Beggar-thy-neighbour versus global environmental concerns: an investigation of alternative motives for environmental tax differentiation

Abstract

Environmental tax schemes in OECD countries typically involve tax rates differentiated across industrial, commercial, and household sectors. At first glance such a policy practise contradicts the economic principle of uniform marginal cost pricing for uniformly dispersed pollutants like CO_2. In this paper, we investigate two motives to deviate from uniform taxation of pollutants when international spillover effects are taken into account: (i) leakage adjustment to increase global environmental effectiveness of unilateral regulation and (ii) terms-of-trade exploitation due to market power in international trade. We introduce a decomposition technique that enables us to separate the leakage adjustment motive from the terms-of-trade motive with respect to environmental tax differentiation. Based on quantitative evidence for the U.S. and other OECD economies we find little economic rationale for the common policy practice of strong tax discrimination in favor of energy-intensive industries when accounting for leakage adjustment or terms-of-trade motives.

Key words: optimal environmental taxation, leakage, terms of trade, computable general equilibrium

JEL classifications: C68, H21, Q4, R13

1 Introduction

Over the last decade, taxes on energy or emissions have played a growing role in environmental policies of OECD countries. As a common feature, environmental tax schemes involve a differentiation of tax rates among industrial, commercial, and household sectors: Tax rates typically discriminate in favor of energy-intensive industries, including complete tax exemptions in many countries (OECD [2007]).

At first glance, differentiation of tax rates for uniformly dispersed pollutants like CO_2 contradicts conventional economic reasoning: 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.[1] Various studies have identified substantial excess cost of differential taxation to reach domestic environmental targets (see e.g. Böhringer and Rutherford [1997] or Babiker et al. [2003]).

In this paper, we investigate two reasons why it can be optimal for an open economy to deviate from uniform environmental taxation when international spillover effects are taken into account.

The first reason is linked to emission *leakage*– the phenomenon where policies meant to reduce emissions in one country may cause emissions to increase in other countries without control(see e.g.Hoel [1991], Felder and Rutherford [1993]). There are three basic channels through which leakagecan occur: 1. Trade channel: Leakage can arise when in countries undertaking emission limitations energy-intensive industries lose in competitiveness and the production of emission-intensive goods relocates thereby raising emission levels in the non-participating regions; 2. Energy channel: Cut-backs of energy demands in a large region due to emission constraints 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 and composition of energy demand in other regions (energy channel); and 3. Terms-of-trade channel: Leakage may be induced by changes in regional income and associated energy demand due to terms-of-trade effects. When national emission regulation aims at combating international externalities (such as global warming) lower tax rates for energy-intensive and trade-exposed industries may reduce emission increases of trading partners without equivalent emission regulation.

The second reason for differential taxation of emissions refers to policy-induced changes in the *terms of trade*: Large open economies may choose to differentiate environmental regulation in order to improve their terms of trade and shift domestic abatement cost to other countries. A

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[1] We do not consider the case of ambient pollution where emission prices must be spatially distributed to achieve quality standards at minimum abatement cost (see Tietenberg [1978]).

country which is a net exporter of "dirty" goods will levy higher environmental taxes on these commodities as a proxy for an optimal export tax – the opposite applies for the case of net imports of "dirty" goods (see e.g. Krutilla [1991], Anderson [1992], Rauscher [1994]).

Both motives for environmental tax differentiation figure prominently in the policy debate on environmental regulation and are of particular importance for the design of unilateral climate policies. On the one extreme, global environmental concerns may induce governments to pursue unilateral policies that compensate for emission leakage in a cost-efficient way. However, the leakage argument is also used by "dirty" industries in unilaterally taxing countries to lobby for complete tax exemptions which can be rather costly for the society as a whole. On the other extreme, differential taxation might be blamed as "beggar-thy-neighbour" policy to exploit international market power thereby violating general WTO rules.

The problem for an informed policy discussion is that both motives are intertwined: It is not clear to what extent tax differentiation by a country can be justified to combat leakage on global efficiency grounds or should be criticized by trading partners because of terms-of-trade manipulation. Likewise, a domestic regulator will have difficulties to sort out the pure leakage adjustment motive in fights on tax rebates with representatives of energy-intensive industries. Since the debate on post-Kyoto climate agreements in the U.S. and other OECD countries clearly evolves around the issues of international spillovers and feedback effects from unilateral policies, deeper insights into the motives for differential regulation of industries are quite important.

The objective of our paper is to investigate the policy relevance of both theoretical arguments for non-uniform taxation – leakage compensation or terms-of-trade exploitation – on the degree and pattern of tax differentiation. Our contribution to the existing literature is twofold: First, we introduce a decomposition technique that enables us to separate the leakage (compensation) motive from the terms-of-trade motive. Within our theoretical analysis, we then show that one can use compensating transfers to switch off the term-of-trade motive for environmental tax differentiation which leaves the leakage compensation as the solely remaining motive for tax differentiation. Second, we use this decomposition technique to quantify the implications of the terms-of-trade motive and the leakage (compensation) motive for the direction and magnitude of tax differentiation across sectors using a large-scale multi-region, multi-sector general equilibrium model of global trade and energy use calibrated to empirical data.

Based on our numerical results for the U.S. and other important OECD countries, we conclude that there is little economic basis for the common policy practice of strong tax discrimination in favor of energy-intensive industries when accounting for leakage or terms-of-trade motives.

