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Strategic investment in climate friendly technologies: the impact of permit trade

Abstract:
Our point of departure is that a group of developed countries invest in the development of greenhouse gas (GHG) abatement technologies both at home and in developing countries. Such investments reduce the cost of future GHG abatement, and influence the future GHG abatement choices of both developed and developing countries. We show how a common permit market affects the industrialized countries' strategic investment decisions. As opposed to a situation without a permit market, the industrialized countries may want to overinvest in new GHG abatement technologies both at home and abroad. That is, they increase their R&D investment to such an extent that the cost reductions from the least profitable project actually fall short of the R&D costs. Earlier research has only pointed to overinvestment abroad. Moreover, the effects of investment abroad may be tougher emission reduction targets at home, which is not possible without permit trade.

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1 Introduction

International cooperation on climate change has proven to be difficult. The Kyoto agreement only sets emission reduction targets for developed countries, the Annex I countries, and only covers the period from year 2008 to 2012. Despite numerous efforts by the UN to come up with a replacement for the Kyoto agreement, there is still no sign of a new treaty that would cover a larger share of global emissions and ensure deeper global emission cuts. Under the Copenhagen Accord (2009), the international climate regime could be moving toward a system in which each country (region) sets emission reduction targets unilaterally. The question then arises: how does a country concerned about global warming get the other countries to set stringent targets?

One answer favored by environmentalists is that developed countries should act as "good examples" and reduce their GHG emissions even more. On the other hand, such an approach is not endorsed by game theoretic analysis. For instance, Hoel (1991) shows that if a country takes a unilateral action to reduce emissions, this can be partly offset by an increase in emissions from other countries. In this paper, we focus on unilateral action related to investments in climate friendly technologies. In the Copenhagen Accord (2009), such investments are highlighted. For example, the parties acknowledge that *"in order to enhance action on development and transfer of technology we decide to establish a Technology Mechanism..."*.

Strategic use of investments in abatement technologies with global pollution externalities are analyzed by Buchholz and Konrad (1994), Stranlund (1996) and Golombek and Hoel (2004). Buchholz and Konrad (1994) conclude that it may be profitable for countries to invest in technologies, implying a high marginal cost of emission reductions at home, as this credibly commits them to low emission reductions in the future and thereby make other countries increase their emission reductions. Stranlund (1996) shows that a country with access to a superior abatement technology has incentives to transfer the superior technology to less developed countries and choose an inferior technology for itself. Both actions tend to shift the burden of reducing emissions on to the other country. Finally, Golombek and Hoel (2004) find that R&D investments in industrialized countries may reduce emissions in developing countries if there are technology spillovers that reduce developing countries' abatement costs.

None of the above mentioned contributions consider permit trade. Permit trade is likely to be one of the elements of the current international climate regime that will remain. Moreover, regions are talking about linking their permit trading systems, moving towards global trade

in emission rights. Thus, in this paper we ask: how does the possible future existence of a common permit market influence the strategic decision to invest in climate friendly technologies?

Following Buchholz and Konrad (1994) and Stranlund (1996), we distinguish between investments that reduce industrialized countries' abatement costs and investments that reduce developing countries' abatement costs. Firstly, we find that the effects of investments abroad may be tougher emission reduction targets at home, which is not possible without permit trade. Secondly, an industrialized country opposed to a situation without a permit market may want to pick superior abatement technologies for both itself and the developing country. Hence, the somewhat depressing conclusion in Buchholz and Konrad (1994) that "*countries have an incentive not to prefer a technology with lower emission reduction cost*" may not hold with permit trade.

Also following Buchholz and Konrad (1994) and Stranlund (1996), we model the global emission reduction outcome as a Nash–Cournot equilibrium where the developed countries act as one Cournot player vis-à-vis the developing countries when setting emission reduction targets.[1] By assuming that the developed countries act as one Cournot player, we ignore the discussion about the stability of cooperation among these countries as that issue is not the focus of this paper. There is considerable literature on international environmental agreements and the stability of such agreements: see, e.g., Barrett (1999), Chander and Tulkens (1995) and Finus (2003).

The Nash–Cournot equilibrium outcome of emission reduction targets is also considered in Helm (2003), Holtsmark and Sommervoll (2008) and Carbone et al. (2009). However, the focus of those papers is whether permit trading improves welfare, given that emissions targets are decided after the decision to have permit trading. None of the above mentioned contributions consider how *ex ante* investments in climate friendly technologies affect the Nash–Cournot equilibrium.

The paper is laid out as follows. In Section 2, we discuss investments in R&D, and present the model. Then, in Section 3, we solve the model in a setting without permit trade. Section 4 contains the main contribution of the paper, which results from our analysis of strategic R&D investments with permit trade. In Section 5, we conclude.

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[1] Buchholz and Konrad (1994) also show that unilateral technology adoption may affect the outcome of international negotiations. If countries at a later stage bargain about emission reductions, the present unilateral actions changes the cooperative outcome through its impact on the disagreement points, which is defined as the noncooperative Nash–Cournot equilibrium. Strategic investment in sunk capital to manipulate the outcome of the terms of an international environmental agreement is also studied in Stranlund (1999).

2 The model

The model is a three stage game between a group of developed countries and a developing country. The group of developed countries is referred to as the home region, or Region h, whereas the developing country is referred to as abroad, or Region a.[2]

In the first stage, Region h invests in two types of R&D as described below. In the second stage, the Region h and Region a set their emission reduction targets. Finally, in the third stage the two regions carry out pollution abatement in order to reach their emission reduction targets.

