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Abstract

The starting point of the paper is that a group of countries (henceforth called "the home country") commit themselves to cooperating, while the remaining countries (henceforth called "the foreign country") act in pure self-interest, taking greenhouse gas emissions from other countries, as well as international prices of fossil fuels, as given. Within this context, the optimal climate policy of the home country is derived. The objective of the home country is to maximize its own income, subject to a constraint on the sum of CO_2 emissions from <u>all</u> countries. In addition to its choice of domestic policies, the home country can induce, using an appropriate transfer, the foreign country to implement policies affecting its consumption and/or production of fossil fuels. The following three main results are derived and elaborated in the paper, assuming a binding emission constraint and considering taxes on consumption and/or production of fossil fuels as the relevant policy instruments: (1) in the home country, it is optimal to have a positive tax on the consumption and/or the production of fossil fuels. The optimal combination of a consumption and production tax depends on how large emissions are permitted to be, and on the size of the home country's net imports of fossil fuels (in particular, of whether net imports are positive or negative); (2) consumer prices of fossil fuels, i.e the tax rates on consumption of fossil fuels, are equal in the home and foreign country if a consumption tax in the foreign country is an available policy option; (3) producer prices of fossil fuels, i.e the tax rates on production of fossil fuels, are equal in the home and foreign country if a production tax in the foreign country is an available policy option.

[1] I am grateful to Rolf Golombek and Cathrine Hagem for useful comments on an earlier version of the paper.

1. Introduction

As long as there is no international law to force countries to participate in an international climate agreement, each country may have an incentive to be a free rider, i.e. to stay outside the agreement instead of participating in it. If the country stays outside the agreement, it can enjoy (almost) the same benefits of reduced emissions as if it participates in the agreement, while it doesn't bear any of the costs of reducing emissions. This free rider incentive remains even if the agreement is such that all countries are better off with the agreement than without: A country may be better off participating in an agreement than it would be without any agreement. But it will usually be even better off if the other countries cooperate, while it itself stays outside the agreement and pursues its self-interest.

The issue of free riding has been studied in more detail by e.g. Barrett (1991), Carrero and Siniscalco (1991) and Hoel (1992a). Here it is shown that in spite of the free rider incentive, a stable coalition of cooperating countries may exist. The coalition is stable in the sense that it is not in the self-interest of any country to break out of the coalition. The reason why such a stable coalition may exist is that each potential defector knows that if it breaks out of the coalition, the optimal response of the remaining countries will be to increase their emissions, which will hurt the defector more than the costs it saves by defecting. However, the studies mentioned above demonstrate that for problems such as the climate problem, the number of countries in a stable coalition is likely to be very small. Moreover, total emissions from all countries will not be much lower than they are in the non-cooperative equilibrium.

So far, no climate agreement between countries exists. It is likely that some form of agreement will be reached during the next decade. However, at least initially, the free rider problem makes it very unlikely that all countries will participate in such an agreement. Nevertheless, it may be possible to reach an agreement between a larger number of countries than the number corresponding to the stable coalition of the type mentioned above. One reason why countries may commit themselves to cooperating is the fact that decisions of greenhouse gas emissions, and of whether or not to participate in an international agreement, may be continuously revised. These decisions may therefore be treated as a repeated game. It is well known from the literature on game theory that it may be possible to sustain tacit cooperation as a perfect equilibrium of a non-cooperative (infinitely) repeated game, see e.g. Mäler (1989) and Torvanger (1992) for a discussion in the context of international environmental agreements. The fact that decisions about greenhouse gas emissions are continuously repeated may thus solve the free rider problem. However, as repeated games of this type have multiple equilibria, the coordination problems of reaching a Pareto optimal equilibrium are large. Obviously, these coordination problems are larger the larger the number of countries involved. It therefore seems likely that only a subset of all countries will commit themselves to cooperation.

The starting point of this paper is that some countries commit themselves to cooperating, in spite of the free rider incentive that each country might have (at least in a static context). This group of countries is in the analysis treated as one country, and henceforth called "the home country". The remaining countries (henceforth called "the foreign country") act in pure self-interest, taking greenhouse gas emissions from other countries, as well as international prices of fossil fuels, as given. Within this context, the optimal climate policy of the home country is derived. Greenhouse gases other than CO_2 are exogenous in the analysis. The objective of the home country is to maximize its own income, subject to a constraint on the sum of CO_2 emissions from all countries. In addition to choosing its own policies, the home country can induce the foreign country to implement policies affecting its consumption and/or production of fossil fuels.[1] This is achieved through a transfer from the home to the foreign country,

[1] Using somewhat different assumptions than the present paper, Carrero and Siniscalco (1991) have studied the possibility of a group of committed countries to expand the cooperating coalition through the use of transfers to the non-committed countries.

making the latter equally well off with the transfer and its policy towards fossil fuel consumption/production as it would have been without the transfer and without this policy.

In a situation where all countries participate in an agreement to reduce CO_2 emissions, it is easily shown that taxes (or other policies) on the consumption of fossil fuels and taxes on the production of fossil fuels have identical economic consequences, see e.g. Hoel (1992b). This is no longer true when there is limited participation in the international agreement, as in the present context. In this case the international price of fossil fuels, and therefore consumption and production of fossil fuels in the foreign country, depend on the policies chosen in the home country, see e.g. Bohm (1992) and Pezzey (1991). There is therefore a particular combination of taxes on consumption and production of fossil fuels in the home country which is optimal. This has been discussed previously by Hoel (1992b) for the case in which demand and supply policies in the foreign country are ignored. In the present context, it is therefore important to distinguish between policies affecting the consumption of fossil fuels and policies affecting the production of fossil fuels.