Our analysis adds to the research on environmental regulation in an optimal tax framework. Over the last decade, the latter has predominantly focused on the implications of pre-existing tax distortions for the efficiency consequences of new environmental taxes. Bovenberg and van der Ploeg [1990], Bovenberg and Goulder [1996] or Goulder et al. [1997] suggest that tax interaction effects increase the gross efficiency costs (i.e. costs net of environmental benefits) of environmental taxes compared to a first-best world leading to optimal second-best environmental tax rates below the Pigovian rate. On the other hand, revenues from environmental taxes can be used to reduce the distortions of existing taxes (Terkla [1984], Oates [1995]) hereby offsetting at least part of potentially negative tax interaction effects (see Goulder [1995] for an overview). While this strand of the optimal tax literature has addressed the issue of tax interaction and revenue recycling with respect to the level of a single environmental tax and its overall economic costs, no evidence is provided on the *optimal differentiation* of environmental taxes across different segments of the economy. Another important issue in optimal taxation (see e.g. Alm [1996]) are equity criteria but distributional concerns have been relatively little studied in the context of (optimal) environmental tax design so far. The usual approach is to assess the impacts of exogenous environmental tax schemes on different income groups or industries (OECD [2007]) rather than determining optimal tax structures. Metcalf [1998], for example, studies the income distribution impacts of a hypothetical environmental tax reform in the U.S., investigating ways to make the tax reform *distributionally* neutral by means of targeted revenue recycling schemes. Böhringer and Rutherford [1997] discuss the use of tax exemptions to reduce worker layoffs in emission-intensive industries and find large excess costs vis-á-vis a mix of policy instruments, i.e. uniform carbon taxes together with sector-specific wage subsidies.

The remainder of the paper is organized as follows. Section 2 provides a stylized theoretical model to illustrate the decomposition of tax differentiation incentives into a leakage adjustment motive and a terms-of-trade motive. Section 3 entails a non-technical summary of the numerical model to quantify efficiency arguments for differential emission taxation in the context of international spillovers. Section 4 discusses our numerical findings. Section 5 concludes.

2 Decomposition of Tax Differentiation Motives

Leakage and terms-of-trade effects provide theoretical arguments for the differentiation of tax rates 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 industries or international energy market effects. An assessment of the relative importance of the leakage adjustment and the terms-of-trade motive requires a decomposition of both international spillover effects. In this section, we develop a simple analytical model to illustrate the decomposition of the terms-of-trade and the leakage adjustment effect which will be used later in our large-scale 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 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 taxation for two reasons, i.e. the terms-of-trade motive and the leakage adjustment 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 $i = 1, \ldots, n$ are produced with capital k^{ir} and energy (emissions) e^{ir}. Energy is produced in the countries with capital k^{er}.

Production in sector $i = 1, \ldots, n$ 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_i ($i = 1, \ldots, n$), and who 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

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

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

We assume that the home country, $r = 1$, wants to reduce some environmental damages from energy use. We hereby allow for transboundary pollution. That is, country 1 wants to restrict energy use such that $e^1 + \alpha e^2 \leq \bar{E}$, where $\alpha \geq 0$.

2.2 The Pareto Optimum

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

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

which leads to the following first-order conditions:

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

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

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

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 $(j = 1, \dots, n)$ 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_e^j. Production decisions are therefore characterized by the first-order conditions

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

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 satisfiy their balance of payments:

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

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 (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 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/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 $e^1 + \alpha e^2 \leq \bar{E}$. Differentiating with respect to τ_e^{i1}, yields

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

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

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

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

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

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 optimal for country 1 for two reasons: (i) the terms-of-trade effect $(dp_y^j/d\tau_e^{i1})$ and 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 1 is 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 $\mathrm{Tr}^1(\tau_e^1)$ that hold the welfare in the other country fixed, i.e. generate $u^2 = \bar{u}^2$. Here, $\bar{u}^2$ 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 the Appendix.

It is thus obvious that in case without leakage ($\alpha = 0$), 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.[2] 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 can solve the first-order conditions (10) when setting $\alpha = 0$. 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 optimal tax differentiation.

3 Numerical Analysis

We have motivated two reasons for differentiation of emission regulation across sectors of the economy when international spillover effects are taken into account: global environmental effectiveness and international market power, i.e., strategic trade policy. It is difficult to rule out any of these arguments on the basis of logical consistency. Although theoretical analysis can provide qualitative insights it lacks actual policy relevance because of very restrictive assumptions: The analytical derivation of the optimal environmental tax structure quickly becomes intractable for equilibrium conditions that exceed the complexity of standard textbook models (see e.g., [Hoel 1996]). Furthermore, marginal calculus does not allow for a generalization of results to structural changes in policy variables. Numerical analysis based on empirical data therefore provides an important complement to our stylized theoretical analysis.

In this section, we first lay out the numerical modeling framework in use to substantiate our theoretical considerations with quantitative evidence on the magnitude and direction of tax differentiation motivated by international spillovers. We then describe our central policy scenarios and interpret the simulation results. Finally we provide sensitivity analysis on the robustness of our findings.

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[2] 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 emissions 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 an Pareto-efficient solution. For those, however, we know that emission prices, i.e. emission taxes, must coincide for all sectors in country 1.

3.1 Basic Modeling Framework

Within the framework of a large-scale computable general equilibrium (CGE) model calibrated to empirical data, we compute the *optimal* structure of emission taxation under alternative assumptions regarding the existence of tax differentiation motives, i.e. leakage compensation and (or) terms-of-trade manipulation. Our CGE model of global trade and energy use is designed to investigate the economic impacts of emission constraints on carbon dioxide, the most important greenhouse gas in the context of global warming. [3]

As is customary in applied general equilibrium analysis, benchmark data determine the free parameters of functional forms from a given set of benchmark quantities, prices, and elasticities. The underlying data base is GTAP7 for the base year 2004 which provides the most recent consistentaccounts of regional production and consumption, as well as bilateral trade flows together with a representation of international energy markets in physical units (see Cen [2007], Rutherford and Paltsev [2000]).

