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SHOULD A CARBON TAX BE DIFFERENTIATED ACROSS SECTORS?

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ABSTRACT

Should a Carbon Tax be Differentiated Across Sectors?*

If some, but not all, countries are cooperating to reduce CO_2 emissions, it can be argued that: A high carbon tax on carbon-intensive tradable sectors in the cooperating countries will reduce the production of goods from these sectors, and therefore CO_2 emissions, in those countries. This will to a large extent be counteracted by increased production of such goods in the countries which have no such policy, however. Since it is *total* CO_2 emissions from *all* countries which is relevant for the climate, there is little advantage in a policy which simply shifts CO_2 emissions from the cooperating countries to other countries. Carbon-intensive tradable sectors should thus face a lower carbon tax than other sectors of the economy.

The paper shows that a carbon tax should *not* be differentiated across sectors in the economy, provided import and export tariffs can be used on all traded goods. It is also shown that such a differentiation of carbon taxes is optimal for the cooperating countries if they are prevented from using tariffs on the traded goods. Informational or political factors constraining the use of tariffs are also likely to constrain the possibility of differentiating carbon taxes between sectors, however.

JEL Classification: F02, F13, H21, H23, Q28, Q48
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NON-TECHNICAL SUMMARY

According to standard welfare theory, all users of carbon should face the same carbon tax, as the environmental externality of carbon use is independent of where it is used. This argument is valid where there are no other distortions in the economy. If other distortions are present, however, it is no longer obvious that it is optimal to equalize carbon taxes across sectors. One important possible distortion is that an international climate agreement may be incomplete. Limited participation in a climate agreement seems probable during the next decade or so. In such a case it can be argued that: A high carbon tax for carbon-intensive tradable sectors in the cooperating countries will reduce the production of goods from these sectors, and therefore CO_2 emissions in the cooperating countries. This will be counteracted to a large extent by increased production of such goods in the countries which have no climate policy, however. Since it is *total* CO_2 emissions from *all* countries which are relevant for the climate, there is little point in a policy which simply shifts CO_2 emissions from the cooperating countries to non-participating countries. Carbon-intensive tradable sectors should thus face a lower carbon tax than other sectors of the economy.

The starting point of the paper is a situation in which a group of countries, e.g. the European Union or the OECD countries, have committed themselves to cooperate. These countries, which we call the signatories, are assumed to coordinate their policies in a way which maximizes the sum of welfare for the signatories. This level of welfare depends on the signatories' consumption of all goods as well as total CO_2 emissions. Since the environmental effect of CO_2 emissions depends on the sum of emissions from *all* countries, it is *total* CO_2 emissions which affect the welfare of the signatories. Emissions from the non-signatories will generally depend on international prices of several goods, in particular of the prices of fossil fuels and of energy intensive traded goods. As international prices generally depend on the net import vector of the signatories, foreign emissions will also depend on the net import vector of the signatories.

An important conclusion is that the social optimum may be implemented by a carbon tax which is the same for all users of fossil fuels, i.e. both for consumers and for all sectors using fossil fuels as an input in production (among the signatories). The possible effect of the consumption and production of traded goods among the signatories on emissions from the non-signatories (through international prices) may be taken care of via tariffs on the traded goods, i.e. as a tax or subsidy on net imports or net exports.

There are two types of externalities within the cooperating countries, which may be internalized through appropriate taxes (or subsidies). First, the environmental externality of the emissions from the signatories may be internalized through a uniform tax on the use of carbon. Second, externalities via the net imports of various goods affect the environment through the effect of net imports on the behaviour of other countries. Obviously, it is not the signatories' production or consumption of a good which affects the behaviour of the non-signatories, but only the net import of the good. This externality may thus be internalized through appropriate taxes (positive or negative) on the net imports of traded goods.

In addition to affecting the environment through the effect on the behaviour of non-signatories, changing the net import of a good will generally have a terms of trade effect. This effect is not internalized by the individual firms in a competitive economy. The optimal tariffs should thus reflect these terms of trade effects as well as the environmental effects.

What happens if, for some reason, the use of tariffs and also production taxes/subsidies and other policy instruments affecting the production of goods are ruled out? Not surprisingly, the constrained social optimum in this case requires a differentiation of carbon taxes across sectors. It is shown that the exact calculation of the optimal tax structure in this case is quite complex, however. In particular, more detailed numerical information on the economy is required for this calculation than for the calculation of the optimal tariffs. There is no simple relationship between, for example, fossil fuel intensity or the effect on foreign emissions on the one hand, and the optimal carbon tax on the other hand.

