Oldenburg Discussion Papers in Economics

Optimal Emission Pricing in the Presence of International Spillovers: Decomposing Leakage and Terms-of-Trade Motives

Christoph Böhringer, Andreas Lange, Thomas F. Rutherford

V-347-12

June 2012

Department of Economics
University of Oldenburg, D-26111 Oldenburg

Optimal Emission Pricing in the Presence of International Spillovers: Decomposing Leakage and Terms-of-Trade Motives

Christoph Böhringer[a], Andreas Lange[b], and Thomas F. Rutherford[c]

Abstract

Carbon leakage provides an efficiency argument for unilateral climate policy to differentiate emission prices in favor of emission-intensive and trade-exposed sectors. At the same time, differential emission pricing can be (mis-)used as a beggar-thy-neighbor policy to exploit terms of trade. Using an optimal tax framework, we propose a method to decompose the leakage motive and the terms-of-trade motive for emission price differentiation. We employ our method for a quantitative impact assessment of unilateral climate policy based on empirical data. We find that the leakage motive yields only small efficiency gains compared to uniform emission pricing. Likewise, the terms-of-trade motive has rather limited potential for strategic burden shifting. We conclude that the simple first-best rule of uniform emission pricing remains a practical guideline for unilateral climate policy design.

Key words: optimal taxation, emission leakage, terms of trade

JEL classifications: H21, Q43, R13, D58

[a] University of Oldenburg, Department of Economics, Germany

[b] University of Hamburg, Department of Economics, Germany

[c] ETH Zürich, CEPE, Switzerland

1 Introduction

Non-differential pricing of uniformly dispersed pollutants across all sources constitutes a first-best strategy to meet some emission reduction target implemented via harmonized emission taxes or likewise a system of tradable emission quotas: the marginal cost (price) to each use of a given pollutant should be the same so that the economy as a whole will employ the cheapest abatement options.

However, incomplete regulatory coverage of emission sources provides an efficiency rationale for emission price differentiation. When unilateral emission regulation aims at combating international externalities, such as global warming, lower emission prices for emission-intensive and trade-exposed industries can reduce emission increases by unregulated trading partners – a phenomenon referred to as emission leakage (Hoel 1991, Felder and Rutherford 1993). There are two basic channels through which emission leakage may occur. First, leakage can arise when emission-intensive and trade-exposed industries in countries with emission constraints lose competitiveness, thereby shifting emission-intensive production to unconstrained regions. Second, emission regulation in open economies may depress international prices for fossil fuels which induces a growth in energy demand of unregulated regions.

Hoel (1996) demonstrates that differentiated emission prices may be desirable for a unilateral abating country in order to counteract emission leakage. While a country cannot impose a uniform emission price on other countries and thereby achieve the first-best outcome, it can influence foreign production and consumption by changing world prices. The logical implication is that unilateral emission regulation should account for international spillovers. In his analysis of optimal unilateral emission pricing, Hoel generalizes the seminal work by Markusen (1975) who shows in a two-sector, two-region model that the optimal tax structure for a unilaterally regulating country in the case of an international externality consists of a pollution tax and a tariff. The intuitive result is that the optimal tariff corresponds to the optimal (Pigouvian) domestic pollution tax discounted by the degree to which demand for the ”dirty” good outside the regulating region is stimulated by the tariff-induced reduction in the world market price of that good. Furthermore, Markusen points out that the optimal pollution tax will differ from the Pigouvian tax in case tariffs are not a viable policy instrument. Hoel provides a more general theoretical model to confirm that a uniform carbon tax on all domestic consumers and producers should be complemented with tariffs on the traded goods (i.e., as a tax on net imports or a subsidy on net exports) in order to counteract leakage. He shows that the differentiation of emission taxes across sectors becomes optimal as the unilaterally abating country is prevented from using tariffs on traded goods.

In view of missing or incomplete international climate agreements as well as the legal and political pitfalls of carbon tariffs, differential emission pricing is an important issue in the design of unilateral climate policies. As a matter of fact, current regulatory practice in the EU boils down to differential emission pricing between emission-intensive industries facing a uniform carbon value through the EU emission trading system and the remaining segments of the EU economy that are subject to complementary national regulations (Böhringer et al. 2009).

While differential emission pricing may be justified as a second-best strategy to reduce leakage and improve global cost-effectiveness of unilateral climate policies, the fundamental problem is that strategic price differentiation can be (mis-)used at the same time to exploit terms of trade. Large open economies may be tempted to differentiate emission prices as a substitute for optimal tariffs shifting the domestic emission abatement burden as much as possible to unregulated trading partners. The terms-of-trade motive induces countries to increase domestic emission taxes on "dirty" commodities which are exported and lower taxes on "dirty" commodities which are imported (Krutilla 1991, Anderson 1992).

The challenge for an informed policy debate on emission price differentiation is that the leakage and terms-of-trade motives are inherently intertwined. It is not obvious to what extent emission price differentiation can be justified on global efficiency grounds (to combat leakage) or should be disguised as undue strategic exploitation of international market power (to manipulate terms of trade). Likewise, a domestic regulator may want to sort out the pure leakage motive for differential emission pricing in negotiations with representatives of influential emission-intensive industries that lobby for preferential treatment at the expense of other sectors in the economy.

In this paper we present an analytical optimal tax framework that decomposes the leakage and terms-of-trade motives for differential emission pricing. We then incorporate the decomposition method in a computable general equilibrium model to investigate the relative importance of the leakage and the terms-of-trade motive for the direction and magnitude of emission price differentiation based on empirical data. Furthermore, the numerical analysis allows us to assess the magnitude of global cost savings as well as the scope for burden shifting through differential emission pricing compared to non-strategic uniform emission pricing.

Our quantitative results suggest that both motives for differential emission pricing – the leakage motive as well as the terms-of-trade motive – are likely to be overstated in the debate on preferential treatment of emission-intensive and trade-exposed industries. While leakage concerns may justify distinct emission price reductions for these sectors, the impacts on leakage and on the overall economic cost of emission abatement are small. Likewise, the potential for exploiting terms of trade through differential pricing of emission-intensive and trade-exposed commodities and the rest of the economy is limited; large open economies such as the EU or the U.S. cannot substantially reduce their abatement cost by using sophisticated tax differentiation. A simple first-best rule of uniform emission pricing performs only slightly worse in terms of economic efficiency in a second-best setting with international spillovers. We conclude that uniform emission pricing remains a practical guideline for unilateral climate policy design.

Our policy conclusion can be traced back to the limited relevance of trade in emission-intensive commodities for achieving *global* emission reduction through differential unilateral emission pricing. Emission leakage and terms-of-trade effects are to a large extent driven by changes in international fossil fuel prices which in turn hinge primarily on reductions in *global* fossil fuel demand. In our cost-effectiveness analysis of unilateral climate policy we keep the targeted global emission reduction constant: as the global emission cutback is directly linked to the reduction of global fossil fuel demand, the international energy market responses are fairly robust to alternative unilateral emission pricing strategies. Trade in emission-intensive goods which can be influenced through differential emission pricing plays an inferior role for leakage and terms-of-trade changes. Leakage concerns warrant price discrimination in favor of emission-intensive and trade-exposed commodities but the potential for global cost savings is small since these goods only account for a smaller share in global trade (emissions) and differential emission pricing bears direct opportunity cost (as domestic marginal abatement cost are no longer equalized). For the same reasons, the scope for burden shifting under the terms-of-trade motive is limited.

The remainder of this paper is organized as follows. Section 2 presents the basic theoretical framework underlying our decomposition of the leakage and the terms-of-trade motives for emission price differentiation. Section 3 entails a non-technical summary of the computable general equilibrium model and discusses our numerical findings. Section 4 concludes.

2. Theoretical Background

Leakage and terms-of-trade effects provide theoretical arguments for emission price differentiation across domestic sectors of a unilaterally regulating country. Both effects are intertwined. Emission constraints in an open economy not only cause adjustments of domestic production and consumption patterns but influence international prices, i.e., the terms of trade, via changes in trade flows. Simultaneously, leakage occurs with changes in relative prices as emission reductions in the regulating country are partially offset through the increase of emission-intensive production and higher energy demands in unregulated countries. A rigorous assessment of the relative importance of the leakage and the terms-of-trade motives for differential emission pricing requires a decomposition of these international spillover effects. Our decomposition method is based on the idea that the unilateral abating country must compensate other countries for induced terms-of-trade losses and thus has no longer an incentive for strategic terms-of-trade manipulation.

In this section we present an analytical framework to illustrate our decomposition technique which will be used later in the empirical general equilibrium analysis. We start with a stylized two-region, multi-commodity economy where we first derive a Pareto-optimal allocation to satisfy a transboundary emission constraint. We show that any unilateral emission tax (price) by one country cannot achieve efficiency as long as transboundary pollution is taken into account. Next, we derive the first-order conditions for optimal unilateral emission policies from the perspective of a large open economy where the domestic regulator might want to deviate from uniform emission pricing for two reasons: the terms-of-trade motive and the leakage motive. We then show that we can suppress the terms-of-trade motive by demanding that the unilaterally taxing region must keep the other region at the initial welfare level through compensating transfers. While the general finding on differential emission pricing is in line with Hoel's seminal contribution (Hoel 1996), our analytical setting allows for an innovative and policy-relevant decomposition of the terms-of-trade and leakage motives.

2.1 The Basic Model

We consider a simple two countries model (regions r = 1, 2) in which consumption goods $i = 1,...,n$ are produced with capital k^{ir} and energy (emissions) e^{ir}. Energy is produced in the countries with capital k^{er}. Production in sector $i = 1,...,n$ (y^{ir}) and the energy sector (y^{er}) are characterized by production functions

$$y^{ir} = f^{ir}(k^{ir}, e^{ir}) \qquad y^{er} = f^{er}(k^{er}) .$$

We assume that capital k^r in each region is immobile across domestic borders such that $k^{er} + \sum_{i=1}^{n} k^{ir} = k^r$.