Table 1 gives an overview on sectors, factors and regions considered for the applied analysis. With respect to our calculations of optimal carbon tax policies, the sectors have been chosen to separate energy/emission-intensive and non energy-intensive activities in the economy. Energy goods in the model include coal (COL), gas (GAS), crude oil (CRU), refined oil products (OIL) and electricity (ELE). This disaggregation is essential in order to distinguish energy goods by carbon intensity and by the degree of substitutability. The remaining sectors include a composite industry producing a non-energy-intensive macro good (ROI) and energy-intensive industries (EIS) – the latter stand out in current environmental tax schemes for reduced tax rates (OECD [2007]) and are likewise considered in the post-Kyoto policy debate for preferential treatment. The regional disaggregation considers major trading regions that are central to the climate policy debate: Beyond the U.S. and other important OECD countries we explicitly incorporate China and India as key players.[4]

The objective of our numerical analysis is to quantify how important theoretical efficiency arguments for environmental tax differentiation are with respect to *practical* policy making. To do so, we must treat the terms-of-trade motive separately from the leakage-adjustment motive building on the decomposition technique that we have formally described in section 2. Our multi-

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[3] Due to the micro-consistent comprehensive representation of market interactions, CGE models have become the standard tool for studying the economy-wide impacts of environmental policy interference (for surveys see e.g. Weyant, ed [1999], or Conrad [2001]).

[4] The Appendix features a more detailed non-technical model summary together with an algebraic exposition and the model parameterization

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

<table>
<tr><th colspan="2">Sectors (Commodities)</th><th colspan="2">Regions</th></tr>
<tr><td>COL</td><td>Coal</td><td>EUR</td><td>Europe (EU15, EFTA)</td></tr>
<tr><td>CRU</td><td>Crude oil</td><td>JPN</td><td>Japan</td></tr>
<tr><td>GAS</td><td>Natural gas</td><td>USA</td><td>United States</td></tr>
<tr><td>OIL</td><td>Refined oil products</td><td>EIT</td><td>Former Soviet Union and Eastern Europe</td></tr>
<tr><td>ELE</td><td>Electricity</td><td>OEC</td><td>Australia and New Zealand</td></tr>
<tr><td>EIS</td><td>Energy-intensive sectors</td><td>CAN</td><td>Canada</td></tr>
<tr><td>ROI</td><td>Other manufactures services</td><td>ASI</td><td>Asia</td></tr>
<tr><td></td><td></td><td>MPC</td><td>Mexico and OPEC</td></tr>
<tr><td></td><td></td><td>ROW</td><td>Rest of World</td></tr>
<tr><th colspan="2">Factors</th><td></td><td></td></tr>
<tr><td>$\bar{L}$</td><td>Labor</td><td></td><td></td></tr>
<tr><td>$\bar{K}$</td><td>Capital</td><td></td><td></td></tr>
<tr><td>$\bar{Q}_{ff}$</td><td>Fossil fuel resources ($ff := COL, CRU, GAS$)</td><td></td><td></td></tr>
</table>

region trade framework readily incorporates terms-of-trade effects induced by policy intervention. Product differentiation in international trade implies finite elasticities for domestically produced goods with respect to import demand functions of trading partners. As a consequence, our model provides each country with a certain degree of market power in international trade. Depending on international exposure, countries can enact carbon taxes to improve terms of trade and thereby shift part of the domestic abatement costs to trading partners via higher prices of carbon-intensive exports and lower prices of imported energy. Leakage concerns are incorporated by adjusting the domestic environmental target of the (unilaterally) abating region by emission increases in non-abating regions. To suppress the terms-of-trade motive in our multi-region framework, we require the abating region to compensate all other regions with lump-sum transfers which keep them at their benchmark welfare level. Thus, the abating country cannot take advantage of changes in international prices and the leakage motive will be covered comprehensively.

In formal terms, our problem can be cast as policy optimization subject to economic equilibrium conditions:

$$\max_t H(z)$$
$$\text{s.t.} \quad F(z;t) = 0$$

where:

$z \in \Re^n$:= is a vector of endogenous variables that is determined by the equilibrium problem, i.e. $z = \binom{p}{y}$, where p are prices and y are activity levels,

$t \in \Re^m$:= is a vector of tax policy instruments which are the choice variables for the problem,

$F : \Re^n \rightarrow \Re^n$:= is a system of equations which represents a general equilibrium conditions, and

$H(z)$: := is the policy objective function.

In our implementation, the constraints F describe the equilibrium conditions of our large-scale CGE model. F also features an emission constraint for the region undertaking unilateral climate policy. Depending on whether we want to account for leakage compensation the emission constraint will include leakage offsets.[5] F may furthermore include transfer constraints imposed on the unilaterally acting country to compensate other regions for potentially adverse terms-of-trade effects (keeping these regions at their base-year welfare levels). Whenever the terms-of-trade compensation is included as a constraint, the terms-of-trade motive for emission tax differentiation is suppressed.

Emission taxes correspond to the set of choice variables t for the unilateral acting region and can be differentiated across different segments of the economy to maximize some policy objective (in our case: welfare in terms of real consumption) as captured by the function $H(z)$.