In the home country, policy options are assumed to include both policies directed towards consumption and/or towards production. Obvious candidates for policy instruments are taxes (or subsidies) on consumption and/or production of fossil fuels. Throughout the paper, it is assumed that these are the policy instruments used to achieve desired levels of consumption and production. However, the focus of the analysis is on the optimal levels of consumption and production of fossil fuels, and not on what instruments one uses to implement these quantities. The results of the paper are therefore valid (with appropriate reformulations) also for other policy instruments than taxes.

In the present paper, three alternative cases are considered for policy options in the foreign country: (a) the only policy instrument available in the foreign country is a policy directed toward its consumption of fossil fuels (e.g. a tax on the consumption of fossil fuels); (b) the only policy instrument available in the foreign country is a policy directed toward its production of fossil fuels (e.g. a tax on the production of fossil fuels); and (c) policy options in the foreign country include policies directed both towards its consumption and its production of fossil fuels. For all three cases the policy instruments assumed in the analysis are consumption and production taxes (or subsidies). However, also for the foreign country it is the levels of consumption and production of fossil fuels which matters, and not what instruments the foreign country uses to reach these levels. With appropriate reformulations, the results are therefore valid also for other policy instruments than taxes in the foreign country.

Throughout the paper, the markets for fossil fuels are treated as one aggregate, competitive market, called the carbon market. In reality, there are of course several (interrelated) markets for different types of fossil fuels, and all of these deviate more or less from perfect competition. However, the intuitive discussion of the results (given in sections 3-5) is not explicitly linked to these simplifying assumptions. There is therefore reason to expect that similar results hold also under less restrictive assumptions than those used in the formal analysis.

All consumers and producers (at home and abroad) are assumed to be price takers. In addition, the authorities of the foreign country regard the price of carbon as exogenous. This is because "the foreign country" in reality consists of many individual countries acting independently, and each of them is assumed to be so small that its influence on the price of carbon is negligible. The "home country", on the other hand, is a group of countries which are explicitly assumed to cooperate to maximize their total income. When choosing their policies, the authorities of the home country are therefore assumed to take into consideration how the policies affect the international price of carbon.

Throughout the analysis, corner solutions are disregarded. In other words, for all relevant prices, both the home and foreign country is assumed to have positive consumption and production of carbon. The main results would remain valid (with appropriate adjustments) even if e.g. either the home or foreign country was assumed to have zero production of carbon.

The main features of the model are presented in section 2. The three cases (a)-(c) above are treated in sections 3-5, before some concluding comments are given in section 6.

2. The model

In addition to the international price of carbon, which is denoted by p, the following notation is used:

Table 1: Notation

	Home country	Foreign country
consumption	y	Y
production	x	X
utility	$u(y)$	$U(Y)$
production cost	$c(x)$	$C(X)$
consumer price	q	Q
producer price	r	R
demand	$d(q)$	$D(Q)$
supply	$s(r)$	$S(R)$
consumer tax	$t^c = q-p$	$T^c = Q-p$
producer tax	$t^p = p-r$	$T^p = p-R$
welfare	$w=u(y)-c(x)-p\cdot(y-x)-I$	$W=U(Y)-C(X)-p\cdot(Y-X)+I$

The demand and supply functions correspond to the utility and cost functions, i.e. $y=d(q)$ is given by $u'(y) = q$, $x=s(r)$ is given by $c'(x)=r$, etc.

The transfer to the foreign country is denoted by I. Notice that in equilibrium we must have $(y-x)+(Y-X)=0$, so that the last line of table 1 gives total welfare as $w+W=[u(y)+U(Y)]-[c(x)+C(X)]$.

The home country is assumed to choose its policy instruments so that total carbon emissions do not exceed a target level V. We thus have

(1) $$y+Y = x+X \leq V$$

Throughout, it is assumed that the home country can choose, through its choice of tax rates t^c and t^p (in the notation of table 1), its own consumption and production of carbon. In other words, x and y are regarded as policy variables, which are chosen optimally. The policy objective of the home country is to maximize its welfare level (given by w in table 1) subject to the constraint (1). The optimal policy depends on what options the home country has for influencing consumption and production of carbon in the foreign country, and on how the international carbon price p and the transfer I are affected by the quantities chosen by the home country. The next three sections treat the three alternative cases in which the home country can determine the level of Y, of X, and of Y and X, respectively.

3. Demand oriented policy in the foreign country

In this section, it is assumed that the home country can induce the foreign country to set its use of carbon (i.e. Y) at a level determined by the home country. To be willing to consume an amount of carbon determined by the home country, the foreign country must receive a transfer. The size of this transfer is determined so that the foreign country is equally well off with its imposed use of carbon and the transfer as it would have been without the transfer, but with the right to choose its consumption optimally. Since $T^p=0$ by assumption in the present case, the optimal production of carbon in the foreign country is given by X=S(p) (or C'(X)=p), i.e. independent of its carbon consumption. It therefore follows from the definition of the foreign country's welfare level (given by W in table 1) that the transfer I is determined by

$$I = I(p,Y) = \max_{\psi}[U(\psi)-p\psi] - [U(Y)-pY] \tag{2}$$

Using the envelope theorem, we find

$$\begin{aligned} I_p &= Y-D(p) \\ I_Y &= -U'(Y)+p \end{aligned} \tag{3}$$

Inserting X=S(p) into (1) gives x+S(p) = y+Y, or

$$p = p(Y+y-x) \tag{4}$$

where p'=1/S'>0. Inserting (2) and (4) into the definition of the welfare level of the home country (give by w in table 1), the maximization problem of the home country may be written as

$$\begin{aligned} &\max_{x,y,Y} \; [u(y)-c(x)-p(Y+y-x)\cdot(y-x)-I(p(Y+y-x),Y)] \\ &s.\ t.\ \; y+Y \le V \end{aligned} \tag{5}$$

For an interior solution (i.e. x, y and Y positive) the first order conditions are (using (3))

$$u'(y) = U'(Y) \tag{6}$$

(7) $$u'(y) = p+H+\lambda$$

(8) $$c'(x) = p+H$$

where λ is the shadow price of the emission constraint $y+Y\leq V$. We must always have $\lambda\geq 0$, with a strict inequality provided the emission constraint is binding, which we assume throughout[2].

