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OPTIMAL EMISSION PRICING IN THE PRESENCE OF INTERNATIONAL SPILLOVERS: DECOMPOSING LEAKAGE AND TERMS-OF-TRADE MOTIVES

Christoph Böhringer
Andreas Lange
Thomas F. Rutherford

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ABSTRACT

Carbon control policies in OECD countries commonly differentiate emission prices in favor of energy-intensive industries. While leakage provides a efficiency argument for differential emission pricing, the latter may be a disguised 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 illustrate our method with a quantitative impact assessment of unilateral climate policies for the U.S. and EU economies. We conclude in these instances that complex optimal emission price differentiation does not substantially reduce the overall economic costs of carbon abatement compared with a simple rule of uniform emission pricing.

Christoph Böhringer
University of Oldenburg
Department of Economics
D-26111 Oldenburg
Germany
christoph.boehringer@uni-oldenburg.de

Andreas Lange
University of Maryland
2200 Symons Hall
College Park, MD 20742
and NBER
alange@arec.umd.edu

Thomas F. Rutherford
ETH Zurich
Zurichbergstrasse 18
8032 Zurich
Switzerland
trutherford@ethz.ch

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.

Incomplete regulatory coverage of emission sources provides an efficiency rationale for emission price differentiation. When domestic emission regulation aims at combating international externalities such as global warming, lower emission prices on energy-intensive and trade-exposed industries may reduce counterproductive emission leakage to unregulated trading partners. There are two basic channels through which emission leakage can occur. First, leakage can arise when in countries with emission limitations energy-intensive and trade-exposed industries lose competitiveness, thereby increasing emission-intensive production in unconstrained regions (the trade channel). Second, emission constraints in larger open economies may depress the demand for fossil fuels and thus induce a significant drop in world energy prices, which in turn could lead to an increase in the level of energy demand in other regions (the energy channel).

While border measures may be justified as a second-best strategy for a subglobal abatement coalition, these interventions can influence terms of trade and thereby shift abatement cost to trading partners.

Both leakage and terms of trade motives for emission price differentiation figure prominently in the debate on unilateral climate policy design.[1] The problem for an informed policy decision on optimal emission price differentiation is that both motives are inherently intertwined: It is not obvious to what extent emission price differentiation within unilateral climate policies 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). In the same vein, a domestic regulator may want to sort out the pure leakage motive for differential emission pricing in negotiations with representatives of influential energy-intensive industries that lobby for preferential treatment. Decision makers thus may search for sound support to address central questions of unilateral climate policy design including:

- What is the relative importance of the leakage and the terms-of-trade motive for the direction and magnitude of emission price differentiation across sectors?
- What are the implications of emission price differentiation for the economy-wide cost of emission abatement?
- How large are the differences in economic cost between differentiated second-best emission pricing strategies as compared to a simple uniform pricing policy neglecting international spillover effects?

In order to provide insights into these fundamental challenges of subglobal climate policies we develop and apply a conceptual optimal tax framework that decomposes the leakage and terms-of-trade motives for differential emission pricing. Our proposed decomposition method is based on a thought experiment which

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[1] As efforts for an effective global emission reduction agreement continue to fail unilateral emission abatement policies become increasingly important for industrialized countries to lead the way in the battle against climate change.

requires the unilateral abating country to compensate other countries for induced welfare changes. The requirement of compensating transfers allows us to switch off the terms-of-trade motive and thereby to gain insights into the relative importance of the terms-of-trade motive vis-à-vis the leakage motive for differential emission pricing. We illustrate our method along an impact analysis of unilateral climate policies for the U.S. and the EU.

Drawing on our quantitative assessment we find that both motives are likely to be overstated in the ongoing policy debate on preferential treatment of energy-intensive and trade-exposed industries. While leakage concerns may in rare circumstances justify second-best emission price reductions for energy-intensive industries, the implications for leakage and overall economic cost are of secondary importance. Likewise, the scope for exploiting terms of trade through differential pricing of energy-intensive goods and the rest of the economy is limited.[2] We conclude that large open economies such as the EU or the U.S. cannot substantially reduce costs by using sophisticated tax differentiation. A simple first-best rule of uniform emission pricing performs only slightly worse in terms of economic efficiency even in a second-best world with international spillovers.

Our policy conclusion hinges on the relative importance of fundamental economic adjustment mechanisms. Emission leakage and terms-of-trade effects are to a large extent driven by the energy channel, i.e. the decrease of international fuel prices due to global reductions in energy demand. The energy demand reductions in turn are directly linked to the targeted reduction in *global* emissions. As we keep the contribution of a unilaterally abating region to the global public good of climate protection constant, the international energy market responses are robust to alternative unilateral emission pricing strategies and dominate both the leakage and the terms-of-trade implications: Fuel importing regions receive terms-of-trade gains from the decrease in international fuel prices, fuel exporting regions face terms-of-trade losses. The trade channel through non-energy goods which can be influenced through strategic emission pricing plays only an inferior role for leakage and additional terms-of-trade changes. Trade in energy-intensive (non-energy) goods accounts for a small share of overall emissions: In order to mitigate leakage through trade, price discrimination in favor of energy-intensive goods is warranted but the increase in the direct cost of abatement due to non-uniform emission pricing works in the opposite direction. In addition, leakage adjustment and terms-of-trade motives are limited through the restricted scope of differential emission pricing between two segments of the economy: In theory, price differentiation should be applied to many good categories. In policy practice, however, the rough categorization across two segments underlying our simulations seems to be a conditio-sine-qua-non for pragmatic reasons. The dominant role of international energy market adjustments for terms-of-trade changes and leakage explains why non-strategic uniform emission pricing as a competitive market outcome comes very close to a second-best policy design under explicit leakage concerns. This conclusions turns out to be sufficiently robust with respect to changes in key

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[2] The implications of the terms-of-trade motive for price differentiation is ambiguous depending on the trade pattern. A net exporter (importer) of energy-intensive goods adopts higher (lower) emission prices on its energy-intensive production as a substitute for export tariffs (import duties).

parameters that affect the relative importance for emission price differentiation under the leakage or terms-of-trade motive such as fossil fuel supply elasticities, trade elasticities or the magnitude of the emission reduction requirement.

The analysis of environmental regulation in an optimal tax framework has been a growing research field during the last two decades. An earlier strand of the literature (see Goulder 2002 for an overview) addresses the implications of initial tax and labor market distortions for the level of environmental taxes and their overall economic cost (e.g. Bovenberg and de Moji 1994; Bovenberg and Goulder 1996; Fullerton 1997; Goulder, Parry and Burtraw 1997). No rigorous assessment, however, is in general provided on how these initial distortions may affect the magnitude and direction of emission price discrimination across different sectors of the economy. A recent contribution by Fischer and Fox investigates the implications of initial tax distortions for unilateral climate policy design showing that with Pigouvian taxation of an emission externality an optimal rebate to production not only reflects the marginal benefit of avoided leakage, but also a component to adjust for labor tax interactions.

Distributional concerns constitute another important criterion in optimal taxation (see e.g. Alm 1996) and can motivate a deviation from uniform emission pricing if complementary policy instruments for compensation are unavailable. Yet, the common approach in the literature is to assess the impacts of exogenous environmental tax schemes on different income groups or industries rather than deriving endogenously optimal tax structures. 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 a mix of policy instruments, i.e. uniform carbon taxes together with sector-specific wage subsidies. Metcalf (1998), as another example, studies the income distribution impacts of a environmental tax reforms in the U.S., investigating ways to make the tax reform distributionally neutral by means of targeted revenue recycling schemes. In an international context, the phenomenon of emission leakage (Hoel 1991; Felder and Rutherford 1993) where domestic policies meant to reduce emissions in one country may cause emissions to increase in other countries provides a global efficiency rationale for differential emission pricing in favor of energy-intensive and trade-exposed industries (Hoel 1996). At the same time, international spillovers may be exploited by larger economies through differential emission pricing in order to improve their 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 (Krutilla 1991; Anderson, 1992; Rauscher 1994). Our analysis contributes to the literature by sorting out the relative importance of the leakage motive and the terms-of-trade motive for optimal emission pricing and the overall economic cost implications for emission abatement as a global public good.

