

Strategic Investment in Climate Friendly Technologies: The Impact of Global Emissions Trading

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Accepted: 21 August 2013 / Published online: 30 August 2013
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Abstract Our point of departure is that a group of industrialized countries invest in research and development (R&D) of greenhouse gas (GHG) abatement technologies. R&D investments influence the future GHG abatement choices of both industrialized and developing countries. We distinguish between investments that reduce industrialized countries' abatement costs and investments that reduce developing countries' abatement costs. Unlike earlier contributions, we include global trading in emission permits. This changes the nature of the game. With global permit trading, industrialized countries should in many cases invest strategically in technologies that only reduce abatement costs at home. This comes in addition to investments abroad. Second, we show that R&D investments always decrease total emissions. Finally, we find that the developing region receiving investments always benefits.

Keywords Greenhouse gas abatement technologies · Climate policy · Strategic investments · Permit trade

JEL Classification D62 · H41 · O38 · Q58

1 Introduction

International cooperation on climate change has proven to be difficult. The Kyoto Protocol sets emission reduction targets for industrialized countries, the Annex I countries, and these countries' share of global emissions is rapidly decreasing. Despite numerous efforts by the UN to come up with a replacement for the Kyoto Protocol, there is still no sign of a new treaty that would cover a larger proportion of global emissions and ensure deeper global emission cuts. Instead, 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. As generally acknowledged in the literature on public goods, this will lead

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to insufficient emission reductions. The question then arises: how does a country that is concerned about global warming convince other countries to set more stringent targets?

One answer favored by environmentalists is that industrialized countries should act as “good examples” by setting stringent domestic emission targets. However, such an approach is not endorsed by game theoretic analysis. For instance, [Hoel \(1991\)](#) shows that, if a country takes unilateral action to reduce emissions, this can be partly offset by an increase in emissions from other countries.

Another possible response by industrialized countries could be to use research and development (R&D) strategically to influence future GHG abatement targets. Improving the capability of developing countries to reduce their emissions of greenhouse gasses is an explicit goal of the ongoing climate negotiations, which, among other things, have led to the creation of a *technology mechanism* (see e.g. [UNFCCC 2009](#)). So far the focus has mostly been on increasing technology diffusion from industrialized countries to developing countries. However, developing countries may have different technology needs than industrialized countries, and industrialized countries may also want to help developing countries to advance these technologies.

Strategic R&D investments are analyzed by [Buchholz and Konrad \(1994\)](#), [Stranlund \(1996\)](#) and [Golombek and Hoel \(2004\)](#). By strategic R&D investments we mean investing more than the cost-minimizing level, e.g. realizing R&D projects that from a commercial point of view appear to be non-profitable. [Buchholz and Konrad \(1994\)](#) and [Stranlund \(1996\)](#) conclude that countries should limit R&D investments that improve their own technologies, because such underinvestment credibly commits them to low emission reductions in the future, and thereby makes other countries increase their emission reductions.

[Buchholz and Konrad \(1994\)](#) and [Stranlund \(1996\)](#) distinguish between investments that reduce industrialized countries’ abatement costs and investments that reduce developing countries’ abatement costs, and they do not consider knowledge spillovers between these two types of investments. Knowledge spillovers are included in [Golombek and Hoel \(2004\)](#), however. In [Golombek and Hoel \(2004\)](#), two regions each invest in R&D of their own abatement technology. In some versions of this game, industrialized countries’ R&D investments could spur abatement abroad due to the spillovers.

Our paper differs from the previous literature in several respects. In particular, we include trading in emission rights between the industrialized and developing countries. This radically changes the nature of the game: First, given global permit trading, we find that industrialized countries may benefit from strategic R&D investments in technologies that only reduce abatement costs at home. 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” does not hold with global permit trading. The main reason is that investments will reduce the future price of emissions rights and benefit the industrialized countries, which will probably become permit buyers.

Second, we find that industrialized countries still have an incentive to invest strategically in technologies that only reduce abatement costs abroad. Such investments could lead to developing countries setting tougher GHG abatement targets, and, as for investments at home, investments abroad will also reduce the future permit price.

Third, we find that investments always reduce total emissions, and that developing countries always benefit from accepting some level of technology transfer. To our knowledge, both these results are also new to the literature. Neither [Buchholz and Konrad \(1994\)](#) nor [Stranlund \(1996\)](#) examine the extent to which the countries receiving R&D investments benefit from the investments. Finally, we show in a numerical example that the incentives to invest

strategically can be quite strong, suggesting that industrialized countries should consider encouraging R&D in abatement technologies.

Our finding that it may pay industrialized countries to overinvest in R&D at home resembles the finding in [Golombek and Hoel \(2004\)](#) that industrialized countries' R&D investments could spur abatement abroad. However, in Golombek and Hoel the result is dependent on the existence of knowledge spillovers. In our paper, there are no knowledge spillovers. Instead the permit market provides another type of "spillover", that is, investments decrease the future price of emissions rights, which makes it more tempting for both developing and industrialized countries to set tougher emission reduction targets.

As in [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. Electricity smart grids are an example of the former, while institutional capacity building could be an example of the latter. Obviously, there also R&D opportunities from which both type of countries would benefit. However, in order to focus on the effect of permit trading, we do not consider spillovers in the present paper, neither within regions nor across regions.

Further, we model the global emission reduction outcome as a Nash–Cournot equilibrium where the industrialized countries act as one Cournot player vis-à-vis the developing countries when setting emission reduction targets.¹ By assuming that the industrialized countries act as one Cournot player, we ignore the discussion about the stability of the cooperation among these countries since that issue is not the focus of this paper. There is extensive 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 under permit trading is also considered in [Helm \(2003\)](#), [Carbone et al. \(2009\)](#) and [Gersbach and Winkler \(2011\)](#). Due to the free-rider problem, the Nash–Cournot outcome leads to emissions above the socially optimal level. [Helm \(2003\)](#) and [Carbone et al. \(2009\)](#) focus on whether permit trading improves welfare, given that emissions targets are set after the decision to have permit trading. To increase the incentives for tighter reduction targets, [Gersbach and Winkler \(2011\)](#) propose an emissions-trading scheme where a proportion of the permits are auctioned and the revenues are distributed to all participants. However, none of the above-mentioned contributions consider how ex ante investments in climate friendly technologies affect the Nash–Cournot equilibrium.

Permit trading is likely to be one of the elements of the current international climate regime that will be retained. The EU ETS is set to continue, and this probably also holds for the Clean Development Mechanism (CDM), which is an emission-trading arrangement between developing and industrialized countries. However, since the developing countries have no quantitative targets so far, the emission reductions achieved through the CDM have to be measured against a counter-factual baseline for emissions in each project. Due to the economic incentives for overstating the actual emission reductions, the performance of the CDM has been questioned in the literature, see, e.g., [Wara \(2007\)](#), [Rosendahl and Strand \(2009\)](#), and [Schneider \(2009\)](#).

Alternatively, developing countries could initiate their own domestic emission trading systems. These national emissions trading systems could later be linked to the EU ETS and other

¹ [Buchholz and Konrad \(1994\)](#) also show that unilateral technology adoption might affect the outcome of international negotiations. If countries at a later stage bargain about emission reductions, the present unilateral actions change the cooperative outcome through their impact on the disagreement point, 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 \(1999\)](#).

similar emission trading systems in industrialized countries. Such a development would also lead to global trading in emission rights. Hence, in the paper we compare two situations: one case in which there is no emission trading between industrialized and developing countries, and one case in which there is such emission trading.

