EFFICIENT CO_2 EMISSIONS CONTROL WITH NATIONAL EMISSIONS TAXES AND INTERNATIONAL EMISSIONS TRADING

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Abstract

In a group of countries like the European Union all countries seek to achieve their national CO_2 emissions target by a joint emissions trading scheme covering some part of their economies (trading sector) and by a national emissions tax in the rest of their economies (nontrading sector). Applicable are also emissions taxes overlapping with the trading scheme that can either be freely chosen or are inert. Welfare-maximizing governments determine tax rates and the tradable-permits budget. It is shown that efficiency requires not to levy overlapping emissions taxes and to set the tax rate in the nontrading sector equal to the permit price. In the small-country case emissions control turns out to be efficient if tax rates in the trading sector are flexible. Otherwise it is second-best to violate cost effectiveness and to choose an excessive endowment of tradable permits. If countries are large and optimal tariffs cannot be applied, emissions taxes or subsidies (!) are shown to serve as a perfect surrogate; efficiency cannot be attained unless there is a central authority mandating cost effectiveness and banning overlapping taxes. Fiscal externalities are specified and the countries' welfare in the large and small country case is compared.

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1 The problem

We consider a group of countries like the European Union whose member states are committed to national CO_2 emissions targets or national emissions caps to be achieved by a joint emissions trading scheme (ETS) and by national emissions taxes. For some part of each country's economy, called the trading sector, participation in the ETS is mandatory. In the rest of the economy, referred to as nontrading sector, emissions are controlled by means of an emissions tax. In addition, we allow for another sectoral emissions tax overlapping with the ETS in the country's trading sector. That tax can be either freely chosen or it preexists and is inert. In such a setting of hybrid emissions control which models the EU scenario in a stylized way welfare-maximizing governments determine the split of the national emissions cap into a cap for the trading and for the nontrading sector[1] and they also set the rates of the sectoral emissions tax(es). Assuming that *national* emissions caps are predetermined, the paper aims at exploring the efficiency implications of national emissions control by welfare-maximizing governments who either account (large-country case) or do not account (small-country case) for their policy's impact on the terms of permit trade.

Pollution control in a (second-best) world of preexisting distortionary taxes has extensively been studied in the context of ecological tax reforms (e.g. Bovenberg and de Mooij 1994 and Goulder et al. 1999). Yet unlike that literature we envisage the use of several policy instruments all of which target CO_2 emissions and we do not deal with the issue of revenue recycling. Our focus on an ETS designed for *international* emissions trade also relates our analysis to the issue of trade and environment as surveyed e.g. by Ulph (1999). However, that literature typically considers countries applying a *single* pollution control instrument to their domestic and exposed sectors. Hoel (1994) shows that differential treatment of these sectors may be warranted, if transboundary pollution occurs and trade policy is infeasible. Rauscher (1996) suggests that for large countries it may be optimal to deviate from efficient pollution control in order to improve the terms of trade. The issue of differential treatment of sectors will also play a role in the present paper. But the sectors in our model are subject to *different* complementary or overlapping *environmental* policy instruments.

While isolated environmental policy instruments are analyzed in a vast number of theoretical and empirical studies, policy interactions appear to be under-researched (Sorrell and Sijm 2003). This certainly applies to the crowded policy space in the EU countries

[1] The trading-sector gap equals the amount of emissions permits the government issues and allocates to its trading sector. The trading sector's effective emissions may deviate from that cap due to exports or imports of emissions permits.

that became even more complex after the ETS started to operate in 2005. Among the few studies directly related to the interaction of an ETS with other policy instruments is Sijm (2005). Without offering a formal analysis he suggests that "... from the perspective of CO_2 efficiency, the coexistence of EU ETS and policies affecting fossil fuel use by participating sectors is hard to justify and, hence, these policies could be considered to be redundant and ready to be abolished" (ibidem, p. 83). Similarly, in an non-technical report on subsidizing renewable energy the Scientific Council to the German Federal Ministry for the Economy (2004) recommends phasing out those subsidies because in combination with the EU ETS the emissions reductions achieved by such subsidization are regarded as excessively costly without improving the ecological effectiveness of the ETS. Böhringer et al. (2006) consider a partial equilibrium model with a national emissions tax in the trading sector and find that if a country unilaterally changes the emissions tax rate in its trading sector (as opposed to uniform changes by all countries) the country's costs as well as the EU's overall costs of implementing a given emissions target increase.[2] Although to our knowledge the extant literature does not provide a rigorous theoretical foundation of that *no-overlap proposition* it appears to endorse it arguing, in essence, that since an ETS is a first-best instrument for implementing a given permit cap, 'killing the bird with two stones' is bound to be less efficient than relying on the ETS alone.

Focussing on competitive economies and welfare-maximizing governments the present paper makes that no-overlap proposition precise and takes it as a starting point for exploring more thoroughly the efficiency implications of the hybrid CO_2 emissions control outlined above. As in the standard theory of international trade, welfare and efficiency implications of national policies will turn out to depend on whether countries are assumed to be 'small' or 'large'. Beginning with the small-country case we first establish the no-overlap proposition in case that the governments are free not to use an overlapping emissions tax or to abolish an existing one. Yet in many EU member states (fully) exempting all firms in the trading sector from prevailing carbon/energy taxes seems to be politically infeasible.[3] That clearly gives rise to explore second-best optimal national emissions controls. We will characterize such policies analytically showing, in particular, their implications with regard to cost effectiveness and the size of the permit cap.

[2]Böhringer et al. also discuss the case of large countries with market power arguing that under some qualifications a permit-importing country may benefit from a tax in its trading sector.

[3]In Germany, various energy-related taxes are levied in both the trading and nontrading sector although possibly at differential rates (www.bundesfinanzministerium.de; following the link 'Steuern' und 'Energiebesteuerung'). Full exemption of the trading sector from that tax cannot be expected in the near future mainly because without reliable substitutes the tax revenues are considered indispensable in view of tight budgets.

The second part of the paper addresses the large-country case. The governments of such countries are aware that their policy affects the price in the international permit market inducing them to manipulate the terms of permit trade in their favor while behaving Nash with regard to the other countries' policies. As known from standard trade theory, subsidies on exports and tariffs on imports of permits would be the first-best instruments for targeting the terms of permit trade. But since such trade policy is not at the EU member states' disposal, their governments might seek to distort their environmental policies as a surrogate for trade policy (Markusen 1975; Ulph 1997). In fact, with tariffs being unavailable welfare-maximizing governments of large countries will be shown to distort the permit price by means of an emissions tax (with a positive or negative rate) levied on their trading sector. If emissions taxes in the trading sector are ruled out, e.g. because a central authority has issued a no-overlap directive, the group allocation (still) fails to be efficient. We also identify the prevailing fiscal externalities and compare the equilibrium allocations of the large and small country case with respect to the countries' welfare positions.

The paper is organized as follows. Section 2 sets up the model, characterizes the efficient allocation and determines the first-best regulation from the perspective of the group of countries in the competitive market system. Section 3 explores the small-country case of governments who can either freely choose an emissions tax in their trading sector or are confronted with such a tax that preexists and is inert. Section 4 deals with the same issues as Section 3 but with governments who account for the impact of their policies on the terms of permit trade, and it also aims at specifying the allocative distortions due to the large-country assumption. Section 5 concludes.

2 Efficient emissions control in the ETS group of countries

In this section we first describe the model, then we characterize the efficient allocation and finally determine in the competitive market system the emissions control policy that is efficient from the perspective of the ETS group of countries.

The model. Consider a group of n countries, such as the European Union, embedded in the world economy. All countries in that group participate in an international CO_2 emissions trading scheme (ETS) to be specified below. The economy of each country i ($i = 1, \ldots, n$) consists of two sectors X^i and Y^i whose outputs x_{si} and y_{si} are produced with some fixed factors and with the inputs e_{xi} and e_{yi}, respectively, of fossil fuel.[4] The strictly concave production functions are[5]

$$x_{si} = X^i \left(\underset{+}{e_{xi}} \right) \qquad \text{and} \qquad y_{si} = Y^i \left(\underset{+}{e_{yi}} \right). \tag{1}$$

CO_2 emissions are proportional to the input of fossil fuel, and therefore we simply take e_{xi} and e_{yi} to denote the fuel input as well as the CO_2 emissions. The consumption x_i and y_i of these goods yields the utility

$$u_i = U^i \left(\underset{+}{x_i}, \underset{+}{y_i} \right) \tag{2}$$

to the representative consumer of country i. The price of the nontradable good X is p_{xi} in country i and the condition for clearing the (domestic) market is

$$x_i = x_{si}. \tag{3}$$

Good Y and fossil fuel are traded on world markets at prices p_y and p_e, respectively. Since the group of countries under consideration is small with respect to the rest of the world, all countries in that group take the prices p_y and p_e as given. No country in the group is endowed with own fossil fuel reserves. Therefore all fuel input needs to be imported (and is (mainly) paid for by exports of good Y; see below).