The paper is organized as follows. Section 2 presents the basic theoretical framework underlying our decomposition of the leakage and the terms-of-trade motive for emission price differentiation. Section 3 entails a brief non-technical summary of the computable general equilibrium (CGE) model in use to quantify the policy relevance of international spillover effects for differential emission pricing. Section 4 discusses our numerical findings. Section 5 concludes.

2. Theoretical Background

Leakage and terms-of-trade effects provide theoretical arguments for emission price differentiation across domestic sectors. Both effects are, however, intertwined: Emission abatement in an open economy not only causes adjustment of domestic production and consumption patterns but also influence international prices, i.e. the terms of trade, via changes in exports and imports; simultaneously leakage occurs as emission reductions in the abating economy are partially offset by increased emissions in non-abating countries due to the relocation of emission-intensive production or international energy market effects. A rigorous assessment of the relative importance of the leakage and the terms-of-trade motive requires a decomposition of these international spillover effects. In this section we present an analytical framework to illustrate our decomposition technique which will be used later in the large-scale CGE application based on empirical data. We start with a stylized two-region, multi-commodity economy where we first derive a Pareto optimal allocation to satisfy a transboundary emission constraint. In this context, 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, i.e. the terms-of-trade motive or 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.

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 $i = 1,...,n$ and the energy sector are characterized by production functions

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

We assume that capital is immobile across regions such that $\sum_{i=1}^{n} k^{ir} = k^r$.

Energy as well as the produced consumption goods can be traded internationally. The total energy use 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, $c_j(i = 1,...,n)$. The representative consumer holds all the capital and income share in the domestic firms. 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 given if

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

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 $e^1 + \alpha e^2 \leq \overline{E}$, where $\alpha \geq 0$.

2.2 The Pareto Optimum

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

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

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 such that output prices in both markets are assumed to be given by p_y^j (j = 1, . . . , n) and p_e, respectively. Capital prices are denoted by $p_k^{jr}\,(j = 1,\dots,n,e)$ and energy prices in sector $j = 1,\dots,n$ by p_j^e. Production decisions are therefore 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

$$U_i^r / U_j^r = p_c^{ir} / p_c^{jr} \qquad p_c^r c^r = I^r \tag{5}$$

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 budget constraint, i.e. 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 costs p_e as well as the external effects of emissions on country 1. In particular, this implies that any unilateral emissions tax by country 1 cannot achieve efficiency if $\alpha > 0$.

2.4 Unilateral Tax Policy of a Large Open Economy

For the case of unilateral action, we study how country 1 should set emissions taxes to unilaterally maximize its welfare. We denote the tax rates in the respective sectors by $\tau_e^{i1}\ (i = 1,\dots,n)$. 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/emissions 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, $(\tau_e^{i1})i$, 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. We suppress this dependence of these equilibrium values on the tax rates in our notation.

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

$$U_c^1 \frac{d_c}{d\tau_e^{i1}} - \overline{\mu}\left(\frac{de^1}{d\tau_e^{i1}} + \alpha \frac{de^2}{d\tau_e^{i1}}\right) = 0$$

As (5) implies that $\mathrm{U}_\mathrm{c}^1 = \lambda \mathrm{p}_\mathrm{c}$ for an appropriately chosen $\lambda >$ 0, we obtain the equivalent condition (with $\mu = \lambda\overline{\mu}$):

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

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):

$$p_c \frac{dc}{d\tau_e^{i1}} = \sum_j \frac{dp_y^j}{d\tau_e^{i1}}(y^{j1} - c^{j1}) + \sum_j \tau_e^{j1} \frac{de^{j1}}{d\tau_e^{i1}} \tag{9}$$

such that the first order condition (8) is given by

$$\sum_j [\tau_e^{j1} - \mu] \frac{de^{j1}}{d\tau_e^{i1}} + \sum_j \frac{dp_y^j}{d\tau_e^{i1}}(y^{j1} - c^{j1}) - \mu\alpha \frac{de^2}{d\tau_e^{i1}} = 0 \tag{10}$$

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 potential leakage effect $(de^2 / d\tau_e^{i1})$. If both effects were absent, $\tau_e^{j1} = \mu$ for all j would solve (10). In general, however, country 1 should differentiate taxes across sectors.

First, consider the terms-of-trade effect. It can be positive or negative: if country 1were 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 imports good j.

Second, consider the carbon leakage effect. It is driven by the change in the domestic demand for energy. This causes energy-prices to decrease, and prices for energy-intensive goods increase. Consequently, energy demand abroad will increase. The marginal effects of sectoral tax rates on leakage may differ such that the accounting for leakage in the policy choice also generally leads to differentiated taxes.

2.5 Decomposition

In order to measure the magnitude of the two effects, we “switch” off the terms-of-trade effect using a simple procedure: country 1 optimizes its taxation policy $\tau_e^1 = (\tau_e^{i1})i$ combined with appropriate transfers $Tr^1(\tau_e^1)$ that hold the welfare in the other country fixed, i.e. generate $\mu^2 = \overline{\mu}^2$. Here, $\overline{\mu}^2$ could be given by the welfare level of country 2 in before emissions taxes are implemented in country 1. 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

$$p_y (dy^1 / d\tau_e^{i1} + dy^2 / d\tau_e^{i1} - dc^1 / d\tau_e^{i1}) = 0 \tag{11}$$

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:

$$0 = \sum_j (\tau_e^{j1} - \mu) \frac{de^{j1}}{d\tau_e^{i1}} - \mu\alpha \frac{de^2}{d\tau_e^{i1}} \tag{12}$$

which we show in Appendix A.

It is thus obvious that in case without leakage (α = 0), taxes will not be differentiated and we obtain the standard results for a small open economy (which can not affect the terms of trade nor cares for leakage). That is, the only remaining reason for differentiating taxes in the case of compensating transfers is leakage.[3] In presence of the requirement for compensating country 2, we can therefore assign the extent of tax differentiation to the leakage motive. That is, the terms-of-trade motive is "switched off".

In turn, we can consider the extent how terms-of-trade may lead to differentiated taxes by "switching off" the leakage motive. For this, we solve the first-order conditions (10) when setting α = 0. That is, we consider the case where country 1 does not consider the marginal effects of its policy choice on foreign emissions. It is then obvious that terms-of-trade remains the only reason for tax differentiation. We will use the described decomposition technique in the numerical analysis to quantify how much the terms-of-trade motive and the leakage motive contribute to the optimal differentiation of emission pricing. 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.[4]

3. Numerical Analysis

Our theoretical analysis has decomposed two reasons for differential emission pricing across sectors of an

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[3] As another way to see this, we can reconsider condition (7). If $\alpha = 0$, 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 $u^2 \geq \overline{u}^2$ must lead to a Pareto-efficient solution. For that, however, we know that emission prices, i.e. emission taxes, must coincide for all sectors in country 1.

open economy when international spillover effects are explicitly taken into account: concerns on global environmental effectiveness and exploitation of international market power. However, the analytical derivation of optimal emission pricing becomes intractable for equilibrium conditions that exceed the complexity of simple textbook models. Furthermore, marginal calculus does not allow for a generalization of results to structural changes in policy variables. We therefore provide a numerical analysis based on empirical data to substantiate our theoretical considerations with quantitative evidence on the magnitude and direction of emission price differentiation motivated by international spillovers as well as the associated economy-wide efficiency implications. In this section, we first provide a non-technical summary of our numerical 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 (CGE) of Global Trade and Energy Use

For our numerical analysis we adopt an established multi-region, multi-sector CGE model of global trade and energy use (see e.g. Böhringer and Rutherford 2009). A multi-region, multi-sector setting with global coverage is essential for capturing terms-of-trade and leakage spillovers induced by unilateral emission regulation of open economies. In addition to the consistent representation of trade links, a detailed tracking of energy flows is a pre-requisite for the assessment of climate policies. Combustion of fossil fuels is a driving force of global warming through the release of the main greenhouse gas CO_2.

