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Abstract

We analyze how a country pursuing a unilateral climate policy may contribute to a reduction in global CO2 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 international trade in electricity and via shifts between domestic and foreign production of other goods. The optimal tax-subsidy scheme is based on an intuitive 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 sector exposed to foreign competition 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. Simulations calibrated to data for the Danish economy suggest that redesigning energy taxes and subsidies to account for carbon leakage can generate a welfare gain.

JEL-Codes: H210, H230, Q480, Q540.

Keywords: optimal unilateral climate policy, carbon leakage, optimal energy taxes and subsidies.

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OPTIMAL ENERGY TAXES AND SUBSIDIES UNDER A COST-EFFECTIVE UNILATERAL CLIMATE POLICY: ADDRESSING CARBON LEAKAGE

Peter Kjær-Kruse Andersen and Peter Birch Sørensen[1]

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 an 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., 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 international trade wars.

[1]This paper has benefited from fruitful discussions with Frederik Silbye and Thomas Bue Bjørner. All remaining shortcomings are our own responsibility.

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

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 energy production based on renewable energy sources. Our tool of analysis is a 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. Like Hoel (1996), we find that optimal taxation in the presence of carbon leakage involves a systematic differentiation of carbon tax rates across sectors. However, while Hoel restricted the set of policy instruments to include emission taxes only, we allow for a broader set of instruments that includes also taxes on consumption of energy and other goods as well as subsidies to renewable energy.

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. We go 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.

One limitation of our analysis should be acknowledged from the outset: By focusing on a small open economy we are able to ignore terms-of-trade effects of energy taxes and subsidies. When such effects are accounted for, the analysis of carbon leakage becomes more complicated, as shown by di Maria and van der Werf (2008) and Jakob et al. (2013), among others. Hence our optimal tax and subsidy rules will not carry over without modification to a large economy with significant impact on world market prices, but the mechanisms highlighted by our analysis will likely still be important for optimal climate policy in a large economy setting.

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] and section 4 derives the set of energy taxes and subsidies that fulfils these optimum conditions. Section 5 calibrates the model to data for the Danish economy and undertakes simulations to illustrate the potential welfare gain from moving towards the proposed optimal tax-subsidy scheme. Section 6 summarizes our main findings and discusses some practical and political economy issues related to the implementation of a tax-subsidy scheme that accounts for carbon leakage.

2 A model of the energy market in a small 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 an internationally traded energy good termed "electricity", reflecting that many countries participate in an international electricity market via interconnectors. Electricity is produced by burning fossil fuel and 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 electricity from domestic and foreign utilities. Households also demand fossil fuels to produce services like transport and heating for their own consumption, and as a supplement to the electricity delivered from utilities firms demand fossil fuels for direct use in their production processes. Like electricity, fossil fuels are traded internationally.

Production of fossil-based electricity and the burning of fossil fuels for other purposes 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

[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.

the government may levy carbon taxes on the various domestic uses of fossil fuels and provide subsidies to production of renewable energy. The government may also choose to subsidize abatement efforts and to levy taxes on final consumption goods. All of these taxes and subsidies may be differentiated across sectors. 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.[4]

We will now describe the details of the model.

2.1 Energy supply

Domestic production of fossil-based electricity (E_F) generates the CO_2 emissions

$$e_E = e_E\left(E_F, A_E\right), \qquad \frac{\partial e_E}{\partial E_F} > 0, \quad \frac{\partial e_E}{\partial A_E} < 0, \tag{1}$$

where A_E is the abatement effort undertaken by the representative utility company producing electricity from fossil fuel. This effort 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, or equipment allowing Carbon Capture and Storage. The company's emissions e_E 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}. Electricity may be traded across borders via international interconnectors. With an international electricity price p_E, the profits π_{EF} of the fossil-based electricity company are given by

$$\pi_{EF} = p_E E_F - C_{EF}\left(E_F\right) - C_{EA}\left(A_E\right) + s_{EA}A_E - \tau_E e_E, \tag{2}$$

$$\frac{dC_{EF}}{dE_F} > 0, \quad \frac{d^2C_{EF}}{\left(dE_F\right)^2} > 0, \qquad \frac{dC_{EA}}{dA_E} > 0, \quad \frac{d^2C_{EA}}{\left(dA_E\right)^2} > 0,$$

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

$$\frac{dC_{EF}}{dE_F} + \tau_E \frac{\partial e_E}{\partial E_F} = p_E, \tag{3}$$

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

$$MAC_E \equiv -\frac{dC_{EA}/dA_E}{\partial e_E/\partial A_E} = \tau_E - \frac{s_{EA}}{\partial e_E/\partial A_E}. \tag{4}$$

According to (3) the utility company will carry power production to the point where the sum of the marginal production cost and the marginal emission tax payment equals the market price of electricity, and according to (4) it will take abatement effort to the point where the marginal abatement cost MAC_E equals the resulting gain from a lower emission tax bill and a larger abatement subsidy.

Electricity may also be produced from an emission-free 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

$$\pi_{ER} = (p_E + s_{ER})\, E_R - C_{ER}(E_R), \qquad \frac{dC_{ER}}{dE_R} > 0, \quad \frac{d^2C_{ER}}{(dE_R)^2} > 0, \tag{5}$$