Energy as well as the produced consumption goods can be traded internationally. Total energy use e^r in the respective countries is denoted by

$$\sum_{i=1}^{n} e^{ir} = e^r$$

such that market clearance requires

$$e^1 + e^2 = y^{e1} + y^{e2} .$$

We assume a representative consumer in country r who derives utility

$$u^r = U^r(c^r)$$

from consuming goods, $c_i (i = 1,...,n)$. The representative consumer receives all income. Energy and consumption goods are traded at world market prices p_e and p^i. We use energy as a numeraire on the world market, i.e., $p_e = 1$.

Finally, market clearance for consumption goods requires

$$c^{i1} + c^{i2} = y^{i1} + y^{i2}$$

and the balance of payments (current accounts) is warranted through

$$0 = p_y(y^r - c^r) + \underbrace{p_e}_{=1}(y^{er} - e^r) - Tr^r$$

where Tr^r are potential transfers paid to the other country $(Tr^1 + Tr^2 = 0)$.

We assume that the home country (r = 1) wants to reduce some environmental damages from energy use. We hereby allow for transboundary pollution. In this setting, country 1 aims at restricting energy use such that $e^1 + \alpha e^2 \leq \bar{E}$, where $\alpha \geq 0$ (α allows for a different weighting of home and foreign emissions: in the case of greenhouse gas emissions α is 1; without international pollution externalities α is 0).

2.2 The Pareto Optimum

A Pareto optimal allocation must guarantee $e^1 + \alpha e^2 \leq \bar{E}$. The allocation maximizes the Lagrangean

$$\begin{aligned}
&U^1(c^1) + \lambda U^2(c^2) + \mu(\bar{E} - \sum_i e^{i1} - \alpha \sum_i e^{i2}) \\
&+ \sum_i \eta^i \left[f^{i1}(k^{i1}, e^{i1}) + f^{i2}(k^{i2}, e^{i2}) - c^{i1} - c^{i2} \right] \\
&+ \eta^e [f^{e1}(k^{e1}) + f^{e2}(k^{e2}) - \sum_i e^{i1} - \sum_i e^{i2}] \\
&+ \eta^{k1}[k^1 - \sum_i k^{i1} - k^{e1}] + \eta^{k2}[k^2 - \sum_i k^{i2} - k^{e2}]
\end{aligned}$$

which leads to the following first-order conditions:

$$U_i^1 = \lambda U_i^2 = \eta^i \tag{1}$$

$$\eta^i f_e^{i1} = \eta^e + \mu \quad \eta^i f_e^{i2} = \eta^e + \alpha\mu \tag{2}$$

$$\eta^i f_k^{ir} = \eta^e f_k^{er} = \eta^{kr} \tag{3}$$

The interpretation is straightforward: the marginal rates of substitution have to be identical across countries η^i / η^j and also be equal to the marginal rate of transformation from reallocating capital and energy across the respective sectors.

2.3 The Decentralized Equilibrium

Producers in the respective countries can sell their products on the domestic or international market where output prices in both markets are assumed to be given by p_y^i (i = 1, . . . , n) and p_e, respectively. Capital prices are denoted by p_k^{jr} $(j = 1, \ldots, n, e)$ and energy prices in sector $i = 1, \ldots, n$ by p_i^e. Production decisions are then characterized by the first-order conditions

$$p_y^i f_k^{ir} = p_k^{er} \qquad p_y^i f_e^{ir} = p_e^{ir} \qquad p_e f_k^{er} = p_k^{er} \tag{4}$$

The consumers, facing consumption prices p_c^r and income I^r, maximize utility by choosing consumption according to

$$U_i^r / U_j^r = p_c^{ir} / p_c^{jr} \qquad p_c^r c^r = I^r \qquad I^r = p_k^{er} k^{er} + \sum_{i=1}^n p_k^{ir} k^{ir} \tag{5}$$

while the countries must satisfy their balance of payments:

$$p_y c^r = p_y y^r + \underbrace{p^e}_{=1} (y^{er} - e^r) - Tr^r \tag{6}$$

A simple comparison of these equilibrium conditions with those for Pareto optimality shows that any Pareto optimum (with the normalization $\eta_e = 1$) can be decentralized by choosing:

$$p_e = \eta_e = 1 \quad p_k^{ir} = p_k^{er} = \eta^{kr} \quad p_y^i = p_c^{ir} = \eta^i \quad p_e^{i1} = \eta^e + \mu \quad p_e^{i2} = \eta^e + \alpha\mu \tag{7}$$

combined with appropriate transfers Tr^r to satisfy the balance of payments (see equation (6)).

Note that in any Pareto optimum, the prices for energy inputs are not differentiated across sectors within each country, while they might differ across countries if $\alpha \neq 1$. Energy prices thereby reflect the production cost p_e as well as the external effects of emissions on country 1. In particular, this implies that any unilateral emission tax by country 1 cannot achieve efficiency if $\alpha > 0$, i.e., in case of transboundary pollution.

2.4 Unilateral Tax Policy of a Large Open Economy

For the case of unilateral action, we study how country 1 should set emission taxes to unilaterally maximize its welfare. We denote the tax rates in the respective sectors by τ_e^{i1} $(i = 1,\ldots,n)$. We thereby assume that country 2 has no emissions policy and no distorting taxes, i.e., $p_k^{i2} = p_k^{e2}$, $p_y^i = p_c^{ir}$ and $p_e^{i2} = p_e$. Furthermore, since we want to focus on reasons for differentiating energy/emission taxes, we assume that country 1 does not consider any taxation of or subsidies on consumption or capital use. That is, $p_k^{i1} = p_k^{e1} = p_k^1$, $p_y^i = p_c^{i1}$.

It is clear that when the choice of τ_e^{i1} influences world market prices for consumption goods p_y, also production decisions and therefore emission levels abroad change. The change in the terms of trade is therefore linked with a potential leakage effect. For any given set of tax rates for the respective sectors, (τ_e^{i1}), the conditions (4)-(6) together with $p_e^{i1} = p_e + \tau_e^{i1}$ define the equilibrium consumption and production levels as well as prices.[1]

Country 1 maximizes $U^1(c^1)$ with respect to τ_e^{i1} $(i = 1,\ldots,n)$ such that $e^1 + \alpha e^2 \leq \bar{E}$. Differentiating with respect to τ_e^{i1} yields

[1] Without loss of generality we suppress this dependence of these equilibrium values on the tax rates in our notation.

$$U_c^1 \frac{dc^1}{d\tau_e^{i1}} - \overline{\mu}(\frac{de^1}{d\tau_e^{i1}} + \alpha \frac{de^2}{d\tau_e^{i1}}) = 0 \tag{8}$$

As (5) implies that $U_c^1 = \lambda p_c$ for an appropriately chosen $\lambda > 0$, we obtain the equivalent condition (with $\mu = \lambda \overline{\mu}$)

$$p_y \frac{dc^1}{d\tau_e^{i1}} - \mu(\frac{de^1}{d\tau_e^{i1}} + \alpha \frac{de^2}{d\tau_e^{i1}}) = 0 \tag{9}$$

To analyze the optimal unilateral choice of emission taxes by country, we must totally differentiate the equilibrium conditions. Differentiating (6) and using (4), we obtain (see Appendix A):

$$p_c \frac{dc}{d\tau_e^{i1}} = \sum_j \frac{dp_y^j}{d\tau_e^{i1}} (y^{j1} - c^{j1}) + \sum_j \tau_e^{j1} \frac{de^{j1}}{d\tau_e^{i1}} \tag{10}$$

such that the first order condition (9) is given by

$$\sum_j [\tau_e^{j1} - \mu] \frac{de^{j1}}{d\tau_e^{i1}} + \sum_j \frac{dp_y^j}{d\tau_e^{i1}} (y^{j1} - c^{j1}) - \mu\alpha \frac{de^2}{d\tau_e^{i1}} = 0 \tag{11}$$

for all i.

It becomes obvious that energy tax differentiation may be optimal for country 1 for two reasons: (i) the terms-of-trade effect $(dp_y^j / d\tau_e^{i1})$ and (ii) the leakage effect $(de^2 / d\tau_e^{i1})$. If both effects were absent, $\tau_e^{j1} = \mu$ for all j would solve (11).[2] In general, however, country 1 should differentiate taxes across sectors in order to exploit terms of trade and counteract emission leakage.

First, consider the terms-of-trade motive for tax differentiation: if country 1 were an exporter of good j $(y^{j1} > c^{j1})$, it would like to increase those tax rates which lead to an increase in p_y^j and decrease the other tax rates. The opposite holds true if country 1 imports good j.

Second, consider the leakage motive for tax differentiation: unilateral emission taxes in country 1 reduce domestic energy demand while increasing energy demand abroad through lower energy prices and higher prices for emission-intensive goods. The marginal effects of sectoral tax rates on leakage differ such that the accounting for leakage in the policy choice also generally leads to differentiated taxes. Country 1 would like to decrease emission taxes on emission-intensive traded goods to reduce counterproductive leakage spillovers to country 2.

2.5 Decomposition

[2] In this case we get the standard result for a small open economy that can neither affect terms of trade nor cares for leakage.