As for CO_2 emissions control, the group of countries as a whole committed itself to restrict its total emissions to some level[6] $\bar{c} > 0$. To meet that emissions target $\bar{c}$ the countries levy a national emissions tax in their sectors X *and* take part in a joint emissions trading scheme (ETS) with mandatory participation of their sectors Y. In addition, each country may also levy an emissions tax in its sector Y which would then overlap with the ETS. To render that policy mix operational each country i is assigned a *national emissions cap*, $c_i \geq 0$, such that $\sum_i c_i = \bar{c}$, and it splits up its national emissions cap into two *sectoral caps*, c_{yi} and c_{xi}, satisfying[7]

$$c_i = c_{xi} + c_{yi}. \tag{4}$$

[4]No distinction is made between types of fossil fuels (oil, gas, coal) that differ with respect to their specific CO_2 release per unit of energy generated.

[5]Upper case letters denote functions and subscripts attached to them indicate partial derivatives. A sign underneath an argument denotes the sign of the respective first partial derivative.

[6]For this upper bound on emissions to be a nontrivial constraint we assume that it is smaller than the group's total business-as-usual emissions level.

[7]Throughout the paper, the national caps are considered to be exogenous while the split into sectoral caps is assumed to be determined by national regulators. In the case of the EU-ETS member-states have some discretion with regard to fixing that split, but the central authority (EU commission) appears to tighten its criteria to be observed by national regulators in the second emissions trading phase (2008-2012).

The sectoral cap c_{xi} in country i is implemented by an emissions tax in sector X^i whose rate is set such that

$$c_{xi} = e_{xi}. \tag{5}$$

Country i issues the amount c_{yi} of marketable emissions permits to be allocated to all firms (or installations) in its sector Y according to some rule.[8] These permits can then be traded among all countries of the group. A market for permits will arise with the aggregate supply being fixed at $\sum_i c_{yi}$ and with a permit price π_e that will clear the market:

$$\sum_i c_{yi} = \sum_i e_{yi}. \tag{6}$$

Note that although (6) allows for exports and imports of permits ($c_{yi} \neq e_{yi}$) and hence for $e_{yi} + e_{xi} = e_{yi} + c_{xi} \neq c_i$, the equations (4) - (6) imply

$$\sum_i (e_{yi} + e_{xi}) = \sum_i c_i = \bar{c}.$$

When the ETS is installed, country i's balance of payments (current account) is

$$\pi_e(c_{yi} - e_{yi}) + p_y(y_{si} - y_i) - p_e(e_{xi} + e_{yi}) = 0. \tag{7}$$

Allocative efficiency. To characterize the efficient allocation for the group of countries taking part in emissions trading consider a social planner's optimization problem implied by the Lagrangean

$$\begin{aligned} \mathcal{L} &= \sum_j \alpha_j U^j(x_j, y_j) + \sum_j \lambda_{xj}\left[X^j(e_{xj}) - x_j\right] + \sum_j \lambda_{cj}(c_j - c_{yj} - e_{xj}) \\ &+ \sum_j \lambda_{hj}\left[\pi_e(c_{yj} - e_{yj}) + p_y\left(Y^j(e_{yj}) - y_j\right) - p_e(e_{xj} + e_{yj})\right], \end{aligned} \tag{8}$$

where $p_e, p_y > 0$ and $\pi_e \geq 0$ are constants and where the α_j for $j = 1, \ldots, n$ denote constant positive welfare weights. Observe that in (8) π_e is assumed to be arbitrarily determined implying that the solution to (8) need not satisfy (6). Nonetheless, the first-order conditions of (8) do correctly characterize the efficient allocation for those values $\pi_e > 0$ for which the solution to (8) satisfies (6).[9]

The first-order conditions of solving (8) for an interior solution read, after some rearrangement of terms,

$$\frac{U_y^i}{U_x^i} = \frac{p_y}{\mu_{xi}} \qquad \text{all } i, \tag{9}$$

$$\mu_{xi} X_e^i = p_y Y_e^i = p_e + \pi_e \qquad \text{all } i, \tag{10}$$

[8]At the high level of abstraction of the present analysis auctioning and gratis distribution of emissions permits are equivalent allocation procedures.

[9]The existence of such a solution can be secured by standard arguments.

where $\mu_{xi} = \lambda_{xi}/\lambda_{hi}$. The interpretation of (9) and (10) is straightforward: (9) represents the usual condition of efficiency in consumption and (10) is the well-known rule for production efficiency (or cost effectiveness) which requires to equalize marginal abatement costs across sectors.

Efficient emissions control. The next step is to characterize the national emissions control that - under conditions of perfect competition - is capable to decentralize the efficient group allocation implicitly given by (9) and (10). To that end suppose each country i in the group has chosen some permit cap $c_{yi} \in]0, c_i[$ and the ETS is in operation. Moreover, let t_{xi} and t_{yi} be the emissions tax rates in country i's sectors X and Y. The associated profits then are

$$p_{xi}X^i(e_{xi}) - (t_{xi} + p_e)e_{xi} \qquad \text{and} \qquad p_y Y^i(e_{yi}) - \pi_e(e_{yi} - c_{yi}) - (t_{yi} + p_e)e_{yi},$$

and the first-order conditions for profit maximization read

$$p_{xi}X^i_e(e_{xi}) = t_{xi} + p_e \qquad \text{and} \qquad p_y Y^i_e(e_{yi}) = t_{yi} + p_e + \pi_e. \tag{11}$$

Maximizing the consumer's utility subject to her budget constraint[10] yields

$$U^i_x(x_i, y_i) = \lambda p_{xi} \qquad \text{and} \qquad U^i_y(x_i, y_i) = \lambda p_y, \tag{12}$$

where λ represents the consumer's marginal utility of income. Comparing (9) and (10) with (11) and (12) immediately yields[11]

Proposition 1.
Set $p_{xi} = \mu_{xi}$, $t_{xi} = \pi_e$ and $t_{yi} = 0$ for all i. Then the international permit market and the national markets for good X are in equilibrium and the associated allocation is efficient for the ETS-group of countries. In addition, the efficient sectoral caps are implicitly defined by $p_{xi}X^i_e(c_i - c_{yi}) = t_{xi} + p_e$.

The unambiguous message of Proposition 1 is that taxes (or subsidies) levied in sector Y are efficiency-reducing. The split of national emissions caps need to be such that the tax rates in all nontrading sectors equal the permit price and are hence the same across countries. Moreover, the unit emissions costs must be the same across sectors and countries implying that marginal abatement costs are the same across sectors and countries. It is tempting to conclude from (10) as Böhringer et al. (2006) seem to do that there are multiple

[10] The budget constraint is $g^*_{xi} + g^*_{yi} + t_{xi}e_{xi} + t_{yi}e_{yi} \geq p_{xi}x_i + p_y y_i$ where g^*_{xi} and g^*_{yi} are maximum profits and where $t_{xi}e_{xi} + t_{yi}e_{yi}$ are the tax revenues recycled to the consumer in a lumpsum way.

[11] See also the stylized analysis of Böhringer et al. (2006).

competitive equilibria exhibiting one and the same equilibrium allocation along with the tax rates $t_{xi} = \pi_e$ for all i (as in Proposition 1) and $t_{yi} = t_y \in]-\infty, \pi_e[$ for all i and with the equilibrium permit price $\tilde{\pi}_e := \pi_e - t_y$. However, closer inspection reveals that $t_y = 0$ is a necessary efficiency condition, because for $\tilde{\pi}_e \neq \pi_e$ the current-account constraint (7) would be violated.

In most EU member states emissions taxes or other emissions control instruments preexisted in their trading sectors when the ETS had been introduced in 2005, and some of these instruments have since been maintained. This gives rise to the question as to how an emissions tax in sector Y affects *an individual country's welfare-maximizing emissions control*, if for some reasons policy makers cannot or do not completely remove that tax.