The term H is given by

(9) $$H = [(y-x) + (Y-D(p))]\cdot p'$$

From (6) our first proposition immediately follows:

<u>Proposition 1</u>: **Buyers in the home and the foreign country should face the same consumer price of carbon, i.e. the consumer tax should be equal at home and abroad.**

<u>Proof</u>: With the notation from section 2, the consumer prices in the two countries are q and Q, giving $u'(y)=q$ and $U'(Y)=Q$. It thus follows from (6) that $q=Q$.

□

Using the notation from section 2, (7) and (8) may be rewritten as

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[2] To be more precise: It is assumed that the optimal value of $y+Y$ from the maximization problem given by (5) is lower than the optimal value of $y+Y$ for the corresponding maximization problem without the constraint $y+Y\leq V$.

$$t^c = q - p = H + \lambda \tag{10}$$
$$t^p = p - r = -H$$

From (10) we immediately get the following propositions:

Proposition 2: The sum of the consumer and producer tax rate in the home country is positive.

Proof: Proposition 2 follows directly from (10), which gives $t^c+t^p=\lambda>0$.

□

Proposition 2 implies that there can never be a subsidy both on production and consumption. This is intuitively obvious, as such a combined subsidy would increase emissions compared with the case of no climate policy.

Proposition 2 says nothing about if and when one should subsidize either consumption or production. Our four next propositions deal with this question. We start by giving the propositions and proofs, after which an interpretation is offered.

Proposition 3: If the home country's consumption of carbon is sufficiently close to its production of carbon (i.e. if |y-x| is sufficiently small), both consumers (at home and abroad) and producers (at home) should be taxed.

Proof: Assume that $t^c=T^c\leq 0$. This implies (using (10)) that $H\leq-\lambda$. Moreover, $Y=D(Q)=D(p+T^c)\geq D(p)$ in this case, which is compatible with $H\leq-\lambda<0$ only if the term y-x is negative and |y-x| is sufficiently large (cf. (9)). So if |y-x| is sufficiently small, we must have $t^c=T^c>0$. Assume next that $t^p\leq 0$. It then follows from (10) that $H\geq 0$ and therefore $t^c=T^c>0$. In this case we thus have $Y=D(Q)=D(p+T^c)<D(p)$, which is

compatible with H≥0 only if the term y-x is positive and sufficiently large (cf. (9)). So if |y-x| is sufficiently small, we must have $t^p>0$.

□

Proposition 4: **For a sufficiently strict emission constraint (i.e. for V sufficiently small), both consumers (at home and abroad) and producers (at home) should be taxed.**

Proof: See Appendix I.

Proposition 5: **For a sufficiently weak emission constraint (i.e. for V sufficiently large), we almost always have either a consumer subsidy (at home and abroad) or a producer subsidy (at home).**

Proof: The size of λ depends on how strict the emission constraint is; λ may be made as close to zero as one wishes by choosing a sufficiently large value of V. For λ sufficiently close to zero, H+λ and - H have opposite signs. Proposition 5 thus follows directly from (10). The only possibility of neither t^c nor t^p being negative is that the equilibrium value of H is always negative but smaller than λ in absolute value, implying that the equilibrium value of H approaches zero as λ approaches zero. (Using (6), (7) and (9), it is easily verified that H and λ approaching zero simultaneously can occur only if y-x approaches zero as λ approaches zero. Proposition 5 does therefore not contradict Proposition 3.)

□

Proposition 6: **If either consumption or production is subsidized, then production is subsidized (at home) if the home country is a net importer of carbon (i.e. if y-x > 0), while consumption is subsidized (at home and abroad) if the home country is a net exporter of carbon (i.e. if y-x < 0).**

Proof: The proposition states that $y-x>0$ is a necessary condition for $t^p<0$, and that $y-x<0$ is a necessary condition for $t^c=T^c<0$. Consider first the case of $t^p<0$ (and $t^c=T^c>0$). For $t^p<0$ it follows from (10) that $H>0$. We thus have $Y=D(Q)=D(p+T^c)<D(p)$ (since $T^c>0$), which is compatible with $H>0$ only if $y-x>0$ (cf. (9)). Consider next the case of $t^c=T^c<0$ (and $t^p>0$). For $t^c<0$ it follows from (10) that $H<0$. Moreover, $Y=D(Q)=D(p+T^c)>D(p)$ in this case, which is compatible with $H<0$ only if $y-x<0$ (cf. (9).

□

To interpret the four previous propositions, it is helpful first to consider the case with no climate policy. In this case the shadow price λ on the emission constraint is zero, and it is clear from (7) and (8) that consumers and domestic producers should face the same price of carbon. This price is equal to the international price of carbon (p) plus an "optimal tariff" term (=H). It is clear from (10) that t^c and t^p have opposite signs as long as $\lambda=0$. Ignoring the case of zero tax rates, one of these tax rates must therefore be negative, so that Proposition 6 and equation (10) imply that H must have the same sign as y-x.

If the home country is a net importer of carbon, it wants the international price of carbon to be kept low. This can be achieved by raising the domestic price of carbon above the international price, which encourages domestic production and discourages domestic consumption. Net imports are thus discouraged, which presses down the price of carbon. The most obvious way to raise the domestic price from p to p+H for both consumers and producers is to have an import tariff equal to H. Alternatively, one could tax consumption and subsidize production, both at the rate H, which is precisely what follows from (10) for $\lambda=0$.