We compare two versions of this game. In the simplest version there is no permit trading between the regions, and the third stage of the game becomes trivial. In the other version of the game the two regions set up a common permit trading system.

2.1 Investments in R&D

We assume that the cost of GHG abatement depends on the technology level in the region in question: see, e.g., Goulder and Mathai (2000). The technology levels can be increased by investments in R&D by the developing countries. R&D investments are defined broadly: R&D investments are everything from basic research to institutional capacity building and advanced GHG abatement technology demonstration projects. In particular, we consider two types of R&D investments: k_h and k_a. R&D of type k_h aims to increase the technology level in developed countries, and hence, we refer to k_h as *investments at home.* Investments at home comprise R&D and pilot projects in advanced GHG abatement technologies, for instance, fusion reactors, superconducting grids and second generation biofuels. For examples of advanced technologies, see Hoffert et al. (2002).

The other type of R&D, k_a, aims to increase the technology level in developing countries, and consequently we coin k_a *investments abroad.* Investments abroad comprise efforts to improve advanced technology transfer, research on technological solutions particularly suited for developing countries, such as off-grid renewable electricity production, and institutional capacity building, for instance, to implement more efficient means to reduce emissions through deforestation (for examples, see UN-FCCC, 2009).

In order to make our model tractable, we make some simplifying assumptions regarding R&D investments. Firstly, we assume that invest-

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[2]One can of course think of the developing country as a group of developing countries like the G77, as long as the group is able to coordinate on one emission reduction target.

ment in k_h is of minor importance for the technology level in developing countries, and *vice versa*. For instance, in order to benefit from R&D of type k_h, the country ought to be at some minimum technological level: see, e.g., Cohen and Levinthal (1989), who argue that a firm's ability to absorb new knowledge depends on its own knowledge base. Furthermore, R&D of type k_a is likely to produce knowledge that is not relevant or already well known in developed countries. Secondly, we assume that R&D of type k_a carried out by developed countries is neutral to any R&D investments carried out by developing countries themselves. Hence, we can abstract away from developing countries' own R&D investments.[3]

2.2 Benefits and costs of emission reductions

Each region benefits from emission reductions in both regions, which we denote e_h and e_a. The benefits can be written as:

$$b_i = b_i(e_h + e_a), \ i = h, a, \tag{1}$$

with the following derivatives $b_i' > 0$ and $b_i'' < 0$. Throughout the paper, we assume that the environmental concern, and hence the benefit derived from global emission reductions, is larger in the rich developed countries than in the developing country, that is, $b_h' > b_a', \ \forall (e_h + e_a)$.

Each region has GHG abatement costs dependent on its level of emissions reductions and the relevant type of investments, which we express by the following quadratic cost function:

$$c_i(e_i, k_i) = \frac{\bar{c}_i}{2}(e_i)^2, \ i = h, a, \tag{2}$$

where $\bar{c}_i$ is a function of k_i i.e. we have $\bar{c}_i = \bar{c}_i(k_i)$ with $\bar{c}_i' < 0$ and $\bar{c}_i'' > 0$. Note that we have $\frac{\partial^2 c_i}{\partial k_i \partial e_i} = \bar{c}_i' e_i < 0$. Thus, R&D investments of type i reduce the marginal GHG abatement costs of Region i. This is a standard approach in the literature.[4]

3 Solving the model without permit trade

As Region h may invest in both k_h and k_a, the total welfare function for this region is given by:

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[3]R&D of type k_a carried out by developed countries could also be a complement or a substitute to R&D investments carried out by developing countries themselves. In the former case, k_a would induce more R&D by the developing countries, while in the latter case, k_a would crowd out R&D by developing countries.

[4]Exceptions can be found in Baker et al. (2008), who give an overview of a number of models that comprise cases where technical change leads to an increase in marginal abatement costs at high levels of abatement. They argue that this will happen any time an innovation is applied to a technology that will be substituted away from at high levels of abatement.

$$\omega^h = b_h(e_h + e_a) - \frac{\bar{c}_h(k_h)}{2}(e_h)^2 - p_h k_h - p_a k_a, \tag{3}$$

where the unit cost of investment i is p_i.

As we abstract away from Region a's own investment, its welfare function is given by:

$$\omega^a = b_a(e_h + e_a) - \frac{\bar{c}_a(k_a)}{2}(e_a)^2. \tag{4}$$

When there is no permit trade between the regions, Stage 3 of the game is trivial, and we can move directly to Stage 2.

3.1 Stage 2: Setting emission reduction targets

At this stage, the regions maximize welfare with respect to the level of emission reductions e_i, for given levels of k_i:

$$\max_{e_i} \omega^i = b_i(e_h + e_a) - \frac{\bar{c}_i(k_i)}{2}(e_i)^2, \quad i = h, a. \tag{5}$$

The two first order conditions are:

$$b_i' - \bar{c}_i e_i = 0. \tag{6}$$

The Nash equilibrium emission reduction targets $e_h^N = e_h^N(k_h, k_a)$ and $e_a^N = e_a^N(k_h, k_a)$ are found by solving the two equations given by (6). It is easy to show formally that: $\frac{\partial e_i^N}{\partial k_i} > 0$ and $\frac{\partial e_j^N}{\partial k_i} < 0$, $i, j = 1, 2$, $i \neq j$.[5] An increase in investment k_h will increase the emission reduction target of Region h, and decrease the emission reduction target of Region a. Hence, as pointed out by Stranlund (1996), investing at home does not seem desirable if one looks for R&D investment strategies that make developing countries set tougher targets. For an investment i k_a it is the other way around.