In order to assess the relative importance of the terms-of-trade and leakage motives for differential emission pricing, we can suppress the terms-of-trade motive following an intuitive idea of cross-country compensation: country 1 optimizes its taxation policy $\tau_e^1 = (\tau_e^{i1})$ combined with endogenous transfers $Tr^1(\tau_e^1)$ that hold the welfare in the other unregulated country fixed at the pre-policy level (denoted $\bar{u}^2$). The tax system τ_e^1 thereby again fully characterizes the resulting equilibrium. With this compensation requirement, any marginal change of the taxation system is accompanied by a change in transfers such that the resulting marginal consumption change in country 2 satisfies $U_c^2 dc^2 / d\tau_e^{i1} = 0$, or equivalently $p_y dc^2 / d\tau_e^{i1} = 0$. For country 1, the market clearance condition therefore implies

$$p_y (dy^1 / d\tau_e^{i1} + dy^2 / d\tau_e^{i1} - dc^1 / d\tau_e^{i1}) = 0 \tag{12}$$

Country 1's first-order conditions for welfare maximization with respect to the emission tax system therefore again satisfy $p_y dc^1 / d\tau_e^{i1} - \mu[de^1 / d\tau_e^{i1} + \alpha de^2 / d\tau_e^{i1}] = 0$ for all i. Using (11), this is equivalent to

$$0 = \sum_j (\tau_e^{j1} - \mu) \frac{de^{j1}}{d\tau_e^{i1}} - \mu\alpha \frac{de^2}{d\tau_e^{i1}} \tag{13}$$

as shown in Appendix A.

As we impose compensating transfers, the only remaining reason for differentiating taxes is leakage.[3] In this case, we can assign the extent of tax differentiation fully to the leakage motive. That is, the terms-of-trade motive is "switched off". In turn, we can consider the extent to which the terms-of-trade motive leads to differentiated taxes by "switching off" the leakage motive. For this, we solve the first-order conditions (11) with α = 0 (i.e., country 1 does not consider the marginal effects of its policy choice on foreign emissions). It is then obvious that the terms-of-trade motive remains the only reason for tax differentiation.

It should be noted that our reasoning is identical when we switch from emission taxes as policy instrument to partitioning some targeted emission budget across sectors without the possibility of cross-sector emission trading.

3. Numerical Analysis

The analytical derivation of optimal emission prices becomes intractable for equilibrium conditions

[3] As another way to see this, we can reconsider condition (7). If α = 0, country 1 could achieve any Pareto optimum by unilaterally setting an emission tax, i.e., a tax on energy use, at $\tau_e^1 = \mu$ and choosing appropriate transfers. It is therefore obvious that the program max u^1 such that $u^2 \geq \bar{u}^2$ must lead to a Pareto-efficient solution. In this case, however, we know that emission prices, i.e., emission taxes, must coincide for all sectors in country 1.

that exceed the complexity of textbook models (Markusen 1975, Hoel 1996). Furthermore, the results obtained through marginal analysis can in general not be transferred to structural shocks. Thus, we must use a computable general equilibrium (CGE) approach based on empirical data to quantify how international spillovers affect the magnitude and direction of emission price differentiation and how the cost implications differ from the case of (non-strategic) uniform emission pricing. Our decomposition technique thereby allows us to ascertain the relative importance of the terms-of-trade and leakage motives.

The numerical analysis is cast as a policy optimization problem subject to economic equilibrium conditions:

$$\max_{\tau} U^{\hat{r}} \quad s.t. \; F(z,\tau)=0$$

where:

$z \in \Re^n$	is the vector of endogenous prices and quantities determined by the general equilibrium conditions,
$\tau \in \Re^m$	is a vector of taxes or likewise emission prices which are the choice variables for the optimization problem (in our case τ comprises the set of two taxes that can be differentiated between the emission-intensive and trade-exposed sectors and the remaining sectors of the economy),[4]
$F: \Re^n \rightarrow \Re^n$	is a system of equations which represents the general equilibrium conditions, and
$U^{\hat{r}}$	is the policy objective function.

The objective function $U^{\hat{r}}$ reflects welfare maximization by region $\hat{r}$ subject to a unilateral emission constraint $\bar{e}^{\hat{r}}$ below business-as-usual emissions $e_0^{\hat{r}}$.

If the unilaterally abating region $\hat{r}$ explicitly cares for global environmental effectiveness and thus accounts for leakage, the domestic emission constraint is replaced with a "leakage-adjusted" global emission constraint. The latter requires that endogenous emissions e^r across all regions *r* equal the sum of the targeted unilateral emission level $\bar{e}^{\hat{r}}$ and the business-as-usual emissions $e_0^{r'}$ of unregulated regions ($r' \neq \hat{r}$)

$$\sum_r e^r = \bar{e}^{\hat{r}} + \sum_{r'} e_0^{r'}$$

where the dual variable associated with the global emission constraint endogenously scales the domestic emission target of the unilaterally abating region to offset leakage.

[4] We impose a non-negativity constraint on emission prices to exclude the possibility of emission subsidies.

In order to suppress the terms-of-trade motive we need to add a transfer constraint for each unregulated region r' that keeps this region at its initial welfare level

$$U^{r'} \geq U_0^{r'}$$

where the respective dual variable denotes the lump-sum transfer between the regulated region $\hat{r}$ and the unregulated region r'. Following our theoretical exposition, the regulated country then has no incentive for strategic terms-of-trade manipulation.

The remaining equilibrium conditions in our numerical analysis are provided by a standard global multi-region, multi-sector CGE model (Böhringer and Rutherford 2010) of global trade and energy use which readily incorporates terms-of-trade and leakage spillover effects.

In this section, we first provide a brief non-technical summary of the CGE model.[5] We then describe alternative unilateral climate policy scenarios to curb global carbon emissions and interpret the simulation results. Finally, we provide sensitivity analysis on the robustness of our findings.

3.1 Computable General Equilibrium Model

Our static CGE model features a representative agent in each region that receives income from three primary factors: labor, capital, and fossil-fuel resources. Labor and capital are intersectorally mobile within a region but immobile between regions. Fossil-fuel resources are specific to fossil fuel production sectors in each region.

Production of commodities, other than primary fossil fuels is captured by nested constant elasticity of substitution (CES) cost functions describing the price-dependent use of capital, labor, energy, and material. At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital, and labor subject to a constant elasticity of substitution. At the second level, a CES function describes the substitution possibilities between the energy aggregate and a value-added composite of labor and capital. At the third level, capital and labor substitution possibilities within the value-added composite are captured by a CES function. The energy aggregate is further split into a fossil fuel composite and electricity subject to a constant elasticity of substitution. 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.

Final consumption demand in each region is determined by the representative agent who maximizes utility subject to a budget constraint with fixed investment (i.e., a given demand for savings) and exogenous government provision of public goods and services. Total income of the representative household consists of factor income and taxes. Consumption demand of the

[5] Appendix B includes a detailed algebraic model description with a graphical exposition of the nesting structure for flexible functional forms that capture production possibilities and consumption preferences.

representative agent is given as a CES composite that combines consumption of energy and non-energy goods.

Bilateral trade is specified following the Armington approach of product heterogeneity where domestic and foreign goods are distinguished by origin (Armington 1969). All goods used on the domestic market in intermediate and final demand correspond to a CES composite that combines the domestically produced good and the imported good from other regions.[6] A balance of payment constraint captures the base-year trade deficit or surplus for each region.

Anthropogenic carbon emissions as the main driving force for climate change are linked in fixed proportions to the use of fossil fuels, with carbon coefficients differentiated by the specific carbon content of fuels. Restrictions to the use of carbon emissions in production and consumption are implemented through exogenous emission constraints or equivalently carbon taxes. Carbon emission abatement takes place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities). Revenues from carbon pricing are recycled lump-sum to the representative agent in the regulating region.

The model builds on the most recent GTAP7 database with detailed accounts of regional production, regional consumption, bilateral trade flows as well as energy flows and carbon emissions for the year 2004 (Badri and Walmsley 2008). The GTAP database is aggregated towards a composite set of sectors and regions to accommodate the policy-relevant assessment of unilateral emission pricing strategies. The energy goods identified in the model are coal, crude oil, natural gas, refined oil products, and electricity which allows us to distinguish energy goods by carbon intensity and to capture price-responsive fossil-fuel switching. The model then features an aggregate of emission-intensive and trade-exposed non-energy goods which are referred to as "sectors at risk of carbon leakage" in the policy debate and are eligible for preferential emission regulation (EU 2009). The aggregate of emission-intensive and trade-exposed commodities includes iron and steel, chemical products, non-ferrous metals, non-metallic minerals, paper-pulp-print, and transport. All remaining commodities are summarized through a composite macro good. With respect to regional disaggregation, the model covers major industrialized and developing regions that are central to the climate policy debate: the EU, the U.S., Canada, Japan, Australia and New Zealand, Russia, China, India, Brazil, Mexico, and South Africa. In addition, the organization of oil exporting countries (OPEC) is incorporated along with a composite region for the rest of the world. As is customary in applied general equilibrium analysis, base year data together with exogenous elasticities determine the free parameters of the functional forms. Elasticity values in international trade (Armington elasticities) and domestic production are based on empirical estimates reported in the GTAP database; supply elasticities for fossil fuels are taken from the econometric literature (Graham et al. 1999, Krichene

[6] Product heterogeneity implicitly provides each country with market power in international trade. Depending on initial trade shares and the ease of substitution between imports and domestically produced goods (captured by trade elasticities) domestic policies affect international prices, i.e., the terms of trade.

2002).

3.2 Policy Scenarios

Theory suggests that international market power and concerns on global environmental effectiveness induce a unilaterally abating region to differentiate emission prices across domestic sectors. From a broader policy perspective the key question, however, is to what extent differential emission pricing can reduce global economic adjustment cost (under the leakage motive) or be used for burden shifting (under the terms-of-trade motive). If it turns out that the potential for both global cost savings and exploitation of international market power is quite limited, then uniform emission pricing appears as a practical – since politically rather uncontroversial – guideline for unilateral climate policy design.

