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ENERGY TAXES AND COST-EFFECTIVE UNILATERAL CLIMATE POLICY: ADDRESSING CARBON LEAKAGE

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Abstract: This paper analyzes how a country pursuing an ambitious unilateral climate policy may contribute to a reduction in global CO_2 emissions in a cost-effective way. To do so its system of energy taxes and subsidies must account for leakage of emissions from the domestic to the foreign economy. We focus on leakage occurring via imports and exports of electricity and via shifts between domestic and foreign production of other tradable goods. The optimal tax-subsidy scheme is based on a consistent principle: Impose a uniform carbon tax on all additions to global emissions caused by changes in domestic production and consumption of energy, including additions to emissions occurring via shifts in international trade. Emissions from the tradable-goods sector should be taxed at reduced rates to avoid excessive carbon leakage, and a part of the carbon tax on electricity should be levied at the consumer rather than the producer level to ensure taxation of the carbon content of imported electricity. Producers of renewables-based electricity should receive a subsidy to internalize their contribution to the reduction of global emissions. In other sectors emissions should be taxed at a uniform rate corresponding to the marginal social cost of meeting the target for emissions reduction.

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1. The problem: Unilateral climate policy and carbon leakage

The 2015 Paris Agreement on international climate policy is based on a bottom-up approach to policy coordination, relying on each participating country to make a "nationally determined contribution" to the global reduction of greenhouse gas emissions. The so-called Intended Nationally Determined Conbributions submitted so far by the parties to the agreement vary considerably across countries, with some countries having much more ambitious targets for greenhouse gas reductions than others. A well-known dilemma for countries that would like to take the lead in climate policy is that a unilateral increase in abatement effort is likely to cause carbon leakage: a country that unilaterally tightens its climate policy may lose international competitiveness, leading to lower domestic production and higher net imports of carbon-intensive goods. As a consequence, a considerable part of domestic emissions may simply leak abroad.

Many writers have discussed how a country with an ambitious climate policy could try to minimize carbon leakage.[2] A popular proposal is to supplement a domestic carbon tax with border carbon adjustment (BCA) in the form of tariffs on imports and rebates on exports differentiated according to the estimated carbon content of the various traded goods (see, e.g., Hoel (1996), Böhringer et al. (2012), Fischer and Fox (2012)). The literature has shown that a BCA policy is a more cost-effective way of reducing global emissions than a policy of granting output-based rebates of emission taxes on carbon-intensive domestic industries. However, a BCA policy may violate WTO rules and invite

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[2]For a survey of the literature on carbon leakage, see e.g. Reinaud (2008) and Marcu et al. (2013).

international trade wars.

This paper proposes to deal with carbon leakage through a tax-subsidy scheme that avoids border carbon adjustment. Instead, the scheme involves reduced emission tax rates for trade-exposed domestic production combined with offsetting taxes on domestic consumption of tradable energy and subsidies to power production based on renewable energy sources. The paper is related to a recent contribution by Böhringer et al. (2017) who set up a two-country model to show that it is welfare-improving for a country that implements emission pricing along with output-based rebates to introduce a consumption tax on emission-intensive trade-exposed goods. The analysis by Böhringer et al. (2017) takes the carbon tax and the associated rebates as given. The present paper goes further by analyzing the optimal simultaneous choice of the consumption tax on emission-intensive tradable goods and the tax rates on and subsidies to energy production and consumption, assuming that the domestic government wants to make some given contribution to the reduction of *global* emissions at the lowest possible social cost. With a focus on global emissions rather than emissions from domestic territory, the government must account for carbon leakage. Our tool of analysis is a fairly detailed partial equilibrium model of the energy market in a small open economy that allows for carbon leakage via international trade in electricity and other goods.

The paper is structured as follows: Section 2 sets up a model of energy production and energy trade in a small open economy and outlines how one may estimate carbon leakage rates. Section 3 uses the model to derive the conditions for a socially optimal mix of fossil and renewable energy production and domestic energy savings, given the government's ambition to reduce global emissions by some target amount.[3] Section 4 derives the set of energy taxes and energy subsidies that fulfils these optimum conditions, and section 5 outlines how the tax-subsidy scheme must be modified if a part of the economy is covered by an international cap-and-trade system such as the European Emissions Trading System. Section 6 summarizes the main findings of the paper and briefly discusses some practical and political economy issues related to the implementation of a tax-subsidy scheme that accounts for carbon leakage.

[3] In the long run the world community will have to phase out fossil fuels to meet the goal of the Paris Agreement. The present paper focuses on an intermediate policy horizon where there is still some room for using fossil fuels.

2. A model of the energy market in an open economy

To study the optimal design of energy taxes and subsidies in an economy vulnerable to carbon leakage, this section sets up a partial-equilibrium model of the energy market in a small open economy. On the supply side of the market utilities produce a non-traded energy good denoted as "heat" and an internationally traded energy good termed "electricity" (reflecting that many countries participate in an international electricity market via interconnectors). These energy goods are produced either by burning fossil fuel or by exploiting a renewable energy source such as wind, solar energy or biomass. On the demand side of the energy market households and firms demand heat and electricity from the utilities (including foreign utilities if electricity is imported). Households also demand energy raw materials such as fossil fuels and biomass to produce services like transport and heating for their own consumption, and as a supplement to the heat and electricity delivered from utilities firms demand fossil fuels and biomass for direct use in their production processes.[4] These fossil and renewable energy raw materials are traded internationally.

Production of fossil-based heat and electricity and domestic extraction of fossil fuels generate CO_2 emissions which may be mitigated by abatement efforts and by energy savings. The target for domestic climate policy is to make a certain contribution to the reduction of *global* CO_2 emissions at the lowest possible social cost. For this purpose the government may levy carbon taxes on emissions from domestic production of fossil fuel and fossil-based heat and electricity, energy taxes on domestic consumption of the various form of energy services and energy raw materials, and subsidies to production of renewable energy. The government may also choose to subsidize abatement efforts. All of these taxes and subsidies may be differentiated across sectors and types of energy. Carbon leakage occurs when domestic climate policy induces a shift from home-produced to imported electricity or when it causes a crowding-out of domestic by foreign production of other tradable goods.[5]

[4] We use the term "biomass" to emphasize that it is an intermediate energy input that needs further processing before delivering the final energy service demanded, but it should be thought of as including a range of bioenergy inputs including biofuels and biogas used for transport purposes and industrial processes.

[5] The literature has also pointed to other channels for carbon leakage such as the "fossil fuel channel":

The subsections below describe the details of the model.

2.1. Energy supply

Heating of buildings can be produced either as district heating by utility companies or by individual households and firms using fossil-based or renewables-based technologies. We start by focusing on district heating.[6] The CO_2 emissions e_H from the production of fossil-based district heating increase with the quantity H_F of heat produced and decrease with abatement effort A_H which may take the form of investment in more energy-efficient equipment or equipment that allows a shift from CO_2-intensive coal to less CO_2-intensive natural gas. Hence

$$e_H = e_H\left(H_F, A_H\right), \qquad \frac{\partial e_H}{\partial H_F} > 0, \quad \frac{\partial e_H}{\partial A_H} < 0. \tag{2.1}$$

The profits π_{HF} of the representative utility company producing heat from fossil fuel are

$$\pi_{HF} = p_H H_F - C_{HF}\left(H_F\right) - C_{HA}\left(A_H\right) + s_{HA}A_H - \tau_H e_H, \tag{2.2}$$
$$\frac{dC_{HF}}{dH_F} > 0, \quad \frac{d^2C_{HF}}{\left(dH_F\right)^2} > 0, \qquad \frac{dC_{HA}}{dA_H} > 0, \quad \frac{d^2C_{HA}}{\left(dA_H\right)^2} > 0.$$

The variable p_H is the price of heat, C_{HF} is the total cost of producing fossil-based heat, C_{HA} is the total cost of abatement effort in fossil-based heat production, s_{HA} is a subsidy to abatement in district heating, and τ_H is a unit carbon tax on emissions from production of district heating. The marginal costs of production and abatement are assumed to be positive and increasing. The competitive utility company takes the market price of heat as given,[7] so the first-order conditions for maximization of its profits subject to the emissions function (2.1) are

$$\frac{dC_{HF}}{dH_F} + \tau_H \frac{\partial e_H}{\partial H_F} = p_H, \tag{2.3}$$

When the demand for fossil fuel falls as a result of a tightening of climate policy in some country, the price of fossil fuel goes down, inducing other countries to increase their emissions. However, the analysis in Hoel (2012, ch. 5) indicates that the "competitiveness channel" in focus here will typically be the dominant channel for leakage.

[6] In many countries district heating only plays a minor role, but in several European countries it constitutes a significant part of total energy use, especially in the Nordic and Baltic countries.

[7] In reality district heating companies are typically local natural monopolies, so our assumption of competitive behaviour is equivalent to a assuming an optimal regulatory regime which ensures production efficiency and marginal cost pricing.

$$MAC_H \equiv -\frac{dC_{HA}/dA_H}{\partial e_H/\partial A_H} = \tau_H - \frac{s_{HA}}{\partial e_H/\partial A_H}. \tag{2.4}$$

According to (2.3) the utility company will carry heat production to the point where the sum of the marginal production cost and the marginal emissions tax payment equals the market price of heat, and according to (2.4) it will take abatement effort to the point where the marginal abatement cost MAC_H equals the resulting gain from a lower emissions tax bill and a larger abatement subsidy.

District heating may also be produced from renewable energy which is assumed not to generate any CO_2 emissions.[8] The profits π_{HR} of the representative competitive renewables-based heat-producing utility company are

$$\pi_{HR} = (p_H + s_{HR}) H_R - C_{HR}(H_R), \qquad \frac{dC_{HR}}{dH_R} > 0, \quad \frac{d^2C_{HR}}{(dH_R)^2} > 0, \tag{2.5}$$

where H_R is the volume of renewables-based heat produced, C_{HR} is the total cost of production, and s_{HR} is a unit subsidy to renewables-based heat production. Profit maximization implies that the marginal cost of production equals the sum of the heat price and the subsidy rate:

$$\frac{dC_{HR}}{dH_R} = p_H + s_{HR}. \tag{2.6}$$

We now turn to the supply of electricity.[9] By analogy to (2.1), domestic production of fossil-based electricity (E_F) generates the CO_2 emissions

$$e_E = e_E(E_F, A_E), \qquad \frac{\partial e_E}{\partial E_F} > 0, \quad \frac{\partial e_E}{\partial A_E} < 0, \tag{2.7}$$

where A_E is the abatement effort undertaken by the representative utility company producing electricity from fossil fuel. The company's emissions are subject to a carbon tax τ_E, and its total costs of production and abatement effort are C_{EF} and C_{EA}. Abatement in the electricity sector may be granted a unit subsidy s_{EA}. With an international

[8] This assumption is warranted if the heat is produced by a heat pump driven by electricity generated by wind or solar energy. In practice much renewable heat production is based on burning wood-based biomass where the effects on total emissions depend crucially on forest management practices, as explained by Ter-Mikaelian et al. (2015). In principle, heat production based on biomass from areas where trees are not replanted should be included in the fossil-based production sector described by eqs. (2.1) and (2.2), since the burning of biomass releases carbon to the atmosphere.