The paper is laid out as follows. In Sect. 2, we discuss investments in R&D, and present the model. Then, in Sect. 3, we solve the model in a setting without permit trading. Section 4 contains the main contribution of the paper, the results of our analysis of strategic R&D investments with permit trading. In Sect. 5, we provide a numerical illustration of our model. Section 6 contains some concluding remarks.

2 The Model

The model is a three-stage game between a group of industrialized countries and a developing country. The group of industrialized countries is referred to as the home region, or Region h , while 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, 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.

By allowing R&D investment to happen before emission targets are set, we have in mind a situation in which it is known that the developing country will not set any emission reduction target before some time has passed. This is precisely the position in many developing countries today. In the meantime the industrialized countries may invest in improving the technology levels for both themselves and the developing country. Such investments will be sunk, and hence given when targets are subsequently set.

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. Note that we do not include the decision to have a global permit market or not in the game. As shown by Helm (2003) it is very difficult to compare welfare levels with and without a common permit market in the general case. We therefore return to this question in the numerical example.

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 industrialized 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 industrialized 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 the term k_a *investments abroad*. Investments abroad comprise

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

efforts to improve advanced technology transfer, research on technological solutions that are particularly suited to developing countries, such as off-grid renewable electricity production, and institutional capacity building, for instance to implement more efficient means of reducing emissions through deforestation (for examples, see [UNFCCC 2009](#)).

In order to isolate the effect of the permit market, we assume that investment in k_h does not influence the technology level in developing countries, and *vice versa*. For some types of investment, this is probably not too far from reality. For instance, in order to benefit from R&D in advanced GHG abatement technologies, 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 industrialized countries.³

In order to make the analysis more tractable, we also make some simplifying assumptions. In the paper, the home government decides k_h and k_a directly. In many cases the government would instead decide k_h and k_a indirectly through R&D subsidies or taxes (or trade barriers to technology transfer). Modelling this explicitly should not change our results in any essential way, however. Finally, we assume that R&D of type k_a carried out by industrialized 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.⁴

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:

$$b_i = b_i(e_h + e_a), \quad i = h, a, \quad (1)$$

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 industrialized countries than in the developing country, that is, $b'_h > b'_a$, $\forall(e_h + e_a)$.

Each region has GHG abatement costs that are dependent on its level of emissions reductions and the relevant type of investments, which we express by the following general cost function: $c_i(e_i, k_i)$, $i = h, a$, where $\frac{\partial c_i}{\partial e_i} > 0$ and $\frac{\partial^2 c_i}{(\partial e_i)^2} > 0$. Furthermore, we have $\frac{\partial c_i}{\partial k_i} < 0$, $\frac{\partial^2 c_i}{(\partial k_i)^2} > 0$ and $\frac{\partial^2 c_i}{\partial k_i \partial e_i} < 0$. Thus, we follow the standard approach in the literature, assuming that R&D investments reduce marginal abatement costs.⁵ For short, we denote the derivatives of the cost function with respect to the emission reductions e_i by c'_i and c''_i .

³ In a supplementary paper to this paper we consider the case of knowledge spillovers between the two types of technology investments. Including the spillover has no qualitative effect on the results for the global permit trading case. The supplementary paper can be obtained from the authors upon request.

⁴ R&D of type k_a carried out by industrialized countries could also complement or be a substitute for 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. As long as the crowding out is less than 100 %, it should in principle be possible for the industrialized region to decide k_a through the use of technology export subsidies/restrictions.

⁵ Exceptions can be found in [Bauman et al. \(2008\)](#) and [Baker et al. \(2008\)](#). The latter provides 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.

Moreover, we denote the derivative of the cost function with respect to investment $\frac{\partial c_i}{\partial k_i}$ by c'_{ik} and the cross derivative $\frac{\partial^2 c_i}{\partial k_i \partial e_i}$ by c''_{iek} .

The cost of R&D is $p_i k_i$ where p_i is the price of one unit of R&D of type i . Finally, we assume that R&D investments are profitable from a cost-minimizing point of view, that is, $\arg \min_{k_i} [c_i(e_i, k_i) + p_i k_i]$ yields a positive k_i for $\forall e_i > 0$ and $i = h, a$.

3 Solving the Model Without Permit Trading

A model of strategic investment *without* permit trading is dealt with in [Stranlund \(1996\)](#), and we will only briefly go through this case here. As Region h may invest in both k_h and k_a , the welfare function for this region is given by:

$$\omega^h = b_h(e_h + e_a) - c_h(e_h, k_h) - p_h k_h - p_a k_a, \quad (2)$$

where we, for the industrialized region, have subtracted the cost of investments both at home and abroad.

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

$$\omega^a = b_a(e_h + e_a) - c_a(e_a, k_a). \quad (3)$$

When there is no permit trading 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 :

$$\max_{e_i} \omega^i = b_i(e_h + e_a) - c_i(e_i, k_i), \quad i = h, a. \quad (4)$$

The two first order conditions are:

$$b'_i - c'_i = 0, \quad i = h, a. \quad (5)$$

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 (5). Given that $c''_{iek} < 0$, it is easy to show formally that: $\frac{\partial e_h^N}{\partial k_i} > 0$ and $\frac{\partial e_j^N}{\partial k_i} < 0$, $i, j = h, a$, $i \neq j$. 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 the aim is to arrive at R&D strategies that make developing countries set tougher targets. For an investment in k_a it is the other way around.

3.2 Stage 1: Investments in Technologies

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:

$$\max_{k_h, k_a} \omega^h = b_h(e_h^N + e_a^N) - c_h(e_h^N, k_h) - p_h k_h - p_a k_a. \quad (6)$$

We find the following first order conditions for investment, given an interior solution:⁶

$$b'_h \frac{\partial e_a^N}{\partial k_h} - c'_{hk} = p_h, \quad (7)$$

$$b'_h \frac{\partial e_a^N}{\partial k_a} = p_a. \quad (8)$$

The term c'_{hk} 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 abroad ($\frac{\partial e_a^N}{\partial k_h}$ and $\frac{\partial e_a^N}{\partial k_a}$). Not considering the strategic effects, optimal investment at home implies $|c'_{hk}| = p_h$. Following [Tirole \(1988\)](#), we will call the situation with $|c'_{hk}| > p_h$ *underinvestment at home*, and a situation with $|c'_{hk}| < p_h$ *overinvestment at home*.⁷

Investment abroad only reduces foreign abatement costs. Hence, an investment abroad has no effect on the marginal saving in abatement costs. We therefore call the situation with $k_a > 0$ *overinvestment abroad*.⁸

From (7), we know that $|c'_{hk}| > p_h$ because the strategic effect of investments at home ($b'_h \frac{\partial e_a^N}{\partial k_h}$) is negative. It is therefore always profitable for Region h to underinvest in k_h . This can be accomplished for instance by taxing R&D in advanced technologies.⁹ Furthermore, from (7), since the strategic effect of investments abroad, $\frac{\partial e_a^N}{\partial k_a}$, is positive, Region h always benefits from overinvestment in k_a .¹⁰ Thus, it is motivated to subsidize technology transfer and institutional capacity building in the developing region although this does not directly benefit the industrialized region. The intuition behind these results is that, by underinvesting at home and overinvesting abroad, the industrialized countries induce the developing countries to set higher GHG emission reduction targets, which of course benefits the industrialized countries.