In our quantitative analysis, scenario *Ref* provides the reference of a non-strategic unilateral climate policy where the abating region is restricted to uniform emission pricing across all sectors.[7] We then investigate how economic impacts change as emission price differentiation becomes a viable policy option. With two potential motives for price differentiation we get four strategic scenarios. Scenario *None* assumes that unilateral regulation fully ignores international spillovers, i.e., neither leakage effects nor international market power are accounted for. Scenario *Leakage* postulates that unilateral regulation considers leakage but can not exploit terms of trade as we require the abating region to compensate non-abating regions at the pre-policy welfare level. Scenario *ToT* considers the case that the unilaterally abating region uses differential emission pricing to exploit terms of trade but does not care for leakage. Scenario *Leakage_ToT* assumes that unilateral climate policy is concerned about leakage and at the same time can take advantage of international market power through differential emission pricing.

Table 1 summarizes the motives for emission price differentiation prevailing in the four strategic scenarios. Scenario *None* serves as a consistency check for the numerical implementation of our optimal taxation framework. In the absence of the leakage and the terms-of-trade motives economic theory yields an unambiguous result for optimal emission pricing when we start from a market equilibrium without prior distortions: emissions should be uniformly priced across all domestic sources to minimize domestic adjustment cost. The difference between scenarios *None* and *Ref* then boils down to income effects because the latter does not impose compensating transfers.

[7] The *Ref* scenario setting corresponds to the standard design rule of unilateral emission abatement where the regulator achieves a mandated domestic emission reduction through uniform (non-strategic) emission pricing. The impact assessment of scenario *Ref* does not require an optimal taxation framework and can be based on conventional CGE analysis without a superordinate objective function.

Table 1: Characterization of strategic emission pricing scenarios

Scenario	Leakage Motive	Terms-of-Trade Motive
None	No	No
Leakage	Yes	No
ToT	No	Yes
Leakage_ToT	Yes	Yes

In the four strategic scenarios we focus on differential emission pricing between emission-intensive and trade-exposed industries (thereafter referred to as EIS) on the one hand and the rest of the economy (thereafter referred to as OTH) on the other hand. The segmentation into these categories reflects ongoing policy practice of differential environmental regulation in industrialized countries (OECD 2007).

Across all five scenarios we must keep the global environmental outcome constant in order to compare cost-effectiveness of alternative unilateral climate policy designs. The global environmental emission target is set equal to the sum of the targeted unilateral emission level and the business-as-usual emissions of all other unregulated regions. For scenarios *Leakage* and *Leakage_ToT* which incorporate the leakage motive the global emission constraint is simply added to the system of general equilibrium conditions. For scenarios *None* and *ToT* the leakage motive must be suppressed and we therefore cannot include the global emission target as a simultaneous equilibrium condition in our optimal taxation problem. Instead we must solve a sequence of optimization problems until we meet the global environmental target through iterative scaling of the unilateral emission abatement target. As to scenario *Ref* where the abating region has no choice for differential emission pricing we can again add the global emission constraint to the simultaneous system of equilibrium conditions.

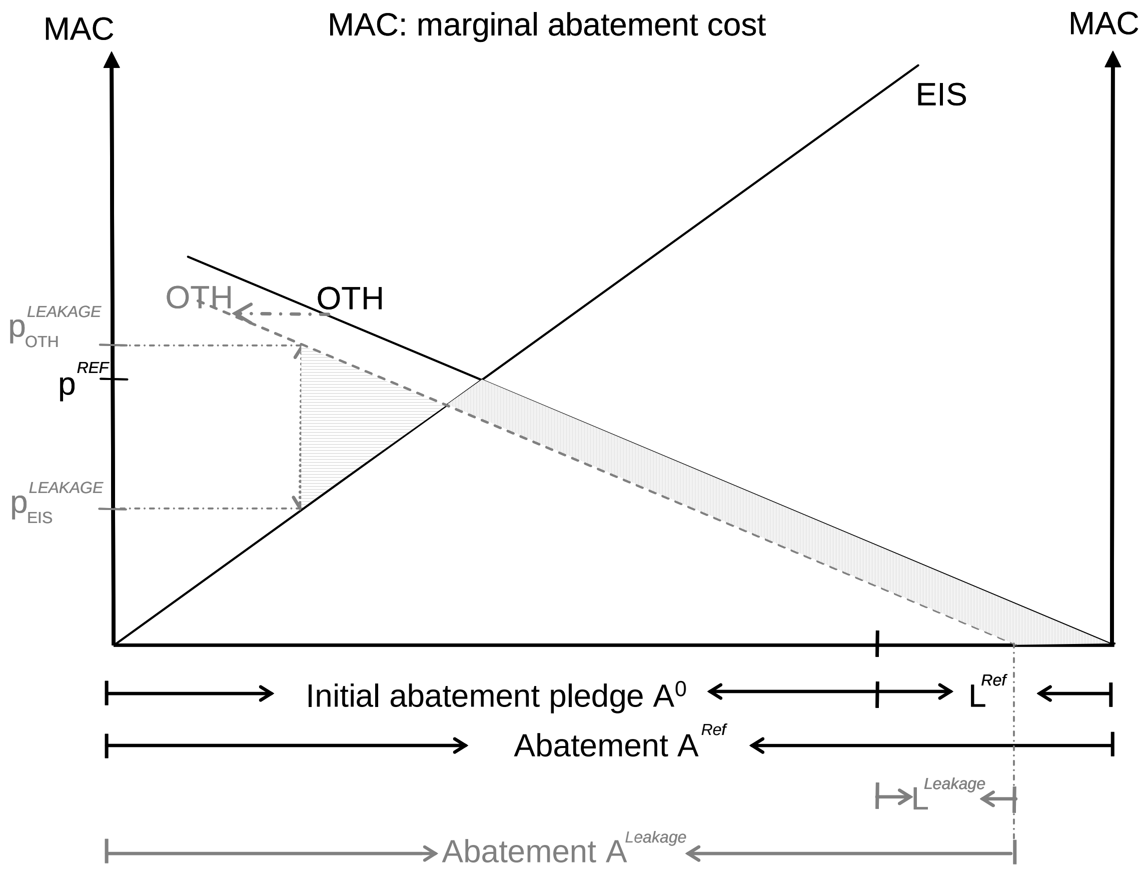
In our central case simulations we consider unilateral abatement of either the EU or the U.S. where policy concerns on leakage are very outspoken and have motivated policy proposals for special treatment of emission-intensive and trade-exposed industries. We assume a unilateral emission reduction target of 20 percent vis-à-vis emission levels in 2004 which roughly reflects pledges of the respective governments for the Post-Kyoto area. Note that the base year (2004) reflects a situation where the Kyoto Protocol has not entered into force and climate policies are almost absent internationally.

3.3 Simulation Results

Prior to the detailed interpretation of simulation results we reflect on important economic mechanisms that drive the marginal and inframarginal cost of unilateral emission abatement in the presence of international spillovers.

Figure 1 draws on the simple notion of marginal abatement cost curves to illustrate the leakage motive for differential emission pricing between EIS and OTH sectors. In the *Ref* scenario without strategic emission pricing the regulating region equalizes marginal abatement cost to minimize direct cost of emission abatement. To offset leakage L^{Ref} the region must increase its original abatement pledge A^0 to A^{Ref}. As we incorporate the leakage motive for strategic price differentiation under scenario *Leakage*, the region reduces leakage through preferential emission pricing of EIS sectors to lower its domestic emission reduction requirement $A^{Leakage}$ for meeting the overall (global) emission reduction constraint. In Figure 1 this leakage reduction is captured through the left shift of the OTH marginal abatement cost curve. The region must trade off the incremental gains from reduced domestic emission abatement with the incremental "excess" cost of emission abatement due to diverging marginal abatement cost (i.e., it maximizes the difference between the vertically and horizontally shaded areas in Figure 1).[8]

Figure 1: Leakage motive for differential emission pricing



In our quantitative analysis below we find that while the leakage motive can lead to a distinct preferential treatment of EIS industries, the scope for leakage reduction is rather small. The reason is that leakage is predominantly driven through robust energy market adjustments associated with the need for fossil fuel use reduction to meet the global carbon constraint. Figure 1 furthermore visualizes that the direct (partial equilibrium) cost of emission reduction depend on the effective emission

[8] Note that the net gains from the exploitation of international market power under the terms-of-trade motive are similarly limited through the excess cost of abatement as marginal abatement cost for OTH and EIS sectors fall apart.

reduction requirement and the ease of substituting away from carbon (captured through the steepness of the marginal abatement cost curve): the higher the targeted emission cutback and the steeper the marginal abatement cost curve, the more expensive emission reduction becomes.

Terms-of-trade effects constitute another important determinant of economic impacts triggered by emission regulation of open economies. With a sizeable reduction of global fossil fuel demand, terms-of-trade effects work largely through the depression of international fuel prices (Böhringer and Rutherford 2002) bringing about gains for fuel importers and losses for fuel exporters.