Figure 1 provides a diagrammatic model structure. A representative agent RA_r in each region r is endowed with three primary factors: labor $\overline{L}_r$, capital $\overline{K}_r$, and fossil-fuel resources $\overline{Q}_{ff,r}$ (used for fossil fuel production). Labor and capital are intersectorally mobile within regions but immobile between regions. Fossil-fuel resources are specific to fossil fuel production sectors in each region. Production Y_{gr} of commodity g, other than primary fossil fuels and electricity production, is captured by nested constant elasticity of substitution (CES) cost functions that describe the price-dependent use of capital, labour, energy, and material in production. At the top level, a CES material composite trades off with an aggregate of energy, capital, and labour 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. At the third level, capital and labour substitution possibilities within the value-added composite are captured by a CES function. The aggregate energy input is further split down into a fossil fuel composite and electricity subject to constant elasticity of substitution. The fossil fuel composite in turn is composed of a CES aggregate of liquid fuels and solid fuels. In the production of fossil fuels, all inputs, except for the sector-specific fossil fuel resource, are aggregated in fixed proportions at the lower nest. At the top level, this aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution. The

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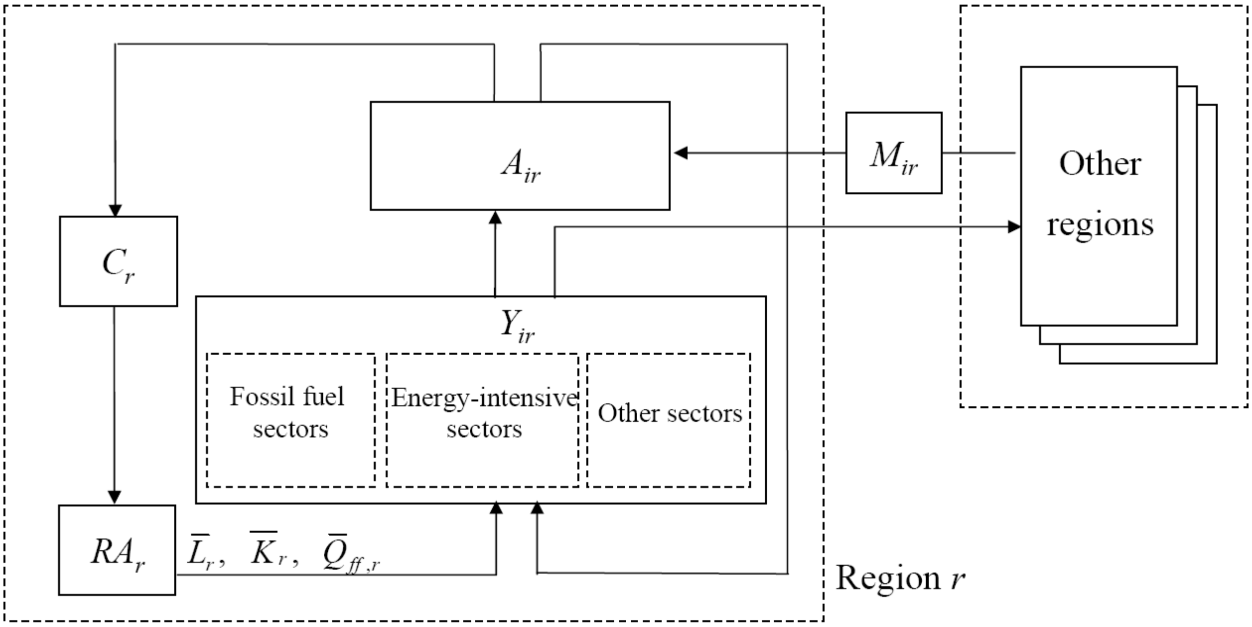
[4] As a prime example EU climate policy regulation stands out for the partitioning of an overall emission budget between energy-intensive industries and the rest of the economy without direct trade links between these segments causing substantial excess cost if international spillover effects are not taken into account (Böhringer et. al. 2009).

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

latter is calibrated in consistency with empirical estimates for the price elasticity of fossil fuel supply.

Final consumption demand C_r in each region is determined by the representative agent who maximizes utility subject to a budget constraint with fixed investment (i.e. given demand for the savings good) and exogenous government provision. Total income of the representative household consists of factor income and taxes. Consumption demand of the representative agent is given as a CES composite that combines consumption of an energy and a non-energy goods aggregate.

Figure 1: Diagrammatic overview of the model structure



Substitution patterns within the non-energy consumption bundle are reflected via a CES function; the energy aggregate in final demand consists of the various energy goods trading off at a constant elasticity of substitution. Bilateral trade is specified following the Armington approach of product heterogeneity, i.e., domestic and foreign goods are distinguished by origin All goods used on the domestic market in intermediate and final demand correspond to a CES Armington aggregate A_{ir} that combines the domestically produced good Y_{ir} and the imported good composite M_{ir} from other regions. The standard Armington assumption of product heterogeneity implicitly provides each country with a certain degree of market power in international trade: Depending on initial trade shares and the ease of substitution between imports and domestically produced goods (captured by the Armington trade elasticities) domestic policies affect international prices, i.e. the terms of trade. The latter can significantly alter the impacts of the primary domestic policy (Böhringer and Rutherford 2002). Domestic production Y_{ir} either enters the formation of the Armington good A_{ir} or is exported to satisfy the import demand of other regions. The balance of payment constraint, which is warranted through flexible exchange rates, incorporates the benchmark trade deficit or surplus for each region.

CO_2 emissions are linked in fixed proportions to the use of fossil fuels with CO_2 coefficients differentiated by the specific carbon content of fuels. CO_2 emission abatement can take place by fuel switching (inter-fuel substitution) or energy savings (either by fuel-non-fuel substitution or a scale reduction of production and final demand activities). Revenues from CO_2 pricing are recycled lump-sum to the representative agent in the abating region.

The model builds on the most recent GTAP7 dataset with detailed accounts of regional production, regional consumption, bilateral trade flows as well as energy flows and CO_2 emissions for the year 2004 (Badri and Walmsley 2008). 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.

As to sectoral and regional model resolution, the GTAP database is aggregated towards a composite dataset that accounts for the specific requirements of climate policy analysis. At the sectoral level the model captures details on sector-specific differences in factor intensities, degrees of factor substitutability and price elasticities of output demand in order to trace back the structural change in production induced by policy interference. The energy goods identified in the model are coal, crude oil, natural gas, refined oil products, and electricity. This disaggregation is essential in order to distinguish energy goods by CO_2 intensity and the degree of substitutability. The model then features an aggregate of energy-intensive and trade-exposed non-energy goods which are referred to as “sectors at risk of carbon leakage” in the policy debate and are considered for preferential emission regulation (EU 2009). This energy-intensive composite includes iron and steel industry, chemical industry, non-ferrous metals, non-metallic minerals, paper-pulp-print, and transport. All other services and industries are summarized through a composite macro good With respect to the regional disaggregation, the model covers all major industrialized and developing regions that are central to the climate policy debate: the U.S., the EU, 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.

General equilibrium conditions constitute the side-constraints of our optimal taxation problem where a unilaterally abating region maximizes consumption welfare using endogenous carbon taxes on sectors as the policy instrument to meet some domestic emission reduction target. The leakage motive for differential emission pricing can be readily incorporated by replacing the domestic emission constraint with a global emission constraint. In this case, emission increases in non-abating regions are endogenously balanced through more stringent emission reductions of the unilaterally abating region. The global emission constraint requires that total word-wide emissions do not exceed the base-year emissions of non-abating regions plus the emission target of the unilaterally abating region. In order to suppress the terms-of-trade motive we impose an additional constraint that requires the abating region to compensate all other regions with lump-sum transfers at their benchmark welfare level. Following our theoretical exposition, the abating country then has no incentive for strategic terms-of-trade manipulations and will go for uniform emission pricing as long as it does not care for leakage spillovers.