To facilitate a comparison with the permit trade case (Section 4), we illustrate how investments affects the agents best response functions and thereby the Nash equilibrium outcomes in a setting without permit trade. The best response functions $e_i(e_j)$ are found from (6). It is easy to check that the best response functions are downward sloping in a $e_h - e_a$ diagram, i.e. $\frac{de_i}{de_j} = \frac{-b_i''}{b_i'' - \bar{c}_i} < 0$. By totally differentiating (6), we get:

$$\frac{de_i(e_j)}{dk_i} = \frac{\bar{c}_i' e_i}{b_i'' - \bar{c}_i} > 0,$$

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[5] Notice that if marginal GHG abatement costs were increasing in the investment, both results would be reversed.

$$\frac{de_j(e_i)}{dk_i} = 0.$$

A k_i investment only affects the marginal costs of emission reductions in Region i. Hence, a k_i investment will make Region i set a higher emission reduction target for any e_j, while a k_i investment will not affect the emission reduction target of Region j, given e_i. In Appendix A, we present the numerical model we use to draw the following diagram:

Figure 1 Effects of investments in k_h and k_a without permit trade
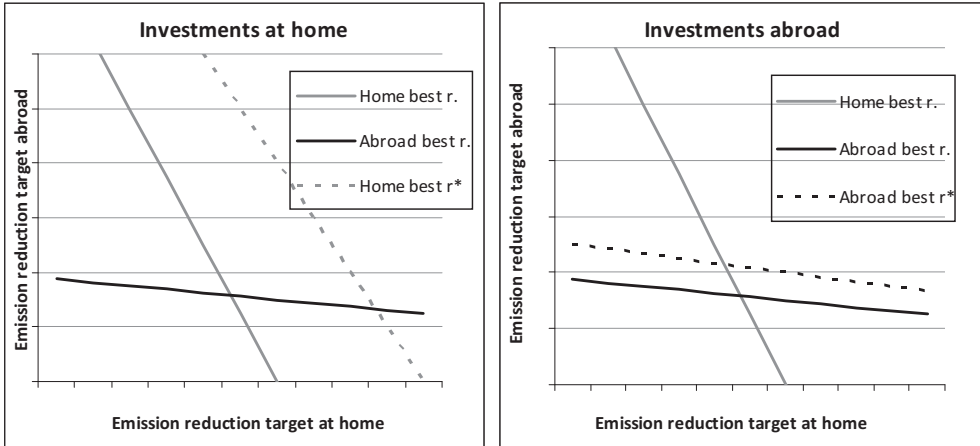
The solid lines illustrate the best response curves before an investment takes place. The stippled lines illustrate agent i's best response curves after an investment in k_i. Recall that agent j's response curve does not change with an investment in k_i. From the left diagram in Figure 1, we see that an increase in investment k_h will increase the emission reduction target of Region h, and decrease the emission reduction target of Region a. The right diagram illustrates the opposite effect of an increase in investment k_a; the emission reduction target of Region h decreases, whereas the emission reduction target of Region a increases.

3.2   Stage 1: Investments

A model of strategic investment without permit trade is treated in Stranlund (1996), and we will only briefly discuss the main results here. In stage 1, Region h invests in abatement technology in its own region and in Region a, given the anticipated outcome of the Nash equilibrium in stage 2:

$$\max_{k_h, k_a} \omega^h = b_h(e_h^N + e_a^N) - \frac{\bar{c}_h(k_h)}{2}(e_h^N)^2 - p_h k_h - p_a k_a. \qquad (7)$$

By the envelope theorem, Region h does not need to take account explicitly of the fact that its own emission target will be influenced by its investment. We find the following first order conditions for investment, given an interior solution:[6]

$$b_h' \frac{\partial e_a^N}{\partial k_h} - \frac{\bar{c}_h'}{2}(e_h^N)^2 = p_h, \qquad (8)$$

$$b_h' \frac{\partial e_a^N}{\partial k_a} = p_a. \qquad (9)$$

The term $\frac{\bar{c}_h'}{2}(e_h^N)^2$ is the marginal saving in abatement costs in Region h from an investment in k_h, and the term p_h is the marginal cost of investment h. There is also a strategic effect of investment as investment affects the equilibrium outcome of the abatement targets ($\frac{\partial e_a^N}{\partial k_h}$ and $\frac{\partial e_a^N}{\partial k_a}$). Not considering the strategic effects, optimal investment at home implies $\left| \frac{\bar{c}_h'}{2}(e_h^N)^2 \right| = p_h$. Accordingly, we will coin the situation with $\left| \frac{\bar{c}_h'}{2}(e_h^N)^2 \right| > p_h$ as *underinvestment at home*, and a situation with $\left| \frac{\bar{c}_h'}{2}(e_h^N)^2 \right| < p_h$ as *overinvestment at home*.

Investment abroad only reduces foreign abatement costs. Hence, there is no effect on the marginal saving in abatement costs from an investment abroad. We therefore coin the situation with $k_a > 0$ as *overinvestment abroad*.

From (8), we have that because the strategic effect of investments at home; $b_h' \frac{\partial e_a^N}{\partial k_h}$, is negative, we must have $\left| \frac{\bar{c}_h'}{2}(e_h^N)^2 \right| > p_h$. Region h should therefore always underinvest in k_h. Furthermore, from (9), since the strategic effect of investments abroad; $\frac{\partial e_a^N}{\partial k_a}$, is positive, Region h should always overinvest in k_a. The intuition behind these results is that by underinvesting at home and overinvesting abroad, the developed countries induce the developing countries to set higher GHG emission reduction targets, which of course benefits the developed countries.