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

$$\frac{dC_{ER}}{dE_R} = p_E + s_{ER}. \tag{6}$$

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 electricity from utilities as well as fossil fuel from which they produce supplementary energy and transport services for themselves. Like before, the subscripts E and F indicate electricity and fossil fuel, 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 electricity and fossil fuel as "energy savings functions" indicating the energy savings undertaken by households and firms relative to a benchmark equilibrium prior to the government intervention considered. Specifically, the saving of energy good i in sector j is given as

$$S_{ij} \equiv \overline{D}_{ij} - D_{ij}, \qquad i = E, F, \quad j = h, T, N, \tag{7}$$

where $\overline{D}_{ij}$ is the demand forthcoming in the no-intervention equilibrium, and D_{ij} is the actual demand after the introduction of the (revised) 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. We therefore specify the total net cost of energy savings in sector j (TC_{Sj}) as

$$TC_{Sj} = C_{Sj}\left(S_{Ej}, S_{Fj}\right) - \left[\left(p_E + t_{Ej}\right) S_{Ej} + \left(p_F + t_{Fj}\right) S_{Fj}\right], \tag{8}$$

$$\frac{\partial C_{Sj}}{\partial S_{Ej}} > 0, \quad \frac{\partial^2 C_{Sj}}{\left(\partial S_{Ej}\right)^2} > 0, \qquad \frac{\partial C_{Sj}}{\partial S_{Fj}} > 0, \quad \frac{\partial^2 C_{Sj}}{\left(\partial S_{Fj}\right)^2} > 0, \qquad j = h, T, N.$$

The function $C_{Sj}\left(S_{Ej}, S_{Fj}\right)$ captures the total gross cost of reducing the inputs of the two energy goods (loss of utility or 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_{Ej} and t_{Fj} are tax rates on the use of the two energy inputs, so the term in the square bracket in (8) is the saving on expenses on the purchase of energy goods, including the reduction in energy tax payments. As part of their maximization of utility or profits, households and firms will minimize their 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.,

$$\frac{\partial C_{ij}}{\partial S_{ij}} = p_i + t_{ij}, \qquad i = E, F, \quad j = h, T, N. \tag{9}$$

The optimum conditions (9) amount to 6 equations determining the 6 different values of S_{ij}. The absolute demand for electricity and fossil fuel in the three sectors may then be backed out from the definition of S_{ij} stated in (7).

2.3 Energy market equilibrium

Electricity and fossil fuel are traded internationally at prices exogenous to the small domestic economy. The net import of electricity (M_E) must make up for any imbalance between domestic demand and domestic supply and is therefore given by

$$M_E = \overbrace{\overline{D}_E - S_{ET} - S_{EN} - S_{Eh}}^{\substack{\text{Total domestic demand} \\ \text{for electricity}}} - \overbrace{(E_F + E_R)}^{\substack{\text{Domestic production} \\ \text{of electricity}}}, \tag{10}$$

$$\overline{D}_E \equiv \overline{D}_{Eh} + \overline{D}_{ET} + \overline{D}_{EN},$$

where $\overline{D}_E$ is the total demand for electricity in the household and business sectors in the pre-intervention equilibrium. Obviously, the net import of electricity may be either positive or negative.

The domestic production of fossil fuel (if any) is treated as exogenous, and any domestic fossil fuel demand in excess of domestic production is likewise satified via imports at the given international fuel price.

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 addition, policy makers must estimate how foreign emissions are affected by a change in domestic consumption of tradables.

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^f_{FE}, and if a unit of foreign fossil-based electricity production generates additional CO_2 emissions amounting to $\partial e^f_E / \partial E^f_F$, the increase in foreign emissions caused by a unit increase in electricity imports (α_E) will be

$$\alpha_E = \alpha^f_{FE} \frac{\partial e^f_E}{\partial E^f_E}, \qquad 0 \leq \alpha^f_{FE} \leq 1. \tag{11}$$

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. Thus we allow for the possibility that a reduction in the domestic use of electricity or fossil fuel 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 or fossil fuel) 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

$$\alpha^f_{iT} \equiv \frac{de^f_T}{dS_{iT}} = \frac{de^f_T}{dy^f_T} \frac{dy^f_T}{dy_T} \frac{dy_T}{dS_{iT}} = \overbrace{\left(b^f_F + \alpha^f_E b^f_E\right)}^{=de^f_T/dy^f_T} \frac{dy^f_T}{dy_T} \frac{dy_T}{dS_{iT}}, \quad i = E, F, \tag{12}$$

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 and b^f_E are marginal input-output coefficients indicating the increases in the inputs of fossil fuel and electricity per unit increase in foreign tradable-goods production, and α^f_E is the additional CO_2 emission per unit increase in foreign power production. 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. Moreover, under perfect competition domestic production will be fully crowded out by foreign production, implying that $dy^f_T / dy_T \to -1$.

In the empirical application of our model we will estimate α^E from a model of carbon leakage via the European Emissions Trading System for CO_2 emission permits, while α^f_{iT} will be estimated on the basis of simulations results from computable general equilibrium models of international trade (see section 5).

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 $S_T \equiv \overline{D}_T - D_T$. To 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

$$\alpha_T^f \equiv -\frac{de_T^f}{dS_T} = -\frac{de_T^f}{dy_T^f} \overbrace{\frac{dy_T^f}{dS_T}}^{\approx -1} \approx \overbrace{\left(b_F^f + \alpha_E^f b_E^f\right)}^{=de_T^f/dy_T^f}. \tag{13}$$

If p_T is the world market price of tradables, and t_T is the ad valorem tax rate on the domestic consumption of tradables, we have

$$S_T = t_T \varepsilon \overline{D}_T, \tag{14}$$

where ε is the numerical price elasticity of domestic consumer demand for tradables. Assuming that tax revenues are recycled to households, the parameter ε may be interpreted (roughly) as the compensated price elasticity of demand. In Appendix B we show how ε and $\overline{D}_T$ may be derived and calibrated when the representative consumer maximizes a CES utility function.[5]

To a second-order approximation, the social welfare loss from the consumption tax on tradables is given by the Harberger triangle $(t_T^2/2)\, \varepsilon p_T \overline{D}_T$ representing the difference between the loss of consumer surplus and the revenue from the tax. Using (14), we may write this welfare loss in the following form:

$$C_T(S_T) = \beta_T S_T^2, \qquad \beta_T \equiv \frac{p_T}{2\varepsilon \overline{D}_T}. \tag{15}$$

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

$$L_c = \alpha_E M_E + \alpha_{ET}^f S_{ET} + \alpha_{FT}^f S_{FT} - \alpha_T^f S_T. \tag{16}$$

[5]Eq. (14) is a first-order approximation to the tax-induced compensated change in demand for tradables implied by the demand function (57) in Appendix B.

