $\lambda_r = \dfrac{\overline{E}_r - e_{r,NTR}^*}{e_{r,TRD}^0}$. The concrete assignment factor depends on various region-specific

characteristics such as the effective emission reduction requirement ($\overline{E}_r$), the relative ease of

carbon reduction in the trading sectors vis-à-vis the non-trading sectors (determining $e_{r,NTR}^*$)

as well as historic emissions $e_{r,TRD}^0$.

Table 1 reports the implied differences of assignment factors across EU member

countries according to simulations with an established multi-region, multi-sector computable

general equilibrium (CGE) model (see e.g. Böhringer 2002a,b or Böhringer and Vogt 2003).

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[9] Cost-minimizing firms that are covered by the Directive will reach optimal emission levels
$e_{r,TRD}^*$ through international emissions trading if the total number of allowances is given by
$\sum_r e_{r,TRD}^* = E_{TRD}^*$. Regarding the overall cost-efficient regulation of sectors that are not covered by
the Directive, each region would have to set a carbon tax equal to the emission price σ^*; alternatively,
the region could establish a domestic permit market and auction off $\sum_r e_{r,NTR}^* = E_{NTR}^*$ to sectors $s \in$
{*NTR*}.

The model is based on most recent consistent accounts of EU Member States' production and consumption, bilateral trade and energy flows for 1997 (as provided by the GTAP5-E database – see McDougall et al. 1999). A detailed model description is provided in Appendix A which is available from *ftp://ftp.zew.de/pub/zew-docs/div/nap_cge.pdf*.

The column labeled "CO_2 emissions – 1990" provides the baseline emissions for 1990 which is the reference year for the emission reduction commitments under the Kyoto Protocol. The Member States' reduction targets under the EU burden sharing agreement are reported in the column labeled "Kyoto targets". The third column "CO_2 emission budget $\overline{E}_r$" gives the resulting overall cap $\overline{E}_r$. The CO_2 emissions for the (model's) base-year 1997 are summarized in column "CO_2 emissions – 1997". These emissions combined with the overall Kyoto budget $\overline{E}_r$ yield the effective reduction targets with respect to 1997 base-year emission levels (column "Effective targets"). Column "CO_2 emissions by trading sectors – 1997" indicates the base-year emissions of those sectors (installations) that are covered by the EU Directive: power, heat and steam generation, oil refineries, coke ovens in iron and steel production, mineral industries (e.g. glass, cement) as well as pulp and paper plants. Next, the column labeled "Cost-efficient CO_2 emissions $e^*_{r,NTR}$" states the (optimal) least-cost[10] emissions in the non-trading sectors emerging from the CGE calculations where we apply the effective reduction targets to the 1997 base-year EU economy. The assignment factors (column "Assignment factors") are then derived via $\lambda_r = \dfrac{\overline{E}_r - e^*_{r,NTR}}{e^0_{r,TRD}}$ where $e^0_{r,TRD}$ represents the 1997 base-year emissions of the trading sectors. The differences across EU Member States are substantial ranging from 0.34 in Denmark up to 1.24 for The Netherlands. Given identical historic emissions levels, a firm in The Netherlands would thus be assigned nearly four times the number of allowances given to the Danish firm.

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[10] That is, marginal abatement costs are equalized across all regions and sectors.

Table 1: Assignment factors under the EU Directive for emissions-based allocation of free allowances (based on 1997 data)

	1990 CO_2 emissions	Kyoto targets	CO_2 emission budget $\overline{E}_r$	1997 CO_2 emissions	Effective targets	1997 CO_2 emissions by trading sectors $e^0_{r,TRD}$	Cost-efficient CO_2 emissions[a] $e^*_{r,NTR}$	Assignment factor λ_r[b]	Minimum assignment factor $\lambda_{min}=\min_r\{\lambda_r\}$	Auction
	[Mt]	[% vis-à-vis 1990]	[Mt]	[Mt]	[% vis-à-vis 1997]	[Mt]	[Mt]			[% of ($\overline{E}_r - e^*_{r,NTR}$)]
Austria	50	13.0	43	54	19.6	17	36	0.41	0.34	17
Belgium	118	7.5	109	132	17.5	33	95	0.42	0.34	19
Germany	975	21.0	770	858	10.3	355	484	0.80	0.34	58
Denmark	55	21.0	44	68	35.8	35	32	0.34	0.34	0
Spain	214	-15.0	247	259	4.8	83	27	0.81	0.34	58
Finland	52	0.0	52	59	10.9	31	313	1.13	0.34	70
France	378	0.0	378	384	1.6	57	328	0.90	0.34	62
United Kingdom	558	12.5	488	522	6.5	177	46	1.21	0.34	72
Greece	71	-25.0	89	84	-6.5	35	17	0.88	0.34	61
Ireland	26	-13.0	29	32	8.3	14	257	0.81	0.34	58
Italy	394	6.5	369	405	8.9	138	6	0.96	0.34	64
Luxembourg	9	28.0	7	7	9.5	1	153	0.57	0.34	40
Netherlands	200	6.0	188	222	15.1	62	35	1.24	0.34	73
Portugal	45	-27.0	57	54	-5.2	18	169	0.94	0.34	64
Sweden	53	-4.0	55	56	1.6	10	45	1.00	0.34	66
EU-15	3198	8.6	2925	3196	8.5	1066	2043	0.83	0.34	59

[a] based on CGE calculations

[b] calculated as $\lambda_r = \left(\overline{E}_r - e^*_{r,NTR} \right) / e^0_{r,TRD}$

Obviously, such an uneven treatment justifies major concerns regarding "competition neutrality" and stronger claims for a (at least partial) harmonization of assignment factors.