4 Solving the model with permit trade

The permit market is assumed to be perfectly competitive. Because there is free trade in emission permits, a region can reach its emission reduction target both through abatement at home and through permit

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[6]It can be shown that the second order conditions for a welfare maximum are fulfilled.

purchases. In a permit trading regime, a region's emission reductions generally differ from its emission reduction target. Therefore, we introduce two new variables $\bar{e}_h$ and $\bar{e}_a$ that denote the emission reduction targets for Region h and Region a, respectively. Furthermore, let t denote the emission permit price.

Region h's welfare function is given by:

$$\bar{\omega}^h = b_h(\bar{e}_h + \bar{e}_a) - t\left[\bar{e}_h - e_h\right] - \frac{\bar{c}_h(k_h)}{2}(e_h)^2 - p_h k_h - p_a k_a, \qquad (10)$$

whereas Region a's welfare function is given by:

$$\bar{\omega}^a = b_a(\bar{e}_h + \bar{e}_a) - t\left[\bar{e}_a - e_a\right] - \frac{\bar{c}_a(k_a)}{2}(e_a)^2. \qquad (11)$$

4.1 Stage 3: Permit trade

We start by looking at the global permit market and the realized emission reductions in the two regions. Given the emission reduction targets $\bar{e}_h$ and $\bar{e}_a$, actual emission reductions e_h and e_a in each region and the emission permit price t are all decided from the following three equations:

$$e_h + e_a = \bar{e}_h + \bar{e}_a, \qquad (12)$$

$$\bar{c}_i e_i = t, \ \ i = h, a, \qquad (13)$$

where the first equation (12) states that the sum of emission reductions must be equal to the combined targets, and the last two equations (13) state that the marginal abatement cost must be equal to the permit price. The equations can be solved easily, and we obtain:

$$t = \frac{\bar{c}_h \bar{c}_a \left[\bar{e}_h + \bar{e}_a\right]}{\bar{c}_h + \bar{c}_a}, e_h = \frac{\bar{c}_a \left[\bar{e}_h + \bar{e}_a\right]}{\bar{c}_h + \bar{c}_a}, e_a = \frac{\bar{c}_h \left[\bar{e}_h + \bar{e}_a\right]}{\bar{c}_h + \bar{c}_a}. \qquad (14)$$

Note that all three variables only depend on total emission reductions, that is, the sum of the targets, and not of the particular emission reduction target in each region. From (14), we obtain:

$$\frac{\partial e_i}{\partial \bar{e}_i} = \frac{\partial e_i}{\partial \bar{e}_j} = \frac{\bar{c}_j}{\bar{c}_h + \bar{c}_a} > 0, \qquad (15)$$

$$\frac{\partial t}{\partial \bar{e}_i} = \frac{\partial t}{\partial \bar{e}_j} = \frac{\bar{c}_h \bar{c}_a}{\bar{c}_h + \bar{c}_a} > 0. \qquad (16)$$

Firstly, note that any increase in the total emission reduction target will lead both regions to abate more and the permit price to rise.

Moreover, the effect is independent of which region tightens its target. Secondly, note that the extent to which Region i will abate more depends on the costs of abating in Region j and *vice versa*. When the total emission reduction target is tightened, at least one of the regions will have to abate more. However, by how much the abatement is increased depends on the second order derivative of the abatement cost function. If the second order derivative of Region i is high, its ability to increase its abatement is limited, and consequently, Region j will do most of the additional abatement.

Given $\bar{e}_h + \bar{e}_a$, any change in k_h or k_a will have a partial effect on the permit market equilibrium through its direct influence on the cost function. We have the following partial derivatives:

$$\frac{\partial e_i}{\partial k_i} = -\frac{\partial e_j}{\partial k_i} = \frac{-\bar{c}_i'(\bar{e}_h + \bar{e}_a)\bar{c}_j}{(\bar{c}_h + \bar{c}_a)^2} > 0, \qquad (17)$$

$$\frac{\partial t}{\partial k_i} = \frac{\bar{c}_i'(\bar{c}_j)^2(\bar{e}_h + \bar{e}_a)}{(\bar{c}_h + \bar{c}_a)^2} < 0. \qquad (18)$$

For given emission reduction targets $\bar{e}_h$ and $\bar{e}_a$, an increase in k_i decreases the marginal abatement cost of Region i, and Region i abates more. Regions j abates correspondingly less, which implies that the permit price has to fall. We reach a new equilibrium in which Region i abates more, Region j abates less and the permit price has fallen. Clearly, a change in k_i also affects the emission reduction targets $\bar{e}_i$, but that is left for the next section.

4.2 Stage 2: Setting emission reduction targets

When setting the emission targets in stage 2, the two regions take into account how the targets affect the permit market in addition to the benefits and costs of emission reductions, for given levels of k_i. The regions' optimization problems are given by:

$$\max_{\bar{e}_i} \bar{\omega}^i = b_i(\bar{e}_h + \bar{e}_a) - t\left[\bar{e}_i - e_i\right] - \frac{\bar{c}_i(k_i)}{2}(e_i)^2, \; i = h, a, \qquad (19)$$

where t, e_h and e_a are given by (14). Notice the second term in (19), which does not appear in (5), and is income from permit sales/spending on permit acquisitions. By using (13), we write the two first order conditions as follows:

$$b_i' - t - \frac{\partial t}{\partial \bar{e}_i}\left[\bar{e}_i - e_i\right] = 0, \; i = h, a. \qquad (20)$$

Again, we obtain the Nash equilibrium outcomes $\bar{e}_h^N = \bar{e}_h^N(k_h, k_a)$ and $\bar{e}_a^N = \bar{e}_a^N(k_h, k_a)$ from (20).