The government aims to reduce global emissions by the exogenous amount Δ, accounting for the carbon leakage induced by climate policy. In the pre-intervention equilibrium 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

$$\overline{e} - \overbrace{e_E}^{\substack{\text{Post-intervention emissions} \\ \text{from production} \\ \text{of electricity}}} - \overbrace{\left(\overline{D}_F - S_{Fh} - S_{FT} - S_{FN}\right)}^{\substack{\text{Post-intervention emissions} \\ \text{from fossil fuel use in} \\ \text{households and non-energy firms}}} - L_c = \Delta. \qquad (17)$$

We will now analyze how the policy goal (17) 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 (17) be met. The social cost of satisfying energy demand is the sum of the costs of domestic production and net imports of electricity plus the costs of emissions abatement, energy savings and fossil fuel use.[6] 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

$$\begin{aligned} SC = \; & \overbrace{C_{EF}\left(E_F\right) + C_{EA}\left(A_E\right) + C_{ER}\left(E_R\right)}^{\text{Production and abatement costs in electricity production}} \\ & + \overbrace{p_F\left(\overline{D}_F - S_{Fh} - S_{FT} - S_{FN}\right)}^{\text{Cost of fossil fuel use}} \\ & + \overbrace{C_{ST}\left(S_{ET}, S_{FT}\right) + C_{SN}\left(S_{EN}, S_{FN}\right) + C_{Sh}\left(S_{Eh}, S_{Fh}\right)}^{\text{Cost of energy savings}} \end{aligned}$$

[6]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 (18). Internalizing these additional externalities would then call for additional Pigouvian taxes as a supplement to the carbon and energy taxes derived below.

$$+\overbrace{C_T\left(S_T\right)}^{\text{Cost of reduced consumption of tradables}}$$

$$\overbrace{+p_E\left(\overline{D}_E - E_F - E_R - S_{Eh} - S_{ET} - S_{EN}\right)}^{\text{Cost of net imports of electricity}}, \tag{18}$$

$$\overline{D}_F \equiv \overline{D}_{FT} + \overline{D}_{FN} + \overline{D}_{Fh}, \qquad \overline{D}_E \equiv \overline{D}_{ET} + \overline{D}_{EN} + \overline{D}_{Eh},$$

where $\overline{D}_F$ is the total demand for fossil fuel in households and non-energy business firms in the pre-intervention equilibrium. Note that the net import term in (18) does not include the cost of imported fossil fuel to the domestic utility companies since this cost is already included in the cost function $C_{EF}\left(E_F\right)$.

A benevolent government will minimize the total social cost (18) subject to the climate policy constraint (17) as well as the carbon leakage mechanism (16) and the electricity import function (10). The first-order conditions for the solution to this policy problem are derived in Appendix A. From these conditions it follows that an optimal resource allocation in the energy sector must satisfy the following intuitive relationships, where λ is the shadow price of CO_2 emissions (the Lagrange multiplier associated with the climate policy target (17)):

Optimal provision of electricity:

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

$$= \overbrace{\frac{\partial C_{SN}}{\partial S_{EN}} - \alpha_E\lambda}^{\substack{\text{Marginal social cost}\\ \text{of electricity savings}\\ \text{in non-tradables sector}}} = \overbrace{\frac{\partial C_{Sh}}{\partial S_{Eh}} - \alpha_E\lambda}^{\substack{\text{Marginal social cost}\\ \text{of electricity savings}\\ \text{in household sector}}} = p_E. \tag{19}$$

Optimal emission abatement in electricity production:

$$-\overbrace{\frac{dC_{EA}/dA_E}{\partial e_E/\partial A_E}}^{\text{Marginal abatement cost}} = \lambda. \tag{20}$$

Optimal fossil fuel use:

$$\overbrace{\frac{\partial C_{ST}}{\partial S_{FT}} - \left(1-\alpha_{FT}^{f}\right)\lambda}^{\substack{\text{Marginal social cost}\\ \text{of fossil fuel savings}\\ \text{in tradable-goods sector}}}$$

$$= \overbrace{\frac{\partial C_{SN}}{\partial S_{FN}} - \lambda}^{\substack{\text{Marginal social cost}\\ \text{of fossil fuel savings}\\ \text{in non-tradables sector}}} = \overbrace{\frac{\partial C_{Sh}}{\partial S_{Fh}} - \lambda}^{\substack{\text{Marginal social cost}\\ \text{of fossil fuel saving}\\ \text{in household sector}}} = p_F. \tag{21}$$

Optimal consumption of tradables:

$$\frac{dC_T}{dS_T} = \overbrace{\alpha_T^{f}\lambda}^{\substack{\text{Marginal social gain}\\ \text{from reduced}\\ \text{consumption of tradables}}}. \tag{22}$$

The optimum condition (19) states that the marginal social costs of electicity production should equal the marginal social costs of electricity savings which in turn should equal the marginal social benefit from electricity savings given by the international price of electricity. The marginal costs of producing and saving electricity 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 $\lambda\left(\partial e_E/\partial E_F\right)$. 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 (19). 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 (19).

The optimum condition (20) requires that abatement of CO_2 emissions from power production be taken to the point where the marginal abatement cost equals the shadow price of emissions (λ), and (21) states that the marginal social cost of fossil fuel savings across all sectors should equal the marginal social benefit given by the world market price on fossil fuel. In the tradable goods sector, a unit cut in fossil fuel use increases foreign emissions by the amount α_{FT}^f via carbon leakage, so the resulting net external benefit from lower emissions is only $\left(1 - \alpha_{FT}^f\right)\lambda$. This external benefit must be deducted from the private marginal cost of fossil fuel saving $\partial C_{ST}/\partial S_{FT}$ to obtain the marginal social cost stated in the first term on the left-hand side of (21). In the other sectors where there is no leakage, the marginal social cost of fossil fuel saving is reduced by the full amount of the shadow price λ representing the social gain from a unit cut in emissions.