If the use of tariffs is ruled out, it may be optimal to differentiate carbon taxes across sectors. It is, however, difficult to find good reasons for why one should rule out the use of tariffs. Trade policy arguments could be made against import and export taxes/subsidies. Similar arguments could also be made against differentiating taxes (in this case carbon taxes) across sectors. Moreover, the non-signatories are not in a very strong position to argue against tariffs which might hurt them. The justification for the tariffs is after all an attempt to avoid excessive carbon emissions from the non-signatories. Any non-signatory which claims to be adversely affected by the tariffs can avoid the tariffs by participating in the climate agreement instead of being a free rider.

1. Introduction.

Should a carbon tax be differentiated across sectors? The answer which follows from standard welfare theory is no: all users of carbon should face the same carbon tax, as the environmental (i.e. climate) externality of using carbon is independent of where it is used. However, the answer is not so obvious in a situation where there is an incomplete international climate agreement. If some, but not all, countries are cooperating to reduce CO_2 emissions, one could make the following argument: A high carbon tax for carbon intensive tradeable sectors in the cooperating countries will reduce the production of goods from these sectors, and therefore CO_2 emissions, in the cooperating countries. However, this will to a large extent be counteracted by increased production of such goods in the countries which have no climate policy. And since it is only total CO_2 emissions from all countries which are relevant for the climate, there is no point in a policy which simply relocates CO_2 emissions from the cooperating countries to the countries which have no climate policy. According to this line of reasoning, carbon intensive tradeable sectors should thus face a lower carbon tax than other sectors of the economy. Arguments of this type have been made by e.g. the Commission of the European Communities (1991).

Limited participation in a climate agreement seems to be quite likely during the next decade or so. 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 (1992), Bauer (1993), Carraro and Siniscalco (1993) and Hoel (1992). These studies demonstrate 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. One 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, most of the studies mentioned above argue 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.

The Rio Convention on Climate Change does not give the signatories any explicit quantitative commitments for greenhouse gas emissions. It seems plausible, however, that some form of agreement will be reached during the next decade. 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 frequently 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. Barrett (1992) and Torvanger (1993) for a discussion in the context of international environmental agreements. The fact that decisions about greenhouse gas emissions are frequently 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 issue of whether a carbon tax should be differentiated across sectors when a climate agreement is incomplete is therefore a highly relevant issue.

The starting point of the paper is a situation in which a group of countries, e.g. the EU or the OECD countries, have committed themselves to cooperate. These countries are assumed to coordinate their policies in a way which maximizes the sum of welfare for the whole of this group. Henceforth, this group of countries is called the home country. The remaining countries in the world act independently and in pure self-interest, each of them taking total greenhouse gas emissions, as well as international prices of all traded goods, as given. We treat these latter countries as an aggregate group, and call the group the foreign country.

A relatively general model of the economy in the home country is given in section 2. Outputs and inputs of all goods (including fossil fuels) must belong to a given production possibility set. Welfare depends on the consumption of all goods, as well as total CO_2 emissions. Since the environmental (=climate) effect of CO_2 emissions depends on the sum of emissions from all countries, it is total CO_2 emissions, and not only emissions from the home country, which affect welfare in the home country. Emissions in the foreign country will generally depend on international prices of several goods, in particular on the prices of fossil fuels and of energy intensive traded goods. As international prices generally depend on the net import vector of the home country, foreign emissions will also depend on the net import vector of the home country. This relationship must be taken into consideration in the optimization problem of the home country.

The conditions for optimal consumption and production in the home country are derived in section 2. In section 3 it is shown how this social optimum may be implemented in a competitive economy. An important conclusion is that the carbon tax should be the same for all domestic users of fossil fuels, i.e. both for consumers and for all sectors using fossil fuels as an input in production. The possible effect of domestic consumption and production of traded goods on foreign emissions (through international prices) should be taken care of via tariffs on the traded goods, i.e. as a tax or subsidy on net imports or net exports.

A somewhat simplified version of the general model is presented in section 4. In this section, we derive optimal carbon taxes under the assumption that tariffs for some reason or other are constrained to be zero. In this case, the carbon tax on fossil fuels used as inputs should in general differ across sectors. A discussion of the main results, as well as key assumptions, is given in section 5.

2. The optimal consumption and production pattern

The consumption vector of the home country is $\mathbf{c}=(c_0,c_1,...,c_n)$, where c_0 is the consumption of fossil fuels (treated as an aggregate). Welfare (W) is equal to the utility of the consumption vector minus the environmental costs of total emissions (from all countries), denoted by z:

(1)
$$W = U(c)-E(z)$$

The consumption vector **c** will typically consist of both tradeable and non-tradeable goods. Among the non-tradeable goods we may include various types of labour, which are measured negatively, so that U is increasing in all its variables.

