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Climate Agreements and Technology Policy

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Climate Agreements and Technology Policy[a]

Rolf Golombek[b] and Michael Hoel[c]

Abstract

We study climate policy when there are technology spillovers within and across countries, and the technology externalities within each country are corrected through a domestic subsidy of R&D investments. We compare the properties of international climate agreements when the inter-country externalities from R&D are not regulated through the climate agreement. With an international agreement controlling abatements directly through emission quotas, the equilibrium R&D subsidy is lower that the socially optimal subsidy. The equilibrium subsidy is even lower if the climate agreement does not specify emission levels directly, but instead imposes a common carbon tax. Social costs are higher under a tax agreement than under a quota agreement. Moreover, for a reasonable assumption on the abatement cost function, R&D investments and abatement levels are lower under a tax agreement than under a quota agreement. Total emissions may be higher or lower in a second-best optimal quota agreement than in the first-best optimum.

Keywords: Climate policy, international environmental agreements, R&D Policy, technology spillovers.

JEL classification: O30; H23; Q20; Q28; Q48

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1 Introduction

If dramatic future climate changes are to be avoided, there must be a significant reduction in global greenhouse gas emissions compared with the "business as usual" development of emissions. Moreover, a significant reduction in global greenhouse gas emissions will require (i) cooperation among countries and (ii) development of new technology if such reductions are to be achieved without excessive costs. The interaction between the design of international climate agreements and endogenous technology development is therefore an important issue.

Several recent articles have studied interactions between endogenous technological change and environmental policy, see e.g. Jaffe *et al.* (2002) and Löschel (2002) for overviews. Most of the contributions dealing explicitly with the climate problem neglect interactions between countries, and simply consider the world as one unit with a central planner.[1] There is, however, a literature that focuses explicitly on interactions between countries in a context of endogenous technology development, see Ploeg and de Zeeuw (1994), Xepapadeas (1995), Katsoulacos (1997), Buonanno et al. (2003), Rosendahl (2002) and Ben Youssef (2003).

Two papers by Carraro and Marchiori (2003) and Buchner and Carraro (2004) are particularly relevant for the issues discussed in the present paper. In both papers it is assumed that there are technology spillovers between countries, but that free riding countries to some extent can be excluded from these spillovers. The issue in Carraro and Marchiori (2003) is whether or not negotiations on R&D cooperation and on emissions reductions should be linked. They derive conditions under which a linkage of these two issues is an equilibrium of the negotiation game. Buchner and Carraro (2004) use a numerical model to study the properties of an agreement only on R&D cooperation, and not explicitly on

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[1] See e.g. Carraro (1998), Fischer (2000), Goulder and Mathai (2000), Goulder and Schneider (1999), Nordhaus (2000) and Rasmussen (2001).

emissions reductions. They show that if a sufficiently large part of the technology spillovers can be limited to the cooperating countries, all countries will wish to participate in the R&D agreement. However, the numerical model used suggests that the total amount of greenhouse gas emissions will be higher under such an agreement than in the case of no cooperation.

None of the articles listed above focus explicitly, however, on how the design of an international agreement on greenhouse gas emissions might affect the incentives for technology development. This is one of the issues treated in Golombek and Hoel (2003), where it is assumed that R&D investments in each country are beneficial also for other countries through technology spillovers[2]. Various types of non-cooperative and cooperative outcomes are studied. In particular, the paper compares different types of climate agreements that regulate emissions, but don't include policies towards R&D investments. The justification for this limitation of the agreements, which is in contrast to what is assumed in Carraro and Marchiori (2003) and Buchner and Carraro (2004), is that policies affecting R&D expenditures are difficult to verify by other countries. If a country is required - through an international agreement - to have more R&D expenditures than what is individually optimal for the country, it will be relatively easy for the country to have less R&D than required by the agreement, but to report other expenditures and/or other policies as R&D activities/policies.

In Golombek and Hoel (2003) it is assumed that R&D expenditures in each country are controlled directly by the government. This assumption reflects that the incentives for any particular firm to undertake R&D expenditures are weak due to technology spillovers – both between countries and between domestic firms. The government must therefore finance the R&D activities, even though

[2] This feature is present also in several of the studies referred to above, although these contributions do not treat the same issues as Golombek and Hoel.

R&D (primarily) takes place in private firms. The government thus controls R&D expenditures through its funding of them. In the present paper we explicitly consider this funding. All R&D is assumed to take place in private firms, but the R&D investments are subsidized by the government. The purpose of the present paper is therefore to study climate policy when R&D takes place in private firms and there are technology spillovers between countries, but there is no instrument to correct for these international externalities. In particular, we compare the properties of different types of international climate agreements when the positive externalities from R&D are not regulated through the climate agreement. By explicitly modeling R&D investments in private firms we derive several results that have not been derived before.[3]

The rest of the paper is organized as follows. In Section 2 we present the model in more detail. In order to keep the analysis as simple as possible, we use a static framework, thus ignoring, for example, the fact that GHG emissions are stock pollutants. We also consider only one type of GHG, namely CO_2. None of our results are affected by this simplification. Moreover, all types of uncertainties – like the rate of return on R&D investments - are disregarded. Finally, all countries are assumed identical, and all firms within each country are also identical. While this of course is a drastic simplification, the analysis nevertheless gives insight that is relevant also in the real world.

In Section 3 we consider the first-best social optimum. This gives a particular abatement level, and a particular level of R&D investments in each firm. This outcome could be implemented through an ideal international agreement that sets a common carbon tax to be used in all countries, as well as a common subsidy rate for R&D investments for all firms in all countries.

[3] Our results are given in 12 propositions. Of these, it is only the result in Proposition 6 that also was derived in Golombek and Hoel (2003), as Proposition 9 of that paper.

