Discussion Paper No. 02-30

In Search of a Rationale for Differentiated Environmental Taxes

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ZEW

Zentrum für Europäische
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Economic Research

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Non-Technical Summary

Over the last decade, taxes have played a growing role in environmental policies of OECD countries. Nearly all tax schemes that have been introduced to date involve a differentiation of tax rates among industrial, commercial, and household sectors. Tax differentiation contradicts conventional textbook economics. The principle of uniform taxation for pollution abatement suggests that the same marginal cost apply to each use of a given pollutant so that the economy as a whole will employ the cheapest abatement options. Economic theory mentions initial tax distortions, distributional concerns, leakage motives or international market power as potential reasons why tax differentiation across different sectors of the economy might be optimal. However, the theoretical arguments remain qualitative since they are based on highly stylized analysis.

The primary objective of this paper is to ascertain whether the degree of tax differentiation observed in many countries can be rationalized on economic grounds. In simulations with a computable general equilibrium model based on empirical data, we calculate *optimal* policies under various settings. Our simulation results for the European and U.S. economies lead us to conclude that there is little economic rationale for the common policy practice to discriminate strongly in favor of heavy industries. Among the four motives for tax differentiation examined in this paper, only very specific concerns about job layoffs give reasons for tax exemptions to energy-intensive industries. Concerns about global environmental effectiveness provide some justification for tax discrimination in favor of energy- and export-intensive industries although leakage must be very high to make the case for substantial tax reductions. Tax interaction with initial fiscal energy taxes, broader-ranged concerns about factor incomes, as well as strategic international tax burden shifting can hardly rationalize the current practice in OECD countries to have only very low environmental taxes on energy-intensive industries or even exempt them.

The contributions of our paper are threefold. First, we develop a comprehensive model framework to address alternative motives for tax differentiation that have previously been considered separately in the literature. Second, we assemble an empirical database that can be used to quantify the relevance of theoretical justifications for departures from uniform taxation. Third, we demonstrate how nonlinear optimization methods can be applied to evaluate optimal policies in an empirical model.

In Search of a Rationale for Differentiated Environmental Taxes

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Abstract

Environmental tax schemes in OECD countries often involve tax rates differentiated across industrial, commercial and household sectors. In this paper, we investigate four potentially important arguments for these deviations from uniform taxation: pre-existing tax distortions, domestic equity concerns, global environmental effectiveness, and strategic trade policy. Our primary objective is to ascertain whether the degree of tax differentiation observed in many countries can be rationalized on economic grounds. In simulations with a computable general equilibrium model, we calculate *optimal* policies under various settings. Our simulation results lead us to conclude that there is little economic rationale for the common policy practice of discriminating strongly in favor of heavy industries, even when accounting for interacting taxes, distributional concerns, leakage, and international market power.

Key words: optimal environmental taxation, computable general equilibrium
JEL classifications: C68, H21, Q4, R13

Acknowledgements
The authors would like to thank Stefan Boeters for helpful comments and suggestions.

1. Introduction

Over the last decade, taxes have played a growing role in environmental policies of OECD countries. Nearly all tax schemes that have been introduced to date involve a differentiation of tax rates among industrial, commercial, and household sectors. Tax rates typically discriminate in favor of energy-intensive industries, including complete tax exemptions in many countries (OECD 2001, pp. 51-67).

Tax differentiation contradicts conventional economic reasoning. The principle of uniform taxation for pollution abatement suggests that the same marginal cost applies to each use of a given pollutant so that the economy as a whole will employ the cheapest abatement options. Beginning from a uniform tax structure, lowering the tax on certain sectors of the economy requires increasing the tax on other sectors if the same environmental goal is to be met. Any deviation from uniform taxation results in excess costs, since the cheapest abatement options are no longer fully exploited.

Complexities omitted from the textbook model, however, may provide several reasons why it can be *optimal* to deviate from uniform taxation:

- *Tax interaction:* Environmental taxes affect the distortionary impacts of existing fiscal taxes. Vis-à-vis uniform taxation, the differentiation of environmental taxes may serve to correct inefficiencies in the existing tax system.
- *Distributional incidence:* Concerns of policy makers for adjustment costs of workers or stakeholders can motivate a deviation from uniform taxation if compensation policy instruments are unavailable.
- *Leakage:* When national tax policies aim at combating international externalities, such as global warming, lower environmental tax rates for energy-intensive and trade-exposed industries may reduce counter-productive emission increases in untaxed trading partners.
- *Terms of Trade:* Large open economies may choose to differentiate environmental taxes in order to improve their terms of trade and shift domestic abatement cost to other countries.

Our objective is to ascertain whether any of these arguments can rationalize observed tax discrimination in favor of energy-intensive industries. To do this, we impose a carbon emissions constraint in an open economy model calibrated to empirical data and then compute the *optimal* sectoral structure of carbon taxes under alternative assumptions concerning preexisting taxes, leakage-adjustment motives, distributional concerns, and market power in international trade.

Based on quantitative evidence for the European and U.S. economies, we find scant economic basis for extreme tax reductions or exemptions of energy-intensive manufactures. In more detail, our key insights can be summarized as follows:

- Higher carbon taxes on energy-intensive sectors to reach an economy-wide carbon reduction target constitutes a second-best strategy towards efficient uniform taxation. The reason is that current energy taxes discriminate in favor of these industries.
- Distributional concerns for the economy-wide interests of workers or capital owners do not justify tax exemptions for energy-intensive industries. Only policies which minimize the *short-run* labor adjustment seem to justify the exemption of energy-intensive production if the sole policy instrument for dealing with labor adjustment is emission tax differentiation. Furthermore, policies focusing on labor adjustment involve a substantial trade-off with overall efficiency.
- Concerns for global effectiveness of unilateral carbon abatement measures justify only modest tax discrimination in favor of energy-intensive industries. A carbon tax applied in one region produces incentives to increase emissions in other regions (leakage), particularly when energy-intensive production methods are relatively inefficient in unconstrained countries. Despite the obvious logic underlying exemptions on these grounds, we find that, in quantitative terms, tax rates optimized to account for leakage involve only modest departures from uniformity.
- Strategic trade motives provide no rationale for larger tax reductions to energy-intensive industries. On the contrary, countries with comparative advantage in energy-intensive goods would benefit from *higher* rather than lower taxes on energy-intensive production, as taxes on energy-intensive exports improve their terms of trade: A tax on energy-intensive goods is paid, in part, by trading partners.

The analysis of environmental regulation in an optimal tax framework has been a growing research field during the last decade. Theoretical and applied work focuses on the implications of pre-existing tax distortions. The latter affect the efficiency consequences of new environmental taxes. Bovenberg and van der Ploeg (1994), Bovenberg and Goulder (1996) or Goulder, Parry and Burtraw (1997) suggest that tax interaction effects increase the gross efficiency costs (i.e. costs net of environmental benefits) of environmental taxes compared to a first-best world leading to optimal second-best environmental tax rates below the Pigouvian rate. On the other hand, revenues from environmental taxes can be used to reduce the distortions of existing taxes

(Terkla 1984, Oates 1995) hereby offsetting at least part of potentially negative tax interaction effects (Goulder 1995). While the optimal tax literature has addressed the issue of tax interaction and revenue recycling with respect to the level of single environmental tax and its overall economic costs, no evidence is provided on the *optimal differentiation* of environmental taxes across different segments of the economy in the presence of other taxes.

Equity constitutes another important criterion in optimal taxation (see Alm 1996 for list of optimal tax criteria) but has been relatively little studied in the context of environmental taxation. The usual approach is to assess the impacts of exogenous environmental tax schemes on different income groups or industries (OECD 1997, 2001) rather than determining optimal tax structures. Metcalf (1998), for example, studies the income distribution impacts of a hypothetical environmental tax reform in the US, investigating ways to make the tax reform *distributionally* neutral by means of targeted revenue recycling schemes. Böhringer and Rutherford (1997) discuss the use of tax exemptions to reduce worker layoffs in emission-intensive industries and find large excess costs vis-à-vis an equivalent alternative policy instrument, i.e. uniform carbon taxes cum sector-specific wage subsidies.

The phenomenon of leakage (see e.g. Pezzey 1992) due to unilateral abatement action provides an obvious theoretical argument for the differentiation of tax rates across domestic sectors. However, the analytical derivation of optimal tax rates is already complex under quite simplifying assumptions and even then does not give a final answer in which direction optimal tax policy should discriminate (Hoel 1996). In numerical calculations with a multi-region model for the European Union, Böhringer (1998) finds that sector-specific exemptions from unilateral carbon taxes in Germany substantially reduce leakage but magnify the total costs of EU-wide emission abatement vis-à-vis a unilateral uniform carbon tax.

Another argument for governments in large open economies to deviate from uniform environmental taxes is market power in international trade. In the absence of trade instruments, environmental taxes may be differentiated across sectors to exploit terms of trade. Stylized theoretical analysis suggests that a country which is a net exporter of “dirty” goods will levy higher environmental taxes on these commodities as a proxy for an optimal export tax - the opposite applies for the case of net imports of “dirty” goods (see e.g. Krutilla 1991, Anderson, 1992, Rauscher 1994).

Against this background, the contributions of our paper are threefold. First, we develop a comprehensive model framework to address alternative motives for tax differentiation that have previously been considered separately. Second, we assemble an empirical database that can be used to quantify the relevance of theoretical justifications for departures from uniform taxation.

Third, we demonstrate how nonlinear optimization methods (Drud 2002) can be applied to evaluate optimal policies in an empirical model. Our model framework represents a *M*athematical *P*rogram with *E*quilibrium *C*onstraints (MPEC), a new class of mathematical programs introduced by Luo, Pang and Ralph (1996). The MPEC problem class permits a formal characterization of tax design within which the objective function depends on tax rates, i.e. policy variables that would be exogenously specified in a conventional application. In this paper, we use the MPEC framework to design carbon tax programs in a static multi-region, multi-sector general equilibrium model of global trade and energy use.