3.2 Policy Scenarios

Our central simulations are based on five unilateral climate policy scenarios that allow us to explore the leakage and the terms-of-trade motive for emission price differentiation between energy-intensive industries (thereafter referred to as EIS) and the rest of the economy (thereafter referred to as nonEIS).[6] Whenever the unilaterally abating country does not explicitly account for emission leakage, it simply pursues a domestic emission constraint. If we want to switch off the terms-of-trade motive for differential emission pricing, we require the unilaterally abating region to compensate other non-abating regions at their base-year welfare level.

- Scenario *Ref* serves as our reference scenario for unilateral climate policy where the abating region is restricted to uniform emission pricing across all sectors. This scenario has no strategic dimension as the leakage motive is absent and terms of trade cannot be exploited due to the lacking possibility of emission price differentiation.
- Scenario *None* assumes that unilateral climate policy design fully ignores international spillovers, i.e. neither leakage effects nor terms-of-trade changes are strategically taken into account. We implement this scenario by switching off the terms-of-trade motive using our compensation method. In the absence of both the leakage and the terms-of-trade motive economic theory yields an unambiguous qualitative result for optimal emission pricing as we start from a market equilibrium without previous distortions: Emissions should be uniformly priced across all domestic sources to minimize economy-wide adjustment costs. Note that scenario *None* imposes terms-of-trade compensation whereas scenario *Ref* maintains terms-of-trade gains and losses for individual countries as the response of competitive market adjustments.
- Scenario *Leakage* postulates that the unilaterally abating region only takes into account counterproductive leakage effects while the terms-of-trade motive is switched off, i.e. we require the abating region to compensate non-abating regions at the (pre-policy) base-year welfare levels. This scenario focuses on the leakage motive for second- best emission price differentiation.
- Scenario *ToT* considers the case that the unilaterally abating region explicitly exploits its international market power associated with the assumption of product heterogeneity of traded goods while not taking leakage into account. As such, this scenario focuses on the pure terms-of-trade motive for emission price differentiation.
- Scenario *Leakage_ToT* assumes that unilateral climate policy accounts for terms-of-trade changes as well as leakage effects in the optimal pricing of emissions between energy-intensive sectors and the rest of the economy. This scenario reflects a standard unilateral policy for a large open economy that pursues a global reduction target.

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

Across all five scenarios we keep the global environmental outcome constant to provide a meaningful metric of comparison for our cost-effectiveness analysis. As noted before, the global environmental emission target is determined as the targeted domestic emission level of the unilaterally abating region and the business-as-usual emission level of all other non-abating regions. For the scenarios *Leakage* and *Leakage_ToT* which explicitly include the leakage motive the global emission constraint is added to the system of general equilibrium conditions.[7] For the scenarios *None* and *ToT* where the explicit leakage adjustment motive needs to be suppressed we can not directly include the global emission constraint as a simultaneous equilibrium condition but need to reach the global environmental target through iterative adjustments of the domestic emission abatement target (until the exogenous global environmental outcome is met). As to scenario *Ref* where the abating region has no option to differentiate prices we can again simply add the global emission constraint to the simultaneous system of equilibrium conditions.

Table 1 provides a brief summary of the different motives for emission price differentiation prevailing in the five scenarios.

Table 1: Characterization of alternative unilateral climate policy scenarios

Scenario	Leakage Motive	Terms-of-Trade Motive
None	No	No
Leakage	Yes	No
ToT	No	Yes
Leakage_ToT	Yes	Yes
Ref	Imposed uniform emission pricing across all sectors	

In our core simulations we consider unilateral abatement of either the U.S. or the EU where policy concerns on leakage are very outspoken and have motivated policy proposals for preferential treatment of energy-intensive industries. We impose a domestic carbon emission reduction of 20% vis-à-vis the 2004 base-year emission level which roughly reflects pledges of the respective governments for the Post-Kyoto area. Note that the 2004 base year captures a clear-cut benchmark situation where the EU emission trading system has not been implemented, and the Kyoto Protocol has not entered into force. Thus, climate policies are almost absent internationally in our benchmark situation, and, importantly, there is no cap on emissions in Annex B countries.

3.3 Simulation Results

We start interpretation of our simulation results with the implications of alternative policy motives for differential emission pricing between energy-intensive industries (EIS) and the rest of the economy (nonEIS) Figure 2 provides insights into the relative importance of the leakage and terms-of-trade motive for the magnitude and direction of emission price differentiation in the U.S. and EU economies.

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[7] The dual variable associated with the global emission constraint endogenously scales the domestic emission target of the unilaterally abating region to compensate for leakage.

Figure 2a: Sector-specific emission prices (USD per ton of carbon) for unilateral action of the U.S. of the EU

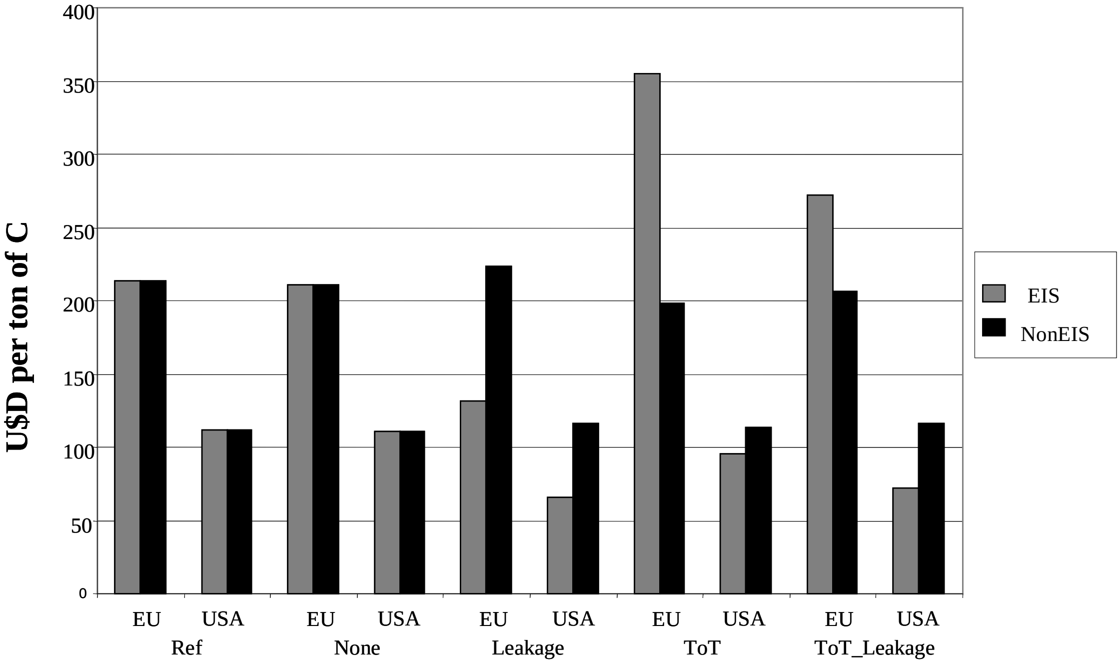
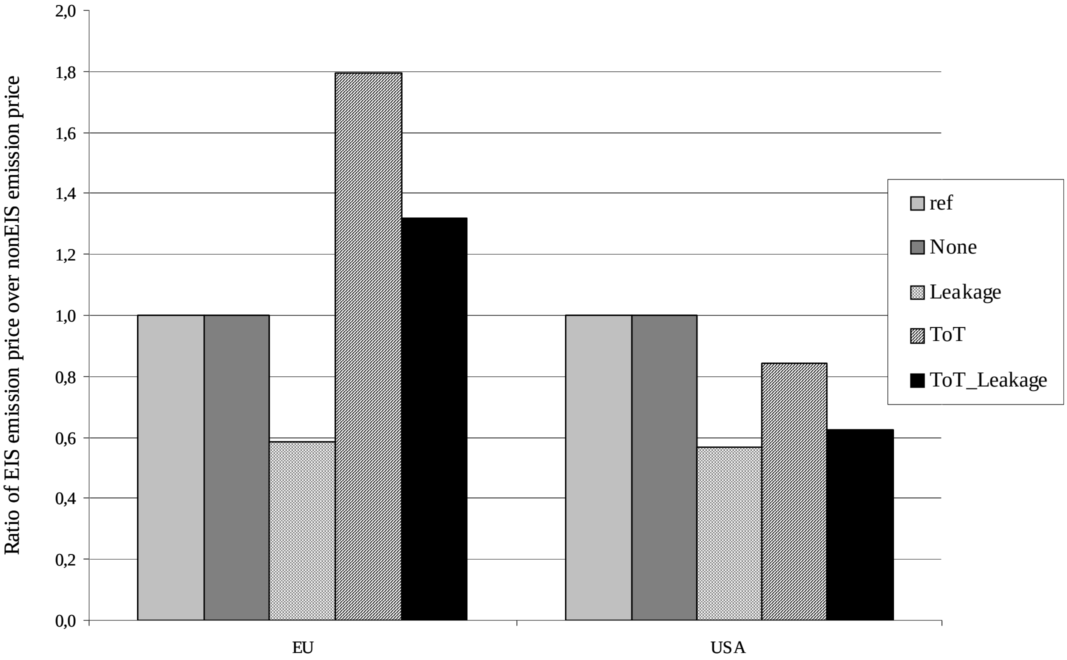