We see from the equations in (20) that for each region, the marginal benefit of the emission reduction target should always be equal to the permit price plus a term telling us whether the region at the margin would benefit or lose from a higher emission permit price induced by a higher emission reduction target.[7] Clearly, the sign of this term depends on the region being a net buyer or a net supplier of emission rights in equilibrium. For instance, if $[\bar{e}_i - e_i]$ is positive, the region is a net buyer, and the last term on the left-hand side of (20) is negative. As noted by Helm (2003), whether Region i becomes a net buyer or net seller depends only on the benefit function. Because $b'_h \geq b'_a$, $\forall (e_h + e_a)$ in our two country case, we can only have $b'_h - t \geq 0$, and $b'_a - t \leq 0$. Hence, we must have $-\frac{\partial t}{\partial \bar{e}_h} [\bar{e}_h - e_h] < 0$, and consequently Region h will be the net buyer. Contrary to the outcome without permit trade, the impact of investments on the Nash equilibrium emission targets are in general ambiguous in a setting with emissions trade. In Appendix B, we prove the ambiguity of the sign of the derivatives $\frac{\partial \bar{e}_h^N}{\partial k_h}, \frac{\partial \bar{e}_h^N}{\partial k_a}, \frac{\partial \bar{e}_a^N}{\partial k_h}$ and $\frac{\partial \bar{e}_a^N}{\partial k_a}$. Hence, allowing for permit trade may lead us to conclude differently from Stranlund (1996).

Proposition 1 *With permit trade, the effects of investments abroad may be tougher emission reduction targets at home, i.e.* $\frac{\partial \bar{e}_h^N}{\partial k_a} > 0$, *which is not possible without permit trade.*

Using our numerical model (see Appendix A), we illustrate in Figure 2 how investment may affect the agents best response functions and thereby the Nash equilibrium outcomes. The best response functions $e_i(e_j)$ are found from each of the equations in (20).

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[7]Note that the permit price will equal the marginal cost of emission reductions in the permit trade equilibrium.

Figure 2 Effects of investments in k_h and k_a with permit trade
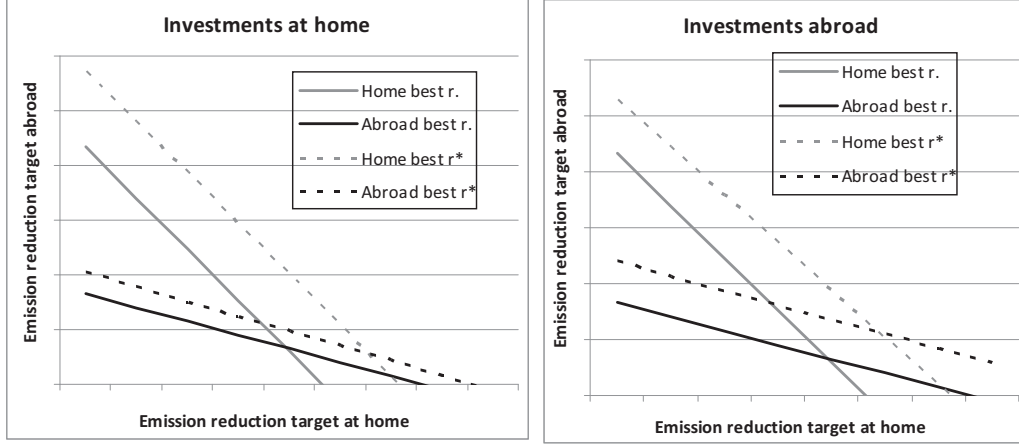
The solid lines illustrate the best response curves before an investment takes place. The stippled lines illustrate the best response curves after an investment in k_i. In the case with permit trade, both types of investment influence both reaction curves through the permit market. However, in our numerical example, when k_h is increased, the new Nash equilibrium value of $\bar{e}_a$ is lower, while the new Nash equilibrium value of $\bar{e}_h$ is higher. On the other hand, when k_a is increased, the shifts in both curves are more equal, and hence, both regions increase their emission reduction target. This cannot happen in the case without permit trade.

4.3   Stage 1: Investments

In Stage 1, Region h invests both at home and abroad, given the anticipated outcome of the Nash equilibrium in stage 2 and the outcome in the permit market. Region h maximizes:

$$\bar{\omega}^h = b_h(\bar{e}_h^N + \bar{e}_a^N) - t\left[\bar{e}_h^N - e_h\right] - \frac{\bar{c}_h(k_h)}{2}(e_i)^2 - p_h k_h - p_a k_a, \quad (21)$$

with respect to k_h and k_a. We assume that the second order conditions are satisfied. The optimal level of investment at home is given by:

$$\frac{\partial \bar{\omega}^h}{\partial k_h} = b_h' \frac{\partial \bar{e}_a^N}{\partial k_h} - \left[\frac{\partial t}{\partial \bar{e}_a}\frac{\partial \bar{e}_a^N}{\partial k_h} + \frac{\partial t}{\partial k_h}\right]\left[\bar{e}_h^N - e_h\right] - \frac{\bar{c}_h'}{2}(e_h)^2 - p_h = 0,$$

which can be rearranged by using (16) and (20) and then written as:

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$$t\frac{\partial \bar{e}_a^N}{\partial k_h} - \frac{\partial t}{\partial k_h}\left[\bar{e}_h^N - e_h\right] + \left|\frac{\bar{c}_h'}{2}(e_h)^2\right| = p_h. \qquad (22)$$

There are two effects that may lead Region h to either under- or overinvest in k_h. Firstly, by investing in k_h, Region h influences the target set by Region a in stage 2 of the game. This is the same strategic effect as in the without permit trade case, but now it could take another sign. To the extent that $\frac{\partial \bar{e}_a^N}{\partial k_h} > 0$, Region h benefits from investing at home because Region a increases its emission reduction target (now valued at the permit price t).

Secondly, investments at home lower the permit price, i.e. $\frac{\partial t}{\partial k_h} < 0$. The permit price effect always benefits Region h as Region h is a net buyer of permits. Remember that without permit trade, Region h should never overinvest in k_h. With permit trade, this is changed as described in the following proposition:

Proposition 2 *Region h should overinvest at home if:*

- *The strategic effect of investments in k_h is positive, i.e. $t\frac{\partial \bar{e}_a}{\partial k_h} > 0$, or if*

- *The strategic effect is negative, but dominated by the permit price effect, i.e. $\left|t\frac{\partial \bar{e}_a^N}{\partial k_h}\right| < \left|\frac{\partial t}{\partial k_h}\left[\bar{e}_h^N - e_h\right]\right|$.*

Clearly, if the volume of permit trade is large, overinvestment in k_h may be desirable independent of the sign of the strategic effect.

We now turn to the optimal choice of investment abroad. By inserting (20), we can write the first order condition for optimal investments abroad as follows:

$$\frac{\partial \bar{\omega}^1}{\partial k_a} = t\frac{\partial \bar{e}_a^N}{\partial k_a} - \frac{\partial t}{\partial k_a}\left[\bar{e}_h^N - e_h\right] - p_a = 0. \qquad (23)$$

As above, the permit price effect $-\frac{\partial t}{\partial k_a}\left[\bar{e}_h^N - e_h\right]$ is positive, and the strategic effect $t\frac{\partial \bar{e}_a^N}{\partial k_a}$ is ambiguous. Remember that without permit trade, Region h should always overinvest in k_a. With permit trade, this is no longer necessarily true as described in the following proposition:

Proposition 3 *Region h should overinvest abroad if:*

- *The strategic effect of investments in k_a is positive, i.e. $t\frac{\partial \bar{e}_a^N}{\partial k_a} > 0$, or if*

- *The strategic effect is negative, but dominated by the permit price effect, i.e.* $\left| t \frac{\partial \bar{e}_a^N}{\partial k_a} \right| < \left| \frac{\partial t}{\partial k_a} \left[\bar{e}_h^N - e_h \right] \right|$.

By comparing the first order conditions in the cases with and without a common permit market among the two regions, we see that the introduction of a future permit market affects the investors expected welfare improvement of the investments. Clearly, it is hard to compare the level of investments as they depend on the functional forms of both the abatement cost functions and benefit functions. The profitability of an investment project depends not only on the strategic effect and permit price effect, but just as much on the total level of GHG abatement to take place. As the total level of GHG abatement to take place in developed countries may be higher under no permit trade, the level of k_h may also be higher with no permit trade.

5   Discussion and conclusion

The main message of our paper is that permit trade changes the strategic effects of investments, and permit trade may make it desirable to both overinvest at home and abroad.

In our model, the government directly decides the amount of both types of R&D in GHG abatement technologies. This is of course a simplification as a large part of the yearly R&D expenditures in these technologies are borne by private R&D firms and by the polluting firms themselves. However, the government can still decide the total amount of R&D by using R&D subsidies and/or taxes of various forms. Typically, the private sector will invest in R&D up to the level at which the cost reductions from the least profitable project equals the R&D costs of the same project. Thus, if the government wants *underinvestment* it must tax R&D, and if the government wants *overinvestment* it must subsidize R&D.

It is generally acknowledged that only a part of the social value of a new successful technology accrues to the inventing firm, and hence, that too few new technologies will be invented. There are many reasons for this shortage in the supply of new technologies: positive knowledge spillovers from current R&D to future R&D, missing or imperfect patent protection and even with perfect patent protection, the patent holder may not be able to reap the total social surplus.

In this paper, we have identified another reason for subsidizing R&D: in addition to the above mentioned arguments, R&D should be subsidized to the extent that R&D today will yield a more beneficial allocation of GHG emission reductions tomorrow. Generally, R&D investments that reduce developing countries marginal GHG abatement costs seem

to have this property. However, more importantly, if developing countries and industrialized countries in the future continue to trade emission rights with each other, investments that only reduce industrialized countries marginal GHG abatement costs could also have this property.

Another question is whether industrialized countries will gain from a common permit market with developing countries. As shown by Helm (2003), it is not possible to answer this question by theory alone. In order to do that, we need a numerical model in the spirit of Carbone et al. (2009), but which includes R&D investments. In our opinion, this is an interesting future avenue of research.