If on the other hand the home country is a net exporter of carbon in equilibrium (i.e. $y<x$), we get the opposite effect: In this case the home country wants the international price of carbon to be kept high. This can be achieved by keeping the domestic price

of carbon below the international price, which discourages domestic production and encourages domestic consumption. Net exports are thus discouraged, which presses up the price of carbon. The most obvious way to reduce the domestic price from p to p+H (remember that H<0 for y<x) for both consumers and producers is to have an export tariff equal to -H. Alternatively, one could tax production and subsidize consumption, both at the rate -H, which is precisely what follows from (10) for λ=0.

With a binding emission constraint, λ is positive. It is useful to first consider what implications this emission constraint has for the optimal tax structure, ignoring the optimal tariff argument above. The welfare level w (which was maximized in (5)) is given by

(11) $$w = u(y) - c(x) - p\cdot(y-x) - I(p,Y)$$

From (1) and (4) we have p=p(V-x), and from the first order condition (6) we know that q=Q is determined by d(q)+D(Q)=V, so that y=d(q) and Y=D(Q) are independent of x. Using these properties, we may differentiate (11) with respect to x, and evaluate this derivative at y=x, in order to exclude the optimal tariff argument:

(12) $$\left(\frac{dw}{dx}\right)_{y=x} = -c'(x) + p + I_p \cdot p'$$

Inserting (3), (8) and (10), and remembering that $Y=D(p+t^c)$ (since $t^c=T^c$), we find

(13) $$\left(\frac{dw}{dx}\right)_{y=x} = t^p - [D(p) - D(p+t^c)]\cdot p'$$

Consider as a starting point a situation in which consumption, but not production, is taxed. In this case the term in square brackets in (13) is positive, while $t^p=0$. It thus follows from (13) and $p'>0$ that $(dw/dx)_{y=x}<0$ in this situation. In other words, w can be increased by reducing x, i.e. by introducing a tax on production. The reason why w increases as x is reduced is that this supply reduction increases the international price of carbon, and therefore reduces the transfer which must be paid to the foreign country to make it consume Y instead of D(p).

Consider next the opposite starting point, i.e. a situation in which production, but not consumption, is taxed. In this case the term in square brackets in (13) is zero, while $t^p>0$. It thus follows from (13) that $(dw/dx)_{y=x}>0$ in this situation. In other words, w can be increased by increasing x. The reason why w increases as x is increased is that there is a production inefficiency as long as $c'(x)<p$. Moreover, at the starting point of $t^c=0$, the reduction in the international price of carbon which follows from the supply increase has a zero first-order effect on the transfer to the foreign country.

The production level x is increased by reducing the producer tax t^p. Since $p=p(V-x)$ is declining in x, and $q=p+t^c$ is independent of x (determined by $d(q)+D(q)=V$), t^c must increase as t^p is reduced.

We have thus shown that w can be increased by increasing t^p if $t^p=0$ initially, and by increasing t^c if $t^c=0$ initially. The optimal tax rates (ignoring the optimal tariff argument) follow from setting the r.h.s. of (13) equal to zero, giving $t^p=[D(p)-D(p+t^c)]p'$, which is positive for $t^c>0$. In words, the optimal mix of a consumption and production tax is given by the equality of the marginal production inefficiency, measured by $t^p=p-c'(x)$, and the marginal effect of a production change on the transfer to the foreign country.

From the discussion above it follows that the optimal tariff argument by itself requires a subsidy on either production or consumption of carbon, and a tax of the same magnitude on the side of the market which is not subsidized. The isolated effect of the emission constraint, on the other hand, is that both production and consumption should be taxed. The message of Propositions 3, 5 and 6 is that as long as the emission constraint is not too strict, and domestic consumption of carbon is not too close to domestic production, the optimal tariff argument for subsidizing production or consumption of carbon is stronger than the argument for taxing both production and consumption of carbon as a consequence of the emission constraint. However, it follows from Propositions 3 and 4 that if the emission constraint is sufficiently strict, or domestic consumption of carbon is sufficiently close to domestic production, then consumption and production should both be taxed. In other words, in these cases the argument for positive taxes on both production and consumption, due to the emission constraint, dominates the optimal tariff argument for subsidizing consumption or production.

The three cases of a tax on both consumption and production, and a subsidy on either consumption or production, and a tax on the other, are illustrated in Figure 1 A-C. In all three cases, the consumer price q=Q is given by the intersection between the aggregate demand curve d(p)+D(p) and the line for the emission constraint V.

If there was no supply policy in the home country, the equilibrium international price would be given by the intersection between the aggregate supply curve s(p)+S(p) and the line for the emission constraint V. If, however, $t^p>0$, as in Figures A and B, home production x=s(r) is lower than s(p), so that x+S(p) lies to the left of s(p)+S(p). The equilibrium price p* is given by the intersection between the curve x+S(p) and the line for the emission constraint V. In Figure A, $p^*<q$, implying that consumption is taxed. In Figure B, on the other hand, supply is taxed so heavily that $p^*>q$, implying that consumption is subsidized.

In Figure 1C, $t^p<0$, so that home production x=s(r) exceeds s(p). In this case x+S(p) therefore lies to the right of s(p)+S(p), and the equilibrium price p* must lie below q, implying that consumption is taxed.