Table 2 summarizes quantitative impacts for unilateral action of either the EU or the U.S. The emission price ratio as our core metric for the degree of emission price differentiation reports marginal abatement cost in emission-intensive and trade-exposed industries (EIS) over marginal abatement cost in the other segments of the domestic economy (OTH). While uniform pricing in scenario *Ref* is externally imposed, it is the optimal choice of the abating region in scenario *None*: as predicted in our theoretical analysis unilateral regulation charges a uniform price for each domestic use of the carbon pollutant if terms-of-trade and leakage motives are absent. The uniform emission price to cut back global emissions by 20 percent of the domestic business-as-usual emissions is higher for the EU than for the U.S. The reason is that the U.S. has cheaper abatement options compared to the EU, both with respect to energy efficiency improvements as well as with respect to fuel switching (particularly in electricity generation which is much more carbon-intensive in the U.S. than the EU). The small difference between uniform emission prices in scenarios *Ref* and *None* is due to income effects.[9]

As expected, the pure leakage motive captured by scenario *Leakage* leads to an unambiguous emission price differentiation in favor of emission-intensive and trade-exposed industries. Lower emission prices alleviate the cost disadvantage for these industries relative to competitors abroad. Under optimal price differentiation the increase in direct abatement cost (due to diverging marginal abatement cost across segments of the domestic economy) are offset at the margin by the indirect gains of reduced emission leakage (and thus reduced domestic abatement). Our quantitative results based on empirical data indicate that emission-intensive and trade-exposed industries in the EU or the U.S. pay substantially lower emission prices under the pure leakage motive than the rest of the economy.

The directional implications of the pure terms-of-trade motive represented by scenario *ToT* are ambiguous and depend on trade characteristics, most notably trade intensities and trade elasticities.

[9] The U.S. and EU economies benefit from terms-of-trade effects (in particular from lower international fossil fuel prices) in scenario *Ref* which must be compensated for in scenario *None*. Thus, their income (and energy demand) is higher in scenario *Ref* which explains the higher emission price compared to scenario *None*.

Table 2: Summary of quantitative impacts for alternative emission pricing strategies

	Ref	*None*	*Leakage*
	Unilateral (domestic) abatement by EU		
Emission price ratio (EIS/OTH)	1,00	1,00	0,59
EIS emission price ($ per ton of C)	214	211	131
OTH emission price ($ per ton of C)	214	211	224
Domestic EIS production (% from *BaU*)	-5,81	-5,55	-4,53
Foreign EIS production (% from *BaU*)	2,48	2,36	1,95
Leakage rate (in %)	36,73	36,75	35,75
Domestic cost (in % HEV)	-0,009	-0,653	-0,640
Foreign cost (in % HEV)	-0,260	0	0
Global cost (in % HEV)	-0,183	-0,202	-0,198
	Unilateral (domestic) abatement by USA		
Emission price ratio (EIS/OTH)	1,00	1,00	0,57
EIS emission price ($ per ton of C)	112	111	66
OTH emission price ($ per ton of C)	112	111	116
Domestic EIS production (% from *BaU*)	-5,27	-5,14	-3,98
Foreign EIS production (% from *BaU*)	0,77	0,75	0,57
Leakage rate (in %)	16,51	16,46	15,31
Domestic cost (in % HEV)	-0,028	-0,241	-0,237
Foreign cost (in % HEV)	-0,095	0	0
Global cost (in % HEV)	-0,074	-0,077	-0,075

Key: EIS – energy-intensive and trade-exposed sectors, OTH – remaining segments of the economy, BaU – business-as-usual, HEV – Hicksian equivalent variation in income

The principle logic behind differential emission pricing as a substitute for optimal tariffs is to make the country act as monopolists on export markets (i.e., increasing the prices of export goods) and as a monopsonist on import markets (i.e., subsidizing domestic production of goods that compete on import markets). Drawing on the benchmark data, the EU is a net exporter of emission-intensive goods and a net importer of the composite macro good – therefore the terms-of-trade motive suggests higher rather than lower emission prices for domestic emission-intensive production. In turn, the U.S. which is a net importer of emission-intensive goods goes for lower emission prices in the emission-intensive sector in order to discriminate against competing imports, thereby reducing import demand and import prices.

A potentially important policy insight in the debate on beggar-thy-neighbour strategies is that unilaterally abating countries with a strong export position for emission-intensive products can hardly be accused of selfish terms-of-trade exploitation should they impose lower emission prices on emission-intensive industries than on the rest of their economy.

If both motives for price discrimination overlap (scenario *ToT_Leakage*), the direction of price discrimination is a priori not clear for the case of net exporters of emission-intensive goods since the terms-of-trade motive and the leakage motive work in opposite direction. The combined effect for net importers of emission-intensive goods, on the other hand, is unambiguous since both leakage and terms-of-trade motives imply lower emission pricing in favor of emission-intensive and trade-exposed industries.

The simulation results indicate that the absolute emission price level for the other segments of the economy (OTH) remains relatively stable independent of strategic emission pricing. The reasoning behind is twofold. First, emission-intensive and trade-exposed industries (EIS) only account for the smaller part of economy-wide emissions in the EU and the U.S.[10] Second, the marginal abatement cost curve for OTH is flatter than that for EIS pointing to cheaper emission mitigation possibilities outside EIS (to a larger extent because of low-cost fuel switching options in the electricity sector).

To a first approximation, the impacts on emission-intensive and trade-exposed production reflect the cost increase for fossil fuel use in these industries. Emission pricing thereby not only affects comparative advantage of domestic emission-intensive and trade-exposed production vis-à-vis production of the same goods abroad but also the competitive situation with respect to the production of other goods. The lower the unilateral emission prices for EIS, the less pronounced is the decrease in domestic EIS production and reversely the increase in EIS production abroad. For the EU, the pure leakage motive leads to the lowest emission prices for emission-intensive industries whereas the pure terms-of-trade motive implies the highest emission prices – recall that the EU as a net exporter of emission-intensive products uses differential emission pricing as a substitute for strategic export taxes

[10] Emission-intensive and trade-exposed industries account for 18.3 percent (22.9 percent) of business-as-usual emissions in the EU (the U.S.).

on these goods. The decline in EU emission-intensive and trade-exposed production is therefore lowest for scenario *Leakage* and highest for scenario *ToT*. For the U.S., which is a net importer of emission-intensive goods, both the terms-of-trade and leakage motives imply a preferential treatment of emission-intensive and trade-exposed industries – EIS production losses are most moderate for scenario *Leakage* followed by scenarios *Leakage-ToT* and *ToT*.

Differential emission pricing under leakage and terms-of-trade motives induces distinct changes in EIS production impacts compared to uniform emission pricing but the implications for emission leakage are quite small. The leakage rate which is defined as the change in emissions of unregulated regions over the change in emissions of the regulating region ranges between 35.7 to 38.3 percent for EU unilateral action and 15.3 to 16.5 percent for U.S. unilateral action. One reason for the substantially higher leakage rates triggered by EU action is that the EU is a more open economy than the U.S., meaning that imports and exports constitute a larger share of the economy in the EU. This is true both for emission-intensive goods and for fossil fuels, where the EU is a much bigger importer (relative to own consumption) than the U.S. Another reason for higher leakage rates with unilateral EU abatement policies is that emission-intensive industries in the EU are less carbon-intensive than the same industries in the U.S. Thus, relocation of industrial activities away from the abating region has more adverse effects on global emissions when the EU imposes unilateral climate policies. In qualitative terms, the changes in leakage rates go along with the differential impacts on emission-intensive and trade-exposed production (both domestically and abroad) triggered by alternative emission pricing strategies. The leakage rate is smallest for the lowest emission price to EIS production which occurs under the pure leakage motive (scenario *Leakage*) for both regions. The leakage rate is biggest for the highest emission price to EIS production which will be set under the pure terms-of-trade motive (scenario *ToT*) for the case of EU action and with uniform emission pricing (either non-strategically under scenario *REF* or in the absence of both motives under scenario *None*) for the case of U.S. action.

As noted before, the scope for leakage reduction through preferential emission pricing of domestic EIS production is quite limited. This can be traced back to the dominant role of robust energy market adjustments for leakage. The sectoral contribution to leakage from emission-intensive and trade-exposed industries amounts to roughly a third of the total leakage rate (other important non-EIS contributors are power generation and refineries) for the EU and the U.S. Leakage is however not only caused by the relocation of production but also through changes in emission intensities: while domestic production reduces emission intensity because of emission cost, production abroad becomes more emission-intensive as international fuel prices go down. If one abstracts from changes in energy intensity then the sectoral contribution of EIS production to leakage drops substantially and it becomes clear that the differential impacts on EIS production from alternative emission pricing strategies has only a limited impact on the global leakage rate.

Finally, we discuss the implications of alternative emission pricing strategies for global cost-effectiveness and the economic burden to the regulating region as well as to the composite of unregulated regions. Economic cost (welfare) are measured as Hicksian equivalent variation (HEV) in income, i.e., the amount of money which is necessary to add to (or deduct from) the business-as-usual income of the representative consumer so that she enjoys a utility level equal to the one in the counterfactual policy scenario on the basis of ex-ante relative prices. The metric for measuring global efficiency costs of the different policies is based on a utilitarian perspective, i.e., we add up money-metric utility with equal weights across all regions (thereby being agnostic on cost distribution).