[9] In practice electricity and heat may be produced as joint outputs in combined heat and power plants. However, this technology allows some variation of the ratio of the two outputs, so for simplicity we model the production of heat and electricity as separate processes.

electricity price p_E, the profits π_{EF} of the fossil-based electricity company are thus given by

$$\pi_{EF} = p_E E_F - C_{EF}(E_F) - C_{EA}(A_E) + s_{EA} A_E - \tau_E e_E, \tag{2.8}$$
$$\frac{dC_{EF}}{dE_F} > 0, \quad \frac{d^2 C_{EF}}{(dE_F)^2} > 0, \quad \frac{dC_{EA}}{dA_E} > 0, \quad \frac{d^2 C_{EA}}{(dA_E)^2} > 0,$$

and the first-order conditions for maximization of the company's profit are

$$\frac{dC_{EF}}{dE_F} + \tau_E \frac{\partial e_E}{\partial E_F} = p_E, \tag{2.9}$$

$$MAC_E \equiv -\frac{dC_{EA}/dA_E}{\partial e_E/\partial A_E} = \tau_E - \frac{s_{EA}}{\partial e_E/\partial A_E}, \tag{2.10}$$

with the same straightforward interpretation as the analogous conditions (2.3) and (2.4).

Electricity may also be produced from a renewable energy source, and the renewables-based electricity production E_R may be granted a unit subsidy s_{ER}, leaving the producer with a profit

$$\pi_{ER} = (p_E + s_{ER}) E_R - C_{ER}(E_R), \qquad \frac{dC_{ER}}{dE_R} > 0, \quad \frac{d^2 C_{ER}}{(dE_R)^2} > 0, \tag{2.11}$$

which is maximized when the marginal cost of production equals the sum of the electricity price and the subsidy rate:

$$\frac{dC_{ER}}{dE_R} = p_E + s_{ER}. \tag{2.12}$$

A third domestic source of CO_2 emissions is the domestic extraction of fossil fuels which may, for example, generate emissions via flaring associated with the drilling of oil and natural gas. These emissions e_F increase with the volume Q_F of fossil fuel extracted and decrease with the abatement effort A_F of the representative drilling company, so

$$e_F = e_F(Q_F, A_F), \qquad \frac{\partial e_F}{\partial Q_F} > 0, \quad \frac{\partial e_F}{\partial A_F} < 0. \tag{2.13}$$

The fossil fuel is sold at a world market price p_F, and the emissions from drilling are subject to the carbon tax τ_F. Emissions abatement in fossil fuel extraction may also be subsidized at the rate s_{FA}. Denoting the extraction company's total costs of extraction and abatement by C_{FQ} and C_{FA}, its net profit π_F is

$$\pi_F = p_F Q_F - C_{FQ}(Q_F) - C_{FA}(A_F) + s_{FA} A_F - \tau_F e_F, \tag{2.14}$$
$$\frac{dC_{FQ}}{dQ_F} > 0, \quad \frac{d^2 C_{FQ}}{(dQ_F)^2} > 0, \quad \frac{dC_{FA}}{dA_F} > 0, \quad \frac{d^2 C_{FA}}{(dA_F)^2} > 0.$$

The extraction company maximizes its profit (2.14) subject to (2.13), taking the fossil fuel price as given.[10] The first-order condition for maximization of profits imply that

$$\frac{dC_{FQ}}{dQ_F} + \tau_F \frac{\partial e_F}{\partial Q_F} = p_F, \tag{2.15}$$

$$MAC_F \equiv -\frac{dC_{FA}/dA_F}{\partial e_F/\partial A_F} = \tau_F - \frac{s_{FA}}{\partial e_F/\partial A_F}, \tag{2.16}$$

where MAC_F is the extraction company's marginal abatement cost.

As an alternative to fossil fuel, and as a supplement to the heat and electricity bought from utility companies, households and firms may use a renewable energy raw material like biomass, biofuel or biogas to produce energy services and transport services for themselves. We will refer to this renewable energy raw material as "biomass" and assume that it is traded internationally, selling at the price p_R in world markets. The dometic production of biomass is denoted by Q_R and may be granted a unit subsidy s_{RQ}. With a notation analogous to that used above, the profit π_R of the representative domestic biomass producer is

$$\pi_R = (p_R + s_{RQ}) Q_R - C_{RQ}(Q_R), \qquad \frac{dC_{RQ}}{dQ_R} > 0, \quad \frac{d^2 C_{RQ}}{(dQ_R)^2} > 0, \tag{2.17}$$

and the first-order condition for its maximization is

$$\frac{dC_{RQ}}{dQ_R} = p_R + s_{RQ}. \tag{2.18}$$

This completes the description of the supply side of the energy market.

2.2. Energy demand

The domestic demand for energy stems from the household sector and the non-energy business sector. The business sector is disaggregated into a tradable-goods sector which is exposed to carbon leakage via international trade, and a non-tradable goods sector with no exposure to leakage. Households and firms demand heat and electricity from utilities as well as fossil fuel and biomass from which they produce supplementary energy and

[10] By modelling fossil fuel extraction as a static problem of maximizing current profit, we implicitly assume that the reserve stock of fossil fuels is not a scarce resource to be exhausted over the firm's planning horizon in accordance with a Hotelling Rule. Instead we may assume that the costs of discovering and developing new reserves to replace the old ones are included in the cost function $C_{FQ}(Q_F)$.

transport services for themselves. Like before, the four energy goods heat, electricity, fossil fuel, and biomass are indicated by the subscripts H, E, F, and R, while the subscripts h, T, and N indicate the household sector, the tradable-goods sector, and the non-tradables sector, respectively.

Striking an optimal balance between energy savings and expansion of renewable energy supply is an important challenge for climate policy. To facilitate an analysis of this issue, we will specify the demands for the four energy goods in the model as "energy savings functions" indicating the energy savings undertaken by households and firms relative to a benchmark equilibrium with no government intervention in the energy market. Specifically, the saving of energy good i in sector j is given as

$$S_{ij} \equiv \overline{D}_{ij} - D_{ij}, \qquad i = H, E, F, R, \quad j = h, T, N, \tag{2.19}$$

where $\overline{D}_{ij}$ is the demand that would be forthcoming in the no-intervention equilibrium, and D_{ij} is the actual demand after the introduction of energy taxes and subsidies. Throughout the following, we will treat the $\overline{D}_{ij}$'s as exogenous constants.

Energy savings involve costs. Some of these costs take the form of expenditures on measures to increase energy efficiency. For households they also include the (money metric) utility loss from a cut in energy consumption, and for firms they include the loss of revenue from the cuts in output induced by a reduction of energy inputs. At the same time energy savings also imply lower expenses on the purchase of energy goods and lower expenditures on energy taxes. For example, the total net cost of energy savings in the representative firm in the tradable-goods sector (TC_{ST}) is

$$\begin{gathered} TC_{ST} = C_{ST}\left(S_{HT}, S_{ET}, S_{FT}, S_{RT}\right) \\ -\left[\left(p_H + t_{HT}\right) S_{HT} + \left(p_E + t_{ET}\right) S_{ET} + \left(p_F + t_{FT}\right) S_{FT} + \left(p_R + t_{RT}\right) S_{RT}\right] \qquad (2.20) \\ \frac{\partial C_{ST}}{\partial S_{HT}} > 0, \quad \frac{\partial^2 C_{ST}}{\left(\partial S_{HT}\right)^2} > 0, \qquad \frac{\partial C_{ST}}{\partial S_{ET}} > 0, \quad \frac{\partial^2 C_{ST}}{\left(\partial S_{ET}\right)^2} > 0, \\ \frac{\partial C_{ST}}{\partial S_{FT}} > 0, \quad \frac{\partial^2 C_{ST}}{\left(\partial S_{FT}\right)^2} > 0, \qquad \frac{\partial C_{ST}}{\partial S_{RT}} > 0, \quad \frac{\partial^2 C_{ST}}{\left(\partial S_{RT}\right)^2} > 0. \end{gathered}$$

The function $C_{ST}\left(S_{HT}, S_{ET}, S_{FT}, S_{RT}\right)$ captures the total gross cost of reducing the inputs of the four energy goods (loss of revenue plus expenses on improving energy efficiency). For each energy good the marginal cost of energy saving is positive and increasing. The policy instruments t_{HT}, t_{ET}, t_{FT}, and t_{RT} are tax rates on the use of the different energy inputs in the tradable-goods sector, so the term in the square bracket in (2.20) is the saving on expenses on the purchase of energy goods, including the reduction in energy tax payments. As part of its maximization of profits, the tradable-goods firm will minimize its total net cost of energy savings. The first-order conditions for the solution to this problem require that the marginal gross cost of energy saving be equal to the cut in the energy tax bill per unit of energy saved, i.e.,

$$\frac{\partial C_{ST}}{\partial S_{iT}} = p_i + t_{iT}, \qquad i = H, E, F, R. \tag{2.21}$$

Analogously, the total net costs of energy savings in the non-tradables sector and in the household sector are, respectively,

$$TC_{SN} = C_{SN}\left(S_{HN}, S_{EN}, S_{FN}, S_{RN}\right)$$

$$-\left[\left(p_H + t_{HN}\right) S_{HN} + \left(p_E + t_{EN}\right) S_{EN} + \left(p_F + t_{FN}\right) S_{FN} + \left(p_R + t_{RN}\right) S_{RN},\right] \tag{2.22}$$

$$TC_{Sh} = C_{Sh}\left(S_{Hh}, S_{Eh}, S_{Fh}, S_{Rh}\right)$$

$$-\left[\left(p_H + t_{Hh}\right) S_{Hh} + \left(p_E + t_{Eh}\right) S_{Eh} + \left(p_F + t_{Fh}\right) S_{Fh} + \left(p_R + t_{Rh}\right) S_{Rh}\right]. \tag{2.23}$$

Again we assume that the cost functions $C_{SN}(\cdot)$ and $C_{Sh}(\cdot)$ display positive and increasing marginal costs of energy savings for each energy good. Profit maximization in the non-tradables sector and utility maximization in the household sector require a minimization of the net costs of energy savings which in turn requires fulfilment of the first-order conditions

$$\frac{\partial C_{SN}}{\partial S_{iN}} = p_i + t_{iN}, \qquad i = H, E, F, R, \tag{2.24}$$

$$\frac{\partial C_{Sh}}{\partial S_{ih}} = p_i + t_{ih}, \qquad i = H, E, F, R. \tag{2.25}$$

The optimum conditions (2.21), (2.24), and (2.25) amount to 12 equations determining the 12 different values of S_{ij}. The absolute demand for the four energy goods in the three sectors may then be backed out from the definition of S_{ij} stated in (2.19).