In such a second-best setting a country's optimal emissions control will be shown to depend on whether or not its government takes into account the impact of its own policy on the equilibrium permit price.[12] In the following Section 3 we explore the 'small country approach' of governments disregarding the impact of their emissions control on the equilibrium permit price. After that the terms-of-permit-trade effect will be included in Section 4.

3 Policy mix in a small open country

Consider an individual country i whose government takes the permit price π_e as given and aims at maximizing its country's welfare defined as its representative consumer's utility. For convenience of notation the index i is suppressed and good Y is chosen as numeraire ($p_y \equiv 1$). The four environmental policy instruments c_x, c_y, t_x and t_y are not independent. If the government fixes c_y, which will be assumed hereafter, then c_x is determined via (4) and t_x via (5), and the choice of t_y remains free. Hence we regard c_y and t_y as autonomous policy instruments, while c_x and t_x are treated as endogenous variables. We will first consider the competitive equilibrium of a small open country for some *given* emissions control (c_y, t_y) and after that the issue of the welfare-maximizing policy choice will be explored. For given (c_y, t_y) and for some given prices p_e and π_e an equilibrium of the small open economy is constituted by an emissions cap c_x, a tax rate t_x, a price p_x and an allocation $(e_x, e_y, x, x_s, y, y_s)$ such that $(e_x, e_y, x, x_s, y, y_s)$ is a solution to the agents' optimization problems and the constraints (3) - (5) hold. The ten variables c_x, t_x, p_x, e_x, e_y, λ, x, x_s, y and y_s are determined by the ten equations contained in (1), (3), (4), (5),

[12]Governments will likely choose to ignore those feedback effects when their country is small relative to the group of countries participating in the ETS.

(7), (11) and (12).[13] We eliminate the variables c_x, e_x, λ, x, x_s and y_s in these equations through substitution thus condensing the ten equations into the four equations

$$\begin{aligned}
\frac{U_x\left[X\left(c-c_y\right), y\right]}{U_y\left[X\left(c-c_y\right), y\right]}-p_x &= 0, && \text{(13a)}\\
\pi_e(c_y-e_y)+\left[Y\left(e_y\right)-y\right]-p_e(c-c_y+e_y) &= 0, && \text{(13b)}\\
Y_e\left(e_y\right)-t_y-p_e-\pi_e &= 0, && \text{(13c)}\\
p_x X_e\left(c-c_y\right)-t_x-p_e &= 0 && \text{(13d)}
\end{aligned}$$

that determine the endogenous variables e_y, p_x, y and t_x. To obtain more qualitative information on how the solution to (13) depends on the permit price π_e and on the policy parameters c_y and t_y we will consider the impact of small changes of those parameters on the equilibrium. Technically speaking, we totally differentiate the equations in (13a)-(13d):

$$\begin{aligned}
\mathrm{d}y-t_y\mathrm{d}e_y-(c_y-e_y)\mathrm{d}\pi_e-(p_e+\pi_e)\mathrm{d}c_y &= 0, && (14)\\
\mathrm{d}p_x-\frac{p_x X_e}{x\sigma}\mathrm{d}c_y-\frac{p_x}{y\sigma}\mathrm{d}y &= 0, && (15)\\
\mathrm{d}e_y+b\mathrm{d}\pi_e+b\mathrm{d}t_y &= 0, && (16)\\
X_e\mathrm{d}p_x-\mathrm{d}t_x-p_x X_{ee}\mathrm{d}c_y &= 0, && (17)
\end{aligned}$$

where $\sigma := \frac{\mathrm{d}\left(\frac{x}{y}\right)}{\frac{x}{y}} \cdot \frac{\frac{U_y}{U_x}}{\mathrm{d}\left(\frac{U_y}{U_x}\right)} \geq 0$ is the elasticity of demand substitution and $b := -\frac{1}{Y_{ee}} > 0$. The solution of (14)-(17) for the endogenous variables $\mathrm{d}e_y$, $\mathrm{d}p_x$ and $\mathrm{d}t_x$ is derived in the Appendix A and summarized in Table 1.[14]

response → shock ↓	$\mathrm{d}p_x$	$\mathrm{d}t_x$	$\mathrm{d}e_x = \mathrm{d}c_x$	$\mathrm{d}e_y$	$\mathrm{d}x_s = \mathrm{d}x$	$\mathrm{d}y_s$	$\mathrm{d}y$	$\mathrm{d}u$
$\mathrm{d}\pi_e$	α^a	α	0	$-$	0	$-$	α	α
$\mathrm{d}t_y$	$-$	$-$	0	$-$	0	$-$	$-$	$-$
$\mathrm{d}c_y$	$+$	$+$	-1	0	$-$	0	$+$	?

[a]where $\alpha := \text{sign}\left[c_y-e_y-bt_y\right]$.

Table 1: Comparative statics of the small open economy for exogenous shocks in π_e, c_y and t_y

Let us first consider $\mathrm{d}t_y > 0$. As a response sector Y reduces both the demand for fossil fuels and the production of good Y. Since the factor demand e_x is fixed due to (4) and (5), the production of sector X is unaffected. The reduction of e_y increases the exogenous

[13]Note that the consumer's budget constraint (c.f. footnote 10) is not included in these equations because owing to Walras law the budget constraint is implied by (3), (7) and the definition of profits.

[14]The last column of Table 1 on the responses of utility to the exogenous shocks is detailed below in (19).

income[15] of country i's representative consumer and hence her demand for good Y. But since the (domestic) supply of good X is inelastic and the price of good Y is normalized to one, p_x and t_x need to decrease to keep demand for good Y in line with supply. The same reasoning applies to sector Y with respect to the shock $\mathrm{d}\pi_e$. As listed in Table 1 the impact of this shock on relevant variables is

$$\operatorname{sign}\left[\frac{\mathrm{d}p_x}{\mathrm{d}\pi_e}\right] = \operatorname{sign}\left[-\frac{\mathrm{d}t_x}{\mathrm{d}\pi_e}\right] = \operatorname{sign}\left[\frac{\mathrm{d}y}{\mathrm{d}\pi_e}\right] = \operatorname{sign}\left[\frac{\mathrm{d}u}{\mathrm{d}\pi_e}\right] = \operatorname{sign}\left[c_y - e_y - bt_y\right] = \alpha. \quad (18)$$

To see the rationale of (18) suppose first that $t_y = 0$ in a permit-exporting country. In that case an exogenous increase in π_e raises the country's exogenous income and thus the demand for both goods, ceteris paribus. Since the (domestic) supply of good X is inelastic, now p_x and t_x rise to keep the demand for good X in line with supply. If $t_y = 0$ and permits are imported, demand for good Y declines and the tendency of the demand for good X to shrink is counterbalanced by declining p_x and t_x. As is straightforward from (18), with an initial positive tax rate t_y these interactions continue to work except that a bias is introduced toward a negative sign of (18). For any given shock $\mathrm{d}\pi_e > 0$ all changes $\mathrm{d}y$, $\mathrm{d}p_x$ and $\mathrm{d}t_x$ are now smaller than in case of $t_y = 0$. As an implication, $\mathrm{d}u$, $\mathrm{d}y$, $\mathrm{d}p_x$ and $\mathrm{d}t_y$ are definitively negative in a permit importing country; in a permit-exporting country they are also negative for large t_y but positive if t_y is sufficiently small. In case of $\mathrm{d}c_y < 0$ the production of sector Y is unaffected whereas the factor demand of sector X increases due to $\mathrm{d}e_x = \mathrm{d}c > 0$. Consequently country i's exogenous income decreases, the demand for good X reduces and the output price p_x and the tax rate t_x decline.

To elaborate the welfare effects of exogenous shocks already included in Table 1 we consider (12), $x_s = x$ and $\mathrm{d}u = U_x\mathrm{d}x + U_y\mathrm{d}y$ from (2), and insert the expression for $\mathrm{d}x$ and $\mathrm{d}y$ derived in the comparative-statics exercise of Appendix A. We thus obtain

$$\frac{\mathrm{d}u}{\lambda} = \left(Y_e - p_x X_e - t_y\right)\mathrm{d}c_y - bt_y\mathrm{d}t_y + (c_y - e_y - bt_y)\mathrm{d}\pi_e. \quad (19)$$

The straightforward implications of (19) are:

(i) For any given emissions control (c_y, t_y), i.e. for $\mathrm{d}c_y = \mathrm{d}t_y = 0$, an increase in the permit price reduces welfare unless the country exports permits *and* its rate of the emissions tax in sector Y is sufficiently small.