Our quantitative results confirm the qualitative theoretical insight that preferential emission pricing of energy-intensive and trade-exposed industries to counteract leakage will improve global cost-effectiveness of unilateral abatement action: as we transit from scenario *None* to scenario *Leakage* or likewise from scenario *ToT* to scenario *ToT_Leakage* global economic adjustment cost to reach a given reduction in global emissions through unilateral action decline. However, the global cost savings are rather small which again can be traced back to the limited potential for cost-effective leakage reduction through emission price differentiation between EIS and OTH industries. We also see that the potential for burden shifting through strategic exploitation of international market power is very limited when we compare differential emission pricing under scenario *ToT* (i.e., the pure terms-of-trade motive) with non-strategic uniform emission pricing under scenario *Ref*: the cost distribution between the unilaterally abating region and the composite of unregulated regions hardly changes. In fact, for the case of EU unilateral action the EU fares even better without strategic pricing at all as its gains from exploiting international market power through higher prices on EIS goods are more than offset through the higher cost of leakage adjustment.[11]

We have introduced compensating transfers in our analysis as a means to decompose the terms-of-trade and leakage motives for emission price differentiation. Yet, they also elucidate the crucial role of terms-of-trade effects on international energy markets for the cost incidence of emission reduction that has been pointed out in previous research (Böhringer and Rutherford 2002). A global emission cutback requires in first place reductions in fossil fuel demand, depressing international fuel prices. Larger fuel importers such as the EU or the U.S. benefit from the decline in international fuel prices which may offset a substantial part of their primary emission abatement cost while shifting the burden in particular to fuel exporters such as OPEC or Russia.[12] For both – the EU and the U.S. – the cheapest unilateral climate policy is to account for leakage and at the same time fully exploit terms of trade (scenario *Leakage_ToT* without compensation). If the EU or the U.S. must compensate the rest of the

[11] Note that – for the EU – the pure terms-of-trade motive leads to the highest leakage rate which needs to be offset by increased domestic abatement; yet, this leakage effect is not endogenous to the optimization problem of the EU since we suppress the leakage motive.

[12] Sensitivity analysis on the stringency of unilateral and thus global emission reduction targets shows that for a lower unilateral emission reduction pledge of 15 % the terms-of-trade gains can even outweigh the primary cost of emission abatement for the U.S. or the EU leaving them better off compared to a business-as-usual situation without climate policy.

world for terms-of-trade losses as requested under scenarios *None* and *Leakage* unilateral abatement is much more costly for them. When we compare the magnitude of economic cost for the EU or the U.S. across scenarios *Ref* (no compensation and no strategic price differentiation), *NONE* (compensation and no leakage adjustment motive) and scenario *ToT* (no compensation and strategic price differentiation to exploit terms of trade) it becomes clear that the bulk part of terms-of-trade changes are not associated with strategic price differentiation between EIS and OTH industries but stem from robust energy market adjustments.

To sum up: while differential emission pricing motivated by global environmental concerns or international market power can lead to substantial deviations from uniform emission pricing, the inframarginal effects on global cost-effectiveness and burden sharing are small. Leakage and terms-of-trade effects are largely determined by robust energy market adjustments under a global emission constraint. The scope for strategic responses to international spillovers through price differentiation between emission-intensive and trade-exposed industries and the rest of the economy is limited through the increase of direct abatement cost associated with differential emission pricing.

3.4 Sensitivity Analysis

We have performed extensive sensitivity analysis to understand how changes in key assumptions affect our conclusions. We find that our insights regarding the implications of the terms-of-trade and leakage motives for differential emission pricing and the inframarginal welfare cost remain robust.

In our central case simulations, energy market adjustments account for a large share of terms-of-trade changes and emission leakage. The responsiveness of international fuel markets to changes in energy demand is determined by supply elasticities. Lower (higher) elasticities imply that fossil fuel prices drop more (less) as a consequence of energy demand reductions with opposite welfare implications for fuel exporting and fuel importing regions. The lower (higher) the energy supply elasticity the stronger (weaker) is the energy market channel for leakage and thus the stronger (weaker) is the case for leakage-motivated price differentiation in favor of emission-intensive industries.

Armington trade elasticities that capture the ease of substitution between domestic goods and imported goods constitute an important driver for the magnitude of leakage and terms-of-trade effects. Changes in these elasticities affect the relative importance of the leakage motive versus the terms-of-trade motive for emission price differentiation. Higher Armington elasticities ceteris paribus imply more leakage and less scope for tax burden shifting so the leakage motive becomes more important compared to the terms-of-trade motive.

Within our central case simulations, the abating region has a unilateral emission reduction pledge of 20 percent with respect to the base-year emission level. Changes in the stringency of the emission reduction level affect both the magnitude of price differentiation associated with different motives as well as the level of economy-wide adjustment cost. Not surprisingly, higher reduction targets lead to an upward-shift of average emission prices and an increase in total economic cost. For sufficiently low reduction targets, fuel importing regions may be able to offset the cost of unilateral abatement through terms-of-trade gains on energy markets. The leakage argument for lowering emission prices in favor of emission-intensive and trade-exposed industries production becomes more important towards higher emission reduction requirements as the increase in domestic emission prices enhances comparative cost advantage of foreign competitors.

The regions considered for unilateral abatement in our central case simulations cover the EU and the U.S. as the most important industrialized regions that are already under way (the EU) or might follow suit with domestic emission constraints. Both, the EU as well as the U.S. are importers of fossil fuels and thus can benefit from the depression of international fossil fuel prices associated with the global reduction in fossil fuel demands. If one considers compensating transfers that include terms-of-trade losses or gains on energy markets as a viable policy option,[13] the ranking of policy scenarios is obviously quite different from the perspective of fossil fuel exporters such as Russia or OPEC. The latter would prefer to get compensated from the rest of the world for their terms-of-trade losses that occur primarily on the energy markets due to targeted (global) carbon emission reductions. As we suppress the terms-of-trade motive, unilaterally abating fuel exporters receive a net transfer from non-abating regions (keeping non-abating regions at their business-as-usual welfare level). Thus, energy exporters are best off under scenario *Leakage* where they receive a net income transfers from the rest of the world and employ price differentiation to mitigate leakage. Most expensive for them – among the four strategic pricing variants – is scenario *ToT*: in this case they can try to exploit terms-of-trade gains on non-energy goods markets but are left with the dominant terms-of-trade losses on the international fuel markets (in addition, efficient leakage adjustment is not strategically taken into account in this scenario).

4. Conclusions

As long as the world community fails to achieve a broad-based international agreement with binding multilateral emission reduction targets, greenhouse gas emission reduction hinges on unilateral action by industrialized countries acknowledging historical responsibility and ability-to-pay. Cost-effectiveness of unilateral climate policy may, however, be seriously hampered through emission leakage to unregulated regions. Concerns on global environmental integrity of unilateral emission control provide an important argument for preferential treatment of emission-intensive and trade-

[13] In our view, compensation for energy market adjustments which are inevitably linked to climate protection is not very realistic though fuel exporting regions may appeal to Articles 4.8 and 4.9 of the United Nations Framework Convention on Climate Change (UN, 1992) that developing countries can claim compensation for induced economic cost of climate policies by industrialized countries. Larger fuel exporters on the one hand may not qualify as developing countries. In addition, compensation for the internalization of the greenhouse gas externalities would contradict the broadly accepted notion of the polluter-pays principle.

exposed sectors. At the same time, the leakage motive for differential emission pricing cannot be easily distinguished from potential interests of the abating region to exploit international market power through strategic terms-of-trade manipulation. In a political economy perspective the leakage argument may also be employed by domestic lobby groups with the objective to dilute inevitable structural change in favor of specific industries.

In this paper we have developed a theoretical framework of how to decompose the leakage motive from the terms-of-trade motive for differential emission pricing in the presence of international spillovers. We then have implemented our decomposition method in a large-scale computable general equilibrium model of global trade and energy use to ascertain the relative importance of these motives for the direction and magnitude of emission price differentiation as well as the induced inframarginal adjustment cost. The main insight from our quantitative analysis is that the scope for global efficiency gains and burden shifting through strategic emission price differentiation is rather limited. The reason is that economic adjustment to global emission constraints to be achieved by unilateral abatement is largely driven by robust international energy market effects independent from alternative domestic emission pricing strategies. Unilaterally climate policy may therefore be well advised to stick to the simple first-best rule of uniform emission pricing rather than embarking on complex second-best arguments which may cause detrimental conflicts with trading partners.

References

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*, University of Michigan Press, 25–48.

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

Badri, N. G. and T. L. Walmsley (2008), "Global Trade, Assistance and Production: The GTAP 7 Data Base, Center for Global Trade Analysis", Purdue University, West Lafayette.

Böhringer, C. and T.F. Rutherford (2002), "Carbon Abatement and International Spillovers", *Environmental and Resource Economics* 22 (3), 391-417.

Böhringer, C., R.S.J. Tol, and T.F. Rutherford (2009), "The EU 20/20/2020 Targets: an Overview of the EMF22 Assessment", *Energy Economics*, 31(2), 268-273.

Böhringer, C. and T.F. Rutherford (2010), "The Costs of Compliance: A CGE Assessment of Canada's Policy Options under the Kyoto Protocol", *The World Economy*, 33 (2), 177-211.

Felder, S. and T. F. Rutherford (1993), "Unilateral Reductions and Carbon Leakage: The Effect of International Trade in Oil and Basic Materials," *Journal of Environmental Economics and Management*, 25, 162–176.

EU (2009), "Commission Decision of Determining, Pursuant to Directive 2003/87/EC of the European Parliament and of the Council, a List of Sectors and Subsectors which are Deemed to be Exposed to a Significant Risk of Carbon Leakage 2010". Available at: http://ec.europa.eu/environment/climat/emission/pdf/draft_dec_carbon_leakage_list16sep.pdf

Graham, P., S. Thorpe and L. Hogan (1999), "Non-competitive market behavior in the international coking coal market", *Energy Economics* 21, 195-212.

Hoel, M. (1991), “Global Environment Problems: The Effects of Unilateral Actions Taken by One Country,” *Journal of Environmental Economics and Management*, *20*, 55–70.

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

Krichene, N. (2002), “World crude oil and natural gas: a demand and supply model”, *Energy Economics* 24, 557-576.

Krutilla, K. (1991), “Environmental Regulation in an Open Economy,” *Journal of Environmental Economics and Management*, *20*, 127–142.

OECD (2007), “OECD/EEA database on instruments used for environmental policy and natural resources management,” Technical Report, Organization for Economic Co-operation and Development, Paris 2007. Available at: http://www2.oecd.org/ecoinst/queries/index.htm

UN (1992), United Nations Framework Convention on Climate Change, New York, 9 May 1992, in force 21, March 1994.