The remainder of the paper is organized as follows. Section 2 entails a non-technical summary of the generic model framework and its refinements to address alternative arguments for environmental tax differentiation. Section 3 lays out the policy simulations and provides an interpretation of results. Section 4 presents sensitivity analysis. Section 5 concludes.

2. The MPEC Framework

The preceding section has laid out several potential reasons for differentiation of environmental taxes: pre-existing tax distortions, domestic equity concerns, global environmental effectiveness and strategic trade policy. It is difficult to rule out any of these arguments on the basis of logical consistency. Theoretical analysis can provide qualitative insights but lacks actual policy relevance because of very restrictive assumptions: The analytical derivation of the optimal environmental tax structure quickly becomes intractable for equilibrium conditions that exceed the complexity of standard textbook models. Furthermore, marginal calculus does not allow for a generalization of results to structural changes in policy variables. Numerical (computable) analysis based on empirical data obviously provides the appropriate approach to our issue.

In formal terms, the problem of optimal environmental taxation can be expressed as a specific case of the general MPEC formulation (see Luo, Pang and Ralph 1996):

$$\max_{t} \; f(z;t)$$

s.t. z solves the equilibrium constraints *F(z;t)*

where:

$t \in \mathbb{R}^m$ is a vector of tax policy variables which are the choice variables for the problem,

$z \in \mathbb{R}^n$ is a vector of endogenous variables that is determined by the equilibrium problem, i.e. $z = \begin{pmatrix} p \\ y \end{pmatrix}$, where *p* are prices and *y* are activity levels,

F(z; t) is a system of equations which represents market equilibrium conditions, and

$f : \mathbb{R}^{n+m} \to \mathbb{R}^1$ is the objective function.

In our case, the constraints *F(z; t)* describe the equilibrium conditions of a well-established multi-sector, multi-region computable general equilibrium (CGE) model of global trade and energy use (see e.g. Böhringer 2000, Rutherford and Paltsev 2000, Böhringer 2002, Böhringer and Rutherford 2002). The model is designed to investigate the economic impacts of emission constraints on carbon dioxide, the most important greenhouse gas in the context of global warming. Due to the micro-consistent comprehensive representation of market interactions, CGE models have become the standard tool for studying the economy-wide impacts of policy interference on resource allocation and the associated implications for incomes of economic agents (for surveys on the use of CGE models in different policy fields, see Bergman 1990, Shoven and Whalley 1992, Peireira and Shoven 1992, Kehoe and Kehoe 1994, Fehr and Wiegard 1996, or Weyant 1999).

In our numerical simulations, *F(z; t)* includes an emission reduction constraint for an open economy that can be achieved through the use of (endogenous) emission taxes. The taxes correspond to the set of choice variables *t* in the optimal taxation problem and can be differentiated across different segments of the economy to maximize an objective such as overall real consumption.

Below, we first provide a non-technical summary of the general equilibrium conditions and the empirical database underlying the parameterization of functional forms. (A detailed algebraic exposition is presented in the Appendix.) We then lay out various variants of the *generic* model that accommodate the isolated analysis of alternative motives for tax differentiation in order to assess their relative importance.

2.1 Non-technical Model Summary

Table 1 indicates the dimensionality of equilibrium conditions in the factor/commodity-space and the regional disaggregation. With respect to our simulations of optimal carbon tax policies, the sectors have been chosen to separate energy/emission-intensive and non energy-intensive activities in the economy. Energy goods in the model include coal (COL), gas (GAS), crude oil

(CRU), refined oil products (OIL) and electricity (ELE). This disaggregation is essential in order to distinguish energy goods by carbon intensity and by the degree of substitutability. The remaining sectors include energy-intensive industries (EIS), which stand out in current environmental tax schemes for their preferential treatment, and a composite industry that produces a non-energy-intensive macro good (Y). The regional aggregation covers major world trading regions that are central to the international carbon abatement debate.

Table 1: Overview of sectors (commodities), factors and regions

Sectors (Commodities)		Regions	
COL	Coal	EUR	Europe (EU15, EFTA)
CRU	Crude oil	JPN	Japan
GAS	Natural gas	USA	United States
OIL	Refined oil products	EIT	Economies in Transition (Former Soviet Union and Eastern Europe)
ELE	Electricity	OEC	Other OECD (Canada, Australia and New Zealand)
EIS	Energy-intensive sectors	ASI	Asia
Y	Macro production (manufactures and services)	MPC	Mexico and OPEC
		ROW	Rest of World
Factors			
$\overline{L}$	Labor		
$\overline{K}$	Capital		
$\overline{Q}_{ff}$	Fossil fuel resources (ff := {COL, CRU, GAS})		

Figure 1 provides a diagrammatic structure of the model. Primary factors of region *r* include labor $\overline{L}_r$, capital $\overline{K}_r$ and fossil-fuel resources $\overline{Q}_{ff,r}$. Labor and capital are intersectorally mobile within a region but cannot move between regions. A specific resource is used in the production of crude oil, coal and gas, resulting in upward sloping supply schedules.

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 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, non-energy 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. Finally, at the third level, capital and labor trade off with a constant elasticity of substitution. As to the formation of the energy aggregate, we allow sufficient levels of nesting to permit substitution between primary energy types, as well as substitution between a primary energy composite and secondary energy, i.e. electricity.

Final demand C_r in each region is determined by a representative agent RA_r, who maximizes utility subject to a budget constraint with fixed investment. Total income of the representative household consists of factor income and tax revenues. Final demand of the representative agent is given as a CES composite which combines consumption of an energy aggregate with a non-energy consumption bundle. 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.

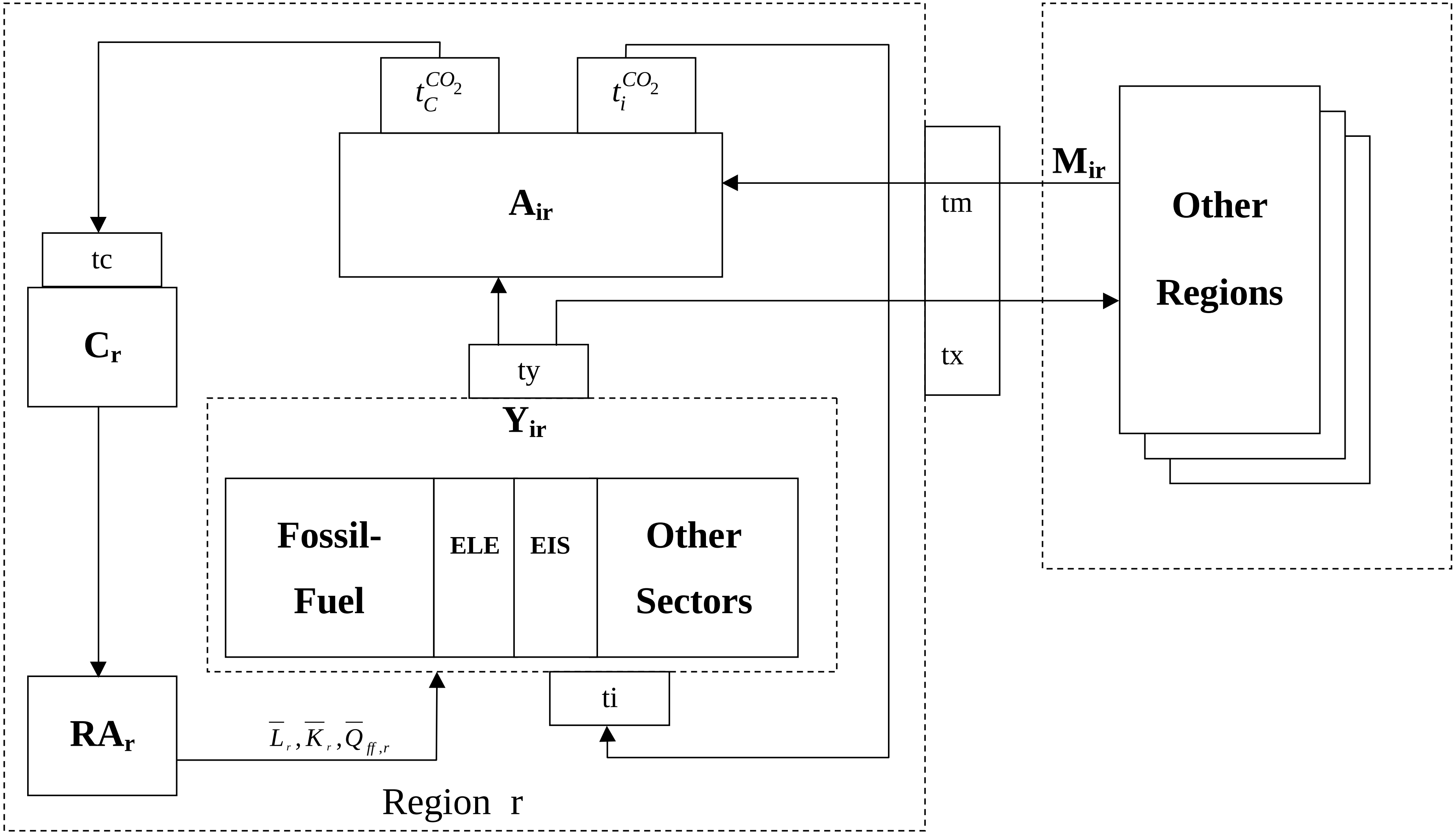
All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{ir} of the domestically produced variety and a CES import aggregate M_{ir} of the same variety from the other regions (the so-called Armington good – see Armington 1969). Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions.