Eq. (22) finally states that the marginal welfare loss from the (tax-induced) fall in the consumption and import of tradables must equal the marginal gain $\alpha_T^f\lambda$ from reduced emissions abroad.

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 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.

The tax rate τ_E is a 'genuine' emission tax levied on emissions from domestic power production. If utility 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 tax to be administered as a tax 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 interpreted 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 (see below), 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.

Using 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:

Tax on domestic electricity production:

$$\tau_E = \lambda\left(1 - \alpha_{FE}^f \varepsilon_E\right), \qquad \varepsilon_E \equiv \frac{\partial e_E^f / \partial E_F^f}{\partial e_E / \partial E_F}. \tag{23}$$

Taxes on domestic energy consumption:

$$t_{FN} = t_{Fh} = \lambda. \tag{24}$$

$$t_{FT} = \lambda\left(1 - \alpha_{FT}^f\right). \tag{25}$$

$$t_{EN} = t_{Eh} = \alpha_E \lambda, \qquad \alpha_E = \alpha^f_{FE} \frac{\partial e^f_E}{\partial E^f_F}. \tag{26}$$

$$t_{ET} = \lambda \left(\alpha_E - \alpha^f_{ET} \right). \tag{27}$$

Tax on consumption of tradable goods:

$$t_T p_T = \alpha^f_T \lambda. \tag{28}$$

Subsidy to renewable electricity production:

$$s_{ER} = \alpha_E \lambda. \tag{29}$$

Subsidy to abatement in electricity sector:

$$s^e_{SA} \equiv \frac{s_{EA}}{-\partial e_E / \partial A_E} = \lambda - \tau_E = \lambda \alpha^f_{FE} \varepsilon_E. \tag{30}$$

The presence of leakage rates (the α-terms) in almost all of the formulas above reflects the fundamental importance of carbon leakage for optimal taxation when the government cares about global rather than domestic emissions. If the government focused only on attaining a target for reduction of emissions from the domestic economy, it would neglect carbon leakage and act as if the α-terms in the formulas (23) through (30) were zero. It would then impose a uniform carbon tax on all domestic CO_2 emissions at the rate λ reflecting the shadow price of emissions. We will term this the standard rate of carbon tax. With such a tax in place, there would be no need for any supplementary taxes on energy consumption and tradable goods or any subsidies to abatement and renewable energy production, as the reader may verify by setting all the α's in the above formulas equal to zero. Thus our model confirms the conventional wisdom that a cost-effective climate policy only requires a uniform carbon tax across all domestic sectors but no subsidies when policy makers focus only on reducing domestic emissions.

In the present context where the government aims at reducing *global* emissions by a certain amount, it follows from the optimal tax formulas above that the standard rate of carbon tax should apply only to fossil fuel use in the household sector and in the non-tradables business sector where there is no carbon leakage (see (24)).

According to (23) the carbon tax on domestic emissions from fossil-based electricity production should only be a fraction $1 - \alpha^f_E \varepsilon_E$ 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 case 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).

Moreover, 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 (25).

The tax rule (26) 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 (28) on tradable goods is similar:[7] 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 amounting to $\alpha_T^f\lambda$ per unit of tradable goods consumption 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

[7]The optimal tax rate (28) is found by combining (22) with (15) and (14).

should only be taxed at the rate $\lambda\left(\alpha_E - \alpha^f_{ET}\right)$, as reported in (27). 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 which is ultimately an empirical matter. We return to this issue in the next section.

The rationale for the subsidy rule (29) 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.

The abatement subsidy s^e_{EA} specified in (30) is measured per unit of emission abated. The need for this subsidy arises from the fact that the carbon tax on domestic power production (τ_E) is kept below the shadow price of emissions in order to reduce carbon leakage. To provide a sufficient incentive for abatement, a positive abatement subsidy at a rate equal to the tax concession $\lambda - \tau_E$ is therefore required.

Table 1 summarizes the qualitative features of the optimal tax-subsidy system when the government targets the domestic economy's contribution to global emissions and compares them to the optimal policy under a target for domestic emissions, i.e., the optimal policy when all the α-terms in the formulas (23) through (30) are set equal to zero.

An important question for policy makers is how much the optimal tax rates should deviate from uniformity and how much the subsidies to abatement and renewable energy should deviate from zero when the government targets global emissions? To answer this question, the next section considers a calibrated version of our model.

Table 1. Optimal climate policies under alternative emission targets

Activity	Instrument	
	Global emission target	Domestic emission target
Production		
Tradable goods sector	Reduced carbon tax	Standard carbon tax
Non-tradable goods sector	Standard carbon tax	Standard carbon tax
Electricity, fossil fuels	Reduced carbon tax	Standard carbon tax
	+ abatement subsidy	
Electricity, renewables	Subsidy	No instrument
Consumption		
Fossil fuels, households	Standard carbon tax	Standard carbon tax
Traded goods	Consumption tax	No instrument
Non-traded goods	No instrument	No instrument
Electricity, tradables sector	Reduced electricity tax	No instrument
Electricity, non-tradables sector	Standard electricity tax	No instrument
Electricity, households	Standard electricity tax	No instrument

5 Empirical application: How much should energy taxes and subsidies be differentiated?

5.1 Calibrating the model

For the purpose of calibrating the model above, we assume the following functional forms which satisfy our theoretical assumptions on the signs of the first and second derivatives:

Cost of fossil-based electricity production:

$$C_{EF}\left(E_F\right) = \beta_{EF} E_F^2 \tag{31}$$

Cost of abating emissions from fossil-based electricity production:

$$C_{EA}\left(A_E\right) = \beta_{EA} A_E^2 \tag{32}$$

Cost of renewables-based electricity production:

$$C_{ER}\left(E_R\right) = \beta_{ER} E_R^2 \tag{33}$$

Cost of electricity and fossil fuel savings in sector j:

$$C_{Sj}\left(S_{Ej}, S_{Fj}\right) = \beta_{Ej}\left(1 + S_{Ej}\right)^2 + \beta_{Fj}\left(1 + S_{Fj}\right)^2, \qquad j = h, N, T \tag{34}$$

Cost of reducing consumption of tradable goods:

$$C_T\left(S_T\right) = \beta_T S_T^2 \tag{35}$$

Emissions from fossil-based electricity production:

$$e_E\left(E_F, A_E\right) = \frac{\gamma E_F}{1 + A_E} \tag{36}$$

Eqs. (31) through (35) imply linearly increasing marginal cost functions. The specification in (34) ensures that the marginal cost of the first unit of energy saving (starting out from $S_{Ej} = 0$ or $S_{Fj} = 0$) is positive. Eq. (35) is just a repetition of the general functional form implied by (15) which also stated the formula for β_T derived from the theory of the excess burden of taxation.