A Mathematical Proofs

Proof of equation (10)

Differentiating the balance of payments in (6), we obtain

$$p_y \frac{dc}{d\tau_e^{i1}} = \frac{dp_y}{d\tau_e^{i1}}(y^1 - c^1) + p_y \frac{dy^1}{d\tau_e^{i1}} + p^e (\frac{dy^{e1}}{d\tau_e^{i1}} - \frac{de^1}{d\tau_e^{i1}})$$

We can now differentiate the respective production functions and obtain:

$$p_y \frac{dc}{d\tau_e^{i1}} = \frac{dp_y}{d\tau_e^{i1}}(y^1 - c^1) + \sum_j p_y^j \left[f_k^{j1} \frac{dk^{j1}}{d\tau_e^{i1}} + f_e^{j1} \frac{de^{j1}}{d\tau_e^{i1}} \right] + p^e (f_k^{e1} \frac{dk^{e1}}{d\tau_e^{i1}} - \frac{de^1}{d\tau_e^{i1}})$$

Noting that $p^{j1} f_k^{j1} = p_k^1$ and $p^{j1} f_e^{j1} = p_e + \tau_e^{j1}$, this leads to

$$p_y \frac{dc}{d\tau_e^{i1}} = \frac{dp_y}{d\tau_e^{i1}}(y^1 - c^1) + p_k^1 \left[\underbrace{\sum_j \frac{dk^{j1}}{d\tau_e^{i1}} + \frac{dk^{e1}}{d\tau_e^{i1}}}_{=0} \right] + \sum_j \tau_e^{j1} \frac{de^{j1}}{d\tau_e^{i1}}$$

which proves equation (10).

Proof of equation (13)

Plugging (12) into the first order condition $p_y dc^1 / d\tau_e^{i1} - \mu[de^1 / d\tau_e^{i1} + \alpha de^2 / d\tau_e^{i1}] = 0$, we immediately obtain:

$$\begin{aligned}
0 &= p_y dc^1 / d\tau_e^{i1} - \mu\left[de^1 / d\tau_e^{i1} + \alpha de^2 / d\tau_e^{i1}\right] \\
&= p(dy^1 / d\tau_e^{i1} + dy^2 / d\tau_e^{i1}) - \mu\left[de^1 / d\tau_e^{i1} + \alpha de^2 / d\tau_e^{i1}\right] \\
&= \sum_j p_y^j [f_k^{j1} \frac{dk^{j1}}{d\tau_e^{i1}} + f_e^{j1} \frac{de^{j1}}{d\tau_e^{i1}}] + \sum_j p_y^j [f_k^{j2} \frac{dk^{j2}}{d\tau_e^{i1}} + f_e^{j2} \frac{de^{j2}}{d\tau_e^{i1}}] - \mu[\frac{de^1}{d\tau_e^{i1}} + \alpha \frac{de^2}{d\tau_e^{i1}}] \\
&= p_k^1 \underbrace{\sum_j \frac{dk^{j1}}{d\tau_e^{i1}}}_{-dk^{e1}/d\tau_e^{i1}} + \sum_j (p_e - \mu + \tau_e^{j1}) \frac{de^{j1}}{d\tau_e^{i1}} + p_k^2 \underbrace{\sum_j \frac{dk^{j2}}{d\tau_e^{i1}}}_{-dk^{e2}/d\tau_e^{i1}} + (p_e - \mu\alpha) \sum_j \frac{de^{j2}}{d\tau_e^{i1}} \\
&= -p_e \underbrace{f_k^{e1} \frac{dk^{e1}}{d\tau_e^{i1}}}_{dy^{e1}/d\tau_e^{i1}} + \sum_j (p_e - \mu + \tau_e^{j1}) \frac{de^{j1}}{d\tau_e^{i1}} - p_e \underbrace{f_k^{e2} \frac{dk^{e2}}{d\tau_e^{i1}}}_{dy^{e2}/d\tau_e^{i1}} + (p_e - \mu\alpha) \sum_j \frac{de^{j2}}{d\tau_e^{i1}} \\
&= \sum_j (\tau_e^{j1} - \mu) \frac{de^{j1}}{d\tau_e^{i1}} - \mu\alpha \frac{de^2}{d\tau_e^{i1}}
\end{aligned}$$

where, in the last step, we used the market clearance condition for the energy market.

B Algebraic Model Summary

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 B.1 – B.6 explain the notations for variables and parameters employed within our algebraic exposition. Note that with respect to the general notation of our policy optimization problem, Table B.2 summarizes the activity variables of vector *y* within $z = \begin{pmatrix} p \\ y \end{pmatrix}$ whereas Table B.3 summarizes the price variables of vector *p*. Figures B.1 – B.4 provide a graphical exposition of the production and final consumption structure.

B.1 Zero Profit Conditions

1. Production of goods except fossil fuels $(i \notin FF)$:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j \notin EG} \theta_{jir} p_{jr}^{A} - \theta_{ir}^{KLE} \left[\theta_{ir}^{E} p_{ir}^{E\ 1-\sigma_{KLE}} + (1-\theta_{ir}^{E}) \left(\theta_{ir}^{L} w_{r}^{1-\sigma_{ir}^{KL}} + \left(1-\theta_{ir}^{L}\right) v_{r}^{1-\sigma_{ir}^{KL}} \right)^{\frac{1-\sigma_{KLE}}{1-\sigma_{ir}^{KL}}} \right]^{\frac{1}{1-\sigma_{KLE}}}$$

$$= 0$$

2. Production of fossil fuels $(i \in FF)$:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \left[\theta_{ir}^{Q} q_{ir}^{1-\sigma_{Q,i}} + (1-\theta_{ir}^{Q}) \left(\theta_{Lir}^{FF} w_{r} + \theta_{Kir}^{FF} v_{r} + \sum_{j} \theta_{jir}^{FF} \left(p_{jr}^{A} + t_{jr}^{CO_2} a_{j}^{CO_2} \right) \right)^{1-\sigma_{i}^{Q}} \right]^{\frac{1}{1-\sigma_{i}^{Q}}}$$

$$= 0$$

3. Sector-specific energy aggregate $(i \notin FF)$:

$$\prod_{ir}^{E} = p_{ir}^{E} -$$

$$\left\{ \theta_{ir}^{ELE} p_{\{ELE,r\}}^{A^{1-\sigma_{ELE}}} + (1-\theta_{ir}^{ELE}) \left[\theta_{ir}^{COA} \left(p_{COA,r}^{A} + t_{ir}^{CO_2} a_{COA}^{CO_2} \right)^{1-\sigma_{COA}} + (1-\theta_{ir}^{COA}) \left(\sum_{j \in LQ} \theta_{jir}^{LQ} \left(p_{jr}^{A} + t_{ir}^{CO_2} a_{j}^{CO_2} \right)^{1-\sigma_{LQ}} \right)^{\frac{1-\sigma_{COA}}{1-\sigma_{LQ}}} \right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}} \right\}^{\frac{1}{1-\sigma_{ELE}}}$$

$$= 0$$

4. Armington aggregate:

$$\prod_{ir}^{A} = p_{ir}^{A} - \left(\theta_{ir}^{A} \, p_{ir}^{1-\sigma_i^A} + (1-\theta_{ir}^{A}) \, p_{ir}^{M\,1-\sigma_i^A} \right)^{\frac{1}{1-\sigma_i^A}} = 0$$

5. Aggregate imports across import regions:

$$\prod_{ir}^{M} = p_{ir}^{M} - \left(\sum_{s} \theta_{isr}^{M} \, p_{is}^{X\;1-\sigma_i^M} \right)^{\frac{1}{1-\sigma_i^M}} = 0$$

6. Household consumption demand:

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

7. Household energy demand:

$$\prod_{Cr}^{E} = p_{Cr}^{E} - \prod_{i \in EG} \left(p_{ir}^{A} + t_{Cr}^{CO_2} a_i^{CO_2} \right)^{\alpha_{ir}} = 0$$

<u>B.2 Market Clearance Conditions</u>

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:

$$C_r p_r^C = w_r \overline{L}_r + v_r \overline{K}_r + \sum_{j \in FF} q_{jr} \overline{Q}_{jr} + p_{CGD,r} \overline{Y}_{CGD,r} + \overline{B}_r$$

$$+ \sum_{i \notin FF} \sum_{j \in FF} \frac{\partial \Pi_{ir}^{E}}{\partial \left(p_{jr}^{A} + t_{ir}^{CO_2} a_j^{CO_2}\right)} a_j^{CO_2} t_{ir}^{CO_2} + \sum_{i \in FF} \sum_{j \notin FF} \frac{\partial \Pi_{ir}^{Y}}{\partial \left(p_{ir}^{A} + t_{jr}^{CO_2} a_i^{CO_2}\right)} a_i^{CO_2} t_{jr}^{CO_2}$$

$$+ \sum_{i \in FF} \frac{\partial \Pi_{ir}^{E}}{\partial \left(p_{ir}^{A} + t_{Cr}^{CO_2} a_i^{CO_2}\right)} a_i^{CO_2} t_{Cr}^{CO_2}$$

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 B.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 B.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 B.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 $\in$ FF)
$t_{dr}^{CO_2}$	Carbon tax in region *r* differentiated across sources d (d={C, i})

Table B.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)
θ_{ir}^{L}	Share of labor in value-added composite of 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 overall energy demand by sector *i* in region *r*
θ_{jir}^{LQ}	Share of liquid fossil fuel *j* in liquid 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 composite energy input in household consumption in region *r*
α_{ir}	Share of energy good *i* in energy household consumption demand in region *r*
γ_{ir}	Share of non-energy good *i* in non-energy household consumption demand in region *r*