2.3. Energy market equilibrium

Since heat is not traded internationally, the domestic price of heat p_H must adjust to ensure that total domestic production of heat equals the total domestic demand for it.

Since the demand for heat in sector j is $D_{Hj} \equiv \overline{D}_{Hj} - S_{Hj}$, domestic heat market equilibrium thus requires that

$$H_F + H_R + S_{HT} + S_{HN} + S_{Hh} = \overline{D}_H, \qquad \overline{D}_H \equiv \overline{D}_{HT} + \overline{D}_{HN} + \overline{D}_{Hh}, \tag{2.26}$$

where $\overline{D}_H$ is the total demand for heat in the pre-intervention equilibrium.

The three remaining energy goods are all traded internationally at prices exogenous to the small domestic economy. The net imports of electricity, fossil fuel, and biomass must therefore make up for any imbalance between domestic demand and domestic supply. Thus the net import of electricity is

$$M_E = \overbrace{\overline{D}_E - S_{ET} - S_{EN} - S_{Eh}}^{\substack{\text{Total domestic demand} \\ \text{for electricity}}} - \overbrace{(E_F + E_R)}^{\substack{\text{Domestic production} \\ \text{of electricity}}}, \quad \overline{D}_E \equiv \overline{D}_{ET} + \overline{D}_{EN} + \overline{D}_{Eh}. \tag{2.27}$$

The net imports of fossil fuel and biomass are given by similar bookkeeping identities which will not be stated here since we will not need them for the analysis below.

2.4. Carbon leakage and the target for climate policy

The domestic government wants to make a certain contribution to the reduction of global CO_2 emissions, accounting for carbon leakage. We focus on leakage of emissions from the domestic to the foreign economy via a shift from domestic to foreign production of electricity or via a shift from domestic to foreign production of other tradable goods. To achieve its target for emissions reduction the government must estimate the increase in foreign emissions occurring when domestic output of electricity and other tradable goods falls as a result of a tightening of domestic climate policy.

In the electricity sector a cut in domestic electricity production will lead to a corresponding increase in electricity imports since domestic demand for electricity is unchanged, given the exogenous international price of electricity. If the share of fossil-based electricity in the marginal supply of foreign electricity is α_{FE}^{f}, and if a unit of foreign fossil-based electricity production generates additional CO_2 emissions amounting to $\partial e_E^f / \partial E_F^f$, the increase in foreign emissions caused by a unit increase in electricity imports (α_E) will be

$$\alpha_E = \alpha^f_{FE}\frac{\partial e^f_E}{\partial E^f_E}, \qquad 0 \leq \alpha^f_E \leq 1. \tag{2.28}$$

In the sector for other tradable goods leakage occurs when a tightening of domestic climate policy induces a fall in the input of energy goods which causes a fall in domestic output, leaving room for an increase in foreign output and a concomitant increase in foreign emissions to satisfy the world demand for tradables. In practice, the high-temperature heat used for production purposes in some energy-intensive industries is not provided by district heating companies. Instead, the heat needed for industrial processes is typically produced in-house by burning some type of (mostly fossil) fuel. We will therefore assume that a saving of energy from lower consumption of district heating in the tradable-goods sector does not have a significant cost-increasing effect that could cause carbon leakage. However, we allow for the possibility that a reduction in the use of electricity, fossil fuel or biomass may generate carbon leakage by lowering the productivity of energy-intensive industrial processes exposed to foreign competition. Specifically, an increase in the energy saving S_{iT} (where the energy good i could be electricity, fossil fuel or biomass) implies a corresponding cut in the input of energy good i in domestic tradable goods production, so the increase α^f_{iT} in the emissions from foreign tradable-goods production per unit of domestic energy saving is

$$\alpha^f_{iT} \equiv \frac{de^f_T}{dS_{iT}} = \frac{de^f_T}{dy^f_T}\frac{dy^f_T}{dy_T}\frac{dy_T}{dS_{iT}} = \frac{dy^f_T}{dy_T}\frac{dy_T}{dS_{iT}}\overbrace{\left(b^f_F + \alpha^f_H b^f_H + \alpha^f_E b^f_E\right)}^{= de^f_T/dy^f_T}, \quad i = E, F, R, \tag{2.29}$$

where de^f_T is the absolute increase in foreign emissions, dy_T and dy^f_T are the changes in domestic and foreign production of tradable goods, b^f_F, b^f_H, and b^f_E are marginal input-output coefficients indicating the increases in the inputs of fossil fuel, heat and electricity per unit increase in foreign tradable-goods production, and α^f_H and α^f_E are the additional CO_2 emissions per unit increase in foreign production of heat and electricity. Since the increase in emissions per unit increase in fossil fuel input has been normalized at unity, the emission coefficient on the input-output coefficient b^f_F is 1. The fraction dy_T/dS_{iT} in (2.29) is the negative of the marginal product MP_{iT} of energy input i in domestic tradable-goods production. In the benchmark case of perfect competition the marginal product of input i will equal the real product price of that input, i.e., $MP_{iT} = p_i/p_T$, so $dy_T/dS_{iT} = -MP_{iT} = -p_i/p_T$, where p_i is the price of input i, and p_T is the world market price of the traded good. The price ratio p_i/p_T is directly observable. Moreover, under perfect competition domestic production will be fully crowded out by foreign production, implying that $dy_T^f/dy_T \to -1$. Estimating the leakage coefficient α_{iT}^f then boils down to estimating the input-output coefficients and the emission coefficients in the term $\left(b_F^f + \alpha_H^f b_H^f + \alpha_E^f b_E^f\right)$ in (2.29).

To get a feeling for the likely order of magnitude of the leakage coefficients α_E and α_{iT}^f, we may consider a stylized example where the output of the foreign tradable-goods sector is given by a Cobb-Douglas function of the form

$$y_T^f = \left(F_T^f\right)^\beta \left(E_T^f\right)^\eta \left(H_T^f\right)^\theta \left(X_T^f\right)^{1-\beta-\eta-\theta}, \qquad 0 < \beta, \eta, \theta < 1, \quad \beta + \eta + \theta < 1. \quad (2.30)$$

The variables F_T^f, E_T^f, and H_T^f are the inputs of fossil fuel, electricity and district heating (for warming up buildings), and X_T^f is a composite of other inputs. Further, let us assume that the production function for foreign fossil-based electricity (E^f) is

$$E^f = \left(F_E^f\right)^\omega \left(Z_E^f\right)^{1-\omega}, \qquad 0 < \omega < 1, \quad (2.31)$$

and that foreign output of fossil-based district heating (H^f) is given by the production function

$$H^f = \left(F_H^f\right)^\gamma \left(K_H^f\right)^{1-\gamma}, \qquad 0 < \gamma < 1, \quad (2.32)$$

where F_E^f and F_H^f are the inputs of fossil fuel in foreign electricity and heat production, and Z_E^f and K_H^f are composites of other inputs. Finally, let us assume that the foreign economy's emissions e_T^f, e_E^f, and e_H^f from the production of tradable goods, electricity and heat are given by the quasi-linear functions

$$e_T^f = F_T^f - a_T\left(A_T^f\right), \qquad e_E^f = F_E^f - a_E\left(A_E^f\right), \qquad e_H^f = F_H^f - a_H\left(A_H^f\right), \quad (2.33)$$

where A_T^f, A_E^f, A_E^f are foreign abatement efforts in the three sectors. With these assumptions Appendix 2 shows that profit maximization under perfect competition implies the following expressions for the leakage coefficients specified in (2.28) and (2.29), where α_{FH}^f and α_{FE}^f are the shares of fossil-based production in total foreign production of heat and electricity, t_{HT}^f, t_{ET}^f, and τ_T^f are the tax rates on the use of heat, electricity and fossil fuel in the foreign tradable-goods sector, and τ_H^f and τ_E^f are the foreign carbon tax rates on emissions from the production of heat and electricity (all tax rates are measured as fractions of the producer prices of the taxed energy goods):

$$\alpha_E = \frac{\alpha_{FE}^f \omega}{1+\tau_E^f} < 1, \tag{2.34}$$

$$\alpha_{iT}^f = (1+t_{iT}) \left(\frac{\beta}{1+\tau_T^f} + \frac{\alpha_{FH}^f \gamma \theta}{\left(1+t_{HT}^f\right)\left(1+\tau_H^f\right)} + \frac{\alpha_{FE}^f \omega \eta}{\left(1+t_{ET}^f\right)\left(1+\tau_E^f\right)} \right), \tag{2.35}$$

$$0 \leq \alpha_{FH}^f, \alpha_{FE}^f \leq 1, \quad i = E, F, R.$$

Since the parameters β, γ, θ, ω, and η are all smaller than one, the leakage coefficients in (2.35) will almost certainly be lower than one unless the domestic energy tax rates t_{iT} are much higher than the foreign tax rates. The attractiveness of the formulas (2.34) and (2.35) is that the parameters β, η, and θ are the cost shares of fossil fuel, electricity and heat in the value of output of tradable goods, and γ and ω are the cost shares of fossil fuels in the value of output of heat and electricity. These cost shares may be estimated from national income accounts once the relevant production sector exposed to foreign competition has been identified, and the shares α_{FH}^f and α_{FE}^f of fossil-based energy production may be estimated from the energy statistics collected by most national statistical agencies.