3.2 Policy Scenarios and Results

Scenarios

Our central policy simulations are based on four different scenarios that allow us to explore the leakage and the terms-of-trade motive for emission tax differentiation:

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[5] If we denote emissions by region r as e_r with base-year emissions of e_r^0 and percentage emission reduction of the unilaterally actiong region r' by $\lambda_{r'}$ the leakage-compensated emission constraint reads as $\sum\limits_r e_r = \sum\limits_{r \neq r'} e_r^0 + (1 - \lambda) e_{r'}^0$.

- *REF* : The reference abatement scenario in which domestic tax design exploits terms of trade but neglects leakage, i.e., this scenario considers the pure terms-of-trade motive for differential regulation.

- *T* : The terms-of-trade adjustment scenario in which compensating transfers remove economic motivation for exploiting terms of trade.

- *L_T* : The scenario which includes adjustment constraint for both leakage and terms-of-trade spillovers, i.e., this scenario looks at the pure leakage-adjustment motive for differential regulation.

- *L* : The leakage adjustment scenario in which domestic emissions are targeted to a level which accounts for induced increases in emissions by other (non-abating) regions.

Across all scenarios we impose a carbon emission reduction of 20% on a unilaterally abating region for our central case simulations.[6] Carbon tax rates represent the choice variables of policy makers and can be differentiated across four segments of the economy: electricity production (ELE), energy-intensive production (EIS), all other production of goods and services (OTHER), and final consumption demand (FINAL).[7] In our numerical calculations, we identify optimal carbon tax policies for Canada (CAN), Europe (EUR), and the United States (USA) to sort out potential cross-country differences.

Results

In the exposition of results,the economic impacts of carbon taxation are measured with respect to the benchmark situation (BMK), where no emission reduction constraint applies. Table 2 reports the optimal tax differentiation across different sectors of the economy, welfare changes (expresses in terms of real consumption losses), impacts on energy-intensive production, and leakage rates[8] across our four scenarios.

We first investigate the relative importance of international market power for the differentiation of carbon taxes. Scenario *REF* reflects the pure terms-of-trade motive for carbon tax differentiation as countries are able to exploit terms of trade while ignoring leakage. The guideline for carbon tax differentiation under *REF* is to make the country act as monopolists on

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[6] Various OECD countries have committed themselves within national and international agreements to carbon emission reductions in the magnitude of 10%-30% vis-á-vis current emission levels.

[7] We have imposed a non-negativity constraint on carbon tax rates to exclude the possibility of emission subsidies.

[8] Leakage measures the induced increase in non-abating regions' carbon emissions as percentage of the unilateral abatement target.

export markets (i.e. increasing the prices of its exports) and as monopsonists on import markets (i.e. favoring domestic production for goods that compete on import markets): Ceteris paribus, sectors (commodities) which command large shares in the trading partners' imports are taxed at a higher level to "export" the economic burden of domestic taxation; the same logic applies to imports from abroad. Apart from trade intensities of commodities, the actual tax scheme depends on additional country-specific characteristics, such as the foreign demand and supply elasticities. Drawing on the benchmark data, Canada and Europe are larger "net" exporter of energy-intensive products and imposes high carbon taxes on these branches to maximize terms-of-trade gains. The U.S., in turn, exploits market power on international markets for its macro good. It is also important to note that terms-of-trade motives do not rationalize the common practice of strong tax discrimination in favor of energy-intensive industries.

As countries solely focus on their national abatement target and can shift part of the domestic tax burden to abroad, the inframarginal adjustment cost to a 20 % domestic emission reduction appear moderate, yet there are substantial cross-country differences. Whereas Europe has almost negligible macroeconomic cost, Canada and the U.S. are markedly worse off – the main reason being the differential ability to pass adjustment cost further to trading partners.

The latter becomes obvious in scenario T when compensating transfer suppress the terms-of-trade motive (note that leakage concerns are still ignored). The changes in inframarginal adjustment cost from scenario REF to scenario T reveal the importance of international market power: In particular, Europe which is very much trade exposed, is able to exploit terms of trade – the compliance cost to the domestic emission reduction target increase in our simulations by an order of magnitude if the terms-of-trade motive is suppressed via compensating transfers. To put it the other way round: Europe can shift more or less the whole domestic carbon tax burden to trading partners – strategic tax differentiation provides secondary terms-of-trade benefits that nearly offset the primary domestic adjustment costs. As with welfare, the optimal carbon tax scheme is quite different under compensating transfers and missing concerns on leakage. In the absence of other distortions, i.e., in a first-best situation, the optimal policy involves uniform carbon taxes: Theoretical analysis suggests that the free trade equilibrium without initial taxes constitutes a Pareto-efficient situation. The use of taxes to exploit terms of trade can make a large open economy better off, but only at the expense of trading partners and decreased *global* welfare. Whenever a region must compensate trading partners for policy-induced terms-of-trade losses, its first-best policy will be to minimize the *global* costs of carbon abatement which leads to uniform carbon tax rates.