The tax system includes all types of indirect taxes (production taxes or subsidies *ty*, intermediate taxes *ti*, consumption taxes *tc*, as well as tariffs *tm* and *tx*) which are used to finance a fixed level of public good provision. A lump-sum tax on the representative household balances the public budget.

In Figure 1, we have also included the carbon taxes $t_i^{CO_2}$ and $t_C^{CO_2}$, that the carbon abating region must impose to meet an exogenous reduction constraint in carbon emissions from the domestic combustion of fossil fuels. Carbon taxes can be differentiated across the energy-intensive sector (i=EIS), the power generation sector (i=ELE), all OTHER production of goods and services ($i \in$ {COL, CRU, GAS, Y}), and FINAL demand ($t_C^{CO_2}$) in order to maximize the region's objective function.

Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities. The underlying data base is GTAP-EG for the year 1995 which provides a consistent representation of energy markets in physical units and detailed accounts of regional production and consumption, as well as bilateral trade flow (see McDougall 1997, Rutherford and Paltsev 2000).

Figure 1: Diagrammatic model structure



2.2 Model Variants

Based on empirical data, the objective of our numerical analysis is to quantify how important various theoretical arguments for environmental (carbon) tax differentiation are with respect to *practical* policy making. We must then specify different variants of our generic MPEC framework to treat the various motives separately. In formal terms, the model variants go along with either changes in the objective f or the constraints $F(z; t)$ of our MPEC.

The multi-region trade (*MRT*) model of section 2.1 incorporates terms-of-trade effects of policy intervention since foreign trade involves international product differentiation. Imported and domestically produced goods are treated as imperfect substitutes. Product differentiation implies finite elasticities for domestically produced goods with respect to import demand functions of trading partners. As a consequence, each country has a certain degree of market power in international trade, and, to a lesser or greater extent depending on international exposure, countries can enact carbon taxes to improve terms of trade and thereby shift part of the domestic abatement costs to trading partners via higher prices of carbon-intensive exports and lower prices of imported energy. Furthermore, our reference model - thereafter referred to as *MRT_TAX* - is calibrated to a benchmark data set which includes initial taxes.

The isolated assessment of arguments for tax differentiation requires in part the suppression of terms-of-trade motives as well as tax interaction features. In order to suppress the terms-of-trade motive within the optimal tax problem of an abating region, we may treat that region as a small open economy (*SOE*) that views the export demand and import supply of trading partners (the rest of the world) as infinitely elastic. In this *SOE* model variant, terms of trade are exogenous. Suppression of the tax interaction effect requires a recalibration of the benchmark economy to a *NoTax* counterfactual equilibrium where all initial taxes are set to zero. The undistorted *NoTax* equilibrium can then serve as the reference situation to which we apply optimal carbon tax policies in the absence of tax interaction effects.

In the investigation of the tax interaction motive (see section 3.1), we do not simply quantify the implications of existing taxes on the magnitude and structure of optimal carbon taxes, but take two intermediate steps - *NETax* and *ETax* - in order to gain further insights. The *NETax* variant refers to a re-calibrated equilibrium without initial energy taxes but with non-energy taxes still in place. Likewise, the *ETax* variant denotes a reference where we maintain all initial energy taxes but drop all non-energy taxes.

The investigation of distributional aspects requires a modification of the MPEC objective function. In the default model setting, we assume that governments maximize economy-wide welfare in terms of disposable real consumption. We then distinguish three additional specifications of the objective function that reflect more specific distributional concerns: In meeting the exogenous emission abatement constraint, policy makers can differentiate taxes to (i) maximize income for either workers (variant: *LAB*), (ii) maximize income of capital owners (variant: *CAP*), or (iii) minimize the total number of workers laid off in all the sectors of the economy (variant: *ADJ*). We emphasize in this context that ours is a full employment model, so layoffs in one sector are balanced by increases in employment in other sectors. The model framework is static, so it maintains a long term perspective and does not quantity the adjustment costs associated with moving workers from one sector to another.

Finally, we have to accommodate leakage concerns. In this variant - denoted *L* - the domestic environmental target of the abating region is adjusted by emission increases in non-abating regions. As the carbon intensity of production varies across countries, the incorporation of leakage concerns from the perspective of an individual country or region ultimately requires a (global) multi-region setting. However, isolation of the leakage-adjustment motives for tax differentiation also demands suppression of policy-induced changes in international prices, otherwise there would be an overlap with the terms-of-trade incentive for tax differentiation. One reasonable approach to coping with these aspects is to run the *SOE* model variant with a carbon emission term which accounts for policy-induced changes in the net carbon emissions associated with non-energy trade. Embodied carbon of imports will be based on the initial bilateral trade flow of the respective *SOE* country given in the benchmark data set. The potential shortcoming of this approach is that it may significantly underestimate the magnitude of leakage, since the impacts of changes in the international prices are not accounted for in the *SOE* framework. Previous analysis (see Paltsev 2001) shows that induced changes in international prices of fossil fuels are the single most important determinant of carbon leakage. We will therefore also employ the *MRT* framework for the analysis of the leakage motive. To suppress the terms-of-trade motive, we require the abating region to compensate all other regions with lump-sum transfers which keep them at their benchmark welfare level (variant *T*). Thus, the abating country cannot take advantage of changes in international prices and the leakage motive will be covered comprehensively.

Table 2 provides a summary of the various model settings that we combine in our policy simulations to assess the relative importance of tax differentiation arguments.

Table 2: Summary of model settings

Abbreviation	Characteristics
	Foreign Closure
SOE	Small open economy with fixed terms of trade
MRT	Multi-region setting with endogenous terms of trade
	Initial Taxes
NoTax	Reference equilibrium without any taxes
NETax	Reference equilibrium with non-energy taxes
Etax	Reference equilibrium with energy taxes
Tax	Reference equilibrium with all (energy and non-energy) taxes
	Objective
{default}	Maximization of consumption
LAB	Maximization of labor income
CAP	Maximization of capital income
ADJ	Minimization of worker lay-offs
	Leakage and Terms-of-Trade Compensation
L	Leakage adjustment constraint
T	Terms-of-trade compensating transfers

3. Policy Simulations and Results

The ideal approach to determine optimal carbon tax strategies is a cost-benefit analysis which requires specification of a damage function. The optimal tax problem would then include the determination of the optimal abatement level. In view of the large uncertainties associated with the economic valuation of damages from carbon emission (see e.g. Fankhauser and Tol 1998), this is not the policy-relevant approach. Instead of balancing benefits and costs, precautionary carbon abatement strategies aim at establishing an ample margin of safety. The latter involves short- to mid-term carbon emission reductions of various OECD countries in the magnitude of 10 % - 30 % vis-à-vis current emission levels. In this vein, we impose a carbon emission reduction of 20 % on a unilaterally abating region in our central case simulations (see section 4.1 for a sensitivity analysis with respect to alternative abatement levels). Carbon tax rates represent the choice variables of policy makers and can be differentiated across four segments of the economy: electricity production (ELE), energy-intensive production (EIS), all other production of goods and services (OTHER), and final consumption demand (FINAL). (We have imposed a non-negativity constraint on carbon tax rates to exclude the possibility of emission subsidies). In our numerical calculations, we identify optimal carbon tax policies for Europe (EUR) and the United States (USA) to sort out potential cross-country differences. In the exposition of results, the economic impacts of carbon taxation are measured with respect to the benchmark situation (*BMK*), where no emission reduction constraint applies.

Table 3 gives a summary of the scenario specifications that are based on the combination of various model settings (see Table 2) to provide the appropriate framework for the analysis of the respective tax differentiation arguments, i.e. tax interaction, distributional concerns, leakage and terms of trade.

Table 3: Scenarios

Scenario abbreviation	Characteristics
Tax Interaction (section 3.1)	
SOE_NoTax	Fixed terms of trade; no initial taxes
SOE_NETax	Fixed terms of trade; initial non-energy taxes
SOE_Etax	Fixed terms of trade; initial energy taxes
SOE_Tax	Fixed terms of trade; initial energy and non-energy taxes
Distributional Concerns (section 3.2)	
SOE_NoTax	Fixed terms of trade; no initial taxes
SOE_NoTax_LAB	Fixed terms of trade; no initial taxes; maximization of labor income
SOE_NoTax_CAP	Fixed terms of trade; no initial taxes; maximization of capital income
SOE_NoTax_ADJ	Fixed terms of trade; no initial taxes; minimization of worker lay-offs
Leakage and Terms of Trade (section 3.3)	
SOE_NoTax_L	Fixed terms of trade; no initial taxes; leakage adjustment
MRT_NoTax	Endogenous terms of trade; no initial taxes
MRT_NoTax_L	Endogenous terms of trade; no initial taxes; leakage adjustment
MRT_NoTax_T	Endogenous terms of trade; no initial taxes; terms-of-trade compensation
MRT_NoTax_L_T	Endogenous terms of trade; no initial taxes; leakage adjustment; terms-of-trade compensation

3.1 Tax Interaction

Our first set of scenarios is designed to identify the implications of existing tax distortions for the optimal pattern of carbon taxes across different sectors. Since we want to exclude overlap with terms-of-trade motives, we adopt the *SOE* framework for these calculations.

We start from a benchmark equilibrium where no initial distortions are present. The *SOE_NoTax* setting not only provides a meaningful reference for quantifying the implications of existing tax distortions on optimal carbon taxation; it also serves as a consistency check for the model specification. Theoretical analysis shows that efficient environmental taxation in a small open economy that has no prior distortions implies uniform (Pigouvian) taxes across all uses of carbon. Indeed, our numerical results confirm the theoretical prediction (see column "*SOE_NoTax*" of Table 4).