Total emissions come from domestic consumption of fossil fuels (c_0), domestic use of fossil fuels as inputs into production, denoted v, and foreign emissions, denoted e:

(2) $$z = c_0 + v + e$$

Net imports are given by the vector **m**, so the domestic net output vector is **y** ≡ **c**-**m**. For all non-traded goods $m_i=0$ by definition, i.e. $y_i=c_i$ for all non-traded goods. The vector **y** will typically have both positive and negative elements. For instance, if good ℓ is some type of (non-tradeable) labour, we have $m_\ell=0$ and $y_\ell=c_\ell<0$)

In most analyses, one is only interested in the net outputs of the goods, and not gross outputs and inputs. In such cases the efficient net output set can be specified by a transformation function of the type $\varphi(\mathbf{y})=0$, where φ is increasing in each y_i. In the present case, however, we are interested in the total amount of fossil fuels used as inputs, and not only in the net output of fossil fuels in the economy. Denoting gross production of fossil fuels by x, and defining $\tilde{y} = (y_1,\dots,y_n)$, we may therefore specify the production possibilities by

(3') $$\phi(\underset{+}{x},\underset{+}{\tilde{y}},\underset{-}{v}) = 0$$

where the signs under the variables denote the signs of the partial derivatives. (3') may be rewritten as

$$F(\underset{+}{x-v},\underset{+}{\tilde{y}},\underset{?}{v}) = 0$$

or

(3) $$F(\underset{+}{\boldsymbol{c}-\boldsymbol{m}},\underset{?}{v})=0$$

since $\boldsymbol{c}-\boldsymbol{m} \equiv \boldsymbol{y} \equiv (y_0,\tilde{y}) \equiv (x-v,\tilde{y})$. In the absence of any externality associated with the use of fossil fuels, one would want net output of fuels (x-v) to be as large as possible for given net outputs of all other goods. Maximization of x-v subject to the technology constraint (3') and a given vector $\tilde{y}$ implies $\phi_x+\phi_v=0$. This is equivalent to $F_v=0$ in (3). For environmental reasons, one is interested in using less fossil fuels than the level maximizing x-v. As we shall soon see, this implies that $F_v>0$ in our equilibrium.

Our goods are indexed so that the first $1+\eta$ ($\leq n$) goods are traded goods. We denote the international prices of these goods, which may depend on net imports, by $\boldsymbol{p}(\boldsymbol{m}) = (p_0(\boldsymbol{m}),p_1(\boldsymbol{m}),...,p_\eta(\boldsymbol{m}))$. Assuming balanced trade, we thus have

(4) $$\boldsymbol{p}(\boldsymbol{m})\boldsymbol{m} = \sum_{i\leq\eta} p_i(m)m_i = 0$$

Balanced trade is defined as the current account being equal to zero. This means that our framework does not rule out capital movements. Denoting a given physical stock of a capital good by x_k, and the use of this capital good as an input in domestic production by v_k, we have net output given as $y_k=x_k-v_k$. From the equation $y_k=c_k-m_k$ we thus have $v_k+c_k=x_k+m_k$. In other words, the more capital is used domestically as an input in production or directly as consumption, the more capital must be imported. Finally, foreign carbon emissions are assumed to depend on net imports via the effect of net imports on international prices:

$$e = e(\boldsymbol{m}) = f(p(\boldsymbol{m})) \qquad (5)$$

In the simplest case in which $\partial p_i/\partial m_j=0$ for $i\neq j$, and $\partial p_j/\partial m_j>0$, the sign of $\partial e/\partial m_j$ is equal to the sign of $\partial f/\partial p_j$. If j is an energy intensive good, we would expect $\partial f/\partial p_j>0$, i.e. an increased international price for such a good increases foreign production and therefore foreign emissions. The opposite is true for good which uses little or no fossil fuels: An increased international price will give more foreign production of this good, and thus lower foreign production of other more energy intensive goods. In this latter case we therefore have $\partial f/\partial p_j<0$ and $\partial e/\partial m_j<0$. Capital may be an example of such a good. With a fixed (short-run) global stock of capital, increased import of capital must reduce the foreign use of capital (via the price, i.e. the interest rate). This tends to reduce foreign production of all or at least most goods, with the consequence that foreign emissions decline.

The social optimum is defined as the vector (**c**,**m**,v) which maximizes (1) subject to (2)-(5) and $m_j=0$ for all non-traded goods.