Sections 4-6 consider three types of international agreements that regulate emissions, but don't include policies towards R&D investments (the justification for this limitation of the agreements was given above). Sections 4 and 5 consider an international agreement controlling abatements directly through emission quotas. In our simple model with identical countries, it makes no difference whether quotas are non-tradable (Section 4) or tradable (Section 5). We show that the equilibrium R&D subsidy is lower than the socially optimal subsidy if there are technology spillovers across countries. The equilibrium subsidy is even lower if the climate agreement does not specify emission levels directly, but instead imposes a common carbon tax faced by all firms in all countries (Section 6).

In the model there are 3 levels of decision makers; (i) the group of all countries in the world, (ii) each country and (iii) firms. In Section 4-6 we study the optimal policy of a country when the climate agreement is taken as given and the country takes into account how domestic and foreign firms will respond to its policy decisions. In Section 7-9 we study the optimal design of climate agreements. We assume that all types of agreements are designed by the group of all countries in order to minimize total social costs, given how countries will respond to the climate agreement (and how firms will respond to the policy decisions of countries).

In Sections 7 and 8 we study how strictly emissions should be regulated in the climate agreement. For the quota case, emissions should be regulated so that marginal abatement costs are higher than the sum of marginal environmental costs in all countries. In the case of an emission tax agreement, it is not obvious whether the common emission tax should be higher or lower than the sum of marginal environmental costs. Under a reasonable assumption about the abatement cost function, however, the common emission tax should be lower than the sum of marginal environmental costs. With this condition on the cost function we also find that the levels of abatement and R&D investments are lower under the optimal tax agreement than under the optimal quota agreement. Under the tax agreement the levels of abatement and R&D investments are also lower than in the first-best optimum.

Section 9 compares total social costs of climate agreements. The second-best agreements will necessarily have higher social costs than the first-best outcome. We show that total social costs are higher in the tax case than in the quota case. Finally, Section 10 sums up our main findings and points at topics for future research.

2 The model

We assume there are *m* firms in each of *n* countries. All firms are identical and undertake R&D investments. As a simplification, we neglect uncertainties and dynamic aspects of R&D as well as patents. We assume the technology level of a particular domestic firm depends on its own R&D investments (X), the amount of R&D investments in the other firms in that country (x), as well as investments in R&D in all firms abroad (x^*).[4]

Technology diffusion is not perfect. For a representative domestic firm, only part ($\gamma < 1$) of the R&D investments undertaken in the other domestic firms are beneficial for the firm. Similarly, only part ($\gamma^* \leq \gamma$) of the R&D investments undertaken in foreign firms are beneficial for the domestic firm. The technology level of a representative domestic firm is thus given by

$$Y = X + (m-1)\gamma x + (n-1)m\gamma^* x^* \tag{1}$$

In (1) we have assumed an additive structure of technology spillovers, that is, the technology level of a firm depends on the sum of R&D investments

[4] With identical firms, R&D investments may be equal in all firms in equilibrium. However, in order to find the equilibrium it is expedient to distinguish between the amount of R&D investments undertaken in a particular domestic firm, in other domestic firms and in foreign firms.

undertaken in all forms, corrected by the technology diffusion parameters (γ and γ^*). This way of modeling spillovers can be found in a wide range of theoretical and empirical contributions, and goes back at least to Spence (1984). It is also used in the literature refereed to above on climate policy in the context of interactions between countries and endogenous technology development. In this literature there is no explicit modeling of knowledge spillovers within each country, but spillovers across countries are modeled as in (1). The assumptions used by Ploeg and de Zeeuw (1994) and Xepapadeas (1995) correspond to the limiting case of $\gamma^* = 1$, while the assumptions used by e.g. Buonanno et al. (2000, 2003) and Rosendahl (2002) correspond to $\gamma^* < 1$.

Although spillovers often are modeled as in (1), it is not obvious that this is the best way of modeling technology spillovers between firms and countries. Cohen and Levinthal (1989) have argued that the ability of a firm to learn from other firms may depend on its own R&D effort. Graevenitz (2002) discusses the policy implications of whether one models spillovers additively as in (1) or in a similar way as Cohen and Levinthal suggest. We shall stick to the "standard" formulation (1).

The technology level of a particular foreign firm (Y^*) is determined in a similar way as (1):

$$Y^* = X^* + (m-1)\gamma x^* + (n-2)m\gamma^* x^* + m\gamma^* x \qquad (2)$$

In (2) the first term is R&D investment in the particular foreign firm, the second term shows the spillover effect from the other ("foreign") firms in the same country, the third term shows the spillover effect from all other foreign firms, whereas the last term shows the spillover effect from the "domestic" firms.

With identical firms, business as usual (BAU) emissions are equal across firms, and normalized to 1. Let A, a and a^* be abatement in a particular domestic firm, in the other domestic firms and in foreign firms, respectively. For domestic firms, emissions are then given by $1-a$.

Each firm is faced by three types of costs; abatement costs, R&D expenditures and emission costs (which may be emission taxes or a price for tradable emission quotas). For all firms, abatement costs are assumed to depend both on the level of abatement and the technology level of the firm. Hence, for domestic firms, costs of abatement are represented by $c(a,y)$, where $c'_a = \partial c/\partial a > 0$, $c''_{aa} > 0$, $c'_y < 0$, $c''_{yy} > 0$, $c''_{ay} < 0$ and $c''_{aa}c''_{yy} - (c''_{ay})^2 > 0$ (i.e. the c function is strictly convex). The price of R&D investments is normalized to one. However, we assume that the domestic government subsidizes R&D investments by the rate σ (and the governments abroad subsidize R&D investments by the rate σ^*).[5] Finally, all firms face a cost of carbon emissions, which we denote q and q^* for domestic and foreign firms, respectively.