4 Solving the Model with Permit Trading

The permit market is assumed to be perfectly competitive. Because there is free trading in emission permits, a region can reach its emission reduction target both through abatement at home and through permit purchases. In a permit trading regime, a region's emission reductions generally differ from its emission reduction target. We therefore 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:

$$\bar{\omega}^h = b_h(\bar{e}_h + \bar{e}_a) - t[\bar{e}_h - e_h] - c_h(e_h, k_h) - p_h k_h - p_a k_a, \quad (9)$$

⁶ The first order conditions are found by differentiating (6) w.r.t k_h and k_a and inserting (5). It can be shown that the second order conditions for a welfare maximum are fulfilled.

⁷ [Tirole \(1988\)](#) defines overinvestment (underinvestment) as a higher (lower) level of investment than the level of investment in the hypothetical case without the strategic effect.

⁸ Without the strategic effect, the level of investment abroad would be zero. Moreover, underinvestment, i.e. $k_a < 0$, is not possible since k_a cannot be negative.

⁹ Note that with technology spillovers, this may no longer hold. See the supplementary paper, which can be obtained from the authors upon request.

¹⁰ Provided that $\lim_{k_a \rightarrow 0} \left[b'_h \frac{\partial e_a^N}{\partial k_a} \right] > p_a$ as assumed by [Stranlund \(1996\)](#).

whereas Region a 's welfare function is given by:

$$\tilde{\omega}^a = b_a(\bar{e}_h + \bar{e}_a) - t[\bar{e}_a - e_a] - c_a(e_a, k_a). \quad (10)$$

Note the second term on the right-hand side of (9), which does not appear in (4), and which is income from permit sales/spending on permit acquisitions.

4.1 Stage 3: Permit Trading

We start by looking at the global permit market and the emission reductions realized in the two regions. Given the emission reduction targets \bar{e}_h and \bar{e}_a , the 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:

$$e_h + e_a = \bar{e}_h + \bar{e}_a, \quad (11)$$

$$c'_i = t, \quad i = h, a, \quad (12)$$

where the first equation (11) states that the sum of emission reductions must be equal to the combined targets, and the last two equations (12) state that the marginal abatement cost must be equal to the permit price. All three variables are only dependent on the total emission reductions $\bar{e}_h + \bar{e}_a$, and not on the particular emission reduction target in each region. Thus, we can write $t = t(\bar{e}_h + \bar{e}_a, k_h, k_a)$, $e_h = e_h(\bar{e}_h + \bar{e}_a, k_h, k_a)$ and $e_a = e_a(\bar{e}_h + \bar{e}_a, k_h, k_a)$. By differentiating the three equations (11) and (12) we obtain:

$$\frac{\partial e_i}{\partial \bar{e}_i} = \frac{\partial e_i}{\partial \bar{e}_j} = \frac{c''_j}{c''_h + c''_a} > 0, \quad (13)$$

$$\frac{\partial t}{\partial \bar{e}_i} = \frac{\partial t}{\partial \bar{e}_j} = \frac{c''_h c''_a}{c''_h + c''_a} > 0, \quad (14)$$

Firstly, note that any increase in the total emission reduction target will lead both regions to abate more and the permit price will rise. Moreover, the effect is independent of which region tightens its target.

Secondly, note that the extent to which Region i will increase abatement more than Region j depends on the differences in the second order derivatives of the Regions' abatement cost functions. If the second order derivative of Region h 's abatement cost function is high, in comparison to that of Region a , ($c''_h > c''_a$), Region a will do most of the additional abatement ($\frac{\partial e_h}{\partial \bar{e}_i} < \frac{\partial e_a}{\partial \bar{e}_i}$), and *vice versa*.

Given $\bar{e}_h + \bar{e}_a$, any change in k_a or k_h will have a partial effect on the permit market equilibrium through its direct influence on the cost function. For instance, if k_i is increased and the marginal abatement cost of Region i decreases, Region i will wish to abate more. In such case the permit price must fall, and we reach a new equilibrium in which Region i abates more and Region j abates less. We have the following partial derivatives:

$$\frac{\partial e_i}{\partial k_i} = -\frac{\partial e_j}{\partial k_i} = -\frac{c''_{iek}}{c''_h + c''_a} > 0, \quad (15)$$

$$\frac{\partial t}{\partial k_i} = \frac{c''_j c''_{iek}}{c''_h + c''_a} < 0. \quad (16)$$

Clearly, a change in k_i will also affects the emission reduction targets \bar{e}_i , but we will return to that in the next section.

4.2 Stage 2: Setting Emission Reduction Targets

While the agents participating in the permit market take the permit price as given when deciding their level of abatement, the two regions take into account how the targets affect the permit price when setting the emission targets. The regions' optimization problems are given by:

$$\max_{\bar{e}_i} \bar{\omega}^i = b_i(\bar{e}_h + \bar{e}_a) - t[\bar{e}_i - e_i] - c_i(e_i, k_i), \quad i = h, a, \quad (17)$$

where $t = t(\bar{e}_h + \bar{e}_a, k_h, k_a)$ and $e_i = e_i(\bar{e}_h + \bar{e}_a, k_h, k_a)$. By using (12), we write the two first order conditions as follows:

$$b'_i - t - \frac{\partial t}{\partial \bar{e}_i} [\bar{e}_i - e_i] = 0, \quad i = h, a. \quad (18)$$

The best response functions (reaction functions) $\bar{e}_i(\bar{e}_j)$ are found from each of the equations in (18). The reaction functions express Region i 's optimal emission targets as a function of Region j 's emission target, for given k_h and k_a . 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 (18).¹¹

We see from the equations in (18) 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.¹² 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 (18) is negative. As noted by Helm (2003), whether a country becomes a net buyer or net seller depends on its benefit function alone. Given our assumptions concerning the regions' benefit functions, we can state the following lemma:

Lemma 1 *As $b'_h > b'_a$, Region h becomes a net buyer of permits, whereas Region a becomes a net seller of permits*

Proof Because $b'_h > b'_a$, $\forall(e_h + e_a)$ in our two country case, we must have that $b'_h - t > b'_a - t$. Hence, it follows from (18) that 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. \square

Contrary to the outcome without permit trading, the impact of investments on the Nash equilibrium emission targets are in general ambiguous in a setting with permit trading. Hence, we have the following proposition:

Proposition 2 *With permit trading, the signs of the strategic effects of investments could go both ways, that is, we may have $\frac{\partial \bar{e}_h^N}{\partial k_h} \geq 0$ and $\frac{\partial \bar{e}_a^N}{\partial k_a} \geq 0$.*

Proof See the numerical example in the section "Solution with global permit trading" of Appendix. \square

¹¹ We assume that the equilibrium is unique. In section "The uniqueness of the Nash-equilibrium in the permit trading case" of Appendix we show this is satisfied for $\frac{\partial^3 c_i}{(\partial e_i)^3} = 0$.