Appendix B explains how we have estimated the parameters in the formula for β_T, assuming a CES utility function with traded and non-traded consumer goods as arguments, and in Kruse-Andersen and Sørensen (2019) we explain in detail how we have calibrated the parameters in eqs. (31) through (36), applying the first-order conditions for the maximization of profits and utility derived in sections 2 and 3 to Danish data for 2016. Since we are interested in the *changes* in resource allocation induced by a move from the current to the optimal tax system, our calibration assumes that the initial equilibrium reflected in the data represents a situation where $S_{Ej} = S_{Fj} = S_T = 0$. To exemplify our procedure, it then follows from the first-order condition (9) and the functional form assumed in (34) that

$$\beta_{Fj} = \frac{p_F + t_{Fj}}{2}, \qquad j = h, N, T. \tag{37}$$

To estimate the value of β_{Fj} from this equation, we calculate the fossil fuel price p_F as a weighted average of the producer prices of coal, oil, and natural gas, weighted by their shares in total energy consumption, and measuring quantities such that (burning) one unit of each type of fuel generates one ton of CO_2 emission. The existing effective carbon tax rates t_{Fj} and electricity tax rates t_{Ej} on the various sectors were estimated on the basis of data from the Danish interdepartmental Secretariat for Taxes and Subsidies on Energy (STSE) and the Danish Energy Agency. Our estimates of the effective current subsidy s_{ER} to renewables-based electricity production (needed to calibrate the parameter β_{ER}) and of the parameters β_{EF} and β_{EA} were also based on information from the STSE as well as data from the Danish Energy Agency.

The leakage rates are particularly important for the optimal tax-subsidy scheme. According to the survey by Carbone and Rivers (2017), studies based on computable general equilibrium models typically find a leakage rate of around 10 to 30 percent for the tradable goods sector. However, given the small size of the Danish economy we expect the leakage rate associated with the use of fossil fuels in the tradable goods sector to be somewhat higher, so based on the Danish study by Beck et al. (2019) we set $\alpha^f_{FT} = 0.5$. For electricity, we set the leakage rate (in million tons of CO_2 per PJ) to 30 percent in the traded goods sector ($\alpha^f_{ET} = 0.3$).

In power production the leakage rate is high due to Denmark's participation in the European Emissions Trading Scheme (ETS). If the ETS worked like a textbook cap-and-trade system with a binding exogenous cap on emissions, the leakage rate would be 100 percent. However, due to the large surplus of emission allowances within the ETS and the recent reform of the system which introduced some endogeneity of allowance supply via the so-called Market Stability Reserve, the leakage rate will be somewhat lower than 100 percent. Based on simulations with two recent models of the ETS (Beck and Kruse-Andersen, 2019; Silbye and Sørensen, 2019), we have estimated the leakage rate for electricity production to be around 60 percent, i.e., $\alpha^f_{FE}\varepsilon_E = 0.6$. Assuming that foreign and domestic fossil-based electricity production are equally CO_2-intensive, we have $\varepsilon_E \equiv \frac{\partial e^f_E/\partial E^f_F}{\partial e_E/\partial E_F} = 1$, implying $\alpha^f_{FE} = 0.6$. From this estimate and the expression for $\partial e_E/\partial E_F$ implied by (36), we obtain an estimate for the coefficient α_E defined in (11) measuring the foreign CO_2 emissions generated by an additional unit of electricity imported to the domestic economy.[8]

[8] According to (36), $\partial e_E/\partial E_F = \gamma/(1 + A_E)$. Kruse-Andersen and Sørensen (2019) explain how γ and A_E are calibrated.

The leakage factor α_T^f for the tradable goods sector defined in (13) expresses the reduction in the amount of CO_{2e} emitted when domestic consumption of tradable goods falls by one unit. We assume that this is roughly equal to Danish emissions from tradable good production divided by the amount of internationally traded goods consumed.

Appendix C provides a complete list of all parameter values used in the simulations below.

5.2 Policy experiments

The first column in Table 2 reports our estimates of the current (2016) effective rates of energy taxes and subsidies in Denmark and compares them to the optimal rates under two alternative policy scenarios. In the middle column of the table we show the optimal tax-subsidy system implied by our calibrated model if policy makers were content to keep Denmark's contribution to global CO_2 emissions unchanged at the current level ($\Delta = 0$). Thus this benchmark scenario does not assume that Danish policy makers wish to reduce global emissions unilaterally; it only assumes that they want to account for carbon leakage in a systematic way.

We see that such a policy goal calls for a substantial cut in the tax rates on the consumption of electricity compared to the current tax rates. This reflects that the current Danish energy tax on electricity is quite high (in fact considerably higher than the energy tax on fossil fuels) and that a low tax on electricity consumption (indeed a subsidy) in the tradable goods sector reduces carbon leakage. It is also optimal to introduce a substantial subsidy to abatement in domestic electricity production to take advantage of opportunities for cheap reductions in emissions from fossil-based power production. With such a subsidy, there is room for some increase in the carbon tax on the electricity sector. Further, we see that our model provides a case for a higher subsidy to renewable electricity generation and for some increase in the general consumption tax (the VAT) on tradable goods, since both of these policy changes help to reduce carbon leakage. Finally, for $\Delta = 0$ our model implies an optimal standard carbon tax rate of 51,7 euros per ton of CO_{2e} to be imposed on fossil fuel use in the non-tradables production sector and in the household sector, whereas the tradable goods production sector should only pay half the standard rate of carbon tax, reflecting the 50 percent rate of carbon leakage from that sector. With these policy changes relative to the current tax-subsidy system, carbon leakage is reduced by 0.2 mt. CO_{2e}, and the total social cost of energy provision is reduced by 0.043 percent of GDP, according to our model.