A particular domestic firm minimizes its total costs by choosing abatement (*A*) and R&D investments (*X*). Hence, the firm minimizes

$$c(A,Y) + (1-\sigma)X + q(1-A) \tag{3}$$

where the second term is net R&D expenditures, the third term is environmental costs of the firm, and the technology level *Y* is given by (1). All (the identical) domestic firms solve a similar problem, and they will thus

[5] In our simple model where all R&D investments reduce abatement costs, subsidization of R&D is an obvious policy to encourage such investments. In a more complex setting where some types of R&D investments might increase BAU emissions, and it is difficult for the regulator to distinguish between different types of R&D investments, subsidizing R&D might not be a good policy. See e.g. Lund (1994) for a detailed discussion.

choose the same values in equilibrium ($A = a$ and $Y = y$). The first order conditions for this problem are thus given by:[6]

$$c_a(a, y) = q \tag{4}$$

$$-c_y(a, y) = 1 - \sigma \tag{5}$$

Equation (4) is the standard condition for optimal abatement; marginal costs of abatement (c_a) should equal marginal benefit of abatement, which in our model equals the price of carbon emissions *q*. Further, marginal costs of R&D investments ($1-\sigma$) should equal marginal benefit of these investments ($-c_y > 0$).

Also all foreign firms minimize their total costs, which give us the following first-order-conditions:

$$c_{a^*}(a^*, y^*) = q^* \tag{6}$$

$$-c_{y^*}(a^*, y^*) = 1 - \sigma^* \tag{7}$$

From (4) and (5) we see that the technology level of domestic firms y, as well as abatement *a*, depend on σ and *q*, whereas (6) and (7) show that the technology level of foreign firms y^*, as well as abatement a^*, depend on σ^* and q^*;

$$y = y(\sigma, q) \tag{8}$$

$$a = a(\sigma, q) \tag{9}$$

$$y^* = y^*(\sigma^*, q^*) \tag{10}$$

$$a^* = a^*(\sigma^*, q^*) \tag{11}$$

[6] Throughout the paper, we assume interior equilibrium outcomes for *a* and *x*, which will be the case for suitable assumptions on the function *c*(*a*,*y*).

It follows from the properties of the abatement cost function that all of these four functions are increasing in both their arguments.

As both y and y^* depend on R&D investments undertaken in all countries, see (1) and (2), we have (using X=x and X*=x*)

$$x = x(\sigma, \sigma^*, q, q^*) \tag{12}$$

$$x^* = x^*(\sigma, \sigma^*, q, q^*) \tag{13}$$

Hence, if the domestic government changes its R&D subsidy, R&D investments will be affected in all (domestic and foreign) firms, and the technology level of domestic firms will change. Note, however, that the technology level of foreign firms will not change since for a foreign firm costs of production, that is, costs of R&D investments and the price of carbon, have not changed, see (10). Similarly, a change in the foreign R&D subsidy will affect R&D investments in all (domestic and foreign) firms as well as the technology level of foreign firms, but has no impact on the technology level of domestic firms.

For the proceeding analysis, it is useful to have an explicit expression for (12). This follows from (1) and (2) (and X=x, X*=x*, Y=y and Y*=y*):

$$x = hy + (H - h)y^* \tag{14}$$

where

$$h = \left[1 + (m-1)\gamma - \frac{(n-1)(m\gamma^*)^2}{1 + (m-1)\gamma + (n-2)m\gamma^*}\right]^{-1} \tag{15}$$

$$H = \left[1 + (m-1)\gamma + (n-1)m\gamma^*\right]^{-1} \tag{16}$$

The following properties can be derived from the expressions above:

- H and h are both positive
- H is lower than h if there are spillovers across countries
- H is equal to h if there are no spillovers across countries (γ*=0)
- H and h are both equal to 1 if there are no spillovers (γ=γ*=0)
- H and h are both decreasing in γ
- H is decreasing in γ*
- h is increasing in γ*
- H is smaller than 1
- h is smaller than 1 if γ* is sufficiently small relative to γ, but may be larger than 1 if γ* is sufficiently close to γ[7]

3 The first-best social optimum

In the first best optimum, all the (mn) identical firms have the same level of abatement (a) as well as identical amounts of R&D investments (x). Total social costs (for a given total emission level) are therefore given by total costs of abatement and R&D investments, that is,

$$mn[c(a,y)+x] \tag{17}$$

Relation (17) is minimized with respect to x subject to the definition of technology level, which can now be written as (see (14) for the case of $y^* = y$)

$$x = Hy \tag{18}$$

where H is given by (16).

For given abatements, the first order condition for the first-best optimum is

[7] For γ*=γ we find $h = \left[1+(nm-m-1)\gamma\right]\left[1+(nm-2)\gamma-(nm-1)\gamma^2\right]^{-1}$, which is larger than 1 for $\gamma > \dfrac{m-1}{nm-1}$.

$$-c_y = H \tag{19}$$

Rewriting this as $-c_y H^{-1} = 1$ gives a straightforward interpretation: The marginal benefit of R&D investments when all spillovers are taken into account ($-c_y H^{-1}$) should equal marginal costs of R&D investments. Using (5) together with (19) we see that the social optimum can be implemented by imposing the subsidy

$$\tilde{\sigma} = 1 - H \tag{20}$$

on all firms. We immediately see from (20) and the properties of *H* that the optimal subsidy is zero for the special case of no spillovers ($\gamma=\gamma^*=0$). Moreover, the optimal subsidy is larger the larger are the diffusion parameters γ and γ^*:

Proposition 1: The optimal subsidy of R&D investments is higher the greater are the technology spillovers within countries and across countries.

The intuition of Proposition 1 is straightforward; the higher the rate of diffusion, the more beneficial are R&D investments in one firm for all other firms. As the social return on R&D investments increases, the optimal level of R&D investments increases, which requires a higher technology subsidy. Finally, note that the subsidy is constant, and hence independent of the abatement level *a* as well as the technology level *y*. This is due to *H* in (20) being independent of both *a* and *y*, which reflects the additive structure of (1).

4 An international agreement on abatement

In this section we assume there is an international agreement that specifies abatement levels in all countries. These levels are implemented through country specific emission taxes (or through country specific tradable emission quota systems). Hence, (4) and (6) apply in this case, with q and q^* being the emission tax (or more generally, the price of carbon) imposed on domestic and foreign firms, respectively.