4. Ensuring „Competition Neutrality"

In our discussion of the endogeneity problem, we assumed "rule neutrality" in the sense that each government (i) implements the optimal (least-cost) emission level in sectors not covered by the Directive and (ii) allocates all of its remaining emission allowances for free to the Directive sectors eligible for international emissions trading. Obviously, a uniform assignment factor λ could be implemented by shifting the abatement burdens between non-trading sectors and trading sectors, i.e. by choosing $e_{r,NTR} = \overline{E}_r - \lambda e^0_{r,TRD}$. This, however, implies potentially large efficiency losses because marginal abatement costs would no longer be equalized between trading and non-trading sectors.

Another possibility which retains efficiency is to change the number of *freely* allocated allowances. For example, one could adopt the minimal (endogenous) assignment factor

$$\lambda_{\min} = \min_r \left\{ \lambda_r \right\}$$

as the allocation rule for country, and then let each country auction off its remaining allowances $e_{r,NTR} = \overline{E}_r - \lambda_{\min} e^0_{r,TRD}$ within the European trading scheme. While maintaining efficiency, this harmonization procedure towards "competition neutrality" requires a fraction of $1 - \lambda_{\min} / \lambda_r$ of allowances to be auctioned off.

The final column of Table 1 reports the necessary fraction of auctioning in EU Member States if the harmonized assignment factor were based on the minimal Danish factor (0.34). The auctioned fraction is largest for the U.K., the Netherlands, and Finland with more than 70 %. In our concrete numerical example, all auctioning rates (except for the minimum Danish one) conflict with the prescriptions of the current EU Directive in which only a maximum of 5 % (10 %) may be auctioned off.[11]

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[11] According to Article 12, Member States must allocate 95% of emission allowances for free until 2007 and can auction at most 10 percent of the allowances in the period 2008-2012 (Article 10, EU 2003).

5. Conclusions

We have shown that it is generally impossible to retain efficiency when requiring free allocation of allowances *and* non-discrimination of firms across countries. Thus, the stated objectives of the European Directive – efficiency, harmonization ("rule neutrality" and "competition neutrality"), and free allocation of allowances – are incompatible. Along the policy-relevant example of lump-sum grandfathering, we illustrated the huge differences in (endogenous) assignment factors which give rise to major concerns regarding competitive distortions from a legal point of view. In our simple partial model the associated differing transfers do not affect firms' emission choice and overall economic efficiency. However, in a more complex setting that incorporates income effects, economic distortions may also be non-negligible.[12]

An efficient way out of the current regulation dilemma posed by the multiple objectives of the EU Directive could be to relax the requirement of free allocation. Then, the minimal fraction of allowances which must be allocated is given by the minimum of assignment factors across EU Member States. As a mean to heading towards a more harmonized allocation of allowances, a continuous increase of the auctioned ratio of tradable allowances may prove a realistic policy option.

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[12] In the CGE model, all firms are owned by the representative agent in each region such that income effects within a region do not occur.

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Downloadable Appendix

(ftp://ftp.zew.de/pub/zew-docs/div/nap_cge.pdf)

Appendix A: CGE Model Summary

A.1. Non-technical model description

For determining the country-specific assignment factors λ_r as reported in Table 1 we make use of a 15-region, 9-sector computable general equilibrium (CGE) model for the EU economy calibrated to empirical data. At the sectoral level the model incorporates sufficient details on differences in factor intensities, degrees of factor substitutability and price elasticities of output demand in order to trace back the structural change induced by carbon abatement policies. The sectors in the model have been carefully selected to keep the most carbon-intensive sectors in the available data as separate as possible. Table A.1 provides an overview of the sectors represented in the model.

Table A.1: Overview of model regions and sectors (commodities)

EU member countries	Production sectors	
Austria	*Primary energy carriers*	
Belgium	COL	Coal
Germany	CRU	Crude oil
Denmark	GAS	Natural gas
Spain	*Energy-intensive sectors (EIS)*	
Finland	OIL	Refined oil products
France	ELE	Electricity
United Kingdom	ORE	Iron and steel
Greece	PPP	Paper, pulp, and printing
Ireland	NFM	Non-ferrous metals
Italy	*Remaining manufacturers and services*	
Luxembourg	ROI	Rest of Industry
Netherlands		
Portugal		
Sweden		

The energy goods identified in the model include primary carriers (coal, natural gas, crude oil) and secondary energy carriers (refined oil products and electricity). Furthermore, the model features three energy-intensive non-energy sectors (iron and steel; paper, pulp and printing; non-ferrous

metals) whose installations – in addition to the secondary energy branches (refined oil products and electricity) – are subject to the EU emissions trading Directive. The remaining manufacturers and services are aggregated to a composite industry that produces a non-energy-intensive macro good.