Table 2: Implications of initial tax distortions

		SOE_NoTax	*SOE_NETax*	*SOE_ETax*	*SOE_Tax*
		Carbon taxes (in USD_{95})			
EUR	EIS	88	67	180	171
	ELE	88	78	215	213
	OTHER	88	73	134	128
	FINAL	88	91	0	0
USA	EIS	70	56	95	80
	ELE	70	62	99	92
	OTHER	70	57	79	69
	FINAL	70	77	16	25
		Consumption (in % wrt *BMK*)			
EUR		-0.26	-0.22	-0.54	-0.56
USA		-0.21	-0.18	-0.28	-0.28

Pre-existing tax distortions lead to non-uniform optimal carbon taxes (see column "*SOE_Tax*"). In these optima, USA and Europe apply lower taxes on carbon-intensive production (OTHER) and final demand (FINAL). Conversely, high taxes are levied on the use of fossil fuels in electricity generation (ELE) and energy-intensive production (EIS). Two intermediate scenarios help to trace the cause of these second-best effects. In scenario *SOE_NETax*, we use a reference equilibrium in which only benchmark *energy taxes* are set to zero, while scenario *SOE_ETax* captures a situation in which benchmark *non-energy* taxes are zero. The results show that non-energy taxes have second-order impacts on carbon tax design and justify only a small deviation from uniform taxation. Pre-existing energy taxes, on the other hand, have first-order impacts, leading to substantially higher carbon tax rates on energy-intensive sectors as well as electricity production. The underlying logic is simple: current energy tax systems (see OECD 2001, pp. 51-67) that are captured by our benchmark data discriminate in favor of electricity and energy-intensive sectors in both the U.S. and Europe. These sectors face lower taxes on fossil fuel inputs than do final demand and other production sectors. The optimal policy therefore involves moving to an equilibrium in which the *effective* tax rate across sectors is closer to uniform, thereby helping to minimize *direct* abatement costs.

From a public finance perspective, our results do not come as a surprise. In the *SOE* setting without initial taxes, public spending is fully covered by lump-sum transfers from the representative household to the government. For a small open economy, this reflects a first-best world since the government cannot enact taxes to alter the terms of trade. Energy taxes as well as other taxes on production or consumption that affect producer and consumer choices will be welfare decreasing. In the presence of a carbon emission constraint, higher carbon taxes on sectors with relatively low initial energy taxes turn out to be optimal as they work towards the first-best polluter pays principle. In Europe, where initial energy taxes are very high for final demand, optimal differentiation would even exempt households from paying additional carbon taxes. It should be noted that the existence of initial energy taxes implies a lower level of initial carbon emissions as compared to the case without energy taxes. The total costs of abatement are substantially higher for the *ETax* case, particularly for Europe, which has much higher initial energy taxes than the USA, because it is more difficult (costly) to restrain a more carbon-efficient economy.

The pattern of tax differentiation emerging from initial non-energy taxes is much more difficult to explain in detail, since this requires the careful analysis of various tax interaction effects with carbon taxes (see Goulder 1995). There is a trade-off between uniform carbon taxes, which minimize the direct costs of carbon abatement, and second-best benefits from carbon tax discrimination. The latter can lower the distortionary effects of existing non-energy taxes. However, our results indicate that accounting for a wide range of initial non-energy taxes does not give much leeway to deviate from uniform environmental taxation.

3.2 Distributional Concerns

The next set of calculations in the *SOE* framework addresses distributional concerns of policy makers. We consider policies which maximize real income either for workers (*LAB*) or for capital owners (*CAP*). In addition, we investigate the case (*ADJ*) that minimizes the economy-wide number of worker layoffs induced by environmental regulation. To suppress tax interaction effects, the benchmark refers to the *SOE_NoTax* setting without initial taxes. When we distinguish between different factor incomes below, it should be noted that we can "decompose" the representative agent into three types of factor owners (workers, capital owners, resource owners) that share identical consumption preferences.

Tables 5 and 6 summarize the implications of alternative distributional concerns as compared to our default setting where policy makers maximize real consumption (i.e. static welfare). We have found that the redistribution of tax revenues plays an important role in the scenarios that concern the income of workers (*SOE_NoTax_LAB*) or the income of capital owners (*SOE_NoTax_CAP*). The simulations reported in Table 5 assume that carbon tax revenues are not directly redistributed to factors (workers, capital owners, resource owners) but are spent on the purchase of the aggregate consumption good without entering the objective function. In this case, tax revenues do not form part of labor or capital income; the policy objective is to maximize direct factor earnings.

Table 5: Distributional concerns without carbon tax rebates to factors

		SOE_NoTax	*SOE_NoTax_LAB*	*SOE_NoTax_CAP*	*SOE_NoTax_ADJ*
Carbon taxes (in USD_{95})					
EUR	EIS	88	74	66	0
	ELE	88	205	189	0
	OTHER	88	9	36	111
	FINAL	88	95	87	160
USA	EIS	70	48	84	0
	ELE	70	155	136	116
	OTHER	70	5	24	135
	FINAL	70	46	33	38
Consumption (in % wrt *BMK*)					
EUR		-0.26	-0.34	-0.31	-0.43
USA		-0.21	-0.32	-0.29	-0.31
Labor income (in % wrt *BMK*)					
EUR		-1.93	-1.87	-1.86	-2.30
USA		-1.32	-1.22	-1.19	-1.43
Capital income (in % wrt *BMK*)					
EUR		-2.11	-1.99	-2.00	-2.49
USA		-1.69	-1.50	-1.52	-1.79
Resource income (in % wrt *BMK*)					
EUR		-21.79	-25.20	-24.69	-17.41
USA		-30.51	-28.08	-28.76	-29.15
Carbon tax revenues (in bn USD_{95})					
EUR		13.09	11.38	11.90	13.20
USA		9.19	7.73	8.19	9.76
Labor adjustment (index of dismissed workers)					
EUR		1.48	1.44	1.41	0.68
USA		1.24	1.17	1.29	0.81

With fixed factor supply, tax differentiation under *CAP* or *LAB* simply minimizes the decline in the real factor price: The changes in the real factor incomes as listed in Table 5 are therefore equivalent to changes in the real factor prices.

Our results indicate that maximization of either labor income or capital income implies a pronounced tax differentiation across production sectors with high carbon taxes on electricity production and low carbon taxes on the production of other goods and services.

How can we explain this tax pattern? In order to maximize the income of a single factor, tax policy must change the output structure of the economy in favor of sectors that are using the respective factor relatively intensively. The sole policy instrument in our case is the carbon tax. (There is no other, potentially more targeted, instrument such as partial factor taxes.) To favor real labor income, carbon taxes should be low in those sectors where the emission-labor ratio of production is high. Benchmark statistics show that this ratio is by far highest for electricity generation, followed by energy-intensive production and the macro good production. The optimal tax rates reflect these differences in the emission-labor intensities. The same reasoning applies for the objective of capital income maximization.

A shift in the policy objective from labor income maximization to capital income maximization induces only slight changes in the optimal tax structure. This is because the ranking of emission-labor intensities and emission-capital intensities across sectors is the same. Furthermore, capital and labor are similar substitutes for emissions (energy), which makes the carbon-tax induced substitution effect in sectoral production between both primary factors rather weak.

While concerns on labor or capital income do not justify tax discrimination in favor of energy-intensive industries (EIS), a policy intended to minimize worker layoffs translates into a blanket exemption for EIS. Changes in labor demand at the sectoral level stem from the interaction of a substitution and output effects. To minimize migration of workers following the imposition of a carbon emission constraint, a first-best policy would employ sector-specific endogenous wage subsidies to offset the aggregate (output and substitution) effect on sectoral labor demand (see e.g. Böhringer and Rutherford 1997). Since carbon taxes are the sole policy instrument in our framework, they will be differentiated to mimic the effects of sector-specific wage subsidies as close as possible. Uniform carbon taxes would distinctly turn comparative advantage against emission-intensive industries with negative output effects on labor demand dominating the positive substitution effect. The "second-best" policy to reduce worker layoffs, then, is to alleviate negative output effects in these industries through reduced carbon taxes. As reported in Table 5, such a policy can lead to the full exemption of energy/emission-intensive industries.

Table 5 also reveals the excess costs that are associated with the pursuit of more narrowly focused distributional objectives. The more tied the policy concerns are to specific interests, the less the weight is given to economy-wide efficiency considerations (as is the case for *SOE_NoTax*) that would imply uniform carbon taxation. Furthermore, policies to minimize short-run labor market adjustment, as measured by worker layoffs, work at the expense of economy-wide labor income, since the negative impacts on overall labor productivity become much more pronounced.

Table 6 summarizes the implications which emerge from alternative distributional concerns for the case that tax revenues in variants *LAB* and *CAP* get distributed among labor, capital and resource owners in proportion to their benchmark shares in overall value-added. (For the sake of comparison we retain the *SOE_NoTax* results in Table 6.) The recycling of carbon tax revenues to factors provides an additional argument in the objective function for the scenarios *SOE_NoTax_LAB* and *SOE_NoTax_CAP*.

Comparison of Tables 5 and 6 reveals the trade-off between increased tax revenues through higher carbon tax rates and decreased income from direct earnings, i.e. lower productivity, of the respective factor. Accounting for tax rebates, the increase in tax revenues is significantly higher under *LAB* than *CAP* (compare the rows "Carbon tax revenues" in Tables 5 and 6). This is because workers that have the highest share in benchmark value-added profit much more from higher tax revenues than capital owners. Due to the different tax shares in the objective function, scenarios *SOE_NoTax_LAB* and *SOE_NoTax_CAP* no longer produce such similar results as in the case in which we have no tax rebates to factors.