Figure 2b: Emission price ratio between energy-intensive sectors and the rest of the economy



It is obvious that the absolute emission price level for the non-EIS segments of the economy remains relatively robust across the different emission pricing scenario. The reasoning behind is twofold: Firstly, the nonEIS segments which includes electricity and oil refineries account for most of the benchmark carbon emissions in the U.S. and the EU.[8] Secondly, the implicit marginal abatement cost curve for the nonEIS segment is much flatter than that for the EIS industries indicating cheaper emission mitigation possibilities outside the EIS industries (to a large extent because of low-cost fuel switching options in the electricity sector). These two factors explain why strategically motivated shifts of the relative abatement burden between EIS and nonEIS sectors (compared to uniform pricing) have a rather moderate impact on the marginal abatement cost in nonEIS sectors and a much more pronounced impact on marginal abatement cost in the EIS sector.

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: Without terms-of-trade and leakage motives the optimal strategy of the unilaterally abating region (in the absence of other initial distortions) is to charge a uniform price for each use of the carbon pollutant. The uniform emission price to meet the exogenous contribution to global emission reduction thereby is higher for the EU than the U.S. The reason is that the U.S. has cheaper abatement options than the EU, both with respect to energy efficiency improvements as well as with respect to fuel switching (in the particular within electricity generation that accounts for a large share of carbon emissions in both regions). There is a slight deviation between equalized marginal abatement cost in scenario *Ref* compared to scenario *None* which stems from different income effects. Differences in income effects arise because the terms-of-trade motive for price differentiation in scenario *None* is switched off using the compensating transfers, whereas no transfers are made in scenario *Ref* to keep non-abating regions at their initial consumption welfare level.

Not surprisingly, the pure leakage motive captured by scenario *Leakage* provides an unambiguous argument for emission price differentiation in favour of energy-intensive industries. Lower emission prices to energy-intensive good production ameliorate the cost disadvantage of unilateral action 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 (global efficiency) gains of reduced emission leakage. Our quantitative results based on empirical data indicate that emission-intensive industries in the U.S. or the EU pay substantially lower emission prices under the pure leakage motive than the rest of the economy.

As compared to the pure leakage motive the directional implications of the pure terms-of-trade motive represented by scenario *ToT* are ambiguous depending on the trade characteristics of the unilaterally abating region. The principle logic behind differential emission pricing 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. favoring domestic production for goods that compete on import markets): Ceteris paribus, emission inputs to sectors (commodities) which command large shares in the trading partners’ imports are priced at a higher level to “export” the economic burden of domestic emission reduction; the inverse reasoning applies to imports from abroad when unilateral emission levies are (mis-)used as a substitute for undue import duties. Apart from trade intensities of commodities, the pricing differentials depend on additional country-specific characteristics, such as the important demand and export supply elasticities of trading partners. Drawing on the benchmark data, the EU is a net exporter of energy-intensive goods and a net importer of the composite

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[8] EIS emissions amount to 18% of total domestic benchmark emissions in the U.S. and 23% in the EU.

macro good – therefore the terms-of-trade motive suggests higher rather than lower emission prices for domestic energy-intensive production. In turn, the U.S. which is a net importer of the energy-intensive composite goes for lower emission prices in the energy-intensive sector in order to discriminate against competing imports, thereby reducing import demand and import prices. A potentially important policy conclusion in the debate on undue beggar-thy-neighbor policies is that unilaterally abating countries with a strong export position for energy-intensive products can hardly be accused of a selfish terms-of-trade exploitation should they impose lower emission prices on energy-intensive industries than on the rest of their economy.

If both motives for price discrimination overlap, the direction of price discrimination is a priori not clear for the case of net exporters of energy-intensive goods since the terms-of-trade motive and the leakage motive work in opposite direction. The combined effect for net importers of energy-intensive goods, however, is unambiguous since both leakage adjustment and strategic terms-of-trade exploitation imply lower emission pricing in favor of energy-intensive industries.

Figure 3 reports the welfare effects of alternative emission pricing strategies for the EU and the U.S. acting unilaterally in order to achieve a fixed global emission reduction.[9] Unilateral abatement policies in large open economies affect both the allocation of domestic resources and international markets. Policy-induced changes in international prices then imply an indirect burden or benefit for all trading countries. For carbon abatement policies associated with significant reductions in fossil fuel demand the terms-of-trade effects work largely through energy markets (Böhringer and Rutherford 2002). Large oil importers such as the EU or the U.S. benefit from the decline in international oil prices which may offset a larger part of the direct emission abatement cost for their domestic economies.[10]

Figure 3 highlights the crucial importance of international spillovers from energy markets for the cost incidence of unilateral climate policies undertaken. For the unilaterally abating region the cost differences between scenarios *Ref*, *ToT_Leakage* and *ToT* are rather negligible. That is neither strategic exploitation of market power on non-energy markets (scenario *ToT*) nor additional leakage concerns (scenario *ToT_Leakage*) provide notable welfare gains as compared to a non-strategic uniform emission pricing in the *Ref* scenario. To put it differently: When we do not impose compensating transfers, the additional welfare gains to be achieved from strategic emission pricing between energy-intensive goods and the rest of the economy are relatively small as compared to blunt uniform emission pricing. Likewise, the additional welfare implications of the pure leakage motive are of second order. As explained above, (i) leakage and terms-of-trade effects are largely determined by robust energy market adjustments, (ii) emission price differentiation comes at an increase of the direct cost of abatement, and (iii) the scope for strategic responses