¹² Note that the permit price will equal the marginal cost of emission reductions in the permit trading equilibrium.

In the absence of permit trading, we know that the strategic effect of investment in k_h is unambiguously negative, and the strategic effect of investment in k_a is unambiguously positive. The reason is that increasing k_i reduces Region i 's marginal cost of abatement and leads to a tougher abatement target in Region i and thus, in response, a laxer abatement target in the other region.

With permit trading, investment in k_i reduces not only Region i 's marginal cost of abatement, but also the permit price. The reduced permit price makes it *cet. par.* less costly for *both* regions to set a tougher emission reduction target. This means that investment in k_i may lead to a positive shift in both regions' reaction functions (18), and we cannot in general tell whether investment in k_i leads to a new Nash equilibrium with a higher or lower abatement target abroad.

Although we cannot in general sign the strategic effect of investment, we are able to sign the impact on the two regions' joint emission target.

Proposition 3 *Investments both at home and abroad lead to a tougher total emission reduction target, that is, $\frac{\partial \bar{e}_h^N}{\partial k_i} + \frac{\partial \bar{e}_a^N}{\partial k_i} > 0$, $i = h, a$*

Proof See section "Proof of proposition 3" of Appendix. \square

4.3 Stage 1: Investments in Technologies

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 solves:

$$\max_{k_h, k_a} \bar{\omega}^h = b_h \left(\bar{e}_h^N + \bar{e}_a^N \right) - t \left[\bar{e}_h^N - e_h \right] - c_h(e_h, k_h) - p_h k_h - p_a k_a, \quad (19)$$

where $\bar{e}_h^N = \bar{e}_h^N(k_h, k_a)$ and $\bar{e}_a^N = \bar{e}_a^N(k_h, k_a)$ and $t = t(\bar{e}_h^N + \bar{e}_a^N, k_h, k_a)$ and $e_h = e_h(\bar{e}_h^N + \bar{e}_a^N, k_h, k_a)$. We assume that the second order conditions are satisfied.¹³ The optimal level of investment at home is given by:

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

which can be rearranged by using (13) and (18), and then written as:

$$t \frac{\partial \bar{e}_a^N}{\partial k_h} - \frac{\partial t}{\partial k_h} \left[\bar{e}_h^N - e_h \right] + |c'_{hk}| = p_h. \quad (20)$$

There are two effects that can 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 ambiguous strategic effect discussed in the previous subsection. 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. $\frac{\partial t}{\partial k_h} < 0$. We denote the term $-\frac{\partial t}{\partial k_i} [\bar{e}_h^N - e_h]$ the permit price effect of investment in k_i . As stated in lemma 1, Region h is a net buyer of permits ($[\bar{e}_h^N - e_h] > 0$), so that the permit price effect of investment in k_h is always positive and benefits Region h . Remember that, without permit trading, Region h never gains from overinvestment in k_h due to the unambiguously negative strategic effect of investments. With permit trading, this is changed. Overinvestment at home may become

¹³ For instance, this holds in our numerical example.

profitable because the permit market changes the strategic effect of investments, and because investments yield a positive income effect due to lower permit prices.

Proposition 4 *Region h benefits from overinvestment 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 positive permit price effect, i.e. $\left| t \frac{\partial \bar{e}_a^N}{\partial k_h} \right| < \left| \frac{\partial t}{\partial k_h} [\bar{e}_h^N - e_h] \right|$.

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

We now turn to the optimal choice of investment abroad. By inserting (18), we can write the first order condition for optimal investments abroad as follows:

$$\frac{\partial \bar{\omega}^h}{\partial k_a} = t \frac{\partial \bar{e}_a^N}{\partial k_a} - \frac{\partial t}{\partial k_a} [\bar{e}_h^N - e_h] - p_a = 0. \quad (21)$$

Without the strategic effect and the permit price effect, the level of investment abroad would be zero, i.e. $\frac{\partial \bar{\omega}^h}{\partial k_a} = -p_a < 0$. However, as above, the permit price effect $(-\frac{\partial t}{\partial k_a} [\bar{e}_h^N - e_h])$ is positive, as $\frac{\partial t}{\partial k_a} < 0$ and Region h is a net buyer of permits $([\bar{e}_h^N - e_h] > 0)$, whereas the strategic effect $(t \frac{\partial \bar{e}_a^N}{\partial k_a})$ is ambiguous.

Remember that, without permit trading, Region h always gains from overinvestment in k_a . With permit trading, this could still be true, as described in the following proposition:

Proposition 5 *Region h benefits from overinvestment abroad if:*

$$\lim_{k_a \rightarrow 0} \left[t \frac{\partial \bar{e}_a^N}{\partial k_a} - \frac{\partial t}{\partial k_a} [\bar{e}_h^N - e_h] \right] > p_a. \quad (22)$$

In order for k_a to be positive, the sum of the strategic effect and the permit price effect must be greater than the marginal cost of investment p_a for k_a close to zero. This is satisfied 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 the strategic effect is negative, but dominated by the permit price effect, i.e. $\left| t \frac{\partial \bar{e}_a^N}{\partial k_a} \right| < \left| \frac{\partial t}{\partial k_a} [\bar{e}_h^N - e_h] \right|$. However, we cannot rule out situations where the permit market makes it unprofitable for Region h to overinvest in Region a , that is (22) is not satisfied.

So far, we have just assumed that the industrialized region is able to invest any amount k_a in the developing region. Objections can be raised to this assumption, however, and it can be argued that the developing region will only allow investments that improve the welfare of the developing region. In this case we should look at the extent to which the developing region would benefit from the investment k_a . The welfare of the developing region is:

$$\bar{\omega}^a = b_a(\bar{e}_h^N + \bar{e}_a^N) - t [\bar{e}_a^N - e_a] - c_a(e_a, k_a)$$

The effect of foreign investment in k_a is then given by:

$$\frac{\partial \bar{\omega}^a}{\partial k_a} = t \frac{\partial \bar{e}_h^N}{\partial k_a} - \frac{\partial t}{\partial k_a} [\bar{e}_a^N - e_a] + c'_{ak} \quad (23)$$

Comparing (23) with (20) above, we note that the marginal cost of R&D investments p_a is missing since the developing region does not pay for the investment. The sign of first term in (23) is ambiguous as the sign of $\frac{\partial \bar{e}_h^N}{\partial k_a}$ is ambiguous (see Proposition 2). The next term is

negative; the developing region is a seller of emission permits, and, consequently, loses on a drop in the permit price. Lastly, the last term is positive since the developing region benefits from lower abatement costs.

The condition $\frac{\partial \bar{\omega}_a}{\partial k_a} = 0$ defines the maximum level k_a^* that the developing country will allow. In section “Proof of Proposition 6” of Appendix we prove the following proposition:

Proposition 6 *The maximum level of R&D investment k_a^* that the developing country will allow is always positive.*

Proof See section “Proof of Proposition 6” of Appendix. \square

If the solution to (21) is below k_a^* , the equilibrium levels of investments are given by (20) and (21). On the other hand, if the solution to (21) is above k_a^* , the equilibrium levels of investments are given by (20) and k_a^* . Even if the industrialized region is constrained to k_a^* decided by the developing region, the industrialized region would still invest up to that level. This follows from the concavity of the welfare expressions.