(ii) If the permit price is given ($\mathrm{d}\pi_e = 0$), the welfare loss due to the emissions tax in sector Y is increasing in the tax rate and enlarging the permit cap reduces/leaves unchanged/increases welfare depending on whether $Y_e - p_x X_e$ is smaller than/equal to/greater than t_y.

[15]It is worth mentioning that using the representative consumer's exogenous income which can be written as $g^*_{xi} + g^*_{yi} + t_{xi}e_{xi} + t_{yi}e_{yi} = \pi_e(c_{yi} - e_{yi}) - p_e(e_{xi} + e_{yi}) + p_{xi}x_{si} + y_{si}$ in her budget constraint one gets country i's trade balance.

The impact of a change in the permit price on welfare is determined in the same way as the impact of $d\pi_e$ on y, p_x and t_x which has already been commented on in the context of (18).

The policy implications of (19) are highlighted in

Proposition 2.
Suppose all governments take the permit price as given and aim at maximizing their countries' welfare.

(i) If governments are free to choose any rate of an emissions tax in their trading sectors, the efficient competitive equilibrium is characterized by $t_{xi} = \pi_e$, $t_{yi} = 0$ and by $Y_e^i = p_{xi} X_e^i$ for all i.

(ii) If $t_{yi} > 0$ and the government of country i is not able to change that tax rate, its (second-best) optimal emissions control is characterized by

$$Y_e^i - p_{xi} X_e^i - t_{yi} = 0 \tag{20}$$

and hence

$$t_{xi} = \pi_e, \tag{21}$$

which renders inefficient the resultant competitive equilibrium.

(iii) If $t_{yi} > 0$ and constant the second-best permit cap is smaller than the cost-effective one.

Proposition 2i states that with price-taking and welfare-maximizing governments who are free to choose their tax rates the equilibrium allocation is not only optimal from the viewpoint of all governments but also efficient for the group of countries. In contrast, under the conditions of Proposition 2ii, the rule (20) for the second-best permit cap clearly requires the government to choose a permit cap that violates cost effectiveness. According to (20) it is optimal that the marginal abatement costs of sector Y exceed those of sector X by the tax rate t_y. The important message of Proposition 2ii is that if countries maximize welfare and an ETS is in operation, emissions taxes in trading sectors are distortionary.

It is interesting to observe that in the political discussion preceding the introduction of the EU ETS as well as in applied academic studies on its impact (e.g. Böhringer et al. 2005) the national allocation plans to be targeted were typically described as the cost-effective ones (here: $Y_e = p_x X_e$). We are not aware of studies that did not call for cost effectiveness as a necessary condition for emissions control to be efficient from an individual country's perspective. Ignoring this guideline, the national allocation plans that were actually implemented by the member states in the first trading period of the EU ETS (2005-07) seem to have assigned permit caps larger than the cost-effective ones, as argued e.g. by Klepper and Peterson (2004) and Böhringer et al. (2005). This gives rise to the interesting question whether in the presence of an emissions tax in sector Y such 'generous' permit caps are required to (approximately) satisfy (20) or whether, on the contrary, they aggravate the welfare loss. Proposition 2iii provides an answer to that question suggesting that the generous permit cap having been fixed by some EU member states might turn out to be appropriate for welfare-maximizing governments (of small countries). To prove Proposition 2iii it is necessary first to develop the full comparative statics of a country's second-best emissions control for the case of a preexisting emissions tax in sector Y. We will carry out this calculation to obtain an answer to the question as to how the government will adjust its permit cap, if it aims to keep that cap at the second-best level in a changing environment. Our particular focus is on the impact of successive increases of the tax rate t_y (starting from $t_y = 0$).

To follow the second-best policy in a changing environment the government needs to abide by the policy rules (20) and (21). As a consequence, c_y and hence $c_x = c - c_y$ are now determined endogenously. The associated comparative statics are delegated to Appendix B and summarized in Table 2.

response → shock ↓	$\mathrm{d}c_y$	$\mathrm{d}p_x$	$\mathrm{d}t_x$	$\mathrm{d}e_x$ $= \mathrm{d}c_x$	$\mathrm{d}e_y$	$\mathrm{d}x_s$ $= \mathrm{d}x$	$\mathrm{d}y_s$	$\mathrm{d}y$	$\mathrm{d}u$
$\mathrm{d}\pi_e$	?, +[a]	?, +	1	?, −	−	?, −	−	?	?, −
$\mathrm{d}t_y$	+	−	0	−	−	−	−	−	−

[a]The sign next to question marks holds for $c_y - e_y - bt_y < 0$.

Table 2: Comparative statics of a small open economy's second-best emissions control

With regard to optimal adjustments of the permit cap to exogenous shocks Table 2 provides the following insights:

(i) If $t_y \geq 0$ and the permit price increases, ceteris paribus, the permit cap is relaxed unless the country exports a sufficiently large amount of permits. The impact on the optimal permit cap of an increasing permit price depends partly on whether the country imports or exports permits. Yet that impact is significantly biased toward $\mathrm{d}c_y/\mathrm{d}\pi_e > 0$, since even if $t_y = 0$, a permit-exporting country relaxes its permit cap if the export volume is not too large. $\mathrm{d}\pi_e > 0$ hits sector Y and increases its production costs with the consequence that its demand for fossil fuels declines and tax revenues $t_{yi}e_{yi}$ shrink. In addition, the permit price affects the consumer's exogenous income directly. The increased permit price reduces [increases] country i's exogenous income if it imports permits [exports permits and

t_y is sufficiently small]. In case of a permit importing country, the consumers' reaction is to demand less of both goods ($dx_s < 0$, $dy_s < 0$) with the consequence that $de_x < 0$ and $de_y < 0$. The reduction of e_x allows the government to raise the permit cap which partly compensates the country's income loss.

(ii) If the rate of the emissions tax in sector Y is increased, ceteris paribus, the permit cap is relaxed. The effect $dc_y/dt_y > 0$ provides the answer to the question raised above in our comments on (20) as to how exactly the second-best permit cap deviates from the cost-effective permit cap:[16] the latter is less stringent than the former proving Proposition 2iii.

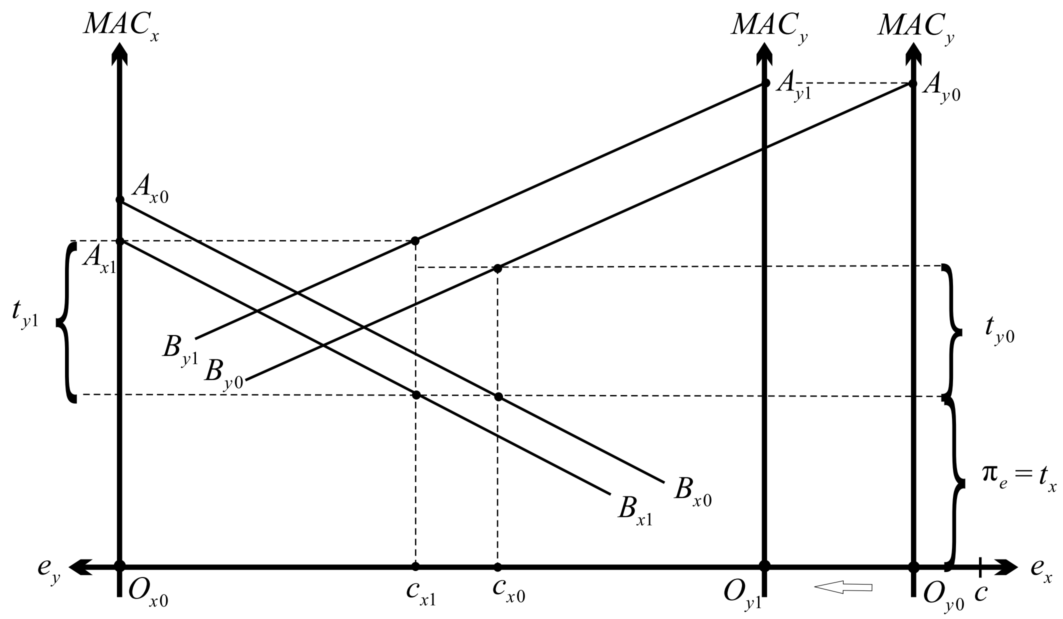

Figure 1: The change in the second-best permit cap induced by an increase in the emissions tax in sector Y

To better understand this result consider the case of a permit-exporting country in Figure 1. In the initial situation (indexed 0) the sectoral marginal abatement curves are $MAC_x = A_{x0}B_{x0}$ and $MAC_y = A_{y0}B_{y0}$ yielding the partition $(c_{x0}, c - c_{x0})$ of the national emissions cap c. t_{y0} is the wedge between both MAC curves at c_{x0} and $c - c_{x0}$, respectively. $de_y < 0$ shifts the origin 0_{y0} to 0_{y1} such that MAC_y is moved from $A_{y0}B_{y0}$ to $A_{y1}B_{y1}$. $dp_x < 0$ shifts MAC_x from $A_{x0}B_{x0}$ to $A_{x1}B_{x1}$. Both of these shifts would increase the wedge (and t_y) if the split (c_{x0}, c_{y0}) would remain unchanged. But we found $dc_x < 0$ such that c_{x0} is shifted to c_{x1} in Figure 1 which tends to reduce the wedge. Hence the reduction in c_x needs to be moderate ensuring that t_{y1} is (still) greater than t_{y0}.