Table 2. The optimal tax system under a global emission target

Policy instrument	Unit	Current Danish tax system	Optimal tax system ($\Delta = 0$)	Optimal tax system ($\Delta = 7.4$mt. CO_2e)
Standard carbon tax (λ)	Euros per t. CO_2e		51.7	157.0
Carbon tax on fossil-based electricity production (τ_E)	Euros per t. CO_2e	8.0	20.7	62.8
Subsidy to renewable electricity production (s_{ER})	M. euros per PJ	5.6	7.1	21.7
Subsidy to abatement in electricity sector (s^e_{EA})	Euros per t. CO_2e	0	30.9	93.7
Tax on electricity use in households (t_{Eh})	M. euros per PJ	54.3	7.1	21.7
Tax on electricity use in non-tradables sector (t_{EN})	M. euros per PJ	25.7	7.1	21.7
Tax on electricity use in tradables sector (t_{ET})	M. euros per PJ	16.1	-8.3	-25.5
Carbon tax on fossil fuel use in household sector (t_{Fh})	Euros per t. CO_2e	197.2	51.7	157.0
Carbon tax on fossil fuel use in non-tradables sector (t_{FN})	Euros per t. CO_2e	122.3	51.7	157.0
Carbon tax on fossil fuel use in tradables sector (t_{FT})	Euros per t. CO_2e	122.3	25.9	78.5
Tax on consumption of tradables (t_T)	Value-added in pct.	0	2.8	8.4

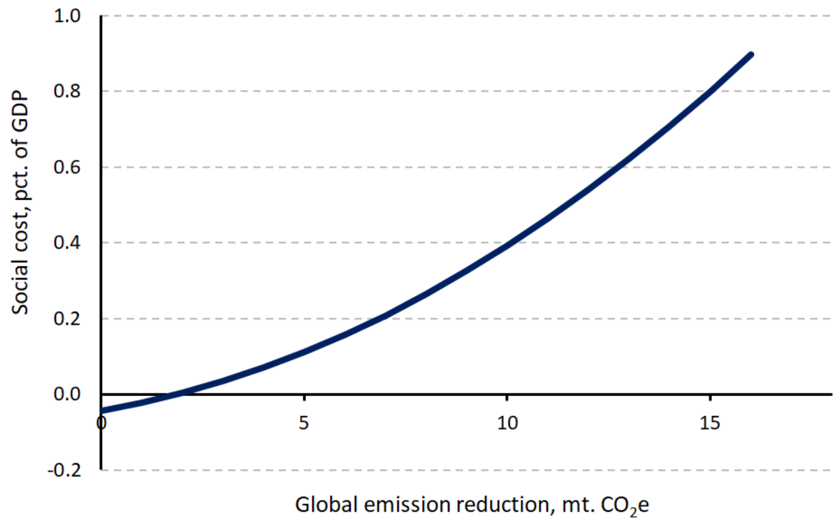
Source: Own calculations based on simulations with the model described above.

In the third column of Table 2 we consider the implications for the optimal tax-subsidy system of tightening the target for reduction of Denmark's contribution to global emissions. Specifically, we assume that the target for Danish reduction of global emissions is twice the EU-mandated 2030 reduction target for domestic emissions from the Danish non-ETS sector. The non-ETS reduction target is 37 mt. CO_2e accumulated over 10 years, i.e. 3.7 mt. per year from 2021 to 2030 (Danish Energy Agency 2018). Our reduction target is therefore 7.4 mt., but this target applies to Denmark's total contribution to global emissions, and not just to domestic emissions from the non-ETS sector ($\Delta = 7.4$). From Table 2 we see that the optimal standard carbon tax on households and producers of non-tradables is now about three times higher compared to the optimal tax system maintaining the current global emission level ($\Delta = 0$). Basically, this means that all the tax rates are around three times higher compared to the previous scenario. The subsidy rates are also notably higher. However, the optimal electricity taxes are still below the current level. The same is true for the carbon tax on fossil fuel use in the household and tradable-goods sector, whereas the non-tradables sector should pay a higher fossil fuel tax than today. Finally, the (additional) value-added tax on internationally traded goods is now over 8 percent.

Our simulation model allows an estimate of the domestic social cost (defined in (18)) of alternative domestic contributions to lower global emissions. The estimated social costs in percent of GDP are illustrated in Figure 1. The figure shows that, by moving from the current Danish tax-subsidy system to the optimal system, it is possible to reduce global emissions by around 2 mt. per year without increasing the domestic social cost of energy provision. As the target for unilateral emission reduction is raised above that level, the social cost moves into positive territory at a slightly increasing pace, reflecting gradually increasing marginal abatement costs across the economy as a whole. For example, reducing the Danish contribution to global emissions by 10 mt. of CO_2e per year, amounting to an almost 20 percent reduction[9], would involve a domestic social cost of roughly 0.4 percent of GDP.

[9] According to Statistics Denmark (2018) Danish domestic emissions (including emissions from agriculture but excluding emissions from the burning of biomass) in 2016 amounted to 51.1 mt. CO_{2e}. In addition, the Danish tax-subsidy system caused a net carbon leakage of 3 mt. according to our calibrated model, so the Danish contribution to global emissions added up to 54.1 mt.

Figure 1. The social cost of reducing Denmark's contribution to global CO_2e emissions



Source: Own calculations based on simulations with the model described above.