Straightforward calculation yields the following conditions for a social optimum (using the notation $U_i=\partial U/\partial c_i$, $F_i=\partial F/\partial(c_i-m_i)$, etc.)

$$\frac{U_0-E'}{U_i} = \frac{F_0}{F_i} \quad i=1,\dots,n \qquad (6)$$

(7) $$\frac{-F_v}{F_i} = \frac{E'}{U_i} \quad i\neq 0$$

(8) $$\frac{p_0+T_0}{p_i+T_i} = \frac{(U_0-E')-E'e_0}{U_i-E'e_i} \quad i=1,\ldots,\eta$$

where

(9) $$T_j = \sum_i m_i \frac{\partial p_i}{\partial m_j} \quad j=0,1,\ldots,\eta$$

Equations (6) are simply the standard requirement "MRS=MRT" (marginal rate of substitution equal to marginal rate of transformation), with the environmental externality included in the MRS between fossil fuels and any other good.

Given (6), equation (7) is one equation. It states that the marginal cost of reducing emissions (in terms of good i) should be equal to the marginal environmental cost of emissions (measured in terms of good i).

The terms T_j defined by (9) measures the terms of trade effect of an increase of the import of good j. In the simplest case in which $\partial p_i/\partial m_j=0$ for $i\neq j$, and $\partial p_j/\partial m_j>0$, it is clear from (9) that T_j is positive for imported goods ($m_j>0$) and negative for exported goods ($m_j<0$). For the more general case in which $\partial p_i/\partial m_j\neq 0$, there is no such simple relationship between the signs of T_j and m_j.

Equations (8) show the relationship between the MRS in consumption and international prices. If foreign emissions were independent of all imports, i.e. all $e_i=\partial e/\partial m_i=0$, it follows from (8) that the MRS between two goods should be equal to the international price ratio after correcting for terms of trade effects. In other words, it is not the ratio of the two prices which is relevant, but the ratio between the two marginal import costs. When foreign carbon emissions depend on the size of the home country's imports, the MRS must be adjusted for this externality before it is equated to the ratio between marginal import costs. Instead of simply being the ratio of the marginal utilities of two goods, the adjusted MRS is the ratio between marginal utilities minus the marginal environmental costs of the foreign increase in emissions caused by increased imports of the two goods.

Equations (6)-(8) consist of $n+\eta+1$ independent equations (after inserting the T_i's from (9)). Together with the 4 equations (2), (3), (4) and (5), and the $n-\eta$ equations $m_j=0$ for the non-traded goods, we thus have $2n+5$ equations determining the $2(n+1)=2n+2$ variables $(\mathbf{c},\mathbf{m})$ as well as the three variables v, e and z[2].

3. Implementation

In this section we shall see how the social optimum described in section 2 may be

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[2] Although the optimization of (1) subject to (2)-(5) will (almost always) have a unique solution, there may be several equilibria satisfying the equations (2)-(8). However, to simplify our discussion, we assume that the properties of the functions included in our analysis imply that there is a unique equilibrium satisfying these equations.

achieved in a competitive economy.

Consider a common carbon tax θ for all users, and tariffs t_j for each traded good, given by

(10)
$$\theta = E' \cdot \frac{p_i + t_i}{U_i} \qquad i \neq 0$$

(11)
$$t_j = T_j + \theta e_j \qquad for \quad j \leq \eta$$
$$t_j = 0 \qquad for \quad j > \eta$$

where T_j as before is defined by (9). A tariff t_j on a good changes the price facing both consumers and producers from p_j to p_j+t_j. If t_j is positive, it is an import tariff, if good j is an imported good, or an export subsidy, if good j is an exported good. Similarly for t_j negative: It is an import subsidy (for $m_j>0$), or an export tax (for $m_j<0$).

Consider first consumers, who will face the price vector $(p_0+\theta+t_0, p_1+t_1, \ldots, p_n+t_n)$[3]. The consumers' optimal consumption vector thus satisfies

$$\frac{U_0}{U_i} = \frac{p_0+\theta+t_0}{p_i+t_i} \qquad i=1,\ldots,n$$

which together with (10) and (11) gives

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[3] Notice that all prices p_i are endogenously determined in the competitive equilibrium. The prices of the traded goods are given by the functions $p_i(m)$, while the prices of the non-traded goods are given by the equilibrium conditions $m_i=c_i-y_i=0$.

$$\frac{U_0}{U_i} = \frac{p_0+t_0}{p_i+t_i}+\frac{E'}{U_i} \quad i=1,\dots,n$$

or

$$\frac{U_0-E'}{U_i} = \frac{p_0+t_0}{p_i+t_i} \quad i=1,\dots,n \tag{12}$$

It is thus clear that $(p_i+t_i)/U_i$ is independent of i for $i\neq0$, so that the choice of i in (10) is arbitrary.