[16]The explanation of the allocative effects of dt_y (row 4 of Table 2) on all endogenous variables is very similar to that of the energy price effects and is therefore omitted here.

The preceding conclusions hold in the small-country case, if and only if a small isolated shock $\mathrm{d}t_{yi} \neq 0$ leaves the permit price unchanged ($\mathrm{d}\pi_e = 0$). Yet this is theoretically correct only for the case of infinitesimally small countries. Whenever the number of countries is finite, each (possibly small) country does have a (possibly small) influence on the permit price. For governments of such countries it may be reasonable, nonetheless, to ignore the small change in the permit price triggered by their policy and, a fortiori, to ignore the adjustments of all other countries' permit caps induced by permit-price changes. To analyze such a scenario, observe first that combining (16) and (6) yields the reaction of the permit price to policy changes:

$$\mathrm{d}\pi_e = -g \sum_j \mathrm{d}c_{yj} - g \sum_j b_j \mathrm{d}t_{yj}, \tag{22}$$

where $g := 1/\sum_j b_j > 0$. As derived in Appendix B (equation (B5)) country i's optimal adjustment of its permit cap to changes in t_{yi} and π_e is given by

$$\mathrm{d}c_{yi} = a_i b_i t_{yi} K_i \mathrm{d}t_{yi} + (1 - a_i \beta_i) K_i \mathrm{d}\pi_e, \tag{23}$$

where $\beta_i := c_{yi} - e_{yi} - b_i t_{yi}$, $a_i := \frac{p_{xi} X_e^i}{y_i \sigma_i} > 0$, $a_{xi} := \frac{p_{xi} X_e^{i2}}{x_i \sigma_i} - p_{xi} X_{ee}^i > 0$ and $K_i := \frac{1}{a_{xi} + a_i p_{xi} X_e^i} = \frac{1}{a_i} \cdot \frac{x_i X_e^i}{X_e^{i2}(y_i + p_{xi} x_i) - x_i y_i X_{ee}^i \sigma_i} > 0$. Inserting (23) into (22) yields, after some rearrangement of terms,

$$\mathrm{d}\pi_e = -\sum_j M_j \mathrm{d}t_{yi}, \tag{24}$$

where $M_j := \frac{b_j(1 + a_j t_{yj} K_j)}{\sum_k [b_k + (1 - a_k \beta_k) K_k]}$. The denominator of M_j is rewritten as

$$\sum_k b_k + \sum_k [(1 - a_k \alpha_k) K_k] = \sum_k b_k + \sum_k [(1 + a_k b_k t_{yk}) K_k] - \sum_k [a_k K_k (c_{yk} - e_{yk})]. \tag{25}$$

Owing to (6) the last term in (25) is the closer to zero the less the terms $a_k K_k$ differ across countries. Since by definition of a_k and K_k we have $\lim_{\sigma_k \to \infty} a_k K_k = 0$, the denominator of M_j in equation (24) is positive if σ_k is sufficiently large (i.e. if the consumption goods X and Y are sufficiently close substitutes). In the sequel we take (25) to be positive.

We now set $\mathrm{d}t_{yi} > 0$, $\mathrm{d}t_{yj} = 0$ for $j \neq i$ and insert (24) into (23) to obtain

$$\mathrm{d}c_{yi} = [a_i b_i t_{yi} K_i (1 + M_i) + K_i M_i - a_i (c_{yi} - e_{yi})] \, \mathrm{d}t_{yi} \tag{26}$$

which is positive unless country i exports large amounts of permits. We summarize our conclusions on the impact of taxes in sector Y on the optimal choice of permit caps in

Proposition 3.
Suppose the governments of all countries take the permit price as given. If some country raises its emissions tax in the trading sector, it is second best for that country to relax its permit cap unless it is a heavy permit-exporter. If that country is so small that the impact of its policy on the permit price is virtually zero it always relaxes its permit cap.

With the help of (24) it is now straightforward to calculate all countries' changes in welfare following some exogenous change in t_y. Again, we set $\mathrm{d}t_{yi} > 0$ and $\mathrm{d}t_{yj} = 0$ for $j \neq i$ and take into account that (20) holds for all i. Combining (24) with (20) then yields

$$\frac{\mathrm{d}u_i}{\lambda_i \mathrm{d}t_{yi}} = -b_i t_{yi}(1 - M_i) - (c_{yi} - e_{yi})M_i, \tag{27}$$

$$\frac{\mathrm{d}u_j}{\lambda_j \mathrm{d}t_{yi}} = -M_i(c_{yj} - e_{yj} - b_j t_{yj}). \tag{28}$$

Proposition 4.
Suppose $\mathrm{d}t_{yi} > 0$, $\mathrm{d}t_{yj} = 0$ *for* $j \neq i$ *and all governments take the permit price as given.*

(i) Let $t_{yi} = 0$ *in the initial equilibrium. Raising* t_{yi} *increases [decreases] country* i*'s welfare if country* i *imports [exports] permits.*

(ii) If $t_{yi} > 0$ *in the initial equilibrium, the welfare effect of raising* t_{yi} *is ambiguous for country* i.

(iii) Raising t_{yi} *enhances the welfare of all countries* $j \neq i$ *except that permit-exporting countries* $j \neq i$ *suffer a welfare loss, if and only if their tax rate* t_{yj} *is sufficiently small.*

4 Policy mix in a large open country

In Section 3 above the determinants of the countries' second-best emissions control have been explored under the assumption that governments ignore the influence of their policy (c_{yi}, t_{yi}) on the permit price π_e. In the sequel we assume that governments take that effect into account. As in Section 3 we now envisage an individual *large* country i with a fixed emissions control (c_{yi}, t_{yi}) and explore the welfare effects of small shocks. Since now that country accounts for (22) we insert (22) into (19) to obtain

$$\begin{aligned}\frac{\mathrm{d}u_i}{\lambda_i} &= \left[Y_e^i - p_{xi}X_e^i - t_{yi} - (c_{yi} - e_{yi} - b_i t_{yi})g\right]\mathrm{d}c_{yi} - \left[b_i t_{yi} + (c_{yi} - e_{yi} - b_i t_{yi})b_i g\right]\mathrm{d}t_{yi} \\ &- (c_{yi} - e_{yi} - b_i t_{yi})g\sum_{j\neq i} b_j \mathrm{d}t_{yj} - (c_{yi} - e_{yi} - b_i t_{yi})g\sum_{j\neq i}\mathrm{d}c_{yj}. \end{aligned} \tag{29}$$

Based on (29) we establish

Proposition 5.
Consider a welfare-maximizing government of a large open country.

(i) If that country has at its disposal an emissions tax in sector Y overlapping with the ETS[17] *and if the rate of the emissions tax in sector Y is not sign-constrained, the country's optimal emissions control is characterized by*

$$\begin{aligned} Y_e^i &= p_{xi} X_e^i, & (30)\\ t_{yi} &= (e_{yi} - c_{yi}) g_{-i}, & (31)\\ t_{xi} &= \pi_e - (c_{yi} - e_{yi}) g_{-i} = \pi_e + t_{yi}, & (32) \end{aligned}$$

where $g_{-i} := 1/\left(\sum_{k \neq i} b_k\right) > 0$.