As discussed in Section 2, a shift in the domestic technology subsidy σ will have impact on R&D investments in all (domestic and foreign) firms, as well as the technology level of domestic firms. The domestic government minimizes total domestic social costs

$$m[c(a,y)+x] \tag{21}$$

with respect to the technology subsidy σ (see (8) - (13)), taking a as given.[8] The first order condition is (using (8) and (14) and the equilibrium conditions $X = x$, $X^* = x^*$, $Y = y$ and $Y^* = y^*$ in addition to the fact that y^* is not affected by a change in σ, cf. the discussion above)

$$(c_y + h)\frac{\partial y}{\partial \sigma} = 0 \tag{22}$$

or, since the derivative $\frac{\partial y}{\partial \sigma}$ is positive,

$$-c_y = h \tag{23}$$

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[8] Strictly speaking, the government minimizes $m[c(a,y)+x]$ subject to q and σ, given that the domestic abatement level *ma* follows from the agreement.

Using (5), the optimal domestic technology level can be implemented through the technology subsidy $\bar{\sigma}$, which is characterized by

$$\bar{\sigma} = 1 - h \tag{24}$$

From (20) and (24) and the properties of *h* we have the following results:

Proposition 2: *With an international agreement on abatement, the equilibrium subsidy of R&D investments is higher the greater are the technology spillovers within countries and lower the greater are the technology spillovers across countries. For sufficiently large spillovers across countries, the equilibrium subsidy may be negative, i.e R&D investments may be taxed.*

The intuition of the first part of Proposition 2, that larger domestic spillovers imply a higher subsidy, is obvious. The intuition on the relationship between the strength of spillovers across countries and the subsidy is as follows: With international spillovers (and abatement given by the international agreement), the technology level of a foreign firm depends only on the foreign technology subsidy σ^* (cf. *(10)*). Hence, if domestic firms, *cet. par.*, increase their R&D investments, foreign firms will reduce their R&D investments so that their technology level is unchanged.[9] Reduced R&D investments abroad will lower the technology level of domestic firms through technology diffusion, and hence lower the domestic return on R&D investments. As the leakage tends to decrease the domestic technology level, the domestic technology subsidy should be reduced. With no international spillovers, there is no leakage, and hence the incentive to increase domestic R&D investments is higher, that is, the technology subsidy is greatest in the case of no international technology diffusion. If on the other hand international spillovers are sufficiently large, each county has a strong incentive to reduce its own R&D investments, thereby

[9] While this effect might be termed a 100 per cent leakage, the reduction in R&D investments of a foreign firm relative to the increase in domestic R&D investments depends on the number of domestic and foreign firms, as well as the diffusion parameters γ and γ^*.

increasing R&D investments in other countries, which it benefits from. Therefore a tax on R&D investments (corresponding to h>1) might be an optimal policy from the perspective of each individual country.

From (19) and (23), and the properties of H and h, we also have the following result:

Proposition 3: With an international agreement on abatement, the equilibrium subsidy of R&D investments is equal to the first-best optimal subsidy if there are no technology spillovers across countries. If there are technology spillovers across countries, the equilibrium subsidy is lower than the first-best optimal subsidy.

As noted above, when abatements are given and there is international technology diffusion, in the non-cooperative equilibrium increased domestic R&D investments are offset by decreased R&D investments in foreign firms. In the first best optimum, the full social effect of R&D investments are taken into account, and hence the optimal technology level is higher in the first best case than in the non-cooperative case. Thus, the technology subsidy should be highest in the first best optimum. Without international spillover effects, there is no leakage in the non-cooperative equilibrium, and hence the technology level, as well as the subsidy, should not differ between the first best optimum and the non-cooperative equilibrium.

5 International tradable emission quotas

In this section we assume that all countries have signed an international climate agreement of the Kyoto type. The agreement specifies the initial distribution of emission quotas between countries, but allows countries to buy or sell quotas from/to other countries. The agreement imposes no restrictions on how the country sets its technology subsidy (or other environmental instruments). The agreement only dictates that emissions should not exceed the country's quotas (i.e. initial endowment adjusted for quotas purchased or sold).

Let E be total emission quotas given to the "domestic" country. We assume that an international market for quotas is established, with an equilibrium price p for quotas. Obviously, the quota price will be lower the more quotas are given to the countries.

The domestic country minimizes

$$m[c(a,y)+x]+p[m(1-a)-E] \tag{25}$$

with respect to abatement a and technology subsidy σ. In (25) the last term shows net environmental costs as $[m(1-a)-E]$ is the country's net purchase of quotas. Because all countries are identical, also with respect to the initial distribution of emission quotas, in equilibrium net purchase of quotas is zero for all countries. Hence, even if the number of identical countries is so low that each country can be considered to be "large" (that is, the country takes into account that the quota price depends on its own decisions), for each country $\frac{dp}{da}[m(1-a)-E]=\frac{dp}{d\sigma}[m(1-a)-E]=0$ in equilibrium.

The first order condition with respect to abatement is

$$c_a(a,y)=p \tag{26}$$

that is, marginal costs of abatement (c_a) should equal marginal benefit of abatement, which equals the price of quotas p (increased abatement reduces net purchase of quotas). The optimal abatement level can be implemented e.g. through a carbon tax imposed on all domestic firms, see (4), where the price of carbon q should equal the quota price p.

As in the case of an international agreement on abatement (see Section 3), the first order condition with respect to the technology subsidy is given by (22), where the term $\frac{\partial y}{\partial \sigma}$ as before is positive, so that (23) is valid also in the present case. Hence, the technology subsidy does not differ between the present case and the case of an international agreement on abatement.

With both types of agreements, R&D investments are determined according to (5) and (7), that is, investments depend on the technology subsidy, which has the same value in the two cases, and investments are also dependent on abatement. Hence, if abatements (at the firm level) do not differ between the two types of agreements, R&D investments will be equal under the two agreements. We have thus shown the following:

Proposition 4: The equilibrium subsidy of R&D investments does not differ between an agreement on abatement and an agreement with tradable quotas. If abatements at the firm level are equal in the two cases, R&D investments are also equal, that is, the two agreements are isomorphic.

