Endogenous Technology and Tradable Emission Quotas

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Summary

We study an international climate agreement that assigns emission quotas to each participating country. Unlike the simplest models in the literature, we assume that abatement costs are affected by R&D activities undertaken in all firms in all countries, i.e. abatement technologies are endogenous. In line with the Kyoto agreement we assume that the international climate agreement does not include R&D policies. We show that for a second-best agreement, marginal costs of abatement should exceed the Pigovian level. Moreover, marginal costs of abatement differ across countries in the second-best quota agreement with heterogeneous countries. In other words, the second-best outcome cannot be achieved if emission quotas are tradable.

Keywords: Climate Policy, International Climate Agreements, Emission Quotas, Technology Spillovers

JEL Classification: H23, O30, Q20, Q25, Q28

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1 Introduction

The Coase theorem suggests that tradable emission quotas will yield efficiency, regardless of the initial allocation of quotas. The reason is that (small) cost minimizing agents will provide cost-effectiveness by trading until all differences in marginal abatement costs between sources are eliminated. Trade in emission quotas is beneficial both nationally, in trade between households and producers, and internationally, in trade between governments, if an international agreement regulates emissions of greenhouse gases through quotas. The Kyoto agreement is an example of such an agreement, as the participating countries are - with some restrictions - allowed to trade in quotas. The EU quota trading scheme, designed to help achieve the EU countries' Kyoto commitments, also allows quota trade among firms located in different EU countries.

A condition for quota trade being beneficial is that imperfections elsewhere in the economy are unaffected by trade in quotas. Otherwise, trade in emission quotas might enhance the efficiency losses associated with the market imperfections. In fact, the welfare benefits of trade in the quota market might then be outweighed by welfare losses in other markets, i.e. quota trade could lower welfare.

The present paper focuses on trade versus no trade within the context in which countries have joined an international climate agreement that assigns emission quotas to each participating country. Unlike most models in the literature, we assume that abatement costs are affected by R&D activities undertaken in all firms in all countries, i.e. abatement technologies are endogenous. More specifically, the abatement costs of each firm are affected by this firm's own R&D investments as well as to some extent R&D investments by all other (domestic and foreign) firms. Hence, in addition to the negative environmental externality between countries, there is a positive externality due to technology spillovers between firms.

According to standard economic theory, an international climate agreement should address both of these externalities in order to achieve the first-best outcome. However, neither the Kyoto agreement nor the EU quota scheme includes elements related to R&D investments.[1] The international climate agreement we examine in this paper therefore does not include R&D

[1] Possible reasons for why R&D policies are not included are discussed briefly in Golombek and Hoel (2006). There is a small but rapidly growing literature discussing how international climate agreements might include R&D policies, see e.g. Barrett (2006), Carraro and Marchiori (2003) and Buchner and Carraro (2005).

policies. This shortcoming of the international agreement represents an imperfection, which might imply that welfare is lower when quota trade is permitted than when it is not.

Our paper builds on Golombek and Hoel (2006), which focused on international climate agreements where each country receives emission quotas and the agreement does not include R&D policies. Assuming identical countries, it was shown that marginal costs of abatement should exceed the Pigovian level. The present paper extends Golombek and Hoel (2006) to the case of heterogeneous countries.

Countries might differ in several ways. In the present paper we focus on differences in size, which is one of the most important differences. As in Golombek and Hoel (2006) we find that the second-best optimum is characterized by marginal costs of abatement exceeding the Pigovian level in all countries. This result is related to the fact that R&D policies are not included in the climate agreement. Each country will then ignore technology spillovers to other countries, and thus tend to choose an R&D policy (formally in our model: an R&D subsidy) that gives less R&D than what is socially optimal. In designing the second-best agreement, the group of all countries takes into account that the stricter the emission requirement, the more R&D investments a country will undertake in the next stage. Setting emission requirements so strict that marginal abatement costs exceed the Pigovian level is thus a way to (partly) compensate for the domestic R&D subsidy being too low.