We have not modelled the decision to have a global permit market or not. One could envision alternative sequences of moves in this extended game. We would argue that the following organization of the game is especially relevant: 1) The industrialized region chooses investment, 2) Both regions set emission targets and 3) Regions decide on whether to have a global permit trading scheme. By backwards induction, we conjecture that given both investments and the targets, regions would always choose to trade. Hence, it is only the trading equilibrium that will be realized.

Of course, the industrialized region could try to commit to not having a global permit scheme before choosing investments, or they could condition a global permit market on a more committing global agreement. However, such commitments might not be credible.

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A   The numerical example

A.1   Benefits and costs

The benefits of emission reduction targets are given by:

$$b_h(\cdot) = 20(\bar{e}_h + \bar{e}_a) - \frac{1}{2}(\bar{e}_h + \bar{e}_a)^2,$$
$$b_a(\cdot) = 10(\bar{e}_h + \bar{e}_a) - \frac{1}{2}(\bar{e}_h + \bar{e}_a)^2.$$

While the costs of emission reductions arev given by:

$$c_h(\cdot) = (2 - k_h)(e_h)^2,$$
$$c_a(\cdot) = (1.5 - k_a)(e_a)^2.$$

We look at investments $k_h, k_a = 0.5$.

A.2 Solution without permit trading

Welfare in Stage 2 can be expressed as follows:

$$W_h = 20(\bar{e}_h + \bar{e}_a) - \frac{1}{2}(\bar{e}_h + \bar{e}_a)^2 - (2 - k_h)(\bar{e}_h)^2,$$

$$W_a = 10(\bar{e}_h + \bar{e}_a) - \frac{1}{2}(\bar{e}_h + \bar{e}_a)^2 - (1.5 - k_a)(\bar{e}_a)^2.$$

From the first-order conditions for a welfare maximum we obtain the following best response curves:

$$e_h^* = \frac{20 - e_a}{5 - 2k_h},$$

$$e_a^* = \frac{10 - e_h}{4 - 2k_a}.$$

These are then plotted for $k_i = 0$ and $k_i = 0.5$, $i = h, a$.

A.3 Solution with permit trading

Equilibrium in the permit market allows us to write e_h, e_a and t as functions of $\bar{e}_h, \bar{e}_a, k_h$ and k_a as follows:

$$e_h = \frac{(1.5 - k_a)(\bar{e}_h + \bar{e}_a)}{3.5 - k_h - k_a}, \; e_a = \frac{(2 - k_h)(\bar{e}_h + \bar{e}_a)}{3.5 - k_h - k_a},$$

$$t = \frac{2(2 - k_h)(1.5 - k_a)(\bar{e}_h + \bar{e}_a)}{3.5 - k_h - k_a}.$$

Welfare in Stage 2 can be expressed as follows:

$$W_h = 20(\bar{e}_h + \bar{e}_a) - \frac{1}{2}(\bar{e}_h + \bar{e}_a)^2 - t\,[\bar{e}_h - e_h] - (2 - k_h)(e_h)^2,$$

$$W_a = 10(\bar{e}_h + \bar{e}_a) - \frac{1}{2}(\bar{e}_h + \bar{e}_a)^2 - t\,[\bar{e}_a - e_a] - (1.5 - k_a)(e_a)^2.$$

Differentiating with respect to $\bar{e}_h$ and $\bar{e}_a$ yields the following first order conditions:

$$20 - (\bar{e}_h + \bar{e}_a) - \frac{\partial t}{\partial \bar{e}_h} [\bar{e}_h - e_h] - t = 0,$$

$$10 - (\bar{e}_h + \bar{e}_a) - \frac{\partial t}{\partial \bar{e}_a} [\bar{e}_a - e_a] - t = 0,$$

which by inserting for e_i, t and $\frac{\partial t}{\partial \bar{e}_i}$ yields the reaction functions. These are then plotted for $k_i = 0$ and $k_i = 0.5$, $i = h, a$.

B Strategic effects in the permit trade case

In this appendix, we prove the ambiguity of the sign of the derivatives $\frac{\partial \bar{e}_h^N}{\partial k_h}$, $\frac{\partial \bar{e}_h^N}{\partial k_a}$, $\frac{\partial \bar{e}_a^N}{\partial k_h}$ and $\frac{\partial \bar{e}_a^N}{\partial k_a}$. For simplicity, we write the second order derivatives of the welfare function in the permit trade case as follows: $\frac{\partial^2 \bar{\omega}^i}{\partial \bar{e}_i \partial \bar{e}_i} = \bar{\omega}_{ii}^i$, $\frac{\partial^2 \bar{\omega}^i}{\partial \bar{e}_i \partial \bar{e}_j} = \bar{\omega}_{ij}^i$, $\frac{\partial^2 \bar{\omega}^i}{\partial \bar{e}_i \partial k_i} = \bar{\omega}_{ik_i}^i$, and $\frac{\partial^2 \bar{\omega}^i}{\partial \bar{e}_i \partial k_j} = \bar{\omega}_{ik_j}^i$, $i, j = h, a$, $i \neq j$. By totally differentiating the two equations (20), we obtain the effects of k_h as follows:

$$sign \left[\frac{\partial \bar{e}_h^N}{\partial k_h} \right] = sign \left[\bar{\omega}_{ha}^h \bar{\omega}_{ak_h}^a - \bar{\omega}_{aa}^a \bar{\omega}_{hk_h}^h \right], \tag{24}$$

$$sign \left[\frac{\partial \bar{e}_a^N}{\partial k_h} \right] = sign \left[\bar{\omega}_{ah}^a \bar{\omega}_{hk_h}^h - \bar{\omega}_{hh}^h \bar{\omega}_{ak_h}^a \right]. \tag{25}$$

Moreover, we have for the effects of k_a:

$$sign \left[\frac{\partial \bar{e}_h^N}{\partial k_a} \right] = sign \left[\bar{\omega}_{ha}^h \bar{\omega}_{ak_a}^a - \bar{\omega}_{aa}^a \bar{\omega}_{hk_a}^h \right], \tag{26}$$

$$sign \left[\frac{\partial \bar{e}_a^N}{\partial k_a} \right] = sign \left[\bar{\omega}_{ah}^a \bar{\omega}_{hk_a}^h - \bar{\omega}_{hh}^h \bar{\omega}_{ak_a}^a \right]. \tag{27}$$

Below, we derive the sign of all the second order derivatives of the welfare functions, (19).