With both types of agreements, the technology subsidy of a country has impact on R&D investments in all (domestic and foreign) firms, as well as the technology level of the country, see (8) - (13). However, there is no direct relation between the technology subsidy and total abatement/emissions of a country. Under an agreement on abatement, the agreement dictates national abatements levels (and hence the national emissions levels as BAU emissions are constant). With tradable emission quotas, national emissions follow solely from the choice of abatement. Because the technology subsidy is determined in the same way in the two cases, the subsidy is equal under the two types of agreements.

6 A harmonized domestic carbon tax

In the previous section we discussed the case of an agreement with direct limits on national emissions. In this section we analyze an agreement that does not specify emission levels for the participating countries. Instead, the agreement specifies policy instruments that the countries must implement domestically. Below we study the case where there is a common domestic carbon tax τ that all countries must implement. We assume that in each country the carbon tax revenue of the government is redistributed domestically.

In the previous case, total emissions (aggregated over all participating countries) followed directly from the agreement. In the present case, we assume that each country determines abatement taking into account environmental costs of emissions. For each country, environmental damage D depends on the sum of total emissions $D(m(1-a)+(n-1)m(1-a^*))$, where the damage function is increasing and convex.

The domestic country now minimizes

$$m[c(a,y)+x]+D(m(1-a)+(n-1)m(1-a^*)) \tag{27}$$

with respect to the technology subsidy σ and the fact that cost of carbon is τ for all firms. The last restriction implies that at the firm level abatement follows from

$$c_a(a,y)=\tau \tag{28}$$

The first order condition with respect to the subsidy is

$$(\tau - D')\frac{\partial a}{\partial \sigma} + (c_y + h)\frac{\partial y}{\partial \sigma} = 0 \tag{29}$$

where we have used (14) and (28).

From (5) and (29) we find that the equilibrium subsidy $\hat{\sigma}$ now is given by

$$\hat{\sigma} = 1 - h - (\tau - D')\frac{\frac{\partial a}{\partial \sigma}}{\frac{\partial y}{\partial \sigma}} \tag{30}$$

Consider the last term in (30). Without any agreement this term would be zero: the (domestic) tax rate would be equal to the marginal benefit of abatement D'. However, in the present case the common tax rate τ will in general be higher than the tax rate the country would have chosen without any agreement. Both derivatives $\frac{\partial a}{\partial \sigma}$ and $\frac{\partial y}{\partial \sigma}$ are positive, see the discussion after equations (8)-(11) .The last term in (30) is therefore negative. Comparing with (24) it therefore follows that $\hat{\sigma} < \bar{\sigma}$.

We have thus shown the following:

Proposition 5: The equilibrium subsidy of R&D investments under a harmonized domestic carbon tax is lower than the corresponding subsidy under an agreement on abatement/tradable emission quotas.

The interpretation of this result is directly linked to the first term in (29). The common tax rate τ will in general be higher than the tax rate the country would have chosen without any agreement. Hence, the level of abatement is distorted away from the country's ideal choice. Because the term $(\tau - D')$ is positive, and since increased R&D increases abatement, increased R&D also increases this distortion. This gives each country a smaller incentive to subsidize R&D investments than when such investments have no effect on the countries' abatement levels.

7 The second-best optimal price of carbon

So far, we have considered different types of agreements, without saying anything about how abatement levels are determined. We have shown that whatever the abatement level and tax rate is, the equilibrium subsidy of R&D investments is lower in a tax agreement than in a quota agreement. Moreover, under both types of agreements the equilibrium subsidies are lower than in the first-best optimum. In this section we shall investigate whether this property of both agreements should affect what the optimal quota/tax should be in the two types of agreements. Whatever the type of agreement, we assume that the agreement is designed (by the group of signatories) in order to minimize total social costs aggregated over all identical firms, that is,

$$mn[c(a,y)+x]+nD(mn(1-a)) \tag{31}$$

is minimized. Let us first consider the first best optimum, that is, (31) is minimized with respect to abatement *a* and *x*, subject to (18). The first order condition is, in addition to (19)

$$c_a = nD' \tag{32}$$

which is the standard requirement that marginal costs of abatement should equal total marginal benefit of abatement. Hence, from a first best perspective the price of carbon in an agreement should equal total marginal benefits of abatement nD'.

According to Propositions 3 and 5, the subsidies under both types of second-best agreements (since R&D subsidies are not included in the agreement) are lower than the subsidy in the first best case (assuming positive technology spillovers across countries). Should the second-best agreement therefore be designed so that the price of carbon is higher than the optimal tax in the first best optimum (to adjust for the difference in the R&D subsidy)? To answer this, we must consider the two types of agreements separately.

Consider first the quota agreement. In this case the common technology level in all countries is determined by (23), which give y as an increasing function of a: $y=y(a)$. In the minimization of (31) with respect to a we must now take into account that $y=y(a)$ and $x=Hy(a)$ (from (18)). Instead of (32) we therefore now get

$$c_a = nD' - (c_y + H)y'(a) > nD' \tag{33}$$

where the inequality sign follows from $y' > 0$ and (for $\gamma^*>0$) $c_y + H < c_y + h = 0$ (from (23)). We thus have the following proposition:

Proposition 6: In an optimally designed quota agreement of the type discussed in Sections 4 and 5, the abatement level is set so that the price of carbon (i.e., the marginal abatement cost) exceeds the sum of the marginal environmental costs.