An important new finding in the present paper is that marginal costs of abatement will generally differ between countries in a second-best optimum. To achieve the second-best optimum quotas must therefore be distributed in a specific manner among countries, and countries should not be allowed to change this quota distribution through quota trade. We show that it is not obvious whether marginal abatement costs should be highest in small or large countries.

The rest of the paper is organized as follows. In Section 2 we present a formal model with identical firms located in two countries of different sizes. For all firms, abatement costs depend both on the technology level of the firm and the level of abatement. The technology level of a firm depends on its own R&D investments as well as all other firms' R&D investments. In each country the government may influence R&D investments through a domestic R&D subsidy.

Section 3 examines the first-best social optimum, i.e. the levels of abatement and R&D investments in each firm that minimize total social costs. The first-best 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 both countries.

In Section 4 we study the optimal design of an international climate agreement under the restriction that the agreement does not contain R&D policy elements. We assume that the climate agreement is designed by the group of all countries such that total social costs are minimized, given how each government will respond to the climate agreement, and how firms will respond to the climate agreement and to the policies chosen by national governments. Each government determines its domestic technology subsidy such that total social costs of the country are minimized, given the emission quotas it receives (determined through the international agreement) and how firms will respond in the final stage. We refer to the international climate agreement as second-best as it has been designed under the restriction not to contain R&D policy elements. This restriction implies that the second-best agreement is unable to mimic the first-best optimum.

As mentioned above, we show that the second-best optimum is characterized by marginal costs of abatement exceeding the Pigovian level in both countries, and that marginal costs of abatement should generally differ across countries. Hence, if countries are free to trade in quotas under a second-best quota agreement, total welfare will be reduced as trade will typically reduce the initial differences in the country-specific marginal costs of abatement (and eliminate all differences in the competitive case). Whether or not trade in quotas will improve efficiency depends on the initial allocation of quotas in a real climate agreement relative to the second-best allocation. As a rule of thumb, trade in quotas is less likely to improve efficiency the closer the initial allocation is to the second-best allocation. Under the second-best quota agreement, quotas should not be tradable.

In Section 5 we discuss various extensions of our model. In particular, we argue that our main results hold also when there are other differences between countries than size. Finally, in Section 6 we summarize our main findings.

2 The model

We use a static framework in which all types of uncertainties are disregarded. Moreover, we consider the case of only two countries (domestic and foreign). There are $m+m^*$ identical firms in the economy, with m located in the domestic country and m^* in the foreign country. The only difference between the two countries is their size, represented by the number of firms. Henceforth, we assume that the domestic county is the larger of the two, i.e. $m > m^*$. In Section 5 we discuss the implications of other possible differences between countries.

All firms invest in R&D and, to simplify, we disregard patents. While technology spillovers allow all other firms to benefit from a firm's R&D investments, technology diffusion is not perfect. For any firm, only part ($0 < \gamma < 1$) of other firms' R&D investments are beneficial.

We assume that the technology level of a particular domestic firm (Y) depends on its own R&D investments (X), the amount of R&D investments of the other firms in the same country (x), and the amount of R&D investments of firms in the other country (x^*):

$$Y = X + \gamma\left[(m-1)x + m^* x^*\right] \qquad (1)$$

In (1) we have assumed an additive structure of technology spillovers, i.e. the technology level of a firm depends on the sum of all firms' R&D investments, corrected by the technology diffusion parameters (γ). This is the standard way of modeling spillovers, and dates back at least to Spence (1984).[2] The technology level of a particular foreign firm (Y^*) is correspondingly given by

$$Y^* = X^* + \gamma\left[(m^*-1)x^* + mx\right] \qquad (2)$$

With identical firms, 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 $1-a$.

[2] In the context of international environmental problems a similar assumption has been used by e.g. van der Ploeg and de Zeeuw (1994), Xepapadeas (1995), Katsoulacos (1997) and Rosendahl (2004).

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 $c(a, y)$. We assume that the function $c(a, y)$ is twice differentiable and has the following properties: $c(0, y) = 0$, $c_a(0, y) = 0$ and $c_a(1, y) = \infty$. Moreover, for $a > 0$ we have $c_a > 0$, $c_{aa} > 0$, $c_y < 0$, $c_{yy} > 0$, $c_{ay} < 0$, $c_{aa}c_{yy} - (c_{ay})^2 > 0$ and $-c_y(a, 0)$ being sufficiently large to avoid corner solutions.