(ii) If $t_{yi} \geq 0$ and the government is not able to change that rate, its (second best) optimal emissions control is characterized by

$$Y_e^i - p_{xi} X_e^i - \frac{b_i g}{g_{-i}} \left[t_{yi} - (e_{yi} - c_{yi}) g_{-i} \right] = 0 \tag{33}$$

and hence

$$t_{xi} = \pi_e + t_{yi} - \frac{b_i g}{g_{-i}} \left[t_{yi} - (e_{yi} - c_{yi}) g_{-i} \right]. \tag{34}$$

Proposition 5 is proved in Appendix C. Since in the scenario of Proposition 5i the government is free to choose any tax rate t_y, it is optimal from the viewpoint of the individual country to set $t_y < 0$ [$t_y > 0$] if and only if it is a net exporter [importer] of permits. The permit-exporting country subsidizes emissions in its trading sector to stimulate that sector's permit demand which then reduces the country's excess supply of permits and thus raises the permit price. The permit-importing country levies a tax on emissions in its trading sector to restrain that sector's permit demand and excess demand which then lowers both the permit price and the country's permit import bill. For this strategy to be optimal, an additional requirement is the condition (30) of cost effectiveness across *sectors*. Note, however, that marginal abatement costs are not equalized across *countries*, in general.

It is also worth noting that the equilibrium allocation of the large-country model of Proposition 5i converges toward the efficient competitive equilibrium characterized in

[17] In the EU context, emissions subsidies are not only ruled out by pertinent EU legislation but would also seem to be politically inacceptable as they would blatantly violate the polluters-pay principle. One might therefore want to explore the government's optimal strategy when the tax in the trading sector is constrained to be nonnegative. With this qualification the optimal strategy of a permit-importing country is the same as in the absence of a sign constraint, hence optimal in the sense of Proposition 5i. The permit-exporting country is forced, however, to use a second-best strategy choosing its tax rate as small as possible, i.e. $t_{yi} = 0$. Its tax rate in the non-trading sector is positive but smaller than the permit price such that $Y_e^i < p_{xi} X_e^i$.

Proposition 1 when the number of countries is increased.[18] This follows because $g_{-i} \to 0$ for $n \to \infty$.

Proposition 5ii is the counterpart of Proposition 2ii for the large-country case. If the fixed rate t_{yi} happens to satisfy (31) the second-best solution is optimal in the sense of Proposition 5i, but otherwise cost effectiveness is violated, where the difference $Y_e^i - p_{xi}X_e^i$ may exhibit either sign. It is interesting to observe that if a tax with $t_{yi} \geq 0$ preexists the distortion of production efficiency in a permit-exporting country is more severe than in a permit-importing country. Hence according to Proposition 5 competitive equilibria turn out to be inefficient in the large-country case, if the responsibility and discretion either of determining the size of the permit cap and/or of setting overlapping taxes rests with the individual countries. If efficiency is reached for, this observation clearly calls for centralized emissions control as specified in

Proposition 6.
Suppose all countries account for the impact of their policies on the terms of permit trade and there is a central authority with the power of ordering (and enforcing that order effectively and costlessly) each country to

(i) equalize marginal abatement costs across sectors ($Y_e^i = p_{xi}X_e^i$ all i) and/or

(ii) refrain from levying a tax or subsidy in the trading sector ($t_{yi} = 0$ all i).

The pertaining competitive equilibrium is efficient if and only if the central authority exercises both of these powers.

Tariffs. As is well known from the standard theory of trade among large countries governments have an incentive to apply tariffs, either import duties or export subsidies, for improving their countries' terms of trade. In the present paper, tariffs (and trade policy altogether) are not at the governments' disposal. The question arises, however, to what extent the optimal emissions taxes t_{yi} specified in (31) serve as a surrogate for (infeasible) optimal tariffs. The answer is readily provided by

[18] An alternative convergence result is obtained for any given number of countries when the countries' strictly concave production functions Y^i tend to become linear ($Y_{ee}^i \to 0$ for all i).

Proposition 7.

Consider a welfare-maximizing government of a large open country that does not use an emissions tax in sector Y but is able, instead, to impose a tariff at rate $\theta \gtreqless 0$ on the country's exports or imports of permits. The optimal policy mix is characterized by (30), (31) and (32) with t_{yi} being replaced by θ in (30) and (31).

To see that equivalence observe that switching from tax to tariff changes the definition of sector Y's profit from $Y^i(e_{yi}) - \pi_e(e_{yi} - c_{yi}) - (t_{yi} + p_e)e_{yi}$ (as introduced in Section 2) to $Y^i(e_{yi}) - (\pi_e + \theta)(e_{yi} - c_{yi}) - p_e e_{yi}$. The first-order condition for profit maximization now reads $Y_e^i(e_{yi}) = \theta + p_e + \pi_e$ which differs from (11) only in that t_{yi} is substituted by θ. Hence the optimal allocation is the same with either policy. However, the maximum profit of sector Y in the scenario of Proposition 5 is smaller than that in Proposition 7 by the lumpsum amount $-\theta c_y$.

Fiscal externalities. While the government of a large country takes into account the permit-price effect of its choice of (c_y, t_y) on the utility of its own residents, it ignores the impact of that effect on the utility of all other countries' residents. To specify these fiscal externalities, suppose a Cournot-Nash equilibrium of the multi-country model is attained and assume that some country i raises either c_{yi} or t_{yi} by a small amount while the policy parameters of all other countries remain unchanged. Invoking (29) and (31) the impact of those policy shifts on the welfare of some country j, $j \neq i$, are calculated as

$$\frac{\mathrm{d}u_j}{\lambda_j \mathrm{d}c_{yi}} = g\left(e_{yj} - c_{yj} + b_j t_{yj}\right) = t_{yj}, \tag{35}$$

$$\frac{\mathrm{d}u_j}{\lambda_j \mathrm{d}t_{yi}} = b_j g\left(e_{yj} - c_{yj} + b_j t_{yj}\right) = b_j t_{yj}. \tag{36}$$

(35) and (36) reveal that $\mathrm{d}c_{yi} > 0$ and $\mathrm{d}t_{yi} > 0$ enhance or diminish country j's welfare depending on whether country j exports ($t_{yj} > 0$) or imports ($t_{yj} < 0$) emissions permits. It follows that Pareto improvements of the Cournot-Nash equilibrium allocation cannot be secured by small out of equilibrium changes of fiscal parameters. More specific results are obtained by applying a utilitarian welfare criterion.

Proposition 8.

Suppose the governments of all countries account for the permit-price effect of their policy on the utility of their country's residents (large-country case).

(i) In a Cournot-Nash equilibrium with more than two countries, the policy parameters (c_y, t_y) of all permit-exporting [permit-importing] countries are inefficiently small

[large] if[19]

$$\text{sign} \sum_{j \neq i} \frac{\mathrm{d}u_j}{\mathrm{d}c_{yi}} = \text{sign}\,(c_{yi} - e_{yi}) \quad \textit{for all } i \quad \textit{and} \tag{37}$$

$$\text{sign} \sum_{j \neq i} \frac{\mathrm{d}u_j}{\mathrm{d}t_{yi}} = \text{sign}\,(c_{yi} - e_{yi}) \quad \textit{for all } i. \tag{38}$$

holds.

(ii) In a Cournot-Nash equilibrium with two countries the policy parameters (c_y, t_y) *of the permit-exporting [permit-importing] country are inefficiently small [large].*