Table B.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∈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*∈*FF*)

Table B.6: Elasticities

η	Transformation between production for the domestic market and production for the export	4
σ_i^{KL}	Substitution between labor and capital in value-added composite of production in sector i	[0.2 – 1.4]
σ_{KLE}	Substitution between energy and value-added in production	0.5
σ_i^{Q}	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF} .	μ_{COA}=4.0 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_{LQ}	Substitution between gas and oil in the liquid fossil fuel composite in production	2
σ_i^{A}	Substitution between the import aggregate and the domestic input	[2.1 – 5.2]
σ_i^{M}	Substitution between imports from different regions	[4.2 – 10.4]
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	1

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

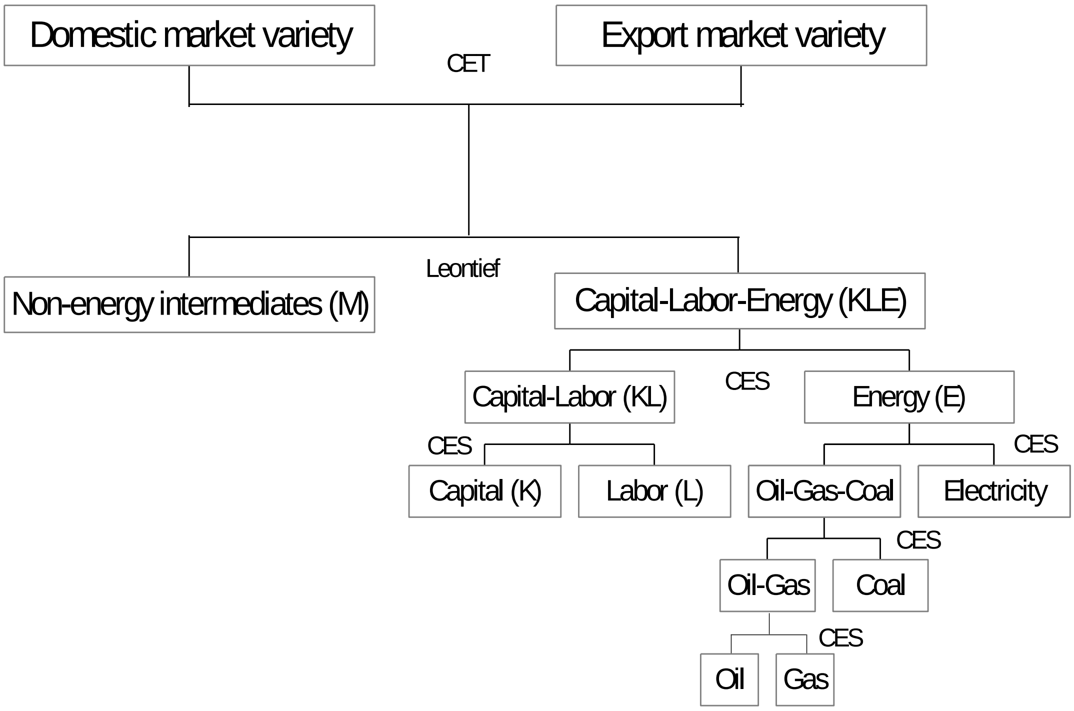


Figure B.2: Nesting in fossil fuel production

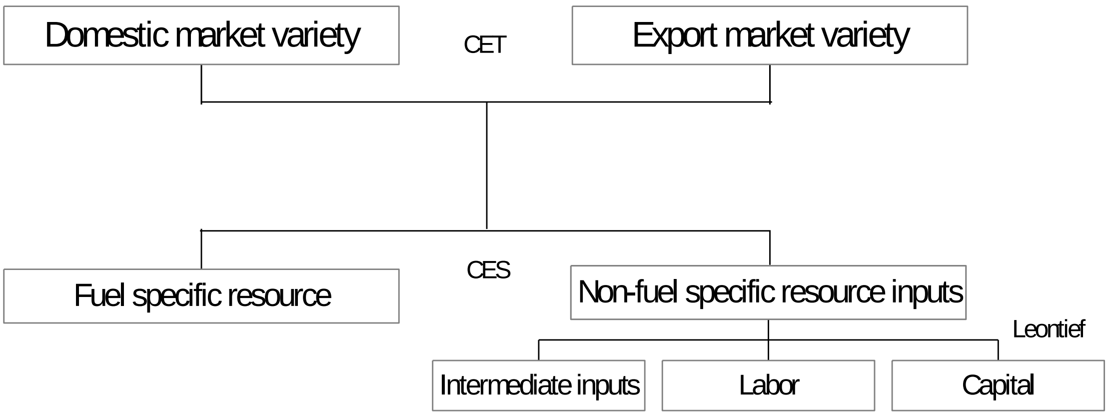


Figure B.3: Nesting in household consumption

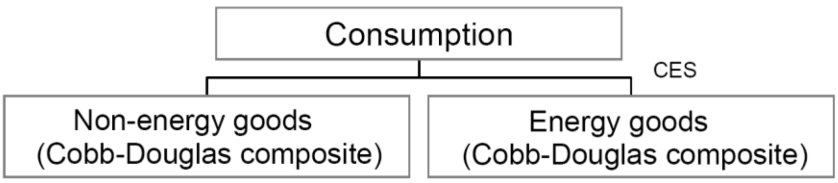
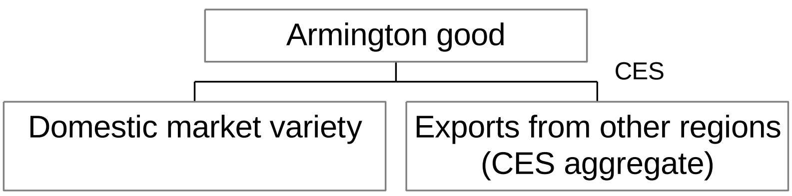


Figure B.4: Nesting in Armington production



Bisher erschienen / previous publications:

V-297-07 **Christoph Böhringer and Carsten Helm**, On the Fair Division of Greenhouse Gas Abatement Cost

V-298-07 **Christoph Böhringer**, Efficiency Losses from Overlapping, Regulation of EU Carbon Emissions

V-299-07 **Udo Ebert**, Living standard, social welfare and the redistribution of income in a heterogeneous population

V-300-07 **Udo Ebert**, Recursively aggregable inequality measures: Extensions of Gini's mean difference and the Gini coefficient

V-301-07 **Udo Ebert**, Does the definition of nonessentiality matter? A clarification

V-302-07 **Udo Ebert**, Dominance criteria for welfare comparisons: Using equivalent income to describe differences in needs

V-303-08 **Heinz Welsch, Jan Kühling**, Pro-Environmental Behavior and Rational Consumer Choice: Evidence from Surveys of Life Satisfaction

V-304-08 **Christoph Böhringer and Knut Einar Rosendahl**, Strategic Partitioning of Emissions Allowances Under the EU Emission Trading Scheme

V-305-08 **Niels Anger, Christoph Böhringer and Ulrich Oberndorfer**, Public Interest vs. Interest Groups: Allowance Allocation in the EU Emissions Trading Scheme

V-306-08 **Niels Anger, Christoph Böhringer and Andreas Lange**, The Political Economy of Environmental Tax Differentiation: Theory and Empirical Evidence

V-307-08 **Jan Kühling and Tobias Menz**, Population Aging and Air Pollution: The Case of Sulfur Dioxide

V-308-08 **Tobias Menz, Heinz Welsch**, Population Aging and Environmental Preferences in OECD: The Case of Air Pollution

V-309-08 **Tobias Menz, Heinz Welsch**, Life Cycle and Cohort Effects in the Valuation of Air Pollution: Evidence from Subjective Well-Being Data

V-310-08 **Udo Ebert**, The relationship between individual and household welfare measures of WTP and WTA

V-311-08 **Udo Ebert**, Weakly decomposable inequality measures

V-312-08 **Udo Ebert**, Taking empirical studies seriously: The principle of concentration and the measurement of welfare and inequality

V-313-09 **Heinz Welsch**, Implications of Happiness Research for Environmental Economics

V-314-09 **Heinz Welsch, Jan Kühling**, Determinants of Pro-Environmental Consumption: The Role of Reference Groups and Routine Behavior

V-315-09 **Christoph Böhringer and Knut Einar Rosendahl**, Green Serves the Dirtiest: On the Interaction between Black and Green Quotas

V-316-09 **Christoph Böhringer, Andreas Lange, and Thomas P. Rutherford**, Beggar-thy-neighbour versus global environmental concerns: an investigation of alternative motives for environmental tax differentiation

V-317-09 **Udo Ebert,** Household willingness to pay and income pooling: A comment

V-318-09 **Udo Ebert,** Equity-regarding poverty measures: differences in needs and the role of equivalence scales

V-319-09 **Udo Ebert and Heinz Welsch**, Optimal response functions in global pollution problems can be upward-sloping: Accounting for adaptation

V-320-10 **Edwin van der Werf,** Unilateral climate policy, asymmetric backstop adoption, and carbon leakage in a two-region Hotelling model

V-321-10 **Jürgen Bitzer, Ingo Geishecker, and Philipp J.H. Schröder,** Returns to Open Source Software Engagement: An Empirical Test of the Signaling Hypothesis

V-322-10 **Heinz Welsch, Jan Kühling**, Is Pro-Environmental Consumption Utility-Maximizing? Evidence from Subjective Well-Being Data

V-323-10 **Heinz Welsch und Jan Kühling**, Nutzenmaxima, Routinen und Referenzpersonen beim nachhaltigen Konsum

V-324-10 **Udo Ebert**, Inequality reducing taxation reconsidered