4. Supply oriented policy in the foreign country.

We now turn to the case in which the home country has no influence over the consumption of carbon in the foreign country, i.e. $T^c=0$. By definition we therefore have Q=p, so that the demand for carbon in the foreign country is D(p). However, it is now assumed that the home country can induce the foreign country to set its production of carbon (i.e. X) at whatever level the home country wants. As in the previous section, the home country must pay a transfer to the foreign country, so that the foreign country is equally well off with its imposed level of production and the transfer as it is without the transfer, but with the right to choose its production optimally. As in the previous section, this transfer is denoted by I, which in the present case is given by

$$(14) \qquad I = I(p,X) = \max_{\chi}[p\chi - C(\chi)] - [pX - C(X)]$$

giving (by the envelope theorem)

$$(15) \qquad \begin{aligned} I_p &= S(p) - X \\ I_X &= -p + C'(X) \end{aligned}$$

The foreign demand of carbon is D(p), inserting this into (1) gives x+X = y+D(p), or

$$(16) \qquad p = p(X + x - y)$$

where p'=1/D'<0. The maximization problem of the home country may now be written as

$$\max_{x,y,Y} \; [u(y)-c(x)-p(X+x-y)\cdot(y-x)-I(p(X+x-y),X)] \tag{17}$$
$$s.\ t.\quad x+X \leq V$$

Assuming an interior solution (i.e. x, X and y positive) the first order conditions are (using (15))

$$u'(y) = p+K \tag{18}$$

$$c'(x) = p+K-\lambda \tag{19}$$

$$c'(x) = C'(X) \tag{20}$$

where λ is the (positive) shadow price of the emission constraint $x+X\leq V$ and

$$K = [(y-x) + (S(p)-X)]\cdot(-p') \tag{21}$$

From (21) we immediately get the following proposition:

<u>Proposition 7</u>: Sellers in the home and the foreign country should face the same producer price of carbon.

Proof: With the notation from table 1, the producer prices in the two countries are r and R, giving c'(x)=r and C'(X)=R. It thus follows from (20) that r=R.

□

Using the notation from table 1, (18) and (19) may be rewritten as

$$(22) \qquad \begin{aligned} t^c &= q-p = K \\ t^p &= p-r = -K+\lambda \end{aligned}$$

It is now straightforward to show that propositions 2 through 6 remain valid also in the present case (with appropriate adjustments in the formulations for what is taxed or subsidized abroad[3]). The proofs are omitted, but follow the same procedure as the proofs in section 3.

5. Demand and supply oriented policy in the foreign country

In this section, it is assumed that the levels of both consumption and production in the foreign country, i.e. both Y and X, are determined by the home country. As before, the foreign country must be compensated for choosing Y and X instead of the consumption and production which is optimal at the international price p, i.e. instead of D(p) and S(p). The necessary transfer from the home country is in this case given by

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[3] For instance, Proposition 3 now reads "If the home country's consumption of carbon is sufficiently close to its production of carbon (i.e. if |y-x| is sufficiently small), both consumers (at home) and producers (at home and abroad) should be taxed."

(23) $$I=I(p,Y,X)=\max_{\chi,\psi}[U(\psi)-C(\chi)-p\cdot(\psi-\chi)] - [U(Y)-C(X)-p\cdot(Y-X)]$$

Using the envelope theorem, we find

(24) $$\begin{aligned} I_p &= Y-X+S(p)-D(p) \\ I_Y &= -U'(Y)+p \\ I_X &= -p+C'(X) \end{aligned}$$

The home country chooses the levels of y, x, Y and X, subject to the constraint (1). This means that demand and supply are equal whatever the international price p is. The international price may therefore be treated as a choice variable for the home country. The interpretation of this is the following. The choice of the vector (y,x,Y,X) implicitly gives a vector of consumer and producer prices (q,r,Q,R), given by d(q)=y, s(r)=x, D(Q)=Y and S(R)=X. For any price p, the corresponding consumer and producer taxes (which may be positive or negative) are t^c=q-p, t^p=p-r, T^c=Q-p, and T^p=p-R. To any vector (y,x,Y,X,p) there thus corresponds a tax vector (t^c,t^p,T^c,T^p). Given these taxes, the international price follows from

(25) $$d(p+t^c)+D(p+T^c)=s(p-t^p)+S(p-T^p)$$

Choosing the vector (y,x,Y,X,p) is thus equivalent to choosing an appropriate tax vector (t^c,t^p,T^c,T^p), and letting the international price of carbon be determined by (25). The taxes t^c,t^p are implemented at home, while the foreign country must be given a transfer I(p,Y,X) (given by (23)) to be willing to impose the taxes T^c and T^p on their consumption and production of carbon. The home country chooses the vector (y,x,Y,X,p) so that the following maximization problem is solved:

$$\text{(26)} \quad \underset{x,y,X,Y,p}{maximize} \quad [u(y)-c(x)-p\cdot(y-x)-I(p,X,Y)]$$
$$s.\ t.\quad y+Y = x+X$$
$$y+Y \leq V$$

From (26), it is clear that whatever the values of (y,x,Y,X), the home country wants to choose a price which minimizes its total payments to the foreign country. In other words, p is chosen to minimize $p\cdot(y-x)+I(p,X,Y)$, which gives $y-x+I_p=0$[4], or, using (24)

$$\text{(27)} \qquad D(p)=S(p)$$

The following proposition follows directly from (27):

Proposition 8: The optimal tax policy (at home and abroad) gives an equilibrium international price which is such that the foreign country in the absence of any taxes would want to consume and produce the same amount of carbon (i.e. have no export or import of carbon).

Notice that Proposition 8 does not say that net imports are zero in both countries in equilibrium. It only says that the international price of carbon is such that if all taxes were removed and the international price of carbon nevertheless remained unchanged, then the foreign country would find it optimal to have zero net imports of carbon.

The remaining first order conditions for the maximization problem (26) are straightforward to calculate (using (24)), and are given by

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[4] Since $I_{pp}=S'(p)-D'(p)>0$ (from (24)), the second order condition for this minimization problem is satisfied.

(28) $$u'(y)=U'(Y)$$

(29) $$c'(x)=C'(X)$$

(30) $$u'(y)=p+\mu+\lambda$$

(31) $$c'(x)=p+\mu$$

where μ and λ are the shadow prices of the constraints $y+Y=x+X$ and $y+Y\leq V$, respectively. The shadow price λ is positive (for a binding emission constraint), while μ cannot in general be signed.

From (28)-(31) we immediately see that in the present case Propositions 1 and 7 are both valid. In other words, both the consumer tax and the producer tax should be equal at home and abroad.