Figure A.1 provides a diagrammatic overview of the model structure. Primary factors of each EU region r include labor $\bar{L}_r$, capital $\bar{K}_r$, and fossil-fuel resources $\bar{Q}_{ff,r}$. Labor and capital are assumed to be mobile across sectors within each region. In fossil fuel production, part of capital is treated as a sector-specific resource, resulting in upward sloping supply schedules consistent with exogenous own-price elasticities of supply.

Production Y_{ir} of commodities i in region r, other than primary fossil fuels, is captured by aggregate production functions which characterize technology through substitution possibilities between various inputs. Nested, separable constant elasticity of substitution (CES) cost functions with three levels are employed to specify the substitution possibilities in domestic production between capital, labor, energy and non-energy intermediate inputs, i.e. material. At the top level, material inputs are employed in fixed proportions with an aggregate of energy, capital and labor. At the second level, a CES function describes the substitution possibilities between the energy aggregate and the aggregate of labor and capital. The value- added composite is a CES function of labor and capital. The energy aggregate is produced with a CES function of a non-electric energy composite and electricity. The non-electric energy composite in turn is a CES function of coal, crude oil, refined oil, and natural gas. In the production of fossil fuels, all inputs, except for the sector-specific fossil fuel resource, are aggregated in fixed proportions at the lower nest. At the top level, this aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution. The latter is calibrated in consistency with exogenous price elasticities of fossil fuel supply.

Final consumption demand C_r in each region is determined by a representative agent RA_r, who maximizes consumption subject to a budget constraint with fixed investment. Aggregate consumption of the representative agent is given as a CES composite which combines composite energy consumption with a non-energy consumption bundle.

III

Figure A.1: Diagrammatic model structure
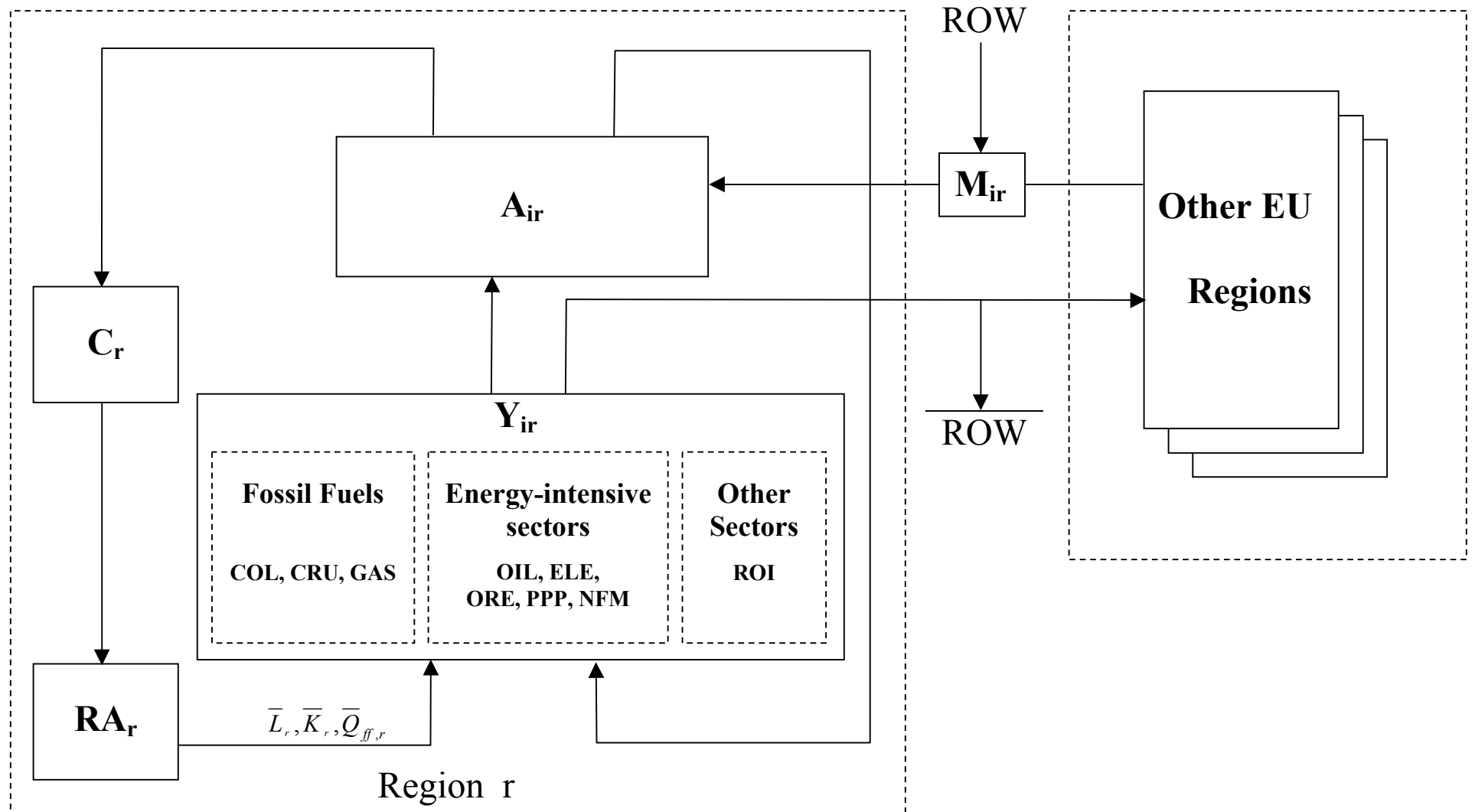
Substitution patterns within the non-energy consumption bundle are reflected via Cobb-Douglas functions. The energy aggregate in final demand consists of the various energy goods trading off at a constant elasticity of substitution. Government demand within each region is fixed at exogenous real levels. Public goods and services are produced with a CES aggregation of commodity inputs. The expenditure for public good provision is handled through the budget constraint of the representative agent.