Consider next producers. For given prices and tariffs, they maximize $(p_0+t_0)x-(p_0+t_0+\theta)v+\sum_{i>0}(p_i+t_i)y_i = \Sigma_i(p_i+t_i)y_i-\theta v$ subject to $F(\mathbf{y},v)=0$. This gives

$$\frac{F_0}{F_i} = \frac{p_0+t_0}{p_i+t_i} \quad i=1,\dots,n \tag{13}$$

$$\frac{-F_v}{F_i} = \frac{\theta}{p_i+t_i} \quad i=1,\dots,n \tag{14}$$

Combining (12) and (13) immediately gives the optimality condition (6). Moreover, using (10) we may rewrite (14) as

$$\frac{-F_v}{F_i} = \frac{E'}{U_i} \quad i\neq0 \tag{15}$$

which is equivalent to the optimality condition (7).

From (10) and (12) we have

$$(16) \qquad \frac{(U_0-E')-E'e_0}{U_i-E'e_i} = \frac{(U_0-E')(1-\frac{\theta e_0}{p_0+t_0})}{U_i(1-\frac{\theta e_i}{p_i+t_i})}$$

Inserting (11) and (12) into the r.h.s. of this expression yields

$$(17) \qquad \frac{U_0-E'-E'e_0}{U_i-E'e_i} = \frac{p_0+T_0}{p_i+T_i} \quad for \quad i = 1,....\eta$$

which is equivalent to our optimality condition (8).

We have thus shown that a competitive economy with the tax/tariff structure defined by (10)-(11) has an equilibrium which is equivalent to the social optimum derived in section 2.

The interpretation of (10) is that the carbon tax is equal to the marginal environmental cost of carbon emissions measured in money: E` is the marginal environmental cost measured in utility, while $(p_i+t_i)/U_i$ is dollars per unit utility (for good i). E`$\cdot(p_i+t_i)/U_i$ is thus a monetary measure of the marginal environmental cost of carbon emissions.

The tariff t_j consists of two terms. The first term (T_j) measures the terms of trade effect of an increase of imports of good j. The second term (θe_j) measures the value of the change in foreign emissions as a consequences of a marginal increase of imports of good j. Since neither T_j nor e_j are unambiguously signed, the sign of t_j is also indetermined. Typically, the vector $(t_0, t_1,...,t_n)$ will have some negative and some positive elements.

An important special case of our general model is the case in which all $\partial p_i/\partial m_j$ are close to zero. This will typically occur if the group of cooperating countries is small compared to the rest of the world. In this case it is clear from (9) that all T_j will be close to zero. Notice also that even if all $\partial p_i/\partial m_j$ are close to zero, the derivatives $e_j=\Sigma_i\partial f/\partial p_i \cdot \partial p_i/\partial m_j$ need not be "small", since some or all $\Sigma_i\partial f/\partial p_i$ may be large. Assume e.g. that a doubling of the domestic consumption of a good j, with a corresponding increase in imports, only increases the world market price of this good by, say, 1 percent. In this case the terms of trade effect is negligible. Although a 1 percent price change will only change foreign emissions by a small amount in percent of world emissions, this emission change may be large relative to the emissions of the home country. In this case $\partial f/\partial p_j$ will thus be "large", so that we cannot set e_j for this good even if all T_js may be approximated by zero.

If all T_js are zero, the sign and magnitude of the optimal import tariff t_j on good j will only depend on the sign and magnitude of e_j for this good. As mentioned previously, we would expect that e_j is positive for an energy intensive good, e.g. that increased import (or reduced export) of such a good will increase foreign emissions. Such a good should thus have a positive import tariff, i.e. an export subsidy if this good is exported by the home country. For goods which use little or no fossil fuels in their production, on the other hand, we would expect e_j to be negative, thus implying an import subsidy or an export tax. We argued earlier that capital may be an example of a good with $e_j<0$. If this is the case, net import of capital should be encouraged by a capital import subsidy/export tax. The interpretation of this is that increased import of capital reduces the foreign use of capital. This tends to reduce foreign production of all or at least most goods, with the consequence that foreign emissions decline.

4. A second best optimum

In this section we consider a second best optimum in which tariffs of the type discussed in the previous section are ruled out. We shall return to a discussion of such a restriction in the concluding section.

In order to simplify to analysis somewhat, we shall restrict ourselves to the special case mentioned above in which we may set $T_j=0$ for all j. More precisely, we assume that

(a) all international prices are fixed

(b) all goods are tradeable

(c) there is no domestic production of fossil fuels.

Assumptions (a) and (b) simplify the analysis significantly, as the only consumer price which is endogenous in this case is the consumer price of fossil fuels. Assumption (c) could easily be disposed of, but makes notation somewhat simpler.

As before, $\tilde{y}=(y_1,...y_n)$ is the vector of net outputs of the n non-fuel goods. Instead of only considering aggregate fuel input use as we did in the previous section, we now distinguish between fuel used in the production of different goods. This vector of fuel use is denoted by $v=(v_1,...v_n)$. The consumption vector is as before given by $c=(c_0,c_1,....c_n)$. Net imports of the n+1 goods are thus given by

$$
(18) \qquad \begin{aligned} m_0 &= c_0+\sum_i v_i \\ m_i &= c_i-y_i \qquad for \quad i>0 \end{aligned}
$$

As before, foreign emissions are given by $e(m_0, m_1,...m_n)$.