5.3 Caveats

Our highly simplified partial equilibrium model can at best only give a rough indication of the order of magnitude of the optimal differentiation of energy taxes and subsidies. In a technical note available on request, we have extended the model to include a distinction between the use of heat, electricity and (carbon-neutral) bioenergy fuels as well as a separate utility sector for district heating and sectors for domestic production of bioenergy fuels and fossil fuels. Importantly, these extentions to the model do not change the formulas for the optimal tax and subsidy rates reported above, but they reveal that a concern for carbon leakage provides a case for a subsidy to the use of bioenergy fuels in the tradable-goods sector. They also reveal that domestic production of fossil fuel and of fossil-based district heating should be subject to the standard carbon tax rate.

Our model 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 optimal tax-subsidy scheme is introduced. The implicit assumption is that the government can adjust a non-distortionary fiscal instrument to maintain its budget balance. However, 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 than 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 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. There is considerable uncertainty regarding the magnitude of carbon leakage rates, and delineating the group of firms vulnerable to leakage is bound to be difficult. Second, differentiation of taxes and subsidies invites lobbyism by interest groups seeking to take 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 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 A: Conditions for optimal resource allocation in the energy market

This appendix derives the first-order conditions for attaining the optimal tax-subsidy system, given that the government must meet its target for climate policy, restated here from eq. (17):

$$\bar{e} - e_E - \left(\overline{D}_F - S_{FT} - S_{FN} - S_{Fh}\right) - L_c - \Delta = 0. \tag{38}$$

According to (1), (16), and (10) we have

$$e_E = e_E\left(E_F, A_E\right), \tag{39}$$

$$L_c = \alpha_E M_E + \alpha^f_{ET} S_{ET} + \alpha^f_{FT} S_{FT} - \alpha^f_T S_T, \tag{40}$$

$$M_E = \overline{D}_E - S_{ET} - S_{EN} - S_{Eh} - \left(E_F + E_R\right). \tag{41}$$

Inserting (39) through (41) in (38), we can write the climate policy target as

$$\bar{e} - e_E\left(E_F, A_E\right) - \overline{D}_F + S_{FT} + S_{FN} + S_{Fh}$$

$$-\alpha_E\left(\overline{D}_E - S_{ET} - S_{EN} - S_{Eh} - E_F - E_R\right) - \alpha^f_{ET} S_{ET} - \alpha^f_{FT} S_{FT} + \alpha^f_T S_T - \Delta = 0. \tag{42}$$

The government wishes to minimize the social cost function stated in (18) subject to the constraint (42). The Lagrangian for this problem is

$$L = C_{EF}\left(E_F\right) + C_{EA}\left(A_E\right) + C_{ER}\left(E_R\right)$$

$$+C_{ST}\left(S_{ET}, S_{FT}\right) + C_{SN}\left(S_{EN}, S_{FN}\right) + C_{Sh}\left(S_{Eh}, S_{Fh}\right) + C_T\left(S_T\right)$$

$$+p_E\left(\overline{D}_E - E_F - E_R - S_{Eh} - S_{ET} - S_{EN}\right) + p_F\left(\overline{D}_F - S_{Fh} - S_{FT} - S_{FN}\right)$$

$$-\lambda\left[\bar{e} - e_E\left(E_F, A_E\right) - \overline{D}_F + S_{FT} + S_{FN} + S_{Fh}\right.$$

$$\left.-\alpha_E\left(\overline{D}_E - S_{ET} - S_{EN} - S_{Eh} - E_F - E_R\right) - \alpha^f_{ET} S_{ET} - \alpha^f_{FT} S_{FT} + \alpha^f_T S_T - \Delta\right], \tag{43}$$

where λ is the Lagrange multiplier associated with the climate policy constraint (42). From (43) we obtain the first-order conditions for the optimal choice of energy production, energy savings, and emissions abatement:

$$\frac{\partial L}{\partial E_F} = 0 \quad \Longrightarrow \quad \frac{dC_{EF}}{dE_F} + \lambda\left(\frac{\partial e_E}{\partial E_F} - \alpha_E\right) = p_E, \tag{44}$$

$$\frac{\partial L}{\partial A_E} = 0 \quad \Longrightarrow \quad \frac{dC_{EA}}{dA_E} = -\lambda \frac{\partial e_E}{\partial A_E}, \tag{45}$$

$$\frac{\partial L}{\partial E_R} = 0 \quad \Longrightarrow \quad \frac{dC_{ER}}{dE_R} - \lambda \alpha_E = p_E, \tag{46}$$

$$\frac{\partial L}{\partial S_{ET}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{ST}}{\partial S_{ET}} + \lambda \left(\alpha_{ET}^f - \alpha_E \right) = p_E, \tag{47}$$

$$\frac{\partial L}{\partial S_{FT}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{ST}}{\partial S_{FT}} - \lambda \left(1 - \alpha_{FT}^f \right) = p_F \tag{48}$$

$$\frac{\partial L}{\partial S_{EN}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{SN}}{\partial S_{EN}} - \lambda \alpha_E = p_E, \tag{49}$$

$$\frac{\partial L}{\partial S_{FN}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{SN}}{\partial S_{FN}} - \lambda = p_F, \tag{50}$$

$$\frac{\partial L}{\partial S_{Eh}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{Sh}}{\partial S_{Eh}} - \lambda \alpha_E = p_E, \tag{51}$$

$$\frac{\partial L}{\partial S_{Fh}} = 0 \quad \Longrightarrow \quad \frac{\partial C_{Sh}}{\partial S_{Fh}} - \lambda = p_F, \tag{52}$$

$$\frac{\partial L}{\partial S_T} = 0 \quad \Longrightarrow \quad \frac{dC_T}{dS_T} = \alpha_T^f \lambda. \tag{53}$$

From (44) through (53) it is straightforward to derive the optimum conditions (19) through (22) explained in section 3.

8 Appendix B. The welfare cost of reduced consumption of tradables

In this appendix we explain how we estimate the parameter β_T in the function (35) for the social welfare loss caused by a cut in the consumption of tradable goods.