Trade between regions is specified using the Armington approach of product heterogeneity, so domestic and foreign goods of the same variety are distinguished by origin. The Armington composite A_{ir} for a traded good is a CES function of an imported composite M_{ir} and domestic production for that sector. The import composite is then a CES function of an EU import composite and imports from the rest of the world (ROW). The EU import composite of a specific EU region in turn is a CES function of production from all other EU countries. EU countries are assumed to be price-takers with respect to world market prices, i.e. ROW import-supply functions and ROW export-demand functions are perfectly elastic. There is an imposed balance of payment constraint to ensure trade balance between the EU and ROW through a flexible exchange rate. That is, the value of imports from the ROW to the EU must equal the value of exports from the EU to the ROW after accounting for the benchmark trade deficit or surplus of EU regions.

The effects of exogenous policy changes are measured with respect to a reference situation. In our comparative-static analysis, the reference situation is captured by economic transactions in a particular benchmark year (here: 1997). As is customary in applied general equilibrium analysis, benchmark quantities and prices – together with exogenous elasticities (see Table A.7 below) – determine the parameters of functional forms. For this model calibration, we employ the GTAP-5E database (McDougall 1999)[13] which provides most recent consistent accounts of regional production and consumption, bilateral trade and energy flows for up to 66 countries and 23 commodities.

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[13] McDougall, R.A. (1999), ed., *Global Trade, Assistance and Protection: The GTAP 5 Data Base*, Center for Global Trade Analysis, Purdue University, West Lafayette.

A.2 Algebraic model description

The model is formulated as a system of nonlinear inequalities. These inequalities correspond to two classes of equilibrium conditions: zero profit and market clearance. The fundamental unknowns of the system are two vectors: activity levels and prices. In equilibrium, each of these variables is linked to one inequality condition: an activity level to a zero-profit condition and a commodity (factor) price to a market-clearance condition.

In the algebraic exposition below, the notation Π_{ir}^{z} is used to denote the (zero-)profit function of sector j in region r where z is the name assigned to the associated production activity. Differentiating the profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotellings's lemma), which appear subsequently in the market clearance conditions. We use i (aliased with j) as an index for commodities (sectors) and r (aliased with s) as an index for regions. The label *EG* represents the set of energy goods and the label *FF* denotes the subset of fossil fuels. Tables A.2 - A.7 explain the notations for variables and parameters employed within our algebraic exposition. Figures A.2 - A.6 provide a graphical exposition of the production and final consumption structure.

The implementation of cost-efficient National Allocation Plans across EU member states is equivalent to a comprehensive carbon trade equilibrium: Marginal abatement costs are equalized across all sectors and EU regions (to be achieved by domestic carbon taxes for non-trading sectors where the tax rate is set at the level of the international permit price for trading sectors). With lump-sum allocation of emission allowances to the trading sectors under the Directive and a representative agent per EU region, the revenues from carbon regulation – either in terms of tax revenues or the implicit value of free allowances – enter the budget constraint of the representative agent.

Zero Profit Conditions

1. Production of goods except fossil fuels:

$$\Pi_{ir}^{Y} = \left(\theta_{ir}^{XROW} p^{W^{1-\eta}} + (1-\theta_{ir}^{X})p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j \notin EG}\theta_{jir}p_{jr}^{A}$$

$$-\theta_{ir}^{KLE}\left[\theta_{ir}^{E}p_{ir}^{E\ 1-\sigma_{KLE}} + (1-\theta_{ir}^{E})\left(w_{r}^{\alpha_{jr}^{L}}v_{r}^{\alpha_{jr}^{K}}\right)^{1-\sigma_{KLE}}\right]^{\frac{1}{1-\sigma_{KLE}}} \leq 0 \qquad i \notin FF$$

where Y_{ir} ($i \notin ff$) is the associated activity variable.