Consider next the effect on foreign emissions of a change in domestic *consumption* of tradable goods. Suppose the consumption of such goods is $\overline{D}_T$ in the pre-intervention equilibrium and D_T in the post-intervention equilibrium. The fall in domestic consumption of tradables induced by government intervention is then $S_T \equiv \overline{D}_T - D_T$. As a first approximation this fall in consumption will cause a corresponding fall in the net import of tradables, since the domestic consumption tax will not influence the international price of tradables, thus leaving domestic production of tradables unaffected (we abstact from possible general equlibrium effects on domestic input prices). The fall in foreign exports to the domestic economy and the concomitant fall in foreign output will reduce the emissions from the foreign tradable goods sector by the amount $\alpha_T^f S_T$ where

$$\alpha_T^f \equiv -\frac{de_T^f}{dS_T} = -\frac{de_T^f}{dy_T^f} \overbrace{\frac{dy_T^f}{dS_T}}^{=-1} = \overbrace{\left(b_F^f + \alpha_H^f b_H^f + \alpha_E^f b_E^f\right)}^{= de_T^f/dy_T^f}. \tag{2.36}$$

For the purpose of determining S_T we may write the private net welfare cost TC_T of reducing the consumption of tradables by the amount S_T as

$$TC_T = C_T(S_T) - (p_T + t_T) S_T, \qquad \frac{dC_T}{dS_T} > 0, \quad \frac{d^2 C_T}{(dS_T)^2} > 0, \tag{2.37}$$

where t_T is a unit tax on consumption of tradables, and $C_T(S_T)$ is the money-metric utility loss measured by the area under the demand curve in the consumption interval $S_T \equiv \overline{D}_T - D_T$. A utility-maximizing consumer will want to minimize the net welfare cost (2.37) of reducing the consumption of tradables, so S_T may be found from the first-order condition

$$\frac{dC_T(S_T)}{dS_T} = p_T + t_T. \tag{2.38}$$

Note that while (2.37) represents the private cost of reducing consumption of tradables by S_T, the social cost of concern to policy makers is given by $C_T(S_T) - p_T S_T$ since the consumption tax is just a transfer from the private to the public sector.

The total net carbon leakage L_c from the domestic to the foreign economy occurring via international trade may now be expressed as

$$L_c = \alpha_E M_E + \alpha^f_{ET} S_{ET} + \alpha^f_{FT} S_{FT} + \alpha^f_{RT} S_{RT} - \alpha^f_T S_T. \tag{2.39}$$

The government aims to reduce global emissions by the exogenous amount Δ, accounting for the carbon leakage induced by climate policy. In a pre-intervention equilibrium without energy taxes and subsidies, the total emissions from the domestic economy would be $\overline{e}$. Recalling our normalization that one unit of fossil fuel use generates one unit of emissions, the target for climate policy may therefore be specified as

$$\overline{e} - \overbrace{(e_H + e_E + e_F)}^{\substack{\text{Emissions from} \\ \text{production of heat,} \\ \text{electricity and fossil fuel}}} - \overbrace{\left(\overline{D}_F - S_{FT} - S_{FN} - S_{Fh}\right)}^{\substack{\text{Emissions from fossil} \\ \text{fuel use in households} \\ \text{and non-energy firms}}} - L_c = \Delta. \tag{2.40}$$

We will now analyze how the policy goal (2.40) may be achieved in an optimal way.

3. Optimal resource allocation in the energy market

An optimal allocation of resources requires a minimization of the sum of the social costs of satisfying the domestic demand for energy and reducing the consumption of tradables, subject to the constraint that the climate policy target (2.40) must be met. The social cost of satisfying energy demand is the sum of the costs of domestic production of heat, electricity, fossil fuel and biomass plus the costs of emissions abatement and energy savings and the expenses on the net imports needed to meet the demand for electricity, fossil fuel, and biomass in the household sector and the non-energy business sectors.[11] In formal terms, the total social cost SC of providing energy to households and non-energy firms and reducing the consumption of tradables for the purpose of reducing foreign emissions is

$$
\begin{aligned}
SC = & \overbrace{C_{HF}(H_F) + C_{HA}(A_H) + C_{HR}(H_R)}^{\text{Production and abatement costs in heat production}} \\
& + \overbrace{C_{EF}(E_F) + C_{EA}(A_E) + C_{ER}(E_R)}^{\text{Production and abatement costs in electricity production}} \\
& + \overbrace{C_{FQ}(Q_F) + C_{FA}(A_F)}^{\text{Production and abatement costs in fossil fuel extraction}} + \overbrace{C_{RQ}(Q_R)}^{\text{Cost of biomass production}} \\
& + \overbrace{C_{ST}(S_{HT}, S_{ET}, S_{FT}, S_{RT})}^{\text{Cost of energy savings in tradable-goods sector}} + \overbrace{C_{SN}(S_{HN}, S_{EN}, S_{FN}, S_{RN})}^{\text{Cost of energy savings in non-tradables sector}} \\
& + \overbrace{C_{Sh}(S_{Hh}, S_{Eh}, S_{Fh}, S_{Rh})}^{\text{Cost of energy savings in household sector}} + \overbrace{C_T(S_T) - p_T S_T}^{\text{Cost of reduced consumption of tradables}} \\
& + \overbrace{p_E\left(\overline{D}_E - E_F - E_R - S_{Eh} - S_{ET} - S_{EN}\right)}^{\text{Cost of net imports of electricity to households and non-energy firms}} \\
& + \overbrace{p_F\left(\overline{D}_F - Q_F - S_{Fh} - S_{FT} - S_{FN}\right)}^{\text{Cost of net imports of fossil fuel to households and non-energy firms}} \\
& + \overbrace{p_R\left(\overline{D}_R - Q_R - S_{Rh} - S_{RT} - S_{RN}\right)}^{\text{Cost of net imports of biomass to households and non-energy firms}} \quad , \qquad (3.1)
\end{aligned}
$$

[11] We abstract here from non-climate externalities from energy production and consumption. It would be straightforward to add the relevant external cost functions to the social cost function (3.1). Internalizing these additional externalities would then call for additional Pigouvian taxes as a supplement to the carbon and energy taxes derived below.

$$\overline{D}_F \equiv \overline{D}_{FT} + \overline{D}_{FN} + \overline{D}_{Fh}, \qquad \overline{D}_R \equiv \overline{D}_{RT} + \overline{D}_{RN} + \overline{D}_{Rh},$$

where $\overline{D}_F$ and $\overline{D}_R$ are the total demands for fossil fuel and biomass in the household and non-energy business sectors in the pre-intervention equilibrium. Note that the net import terms in the last three lines of (3.1) do not include the costs of imported fossil fuels and biomass to the domestic utility companies since these costs are already included in the cost functions $C_{HF}(H_F)$, $C_{HR}(H_R)$, $C_{EF}(E_F)$, and $C_{ER}(E_R)$.

A benevolent government will wish to minimize the total social cost (3.1) subject to the constraint (2.26) that domestic heat production must equal domestic demand for heat and subject to the climate policy constraint (2.40) as well as the carbon leakage mechanism (2.39) and the electricity import function (2.27). The first-order conditions for the solution to this policy problem are derived in Appendix 1. From these conditions it follows that an optimal resource allocation in the energy sector must satisfy the following intuitive relationships, where μ is the shadow price of district heating (the Lagrange multiplier associated with the constraint (2.26)), and λ is the shadow price of CO_2 emissions (the Lagrange multiplier associated with the climate policy target (2.40)):

Optimal provision of heat:

$$\overbrace{\frac{dC_{HF}}{dH_F} + \lambda \frac{\partial e_H}{\partial H_F}}^{\substack{\text{Marginal social cost of} \\ \text{fossil-based heat production}}} = \frac{dC_{HR}}{dH_R} = \frac{\partial C_{ST}}{\partial S_{HT}} = \frac{\partial C_{SN}}{\partial S_{HN}} = \frac{\partial C_{Sh}}{\partial S_{Hh}} = \mu, \tag{3.2}$$

Optimal provision of electricity:

$$\overbrace{\frac{dC_{EF}}{dE_F} + \lambda \left(\frac{\partial e_E}{\partial E_F} - \alpha_E \right)}^{\substack{\text{Marginal social cost} \\ \text{of fossil-based} \\ \text{electricity production}}} = \overbrace{\frac{dC_{ER}}{dE_R} - \alpha_E \lambda}^{\substack{\text{Marginal social cost} \\ \text{of renewables-based} \\ \text{electricity production}}} = \overbrace{\frac{\partial C_{ST}}{\partial S_{ET}} + \lambda \left(\alpha_{ET}^f - \alpha_E \right)}^{\substack{\text{Marginal social cost} \\ \text{of electricity savings} \\ \text{in tradable-goods sector}}}$$

$$= \overbrace{\frac{\partial C_{SN}}{\partial S_{EN}} - \alpha_E \lambda}^{\substack{\text{Marginal social cost}\\ \text{of electricity savings}\\ \text{in non-tradables sector}}} = \overbrace{\frac{\partial C_{Sh}}{\partial S_{Eh}} - \alpha_E \lambda}^{\substack{\text{Marginal social cost}\\ \text{of electricity savings}\\ \text{in household sector}}} = p_E, \tag{3.3}$$

Optimal provision of fossil fuel:

$$\overbrace{\frac{dC_{QF}}{dQ_F} + \lambda \frac{\partial e_F}{\partial Q_F}}^{\substack{\text{Marginal social cost}\\ \text{of fossil}\\ \text{fuel production}}} = \overbrace{\frac{\partial C_{ST}}{\partial S_{FT}} - \left(1 - \alpha^f_{FT}\right)\lambda}^{\substack{\text{Marginal social cost}\\ \text{of fossil fuel savings}\\ \text{in tradable-goods sector}}}$$

$$= \overbrace{\frac{\partial C_{SN}}{\partial S_{FN}} - \lambda}^{\substack{\text{Marginal social cost}\\ \text{of fossil fuel savings}\\ \text{in non-tradables sector}}} = \overbrace{\frac{\partial C_{Sh}}{\partial S_{Fh}} - \lambda}^{\substack{\text{Marginal social cost}\\ \text{of fossil fuel saving}\\ \text{in household sector}}} = p_F, \tag{3.4}$$