In the following analysis, we shall assume that emissions in each country are set through the international agreement. With identical firms in each country, emissions levels per firm are thus 1/*m* and 1/*m** of the exogenously set abatement levels for the domestic and foreign country, respectively. The only variable chosen by each firm is R&D investments. The price of R&D investments is normalized to one. We assume, however, that the domestic government subsidizes R&D investments by the rate σ (and the governments abroad subsidize R&D investments by the rate σ^*).

A particular domestic firm minimizes its total costs by choosing R&D investments (X), taking R&D expenditures in all other firms as given, and also taking its abatement ($A = a = 1/m$) as given (set through the international agreement). Hence, the firm minimizes

$$c(a, Y) + (1 - \sigma)X \qquad (3)$$

The second term in (3) is net R&D expenditures, and the technology level Y is given by (1). All domestic firms solve a similar problem, and they will thus choose the same values in equilibrium ($X = x$ and $Y = y$). The first-order condition for this problem is thus given by:

$$-c_y(a, y) = 1 - \sigma \qquad (4)$$

According to (4) marginal costs of R&D investments ($1 - \sigma$) should equal marginal benefits of these investments ($-c_y > 0$). From (4) we see that the technology level of domestic firms *y* depends only on σ and *a*, i.e.

$$y = y(a, \sigma) \qquad (5)$$

It follows from the properties of the abatement cost function that $y_a(a,\sigma) = -\dfrac{c_{ya}}{c_{yy}} > 0$.

In equilibrium, $X = x$ and $Y = y$ in the home country, whereas $X^* = x^*$ and $Y^* = y^*$ in the foreign country. Solving (1) and (2) for equilibrium values of x and x^*, we obtain

$$x = hy + ky^* \tag{6}$$

$$x^* = h^* y^* + k^* y \tag{7}$$

where (for $m > m^*$) $h^* > h > 0$ and $k^* < k < 0$.[3] As countries differ in size, they might also have different environmental damage costs; a large country will, *cet. par.*, suffer more from climate changes than a small country. We therefore let the environmental damage of the home country be $md[m(1-a) + m^*(1-a^*)]$, where d is the constant marginal damage per firm (proxy for size) and $[m(1-a) + m^*(1-a^*)]$ is total emissions. Correspondingly, the environmental damage of the foreign country is $m^* d[m(1-a) + m^*(1-a^*)]$.

3 The first-best social optimum

The first-best social optimum is defined as the outcome that minimizes total social costs, that is, the sum of abatement costs, R&D expenditures and environmental costs. Since all firms are equal[4], the optimal outcome will be characterized by abatement levels and R&D expenditures being equal in all firms. The first-best optimum is thus found by minimizing

$$(m+m^*)\left\{c(a,y) + x + d[(m+m^*)(1-a)]\right\} \tag{8}$$

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[3] We have $h = \dfrac{1+(m^*-1)\gamma}{(1-\gamma)[1+\gamma(m+m^*-1)]}$, $k = \dfrac{-m^*\gamma}{(1-\gamma)[1+\gamma(m+m^*-1)]}$, $h^* = \dfrac{1+(m-1)\gamma}{(1-\gamma)[1+\gamma(m+m^*-1)]}$ and $k^* = \dfrac{-m\gamma}{(1-\gamma)[1+\gamma(m+m^*-1)]}$.

[4] In addition to abatement cost functions being identical across firms, the technology spillovers are the same for all firms: The diffusion parameter between firms in the same country is assumed equal to the diffusion parameter between firms in different countries. We return to this assumption in Section 5.

with respect to abatement and technology levels in the two countries, subject to (6) and $y^* = y$. The first-order condition with respect to abatement is

$$c_a(a, y) = (m + m^*)d \tag{9}$$

Hence, marginal abatement costs should be equalized across firms, and the common value should be equal to the sum of marginal environmental costs of the two countries.