Proposition 2, which says that the sum of the consumer and producer tax rate is positive, also remains valid in the present case. This is easily seen by rewriting (28)-((31) as

(32)
$$\begin{aligned} t^c &= q-p = \mu+\lambda \\ T^c &= Q-p = \mu+\lambda \\ t^p &= p-r = -\mu \\ T^p &= p-R = -\mu \end{aligned}$$

which gives $t^c+t^p=T^c+T^p=\lambda>0$.

To see whether or not Proposition 3-6 remain valid, it is useful to illustrate the equilibrium of the present situation. In Figure 2, the equilibrium price p* is given by the intersection of the foreign demand and supply curve (cf. (27)). The aggregate demand and supply curves must always lie outside (i.e. to the right) of the corresponding curves for the foreign country. In Figure 2, the intersection between the aggregate demand and supply curves is denoted by A. This intersection point, with corresponding price p^A, will generally lie above (as in Figure 2) or below the p*-line; only by coincidence will $p^A=p^*$.

From Figure 2, it is easily verified that Proposition 4 and 5 are valid also for the present case. For a sufficiently small value of V, such as V^0 in Figure 2, it is clear that consumer and producer prices satisfy $Q^0 = q^0 > p^*>r^0 = R^0$, giving

(33)
$$t^c=T^c=q^0-p^*>0$$
$$t^p=T^p=p^*-r^0>0$$

which proves Proposition 4. Similarly, if the value of V is sufficiently large, such as V^1 in Figure 2, the heavily drawn line segment BC must lie entirely above (as in Figure 2) or entirely below the p*-line, except for the special case in which $p^A=p^*$. If $p^A>p^*$, as in Figure 2, we therefore get $q^1>r^1>p^*$, i.e. $t^p=T^p=p^*-r^1<0$, i.e. production is subsidized. If $p^A<p^*$, we would have $p^*>q^1>r^1$, i.e. $t^c=T^c=q^1-p^*<0$, i.e. consumption is subsidized. This proves Proposition 5.

Finally, it is shown in the Appendix that also Propositions 3 and 6 remain valid in the present case.

6. Conclusions

An important conclusion of the paper is that the home country should try to achieve the same production and consumption tax abroad as at home, if possible. If for some reason it is not possible to tax both consumption and production abroad, whatever is taxed should be taxed at the same rate as at home.

Independent of what policy options one has abroad, there is some optimal policy mix of a consumption and production tax at home. One of these taxes may be negative, but the sum of the two tax rates is always positive.

Propositions 3-6 describe some of the properties of the optimal mix of consumption and production taxes. Loosely speaking, these propositions say that production should be subsidized if the emission constraint is sufficiently weak and the home country has sufficiently large imports of carbon. Consumption should be subsidized if the emission constraint is sufficiently weak and the home country has sufficiently large exports of carbon. In all other cases both production and consumption of carbon should be taxed at a positive rate.

Appendix I: Proof of Proposition 4

From (1) and (9) we obtain

$$(34) \qquad \frac{H}{p'} = X - D(p) = X - D(S^{-1}(X))$$

Since V=x+X and x and X are non-negative, X→0 as V→0. Under the reasonable assumption that $D(S^{-1}(0)) > 0$, we therefore have

$$(35) \qquad \lim_{V \to 0} \frac{H}{p'} = -D(S^{-1}(0) < 0$$

Since p'>0, it follows from (35) that H<0, giving $t^p>0$ from (10).

Assume that $t^c=T^c \leq 0$. Then $Y=D(p+t^c) \geq D(p)$, i.e. (from (34))

$$(36) \qquad \frac{H}{p'} \geq X - Y$$

Since X and Y both approach zero as V approaches zero, we thus have

$$(37) \qquad \lim_{V \to 0} \frac{H}{p'} \geq 0$$

which contradicts (35). This contradiction proves that $t^c=T^c>0$.

We have thus shown that t^p and $t^c=T^c$ are positive, which proves proposition 4.

□

Appendix II: Proof of Propositions 3 and 6 for the case in which both supply and demand policies are used in the foreign country.

We start by proving Proposition 6. From (1) it is clear that

$$y-x=X-Y=S(R)-D(Q) \tag{38}$$

If production is subsidized, Q>R>p* (from Proposition 2). Inserting this into (38) gives

$$y-x>S(p*)-D(p*)=0 \tag{39}$$

If consumption is subsidized, p*>Q>R (from Proposition 2). Inserting this into (38) gives

$$y-x<S(p*)-D(p*)=0 \tag{40}$$

We have thus shown that a subsidy on production can occur only if y-x>0, and that a subsidy on consumption can occur only if y-x<0. This proves that Proposition 6 is valid for the present case.

We now turn to Proposition 3. From (32) we know that Q=R+λ, so (38) may be written as

$$y - x = S(R) - D(R + \lambda) \tag{41}$$

For any given λ-value, the r.h.s. of (41) is increasing in R. If production is not taxed, $R \geq p^*$, i.e.

$$y - x \geq S(p^*) - D(p^* + \lambda) = \alpha(\lambda) \tag{42}$$

where $\alpha(\lambda)$ is a positive number (increasing in λ), since $S(p^*) = D(p^*)$, $\lambda > 0$ and $D' < 0$.

From $Q = R + \lambda$ we could rewrite (38) as

$$y - x = S(Q - \lambda) - D(Q). \tag{43}$$

If consumption is not taxed, $Q \leq p^*$, i.e.

$$y - x \leq S(p^* - \lambda) - D(p^*) = \beta(\lambda) \tag{44}$$

where $\beta(\lambda)$ is a negative number (with $\beta' < 0$), since $S(p^*) = D(p^*)$, $\lambda > 0$ and $S' > 0$.

From the discussion above, it is clear that if

$$\beta(\lambda) < y - x < \alpha(\lambda) \tag{45}$$

then neither of the inequalities (42) or (44) are satisfied. In other words, both production and consumption must be taxed if (45) is valid. This proves Proposition 3 for the present case.