Scenario L_T that captures the pure leakage motive is based on a fixed *global* emissions target

Table 2: Differentiated carbon taxes, welfare, energy-intensive output, and leakage

		REF	*T*	*L_T*	*L*
Carbon taxes (in USD$_{95}$ per ton of carbon)					
CAN	EIS	177	76	112	176
	ELE	70	76	221	229
	OTHER	55	76	204	189
	FINAL	66	76	241	235
EUR	EIS	144	113	130	166
	ELE	82	113	205	175
	OTHER	125	113	205	214
	FINAL	119	113	197	199
USA	EIS	65	75	94	84
	ELE	64	75	103	92
	OTHER	86	75	98	110
	FINAL	93	75	88	106
Welfare (in % change from BMK)					
CAN		-0.20	-0.27	-1.15	-1.10
EUR		-0.03	-0.30	-0.70	-0.33
USA		-0.15	-0.21	-0.32	-0.25
Energy-intensive production (in % change from BMK)					
CAN		-9.0	-4.3	-6.1	-9.1
EUR		-2.7	-2.2	-2.8	-3.3
USA		-1.5	-1.7	-2.2	-1.9
Leakage rates (in %)					
CAN		46.7	43.3	45.4	44.3
EUR		32.0	31.8	31.1	31.0
USA		17.8	17.1	17.4	16.9

REF: reference (no adjustments)
L: leakage adjustment
T: terms-of-trade adjustment
L_T: leakage and terms-of-trade adjustment

(letting the regional target of the abating region be determined endogenously) and it includes compensating transfers. Concerns on leakage justify tax-cuts for energy-intensive sectors – yet, the optimal tax-breaks are far from exemptions. Regarding economy-wide adjustment costs, more stringent domestic abatement to offset emission leakage through non-abating countries is very costly for unilaterally abating regions, in particular, when leakage rates are very high which is the case for Canada.

It should be noted that leakage compensation has virtually no effect on the leakage rates, although carbon tax rates are discriminated in favor of energy-intensive industries. In order to offset additional emissions elsewhere, the abating country must implicitly meet a higher reduction target which raises the effective carbon tax and, thus, offsets the primary effect of tax discrimination on the magnitude of leakage. Leakage rates are higher in regions such as Canada whose trade flows incorporate higher levels of embodied carbon.

From a practical policy standpoint, it seems rather unlikely that a country would be willing to compensate for any emission increase elsewhere *and* at the same time compensate non-abating countries that are not contributing to climate protection (as captured by scenario L_T). Against this background, we have constructed a final scenario L which is based on a *global* emission target to account for leakage, but excludes compensating transfers. Optimal taxes then incorporate both leakage concerns and terms-of-trade motives. In this case, the results suggest slight tax discrimination in favor of energy-intensive production whereby terms-of-trade gains can partially offset the additional costs of leakage compensation. The scope for cost offsets for leakage adjustment through terms-of-trade gains is quite different. Canada, for example, has only limited scope since it must compensate high leakage rates with rather weak international market power.

3.3 Sensitivity Analysis

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

Alternative Reduction Targets

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

The leakage argument for lowering carbon tax rates on energy-intensive production becomes more important for higher emission reduction requirements, since higher carbon taxes increase the scope for relocation of domestic emission-intensive production to (non-taxing) trading partners. However, tax reductions for energy-intensive industries remain far from exemption even for high reduction targets. Leakage compensation through the adjustment of domestic abatement efforts gets very expensive with increasing reduction targets. For low reduction targets, abating countries can offset domestic adjustment costs with terms-of-trade gains from strategic tax differentiation. Towards higher reduction targets, the primary costs of domestic adjustment dominate secondary terms-of-trade benefits, and abating countries face substantial consumption losses.

Armington Elasticities

In the central case simulations, the Armington elasticity of substitution between the domestic good and the import aggregate is set equal to 4.0. The values of Armington elasticities affect the magnitude of leakage and terms-of-trade effects. Higher Armington elasticities imply more leakage and less scope for tax burden shifting. Higher Armington elasticities decrease international market power and thus the scope for tax burden shifting. The associated loss in terms-of-trade more than offsets the cost gains through improved carbon substitutability such that unilaterally abating countries face slightly increasing consumption losses towards higher values for the Armington elasticities. Tax discrimination in favor of emission-intensive industries becomes more pronounced towards higher Armington elasticities that imply more leakage; yet, the optimal tax reductions remain far from tax exemptions.

4 Conclusions

In quantitative terms, tax rates optimized to account for leakage are far from justifying the common practice of strong tax discrimination in favor of energy-intensive industries. Strategic trade motives involve only modest deviation from uniform taxation to exploit terms of trade with the direction of tax differentiation depending on a country's comparative advantage.

Environmental taxes in OECD countries deviate from uniformity as the basic principle for cost-effective regulation of uniformly dispersed pollutants such as CO_2.

Economic theory mentions leakage motives or terms-of-trade manipulation (international market power) as efficiency arguments why tax differentiation across different sectors of the economy might be optimal when international spillover effects are taken into account. However, the theoretical arguments remain qualitative, since they are based on highly stylized analysis.

In this paper, we have used a multi-region, multi-sector general equilibrium model of global trade and energy use calibrated to empirical data to quantify the relative importance of theoretical efficiency arguments for tax differentiation. We find that concerns about global environmental effectiveness provide some justification for tax discrimination in favor of energy- and export-intensive industries. Yet, leakage and thus the stringency of unilateral emission constraints must be very high to make the case for substantial tax reductions. Likewise, strategic international tax burden shifting can hardly rationalize the current practice in OECD countries to have only very low environmental taxes on energy-intensive industries or even exempt them.

Our empirical application to optimal carbon taxation in OECD countries serves as a specific example of the more general issue of differentiated environmental regulation. While the concrete quantitative implications might be different, a similar qualitative reasoning would apply to many related environmental issues.