The tax schemes for *LAB* or *CAP* in Table 5 maximize the level of the real wage or rents. This is an extreme case of the extended objective underlying Table 6 when we set the shares of factor owners in tax revenues to zero and assume that tax revenues are just "consumed away". Redistribution of tax revenues to factors provides an incentive to raise higher revenues through increased effective tax rates at the expense of factor productivity. The inclusion of tax rebates implies much higher tax rates on energy-intensive industries and, particularly, OTHER production. The labor-emission ratios or capital-emission rates that have determined the tax pattern of Table 5 are now traded off with the responsiveness of the tax bases across sectors that are crucial to the tax generation objective. In total, we obtain a rather uniform taxation scheme on the productive use of carbon.

It is important to note that the trade-off between tax revenues and factor productivity is factor-specific. In the benchmark, labor income has by far the highest share in overall value-added. Thus, labor receives a much higher share in tax revenue than capital, which explains why *SOE_NoTax_LAB* produces a much higher decline in the real wage rate than in is the case for real rents in scenario *SOE_NoTax_CAP*. Not surprisingly, the owners of energy resources are affected the most from the imposition of the carbon constraint regardless of alternative distributional concerns and tax recycling options. Carbon taxes work as implicit taxes on fossil fuel resources by driving down resource rents.

Table 4: Distributional concerns with carbon tax rebates to factors

		SOE	*Lab*	*Cap*
Carbon Taxes (in USD_{95})				
EUR	EIS	88	210	174
	ELE	88	181	146
	OTHER	88	168	273
	FINAL	88	35	27
USA	EIS	70	89	233
	ELE	70	112	69
	OTHER	70	73	165
	FINAL	70	24	8
Consumption (in % wrt *BMK*)				
EUR		-0.26	-0.41	-0.49
USA		-0.21	-0.26	-0.37
Labor income including tax rebates (in % wrt *BMK*)				
EUR		-0.52	-0.37	-0.35
USA		-0.05	0.01	0.09
Capital income including tax rebates (in % wrt *BMK*)				
EUR		-0.71	-0.58	-0.61
USA		-0.42	-0.37	-0.46
Resource income including tax rebates (in % wrt *BMK*)				
EUR		-20.15	-19.86	-17.92
USA		-29.26	-28.45	-28.37
Carbon tax revenues (in bn USD_{97})				
EUR		13.09	16.03	17.82
USA		9.19	9.04	11.67
Labor adjustment (index of dismissed workers)				
EUR		1.48	2.09	1.99
USA		1.24	1.30	1.77
Real wages (in % wrt *BMK*)				
EUR		-1.93	-2.09	-2.26
USA		-1.32	-1.24	-1.53
Real rents (in % wrt *BMK*)				
EUR		-2.11	-2.30	-2.52
USA		-1.69	-1.62	-2.07

3.3 Leakage and Terms of Trade

Our last set of simulations investigates the implications of leakage concerns and international market power for the optimal pattern of environmental taxes across domestic sectors. To suppress the tax interaction motive, the benchmark data excludes pre-existing tax distortions. Furthermore, the policy objective is to maximize overall welfare in order to abstract from any distributional concerns.

Leakage

The incorporation of leakage concerns requires an adjustment of the carbon emission constraint for the abating country to offset increased emissions in other non-abating countries. We can suppress the terms-of-trade motive for tax differentiation by using the *SOE* framework with exogenous international market prices. Scenario *SOE_NoTax_L* in Table 7 thus adjusts the carbon emission constraints for changes in net carbon emissions associated with non-energy trade flows. Accounting for changes in embodied carbon for the net trade of non-energy intensive goods, leakage by unilateral action is very small (around 2.5 % for Europe with higher effective tax rates and 1.3 % for USA) and so is the deviation from uniform carbon taxes to compensate for leakage (compare columns "*SOE_NoTax*" and "*SOE_NoTax_L*"). Although energy- and export-intensive industries (EIS) are assigned somewhat lower tax rates to reduce leakage, the cutbacks relative to the other sectors are rather small. Not surprisingly, leakage-adjustment causes higher total costs to the unilaterally acting region, since the effective carbon constraint becomes more stringent when leakage must be offset.

As noted in section 2.1, the shortcoming of the *SOE* approach to leakage adjustment is that the calculation fails to account for indirect leakage impacts which enter through changes in international energy and EIS prices. Ultimately, the comprehensive assessment of the leakage motive should be based on the multi-region *MRT* framework in which bilateral trade flows are endogenous and where we can impose a *global* rather than *regional* carbon emission constraint. Working with the *MRT* framework for the isolated assessment of leakage concerns, however, requires that we expunge terms-of-trade motives for tax differentiation. This is possible by the imposition of endogenous compensating transfers from the abating region to all other regions (variant: *T*).

Scenario *MRT_NoTax_T* in Table 7 reveals the implications of compensating transfers on the optimal carbon tax scheme when leakage concerns are ignored. In the absence of other taxes, the optimal policy involves uniform carbon taxes as is the case for the *SOE_NoTax* scenario. Theoretical analysis suggests that the free trade equilibrium without initial taxes constitutes a pareto-efficient situation. The use of taxes to exploit terms of trade can make a large open economy better off, but only at the expense of trading partners and decreased *global* welfare. Whenever a region must compensate trading partners for policy-induced terms-of-trade losses, its first-best policy will be to minimize the *global* costs of carbon abatement which leads to uniform carbon tax rates. We see that tax rates are substantially higher in the *MRT_NoTax_T* case than in the *SOE_NoTax* case to reach the same domestic emission reduction target. Because of infinitely elastic import supply and export demand schedules, the same carbon tax rate in the *SOE* setting has a stronger impact on adjustment towards less carbon-intensive domestic production and consumption than in the *MRT* setting.

In the *MRT* framework, leakage rates become drastically higher (32 % for Europe and 18 % for USA) as compared to the *SOE* framework, which highlights the importance of endogenous international price changes. In particular, the depression of international fossil fuel prices induced by cutbacks in energy demand of larger energy importing regions constitute an important channel for leakage (Paltsev 2001) that is not captured by the *SOE* framework (We therefore regard the *SOE* results with respect to leakage adjustment motives as illustrative but of limited relevance.).

Scenario *MRT_NoTax_L_T* is based on a fixed *global* emissions target (letting the regional target of the abating region be determined endogenously) and it includes compensating transfers. In this case, the abating country has no incentive to differentiate carbon taxes for terms-of-trade reasons, so policy is purely driven by leakage-adjustment concerns. Leakage justifies tax-cuts for energy-intensive sectors – yet, these "optimal tax-breaks" are far from exemptions. More stringent domestic abatement to offset emission leakage through non-abating countries is very costly for unilaterally abating regions (here in particular: Europe).

It should be noted that leakage compensation has virtually no effect on the leakage rates, although carbon tax rates are discriminated in favor of EIS. In order to offset additional emissions elsewhere, the abating country must implicitly meet a higher reduction target that raises the effective carbon tax and, thus, offsets the primary effect of tax discrimination on the magnitude of leakage.

Terms of Trade

Finally, we investigate the relative importance of international market power for the differentiation of carbon taxes. In Table 7, the scenario *MRT_NoTax* reflects the pure terms-of-trade motive for carbon tax differentiation. Comparison between *MRT_NoTax* and *MRT_NoTax_T* reveals how countries deviate from uniform emission taxation when they are able to exploit terms of trade. The guideline for carbon tax differentiation is, then, to make the country act as monopolists on export markets (i.e. increasing the prices of its exports) and as monopsonists on import markets (i.e. favoring domestic production for goods that compete on import markets). Apart from this basic rule of thumb, the actual tax scheme depends on a number of country-specific characteristics, such as the foreign demand and supply elasticities, as well as the trade intensities of commodities. Drawing on the benchmark data, Europe is a larger "net" exporter of energy-intensive products and imposes high carbon taxes on these branches to maximize terms-of-trade gains. USA, in turn, exploits market power on international markets for its macro good.

Comparison of compliance costs to domestic emission constraints between *MRT_NoTax* and *MRT_NoTax_T* shows that larger open economies, such as Europe and USA, have sufficient market power to shift a substantial part of domestic adjustment costs via higher export prices to trading partners. In fact, Europe, which is very much trade exposed, can shift more or less the whole domestic burden to trading partners: Strategic tax differentiation provides secondary terms-of-trade benefits that nearly offset the primary domestic adjustment costs. It is also important to note that terms-of-trade motives do not rationalize the common practice of strong tax discrimination in favor of energy-intensive industries.

Leakage Adjustment with Terms of Trade Exploitation

From a practical standpoint, it seems rather unlikely that a country would be willing to compensate for any emission increase elsewhere *and* at the same time compensate non-abating countries that are not contributing to the provision of the global public good (scenario: *MRT_NoTax_L_T*). In this context, we construct a final scenario *MRT_NoTax_L* which is based on a *global* emission target to account for leakage, but excludes compensating transfers. Hence, optimal taxes which suggest slight discrimination in favor of energy-intensive production incorporate both leakage and terms-of-trade motives. We see that terms-of-trade gains can (partially) offset the additional costs of leakage.