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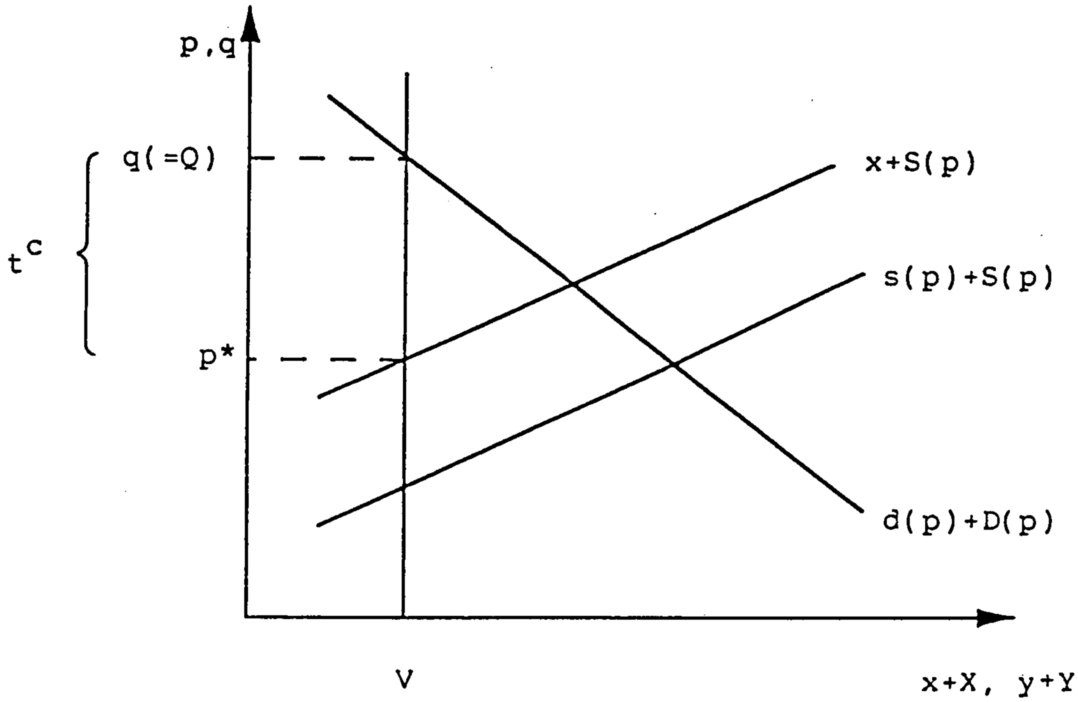