The first-order condition with respect to the technology level is

$$-c_y(a, y) = h + k = [1 + \gamma(m + m^* - 1)]^{-1} \tag{10}$$

Using (4) the technology subsidy in both countries should be

$$\sigma^F = 1 - (h + k) = 1 - [1 + \gamma(m + m^* - 1)]^{-1} \tag{11}$$

4 The second-best quota agreement

We now turn to pure quota agreements, i.e. agreements specifying emission quotas but not containing any elements related to R&D investments. We assume that both countries have signed an international climate agreement that specifies the distribution of emission quotas between countries. Finally, we assume that the agreement is second-best, i.e. the group of signatories determines the amount of emission quotas assigned to each country such that total social costs - aggregated over all identical firms in both countries - are minimized subject to behavioral restrictions on firms and governments.

For a given amount of emission quotas, i.e. given abatement level a, a country's choice of a technology subsidy σ is equivalent to choosing a technology level y (see (5)). While σ is the actual choice variable of the government, for mathematical simplicity we will use y as the choice variable. For a given amount of emission quotas, the domestic country thus minimizes

$$m[c(a, y) + x] \tag{12}$$

with respect to its own technology level, subject to the technology constraint (6) and taking the technology subsidy (and thus the technology level) abroad as given. The first-order condition is given by

$$-c_y(a,y) = h \tag{13}$$

Hence, the marginal benefits of R&D investments when (only) domestic spillovers are taken into account should equal marginal costs of R&D investments ($-c_y h^{-1} = 1$). Using (4), the optimal technology level in each country can be implemented through the subsidies

$$\sigma^Q = 1 - h \tag{14}$$

$$\sigma^{*Q} = 1 - h^* \tag{15}$$

We have previously shown that $h^* > h$ since $m > m^*$. Hence, the largest country will have the highest subsidy as increased technology level in this country benefits more firms domestically:

Proposition 1: In a quota agreement the equilibrium technology subsidy will be highest in the largest country.

Moreover, since k and k^* are negative a comparison of (14) and (15) with (11) gives the following proposition:

Proposition 2: In a quota agreement the technology subsidy in both countries will be lower than in the first-best optimum.

The results above hold for *any* quota agreement. We now turn to the second-best optimal design of a quota agreement. From (5), (14) and (15) it follows that $y = y(a, \sigma^Q)$ and $y^* = y(a^*, \sigma^{*Q})$. The group of all countries chooses the level of abatement for each country so that total social costs are minimized. We find the optimal amounts of abatement by minimizing (8) with respect to abatement in the two countries (a and a^*), taking into account (6), (7), $y = y(a, \sigma^Q)$ and $y^* = y(a^*, \sigma^{*Q})$. The first-order conditions of this problem imply

$$c_a - (m+m^*)d = \frac{\gamma}{(1-\gamma)[1+\gamma(m+m^*-1)]} m^* y_a > 0 \qquad (16)$$

$$c_{a^*} - (m+m^*)d = \frac{\gamma}{(1-\gamma)[1+\gamma(m+m^*-1)]} m y_{a^*} > 0 \qquad (17)$$

where we have used (13). According to (16) and (17), for each country marginal costs of abatement should exceed the sum of marginal environmental costs. Hence, we have the following proposition:

Proposition 3: The abatement levels in a second-best quota agreement are set so that for each country, the price of carbon (i.e. the marginal abatement cost) exceeds the sum of marginal environmental costs.

The intuition behind this result follows from the equilibrium subsidy under the second-best quota agreement being lower than the first-best subsidy (Proposition 2). The difference reflects the fact that each country neglects the international technology spillovers arising from its own R&D investments. Since the optimal technology level is increasing in abatement ($y_a > 0$), in our model increased abatement provides an incentive to increase R&D expenditures. Hence, collective rationality suggests having a "high" level of abatement ("few" quotas) in order to increase domestic R&D, thus (partly) compensating for the domestic R&D subsidy being too low.