We next turn to the case of a tax agreement of the type discussed in Section 6. In this case the abatement level is endogenously determined in each country by equation (28). We can write this as $a = a(y, \tau)$ where τ is considered as exogenous by each country, while each country chooses its level of y (which in equilibrium will be the same for all countries) through its choice of the subsidy rate σ. From the properties of the abatement cost function it follows that

$a = a(y,\tau)$ is increasing in both arguments. The first order condition (29) may be rewritten as

$$(\tau - D')\frac{\partial a(y,\tau)}{\partial y} + (c_y + h) = 0 \tag{34}$$

The optimal value of y (and therefore also the subsidy rate σ) will obviously depend on the common tax rate τ. We saw above that when the agreement directly specified the abatement level, y was larger the larger was a. We might therefore expect that in the present case y is increasing in τ. This is, however, not necessarily the case. In Appendix 1 we show the following:

Proposition 7: The equilibrium level of R&D investments under a harmonized domestic carbon tax is lower the higher is the tax rate if $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$. *If D''=0,* $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} < 0$ *is a necessary and sufficient condition for the equilibrium level of R&D investments to be increasing in the tax rate.*

From this proposition it is clear that y may very well be lower the higher is τ. The term $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau}$ is positive if the rightward shift, measured horizontally, in the marginal abatement cost curve is larger the higher up on this curve we are initially.[10] This seems to be more plausible than the opposite case. We should therefore expect less R&D investments the higher is the common tax rate.

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[10] It is easily verified that the sign of the term $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau}$ is identical to the sign of $c_{ay}c_{aaa} - c_{aa}c_{aay}$. Note that $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$ for e.g. $c(a,y) = Ka^{\alpha} y^{-\beta}$, where we must have $\alpha > \beta + 1 > 0$ in order to meet the imposed properties on the cost function (see Section 2).

Notice also that if R&D investments are reduced as a response to a higher tax, the subsidy rate must also be lower the higher is the tax. This follows immediately from

equations (8)-(11) and the discussion after these. If the common tax rate goes up, and as a response to this all countries either leave their R&D subsidies unchanged or increase their subsidies, both abatement and technology levels will increase in all countries. A higher technology level in all countries requires increased R&D in all countries, which contradicts that R&D investments are reduced as a response to a higher tax.

The reason why countries might respond to an increased common carbon tax by reducing their R&D subsidies is related to with the discussion after Proposition 5: A higher common carbon tax increases each country's distortion of its abatement level away from its ideal choice. Reducing R&D subsidies reduces abatement (cet. par.), and therefore mitigates this increased distortion.

For an optimal quota agreement, the marginal abatement cost was higher than the sum of marginal environmental costs. The reason for this was that higher abatement gave more R&D investments. For a tax agreement we should therefore expect that if a higher tax gives *lower* abatement, the optimal tax should be *lower* than the sum of marginal environmental costs. This is indeed the case. The optimal tax is found by minimizing (31) with respect to τ after inserting $a = a(y,\tau)$ and $y = y(\tau)$ and $x=Hy(\tau)$.[11] The first order condition is

$$(\tau - nD')\left[\frac{\partial a(y,\tau)}{\partial \tau} + \frac{\partial a(y,\tau)}{\partial y}\frac{dy(\tau)}{d\tau}\right] + (c_y + H)\frac{dy(\tau)}{d\tau} = 0 \qquad (35)$$

[11] Note that (31) does not distinguish between domestic and foreign firms. We can use this expression because with a common price of carbon the response to a change in an instrument does not differ between domestic and foreign firms.

where we have used (28). Combining this with (34) gives, after some straightforward derivations

$$(\tau - nD') = \frac{(n-1)D'\dfrac{\partial a(y,\tau)}{\partial y} + h - H}{\dfrac{\partial a(y,\tau)}{\partial \tau}} \frac{dy(\tau)}{d\tau} \tag{36}$$

Since $a = a(y,\tau)$ is increasing in its arguments and *H*<*h*, the large fraction is positive. $(\tau - nD')$ must therefore have the same sign as $\frac{dy(\tau)}{d\tau}$. Combining this result with Proposition 7 therefore gives the following Proposition:

Proposition 8: In an optimally designed tax agreement of the type discussed in Section 6, the common emission tax (equal to the marginal abatement cost) is lower than the sum of the marginal environmental costs if $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$. *If D''=0,* $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} < 0$ *is a necessary and sufficient condition for the optimal common emission tax to be higher than the sum of the marginal environmental costs.*

8 Second best abatement and technology levels

In the previous section we found the optimal price of carbon under a quota agreement and under a harmonized domestic carbon tax. We showed that under a quota agreement the price of carbon should exceed the sum of the marginal environmental costs, that is, the Pigovian level. On the other hand, with a harmonized carbon tax the price of carbon should be lower than the Pigovian level (provided $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$). In this section we compare abatement and technology levels in the two types of agreement, and also compare these with the first-best social optimum.

From Proposition 5 we know that the equilibrium subsidy of R&D investments under a harmonized domestic carbon tax is lower than the corresponding subsidy under an agreement on tradable emission quotas. Moreover, it follows from Proposition 6 and 8 that the price of carbon is lower under a harmonized domestic carbon tax than under an agreement on tradable emission quotas (provided $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$). Because both abatement and technology level are increasing in the technology subsidy and the price of carbon, see the discussion after equations (8)-(11), we have demonstrated the following:

Proposition 9: Suppose that $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$. *Then abatement and technology level are lower under a harmonized domestic carbon tax than under an agreement on tradable emission quotas. In addition, R&D investments are lower under a harmonized domestic carbon tax than under an agreement on tradable emission quotas.*

Note that the last part of Proposition 9 follows directly from the first part because lower technology level in all firms implies lower R&D investments in all (identical) firms.

We now compare the outcome of the international agreements with the first-best social optimum. Proposition 3 and 5 imply that the equilibrium subsidy of R&D investments under a harmonized domestic carbon tax is lower than the first-best optimal subsidy. Moreover, from Proposition 8 we know that the price of carbon under a harmonized domestic carbon tax is lower than the first-best price of carbon (the Pigovian level), provided that $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$. Because both abatement and technology level are increasing in the technology subsidy and the price of carbon, we have demonstrated the following:

Proposition 10: Suppose that $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$. *Then abatement and technology level are lower under a harmonized domestic carbon tax than in the first-best social optimum. In addition, R&D investments are lower under a harmonized domestic carbon tax than in the first-best social optimum.*

As mentioned above, we have showed that under a quota agreement the price of carbon should exceed the Pigovian level, see Proposition 6. Moreover, from Proposition 3 we know that the equilibrium subsidy under quotas is lower than in the first-best optimum (provided there are technology spillovers across countries). Because both abatement and technology level are increasing in the technology subsidy and the price of carbon, it is not obvious how abatement and technology levels are in the optimal quota agreement compared with the first-best levels. In Appendix 2 we show the following:

Proposition 11: If international technology spillovers are positive but sufficiently small, technology levels, and thus also R&D investments, are lower under a quota agreement than in the first-best optimum. The abatement level in the quota agreement can be either lower or higher than in the first-best optimum.