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Table 5: Terms of trade and Leakage

		SOE_NoTax	*SOE_NoTax_L*	*MRT_NoTax_T*	*MRT_NoTax_L_T*	*MRT_ NoTax*	*MRT_ NoTax_L*
Carbon Taxes (in USD_{95})							
EUR	EIS	88	83	114	131	145	167
	ELE	88	92	114	207	82	177
	OTHER	88	93	114	207	126	216
	FINAL	88	91	114	199	120	201
USA	EIS	70	68	75	93	63	82
	ELE	70	72	75	103	64	92
	OTHER	70	72	75	98	86	110
	FINAL	70	71	75	88	93	106
Consumption (in % wrt *BMK*)							
EUR		-0.26	-0.28	-0.30	-0.70	-0.03	-0.33
USA		-0.21	-0.22	-0.21	-0.32	-0.15	-0.26
Leakage rates (in %)							
EUR		2.5	2.5	31.9	31.1	32.1	31.3
USA		1.3	1.3	17.4	17.2	18.0	17.6

4. Sensitivity Analysis

The preceding section provided a detailed point estimate assessment of the alternative rationales for carbon tax differentiation under central case assumptions. We have done a number of additional calculations to understand how changes in key assumptions affect our conclusions. This section summarizes the results. We have found that our qualitative insights regarding the implications of various motives for tax differentiation remain robust.

4.1 Alternative reduction targets

In the central case, the abating region must cut back carbon emissions by 20 % with respect to the benchmark emission level. We have run all the simulations for significantly lower (10 %) or higher (30 %) reduction targets. The stringency of carbon emission levels does not affect the implications of our different policy concerns for the optimal carbon tax scheme. Not surprisingly, higher reduction targets lead to an upward-shift of tax rates and an overproportional increase in total cost.

As to the interaction with initial energy taxes, a higher carbon reduction target can imply that final demand is no longer fully exempted from carbon taxes, since this would more than compensate the initial energy tax discrimination. However, carbon taxes will still be lowest on final demand and non-energy intensive production and highest on ELE and EIS. As to the distributional concerns on factors, the most notable result is that narrowly-focused policies to minimize job layoffs become very costly - in overall efficiency terms - for higher carbon emission constraints. The leakage argument for lowering carbon tax rates on energy-intensive production becomes more important for higher emission reduction requirements, since rising carbon taxes increase the scope for relocation of domestic emission-intensive production to (non-taxing) trading partners. However, tax reductions for EIS remain far from exemption even for high reduction targets. Leakage compensation through the adjustment of domestic abatement efforts gets very expensive with increasing reduction targets. For low reduction targets, abating countries can offset domestic adjustment costs with terms-of-trade gains from strategic tax differentiation. Towards higher reduction targets, the primary costs of domestic adjustment dominate secondary terms-of-trade benefits, and abating countries face substantial consumption losses.

4.2 Armington Elasticities

In the central case, the Armington elasticity of substitution between the domestic good and the import aggregate is set equal to 4.0. We either halve or double these values in the sensitivity analysis. In the *SOE* framework, where terms-of-trade effects are absent, the Armington elasticities affect the magnitude of adjustment cost to emission constraints. Costs move inversely with trade elasticities, because when domestic and imported goods are closer substitutes, countries can more easily substitute away from carbon-intensive inputs into production and consumption. In the *MRT* framework, the values of Armington elasticites affect the magnitude of leakage and terms-of-trade effects. Higher Armington elasticities imply more leakage and less scope for tax burden shifting.

The relative magnitudes of carbon taxes under different policy objectives remain robust with respect to the choice of the Armington elasticities. As the latter increase, the level of carbon taxes slightly go down. In the *SOE* framework, the improved possibilities of substituting carbon through trade decrease overall adjustment costs; however, cost changes are rather small. Leakage rates in the *SOE* framework may more than double between the lower bound and upper bound value of the Armington elasticity. However, leakage rates remain small such that leakage compensation policies are cheap and imply only very modest tax reductions for EIS. In the *MRT* framework, higher Armington elasticities decrease international market power. The associated loss in terms-of-trade more than offsets the cost gains through improved carbon substitutability such that both - Europe and USA - face slightly increasing consumption losses towards higher values for the Armington elasticities. Tax discrimination in favor of emission-intensive industries becomes more pronounced towards higher Armington elasticities that imply more leakage; yet, the optimal tax reductions remain far from tax exemptions.

5. Conclusions

Environmental taxes in OECD countries deviate from uniformity as the basic principle for cost-effective regulation. Economic theory mentions initial tax distortions, distributional concerns, leakage motives, or international market power as potential reasons why tax differentiation across different sectors of the economy might be optimal. However, the theoretical arguments remain qualitative, since they are based on highly stylized analysis.

In this paper, we have developed a modeling framework for isolating alternative motives for tax differentiation and quantifying their implications on the optimal structure of an environmental tax based on a comprehensive data set of global trade and energy use. Among the four motives for tax differentiation examined in this paper, only very specific concerns about job layoffs give reasons for tax exemptions to energy-intensive industries. Concerns about global environmental effectiveness provide some justification for tax discrimination in favor of energy- and export-intensive industries, although leakage must be very high to make the case for substantial tax reductions. Tax interaction with initial fiscal energy taxes, broader-ranged concerns about factor incomes, as well as strategic international tax burden shifting can hardly rationalize the current practice in OECD countries to have only very low environmental taxes on energy-intensive industries or even exempt them.

There are several issues absent from the present analysis that are potentially important. We have not studied the implications of initial income taxes, which are omitted in the original data set underlying our analysis. A more comprehensive representation of the tax system would also allow for alternative options to recycle carbon tax revenues through cuts in existing distortionary taxes. Our analysis adopts a short- to mid-term horizon since capital is kept immobile across borders. It would be interesting to see how results change in the long run when we allow for global capital mobility. Finally, we did not incorporate public choice arguments for tax differentiation in the current analysis. We plan to address these issues in future research using the current model framework to the extent possible with available data.

References

Alm, J. (1996), What is an Optimal Tax System?, National Tax Journal, 49 (1), 117-133.

Anderson, K. (1992), The Standard Welfare Economics of Policies Affecting Trade and the Environment, in K.Anderson and R. Blackhurst (eds.), *The Greening of World Trade,* Hemel Hemspstead.

Armington, P.S. (1969), A Theory of Demand for Producers Distinguished by Place of Production, *IMF Staff Papers* 16, 159-178.

Bergman, L. (1990), The Development of Computable General Equilibrium Models, in Bergman, L., D. W. Jorgenson and E. Zalai (eds): *General Equilibrium Modeling and Economic Policy Analysis*, Cambridge, 3-30.

Bovenberg, A.L. and F. van der Ploeg (1994), Environmental Policy, Public Finance and the Labor Market in a Second-Best World, *Journal of Public Economics*, 55, 340-390.

Bovenberg, A.L. and L.H. Goulder (1996), Optimal Environmental Taxation in the Presence of Other Taxes: General Equilibrium Analyses, *American Economic Review*, 86 (4), 985-1000.

Böhringer, C. (1998), Unilateral Taxation of International Environmental Externalities and Sectoral Exemptions, in: A. Fossati and J.Hutton (eds.): *Policy Simulations in the European Union*, Routledge, London, 140-155.

Böhringer, C. (2000), Cooling Down Hot Air - A Global CGE Analysis of Post-Kyoto Carbon Abatement Strategies, *Energy Policy*, 28, 779-789.

Böhringer, C. (2002), Climate Politics from Kyoto to Bonn: From Little to Nothing?, *Energy Journal* 23, 51-71.

Böhringer, C. and T.F. Rutherford (1997): Carbon Taxes with Exemptions in an Open Economy - A General Equilibrium Analysis of the German Tax Initiative, *Journal of Environmental Economics and Management 32*, 189-203.

Böhringer, C. and T. F. Rutherford (2002), Carbon Abatement and International Spillovers, *Environmental and Resource Economics* 22, 391-417.

Drud, A.S. (2002), On the Use of Second Order Information in GAMS/CONOPT3, SIAM Optimization Meeting, May 2002, Toronto

Fankhauser, S. and R.S.J. Tol (1998), On the Representation of Impact in Integrated Assessment Models of Climate Change, *Environmental Modelling and Assessment*, 3, 63-74.

Fehr, F. and W. Wiegard (1996), Numerische Gleichgewichtsmodelle: Grundstruktur, Anwendungen und Erkenntnisgehalt, *Ökonomie und Gesellschaft*, *Jahrbuch 13: Experiments in Economics*, Frankfurt: Campus-Verlag, 297–339.

Goulder, L. H. (1995), Environmental Taxation and the Double Dividend: A Readers' Guide, *International Tax and Public Finance* 2, 157-183.

Goulder, L., I.W.H. Parry and D. Burtraw (1997), Revenue-Raising vs. Other Approaches to Environmental Protection: The Critical Significance of Preexisting Tax Distortions, RAND Journal of Economics, 28 (4), 708-731.

Hoel, M. (1996): Should a carbon tax be differentiated across sectors? *Journal of Public Economics* 59, 17-32.

IEA (1997), International Energy Agency, Energy Prices and Taxes / Energy Balances of OECD and Non-OECD countries, Paris: IEA publications.

Kehoe, P. J. and T. J. Kehoe (1994), ‘A Primer on Static Applied General Equilibrium Models’, *Federal Reserve Bank of Minneapolis Quarterly Review*.

Krutilla, K. (1991), Environmental regulation in an open economy, Journal of Environmental Economics and Management 20, 127-142.

Luo, Z.-Q., Ralph, D. and J. S. Pang (1996), Mathematical programs with Equilibrium Constraints, Cambridge University Press.

McDougall, R.A. (1997), ed., *Global Trade*, *Assistance and Protection: The GTAP 4 Data Base*, Center for Global Trade Analysis, Purdue University, West Lafayette.

Metcalf (1998), A Distributional Analysis of an Environmental Tax Shift, NBER Working Paper 6546. Available at: http://papers.nber.org/

Oates, W.E. (1995), Green Taxes: Can We Protect the Environmenta and Improve the Tax System at the Same Time, Southern Economic Journal, 61 (4), 915-922.