Since $m^* y_a$ generally differs from $m y_{a^*}$, it follows from (16) and (17) that marginal costs of abatement will generally differ across countries in a second-best optimum. As a competitive international quota market equalizes marginal costs of abatement across countries, we have the following proposition:

Proposition 4: In a second-best quota agreement marginal costs of abatement will generally differ across countries. Hence, if all countries receive the second-best amount of quotas, there should be no trade in quotas across countries.

It is not obvious whether marginal abatement costs should be highest in the small or in the large country. On the one hand, (16) and (17) suggest that marginal costs of abatement should be highest in the smallest country ($m > m^*$). The interpretation is that more of the total spillovers accrue to foreign firms when R&D is undertaken in a small country than in a large country. Marginal abatement costs should therefore be larger the smaller a country is, thereby providing extra incentives for small countries to increase their R&D expenditures. On the other hand, the sign of $c_a - c_{a*}$ depends also on y_a and y_{a^*}. The larger these derivatives are, the more will R&D expenditures in the two countries increase as a response to increased abatement. The stronger the effect, the larger is the social gain of increasing the abatement level beyond the level given by the first-best rule. Unless $y_{a\sigma}$ and $y_{a^*\sigma^*}$ are zero, the derivatives y_a and y_{a^*} depend on the size of the subsidies, and we know from Proposition 1 that the R&D subsidy is highest in the largest country. Although we know the ranking of the subsidies, the ranking of the derivatives y_a and y_{a^*} depends on third-order derivatives of the abatement cost function (see the discussion after (5)). It is therefore not obvious whether marginal abatement costs should be highest in the small or in the large country.

5 Extensions

In the analysis we have assumed that the location of firms has no bearing on the technology spillovers between them. One could, however, argue that spillovers between firms in the same country are larger than spillovers between firms located in different countries as the benefits from spillovers might declinine with distance, see e.g. Keller (2002). If we instead had assumed that the diffusion parameter between firms in different countries was smaller than the diffusion parameter between firms in the same country, most of our results would remain valid. The one important difference would be that in this case the first-best technology subsidy should be highest in the largest country. The reason for this result is that R&D investments in a firm creates more positive externalities in the large country than in the small one (when the common domestic diffusion parameter exceeds the common international diffusion parameter) simply because there are more firms in the largest country. The conclusion that the carbon price should be the same across all firms in the first-best outcome remains valid, as do our results in Propositions 1-4.

Above, we assumed that countries differed only in size. Other possible differences would be different spillover parameters and different abatement cost functions. Introducing differences of this type would not change the property of the first-best outcome that marginal abatement costs should be equalized across firms. However, in general the first-best technology subsidies will differ across firms (and across firms in the same county if firms are not identical within countries). The relevant results regarding the second-best quota agreement, given by Propositions 2-4, remain valid.

One difference between countries that will not change any results is differences in marginal environmental costs: If these are *d* and *d** per firm for the two countries (instead of *d* in both), $(m+m^*)d$ is simply replaced by $(md+m^*d^*)$ in the relevant formulas, but otherwise all our results remain unchanged. Finally, none of our results would be changed if we instead assumed two groups of countries, with countries within each group being identical. From the intuition of the results it is also clear that Propositions 1-4 are valid also for the case of several different countries.

6 Concluding remarks

The purpose of the present article has been to examine second-best quota agreements with no R&D elements. There are several important results. First, when countries differ in size, the equilibrium technology subsidy will be highest in the largest country (Proposition 1), and in both countries the equilibrium subsidy will be lower than what is socially optimal (Proposition 2). Second, the number of quotas should be determined so that in each country, the price of carbon exceeds the Pigovian level (Proposition 3). Finally, in the second-best quota agreement the price of carbon should differ across countries (Proposition 4).

The last result, i.e. that marginal costs of abatement should differ across countries, implies that international trade in emission quotas should not be allowed in a second-best quota agreement. It is important to emphasize that this conclusion is based on the quota agreement being second-best. A second-best agreement requires detailed information from all countries (including estimates of diffusion parameters), and also that politicians are capable of implementing the second-best agreement. In the real world, the initial allocation of quotas in an approved climate agreement – for example the Kyoto agreement – might be far from being second-best, and in that case it is an open question whether trade in quotas will improve welfare.

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