9 Social costs of second-best climate agreements

In the previous two sections, we have compared the two types of international agreements, provided both are (second-best) optimally designed. We also compared both types of agreements with the first-best optimum. Obviously, both types of second-best climate agreements give higher social costs than the first-best outcome. We have, however, not yet discussed which of the two types of second-best agreements give the lowest total costs. Given the results in the two previous sections, the comparison of total costs is easily illustrated by Figure 1.

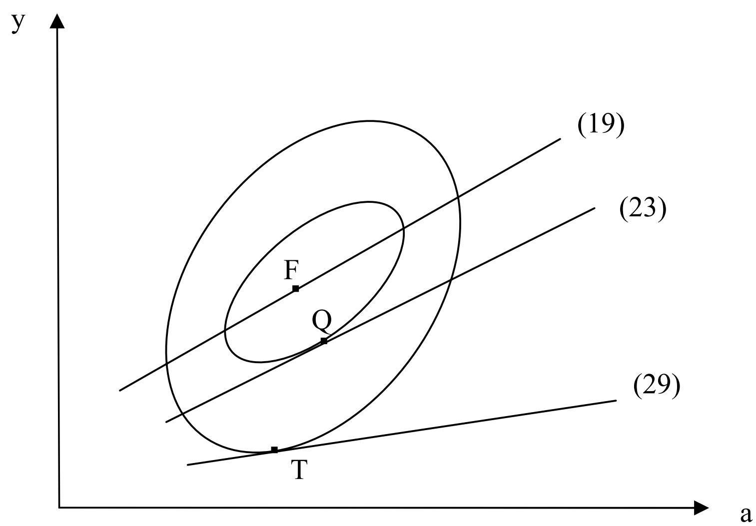

Figure 1

In this Figure, the iso-welfare curves stand for the negative of total costs. The highest obtainable welfare (i.e. lowest possible costs) is given by the common abatement and technology level corresponding to *F*(irst best) in Figure 1.The curve (19) is given by equation (19): It tells us which technology level maximizes social welfare given any abatement level. Clearly, this curve must go through all vertical tangents to the iso-welfare curves. Moving outwards along (19) in the northeast direction is like hiking along a ridge that drops off directly north and directly south. The position of this ridge is independent of the environmental damage function *D*. However, the position of the summit (given by *F* in Figure 1), and also the steepness along the ridge to both sides of the summit, depend on the function *D* as *F* is determined by (19) and (32).

Consider next a quota agreement. The relationship between abatement and technology level for such an agreement is given by equation (23). Since $h>H$ when there are international technology spillovers, the line defined by (23) must lie below the line defined by (19). The highest possible social welfare obtainable given that we must lie on (23) is given by the point *Q*(uota) in Figure 1, and must obviously give a lower welfare level than the point *F*. We have drawn the curves so that *Q* lies below *F*, which must be the case if international spillovers are sufficiently low (cf. Proposition 11). In the Figure, *Q* lies to the right of *F*, but it follows from Proposition 11 that the opposite is also possible.

Finally, consider a tax agreement. The relationship between abatement and technology level for such an agreement is given by equation (29), which may be rewritten as

$$-c_y = h + (\tau - D')\frac{\frac{\partial a}{\partial \sigma}}{\frac{\partial y}{\partial \sigma}}$$

The right-hand side is larger than *h*, cf. the discussion after (30). It follows that the line defined by (29) must lie below the line defined by (29). [12] The highest possible social welfare obtainable given that we must lie on (29) is given by the point *T*(ax) in Figure 1, and must obviously give a lower welfare level than the point *Q*. We have drawn the curves so that *T* lies below and to the left of *F* and *Q*, which must be the case if $\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} > 0$ (cf. Propositions 9 and 10).

To summarize, we have shown the following:

[12] Notice that while the curves defined by (19) and (23) for certain are rising in Figure 1, this is not obvious for the curve defined by (29).

Proposition 12: If there are international technology spillovers, total social costs are higher under an optimally designed tax agreement of the type discussed in Section 6 than they are under an optimally designed quota agreement of the type discussed in Sections 4 and 5. Both types of agreements have higher total social costs than the first-best outcome.

10 Concluding remarks

We have studied two types of international climate agreements that do not include R&D policies. *Without* international technology spillovers, these agreements would be equivalent, and both could give the first-best outcome. In the presence of international technology spillovers, it is not possible to reach the first-best outcome with either of these agreements. One reason is that the R&D subsidies that are optimal for an individual country under an agreement are too low compared with the subsidies that must be imposed in order to reach the first-best outcome.

Although both types of agreements are inferior compared with the first-best outcome, under an optimally designed quota agreement global emissions may be lower than in the first-best outcome. Under an optimally designed tax agreement, emissions are – under a reasonable assumption - higher than under a quota agreement and higher than in the first-best outcome.

We concluded that with optimally designed agreements a quota agreement was preferable to a tax agreement as the first gives lower social costs. Compared with the tax agreement, the quota agreement has higher R&D subsidies and (under a reasonable assumption) higher abatement.