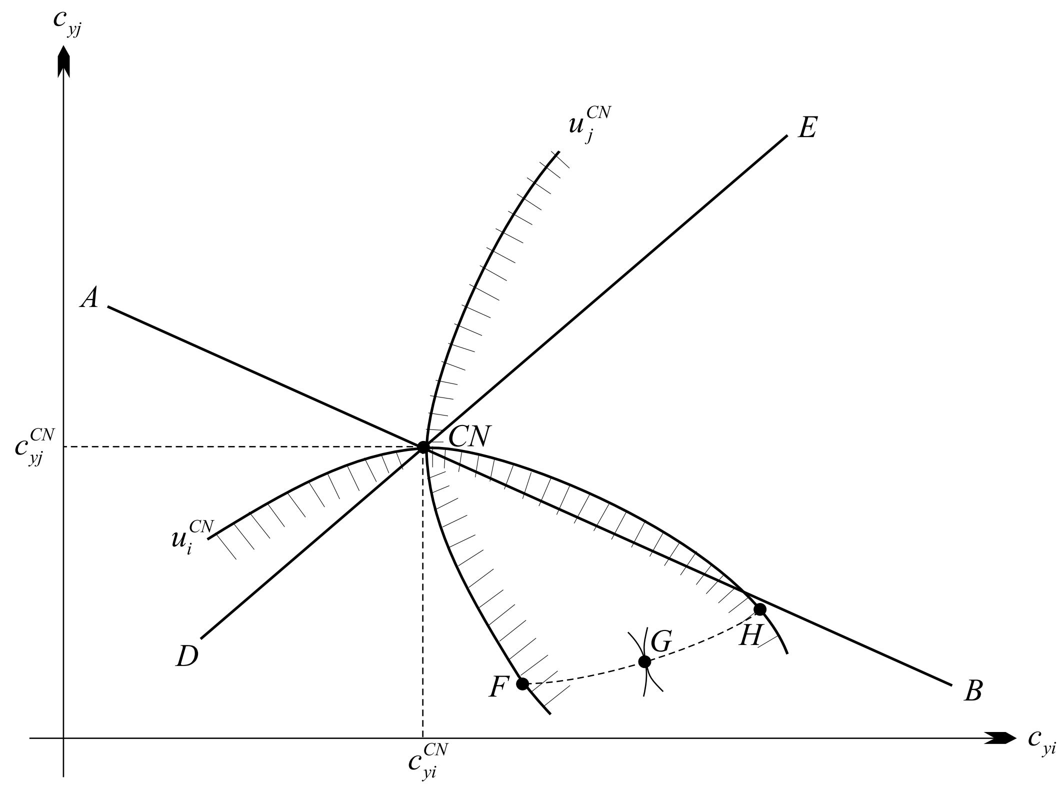

Figure 2: Cournot-Nash equilibrium for two-large countries

The two country-case of Proposition 8ii is illustrated in Figure 2, where DE and AB are the reaction curves of the countries i and j, respectively. In equilibrium (point CN in Figure 2) the countries' welfare levels are u_i^{CN} and u_j^{CN}. Country i's [country j's] better set is below CN [to the right side of CN] so that owing to (35) and (36) country i exports permits and country j imports permits. The full comparative statics reveals that the slope of the permit-importing country j's reaction curve is unambiguously negative while

[19]It is sufficient but by no means necessary for the conditions (37) and (38) to hold that $\lambda_j = \lambda_i$ and $b_j = b_i$ for all countries i and j.

the slope of the permit-exporting country i's reaction curve may be positive or negative. Shifting the allocation from the equilibrium point CN to a Pareto-optimal point such as G in Figure 2 clearly raises both countries' welfare. Figure 2 offers a partial illustration of the Cournot-Nash equilibrium only because the tax rates t_{yi} and t_{yj} need to be determined simultaneously. This can be shown in a (two-dimensional) diagram that is similar as Figure 2. Starting from equilibrium both countries welfare can be enhanced by increasing t_{yi} and reducing t_{yj}.[20]

Comparing the cases of small and large countries As already mentioned above, governments need not necessarily account for the terms-of-permit-trade effect even if their policy does have some impact on the permit price. They have the alternative option of behaving as permit price takers. Denoting as economy S our multi-country model when all governments behave as price takers and as economy L the model where all governments manipulate the terms of permit trade we wish to carry out a welfare comparison of the equilibrium allocations of these two types of economies. Clearly, a competitive equilibrium of economy S [economy L] is characterized by Proposition 1 [Proposition 5]. Since the equilibrium allocation of economy L is inefficient from the perspective of the group of countries, some countries necessarily suffer a welfare loss by switching from economy S to economy L. It cannot be ruled out, however, that some country benefits from that switch. More specific insights are provided in

Proposition 9.
Consider a competitive equilibrium of the economy L and a competitive equilibrium of the economy S and denote the equilibrium permit price by π_e^L in the former and by π_e^S in the latter economy. Country i experiences a welfare gain when the (initial) economy L is turned into an economy S,

(i) if country i is exporting permits in economy L and if $\pi_e^L \leq \pi_e^S$ or

(ii) if country i is importing permits in economy L and if $\pi_e^L \geq \pi_e^S$.

Proposition 9 is proved in Appendix D. For the countries not covered by Proposition 9 the likelihood to fare better in economy L than in economy S is small for the following reason. As shown in the proof of Proposition 9 a necessary condition for a welfare-enhancing shift from economy L to economy S is a sufficiently large divergence of π_e^L and π_e^S. But if one starts from an equilibrium of economy L and all tax rates are reduced in absolute value, the following partial effects on the permit price are observed: If a permit-exporting country

[20] Assuming that the payoff functions are strictly concave we arrive at the inefficiencies of Proposition 8ii.

lowers its emissions subsidy its excess supply of permits increases which tends to lower the permit price, ceteris paribus. On the other hand, if a permit-importing country lowers its emissions tax, its excess demand of permits increases which tends to raise the permit price, ceteris paribus. Although these opposite effects will not necessarily eliminate divergences between the equilibrium permit prices π_e^L and π_e^S altogether, they will work toward reducing them.

5 Concluding Remarks

In a stylized way, our paper addresses efficiency implications of a hybrid regime of CO_2 emissions control designed to capture some basic features of the regime applied in the EU since 2005. Characteristic of the EU regime is an EU-wide international ETS that coexists with national complementary and overlapping national emissions taxes. In the small-country case, national governments are shown to receive correct incentives to accomplish efficiency for the group of countries. In particular, governments find it optimal to refrain from levying an emissions tax in their trading sector overlapping with the ETS. Insofar, our result supports the 'no-overlap proposition' alluded to in the introduction.

Yet in the more realistic case of inert preexisting emissions taxes in the trading sector, we show that it is optimal for small countries to choose for their trading sector an emissions cap that is 'excessive' from the viewpoint of the group of countries. It is interesting to confront that result with economic assessments of the EU countries' national allocation plans set up in 2004 for the first trading period 2005-2007. The pertaining literature (e.g. Klepper and Peterson 2004, Böhringer et al. 2005) almost unisonously criticized those plans on the grounds of an allegedly overly generous allocation of permits to their trading sector. Yet these studies did not account for inert overlapping emissions taxes. If this is done as in our analysis above, the permit caps actually chosen in 2004 might not have been excessive, after all, from the welfare point of view of small countries.

Nonetheless, with some reservations (see below) the no-overlap rule can be considered a sensible guideline for small countries. However, that rule is definitively not in the interest of countries whose governments take into account the impact of their policies on the terms of permit trade. Even if there were a central authority such as the EU Commission with the competence to enforce the rule in the large-country case and at the same time leaves some discretion with national governments for determining their own permit caps, the outcome would not be efficient for the group of countries under consideration. Moreover, a preexisting inert emissions tax in a country's trading sector tends to improve [reduce] the country's welfare as compared to the no-tax situation, if that country imports [exports] permits. Provided that countries are not too small, this is even true in the small-country case implying, in fact, that countries with permit-price taking governments have an incentive to remove that tax if and only if they export permits. In contrast, permit-importing countries would benefit from a tax in their trading sector irrespective of whether their governments choose to ignore the permit-price reducing effect of their policy.

The model scrutinized in the present paper maps the EU CO_2 emissions control scenario in a very simple way. One would need to add more structure and complexity to address further important issues such as the impact of the ETS on the competitiveness of trading-sector firms relative to competing firms in other EU countries and in non-EU countries. Another feature deserving more attention is the power-generating industry. It plays a key role in most countries' trading sectors since it supplies electricity for other branches in the domestic trading and nontrading sector and for other EU countries. Further research along these lines will improve our understanding of the efficiency implications of hybrid emissions control strategies such as the one employed in the EU.

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Appendix A: Comparative statics of the small open country when c_y and t_y are arbitrarily fixed (Table 1)

For given p_e, $p_y \equiv 1$ and π_e and for given policy parameters c, c_y and t_y the equilibrium of an individual economy is determined by the ten equations $x = X(e_x)$, $y = Y(e_y)$, $x = x_s$, $c = c_x + c_y$, $\pi_e(c_y - e_y) + p_y(y_s - y) - p_e(e_x + e_y) = 0$, $p_x X_e(e_x) = t_x + p_e$, $p_y Y_e(e_y) = t_y + p_e + \pi_e$, $U_x(x, y) = \lambda p_x$ and $U_y(x, y) = \lambda p_y$.
These equations can be reduced to the equations listed in (13) that determine the variables e_y, p_x, y and t_y. Total differentiation of these equations yields (14) - (17). The solution of this system of equations is

$$\mathrm{d}e_y = -b\mathrm{d}t_y - \mathrm{d}\pi_e, \tag{A1}$$

$$\mathrm{d}y = (c_y - e_y - bt_y)\mathrm{d}\pi_e - bt_y\mathrm{d}t_y + (p_e + \pi_e)\mathrm{d}c_y, \tag{A2}$$

$$\mathrm{d}p_x = \left(\frac{p_x}{\sigma y}\right) \cdot \left[(c_y - e_y - bt_y)\mathrm{d}\pi_e - bt_y\mathrm{d}t_y + \left(p_e + \pi_e + \frac{y}{x}X_e\right)\mathrm{d}c_y\right], \tag{A3}$$

$$\mathrm{d}t_x = a(c_y - e_y - bt_y)\mathrm{d}\pi_e - abt_y\mathrm{d}t_y + \left[a\left(p_e + \pi_e + \frac{y}{x}X_e\right) - p_x X_{ee}\right]\mathrm{d}c_y, \tag{A4}$$

where $a := \frac{p_x X_e}{y\sigma}$.