The government of the home country wishes to choose carbon tax rates $(\theta_0,\theta)=(\theta_0,\theta_1,...\theta_n)$ to maximize welfare given by (1). To give a precise formulation of this optimization problem it is useful first to define the indirect utility function V and the profit function π. The price vector facing households is $(p_0+\theta_0, p_1,....p_n)$. Since all international prices are assumed fixed, the indirect utility function is defined by

$$
(19) \qquad V(\theta_0,\mathrm{I}) = \max \; U(c_0,c) \quad \text{s.t.} \, (p_0+\theta_0)c_0+\sum_{i>0} p_i c_i \leq \mathrm{I}
$$

where I is household income. The function V has the following properties:

The profit function is given by

(20)
$$\frac{\partial V}{\partial c_0} = -c_0\lambda$$
$$\lambda \equiv \frac{\partial V}{\partial I}$$

(21)
$$\pi(\theta) = \max \ \Sigma_i p_i y_i - \Sigma_i (p_0 + \theta_i) v_i$$

where the vector (**y**,**v**) is constrained by the set of feasible technologies. The profit function has the properties

(22)
$$\frac{\partial \pi}{\partial \theta_i} = -v_i$$

Finally, household income consists of profits plus reimbursed tax revenue, i.e.

(23)
$$I = \pi(\theta) + \theta_0 c_0(\theta_0, I) + \Sigma_i \theta_i v_i(\theta_i)$$

Using the expressions above, the welfare level W may now be written as

(24)
$$\begin{aligned} W = {} & V(\theta_0, I) - E(c_0(\theta_0, I) + \Sigma_i v_i(\theta) \\ & + e(c_0(\theta_0, I) + \Sigma_i v_i(\theta),\ c_1(\theta_0, I) - y_1(\theta),\ \ldots,\ c_n(\theta_0, I) - y_n(\theta))) \end{aligned}$$

In the Appendix, it is shown that the emission taxes which maximize W are given by

(25)
$$\theta_0 = \frac{E'}{\mu} \cdot [1 + e_0 + \frac{\sum_{i>0} e_i (\frac{\partial c_i}{\partial \theta_0})_{u=\bar{u}}}{(\frac{\partial c_0}{\partial \theta_0})_{u=\bar{u}}}]$$

and

(26)
$$\theta_j = \alpha_j \cdot \frac{E'}{\mu} \cdot \left[1 + e_0 + \frac{\Sigma_i e_i \left(-\frac{\partial y_i}{\partial \theta_j}\right)}{\Sigma_i \frac{\partial v_i}{\partial \theta_j}} \right]$$

where

(27)
$$\alpha_j = \frac{\theta_j \, \Sigma_i \, \frac{\partial v_i}{\partial \theta_j}}{\Sigma_i \, \theta_i \, \frac{\partial v_i}{\partial \theta_j}}$$

Consider first the term E'/μ. The term E' is the marginal cost in terms of utility, and μ is the marginal welfare increase (i.e. increase in U-E) from a hypothetical transfer of money to the households. The term E'/μ thus measures the marginal cost of CO_2 emissions in money terms.

The term e_0 measures the change in foreign emissions per unit increase in domestic emissions, so that $1+e_0$ gives the direct effect on global emissions per unit increase of domestic fossil fuel use. The terms $(E'/\mu)(1+e_0)$ in (25) and (26) thus give the marginal environmental cost of the direct effect of increasing domestic fuel use. In addition to this direct effect, global emissions may be affected indirectly via changes in net imports of non-fuel goods. These indirect effects are captured in the last terms of (25) and (26).

Consider the last term of (25). The derivatives in this term are compensated price derivatives. The denominator is the compensated direct price derivative of the demand for fossil fuels, and is thus negative. The numerator measures the effect of a compensated increase in the consumer price of fossil fuels on foreign emissions, via the effects such a price increase has on the consumption of all other goods. This numerator can clearly not be unambiguously signed.

Consider next the last terms of (26). The denominator in this term for sector j measures the change in total fuel input in all sectors as a consequence of a rise in the price of fuel in sector j. Although it seems most likely that these denominators are negative, the opposite cannot be ruled out. The numerator of the last term of (26) for sector j is the effect on foreign emissions, via the effects on net outputs of all goods, of a rise in the price of fuel in sector j. This numerator can clearly not be unambiguously signed. Moreover, it is clear that the last term of (26) will generally differ between sectors, implying different optimal carbon taxes for different sectors. (Notice that <u>if</u> the last term in the square brackets of (26) was the same for all j, than all $\alpha_j=1$, so that the optimal carbon tax would be equal for all sectors.)