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A Mathematical Proofs

Proof of equation (9):

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

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

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 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:

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

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

B Non-technical Model Summary

Figure 1 provides a diagrammatic structure of the model. Primary factors of region r include labor $\bar{L}_r$, capital $\bar{K}_r$ and fossil-fuel resources $\bar{Q}_{ff,r}$. Labor and capital are intersectorally mobile within a region but cannot move between regions. A specific resource is used in the production of crude oil, coal and gas, resulting in upward sloping supply schedules. Production Y_{ir} of commodities i in region r, other than primary fossil fuels, is captured by aggregate production functions which characterize technology through substitution possibilities between various inputs.

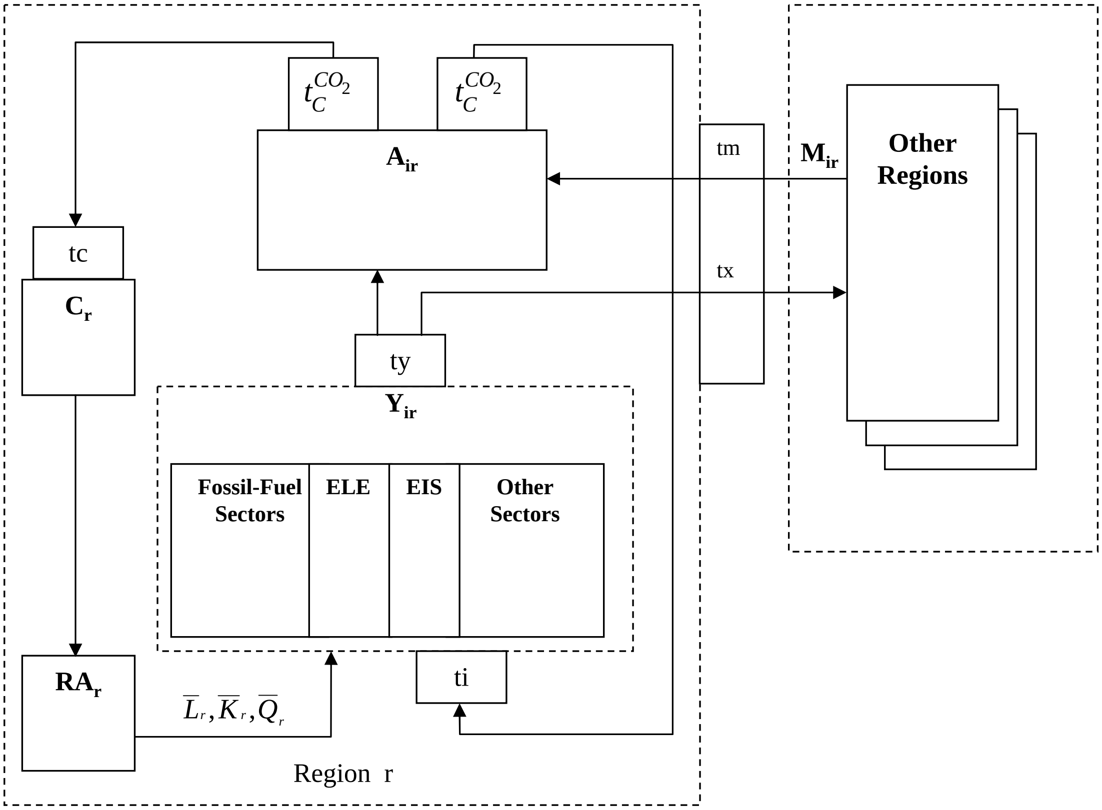

Figure 1: *Diagrammatic overview of the model structure*

Nested constant elasticity of substitution (CES) cost functions with three levels are employed to specify the substitution possibilities in domestic production between capital, labor, energy and non-energy, intermediate inputs, i.e. material. At the top level, non-energy inputs are employed in fixed proportions with an aggregate of energy, capital and labor. At the second level, a CES function describes the substitution possibilities between the energy aggregate and the aggregate of labor and capital. Finally, at the third level, capital and labor trade off with a constant elasticity of substitution. As to the formation of the energy aggregate, we allow sufficient levels of nesting to permit substitution between primary energy types, as well as substitution between a primary energy composite and secondary energy, i.e. electricity.

Final demand C_r in each region is determined by a representative agent RA_r, who maximizes utility subject to a budget constraint with fixed investment. Total income of the representative household consists of factor income and tax revenues. Final demand is given as a CES composite which combines consumption of an energy aggregate with a non-energy consumption bundle. Substitution patterns within the non-energy consumption bundle are reflected via Cobb-Douglas functions. The energy aggregate in final demand consists of the various energy goods trading off at a constant elasticity of substitution. All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{ir} of the domestically produced variety and a CES import aggregate M_{ir} of the same variety from the other regions (the so-called Armington good - Armington 1969). Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions. The tax system includes all types of indirect taxes (production taxes or subsidies ty, intermediate taxes ti, consumption taxes tc, as well as tariffs tm and tx) which are used to finance a fixed level of public good provision. A lump-sum tax on the representative household balances the public budget. In Figure 1, we have also included the carbon taxes $t_i^{\mathrm{CO_2}}$ and $t_C^{\mathrm{CO_2}}$, that the carbon abating region must impose to meet an exogenous reduction constraint in carbon emissions from the domestic combustion of fossil fuels. Carbon taxes can be differentiated across the energy-intensive sector ($i = \mathrm{EIS}$), the power generation sector ($i = \mathrm{ELE}$), all OTHER production of goods and services ($i \in \{COL, CRU, GAS, ROI\}$), and FINAL demand ($t_C^{\mathrm{CO_2}}$) in order to maximize the region's objective function.