5 Numerical Example

In order to illustrate our findings, we have developed a numerical example (see section “The numerical example” of Appendix). We assume that the US, the EU and Japan cooperate and constitute the home region, while China is the “abroad” region. For the benefits of emission reductions we use the following functions: $b_h(\cdot) = \eta_0(\bar{e}_h + \bar{e}_a) - \frac{\eta_1}{2}(\bar{e}_h + \bar{e}_a)^2$ and $b_a(\cdot) = \alpha_0(\bar{e}_h + \bar{e}_a) - \frac{\alpha_1}{2}(\bar{e}_h + \bar{e}_a)^2$. When setting the value of η_0 and α_0 we draw on Carbone et al. (2009). Further, in our base case we assume that the marginal benefit of emission reductions is halved if global emissions are halved. This yields the values for η_1 and α_1 . Some papers suggest that η_1 and α_1 may be close to zero; see e.g. Pizer (2002). We therefore also include simulations in which this is the case.

Moreover, we use the following symmetric cost functions: $c_i(\cdot) = \frac{c_i}{2}(e_i)^2 - \sqrt{k_i}e_i$ with a price on k_i given by p_i , $i = h, a$. The parameters c_i are set by assuming that it costs 5 % of GDP to reduce region-specific business as usual emissions by 50 %. This is at the high end of most CGE studies on the topic (see e.g. Hoel et al. 2010). However, since the cost function is region-specific, one would expect higher costs than for the world as a whole. Furthermore, this cost figure is without R&D.

Clearly, setting the prices, p_h and p_a , of R&D in a meaningful way is very difficult. We have therefore chosen to run simulations with a range of prices of R&D that yields a total cost reduction between 30 and 15 % for both regions in the sub-game perfect equilibrium (with permit trading and optimal R&D investments).

In the figures below the price of R&D is given along the x-axis, while the level of R&D investments is given on the y-axis. Note that our numerical model is purely illustrative, and we do not pretend to predict real world effects of R&D investments and linking permit markets as Carbone et al. (2009) do.

Each set of R&D prices yields a sub-game perfect equilibrium. The black lines are the strategic levels of R&D investment, while the dashed lines are the non-strategic levels of R&D investment. Firstly, observe that we have overinvestment at home in the permit trading case, and underinvestment at home in the case without permit trading. Naturally, the levels of investment decline as R&D gets more costly.

In Fig. 2 we show the level of investments when the marginal benefits of emission reductions are constant.

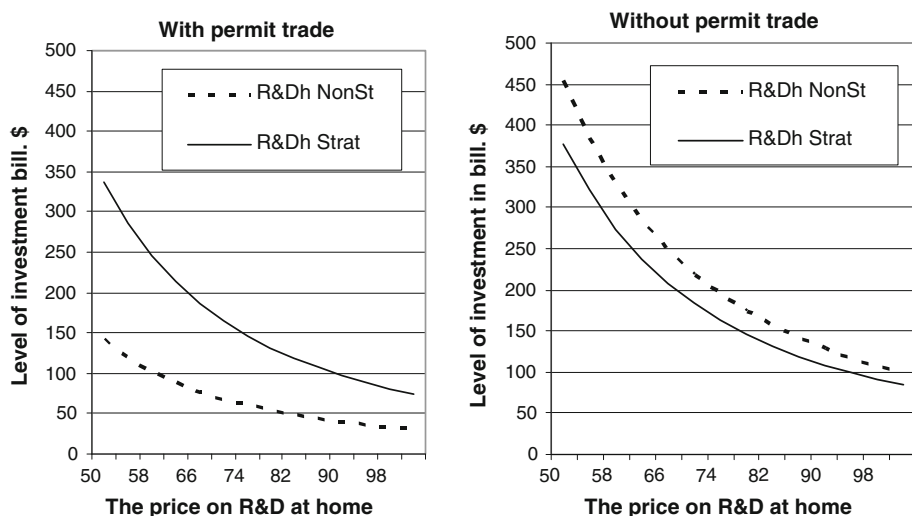


Fig. 1 The degree of overinvestment at home

First, note that there is still a strong incentive to overinvest at home with global permit trading. Investments still reduce the future permit price, which benefits the industrialized region. Second, note that the incentive to invest strategically disappears in the case without global permit trading. The strategic effect depends on α_1 being positive, and without a global permit market, there is no permit price effect. In fact, we can show that, with permit trading, the industrialized region is motivated to overinvest both at home and abroad, while in the case of no global permit trading, it will only invest strategically abroad.¹⁴

Finally, for both Figs. 1 and 2, note the big differences between the strategic and the non-strategic levels of R&D in the global permit trading case. This could be important for public R&D policy. The private sector will presumably only invest according to the non-strategic level.¹⁵ Then, if the government believes in future linked permit markets, it is motivated to support R&D in advanced abatement technology. In Fig. 1, when $p_h = 50$, the strategic level of investments at home amounts to nearly 1 % of GDP, and the non strategic level is about 0.35 % of GDP.

In the next figure we look at investments abroad. In addition to the level of k_a , we have also plotted the derivative $\frac{\partial W_a}{\partial k_a}$, e.g. the change in welfare in the developing region if the investment from the industrialized region is increased marginally (the dashed lines). We see that the derivative is positive for the optimal k_a . Moreover, in the numerical model, it is positive for all lower values of k_a , and hence, the developing region will accept the investment in k_a (it would actually like to have more investment).

The non-strategic level of investment abroad k_a , is zero. Observe that we have overinvestment both in the permit trading case and in the case without permit trading. In fact, the strategic levels of investment abroad are fairly similar in the two cases.

Note that in Fig. 3 the range for the price on R&D abroad p_a is different from the range for the price on R&D at home p_h in Figs. 1 and 2. Since costs are measured as a percentage

¹⁴ In the supplementary paper to this paper mentioned in Note 3, we also consider the case of $\eta_1 = \alpha_1 = 0$ analytically.

¹⁵ Note that this paper ignores technology spill-overs, which is another source of too little private investment (see further discussion in the next section).