2. Production of fossil fuels:

$$\Pi_{ir}^{Y} = \left(\theta_{ir}^{XROW}p^{W^{1-\eta}} + (1-\theta_{ir}^{X})p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}}$$

$$-\left[\theta_{ir}^{Q}q_{ir}^{1-\sigma_{Q,i}} + (1-\theta_{ir}^{Q})\left(\theta_{Lir}^{FF}w_{r} + \theta_{Kir}^{FF}v_{r} + \sum_{j}\theta_{jir}^{FF}p_{jr}^{A}\right)^{1-\sigma_{Q,i}}\right]^{\frac{1}{1-\sigma_{Q,i}}} \leq 0 \qquad i \in FF$$

where Y_{ir} ($i \in ff$) is the associated activity variable.

3. Sector-specific energy aggregate:

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

where E_{ir} is the associated activity variable.

4. Armington aggregate:

$$\Pi_{ir}^{A} = p_{ir}^{A} - \left[\left(\theta_{ir}^{A}p_{ir}^{1-\sigma_{A}} + (1-\theta_{ir}^{A})p_{ir}^{M^{1-\sigma_{A}}}\right)^{\frac{1}{1-\sigma_{A}}} + p_{r}^{CO2}a_{i}^{CO2}\right] \leq 0$$

where A_{ir} is the associated activity variable.

5. Aggregate imports across import regions:

$$\Pi_{ir}^{M} = p_{ir}^{M} - \left(\sum_{s}\theta_{isr}^{M}p_{is}^{X\ 1-\sigma_{M}} + \theta_{ir}^{MROW}p^{W\ 1-\sigma_{M}}\right)^{\frac{1}{1-\sigma_{M}}} \leq 0$$

where M_{ir} is the associated activity variable.

6. Household consumption aggregate:

$$\Pi_r^C = p_r^C - \left(\theta_{Cr}^E \, p_{Cr}^E \,^{1-\sigma_{EC}} + (1-\theta_{Cr}^E) \left[\prod_{i \notin FF} p_{ir}^{A^{\gamma_{ir}}} \right)^{1-\sigma_{EC}} \right]^{\frac{1}{1-\sigma_{EC}}} \le 0$$

where C_r is the associated activity variable.

7. Household energy aggregate:

$$\Pi_{Cr}^E = p_{Cr}^E - \left[\sum_{i \in FF} \theta_{iCr}^E \, p_{ir}^A \,^{1-\sigma_{FF,C}} \right]^{\frac{1}{1-\sigma_{FF,C}}} \le 0$$

where E_{Cr} is the associated activity variable.

8. Investment:

$$\Pi_r^I = p_r^I - \sum_i \theta_{ir}^I \, p_{ir}^A \le 0$$

where I_r is the associated activity variable.

Market Clearance Conditions

9. Labor:

$$\overline{L}_r \ge \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial w_r}$$

where w_r is the associated price variable.

10. Capital:

$$\overline{K}_r \ge \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial v_r}$$

where v_r is the associated price variable.

11. Natural resources:

$$\overline{Q}_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial q_{ir}} \qquad i \in FF$$

where q_{ir} is the associated price variable.

12. Output for internal markets:

$$Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}} \geq A_{ir} \frac{\partial \Pi_{ir}^A}{\partial p_{ir}} + \sum_{s \neq r} M_{is} \frac{\partial \Pi_{is}^M}{\partial p_{ir}}$$

where p_{ir} is the associated price variable.

13. Sector-specific energy aggregate:

$$E_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^E}$$

where p_{ir}^E is the associated price variable.

14. Import aggregate:

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

where p_{ir}^M is the associated price variable.

15. Armington aggregate:

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

where p_{ir}^A is the associated price variable.

16. Investment aggregate:

$$\overline{I}_r \geq I_r$$

where p_r^I is the associated price variable.

17. Household consumption:

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

where p_r^C is the associated price variable.

18. Aggregate household energy consumption:

$$E_{Cr} = C_r \frac{\partial \Pi_r^C}{\partial p_{Cr}^E}$$

where p_{Cr}^E is the associated price variable.

19. Carbon emissions:

$$\overline{CO2}_r = \sum_i A_{ir} a_i^{CO2}$$

where p_r^{CO2} is the associated price variable.

20. Balance of payments:

$$\sum_{i,r} Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p^W} + \sum_r \overline{B}_r = \sum_{i,r} M_{ir} \frac{\partial \Pi_{ir}^M}{\partial p^W}$$

where p^W is the associated price variable.