OECD (1997, Environmental Taxes and Green Tax Reform, Paris.

OECD (2001), Database on environmentally related taxes in OECD countries. Available at: http://www.oecd.org/env/policies/taxes/index.htm

Paltsev, S.V. (2001), The Kyoto Protocol: Regional and Sectoral Contributions to the Carbon Leakage, *The Energy Journal* 22 (4), 53-79.

Peireira, A. M and J. B. Shoven (1992), 'Survey of Dynamic Computational General Equilibrium Models for Tax Policy Evaluation', *Journal of Policy Modeling*, 10, 401–426.

Pezzey, J. (1992), Analysis of unilateral CO_2 control in the European Community, *The Energy Journal* 13, 159-172.

Rauscher, M. (1994), On Ecological Dumping, Oxford Economic Papers 46 (4), 822-840.

Rutherford, T.F. and S.V. Paltsev (2000), GTAP-Energy in GAMS, University of Colorado, Working Paper 00-2, http://debreu.colorado.edu/download/gtap-eg.pdf

Shoven, J. B. and J. Whalley (1992), *Applying General Equilibrium*, Cambridge: Cambridge University Press.

Terkla, D. (1984), The Efficiency Value of Effluent Tax Revenues, Journal of Environmental Economics and Management, 11, 107-123.

Weyant, J. (ed) (1999), The Costs of the Kyoto Protocol: A Multi-Model Evaluation, *The Energy Journal*, Special Issue.

APPENDIX

Appendix A: Algebraic Model Summary

Our optimal taxation problem is a specific case of the general MPEC formulation (see Luo, Pang and Ralph 1996), where one chooses *t*, a vector of tax policy variables, to solve the following problem:

$$\max_{t} \ f(z;t)$$

s.t. z solves the equilibrium constraints *F(z;t)*

where:

$t \in \mathbb{R}^m$	is a vector of tax policy variables which are the choice variables for the problem (in our case *t* comprises the set of four carbon taxes that can be differentiated across the energy-intensive sector (EIS), the power generation sector (ELE), all other production of goods and services (OTHER) and final demand (FINAL)),
$z \in \mathbb{R}^n$	is a vector of endogenous variables that are determined by the equilibrium problem, i.e. $z = \begin{pmatrix} p \\ y \end{pmatrix}$, where *p* are prices and *y* are activity levels,
F(z; t)	is a system of equations which represents a general equilibrium Arrow-Debreu economy,
$f : \mathbb{R}^{n+m} \rightarrow \mathbb{R}^1$	is the objective function for which we adopt alternative arguments including real consumption (the default setting), labor income (*lab*), capital income (*cap*) or - with inverted sign - the number of worker layoffs (*ladj*).

Before presenting the algebraic exposition of the equilibrium conditions *F(z;t)* for our multi-region, multi-sector model, we state our main assumptions and introduce the notation:

- Nested separable constant elasticity of substitution (CES) functions characterize the use of inputs in production. All production exhibits non-increasing returns to scale. Goods are produced with capital, labor, energy and material (KLEM).
- A representative agent (RA) in each region is endowed with three primary factors: natural resources (used for fossil fuel production), labor and capital. The RA maximizes utility from consumption of a CES composite subject to a budget constraint with fixed investment demand (i.e. fixed demand for the savings good). The aggregate consumption bundle

combines demands for fossil fuels, electricity and non-energy commodities. Total income of the RA consists of factor income and taxes (including carbon tax revenues).

- Supplies of labor, capital and fossil-fuel resources are exogenous. Labor and capital are mobile within domestic borders but cannot move between regions; natural resources are sector specific.
- All goods are differentiated by region of origin. Constant elasticity of transformation functions (CET) characterize the differentiation of production between production for the domestic markets and the export markets. Regarding imports, nested CES functions characterize the choice between imported and domestic varieties of the same good (Armington).

Two classes of conditions characterize the competitive equilibrium for our model: zero profit conditions and market clearance conditions. The former class determines activity levels and the latter determines price levels. In our algebraic exposition, the notation Π_{ir}^{u} is used to denote the profit function of sector *j* in region *r* where *u* 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 (Shepard'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.1 – A.6 explain the notations for variables and parameters employed within our algebraic exposition. Note that with respect to the general notation of our MPEC, Table A.2 summarizes the activity variables of vector *y* within $z = \begin{pmatrix} p \\ y \end{pmatrix}$ whereas Table A.3 summarizes the price variables of vector *p*. Figures A.1 – A.4 provide a graphical exposition of the production and final consumption structure.

For the sake of transparency, we omit all indirect taxes in the algebraic exposition except for the differentiated carbon taxes that are levied by region *r* in order to meet the unilateral carbon emission constraint.

I.1 Zero Profit Conditions

1. Production of goods except fossil fuels:

$$\Pi_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j \notin EG} \theta_{jir} p_{jr}^{A} - \theta_{ir}^{KLE} \left[\theta_{ir}^{E} p_{ir}^{E\ 1-\sigma_{KLE}} + (1-\theta_{ir}^{E}) \left(w_r^{\alpha_{jr}^{L}} v_r^{\alpha_{jr}^{K}} \right)^{1-\sigma_{KLE}} \right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \qquad i \notin FF$$

2. Production of fossil fuels:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \left[\theta_{ir}^{Q} q_{ir}^{1-\sigma_{Q,i}} + (1-\theta_{ir}^{Q})\left(\theta_{Lir}^{FF} w_r + \theta_{Kir}^{FF} v_r + \sum_j \theta_{jir}^{FF}\left(p_{jr}^{A} + t_{ir}^{CO2} a_j^{CO2}\right)\right)^{1-\sigma_{Q,i}}\right]^{\frac{1}{1-\sigma_{Q,i}}} = 0 \quad \text{i} \in$$

3. Sector-specific energy aggregate:

$$\prod_{ir}^{E} = p_{ir}^{E} - \left\{\theta_{ir}^{ELE} p_{\{ELE,r\}}^{A^{1-\sigma_{ELE}}} + (1-\theta_{ir}^{ELE})\left[\theta_{ir}^{COA}\left(p_{\{COA,r\}}^{A} + t_{ir}^{CO2} a_{COA}^{CO2}\right)^{1-\sigma_{COA}} + (1-\theta_{ir}^{COA})\left(\prod_{j \in LQ}\left(p_{jr}^{A} + t_{ir}^{CO2} a_j^{CO2}\right)^{\beta_{jir}}\right)^{1-\sigma_{COA}}\right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}}\right\}$$

4. Armington aggregate:

$$\prod_{ir}^{A} = p_{ir}^{A} - \left[\left(\theta_{ir}^{A} p_{ir}^{1-\sigma_A} + (1-\theta_{ir}^{A}) p_{ir}^{M^{1-\sigma_A}}\right)^{\frac{1}{1-\sigma_A}} + t_r^{CO2} a_i^{CO2}\right] = 0$$

5. Aggregate imports across import regions:

$$\prod_{ir}^{M} = p_{ir}^{M} - \left(\sum_s \theta_{isr}^{M} p_{is}^{X^{1-\sigma_M}}\right)^{\frac{1}{1-\sigma_M}} = 0$$

6. Household consumption demand:

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

7. Household energy demand:

$$\prod_{Cr}^{E} = p_{Cr}^{E} - \left[\sum_{i \in FF} \theta_{iCr}^{E}\left(p_{ir}^{A} + t_{ir}^{CO2} a_j^{CO2}\right)^{1-\sigma_{FF,C}}\right]^{\frac{1}{1-\sigma_{FF,C}}} = 0$$

I.2 Market Clearance Conditions

8. Labor:

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

9. Capital:

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

10. Natural resources:

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

11. Output for domestic markets:

$$Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}} = \sum_{j} A_{jr} \frac{\partial \Pi_{jr}^{A}}{\partial p_{ir}}$$

12. Output for export markets:

$$Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{X}} = \sum_{s} M_{is} \frac{\partial \Pi_{is}^{M}}{\partial p_{ir}^{X}}$$

13. Sector specific energy aggregate:

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

14. Import aggregate:

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

15. Armington aggregate:

$$A_{ir} = \sum_{j} Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ir}^{A}} + C_{r} \frac{\partial \Pi_{r}^{C}}{\partial p_{ir}^{A}}$$

16. Household consumption:

$$C_{r}\, p_{r}^{C} = w_{r} \overline{L}_{r} + v_{r} \overline{K}_{r} + \sum_{j \in FF} q_{jr} \overline{Q}_{jr} + t_{r}^{CO2} \overline{CO2}_{r} + p_{CGD,r} \overline{Y}_{CGD,r} + \overline{B}_{r}$$

17. Aggregate household energy consumption:

$$E_{Cr} = C_{r} \frac{\partial \Pi_{r}^{C}}{\partial p_{Cr}^{E}}$$

18. Carbon emissions:

$$\overline{CO2}_{r} = \sum_{i} A_{ir} a_{i}^{CO_2}$$

Table A.1: 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.2: 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 for good *i* in region *r*
C_r	Aggregate household consumption in region *r*
E_{Cr}	Aggregate household energy consumption in region *r*

Table A.3: Price variables

p_{ir}	Output price of good *i* produced in region *r* for domestic market
p_{ir}^X	Output price of good *i* produced in region *r* for export market
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*
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 ∈ FF)
$t_{dr}^{CO_2}$	CO_2 tax in region *r* differentiated across destination d (d={C, i})

Table A.4: Cost shares

θ_{ir}^{X}	Share of 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}^{A}	Share of domestic variety in Armington good *i* of region *r*
θ_{Cr}^{E}	Share of fossil fuel composite in aggregate household consumption in region *r*
γ_{ir}	Share of non-energy good *i* in non-energy household consumption demand in region *r*
θ_{iCr}^{E}	Share of fossil fuel *i* in household energy consumption in region *r*