Appendix B: Determinants of the (second) best permit emissions control when the government levies a tax in sector Y and takes the permit price as given (Table 2)

The efficient split requires (20) to hold irrespective of whether $t_y \equiv 0$ or $t_y > 0$. In addition, c_y is now endogenous. With this modifications the equations (13) carry over. Total differentiation with respect to the parameters p_e, π_e and c yields (14), (15), (16) and

$$X_e \mathrm{d}p_x - p_x X_{ee} \mathrm{d}c_y - \mathrm{d}\pi_e = 0. \tag{B1}$$

Next we combine (14) and (16) to get

$$-p_x X_e \mathrm{d}c_y + \mathrm{d}y = (c_y - e_y - bt_y)\mathrm{d}\pi_e - bt_y \mathrm{d}t_y. \tag{B2}$$

The equations (B1), (B2) and (15) jointly determine $\mathrm{d}p_x$, $\mathrm{d}c_y$ and $\mathrm{d}y$. To solve for these variables we rewrite these equations in matrix form

$$\begin{pmatrix} 1 & -\frac{p_x X_e}{x\sigma} & -\frac{p_x}{y\sigma} \\ X_e & -p_x X_{ee} & 0 \\ 0 & -p_x X_e & 1 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{d}p_x \\ \mathrm{d}c_y \\ \mathrm{d}y \end{pmatrix} = \begin{pmatrix} 0 \\ \mathrm{d}\pi_e \\ (c_y - e_y - bt_y)\mathrm{d}\pi_e - bt_y \mathrm{d}t_y \end{pmatrix}. \tag{B3}$$

The determinant of the matrix in (B3) is $H := a_x + ap_x X_e > 0$, where $a_x := \frac{p_x X_e^2}{x\sigma} - p_x X_{ee} > 0$. Applying Cramer's rule yields after some rearrangement of terms

$$\begin{aligned} \mathrm{d}p_x \cdot H &= ap_x X_{ee} bt_y \mathrm{d}t_y + \left[\frac{p_x X_e}{x\sigma} + \frac{p_x^2 X_e}{y\sigma} - \frac{p_x^2 X_{ee}}{y\sigma}(c_y - e_y - bt_y)\right] \mathrm{d}\pi_e, && \text{(B4)} \\ \mathrm{d}c_y \cdot H &= abt_y \mathrm{d}t_y + [1 - a(c_y - e_y - bt_y)]\,\mathrm{d}\pi_e, && \text{(B5)} \\ \mathrm{d}y \cdot H &= a_x bt_y \mathrm{d}t_y + [p_x X_e + (c_y - e_y - bt_y)a_x]\,\mathrm{d}\pi_e. && \text{(B6)} \end{aligned}$$

Differentiating $e_x = c_x = c - c_y$ with respect to $\mathrm{d}c$ accounting for (B5) we get

$$\frac{\mathrm{d}c_x}{\mathrm{d}c} = \frac{\mathrm{d}e_x}{\mathrm{d}c} = \frac{t_x a}{H}. \tag{B7}$$

All other signs of Table 2 are straightforward.

Appendix C: Proof of Proposition 5

To prove Proposition 5i we infer from (29) that the efficient t_{yi} satisfies $\mathrm{d}u_i/(\lambda_i \mathrm{d}t_{yi}) = 0$ and hence $t_{yi} + (c_{yi} - e_{yi} - b_i t_{yi})g = 0$ which implies (30). $t_{yi} + (c_{yi} - e_{yi} - b_i t_{yi})g = 0$ can be transformed to read

$$t_{yi}(1 - b_i g) - (c_{yi} - e_{yi})g = 0. \tag{C1}$$

By definition of g we obtain $1-b_i g = 1-\frac{b_i}{\sum_k b_k} = \frac{\sum_k b_k - b_i}{\sum_k b_k} = \frac{g}{g_{-i}} > 0$. Inserting this result in (C1) yields (31). (29) further implies that the efficient c_{yi} is characterized by the equation

$$\frac{\mathrm{d}u_i}{\lambda_i \mathrm{d}t_{yi}} = \pi_e - t_{xi} - (c_{yi} - e_{yi} - b_i t_{yi})g = 0. \tag{C2}$$

From (C2) it is straightforward that $t_{xi} = \pi_e - (c_{yi} - e_{yi})g + b_i t_{yi} g$. We invoke t_{yi} from (31) to obtain $t_{xi} = \pi_e - (c_{yi} - e_{yi})(1 + b_i g_{-i})g$. We also find that $1 + b_i g_{-i} = \frac{\sum_{k\neq i} b_k + b_i}{\sum_{k\neq i} b_k} = \frac{g_{-i}}{g}$, and therefore (32) follows. The proof of Propsition 5ii is similar to that of Propsition 5i and therefore omitted.

Appendix D: Proof of Proposition 9

To prove Proposition 9 we start from the equilibrium allocation of an individual country in economy L which is described by (13) and the additional equation

$$t_x = t_y + \pi_e^L. \tag{D1}$$

The first step is to keep π_e^L constant and to determine the effects on welfare of the small exogenous changes in t_y under the constraint of maintaining the equation $p_x X_e = Y_e$ which requires appropriate endogenous adjustments of c_y. We show that successive small changes of t_y toward zero raise welfare monotonously. When $t_y = 0$ is reached we consider small changes of π_e^L toward π_e^S keeping $t_y = 0$. If in that second step welfare is also increasing Proposition 9 is proved.

Step 1. if $\mathrm{d}t_x = \mathrm{d}t_y + \mathrm{d}\pi_e$ from (D1) is combined with (14)-(17) one obtains the system of equations

$$\begin{pmatrix} -X_e & p_x X_{ee} & 0 \\ -1 & \frac{p_x X_e}{x\sigma} & \frac{p_x}{y\sigma} \\ 0 & p_e + \pi_e & -1 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{d}p_x \\ \mathrm{d}c_y \\ \mathrm{d}y \end{pmatrix} = \begin{pmatrix} -\mathrm{d}t_y \\ 0 \\ b t_y \mathrm{d}t_y \end{pmatrix}. \tag{D2}$$

The determinant is $D = a_x + a(p_e + \pi_e) > 0$. We also obtain

$$\mathrm{d}y = \frac{p_e + \pi_e - a_x b t_y}{D} \qquad \text{and} \qquad \mathrm{d}c_y = \frac{1 + a b t_y}{D}. \tag{D3}$$

Inserting (D3) into $\frac{\mathrm{d}u}{\lambda} = p_x \mathrm{d}x + \mathrm{d}y = -p_x X_e \mathrm{d}c_y + \mathrm{d}y$ yields

$$D \cdot \frac{\mathrm{d}u}{\lambda} = -\left[1 + (a p_x X_e + a_x)b\right] t_y \mathrm{d}t_y. \tag{D4}$$

(D4) implies that shifting t_y toward zero (from some given positive or negative value of t_y) is unambiguously welfare enhancing.

Step 2. We invoke (20) for $t_y = 0$ and consider $\pi_e = \pi_e^L$ as the starting point. If $c_{yi} > e_{yi}$

and $\pi_e^S < \pi_e^L$ then small reductions of π_e to shift π_e^L toward π_e^S are welfare decreasing. Hence the partial welfare effects of the first and second step are opposite in sign such that the sign of the net welfare effect is unclear. If $c_{yi} > e_{yi}$ and $\pi_e^S \geq \pi_e^L$ the partial welfare effects in both steps are positive which proves Proposition 9i. Proposition 9ii follows by analogous arguments.

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