Table A.2: Sets

I	Sectors and goods
J	Aliased with i
R	Regions
S	Aliased with r
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas
LQ	Liquid fuels: Crude oil and gas

Table A.3: Activity variables

Y_{ir}	Production in sector i and region r
E_{ir}	Aggregate energy input in sector i and region r
M_{ir}	Aggregate imports of good i and region r
A_{ir}	Armington aggregate of good i in region r
C_r	Aggregate household consumption in region r
E_{Cr}	Aggregate household energy consumption in region r
I_r	Aggregate investment in region r

X

Table A.4: Price variables

p_{ir}	Output price of good i produced in region r for domestic market
p^W	Real exchange rate with the rest of the world (ROW)
p_{ir}^E	Price of aggregate energy in sector i and region r
p_{ir}^M	Import price aggregate for good i imported to region r
p_{ir}^A	Price of Armington good i in region r
p_r^C	Price of aggregate household consumption in region r
p_{Cr}^E	Price of aggregate household energy consumption in region r
p_r^I	Price of aggregate investment good in region r
w_r	Wage rate in region r
v_r	Price of capital services in region r
q_{ir}	Rent to natural resources in region r ($i \in$ FF)
p_r^{CO2}	Shadow price of CO_2 unit in region r

Table A.5: Cost shares

θ_{ir}^{XROW}	Share of ROW exports in sector i and region r
θ_{jir}	Share of intermediate good j in sector i and region r ($i \notin$ FF)
θ_{ir}^{KLE}	Share of KLE aggregate in sector i and region r ($i \notin$ FF)
θ_{ir}^E	Share of energy in the KLE aggregate of sector i and region r ($i \notin$ FF)
α_{ir}^T	Share of labor ($T=L$) or capital ($T=K$) in sector i and region r ($i \notin$ FF)
θ_{ir}^Q	Share of natural resources in sector i of region r ($i \in$ FF)
θ_{Tir}^{FF}	Share of good i ($T=i$) or labor ($T=L$) or capital ($T=K$) in sector i and region r ($i \in$ FF)
θ_{ir}^{COA}	Share of coal in fossil fuel demand by sector i in region r ($i \notin$ FF)
θ_{ir}^{ELE}	Share of electricity in energy demand by sector i in region r
β_{jir}	Share of liquid fossil fuel j in energy demand by sector i in region r ($i \notin$ FF, $j \in$ LQ)
θ_{isr}^M	Share of imports of good i from region s to region r
θ_{ir}^{MROW}	Share of ROW imports of good i in region r
θ_{ir}^A	Share of domestic variety in Armington good i of region r

θ^E_{Cr}	Share of fossil fuel composite in aggregate household consumption in region r	
θ^I_{ir}	Share of good i in investment composite in region r	
γ_{ir}	Share of non-energy good i in non-energy household consumption demand in region r	
θ^E_{iCr}	Share of fossil fuel i in household energy consumption in region r	

Table A.6: Endowments and emissions coefficients

$\overline{L}_r$	Aggregate labor endowment for region r	
$\overline{K}_r$	Aggregate capital endowment for region r	
$\overline{Q}_{ir}$	Endowment of natural resource i for region r ($i \in FF$)	
$\overline{B}_r$	Balance of payment deficit or surplus in region r (note: $\sum_r \overline{B}_r = 0$)	
$\overline{CO_2}_r$	Endowment of carbon emission rights in region r	
$a^{CO_2}_i$	Carbon emissions coefficient for fossil fuel i ($i \in FF$)	

Table A.7: Elasticities

η	Transformation between production for the domestic market and production for the export	4
σ_{KLE}	Substitution between energy and value-added in production (except fossil fuels)	0.5
$\sigma_{Q,i}$	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF}.	μ_{COA}=0.5 μ_{CRU}=0.5 μ_{GAS}=1.0
σ_{ELE}	Substitution between electricity and the fossil fuel aggregate in production	0.3
σ_{COA}	Substitution between coal and the liquid fossil fuel composite in production	0.5
σ_A	Substitution between the import aggregate and the domestic input	2
σ_M	Substitution between imports from different regions	4
σ_{EC}	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.8
$\sigma_{FF,C}$	Substitution between fossil fuels in household fossil energy consumption	0.3

For the sensitivity analysis reported in Appendix B the lower and upper values of the uniform probability distributions for six key elasticities are as follows:

$1 < \sigma_A < 4$; $2 < \sigma_M < 8$; $0.25 < \sigma_{KLE} < 0.75$; $0.6 < \sigma_{EC} < 1$; $0.25 < \mu_{CRU} < 1$; $0.25 < \mu_{COL} < 1$.