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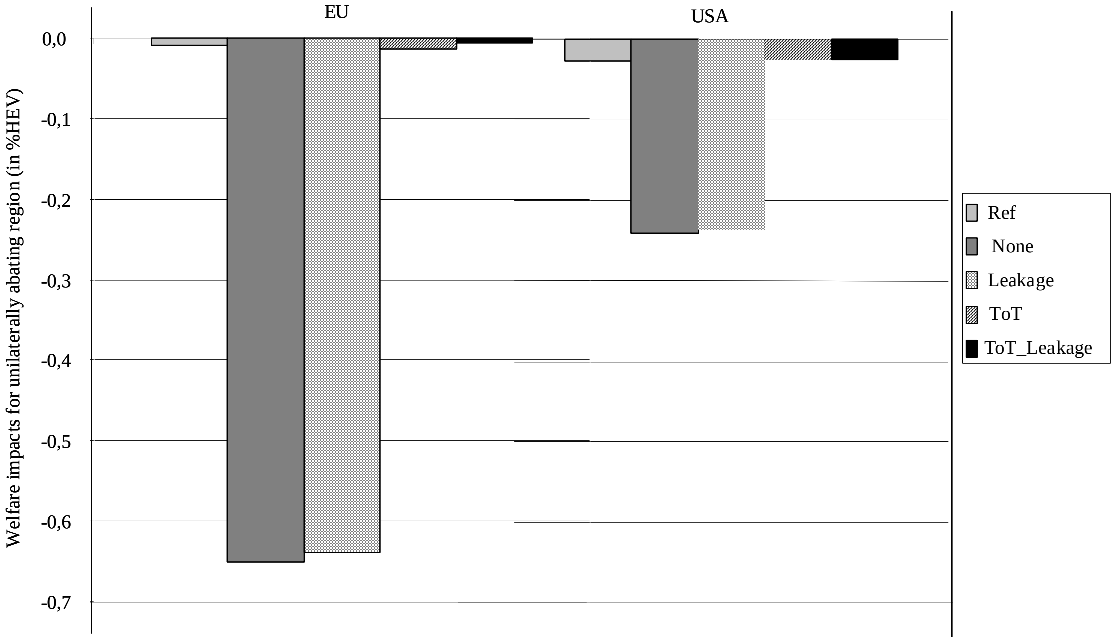
[9] Recall that the effective global emission reduction equals the targeted domestic emission cutback of the unilaterally abating region. Welfare impacts are measured as Hicksian equivalent variation in income, i.e. the amount of money which is necessary to add to (or deduct from) the benchmark income of the 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.

[10] In fact, for the more moderate emission reduction target of 15% the energy market terms-of-trade gains more than offset the direct emission abatement costs for unilaterally abating regions U.S. or the EU making them better off as compared to the benchmark situation without climate policy.

is limited to price differentiation between energy-intensive industries and the rest of the economy. The scenarios *None* and *Leakage* where non-abating trading partners must be kept at their initial welfare level through compensating transfers are much more costly for the U.S. and the EU as both regions can no longer benefit from terms-of-trade gains. By comparing *None* and *Leakage* we see that leakage mitigation through preferential pricing of energy-intensive trade goods has only very minor welfare implications.[11]

Figure 3: Change in real consumption due to unilateral abatement (% change from doing-nothing case)



Although we have introduced compensating transfers in our analysis mainly as a means to decompose the terms-of-trade and leakage motives, the issue of compensation has some serious dimension in the international climate policy debate. [12] If we consider compensating transfers as a viable policy option, the ranking of alternative unilateral policies are obviously quite different from the perspective of fuel-importing or fuel-exporting regions. Larger importers of fossil fuels such as the EU and the USA can minimize their cost of unilateral abatement action if the region is allowed to simultaneously take into account the leakage motive as well as the terms-of-trade motive (scenario *Leakage_ToT*) while omission of the leakage motive (scenario *Leakage_ToT*) is only slightly less attractive. As indicated before, the cost of unilateral action for fuel importing regions become drastically higher when they are required to compensate other regions under scenarios *Leakage* and *None* – with scenario *None* being most costly as the leakage motive is not accounted for. The basic reasoning on the attractiveness of alternative policy strategies applies with opposite implications for fuel importing regions. The latter would obviously prefer to ameliorate their terms-of-trade

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[11] As we suppress terms-of-trade changes through compensating transfers, the differences in the ease of decarbonising the domestic economy that have been apparent in marginal abatement cost are mirrored in the differences of inframarginal economic adjustment cost.

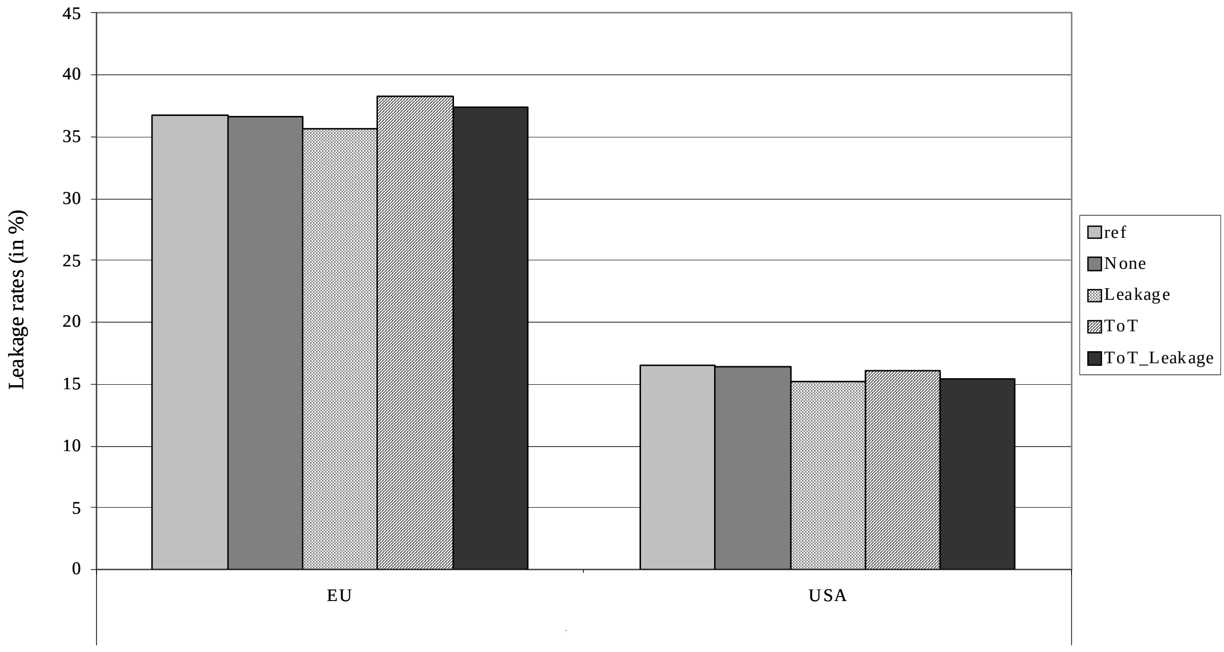
[12] Under Articles 4.8 and 4.9 of the United Nations Framework Convention on Climate Change (UNFCCC, 1997) at least developing countries may claim compensation for induced economic costs of climate policies in industrialized countries. The Kyoto Protocol explicitly reflects concerns on adverse terms-of-trade-effects by postulating that developed countries '. . . shall strive to implement policies and measures . . . in such a way as to minimize adverse . . . economic impacts on other Parties, especially developing countries Parties . . . ' (UNFCCC, 1997, Article 2, paragraph 3) – see Böhringer and Rutherford (2004) for a provoking analysis of this provision

losses that occur on the energy markets due to targeted (global) carbon emission reductions. As we suppress the terms-of-trade motive, unilaterally abating fuel exporters receive transfers from non-abating regions that would benefit otherwise from terms-of-trade spillovers. Thus, energy exporters are best off under scenario *Leakage* where they avoid additional income transfers to the rest of the world through terms-of-trade spillovers and simply can focus on the optimal price differentiation to mitigate leakage. Most expensive for them – among the four strategic pricing variants – is scenario *ToT* where 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). The non-strategic *Ref* scenario imposes the highest cost to fuel exporting unilaterally abating regions: Here the region faces larger terms-of-trade losses on energy markets due to its unilateral emission reduction and does not employ differential emission pricing to save at least some cost through strategic exploitation of terms-of-trade changes on non-energy markets a efficient leakage adjustment.