Suppose the representative consumer seeks to maximize the CES utility function

$$U = \left[\delta^{\frac{1}{\sigma}} Z^{\frac{\sigma-1}{\sigma}} + (1-\delta)^{\frac{1}{\sigma}} D_T^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \qquad 0 < \delta < 1, \quad \sigma > 0, \quad \sigma \neq 1, \tag{54}$$

subject to the budget constraint

$$p_z Z + p_T D_T \leq I, \tag{55}$$

where Z is consumption of non-tradable goods, D_T is consumption of tradables, p_z and p_T are the consumer prices of the two types of goods, and I is the exogenous total income. Note that U may be interpreted as aggregate consumption, and that σ is the elasticity of substitution between the two goods categories. The solution to the consumer's problem can be shown to imply that

$$Z = \delta \left(\frac{p_z}{P}\right)^{-\sigma} U, \tag{56}$$

$$D_T = (1 - \delta) \left(\frac{p_T}{P}\right)^{-\sigma} U, \tag{57}$$

$$P = \left[\delta p_z^{1-\sigma} + (1 - \delta)\, p_T^{1-\sigma}\right]^{\frac{1}{1-\sigma}}, \tag{58}$$

$$\theta \equiv \frac{p_z Z}{I} = \delta \left(\frac{p_z}{P}\right)^{1-\sigma}, \tag{59}$$

where P is an ideal consumer price index (equal to the inverse of the marginal utility of money income), and θ is the budget share of non-tradables.

According to (57) the substitution elasticity σ is the compensated price elasticity of demand in our formula (15) for the welfare loss from a tax-induced fall in the consumption of tradable goods which also includes the initial consumption of tradables $\overline{D}_T$ and their world market price p_T. To estimate these parameters, we will also need to estimate δ and p_z. From (59) it follows that

$$\ln \theta = \ln \delta + (1 - \sigma) \ln \left(\frac{p_z}{P}\right). \tag{60}$$

An econometric version of this formula is

$$\ln \theta_t = \beta_0 + \beta_1 \ln \left(\frac{p_z}{P}\right)_t + \varepsilon_t, \tag{61}$$

where t is a time index and ε_t is an error term. Using Danish national accounts data, we have split the Danish economy into a tradables and a non-tradables sector, allowing us to construct a time series for the budget share θ_t for the period 2001-2017 (see Kruse-Andersen and Sørensen 2019 for details). We also constructed a time series for the relative price $(p_z/P)_t$ for the same period by dividing the consumer price index for services by the overall consumer price index. An OLS regression using these data yielded the estimates $\beta_0 = -0.26$ and $\beta_1 = 0.61$, implying $\delta = \exp(-0.26) = 0.77$ and $\sigma = 1 - 0.61 = 0.39$.

From the first-order conditions (56) and (57) it follows that

$$\frac{p_T \overline{D}_T}{p_z Z} = \left(\frac{1 - \delta}{\delta}\right) \left(\frac{p_z}{p_T}\right)^{\sigma - 1}, \tag{62}$$

which can be rearranged to give

$$p_T = p_z \left(\frac{p_T \overline{D}_T}{p_z Z} \frac{\delta}{1 - \delta}\right)^{\frac{1}{1-\sigma}}. \tag{63}$$

Setting $P = 1$ in (58) and rearranging the resulting equation, we also find that

$$p_z = \delta^{\frac{1}{\sigma-1}} \left[1 + \left(\frac{1-\delta}{\delta} \right) \left(\frac{p_z}{p_T} \right)^{\sigma-1} \right]^{\frac{1}{\sigma-1}}. \tag{64}$$

In 2016 the ratio $p_T \overline{D}_T / p_z Z$ was 0.29 according to our data derived from the national accounts. Using this number along with our estimates of δ and σ, we obtain the estimates $p_T = 0.97$ and $p_z = 1.01$ from (63) and (64). From (62) and the budget constraint (55) we can then crank out an estimate for $\overline{D}_T$. As mentioned in section 2.4, the numerical price elasticity ε in formula (15) is a compensated elasticity which can be shown to be given by

$$\varepsilon = (1 - e_T)\,\sigma, \qquad e_T \equiv \frac{p_T \overline{D}_T}{p_z Z + p_T \overline{D}_T}, \tag{65}$$

where e_T is the budget share of tradables. Armed with the estimates of σ, p_T, $\overline{D}_T$, and $p_T \overline{D}_T / p_z Z$, we can use (65) and the formula in (15) to calculate the value of β_T consistent with our CES utility function and the theory of the excess burden of taxation.

9 Appendix C. Calibrated parameter values

The parameters of our simulation model are specified in section 5.1. Applying the calibration procedures described in detail in Kruse-Andersen and Sørensen (2019) to data for the Danish economy in 2016, we arrived at the parameter values summarized in Table C.

Table C. Model parameters

Parameters	Unit	Calibrated value
α^f_{FE}	Ratio	0.60
α^f_{ET}	Mt. CO_{2e} per PJ	0.30
α^f_{FT}	Ratio	0.50
α^f_{T}	Mt. CO_{2e} per consumption unit	6.83×10^{-5}
γ	Mt. CO_{2e} per PJ	0.23
β_{EF}	M. DKK per $(\text{PJ})^2$	2.13
β_{EA}	M. DKK per $(\text{abatement effort})^2$	4.13×10^{-5}
β_{ER}	M. DKK per $(\text{PJ})^2$	1.81
β_{Eh}	M. DKK per $(\text{PJ})^2$	302.00
β_{EN}	M. DKK per $(\text{PJ})^2$	231.50
β_{ET}	M. DKK per $(\text{PJ})^2$	159.50
β_{Fh}	M. DKK per $(\text{mt. } CO_2 e)^2$	1006.50
β_{FN}	M. DKK per $(\text{mt. } CO_2 e)^2$	727.00
β_{FT}	M. DKK per $(\text{mt. } CO_2 e)^2$	727.00
β_{T}	M. DKK per $(\text{cons. unit})^2$	3.71×10^{-6}
p_E	M. DKK per PJ	199.00
p_F	M. DKK per mt. $CO_2 e$	542.00
p_T	M. DKK per cons. unit	0.95

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