Table A.5: 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: $\sum_r \overline{B}_r = 0$)
$\overline{CO2}_r$	Carbon emission constraint for region *r*
$a_i^{CO_2}$	Carbon emissions coefficient for fossil fuel *i* (*i*$\in$*FF*)

Table A.6: 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}=1.0 μ_{CRU}=1.0 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	4
σ_{M}	Substitution between imports from different regions	8
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

Figure A.1: Nesting in non-fossil fuel production

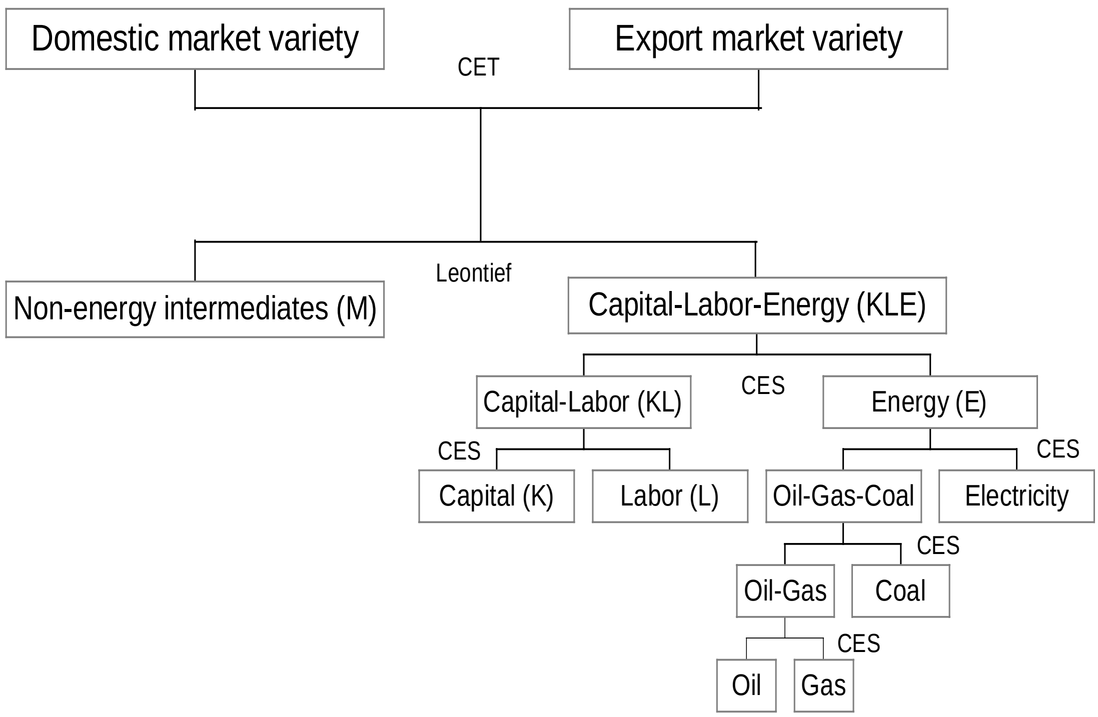


Figure A.2: Nesting in fossil fuel production

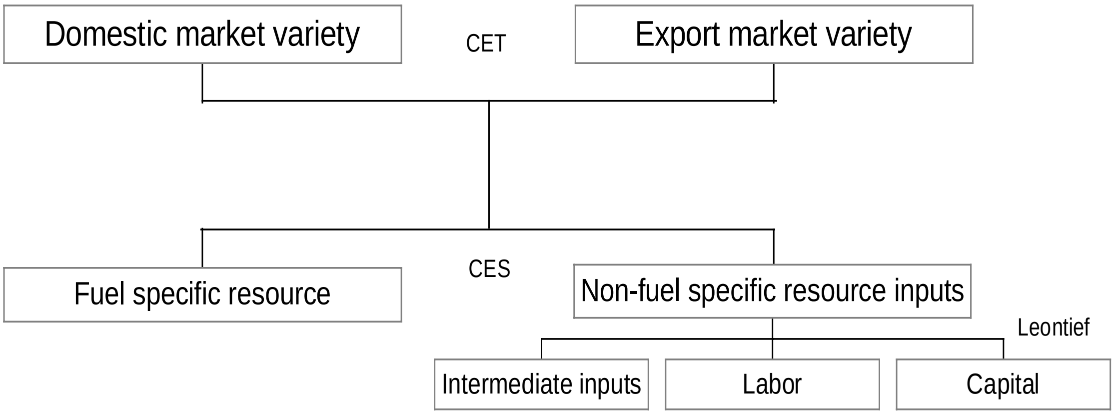


Figure A.3: Nesting in household consumption

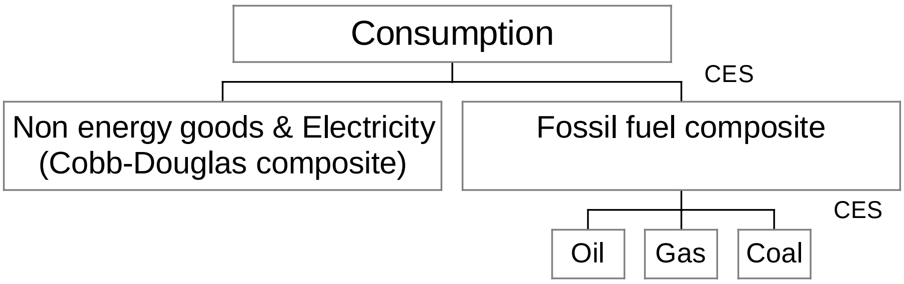
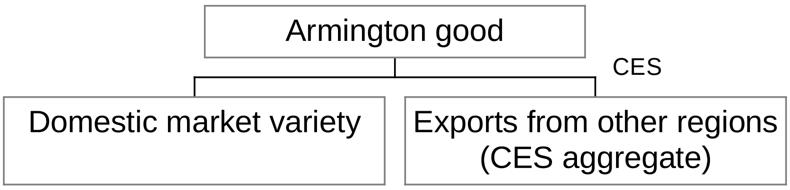


Figure A.4: Nesting in Armington production



Appendix B: Benchmark Data - Regional and Sectoral Aggregation

The model is built on a comprehensive energy-economy data set that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flow. The underlying data base is GTAP-EG which reconciles the GTAP economic production and trade data set for the year 1995 with OECD/IEA energy statistics for 45 regions and 22 sectors (Rutherford and Paltsev 2000). Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities. Sectors and regions of the original GTAP-EG data set are aggregated according to Tables B.1 and B.2 to yield the model's sectors and regions (see Table 1).

Table B.1: Sectoral aggregation

Sectors in GTAP-EG			
AGR	Agricultural products	NFM	Non-ferrous metals
CNS	Construction	NMM	Non-metallic minerals
COL	Coal	OIL	Refined oil products
CRP	Chemical industry	OME	Other machinery
CRU	Crude oil	OMF	Other manufacturing
DWE	Dwellings	OMN	Mining
ELE	Electricity and heat	PPP	Paper-pulp-print
FPR	Food products	SER	Commercial and public services
GAS	Natural gas works	T_T	Trade margins
I_S	Iron and steel industry	TRN	Transport equipment
LUM	Wood and wood-products	TWL	Textiles-wearing apparel-leather

Mapping from GTAP-EG sectors to model sectors as of Table 1		
	Energy	
COL	Coal	COL
CRU	Crude oil	CRU
GAS	Natural gas	GAS
OIL	Refined oil products	OIL
ELE	Electricity	ELE
	Non-Energy	
EIS	Energy-intensive sectors	CRP, I_S, NFM, NMM, PPP, TRN
Y	Rest of industry	AGR, CNS, DWE, FPR, LUM, OME, OMF, OMN, SER, T_T, TWL

Table B.2: Regional aggregation

Regions in GTAP-EG			
ARG	Argentina	MYS	Malaysia
AUS	Australia	NZL	New Zealand
BRA	Brazil	PHL	Philippines
CAM	Central America and Caribbean	RAP	Rest of Andean Pact
CAN	Canada	RAS	Rest of South Asia
CEA	Central European Associates	REU	Rest of EU
CHL	Chile	RME	Rest of Middle East
CHN	China	RNF	Rest of North Africa
COL	Columbia	ROW	Rest of World
DEU	Germany	RSA	Rest of South Africa
DNK	Denmark	RSM	Rest of South America
EFT	European Free Trade Area	RSS	Rest of South-Saharan Africa
FIN	Finland	SAF	South Africa
FSU	Former Soviet Union	SGP	Singapore
GBR	United Kingdom	SWE	Sweden
HKG	Hong Kong	THA	Thailand
IDN	Indonesia	TUR	Turkey
IND	India	TWN	Taiwan
JPN	Japan	URY	Uruguay
KOR	Republic of Korea	USA	United States of America
LKA	Sri Lanka	VEN	Venezuela
MAR	Morocco	VNM	Vietnam
MEX	Mexico		

Mapping from GTAP-EG regions to model regions as of Table 1		
EUR	EU15 and EFTA	DEU, DNK, EFT, FIN, GBR, REU, SWE
JPN	Japan	JPN
USA	United States	USA
EIT	Economies in Transition	EEC, FSU
OEC	Canada, Australia, New Zealand	CAN, AUS, NZL
ASI	Other Asia	KOR, MYS, PHL, SGP, THA, VNM, CHN, HKG, TWN,IND, LKA, RAS
MPC	Mexico and OPEC	MEX, RNF
ROW	Rest of the World	IDN, CAM, VEN, COL, RAP, ARG, BRA, CHL, URY, RSM, TUR, RME, MAR, SAF, RSA, RSS, ROW