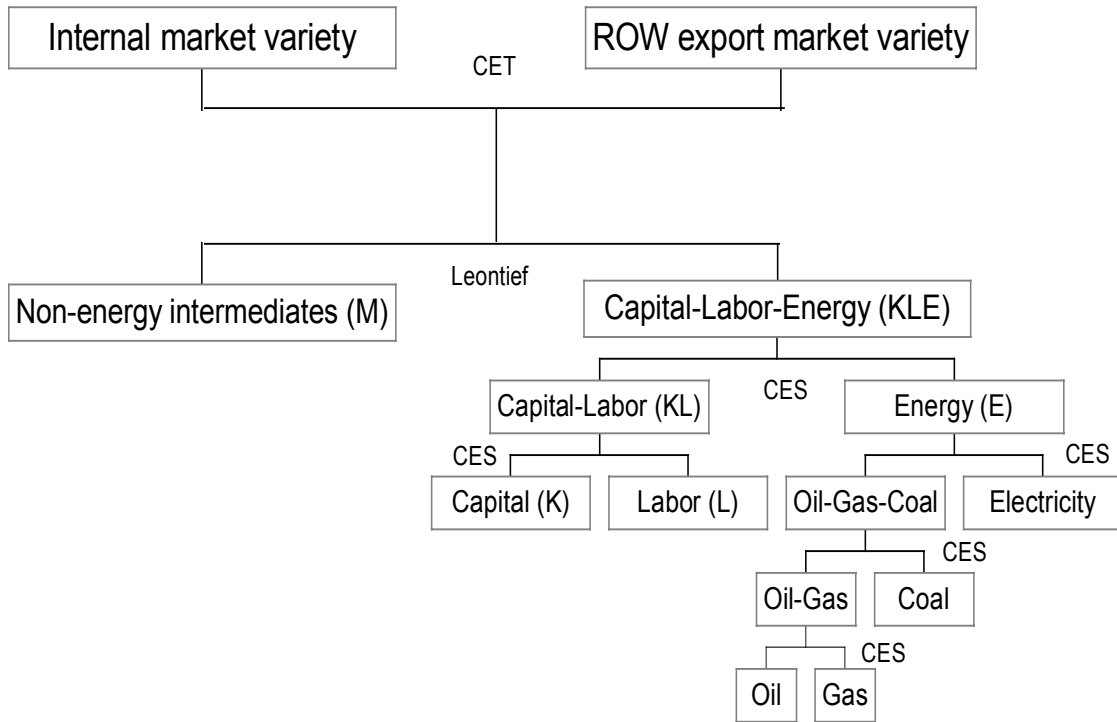Figure A.2: Nesting in non-fossil fuel production
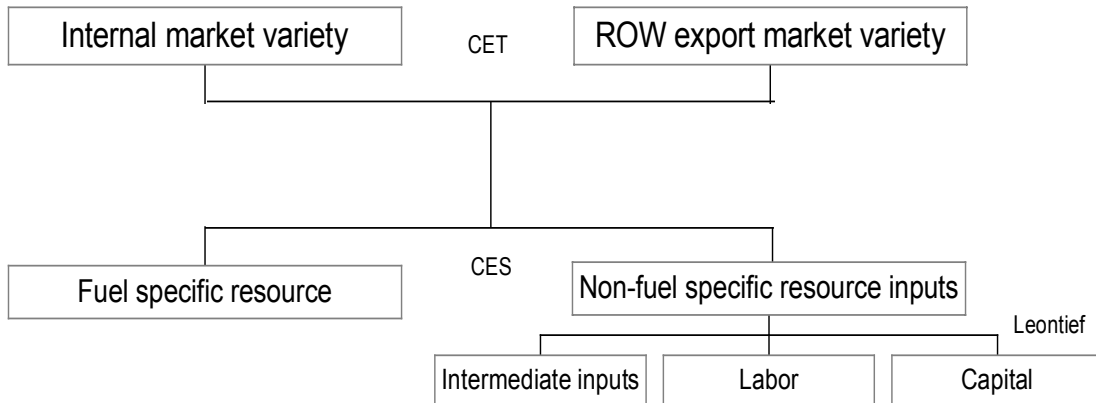

Figure A.3: Nesting in fossil fuel production

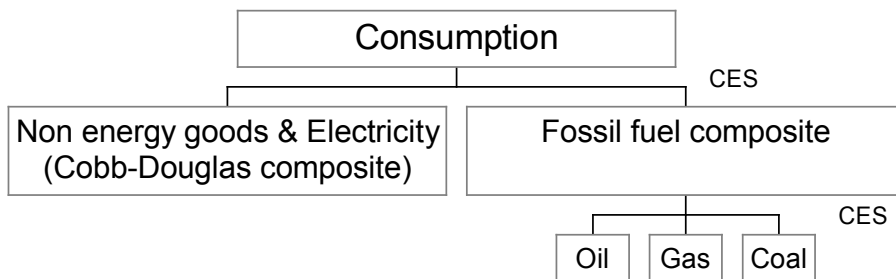Figure A.4: Nesting in household consumption