FIGURE 1 A: $t^p > 0$, $t^c > 0$

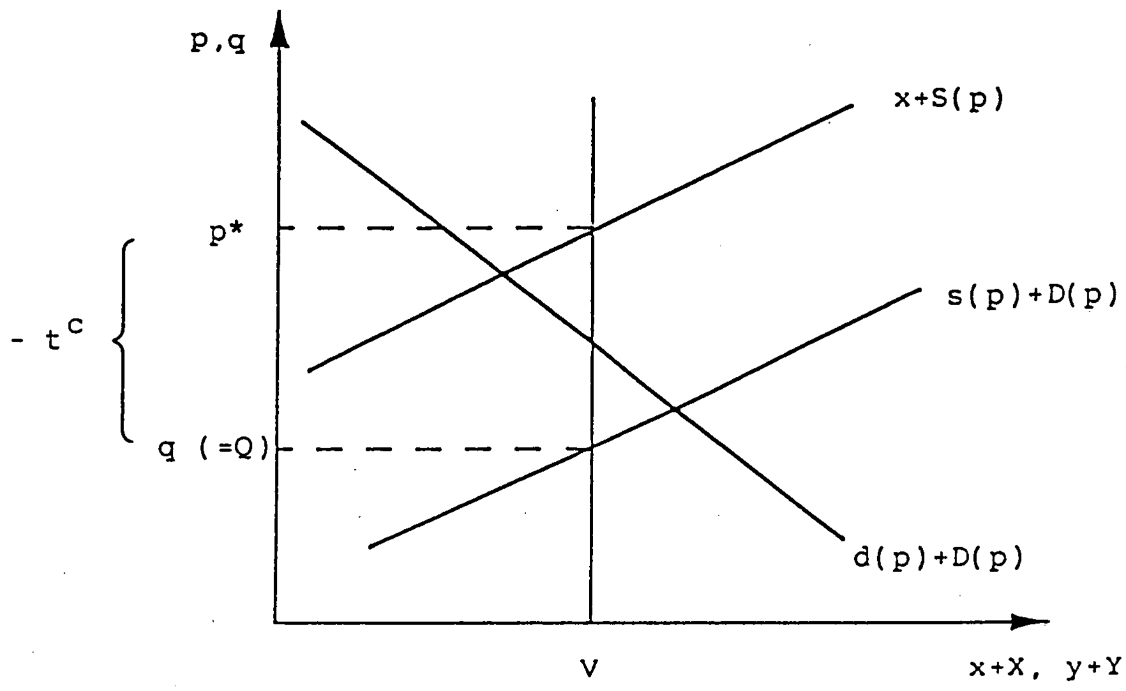

FIGURE 1 B: $t^p>0$, $t^c<0$

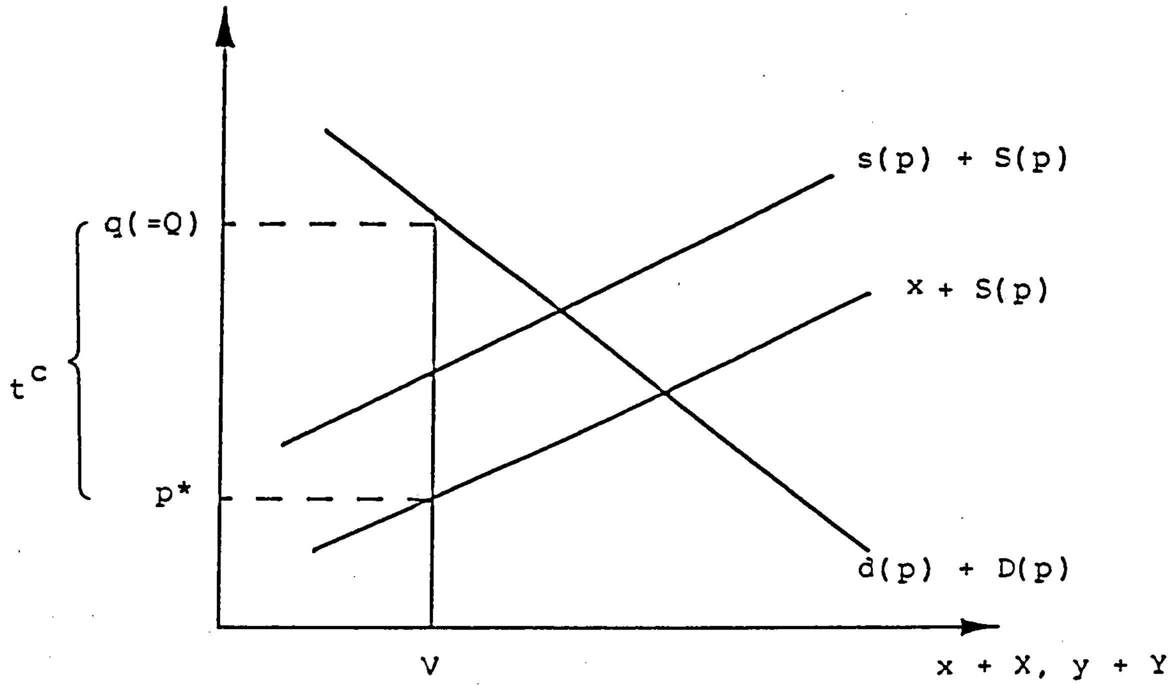

FIGURE 1C: $t^p < 0$, $t^c > 0$

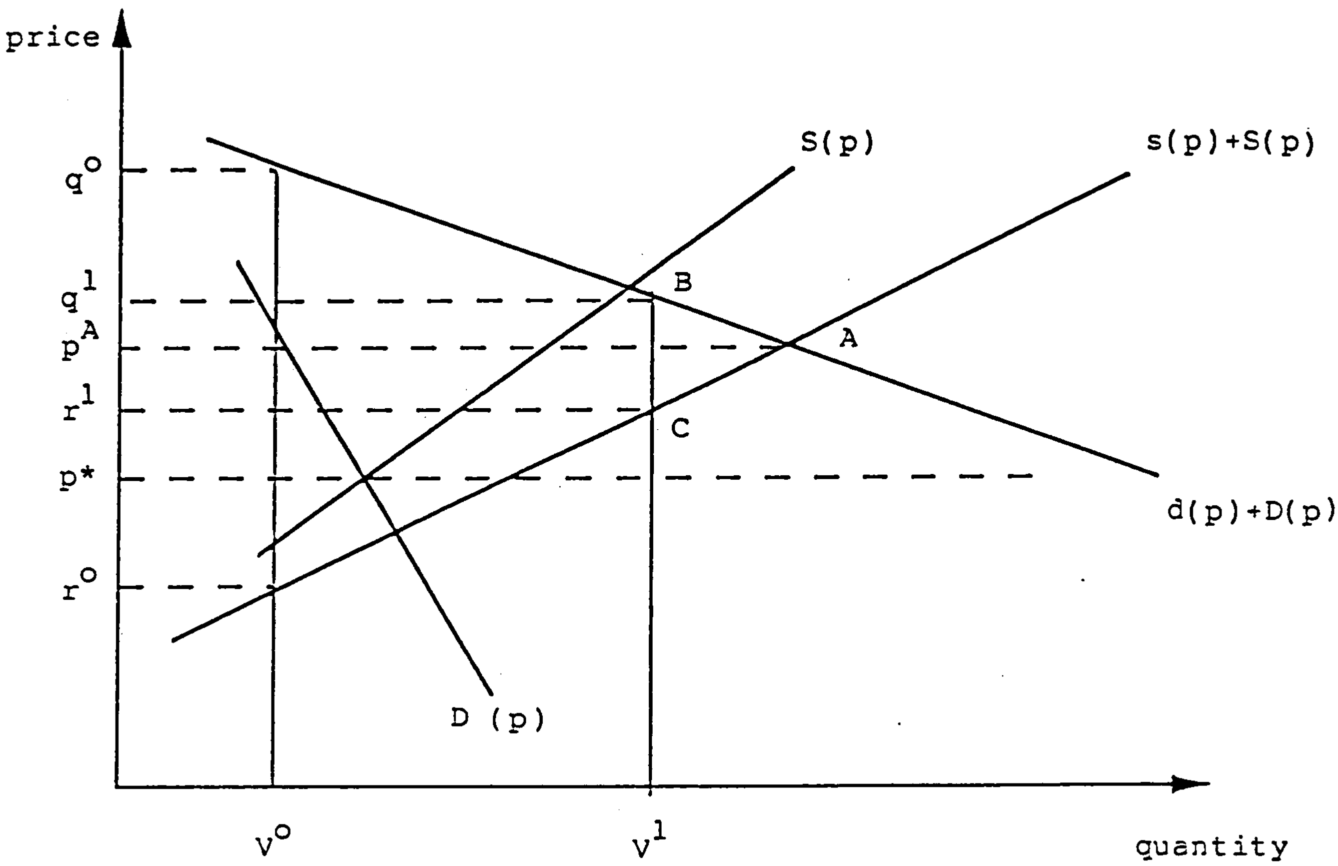

FIGURE 2