C Algebraic Model Summary

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

- Nested separable constant elasticity of substitution (CES) functions characterize the use of inputs in production. All production exhibits non-increasing returns to scale. Goods are produced with capital, labor, energy and material (KLEM).
- A representative agent in each region is endowed with three primary factors: natural resources (used for fossil fuel production), labor and capital. The representative agent maximizes utility from consumption of a CES composite subject to a budget constraint with fixed investment demand (i.e. fixed demand for the savings good). The aggregate consumption bundle combines demands for fossil fuels, electricity and non-energy commodities. Total income of the representative agent consists of factor income and taxes (including carbon tax revenues).
- Supplies of labor, capital and fossil-fuel resources are exogenous. Labor and capital are mobile within domestic borders but cannot move between regions; natural resources are sector specific.
- All goods are differentiated by region of origin. Constant elasticity of transformation functions (CET) characterize the differentiation of production between production for the domestic markets and the export markets. Regarding imports, nested CES functions characterize the choice between imported and domestic varieties of the same good (Armington).

Two classes of conditions characterize the competitive equilibrium for our model: zero profit conditions and market clearance conditions. The former class determines activity levels and the latter determines price levels. In our algebraic exposition, the notation Π_{ir}^{u} is used to denote the profit function of sector j in region r where u is the name assigned to the associated production activity. Differentiating the profit function with respect to input and output prices provides compensated demand and supply coefficients (Shephard'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 C.1-C.6 explain the notations for variables and parameters employed within our algebraic exposition.

C.1 Zero Profit Conditions

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

$$\begin{aligned}
\Pi^Y_{ir} &= \left[\theta^X_{ir} {p^X_{ir}}^{1-\eta} + (1-\theta^X_{ir}) p_{ir}^{1-\eta}\right]^{\frac{1}{1-\eta}} - \sum_{j \notin EG} \theta_{jir} p^A_{jr} \\
&\quad -\theta^{KLE}_{ir}\left[\theta^E_{ir} {p^E_{ir}}^{1-\sigma_{KLE}} + (1-\theta^E_{ir})(w_r^{\alpha^L_{jr}} v_r^{\alpha^K_{jr}})^{1-\sigma_{KLE}}\right]^{\frac{1}{1-\sigma_{KLE}}} \\
&= 0
\end{aligned} \tag{13}$$

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

$$\begin{aligned}
\Pi^Y_{ir} &= \left[\theta^X_{ir} {p^X_{ir}}^{1-\eta} + (1-\theta^X_{ir}) p_{ir}^{1-\eta}\right]^{\frac{1}{1-\eta}} - \Big\{\theta^Q_{ir} q_{ir}^{1-\sigma_{Q,i}} \\
&\quad +(1-\theta^Q_{ir})\Big[\theta^{FF}_{Lir} w_r + \theta^{FF}_{Kir} v_r + \sum_j \theta^{FF}_{jir}(p^A_{jr} + t^{\mathrm{CO_2}}_{jr} a^{\mathrm{CO_2}}_j)\Big]^{1-\sigma_{Q,i}}\Big\}^{\frac{1}{1-\sigma_{Q,i}}} \\
&= 0
\end{aligned} \tag{14}$$

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

$$\begin{aligned}
\Pi^E_{ir} &= p^E_{ir} - \Big\{\theta^{ELE}_{ir} {p^A_{ELE,r}}^{1-\sigma_{ELE}} + (1-\sigma^{ELE}_{ir})\Big[\theta^{COL}_{ir}(p^A_{COL,r} + t^{\mathrm{CO_2}}_{ir} a^{\mathrm{CO_2}}_{COL})^{1-\sigma_{COL}} \\
&\quad +(1-\theta^{COA}_{ir})\Big(\prod_{j \in LQ}(p^A_{ir} + t^{\mathrm{CO_2}}_{ir} a^{\mathrm{CO_2}}_j)^{\beta_{jir}}\Big)^{1-\sigma_{COL}}\Big]^{\frac{1-\sigma ELE}{1-\sigma_{COL}}}\Big\}^{\frac{1}{1-\sigma_{ELE}}} \\
&= 0
\end{aligned} \tag{15}$$

4. Armington aggregate:

$$\Pi^A_{ir} = p^A_{ir} - \left[\theta^A_{ir} p_{ir}^{-\sigma_A} + (1-\theta^A_{ir}) {p^M_{ir}}^{1-\sigma_A}\right]^{\frac{1}{1-\sigma_A}} = 0 \tag{16}$$

5. Aggregate imports across import regions:

$$\Pi^M_{ir} = p^M_{ir} - \Big(\sum_s \theta^M_{isr} {p^X_{is}}^{1-\sigma_M}\Big)^{\frac{1}{1-\sigma_M}} = 0 \tag{17}$$

6. Household consumption demand:

$$\Pi^C_r = p^C_r - \Big[\theta^E_{Cr} {p^E_{Cr}}^{1-\sigma_{EC}} + (1-\theta^E_{Cr})\Big(\prod_{i \notin FF} {p^A_{ir}}^{\gamma_{ir}}\Big)^{1-\sigma_{EC}}\Big]^{\frac{1}{1-\sigma_{EC}}} = 0 \tag{18}$$

7. Household energy demand:

$$\Pi^E_{Cr} = p^E_{Cr} - \Big[\sum_{i \in FF} \theta^E_{iCr}(p^A_{ir} + t^{\mathrm{CO_2}}_{Cr} a^{\mathrm{CO_2}}_i)^{1-\sigma_{FF,C}}\Big]^{\frac{1}{1-\sigma_{FF,C}}} = 0 \tag{19}$$