It is clear from the discussion above that even with the simplifications we have made, the optimal carbon taxes will in general differ across sectors. Moreover, unlike the optimal tariffs in the first best optimum in the absence of terms of trade effects, there is no simple relationship between the sign and size of e_j and the optimal carbon tax for sector j.

Consider finally the case in which not only tariffs are ruled out, but in which one also for some reason must have the same carbon tax on all industries using fossil fuels as inputs. Assume however, that the carbon tax may be differentiated between households and producers. In this case the government of the home country wishes to choose the two carbon tax rates (θ_0,θ) to maximize welfare given by (1). Compared with the expression (24) above for total welfare, the only change is that a single carbon tax θ takes the place of the carbon tax vector θ. In the Appendix, it is shown that (25) remains valid, while the only change in (26) is that the subscript j must be omitted, and that α_j is replaced by 1. For this case it is thus clear that the optimal carbon tax facing households will usually differ from the carbon tax rate facing industry. However, the difference between the two tax rates is not unambiguously signed.

5. Discussion

The analysis above shows that as long as tariffs (i.e. taxes or subsidies on import and export) may be optimally chosen, the carbon tax should be equal for all users of fossil fuels. If, however, tariffs are ruled out, it is optimal for the cooperating countries to differentiate the carbon tax across sectors. Even for the simple model of section 4, the determination of optimal carbon taxes was quite complex. There is no simple relationship between e.g. fossil fuel intensity or the effect on foreign emissions on the one hand and the optimal carbon tax on the other hand.

It is difficult to find good reasons for ruling out the use of tariffs. One argument could be that quite a substantial amount of information is needed to calculate optimal tariffs. However, it is clear from section 4 that the information requirement needed for calculating optimal carbon taxes with zero tariffs is considerable larger than the information required for calculating optimal tariffs. Limited information about characteristics of the economy is thus not a reason to differentiate carbon taxes across sectors instead of supplementing a uniform carbon tax with tariffs.

Trade policy arguments could be made against import and export taxes/subsidies. However, similar arguments could also be made against differentiating taxes (in this case carbon taxes) across sectors. Moreover, the non-cooperating countries are not in a very strong position to argue against tariffs which might hurt them. The justification for the tariffs is after all an attempt to avoid excessive carbon emissions from the non-cooperating countries. Any non-cooperating country which claims to be adversely affected by the tariffs can avoid the tariffs by participating in the climate agreement instead of being a free rider.

Tariffs are generally not permitted according to trade agreements such as GATT, NAFTA, etc. It is not clear whether exceptions from this general rule may be made when there are good environmental reasons for imposing such tariffs. The use of trade restrictions is explicitly permitted under the Montreal Protocol on Substances that Deplete the Ozone Layer, although the GATT Secretariat has voiced its opposition to such use of trade restrictions, see Barrett (1994b) for a further discussion. Different tax treatment of different industries is also restricted under most trade agreements. A differentiated carbon tax may thus be equally difficult to impose as tariffs. As shown in section 4, an optimal policy may therefore consist of one carbon tax rate for direct consumption of fossil fuels, and one rate for the use of fossil fuels as inputs in production. As long as this latter rate is uniform across industries, the differentiation between households and industries will probably not violate any trade agreements.

One limitation of our analysis is that the cooperating coalition was exogenously given. However, the use of tariffs or a differentiated carbon tax might affect which countries choose to join a coalition. This has been studied by Barrett (1994a), who shows that trade restrictions may help deter free riding, and thus make the coalition of cooperating countries larger. The free rider deterrence may be different for a uniform carbon tax combined with tariffs, on the one hand, and a differentiated carbon tax, on the other hand. A careful analysis of this issue is, however, beyond the scope of the present paper.

The analysis has focused on the climate problem. However, the qualitative results are relevant also for other international environmental problems. For several such problems the policies in a group of countries which reduce their emissions will also affect international prices of traded goods. This may in turn affect production and consumption patterns, and thereby emissions, in other countries. Whenever there are international spillovers of harmful emissions, this should be taken into consideration by the countries which have an explicit environmental policy. Optimal environmental policies for such problems will consist of a combination of emission taxes and tariffs (positive or negative) on imports and exports for those traded goods whose prices may affect harmful emissions from countries which have no explicit environmental policy.

Appendix: Derivation of equations 25 and 26.