First, we see by using (13), that:

$$\bar{\omega}_{ii}^i = b_i'' - 2 \frac{\partial t}{\partial \bar{e}_i} + \frac{\partial t}{\partial \bar{e}_i} \frac{\partial e_i}{\partial \bar{e}_i}, \tag{28}$$

$$\bar{\omega}_{ij}^i = b_i'' - \frac{\partial t}{\partial \bar{e}_j} + \frac{\partial t}{\partial \bar{e}_i} \frac{\partial e_i}{\partial \bar{e}_j}. \tag{29}$$

Because $b_i'' < 0$, $\frac{\partial t}{\partial \bar{e}_i} = \frac{\partial t}{\partial \bar{e}_j} > 0$ and both $\frac{\partial e_i}{\partial \bar{e}_i}, \frac{\partial e_i}{\partial \bar{e}_j} \in \langle 0, 1 \rangle$, we have $\bar{\omega}_{ii}^i$, $\bar{\omega}_{ij}^i < 0$, and $\left|\bar{\omega}_{ii}^i\right| > \left|\bar{\omega}_{ij}^i\right|$. Thus, the sufficient condition for uniqueness of is satisfied.

Furthermore:

$$\bar{\omega}_{hk_h}^h = -\frac{\partial t}{\partial k_h} - \frac{\bar{c}_h'(\bar{c}_a)^2}{(\bar{c}_h + \bar{c}_a)^2}\left[\bar{e}_h - e_h\right] + \frac{\partial t}{\partial \bar{e}_h}\frac{\partial e_h}{\partial k_h},$$

where we have used $\frac{\partial^2 t}{\partial k_h \partial \bar{e}_h} = \frac{\bar{c}_h'(\bar{c}_a)^2}{(\bar{c}_h + \bar{c}_a)^2}$ (see (16)). Because Region h is a net buyer of permits, all terms in the expression above are positive, such that $\bar{\omega}_{hk_h}^h > 0$. Furthermore, we have:

$$\bar{\omega}_{hk_a}^h = -\frac{\bar{c}_a'(\bar{c}_h)^2}{(\bar{c}_h + \bar{c}_a)^2}\left[\bar{e}_h - e_h\right] + \frac{\partial t}{\partial \bar{e}_h}\frac{\partial e_h}{\partial k_a} - \frac{\partial t}{\partial k_a},$$

where $\frac{\partial t}{\partial \bar{e}_h}\frac{\partial e_h}{\partial k_a} - \frac{\partial t}{\partial k_a} = -\bar{c}_a'\left[1 - \frac{\bar{c}_a}{\bar{c}_h + \bar{c}_a}\right]\frac{(\bar{c}_h)^2(\bar{e}_h + \bar{e}_a)}{(\bar{c}_h + \bar{c}_a)^2} > 0$, and hence, we have $\bar{\omega}_{hk_a}^h > 0$.

We find that:

$$\bar{\omega}_{ak_a}^a = -\frac{\partial t}{\partial k_a} + \frac{\partial t}{\partial \bar{e}_a}\frac{\partial e_a}{\partial k_a} - \frac{\bar{c}_a'(\bar{c}_h)^2}{(\bar{c}_h + \bar{c}_a)^2}\left[\bar{e}_a - e_a\right],$$

where the two first terms are positive, but because abroad is a net seller of permits, the last term in the expression above is negative. Thus, we are not able to sign $\bar{\omega}_{ak_a}^a$. Finally, we have:

$$\bar{\omega}_{ak_h}^a = -\frac{\bar{c}_h'(\bar{c}_a)^2}{(\bar{c}_h + \bar{c}_a)^2}\left[\bar{e}_a - e_a\right] - \bar{c}_h'\left[1 - \frac{\bar{c}_h}{\bar{c}_h + \bar{c}_a}\right]\frac{(\bar{c}_a)^2(\bar{e}_h + \bar{e}_a)}{(\bar{c}_h + \bar{c}_a)^2},$$

and again, because $(\bar{e}_a - e_a) < 0$, we are not able to sign $\bar{\omega}_{ak_h}^a$.

We see from (24) - (27), that because we cannot sign $\bar{\omega}_{ak_a}^a$ and $\bar{\omega}_{ak_h}^a$, we cannot sign any of the total derivatives $\frac{\partial \bar{e}_h^N}{\partial k_h}, \frac{\partial \bar{e}_h^N}{\partial k_a}, \frac{\partial \bar{e}_a^N}{\partial k_h}$ and $\frac{\partial \bar{e}_a^N}{\partial k_a}$. Clearly, introducing a general cost function $c_i = c_i(e_i; k_i)$ does not change the result regarding the ambiguity of the sign of the derivatives.