Optimal provision of biomass:

$$\frac{dC_{RQ}}{dQ_R} = \overbrace{\frac{\partial C_{ST}}{\partial S_{RT}} + \alpha^f_{RT}\lambda}^{\substack{\text{Marginal social cost}\\ \text{of biomass savings}\\ \text{in tradable-goods sector}}} = \frac{dC_{SN}}{dS_{RN}} = \frac{dC_{Sh}}{dS_{Rh}} = p_R, \tag{3.5}$$

Optimal emissions abatement:

$$\overbrace{-\frac{dC_{HA}/dA_H}{\partial e_H/\partial A_H} = -\frac{dC_{EA}/dA_E}{\partial e_E/\partial A_E} = -\frac{dC_{FA}/dA_F}{\partial e_F/\partial A_F}}^{\text{Marginal abatement costs}} = \lambda. \tag{3.6}$$

Optimal reduction of consumption of tradables:

$$\frac{dC_T}{dS_T} = \overbrace{p_T + \alpha^f_T \lambda}^{\substack{\text{Marginal social gain from}\\ \text{reduced consumption of tradables}}} . \tag{3.7}$$

The optimum conditions (3.2) through (3.5) state that the marginal social costs of energy production should equal the marginal social cost of energy savings which in turn should equal the marginal benefits from energy savings. The marginal benefit from heat savings stated on the right-hand side of (3.2) equals the shadow price of heat (μ). For the other types of energy, the marginal benefits of energy savings are given by the relevant world market energy prices. The optimum condition (3.6) requires that the marginal costs of abating CO_2 emissions be equalized across the emitting sectors at a level equal to the shadow price of emissions (λ), and (3.7) states that the marginal utility loss from reduced consumption of tradables must equal the marginal gain given by the lower social cost of imports (p_T) plus the gain $\alpha_T^f \lambda$ from reduced emissions abroad.

The marginal costs of energy production and energy savings include the (shadow) costs and benefits of changes in domestic emissions plus any changes in foreign emissions occuring through carbon leakage. For example, when domestic fossil-based electricity production goes up by one unit, domestic emissions increase by the amount $\partial e_E / \partial E_F$, generating a social cost of $\lambda (\partial e_E / \partial E_F)$. At the same time the unit rise in domestic electricity production induces a corresponding fall in electricity imports (since the electricity price and hence domestic electricity demand is unchanged) which reduces the emissions from foreign power production by the amount α_E, creating a social benefit $\lambda \alpha_E$. Hence the net marginal social cost of domestic electricity production is $\frac{dC_{EF}}{dE_F} + \lambda \left(\frac{\partial e_E}{\partial E_F} - \alpha_E \right)$, as stated in the first term on the left side of (3.3).

As another example, when the domestic tradable-goods sector saves an extra unit of electricity, the resulting shift from domestic to foreign production of tradable goods increases foreign emissions by the amount α_{ET}^f, thus adding an amount $\lambda \alpha_{ET}^f$ to the marginal social cost of electricity saving in the domestic tradable-goods sector. On the other hand the domestic electricity saving reduces electricity imports by a corresponding amount, thereby generating a social benefit $\lambda \alpha_E$ from lower emissions from foreign electricity producers. The net marginal social cost of electricity savings in the domestic tradable-goods sector is therefore equal to $\frac{\partial C_{ST}}{\partial S_{ET}} + \lambda \left(\alpha_{ET}^f - \alpha_E \right)$, as indicated in the third term on the left side of (3.3). In a similar way, when the tradable-goods sector saves an extra unit of fossil fuel input, thus reducing domestic emissions by one unit, the benefit to society is λ, but the resulting leakage α_{FT}^f of emissions to other countries creates a social cost of $\lambda\alpha^{f}_{FT}$, so the net marginal social cost of fossil fuel savings in the tradables-sector is $\frac{\partial C_{ST}}{\partial S_{FT}} - \left(1 - \alpha^{f}_{FT}\right)\lambda$.

4. Optimal energy taxes and subsidies

By comparing the equations describing energy market behaviour in section 2 to the conditions for optimal energy provision in section 3, we may now derive the energy tax-subsidy scheme that will implement the optimal allocation of resources in the energy market. To facilitate the interpretation of the tax rules stated below, it may be useful to remind the reader of the base for the various taxes and subsidies.

The taxes τ_F, τ_H, and τ_E are 'genuine' emissions taxes levied on emissions from domestic extraction of fossil fuels and from domestic production of district heating and electricity. If companies use end-of-pipe technologies such as Carbon Capture and Storage, the tax base will thus be de-coupled from the burning of fossil fuels. In practice emissions will typically be proportional to the use of fossil fuel inputs, allowing the carbon taxes to be administered as taxes on fuel inputs, differentiated according to their estimated carbon content. For simplicity our model aggregates all fossil fuels into one composite fuel input which generates one unit of CO_2 emissions when burned.

The tax rates t_{FN}, t_{Fh}, and t_{FT} in the equations below are also taxes on fossil fuel inputs, and given the assumed one-to-one relationship between fossil fuel use and emissions these taxes should likewise be interpreted as carbon taxes.

The electricity tax rates t_{ET}, t_{EN} and t_{Eh} on electricity use in the domestic economy are levied on the amount of electricity consumed, measured in, say, kiloWatt hours. Hence they may be seen as conventional energy taxes, but since these tax rates are systematically related to the estimated amount of carbon emitted at the margin of electricity production, they may also be seen as carbon taxes. The tax t_T on consumption of tradable goods is likewise a kind of carbon tax since it is differentiated according to the estimated amount of carbon emitted in the process of producing an extra unit of the taxed good.

By contrast, the taxes on heat consumption t_{HT}, t_{HN}, t_{Hh}, and the taxes on biofuel use t_{RT}, t_{RN}, t_{Rh} are not related to CO_2 emissions and may thus be interpreted as specific taxes on energy consumption or energy inputs.

The interpretation of the subsidies s_{ER}, s_{HR}, s_{RQ} is straightforward since they are all granted per unit of output produced, and the abatement subsidies s_{HA}, s_{FA}, s_{EA} are granted per unit of CO_2 emission abated. In the absence of end-of-pipe abatement, these subsidies may be obtained by investing in more energy-efficient technologies.

As a further preliminary, note that in a competitive market equilibrium satisfying the social optimum conditions stated in the previous section, the market price of heat will equal the shadow price μ appearing on the right-hand side of (3.2), in which case we may set $p_H = \mu$. Using this result plus the results in section 2 and 3, we find that the following tax-subsidy scheme will minimize the social cost of energy provision while satisfying the target for reduction of CO_2 emissions:

Taxes on domestic energy production:

$$\tau_F = \tau_H = \lambda \tag{4.1}$$

$$\tau_E = \lambda \left(1 - \alpha_E^f \varepsilon_E\right), \qquad \varepsilon_E \equiv \frac{\partial e_E^f / \partial E_F^f}{\partial e_E / \partial E_F} \tag{4.2}$$

Taxes on domestic energy consumption:

$$t_{FN} = t_{Fh} = \lambda \tag{4.3}$$

$$t_{FT} = \lambda \left(1 - \alpha_{FT}^f\right) \tag{4.4}$$

$$t_{EN} = t_{Eh} = \alpha_E \lambda, \qquad \alpha_E = \alpha_E^f \frac{\partial e_E^f}{\partial E_E^f} \tag{4.5}$$

$$t_{ET} = \lambda \left(\alpha_E - \alpha_{ET}^f\right) \tag{4.6}$$

$$t_{HT} = t_{HN} = t_{Hh} = t_{RN} = t_{Rh} = 0 \tag{4.7}$$

Tax on consumption of tradable goods:

$$t_T = \alpha_T^f \lambda \tag{4.8}$$

Subsidies to production and consumption of renewable energy:

$$s_{ER} = \alpha_E \lambda \tag{4.9}$$

$$s_{HR} = s_{RQ} = 0 \tag{4.10}$$

$$t_{RT} = -\alpha_{RT}^f \lambda \tag{4.11}$$

Subsidies to emissions abatement:

$$s_{HA} = s_{FA} = 0 \tag{4.12}$$

$$s_{EA} = -\frac{\partial e_E}{\partial A_E}(\lambda - \tau_E) = -\frac{\partial e_E}{\partial A_E}\lambda \alpha_E^f \varepsilon_E \tag{4.13}$$

Eq. (4.1) says that the tax rate on emissions from fossil fuel extraction and from fossil-based heat production should equal the marginal social cost of emissions, defined here as the marginal cost of attaining the government's target for climate policy (λ). We will term this the standard rate of carbon tax. According to (4.2) the carbon tax on domestic emissions from fossil-based electricity production should only be a fraction $1 - \alpha_E^f \varepsilon_E$ of the standard rate, because a unit increase in domestic emissions caused by higher domestic power production generates a fall of $\alpha_E^f \varepsilon_E$ in foreign emissions, since higher domestic electricity output crowds out a similar amount of electricity imports. Hence the optimal carbon tax rate on power production is $\lambda \left(1 - \alpha_E^f \varepsilon_E\right)$, corresponding to the social cost of the net increase in global emissions associated with a unit rise in the emissions from domestic power production. In the benchmark situation where domestic and foreign electricity production is equally fossil-intensive at the margin, the parameter ε_E is equal to one. In that case the reduction of the carbon tax on domestic electricity production relative to the standard rate will equal the share of fossil-based electricity production in total foreign electricity production (α_E^f).

From (4.3) we see that fossil fuels used by domestic households and domestic firms in the non-tradable goods sector should be taxed at the standard carbon tax rate, since fossil fuels burned in these sectors will contribute one-to-one to global emissions (given our normalization that one unit of fossil fuel use generates one unit of CO_2 emissions). However, in the tradable-goods sector a unit increase in domestic fossil fuel use only increases global emissions by the amount $1 - \alpha_{FT}^f$ as the rise in domestic output made possible by the larger input of fuel crowds out foreign output of tradables, resulting in "negative carbon leakage". Hence fossil fuel used in this sector should only be taxed at the rate $\lambda \left(1 - \alpha_{FT}^f\right)$, as stated in (4.4).