The Lagrangian corresponding to the maximization of W (given by (24)) subject to (23) is

$$\begin{aligned} L = {} & V(\theta_0, \mathrm{I}) - E(c_0(\theta_0, \mathrm{I}) + \textstyle\sum_i v_i(\theta) \\ & + e(c_0(\theta_0, \mathrm{I}) + \textstyle\sum_i v_i(\theta), c_1(\theta_0, \mathrm{I}) - y_1(\theta), \dots, c_n(\theta_0, \mathrm{I}) - y_n(\theta))) \\ & + \mu[\pi(\theta) + \theta_0 c_0(\theta_0, \mathrm{I}) + \textstyle\sum_i \theta_i v_i(\theta_i) - \mathrm{I}] \end{aligned} \tag{28}$$

The first order conditions for the maximization problem are

$$\begin{aligned} \frac{\partial L}{\partial \mathrm{I}} = {} & \lambda - E' \cdot [(1 + e_0) \frac{\partial c_0}{\partial \mathrm{I}} + \sum_{i>0} e_i \frac{\partial c_i}{\partial \mathrm{I}}] \\ & + \mu\ [\theta_0 \frac{\partial c_0}{\partial \mathrm{I}} - 1] \quad = 0 \end{aligned} \tag{29}$$

$$\begin{aligned} \frac{\partial L}{\partial \theta_0} = {} & -\lambda c_0 - E' \cdot [(1 + e_0) \frac{\partial c_0}{\partial \theta_0} + \sum_{i>0} e_i \frac{\partial c_i}{\partial \theta_0}] \\ & + \mu\ [c_0 + \theta_0 \frac{\partial c_0}{\partial \theta_0}] \quad = 0 \end{aligned} \tag{30}$$

$$\begin{aligned} \frac{\partial L}{\partial \theta_j} = {} & -E' \cdot [(1 + e_0) \textstyle\sum_i \frac{\partial v_i}{\partial \theta_j} - \textstyle\sum_i e_i \frac{\partial y_i}{\partial \theta_j}] \\ & + \mu \textstyle\sum_i \theta_i \frac{\partial v_i}{\partial \theta_j} \quad = 0 \end{aligned} \tag{31}$$

Multiplying (29) by c_0 and adding it to (30) yields

$$\begin{aligned} & -E' \cdot [(1 + e_0) (\frac{\partial c_0}{\partial \theta_0} + c_0 \frac{\partial c_0}{\partial I}) + \sum_{i>0} e_i (\frac{\partial c_i}{\partial \theta_0} + c_0 \frac{\partial c_i}{\partial I}] \\ & + \mu \theta_0\ [\frac{\partial c_0}{\partial \theta_0} + c_0 \frac{\partial c_i}{\partial I}] \quad = 0 \end{aligned} \tag{32}$$

The compensated demand derivatives are given by (for all i)

$$(33)\qquad \left(\frac{\partial c_i}{\partial \theta_0}\right)_{u=\bar{u}} = \frac{\partial c_i}{\partial \theta_0} + c_0 \frac{\partial c_i}{\partial I}$$

Dividing (32) through by the compensated demand derivative for fuels immediately gives us equation (25).

It follows from the definition of α_j (given by (27)) that equation (31) may be rewritten as

$$(34)\qquad \begin{aligned} &-E'\cdot[(1+e_0)\ \Sigma_i\ \frac{\partial v_i}{\partial \theta_j} - \Sigma_i\ e_i\ \frac{\partial y_i}{\partial \theta_j}] \\ &+\mu\ \frac{\theta_j}{\alpha_j}\ \Sigma_i\ \frac{\partial v_i}{\partial \theta_j} \qquad = 0 \end{aligned}$$

Dividing (34) through by $\Sigma_i \theta_i (\partial v_i / \partial \theta_i)$ immediately gives us equation (26).

If we add the restriction $\theta_j = \theta$ for all $j \neq 0$, (31) is replaced by

$$(35)\qquad \begin{aligned} \frac{\partial L}{\partial \theta} = &-E'\cdot[(1+e_0)\ \Sigma_i\ \frac{\partial v_i}{\partial \theta} - \Sigma_i\ e_i\ \frac{\partial y_i}{\partial \theta}] \\ &+\mu\ \theta\ \Sigma_i\ \frac{\partial v_i}{\partial \theta} \qquad = 0 \end{aligned}$$

This equation may be rewritten as

$$(36)\qquad \begin{aligned} &-E'\cdot[(1+e_0)\ \Sigma_i\ \frac{\partial v_i}{\partial \theta} - \Sigma_i\ e_i\ \frac{\partial y_i}{\partial \theta}] \\ &+\mu\ \theta\ \Sigma_i\ \frac{\partial v_i}{\partial \theta} \qquad = 0 \end{aligned}$$

Dividing (36) through by $\Sigma_i (\partial v_i / \partial \theta)$ immediately gives us equation (26) without subscript j and with α_j replaced by 1.

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