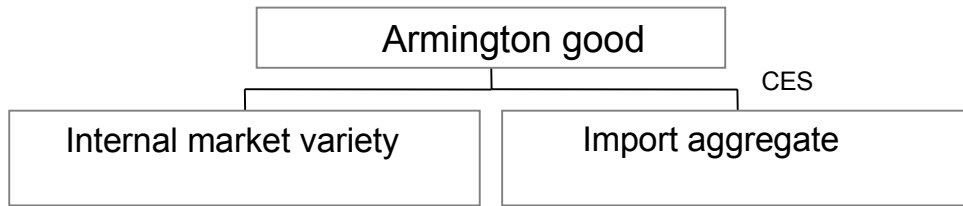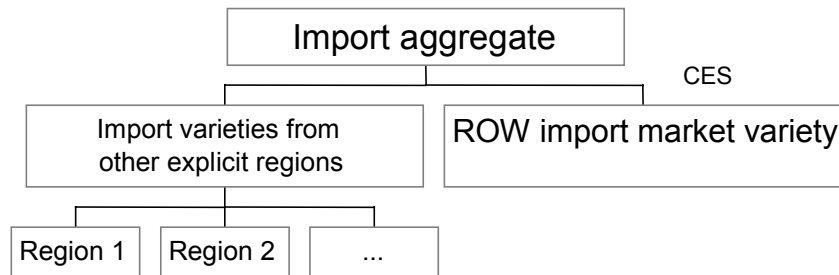Figure A.5: Nesting in Armington production

Figure A.6: Nesting in import aggregate

Appendix B: Sensitivity Analysis

In order to evaluate the sensitivity of our core simulation results with respect to uncertainties in the elasticity space we have conducted 1000 Monte Carlo simulations. In each simulation, values for six elasticities (trade elasticities, energy demand elasticities and fossil fuel supply elasticities) that are key determinants for the economic adjustment associated with carbon emission constraints are drawn from uniform probability distributions around the model central values (see Table A.7 in Appendix A).

Table B.1 provides a statistical summary of results for the cost-efficient emission allocation to the non-trading sectors (and, thus, also to the trading sectors), the assignment factors as well as the share of tradable allowances that must be auctioned within each region in order to preserve competition neutrality. It is obvious that all of our central case CGE estimates remain very robust even when accounting for substantial uncertainty in the parameterization space.

Table B.1: Sensitivity analysis

	core value	5% quantile	median	mean	95% quantile	standard deviation
Cost-efficient CO$_2$ emissions e$^*_{NTR}$ [Mt]						
Austria	36	36	36	36	36	0.00
Belgium	95	95	95	95	96	0.45
Germany	484	481	483	483	486	1.68
Denmark	32	32	32	32	32	0.16
Spain	27	168	169	169	171	1.04
Finland	313	27	27	27	27	0.00
France	328	312	313	313	315	1.02
United Kingdom	46	327	328	328	329	0.60
Greece	17	46	46	46	47	0.48
Ireland	257	17	17	17	18	0.49
Italy	6	256	257	257	258	0.60
Luxembourg	153	6	6	6	6	0.00
Netherlands	35	152	153	153	153	0.39
Portugal	169	34	35	35	35	0.36
Sweden	45	44	45	45	45	0.50
EU-15	2043	2033	2042	2043	2054	1.50
Assignment factor $\square_r$						
Austria	0.41	0.41	0.41	0.41	0.41	0.00
Belgium	0.42	0.39	0.42	0.41	0.42	0.01
Germany	0.80	0.80	0.81	0.81	0.81	0.00
Denmark	0.34	0.34	0.34	0.34	0.34	0.00
Spain	0.81	0.91	0.94	0.93	0.95	0.01
Finland	1.13	0.81	0.81	0.81	0.81	0.00
France	0.90	1.10	1.13	1.13	1.15	0.02
United Kingdom	1.21	0.90	0.90	0.90	0.91	0.00
Greece	0.88	1.19	1.21	1.20	1.21	0.01
Ireland	0.81	0.81	0.88	0.85	0.88	0.04
Italy	0.96	0.81	0.81	0.81	0.82	0.00
Luxembourg	0.57	0.96	0.96	0.96	0.96	0.00
Netherlands	1.24	0.57	0.57	0.57	0.58	0.01
Portugal	0.94	1.24	1.24	1.25	1.30	0.02
Sweden	1.00	1.00	1.00	1.05	1.10	0.05
EU-15	0.83	0.82	0.83	0.83	0.84	0.01
Minimum assignment factor $\square_{min}$						
	0.34	0.34	0.34	0.34	0.34	0.00
Auction [% of tradable permits]						
Austria	17	17	17	17	17	1.11
Belgium	19	13	19	17	19	2.81
Germany	58	57	58	58	58	0.62
Denmark	0	0	0	0	0	0.00
Spain	58	63	64	64	64	0.62
Finland	70	58	58	58	58	0.48
France	62	69	70	70	70	0.56
United Kingdom	72	62	62	62	63	0.58
Greece	61	71	72	72	72	0.54
Ireland	58	58	61	60	61	1.48
Italy	64	58	58	58	58	0.48
Luxembourg	40	64	64	64	64	0.48
Netherlands	73	38	40	40	42	0.93
Portugal	64	73	73	73	74	0.37
Sweden	66	66	66	67	69	1.47
EU-15	59	58	59	59	59	0.62