The tax rule (4.5) reflects that a unit increase in domestic electricity consumption causes a corresponding increase in imported electricity, since the international price of electricity and hence domestic production is unchanged in a small open economy. The rise in imports increases emissions abroad by the amount α_E as foreign electricity production goes up. Households and firms in the non-tradables sector should therefore pay an electricity tax equal to the social cost of the rise in global emissions caused by the marginal unit of electricity consumed, i.e., a tax amounting to $\alpha_E \lambda$. The motivation for the consumption tax (4.8) on tradable goods is similar: A unit increase in the consumption of such goods raises the import of tradables by one unit, and the concomitant unit rise in foreign output drives up foreign emissions by the amount α_T^f. To internalize the resulting marginal social cost, a carbon tax rate $\alpha_T^f \lambda$ on tradables is needed.

An increase in electricity use in the domestic tradable-goods sector likewise increases the emissions from imported electricity by the amount α_E. However, it also allows an increase in domestic output at the expense of foreign output of tradables, thereby reducing foreign emissions by α_{ET}^f units. Hence the use of electricity in the tradable-goods sector should only be taxed at the rate $\lambda \left(\alpha_E - \alpha_{ET}^f \right)$, as reported in (4.6). To put it another way, taxing electricity use in the tradable-goods sector causes carbon leakage and thus calls for a lower rate of tax than the electricity tax on the sheltered sectors. Whether the tax rate on electricity use in the tradable-goods sector should be positive or negative will depend on the details of the technology for electricity production and the importance of fossil fuels in the production process. In the Cobb-Douglas example underlying the formulas (2.34) and (2.35), we get the following expression for t_{ET} in the benchmark case where foreign and domestic electricity use in the tradables sector is taxed at the same rate ($t_{ET}^f = t_{ET}$):

$$t_{ET} = \lambda \left\{ \frac{\alpha_{FE}^f \omega (1 - \eta)}{1 + \tau_E^f} - (1 + t_{ET}) \left[\frac{\beta}{1 + \tau_T^f} + \frac{\alpha_{FH}^f \gamma \theta}{\left(1 + t_{HT}^f\right)\left(1 + \tau_H^f\right)} \right] \right\}. \tag{4.14}$$

In practice the cost share of district heating in tradable-goods production will typically be quite small, so the parameter θ will be close to zero. According to (4.14) the tax rate on electricity use by domestic tradable-goods firms should then be positive if the cost share of fossil fuel input in foreign competing firms (β) is relatively low and the fossil fuel intensity of foreign electricity production (captured by the product $\alpha_{FE}^f \omega$) is relatively high. This is intuitive: When the fossil fuel intensity of foreign power production is high, an increase in domestic electricity imports will generate a noticeable increase in foreign emissions. This calls for a positive tax rate on domestic electricity use to curb electricity imports. Moreover, if the fossil fuel intensity of foreign tradable-goods production (β) is relatively low, the shift from domestic to foreign production of tradables induced by the domestic electricity tax will not boost foreign emissions very much which increases the likelihood that a positive tax rate is in fact optimal.

Since the external cost of emissions from domestic heat production is fully internalized by the carbon tax on those emissions and there is no (significant) leakage associated with the use of district heating in the non-energy sector, the use of this input should not be taxed or subsidized, as stated in (4.7).

The rationale for the subsidy rule (4.9) is that a unit increase in domestic renewables-based power production crowds out a similar amount of foreign-produced electricity, thereby reducing global emissions by the amount α_E as the domestic net import of electricity falls by one unit. The resulting external social benefit is $\lambda\alpha_E$ which is internalized when producers of renewables-based electricity receive a corresponding subsidy per unit of power produced. Note that this subsidy equals the electricity tax on households and firms in the non-tradables sector, ensuring that the net tax on renewables-based electricity used in the sheltered sectors is zero.

Production of biomass and renewables-based heat does not generate any emissions or carbon leakage, so according to (4.10) there is no need for taxing or subsidizing these energy goods. However, a unit increase in the use of bioenergy in the tradable-goods sector will reduce foreign emissions by the amount α_{RT}^f as the resulting rise in domestic output crowds out foreign output. To internalize this externality, a subsidy $\lambda\alpha_{RT}^f$ to the input of bioenergy in domestic production of tradable goods is needed, as stated in (4.11).

The result in (4.12) reflects that the standard carbon tax λ on domestic production of heat and fossil fuel provides an appropriate incentive to abate emissions, so no subsidy to abatement is needed in these sectors. In the power sector the carbon tax is reduced by the amount $\lambda - \tau_E$ relative to the standard rate to account for carbon leakage. Hence there is a weaker incentive for abatement in this sector. To ensure an equalization of marginal abatement costs across all emitting sectors the government must therefore offer an abatement subsidy to electricity companies which is proportional to the reduction in the carbon tax rate, as seen from (4.13).

5. Caveats

5.1. An EU perspective: Emissions trading and national energy taxes

Economists have long pointed out that the international costs of cutting global greenhouse gas emissions may be reduced by allowing international trade in emission rights. The Emissions Trading System (ETS) in the European Union is so far the most important attempt to reap the gains from trade in CO_2 emission allowances, accounting for over three quarters of international carbon trading. The ETS covers the energy sector and energy-intensive industrial emitters, representing about 45 percent of total greenhouse gas emissions in the EU (see European Commission (2017)).

An international emissions trading system where the total supply of emission allowances acts as a binding cap on total emissions from utility companies and energy-intensive firms means that national policy makers concerned about their country's contribution to global emissions do not have to worry about emissions from these sectors since total emissions are fixed by the cap. In terms of our model, the government may then ignore the emissions from the production of fossil fuels and fossil-based heat and electricity (our variables e_F, e_H and e_E) as well as emissions from energy-intensive production of tradable goods and carbon leakage from such production. For firms covered by the cap-and-trade system the cost of emission allowances will be included in our fossil fuel price variable p_F, and there is no rationale for an additional domestic carbon tax on firms within the system since this would only distort their input mix without affecting global emissions. Similarly there is no need for a tax on the domestic use of electricity nor for a subsidy to domestic renewables-based power production when electricity production is included in the emissions trading system. The national government should then focus on reducing emissions from emitters outside the cap-and-trade system, and assuming that (roughly) all energy-intensive industrial firms vulnerable to carbon leakage are covered by the system, this can be done in a cost-effective way by imposing a uniform carbon tax on all emissions outside the system, with no need for differentiation of carbon tax rates, selective subsidies or taxes on energy consumption.

However, in reality the total supply of emission allowances in the European ETS is not a binding cap on current emissions from the ETS sector. At the time of writing there is an excess allowance supply amounting to almost one year of current emissions. Since ETS emission allowances can be "banked" for later use, the current positive price of allowances reflects a bet by market participants that the emissions cap could become binding at some point in the future, but given the prospects for the future demand for and supply of allowances under the policy planned for the coming Phase IV of the ETS, it may well take three decades or even longer before the excess supply is eliminated, according to the quantitative analysis in Silbye and Sørensen (2017). As a consequence, if the demand for ETS allowances in some EU member country falls as a result of a cut in emissions, it will take a long time before that decrease in emissions is fully offset by a corresponding rise in emissions from other EU countries. In the short and medium term there will be some offset as the lower demand for emission allowances will drive down the allowance price, thereby reducing the cost of emissions, but the full offset will not occur until the time when the excess allowance supply has been fully eliminated. If policy makers value a cut in current emissions higher than a corresponding cut in future emissions, say, because they fear that a target for keeping global warming below a certain threshold may be compromised if emissions cuts are postponed, the "offset coefficient" implied by the ETS will be lower than one. The offset coefficient (c) is defined here as

$$c \equiv \frac{\text{Present value of offsetting increase in foreign ETS emissions}}{\text{Cut in domestic ETS emissions}} \tag{5.1}$$

We may also define the "Coefficient of Emissions Reduction" as

$$CER \equiv 1 - c = \frac{\text{Present value of total cut in ETS emissions}}{\text{Cut in domestic ETS emissions}} \tag{5.2}$$

The CER indicates the fraction of a cut in domestic emissions from the ETS sector that will translate into a fall in global emissions, measured in present-value terms. When the discount rate applied in the valuation of future relative to present changes in emissions is positive and the cap on emissions does not become binding until some time in the future, the offset coefficient will be less than one and the Coefficient of Emissions Reduction will be positive. The estimates presented in Silbye and Sørensen (2017) suggest that, for plausible discount rates and policy horizons, the CER in the EU ETS is currently not far below 1, indicating that the offset coefficient is not far above zero.

Accounting for the offset coefficient, and assuming that the energy-intensive firms vulnerable to carbon leakage are included in the ETS, the model set up in section 2 may be modified in a simple way for a country participating in the EU ETS. For such a country the emission functions $e_H(\cdot)$, $e_E(\cdot)$, $e_F(\cdot)$ and the carbon leakage coefficients α_E, α_{ET}^f, α_{FT}^f, and α_{RT}^f should be multiplied by the CER to reflect that changes in emissions in one part of the ETS will be partly offset (in present value terms) by a change in emissions of the opposite sign in other parts of the system. The tax and subsidy rates in section 4 that are targeted at emissions within the ETS (i.e., τ_H, τ_F, τ_E, t_{FT}, t_{EN}, t_{Eh}, t_{ET}, t_T, s_{ER}, t_{RT}, and s_{EA}) would then also be multiplied by the CER to ensure that taxes and subsidies are calibrated to the present value of the changes in emissions. Thus the tax and subsidy rates applied to emissions covered by the ETS should be scaled down proportionately, and the price of emission allowances should count as part of the overall tax payment, but the general principles underlying the optimal tax-subsidy scheme described in section 4 should still be applied.

5.2. Interactions with other taxes

Our partial equilibrium model of the energy market does not account for the effects of the changes in other tax rates that may be needed to keep the government budget balance unchanged when the tax-subsidy scheme described in section 4 is introduced. The implicit assumption is that the government can adjust some non-distortionary fiscal instrument to maintain its budget balance.

Instead of recycling the net revenue from energy taxes as a lump sum transfer to the private sector, the government could use it to cut existing distortionary taxes on income. It might be thought that this would generate an additional efficiency gain which is not accounted for in the analysis above, but this reasoning neglects that the introduction of a carbon tax discourages labour supply by eroding real wages, thereby exacerbating the pre-existing tax distortions to labour supply. According to the studies by Bovenberg and Goulder (1996), Parry (1997) and Goulder (2013), the second-best optimal environmental taxes may be substantially lower than the first-best Pigouvian level (represented by the shadow price λ in our analysis) when the green taxes interact with pre-existing tax distortions in other markets such as the labour market.