C.2 Market Clearance Conditions

8. Labor:

$$\bar{L}_r = \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial v_r} \tag{20}$$

9. Capital:

$$\bar{K}_r = \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial v_r} \tag{21}$$

10. Natural resources:

$$\bar{Q_{ir}} = Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial q_{ir}} \quad i \in FF \tag{22}$$

11. Output for domestic markets:

$$Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p_{ir}} = \sum_j A_{jr} \frac{\partial \Pi^A_{jr}}{\partial p_{ir}} \tag{23}$$

12. Output for export markets:

$$Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^X_{ir}} = \sum_s M_{is} \frac{\partial \Pi^M_{is}}{\partial p^X_{ir}} \tag{24}$$

13. Sector specific energy aggregate:

$$E_{ir} = Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^E_{ir}} \tag{25}$$

14. Import aggregate:

$$M_{ir} = A_{ir} \frac{\partial \Pi^A_{ir}}{\partial p^M_{ir}} \tag{26}$$

15. Armington aggregate:

$$A_{ir} = \sum_j Y_{jr} \frac{\partial \Pi^Y_{jr}}{\partial p^A_{ir}} + C_r \frac{\partial \Pi^C_r}{\partial p^A_{ir}} \tag{27}$$

16. Household consumption:

$$\begin{aligned}
C_r p^C_r \quad = \quad & w_r \bar{L}_r v_r \bar{K}_r + \sum_{j \in FF} q_{jr} \bar{Q}_{jr} \\
& + p_{CGD,r} \bar{Y}_{CGD,r} + \bar{B}_r \\
& + \sum_{i \notin FF} \sum_{j \in FF} \frac{\partial \Pi^E_{ir}}{\partial (p^A_{jr} + t^{\mathrm{CO_2}}_{ir} a^{\mathrm{CO_2}}_j)} a^{\mathrm{CO_2}}_j t^{\mathrm{CO_2}}_{Cr} \\
& + \sum_{i \in FF} \sum_{j \notin FF} \frac{\partial \Pi^Y_{ir}}{\partial (p^A_{ir} + t^{\mathrm{CO_2}}_{jr} a^{\mathrm{CO_2}}_i)} a^{\mathrm{CO_2}}_i t^{\mathrm{CO_2}}_{jr} \\
& + \sum_{i \in FF} \frac{\partial \Pi^E_{ir}}{\partial (p^A_{ir} + t^{\mathrm{CO_2}}_{Cr} a^{\mathrm{CO_2}}_i)} a^{\mathrm{CO_2}}_i t^{\mathrm{CO_2}}_{Cr}
\end{aligned} \tag{28}$$

17. Aggregate household energy consumption:

$$E_{Cr} = C_r \frac{\partial \Pi_r^C}{\partial p_{Cr}^E} \tag{29}$$

18. Carbon emissions:

$$C\bar{O}2_r = \sum_i A_{ir} a_i^{\mathrm{CO_2}} \tag{30}$$

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

Table C.4: Cost shares

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

Table C.5: Endowments and emissions coefficients

$\bar{L}_r$	Aggregate labor endowment for region r
$\bar{K}_r$	Aggregate capital endowment for region r
$\bar{Q}_{ir}$	Endowment of natural resource i for region r ($i \in FF$)
$\bar{B}_r$	Balance of payment deficit or surplus in region r (note: $\sum_r \bar{B}_r = 0$)
$C\bar{O}2_r$	Carbon emission constraint for region r
$a_i^{\mathrm{CO}_2}$	Carbon emissions coefficient for fossil fuel i ($i \in FF$)

Table C.6: Elasticities

η	Transformation between production for the domestic market and production for the export	4
σ_{KLE}	Substitution between energy and value-added in production (except fossil fuels)	0.5
$\sigma_{Q,i}$	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF}	$COA = 1.0$ $CRU = 1.0$ $GAS = 1.0$
σ_{ELE}	Substitution between electricity and the fossil fuel aggregate in production	0.3
σ_{COA}	Substitution between coal and the liquid fossil fuel composite in production	0.5
σ_{A}	Substitution between the import aggregate and the domestic input	4
σ_{M}	Substitution between imports from different regions	8
σ_{EC}	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.8
$\sigma_{FF,C}$	Substitution between fossil fuels in household fossil energy consumption	0.3

D Benchmark Data – Regional and Sectoral Aggregation

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

Table D.1: Sectoral aggregation

Sectors in GTAP-EG			
AGR	Agricultural products	NFM	Non-ferrous metals
CNS	Construction	NMM	Non-metallic minerals
COL	Coal	OIL	Refined oil products
CRP	Chemical industry	OME	Other machinery
CRU	Crude oil	OMF	Other manufacturing
DWE	Dwellings	OMN	Mining
ELE	Electricity and heat	PPP	Paper-pulp-print
FPR	Food products	SER	Commercial and public services
GAS	Natural gas works	T_ T	Trade margins
I_ S	Iron and steel industry	TRN	Transport equipment
LUM	Wood and wood-products	TWL	Textiles-wearing apparel-leather
Mapping from GTAP-EG sectors to model sectors as of Table 1			
		Energy	
COL	Coal	COL	
CRU	Crude oil	CRU	
GAS	Natural gas	GAS	
OIL	Refined oil products	OIL	
ELE	Electricity	ELE	
		Non-Energy	
EIS	Energy-intensive sectors	CRP, I_ S, NFM, NMM, PPP, TRN	
ROI	Rest of industry	AGR, CNS, DWE, FPR, LUM, OME OMF, OMN, SER, T_ T, TWL	

Table D.2: Regional aggregation

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

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