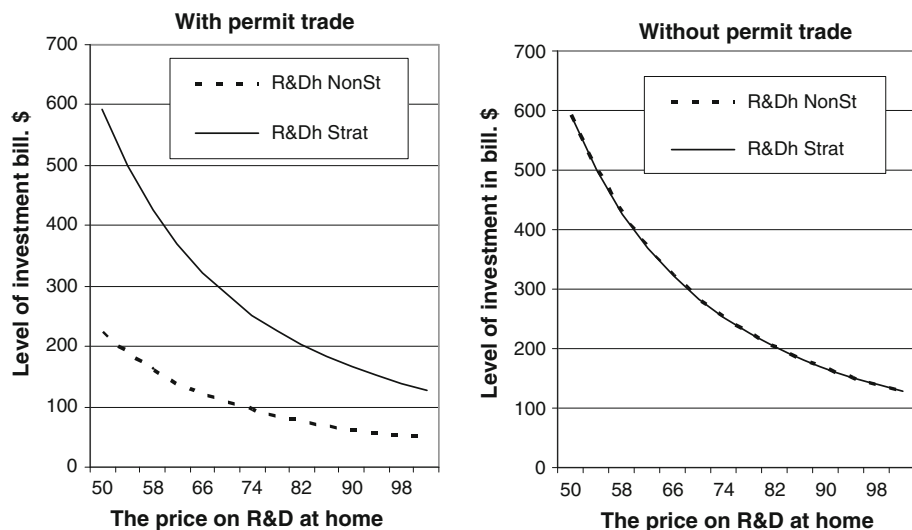


Fig. 2 The degree of overinvestment at home when $\eta_1 = a_1 = 0$

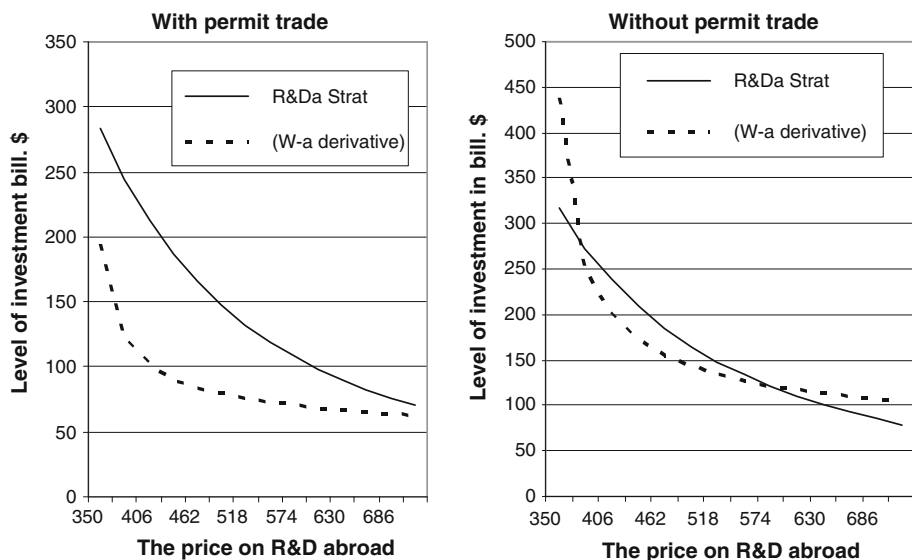


Fig. 3 The degree of overinvestment abroad

of GDP and the “abroad” region has lower GDP, p_a must be higher than p_h in order for the two regions to have approximately the same cost reduction opportunities.¹⁶

Would the industrialized region and the developing country agree to have a common permit market? The answer is clearly yes, in our simulations, welfare levels for both jurisdictions are far higher if a common permit market is established. The total emission reductions are also far higher. This is in line with [Carbone et al. \(2009\)](#). In particular, when R&D is at its

¹⁶ See the Appendix for further comments on the parameter choices.

lowest level, we obtain a 30 % reduction in world emissions with permit trading, and a 20 % reduction without permit trading.

6 Discussion and Conclusion

The main message of our paper is that permit trading changes the strategic effects of investments, and permit trading could make it desirable for industrialized countries to overinvest both at home and abroad. Moreover, we show that the developing region receiving part of the investments will benefit from them. In a way, the permit market provides another type of “spillover”. That is, even if the developing region does not set a tougher emission reduction target as a result of a k_h investment, the industrialized region could still benefit from over-investing. The reason is that it lowers the price of emission permits that the region will need in the future.

In our model, the government directly decides the amount of both types of R&D in GHG abatement technologies. This is a simplification, of course, as a large part of the yearly R&D expenditures on these technologies is 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 kinds.

It is generally acknowledged that only 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 today can result in a more beneficial allocation of GHG emission reductions tomorrow. In general, 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 continue to trade emission rights with each other in the future, 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 so, we need better estimates of future region-specific abatement costs and the effects of R&D investments. In our opinion, this is an interesting future avenue of research.

We have not modelled the decision whether or not to have a global permit market. It is possible to 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. Given both the investments and the targets, both regions would benefit from trading, and by backwards induction, we conjecture that 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 it could make a global permit market conditional on a more ambitious global agreement. However, such commitments might not be credible. A global permit trading regime, as analyzed in this paper, is therefore a realistic scenario.

Acknowledgments Valuable comments by Erling Holmøy, Jon Hovi, Nils-Henrik M. von der Fehr and two anonymous referees are gratefully acknowledged. The financial support of the Norwegian Research Council is also highly appreciated.

Appendix 1: The Uniqueness of the Nash-Equilibrium in the Permit Trading Case

We have assumed that the Nash equilibrium following from (18) is unique. In this Appendix, we show that this is satisfied for $\frac{\partial^3 c_i}{(\partial e_i)^3} = 0$. For simplicity, we write the second order derivatives of the welfare function in the permit trading case as follows: $\frac{\partial^2 \bar{\omega}^i}{\partial \bar{e}_i \partial \bar{e}_i} = \bar{\omega}_{ii}^i$, $\frac{\partial^2 \bar{\omega}^j}{\partial \bar{e}_i \partial \bar{e}_j} = \bar{\omega}_{ij}^i$, $i, j = h, a$, $i \neq j$. The derivatives are given by:

$$\bar{\omega}_{ii}^i = b_i'' - 2 \frac{\partial t}{\partial \bar{e}_i} + \frac{\partial t}{\partial \bar{e}_i} \frac{\partial e_i}{\partial \bar{e}_i} - \frac{\partial^2 t}{(\partial \bar{e}_i)^2} [\bar{e}_i - e_i^*], \quad (24)$$

$$\bar{\omega}_{ij}^i = b_i'' - \frac{\partial t}{\partial \bar{e}_j} + \frac{\partial t}{\partial \bar{e}_i} \frac{\partial e_i}{\partial \bar{e}_j} - \frac{\partial^2 t}{\partial \bar{e}_i \partial \bar{e}_j} [\bar{e}_i - e_i^*]. \quad (25)$$

The second-order conditions of the regions' optimization problems demand that $\bar{\omega}_{ii}^i < 0$. A sufficient condition for uniqueness is that the reaction functions are downward sloping with an absolute value of the slope less than one (Tirole 1988, chapter 5.4). The slope of the reaction function is given by $-\frac{\bar{\omega}_{ij}^i}{\bar{\omega}_{ii}^i}$. The sufficient condition for uniqueness is thus satisfied for $\bar{\omega}_{ij}^i < 0$ and $|\bar{\omega}_{ii}^i| > |\bar{\omega}_{ij}^i|$.

Note that the derivative $\frac{\partial t}{\partial \bar{e}_i}$ equals $\frac{\partial t}{\partial \bar{e}_j}$, $\frac{\partial^2 t}{(\partial \bar{e}_i)^2}$ equals $\frac{\partial^2 t}{\partial \bar{e}_i \partial \bar{e}_j}$, and $\frac{\partial e_i}{\partial \bar{e}_i}$ equals $\frac{\partial e_i}{\partial \bar{e}_j}$. Hence, for $\bar{\omega}_{ii}^i, \bar{\omega}_{ij}^i < 0$, we must have $|\bar{\omega}_{ii}^i| > |\bar{\omega}_{ij}^i|$. $\frac{\partial^2 t}{(\partial \bar{e}_i)^2}$ is equal to zero when $\frac{\partial^3 c_i}{(\partial e_i)^3} = 0$. Then, since $b_i'' < 0$, $\frac{\partial t}{\partial \bar{e}_i} = \frac{\partial t}{\partial \bar{e}_j} > 0$ and $\frac{\partial e_i}{\partial \bar{e}_i} = \frac{\partial e_i}{\partial \bar{e}_j} \in (0, 1)$, we have $\bar{\omega}_{ii}^i, \bar{\omega}_{ij}^i < 0$ for $\frac{\partial^3 c_i}{(\partial e_i)^3} = 0$, and equilibrium is unique.