On the other hand, this view has been challenged by Kaplow (2004; 2012) who argues that when the marginal external cost of producing a polluting good has not been fully internalized by a Pigou tax, there is a potential for a Pareto improvement by introducing (or raising) such a tax if the government has full flexibility in adjusting the income tax schedule at each level of income. By undertaking a sufficiently fine-tuned adjustment of the income tax system, the government can in principle ensure that each person has the same incentive to supply labour as before the Pigou tax was introduced so that no additional non-environmental distortion from the Pigou tax arises. To the extent that this Kaplow argument is valid, it may justify the neglect of tax interactions with the non-energy markets in the present paper. The presence of a progressive non-linear income tax which may be adjusted to achieve the government's distributional goals may also justify why the present analysis abstracts from the effects of energy taxes on income distribution.

6. Concluding remarks

This paper has analyzed how a country pursuing a unilateral climate policy may contribute to a reduction in global CO_2 emissions in a cost-effective way. To do so its system of energy taxes and subsidies must account for leakage of emissions from the domestic to the foreign economy. We focused on leakage occurring via imports and exports of electricity and via shifts between domestic and foreign production of other tradable goods. Emissions from the tradable-goods sector should be taxed at reduced rates to avoid excessive carbon leakage, and a part of the carbon tax on electricity should be levied at the consumer rather then the producer level to ensure taxation of the carbon content of imported electricity. In other sectors emissions should be taxed at a uniform rate corresponding to the marginal social cost of meeting the target for emissions reduction. Producers of renewables-based electricity should receive a subsidy to internalize their contribution to the reduction of global emissions. There is also a case for an abatement subsidy to the production of fossil-based electricity and a subsidy to the use of bioenergy in the tradable-goods sector.

Although the optimal tax-subsidy scheme may seem somewhat complicated, it is in fact governed by a simple and consistent principle: Impose a uniform carbon tax on all additions to global emissions caused by changes in domestic production and consumption of energy, including additions to emissions occuring via shifts in international trade.

To achieve such uniformity, some differentiation of taxes on and subsidies to domestic production and consumption of energy is called for.

A systematic differentiation of taxes and subsidies is vulnerable to two well-known problems: First, the authorities may not have the information and administrative capacity to implement the differentiation in a consistent way. Although the paper has sketched how the relevant carbon leakage rates may be estimated, there will be considerable uncertainty regarding their magnitude, and delineating the group of firms vulnerable to carbon leakage is bound to be difficult. Second, and related to the first problem, differentiation of taxes and subsidies invites lobbyism by interest groups seeking to take undue advantage of reduced tax rates and selective subsidies, especially if fulfilment of the criteria for differentiation of taxes and subsidies is not easy to verify. To minimize these problems, the government should only offer reduced carbon tax rates and bioenergy subsidies in industries where the risk of carbon leakage is significant and obvious, i.e., in cases where firms are heavily dependent on energy and heavily engaged in international trade.

Furthermore, it is widely acknowledged that the countries of the world will have to tighten their climate policies significantly in the coming years to achieve the goal of the Paris agreement that global warming should be kept below 2 degrees Celsius. As a growing number of countries adopt binding targets for reduction of greenhouse gas emissions, the risk of carbon leakage from the countries that pursue the most ambitious climate policies will gradually diminish. This will allow these countries to move towards more uniform carbon tax rates on domestic activities which will be simpler to administer and less exposed to lobbyism.

7. Appendix 1: Conditions for optimal resource allocation in the energy market

This appendix derives the first-order conditions for a cost-effective provision of energy, given that the government must meet its target for climate policy, restated here from eq. (2.40):

$$\bar{e} - (e_H + e_E + e_F) - \left(\overline{D}_F - S_{FT} - S_{FN} - S_{Fh}\right) - L_c - \Delta = 0. \tag{7.1}$$

According to (2.1), (2.7), (2.13), (2.39), and (2.27) we have

$$e_H = e_H\left(H_F, A_H\right), \qquad e_E = e_E\left(E_F, A_E\right), \qquad e_F = e_F\left(Q_F, A_F\right), \tag{7.2}$$

$$L_c = \alpha_E M_E + \alpha^f_{ET} S_{ET} + \alpha^f_{FT} S_{FT} + \alpha^f_{RT} S_{RT} - \alpha^f_T S_T, \tag{7.3}$$

$$M_E = \overline{D}_E - S_{ET} - S_{EN} - S_{Eh} - \left(E_F + E_R\right). \tag{7.4}$$

Inserting (7.2) through (7.4) in (7.1), we can write the climate policy target as

$$\begin{gathered}\overline{e} - e_H\left(H_F, A_H\right) - e_E\left(E_F, A_E\right) - e_F\left(Q_F, A_F\right) - \overline{D}_F + S_{FT} + S_{FN} + S_{Fh} \\ -\alpha_E\left(\overline{D}_E - S_{ET} - S_{EN} - S_{Eh} - E_F - E_R\right) - \alpha^f_{ET} S_{ET} - \alpha^f_{FT} S_{FT} - \alpha^f_{RT} S_{RT} + \alpha^f_T S_T - \Delta = 0.\end{gathered} \tag{7.5}$$

The government must also respect the constraint that the supply of district heating must equal the demand for it, implying

$$H_F + H_R + S_{HT} + S_{HN} + S_{Hh} - \overline{D}_H = 0. \tag{7.6}$$

The government wishes to minimize the social cost of energy provision stated in (3.1) subject to the constraints (7.5) and (7.6). The Lagrangian for this problem is

$$\begin{gathered}L = C_{HF}\left(H_F\right) + C_{HA}\left(A_H\right) + C_{HR}\left(H_R\right) + C_{EF}\left(E_F\right) + C_{EA}\left(A_E\right) + C_{ER}\left(E_R\right) \\ +C_{FQ}\left(Q_F\right) + C_{FA}\left(A_F\right) + C_{RQ}\left(Q_R\right) + C_{ST}\left(S_{HT}, S_{ET}, S_{FT}, S_{RT}\right) \\ +C_{SN}\left(S_{HN}, S_{EN}, S_{FN}, S_{RN}\right) + C_{Sh}\left(S_{Hh}, S_{Eh}, S_{Fh}, S_{Rh}\right) \\ +p_E\left(\overline{D}_E - E_F - E_R - S_{Eh} - S_{ET} - S_{EN}\right) + p_F\left(\overline{D}_F - Q_F - S_{Fh} - S_{FT} - S_{FN}\right) \\ +p_R\left(\overline{D}_R - Q_R - S_{Rh} - S_{RT} - S_{RN}\right) - \mu\left(H_F + H_R + S_{HT} + S_{HN} + S_{Hh} - \overline{D}_H\right) \\ -\lambda\left[\overline{e} - e_H\left(H_F, A_H\right) - e_E\left(E_F, A_E\right) - e_F\left(Q_F, A_F\right) - \overline{D}_F + S_{FT} + S_{FN} + S_{Fh}\right. \\ \left.-\alpha_E\left(\overline{D}_E - S_{ET} - S_{EN} - S_{Eh} - E_F - E_R\right) - \alpha^f_{ET} S_{ET} - \alpha^f_{FT} S_{FT} - \alpha^f_{RT} S_{RT} + \alpha^f_T S_T - \Delta\right],\end{gathered} \tag{7.7}$$

where μ is the Lagrange multiplier associated with the heat market equilibrium constraint (7.6), and λ is the Lagrange multiplier associated with the climate policy constraint (7.5). From (7.7) we obtain the first-order conditions for the optimal choice of energy production, energy savings, and emissions abatement:

$$\frac{\partial L}{\partial H_F} = 0 \quad \Longrightarrow \quad \frac{dC_{HF}}{dH_F} + \lambda \frac{\partial e_H}{\partial H_F} = \mu, \tag{7.8}$$

$$\frac{\partial L}{\partial A_H} = 0 \quad \Longrightarrow \quad \frac{dC_{HA}}{dA_H} = -\lambda \frac{\partial e_H}{\partial A_H}, \tag{7.9}$$

$$\frac{\partial L}{\partial H_R} = 0 \quad \Longrightarrow \quad \frac{dC_{HR}}{dH_R} = \mu, \tag{7.10}$$

$$\frac{\partial L}{\partial E_F} = 0 \quad \Longrightarrow \quad \frac{dC_{EF}}{dE_F} + \lambda \left(\frac{\partial e_E}{\partial E_F} - \alpha_E \right) = p_E, \tag{7.11}$$

$$\frac{\partial L}{\partial A_E} = 0 \quad \Longrightarrow \quad \frac{dC_{EA}}{dA_E} = -\lambda \frac{\partial e_E}{\partial A_E}, \tag{7.12}$$

$$\frac{\partial L}{\partial E_R} = 0 \quad \Longrightarrow \quad \frac{dC_{ER}}{dE_R} - \lambda \alpha_E = p_E, \tag{7.13}$$

$$\frac{\partial L}{\partial Q_F} = 0 \quad \Longrightarrow \quad \frac{dC_{FQ}}{dQ_F} + \lambda \frac{\partial e_F}{\partial Q_F} = p_F, \tag{7.14}$$

$$\frac{\partial L}{\partial A_F} = 0 \quad \Longrightarrow \quad \frac{dC_{FA}}{dA_F} = -\lambda \frac{\partial e_F}{\partial A_F}, \tag{7.15}$$

$$\frac{\partial L}{\partial Q_R} = 0 \quad \Longrightarrow \quad \frac{dC_{RQ}}{dQ_R} = p_R, \tag{7.16}$$

$$\frac{\partial L}{\partial S_{HT}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{ST}}{\partial S_{HT}} = \mu, \tag{7.17}$$

$$\frac{\partial L}{\partial S_{ET}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{ST}}{\partial S_{ET}} + \lambda \left(\alpha^f_{ET} - \alpha_E \right) = p_E, \tag{7.18}$$

$$\frac{\partial L}{\partial S_{FT}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{ST}}{\partial S_{FT}} - \lambda \left(1 - \alpha^f_{FT} \right) = p_F \tag{7.19}$$

$$\frac{\partial L}{\partial S_{RT}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{ST}}{\partial S_{RT}} + \lambda \alpha^f_{RT} = p_R, \tag{7.20}$$

$$\frac{\partial L}{\partial S_{HN}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{SN}}{\partial S_{HN}} = \mu, \tag{7.21}$$

$$\frac{\partial L}{\partial S_{EN}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{SN}}{\partial S_{EN}} - \lambda \alpha_E = p_E, \tag{7.22}$$

$$\frac{\partial L}{\partial S_{FN}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{SN}}{\partial S_{FN}} - \lambda = p_F, \tag{7.23}$$

$$\frac{\partial L}{\partial S_{RN}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{SN}}{\partial S_{RN}} = p_R, \tag{7.24}$$

$$\frac{\partial L}{\partial S_{Hh}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{Sh}}{\partial S_{Hh}} = \mu, \tag{7.25}$$

$$\frac{\partial L}{\partial S_{Eh}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{Sh}}{\partial S_{Eh}} - \lambda \alpha_E = p_E, \tag{7.26}$$

$$\frac{\partial L}{\partial S_{Fh}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{Sh}}{\partial S_{Fh}} - \lambda = p_F, \tag{7.27}$$

$$\frac{\partial L}{\partial S_{Rh}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{Sh}}{\partial S_{Rh}} = p_R, \tag{7.28}$$

$$\frac{\partial L}{\partial S_T} = 0 \quad \Longrightarrow \quad \frac{dC_T}{dS_T} = p_T + \alpha_T^f \lambda. \tag{7.29}$$

From (7.8) through (7.29) it is straightforward to derive the optimum conditions (3.2) through (3.7) explained in section 3.