While terms-of-trade compensation is crucial from an individual countries' perspective, the global efficiency changes across our key scenarios are negligible. As leakage and terms of trade effects for some given global emission reduction are robustly driven through the energy market channel, the efficiency implications of differential emission pricing to reduce emission leakage through the trade channel (as a second-best strategy) or selfishly exploit terms-of-trade on non-energy markets are minor.

Figure 4 summarizes the impacts of alternative emission pricing strategies on global emission leakage for unilateral action on behalf of the U.S. or the EU.

Figure 4: Leakage rates (in %)

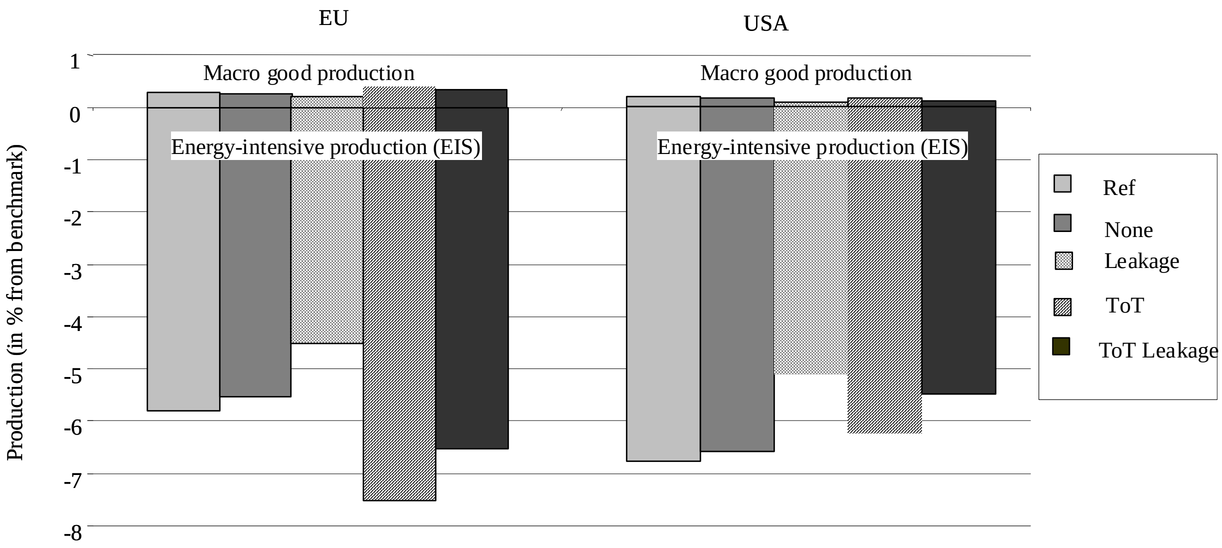


Leakage rates are in general much higher for the EU than for the U.S. One reason for this difference is that the EU is a more open economy than the U.S., meaning that imports and exports constitute a larger share of the economy in the EU. This is true both for energy-intensive goods and for fossil fuels, where the EU is a much bigger importer (relative to own consumption) than the U.S. Another reason for higher leakage with unilateral EU policies is that energy-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.

Alternative emission pricing strategies have very small impacts on global leakage rates. Leakage is mainly caused through the reduction requirements of fossil fuels associated with the respective global emission constraint and only to a minor extent through changes in the pattern of trade for energy-intensive goods. Leakage rates are minimized if the unilaterally abating region only adopts the leakage motive for emission price differentiation but the differences as compared to the other policy variants are negligible.

Figure 5 sketches the impacts on energy-intensive production and the effects for production of all other goods and services of the unilaterally abating region.

Figure 5: Impacts on industrial production in unilaterally abating regions (% change from benchmark)



The differences across policy variants are in first order correlated with the cost increase from emission pricing (see Figure 2). Differential emission pricing thereby not only affects comparative advantage of domestic energy-intensive production vis-à-vis production of the same goods abroad but also the competitive situation with respect to non-energy-intensive production. The lower the ratio between emission prices paid by energy-intensive industries and emission prices paid by the rest of the economy, the better ceteris paribus becomes the competitive situation for the energy-intensive industries.

As to the EU, the pure leakage motive leads to the lowest emission prices for energy-intensive industries whereas the pure terms-of-trade motive implies the highest emission prices – recall that the EU as a net exporter of energy-intensive products uses differential emission pricing at the expense of energy-intensive traded goods to substitute for strategic export taxes. The decline in energy-intensive production is thus lowest for scenario *Leakage* and highest for scenario *ToT*. As to the U.S. which is a net importer of energy-intensive goods the terms-of-trade motive works in the same direction as the leakage motive (i.e. towards a preferential treatment of emission-intensive industries) such that the modest impacts on production occur under scenarios *Leakage* and *ToT*.

3.4 Sensitivity Analysis

We have performed extensive sensitivity analysis to understand how changes in key assumptions affect our conclusions. We have found that our qualitative insights regarding the implications of various 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 some energy demand reduction 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 price differentiation in favor of energy-intensive industries. Yet, for a plausible range of supply elasticities as given by the empirical literature the dominant role of energy market adjustment relative to the importance of alternative emission pricing strategies prevails.

Armington trade elasticities capturing the ease of substitution between domestic goods and imported goods constitute an important driver for the magnitude of leakage and terms-of-trade effects. In our central case simulations we have adopted GTAP-based empirical estimates for these elasticities. Changes in these values affect the relative importance of 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 the core simulations, the abating region had a unilateral emission reduction pledge of 20 % 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 over-proportional increase in total 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 energy-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.

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 climate policies by industrialized countries that assume leading role in the battle against climate change. Cost-effectiveness of unilateral emission regulation with respect to the global greenhouse gas externality may however be seriously hampered through counterproductive emission leakage to non-abating regions triggered by shifts in comparative advantage and international energy market effects. Concerns on global environmental integrity of unilateral emission control provide an important policy argument for preferential treatment of energy-intensive and trade-exposed sectors. Yet, the basic leakage motive in favor of lower emission pricing for energy-intensive industries cannot be easily distinguished from selfish interests of the abating region to exploit international market power through the strategic terms-of-trade manipulation. In a political economy perspective the leakage argument may also be (mis-)used by domestic lobby groups with the objective to dilute inevitable structural change in favor of specific industries under the vague catchword of competitiveness.

In this paper we have developed and implemented a conceptual framework of how to decompose the leakage motive from the terms-of-trade motive for differential emission pricing in the presence of international spillovers. Our decomposition method is based on the hypothetical requirement for the unilateral abating region to compensate other countries for policy-induced welfare changes (doing so, allows us to switch off the terms-of-trade effect).

Our main insight is that leakage and economic adjustment cost of unilateral action are predominantly driven by international energy market effects. The latter are robust to alternative domestic emission pricing strategies as the global emission target is not changed. If the cost incidence triggered by international energy market adjustments is politically accepted as the “natural” outcome of emission reduction then unilateral climate policy might stick to a simple first-best rule of uniform emission pricing even in a second-best world. Second-best emission price discrimination in favor of energy-intensive sectors has only negligible global efficiency effects as the trade channel for leakage is of secondary importance. Likewise, the potential for strategic terms-of-trade manipulation under the smokescreen of climate policies seem to be quite limited. On the other hand, the cost of preferential emission pricing to energy-intensive and trade-exposed industries may turn out high if such a policy route causes detrimental conflicts with important trading partners or windfall profits to sectors that are successfully lobbied for.

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A Mathematical Proofs

Proof of equation (9)

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

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

We can now differentiate the respective production functions and obtain:

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

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 immediately proves equation (9).