Our results suggest that with international spillovers, there is a social loss of not including R&D policies in an international climate agreement. In the Introduction, we argued that one reason for not including R&D policies in an agreement is difficulties in monitoring compliance of this element of an agreement. However, even if it is difficult or impossible to design a first-best type of agreement, our results suggest that agreements where R&D policies are included in an imperfect manner may be superior to agreements that ignore R&D policies. Moreover, the implicit assumption in our model that there are no problems with monitoring and/or compliance with respect to policy instruments and emissions is obviously also a simplification. Some economists, including Barrett (2003), have argued that traditional agreements of the quota type discussed in the present paper are inherently flawed, due to large free rider incentives. Barrett argues (op.cit, chapter 15) that agreements that to a larger degree focus on the development of new technology might be more likely to be successful than traditional quota type agreements.[13]

An interesting topic for future research would be to examine various types of agreements that include R&D policies under imperfect monitoring or incomplete compliance. In such a study it is important how the development of new technology is modeled. While we in the present paper have used the standard assumption of additive spillovers, a more sophisticated modeling would be to e.g. assume that for each firm spillovers from other firms have "decreasing returns" or that for each firm the benefits of R&D investments in other firms depend on the magnitude of its own R&D investments. The implications of different technology assumptions will be investigated in future research.

Appendix 1: The relationship between R&D investment and the common carbon tax rate

Denote the left hand side of (34) by $L(= L(y,\tau))$. We have

[13] Cf. also the discussion of Buchner and Carraro (2004) in the Introduction.

$$\frac{dy(\tau)}{d\tau} = \frac{-\frac{\partial L}{\partial \tau}}{\frac{\partial L}{\partial y}} \quad (37)$$

The denominator of this expression is positive from the second order conditions.

Remembering that the environmental cost is $D(m(1-a)+(n-1)m(1-a^*))$, it follows from (34) that

$$\frac{\partial L}{\partial \tau} = (\tau - D')\frac{\partial a^2(y,\tau)}{\partial y \partial \tau} + \left[1 + mD''\frac{\partial a(y,\tau)}{\partial \tau} + (n-1)mD''\frac{da^*}{d\tau}\right]\frac{\partial a(y,\tau)}{\partial y} + c_{ya}\frac{\partial a(y,\tau)}{\partial \tau}$$

(38)

The effect of a tax change on abatement in other countries is identical to the effect on abatement of the country we are considering, i.e. the sum of the direct effect and the effect via the technology level:

$$\frac{da^*}{d\tau} = \frac{\partial a(y,\tau)}{\partial \tau} + \frac{\partial a(y,\tau)}{\partial y}\frac{dy(\tau)}{d\tau} \quad (39)$$

We can therefore rewrite (38) as (simplifying by writing *a* instead of $a(y,\tau)$):

$$\frac{\partial L}{\partial \tau} = (\tau - D')\frac{\partial^2 a}{\partial y \partial \tau} + mD''\left[n\frac{\partial a}{\partial \tau} + (n-1)\frac{\partial a}{\partial y}\frac{dy(\tau)}{d\tau}\right]\frac{\partial a}{\partial y} + \left[\frac{\partial a}{\partial y} + c_{ya}\frac{\partial a}{\partial \tau}\right] \quad (40)$$

From (28) we have

$\frac{\partial a}{\partial y} = \frac{-c_{ay}}{c_{aa}}$ and $\frac{\partial a}{\partial \tau} = \frac{1}{c_{aa}}$, which imply that the second term in square brackets in (40) is zero. Using (38) we therefore have

$$\frac{dy(\tau)}{d\tau} = \frac{1}{\frac{\partial L}{\partial y}}\left[-(\tau - D')\frac{\partial^2 a}{\partial y \partial \tau} - nmD''\frac{\partial a}{\partial \tau}\frac{\partial a}{\partial y} - (n-1)mD''\left(\frac{\partial a}{\partial y}\right)^2 \frac{dy}{d\tau}\right] \tag{41}$$

or

$$\left[\frac{\partial L}{\partial y} + (n-1)mD''\left(\frac{\partial a}{\partial y}\right)^2\right]\frac{dy}{d\tau} = -(\tau - D')\frac{\partial^2 a}{\partial y \partial \tau} - nmD''\frac{\partial a}{\partial \tau}\frac{\partial a}{\partial y} \tag{42}$$

Since the term in square brackets is positive, $\tau > D'$, and $a(y,\tau)$ is increasing in both arguments, Proposition 7 immediately follows.

Appendix 2: Proof of Proposition 11

We know that if $h=H$, which will be the case if there are no international spillovers, the optimal quota agreement is identical to the first-best optimum. If we can identify in what direction abatement and technology levels change as h is increased ($h>H$ when there are international spillovers), we therefore know how the quota agreement differs from the first-best optimum when there are international spillovers.[14]

The optimal quota agreement is given by (23) and (33). Combining these we obtain

$$c_a(a,y) = nD'(mn(1-a)) + (h-H)\phi(a,y) \tag{43}$$

[14] An increase in h, while keeping H unchanged, is accomplished through a suitable increase in γ^* and a suitable decrease in γ.

where

$$\phi(a,y) = y'(a) = \frac{c_{ay}(a,y)}{-c_{yy}(a,y)} > 0 \tag{44}$$

Differentiating (23) and (43) w.r.t. *h* we find (using (44))

$$\frac{\partial a}{\partial h} = \frac{1}{D}(h-H)\phi_y \tag{45}$$

$$\frac{\partial y}{\partial h} = \frac{1}{D}\left[-n^2 m D'' - \frac{1}{c_{yy}}\left(c_{aa}c_{yy} - c_{ay}{}^2\right) + (h-H)\phi_a\right] \tag{46}$$

where

$$D = (c_{aa}c_{yy} - c_{ay}{}^2) + mn^2 D'' c_{yy} + (h-H)(\phi_y c_{ay} - \phi_a c_{yy}) \tag{47}$$

The first two terms in *D* are positive, and will dominate the last term as long as *h*-*H* is sufficiently small. From (46) and our assumptions on the functions *D* and *c* it is therefore clear that as *h* increases, *y* will decline. This will be true at least for *h* close to *H* (but might also hold when *h*-*H* is large). As long as the international spillovers are sufficiently small, *h*-*H* will be small, so we can conclude that in this case the technology levels *y* are lower in the quota agreement than in the first-best optimum. Moreover, it follows directly from (45) that since we do not generally know the sign of ϕ_y, we do not know whether abatement levels under the quota agreement are lower or higher than in the first-best optimum. This concludes the proof of Proposition 11.

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