8. Appendix 2. Deriving carbon leakage rates

In this appendix we derive the expression for the carbon leakage rate α_{iT}^f stated in (2.35). Normalizing the international price of traded goods to one and using (2.30) and (2.33), we may write the profits of the representative foreign tradable-goods producer (π_T^f) as

$$\pi_T^f = \overbrace{\left(F_T^f\right)^\beta \left(E_T^f\right)^\eta \left(H_T^f\right)^\theta \left(X_T^f\right)^{1-\beta-\eta-\theta}}^{= y_T^f} - p_F F_T^f - \left(p_E + t_{ET}^f\right) E_T^f$$
$$- \left(p_H^f + t_{HT}^f\right) H_T^f - p_X^f X_T^f - \tau_T^f \left[F_T^f - a_T\left(A_T^f\right)\right], \tag{8.1}$$

where t_{ET}^f and t_{HT}^f are foreign tax rates on the use of electricity and district heating in the tradable-goods sector, τ_T^f is the foreign carbon tax rate on emissions from that sector, p_H^f is the foreign producer price of district heating, and p_X^f is the price of the composite input X_T^f. The competitive foreign tradable-goods producer maximizes the profit (8.1), taking all prices as given. The first-order condition for the profit-maximizing choice of the fossil fuel input F_T^f yields the following expression for the input-output coefficient b_F^f:

$$b_F^f \equiv \frac{F_T^f}{y_T^f} = \frac{\beta}{p_F + \tau_T^f}. \tag{8.2}$$

Similarly, profit-maximization with respect to the inputs of electricity and heat imply the input-output coefficients

$$b_E^f \equiv \frac{E_T^f}{y_T^f} = \frac{\eta}{p_E + t_{ET}^f}, \tag{8.3}$$

$$b_H^f \equiv \frac{H_T^f}{y_T^f} = \frac{\theta}{p_H^f + t_{HT}^f}. \tag{8.4}$$

We will now derive the CO_2 emissions generated by the foreign tradable-goods producer's use of electricity and heat. From (2.31) and (2.33) it follows that the profits from foreign fossil-based electricity production (π_E^f) are

$$\pi_E^f = p_E \overbrace{\left(F_E^f\right)^\omega \left(Z_E^f\right)^{1-\omega}}^{= E^f} - p_F F_E^f - p_Z Z_E^f - \tau_E^f \left[F_E^f - a_E\left(A_E^f\right)\right], \tag{8.5}$$

where τ_E^f is the foreign carbon tax rate on emissions from power production, and p_Z is an index of the price of the other inputs used by foreign electricity producers. Maximization of the profit π_E^f with respect to fossil fuel input implies that the amount of fossil fuel input per unit of electricity produced will be

$$\frac{F_E^f}{E^f} = \frac{\omega p_E}{p_F + \tau_E^f}. \tag{8.6}$$

If the share of fossil-based electricity production in total foreign electricity production is α_{FE}^f, it follows from (8.6) that the additional CO_2 emissions per unit increase in foreign power production (α_E^f) will be given by the following expression (where we have maintained our normalization that one unit of fossil fuel burned generates one unit of CO_2 emissions):

$$\alpha_E^f = \alpha_{FE}^f \frac{F_E^f}{E^f} = \frac{\alpha_{FE}^f \omega p_E}{p_F + \tau_E^f}. \tag{8.7}$$

Following a similar procedure and using analogous notation, we can use (2.32) and (2.33) to write the profits from foreign fossil-based heat production as

$$\pi_H^f = p_H^f \overbrace{\left(F_H^f\right)^\gamma \left(K_H^f\right)^{1-\gamma}}^{=H^f} - p_F F_H^f - p_K K_H^f - \tau_H^f \left[F_H^f - a_H \left(A_H^f\right)\right]. \tag{8.8}$$

Maximization of the heat-producer's profit with respect to fossil fuel input requires that

$$\frac{F_H^f}{H^f} = \frac{\gamma p_H^f}{p_F + \tau_H^f}, \tag{8.9}$$

so if the share of fossil-based heat production in total foreign (district) heat production is α_{FH}^f, the additional CO_2 emissions per unit increase in foreign heat production (α_H^f) is

$$\alpha_H^f = \alpha_{FH}^f \frac{F_H^f}{H^f} = \frac{\alpha_{FH}^f \gamma p_H^f}{p_F + \tau_H^f}. \tag{8.10}$$

Now recall from (2.29) that the carbon leakage coefficient associated with a reduction in the use of energy input i in the domestic tradable-goods sector is

$$\alpha_{iT}^f = \frac{dy_T^f}{dy_T} \frac{dy_T}{dS_{iT}} \left(b_F^f + \alpha_H^f b_H^f + \alpha_E^f b_E^f\right), \quad i = E, F, R. \tag{8.11}$$

With perfect competition in the international market for tradable goods the ratio dy_T^f/dy_T will be minus one, as a reduction in domestic output of the tradable good will be offset one-to-one by an increase in foreign output, since world demand for the good will be unchanged at the given world price of the output. The ratio dy_T/dS_{iT} is roughly the negative of the marginal product of the energy input of type i which will equal the tax-inclusive price of that input when firms maximize profits. Denoting the marginal product of energy good i by MP_{iT}, we thus have

$$\frac{dy_T^f}{dy_T} = -1, \qquad \frac{dy_T}{dS_{iT}} = -MP_{iT} = -\left(p_i + t_{iT}\right), \quad i = E, F, R. \tag{8.12}$$

Inserting (8.2), (8.3), (8.4), (8.7), (8.10), and (8.12) in (8.11), we get

$$\alpha_{iT}^f = \left(p_i + t_{iT}\right)\left(\frac{\beta}{p_F + \tau_T^f} + \frac{\alpha_{FH}^f \gamma \theta p_H^f}{\left(p_H^f + t_{HT}^f\right)\left(p_F + \tau_H^f\right)} + \frac{\alpha_{FE}^f \omega \eta p_E}{\left(p_E + t_{ET}^f\right)\left(p_F + \tau_E^f\right)}\right), \tag{8.13}$$

Without loss of generality we may choose units such that $p_F = p_E = p_H^f = p_R = 1$ in the initial equilibrium. We then obtain the expression for the leakage coefficient α_{iT}^f stated in (2.35) where the normalization implies that the various tax rates are measured as a fraction of the producer prices of the relevant energy goods.

Further, since α_E is defined as the additional CO_2 emissions generated by a unit increase in domestic electricity imports (i.e., the rise in emissions caused by a unit rise in foreign power production), it follows from (8.7) that α_E will be given by eq. (2.34) when $p_F = p_E = 1$.

REFERENCES

Böhringer, C., E.Balistreri, and T.F. Rutherford (2012). The role of border carbon adjustment in unilateral climate policy: overview of an energy modelling forum study (EMF29). *Energy Economics* 34 (Supplement 2), 97-110.

Böhringer, C., K.E. Rosendahl, and H.B. Storrøsten (2017). Robust policies to mitigate carbon leakage. *Journal of Public Economics* 149, 35-46.

Bovenberg, A. L. and L.H. Goulder (1996). Optimal environmental taxation in the presence of other taxes: general equilibrium analyses. *American Economic Review* 86, 985-1000.

European Commission (2017). Report on the functioning of the European carbon market. Report from the Commission to the European Parliament and Council, COM(2017) 693 final.

Fischer, C. and A.K. Fox (2012). Comparing policies to combat emission leakage: border carbon adjustments versus rebates. *Journal of Environmental Economics and Management* 64, 199-216.

Goulder, L.H. (2013). Climate change policy's interactions with the tax system. *Energy Economics* 40, S3-S11.

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

Hoel, M. (2012). Klimatpolitik och ledarskap - vilken roll kan et litet land spela? Rapport till Expertgruppen för miljöstudier 2012:3, Finansdepartementet, Stockholm.

Kaplow, Louis (2004). On the (ir)relevance of distribution and labor supply distortion to government policy. *Journal of Economic Perspectives* 18, 159-175.

Kaplow, Louis (2012). Optimal control of externalities in the presence of income taxation. *International Economic Review* 53, 487-509.

Marcu, A., C. Egenhofer, S. Roth, and W. Stoefs (2013). Carbon leakage - An overview. CEPS Special Report no. 79/December 2013, Centre for European Policy Studies, Brussels.

Parry, Ian W.H. (1997). Environmental taxes and quotas in the presence of distorting taxes in factor markets. *Resource and Energy Economics* 19, pp. 203-220.

Reinaud, J. (2008). Issues behind competitiveness and carbon leakage - Focus on heavy industry. IEA Information Paper, International Energy Agency, October 2008.

Silbye, F. and P.B. Sørensen (2017). Subsidies to renewable energy and the European Emissions Trading System: is there really a waterbed effect?. Working Paper, Danish Council on Climate Change, March 2017
(file:///C:/Users/kzj109/Downloads/working_paper_-_is_there_really_a_waterbed%20(1).pdf).

Ter-Mikaelian, M.T., S.J. Colombo, and J. Chen (2015). The burning question: does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting. *Journal of Forestry* 113, 57-68.