Proof of equation (12)

Plugging (11) 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

In formal terms, our model-based analysis is cast as a policy optimization problem subject to economic equilibrium conditions:

$$\max_{\tau} H(z,\tau) \;\; s.t. \;\; F(z,\tau)=0$$

where:

$z \in \Re^n$	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,
$\tau \in \Re^{m}$	is a vector of tax policy variables which are the choice variables for the problem (in our specific application τ comprises the set of two taxes that can be differentiated across the energy-intensive sector (EIS) and the remaining sectors of the economy),
$F: \Re^{n} \rightarrow \Re^{n}$	is a system of equations which represents general equilibrium conditions, and
H(z)	is the policy objective function.

In our implementation, the objective function H(z) denotes the welfare maximization by a region $\hat{r}$ that has to keep with some unilateral emission budget. If the region explicitly accounts for leakage concern the domestic emission constraint is replaced with a global emission constraint given by the sum of the targeted domestic emission level on behalf of the unilaterally abating region and the business-as-usual emission level of all other non-abating regions. If the region does not pursue any terms-of-trade exploitation motive then compensating transfer constraints are added to the system of equilibrium conditions that keep non-abating regions at their initial welfare level.

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 $\left(i \notin FF\right)$:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X}\, p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X})\, p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j\notin EG}\theta_{jir}\, p_{jr}^{A} - \theta_{ir}^{KLE}\left[\theta_{ir}^{E}\, p_{ir}^{E\;1-\sigma_{KLE}} + (1-\theta_{ir}^{E})\left(\theta_{ir}^{L} w_{r}^{1-\sigma_{ir}^{KL}} + \left(1-\theta_{ir}^{L}\right) v_{r}^{1-\sigma_{ir}^{KL}}\right)^{\frac{1-\sigma_{KLE}}{1-\sigma_{ir}^{KL}}}\right]^{\frac{1}{1-\sigma_{KLE}}} = 0$$

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

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

$$= 0$$

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

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

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

$$= 0$$

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:

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

B.2 Market Clearance Conditions

8. Labor:

$$\bar{L}_{r} = \sum_{i} Y_{ir}\,\frac{\partial \Pi_{ir}^{Y}}{\partial w_{r}}$$

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:

$$\begin{aligned} C_r p_r^C = {} & w_r \overline{L}_r + v_r \overline{K}_r + \sum_{j \in FF} q_{jr} \overline{Q}_{jr} + p_{CGD,r} \overline{Y}_{CGD,r} + \overline{B}_r \\ & + \sum_{i \notin FF} \sum_{j \in FF} \frac{\partial \Pi_{ir}^{E}}{\partial \left(p_{jr}^{A} + t_{ir}^{CO_2} a_j^{CO_2} \right)} a_j^{CO_2} t_{ir}^{CO_2} + \sum_{i \in FF} \sum_{j \notin FF} \frac{\partial \Pi_{ir}^{Y}}{\partial \left(p_{ir}^{A} + t_{jr}^{CO_2} a_i^{CO_2} \right)} a_i^{CO_2} t_{jr}^{CO_2} \\ & + \sum_{i \in FF} \frac{\partial \Pi_{ir}^{E}}{\partial \left(p_{ir}^{A} + t_{Cr}^{CO_2} a_i^{CO_2} \right)} a_i^{CO_2} t_{Cr}^{CO_2} \end{aligned}$$

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)
$t_{dr}^{CO_2}$	CO_2 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$\in$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 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

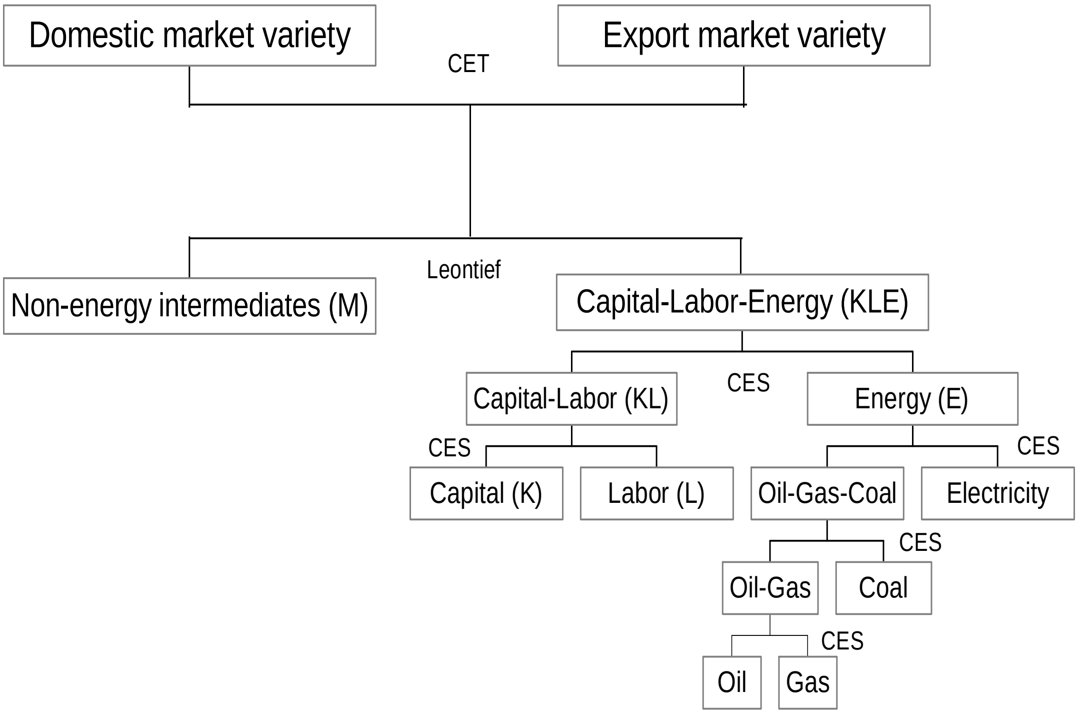

Figure B.2: Nesting in fossil fuel production

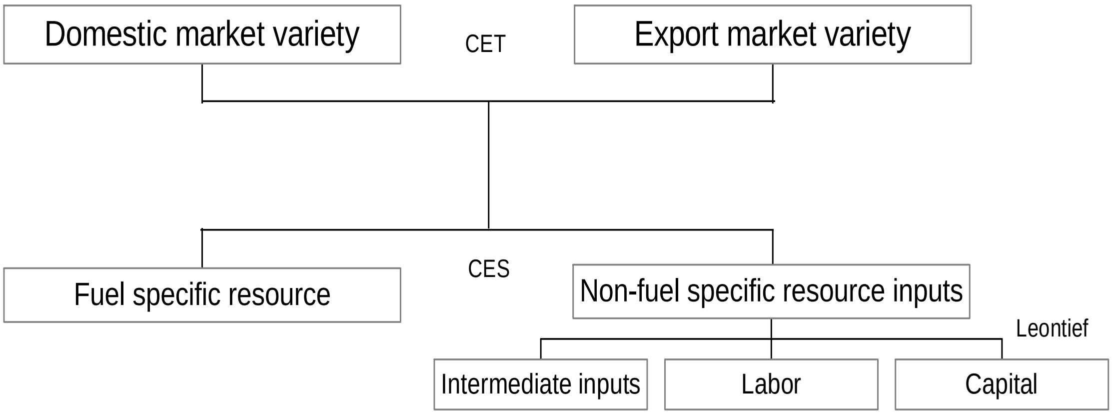

Figure B.3: Nesting in household consumption

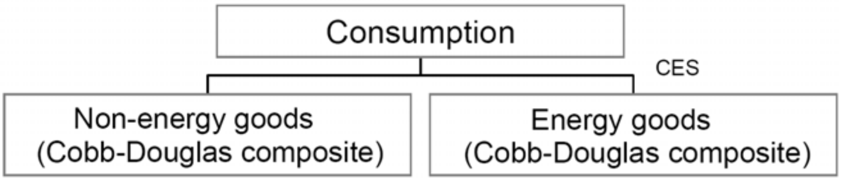

Figure B.4: Nesting in Armington production