Appendix 2: The Numerical Example

Benefits and Costs

The benefits of emission reduction targets are given by:

$$b_h(\cdot) = \eta_0(\bar{e}_h + \bar{e}_a) - \frac{\eta_1}{2}(\bar{e}_h + \bar{e}_a)^2,$$

$$b_a(\cdot) = \alpha_0(\bar{e}_h + \bar{e}_a) - \frac{\alpha_1}{2}(\bar{e}_h + \bar{e}_a)^2.$$

While the costs of emission reductions are given by:

$$c_h(\cdot) = \frac{c_h}{2}(e_h)^2 - \sqrt{k_h}e_h,$$

$$c_a(\cdot) = \frac{c_a}{2}(e_a)^2 - \sqrt{k_a}e_a.$$

The level of investment k_i is bounded such that $c_i e_i > 2\sqrt{k_i}$. The derivative of the cost function with respect to k_i can then be written:

$$\frac{\partial c_i(\cdot)}{\partial k_i} = \frac{-e_i}{2\sqrt{k_i}}$$

For investments at home we have overinvestment if $\frac{e_h}{2\sqrt{k_h}} < p_h$, while for investments abroad we have overinvestment if $k_a > 0$.

Parameter Values

The parameters in the benefit functions originate partly from [Carbone et al. \(2009\)](#). The initial emissions reduction for the home region is valued as 219 \$/ton CO₂, which is a GDP weighted average of the numbers given in [Carbone et al. \(2009\)](#) for the three countries: the US, EU and Japan. Moreover, we assume that the marginal benefit of emission reductions is halved if world emissions are halved. Hence, we have $\eta_0 = 219$ and $\eta_1 = 0.0049$. Following the same procedure for China, we obtain $\alpha_0 = 50$ and $\alpha_1 = 0.0011$.

The parameters c_i are set by assuming that it costs 5 % of GDP to reduce region specific business as usual emissions by 50 %. This yields $c_h = 0.1$ and $c_a = 0.014$. For the GDP figures we have used IMF World Economic Outlook year 2016 predictions (<http://www.imf.org/external/pubs/ft/weo/2011/02/weodata/index.aspx>). For the CO₂ emissions we have used CDIAC 2008 figures (<http://cdiac.ornl.gov/>). These are projected to 2016 by assuming the same emissions/GDP ratio in 2016 as in 2008.

Finally, for the prices of R&D we have $p_h \in [50, 102]$ and $p_h = p_a/7$. This yields a cost reduction in the range 30–15 % for both regions in the sub-game perfect equilibrium with investments never amounting to more than 1.3 % of GDP in total ($k_h + k_a$), which to us seems reasonable. Note that with $p_a = p_h$, we would see cost reductions in the developing country far in excess of 30 % in the sub-game perfect equilibrium. This would not change the results qualitatively, but in the example we prefer to have similar cost reduction opportunities.

Solution Without Permit Trading

Welfare in Stage 2 can be expressed as follows:

$$\begin{aligned} W_h &= \eta_0(\bar{e}_h + \bar{e}_a) - \frac{\eta_1}{2}(\bar{e}_h + \bar{e}_a)^2 - \frac{c_h}{2}(e_h)^2 + \sqrt{k_h}e_h, \\ W_a &= \alpha_0(\bar{e}_h + \bar{e}_a) - \frac{\alpha_1}{2}(\bar{e}_h + \bar{e}_a)^2 - \frac{c_a}{2}(e_a)^2 + \sqrt{k_a}e_a, \end{aligned}$$

where $\bar{e}_h = e_h$ and $\bar{e}_a = e_a$.

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

$$\begin{aligned} \eta_0 - \eta_1(\bar{e}_h + \bar{e}_a) - c_h\bar{e}_h + \sqrt{k_h} &= 0 \\ \alpha_0 - \alpha_1(\bar{e}_h + \bar{e}_a) - c_a\bar{e}_a + \sqrt{k_a} &= 0 \end{aligned}$$

$$\bar{e}_h = \frac{\eta_0 + \sqrt{k_h} - \eta_1\bar{e}_a}{\eta_1 + c_h}, \quad \bar{e}_a = \frac{\alpha_0 + \sqrt{k_a} - \alpha_1\bar{e}_h}{\alpha_1 + c_a}.$$

These are then plotted for values of k_i such that $c_i =$ and $c_i =$, $i = h, a$. We can also find the equilibrium values of \bar{e}_h and \bar{e}_a :

$$\bar{e}_h^N = \frac{\alpha_1 \eta_0 - \alpha_0 \eta_1 + \eta_0 c_a + (\alpha_1 + c_a) \sqrt{k_h} - \eta_1 \sqrt{k_a}}{\eta_1 c_a + \alpha_1 c_h + c_a c_h}$$

$$\bar{e}_a^N = \frac{\alpha_0 \eta_1 - \alpha_1 \eta_0 + \alpha_0 c_h + (\eta_1 + c_h) \sqrt{k_a} - \alpha_1 \sqrt{k_h}}{\eta_1 c_a + \alpha_1 c_h + c_a c_h}$$

In order to find the equilibrium values of k_h and k_a we solve the following optimizing problem numerically:

$$\max_{k_h, k_a} \left\{ \eta_0 (\bar{e}_h^N + \bar{e}_a^N) - \frac{\eta_1}{2} (\bar{e}_h^N + \bar{e}_a^N)^2 - \frac{c_h}{2} (\bar{e}_h^N)^2 + \sqrt{k_h} \bar{e}_h^N - p_h k_h - p_a k_a \right\}$$

The results are reported in the text. For the derivative $\frac{\partial W_a}{\partial k_a}$ we have:

$$\frac{\partial W_a}{\partial k_a} = -\frac{\alpha_0 - \alpha_1 (\bar{e}_h + \bar{e}_a)}{2\sqrt{k_a}} \frac{\eta_1}{\eta_1 c_a + \alpha_1 c_h + c_a c_h} + \frac{\bar{e}_a}{2\sqrt{k_a}}$$

which can be plotted.

Solution with Global 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:

$$e_h = \frac{(\bar{e}_a + \bar{e}_h) c_a - \sqrt{k_a} + \sqrt{k_h}}{c_a + c_h}, \quad e_a = \frac{(\bar{e}_a + \bar{e}_h) c_h + \sqrt{k_a} - \sqrt{k_h}}{c_a + c_h},$$

$$t = \frac{(\bar{e}_a + \bar{e}_h) c_h c_a - c_a \sqrt{k_h} - c_h \sqrt{k_a}}{c_a + c_h}.$$

Welfare in Stage 2 can be expressed as follows:

$$W_h = \eta_0 (\bar{e}_h + \bar{e}_a) - \frac{\eta_1}{2} (\bar{e}_h + \bar{e}_a)^2 - t [\bar{e}_h - e_h] - \frac{c_h}{2} (e_h)^2 + \sqrt{k_h} e_h,$$

$$W_a = \alpha_0 (\bar{e}_h + \bar{e}_a) - \frac{\alpha_1}{2} (\bar{e}_h + \bar{e}_a)^2 - t [\bar{e}_a - e_a] - \frac{c_a}{2} (e_a)^2 + \sqrt{k_a} e_a.$$

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

$$\eta_0 - \eta_1 (\bar{e}_h + \bar{e}_a) - \frac{\partial t}{\partial \bar{e}_h} [\bar{e}_h - e_h] - t = 0,$$

$$\alpha_0 - \alpha_1 (\bar{e}_h + \bar{e}_a) - \frac{\partial t}{\partial \bar{e}_a} [\bar{e}_a - e_a] - t = 0,$$

which by inserting for e_i , t and $\frac{\partial t}{\partial \bar{e}_i}$ yields the reaction functions. We can then find the Nash-equilibrium values of \bar{e}_h and \bar{e}_a :

$$\bar{e}_h^N = \frac{\theta_h + c_a (2c_a c_h + 2\alpha_1 c_h + \alpha_1 c_a - \eta_1 c_a) \sqrt{k_h} + c_h (\alpha_1 c_h - \eta_1 c_h - 2\eta_1 c_a) \sqrt{k_a}}{\varphi}$$

$$\bar{e}_a^N = \frac{\theta_a + c_a (\eta_1 c_a - \alpha_1 c_a - 2\alpha_1 c_h) \sqrt{k_h} + c_h (2c_a c_h + 2\eta_1 c_a + \eta_1 c_h - \alpha_1 c_h) \sqrt{k_a}}{\varphi}$$

where $\theta_h = (2\eta_0 c_a + \eta_0 c_h - \alpha_0 c_h) c_a c_h - (\alpha_0 \eta_1 - \alpha_1 \eta_0) [(c_a)^2 + (c_h)^2 + 2c_a c_h]$ and $\theta_a = (2\alpha_0 c_h + \alpha_0 c_a - \eta_0 c_a) c_a c_h + (\alpha_0 \eta_1 - \alpha_1 \eta_0) [(c_a)^2 + (c_h)^2 + 2c_a c_h]$ and $\varphi = [2c_a c_h + (\alpha_1 + \eta_1)(c_h + c_a)] c_a c_h$.

In order to show that the effects of investments k_h and k_a are ambiguous, we use $c_h = c_a = c$. We then have:

$$\begin{aligned} \text{sign} \left[\frac{d\bar{e}_h^N}{dk_a} \right] &= \text{sign} [\alpha_1 - 3\eta_1] \\ \text{sign} \left[\frac{d\bar{e}_h^N}{dk_h} \right] &= \text{sign} [2c + 3\alpha_1 - \eta_1] \\ \text{sign} \left[\frac{d\bar{e}_a^N}{dk_a} \right] &= \text{sign} [2c + 3\eta_1 - \alpha_1] \\ \text{sign} \left[\frac{d\bar{e}_a^N}{dk_h} \right] &= \text{sign} [\eta_1 - 3\alpha_1] \end{aligned}$$

Note that all signs depend on the parameters of the benefit functions α_1 and η_1 .

In order to find the equilibrium values of k_h and k_a and the degree of overinvestment we solve the following optimization problem numerically:

$$\max_{k_h, k_a} \left\{ \eta_0 (\bar{e}_h^N + \bar{e}_a^N) - \frac{\eta_1}{2} (\bar{e}_h^N + \bar{e}_a^N)^2 + t(e_h - \bar{e}_h^N) - \frac{c_h}{2} (e_h)^2 + \sqrt{k_h} e_h - p_h k_h - p_a k_a \right\}.$$

The results are reported in the text. For the derivative $\frac{\partial W_a}{\partial k_a}$ in the with global permit trading case we have:

$$\frac{\partial W_a}{\partial k_a} = \frac{1}{2\sqrt{k_a}} \left[\frac{c_h (\alpha_1 c_h - \eta_1 c_h - 2\eta_1 c_a) [\alpha_0 - \alpha_1 (\bar{e}_h + \bar{e}_a)]}{[2c_a c_h + (\alpha_1 + \eta_1)(c_h + c_a)] c_a c_h} + \frac{(\bar{e}_a - e_a) c_h}{c_a + c_h} + e_a \right]$$

which can be plotted.

Appendix 3: Proof of Proposition 3

In this Appendix we prove that $\frac{d\bar{e}_h^N}{dk_i} + \frac{d\bar{e}_a^N}{dk_i} > 0$. By totally differentiating the two equations (18), we obtain the effects of k_h and k_a as follows:

$$\frac{\partial \bar{e}_h^N}{\partial k_h} = \frac{[\bar{\omega}_{ha}^h \bar{\omega}_{ak_h}^a - \bar{\omega}_{aa}^a \bar{\omega}_{hk_h}^h]}{D}, \quad (26)$$

$$\frac{\partial \bar{e}_a^N}{\partial k_h} = \frac{[\bar{\omega}_{ah}^a \bar{\omega}_{hk_h}^h - \bar{\omega}_{hh}^h \bar{\omega}_{ak_h}^a]}{D}, \quad (27)$$

$$\frac{\partial \bar{e}_h^N}{\partial k_a} = \frac{[\bar{\omega}_{ha}^h \bar{\omega}_{ak_a}^a - \bar{\omega}_{aa}^a \bar{\omega}_{hk_a}^h]}{D}, \quad (28)$$

$$\frac{\partial \bar{e}_a^N}{\partial k_a} = \frac{[\bar{\omega}_{ah}^a \bar{\omega}_{hk_a}^h - \bar{\omega}_{hh}^h \bar{\omega}_{ak_a}^a]}{D}, \quad (29)$$

where ω_{ii}^i and ω_{ij}^i are given by (24) and (25), respectively, and

$$\bar{\omega}_{ik_i}^i = -\frac{\partial t}{\partial k_i} + \frac{\partial t}{\partial \bar{e}_i} \frac{\partial e_i}{\partial k_i} - \frac{\partial^2 t}{\partial k_i \partial \bar{e}_i} [\bar{e}_i - e_i], \quad (30)$$

$$\bar{\omega}_{ik_j}^i = -\frac{\partial t}{\partial k_j} + \frac{\partial t}{\partial \bar{e}_i} \frac{\partial e_i}{\partial k_j} - \frac{\partial^2 t}{\partial k_j \partial \bar{e}_i} [\bar{e}_i - e_i^*], \quad (31)$$

$$D = \bar{\omega}_{ii}^i \bar{\omega}_{jj}^j - \bar{\omega}_{ij}^i \bar{\omega}_{ji}^j > 0$$

(see section “The uniqueness of the Nash-equilibrium in the permit trading case” of Appendix)

By using (26)–(29) above we have:

$$\frac{\partial \bar{e}_h^N}{\partial k_i} + \frac{\partial \bar{e}_a^N}{\partial k_i} = \frac{[\bar{\omega}_{ah}^a - \bar{\omega}_{aa}^a] \bar{\omega}_{hk_i}^h + [\bar{\omega}_{ha}^h - \bar{\omega}_{hh}^h] \bar{\omega}_{ak_i}^a}{D}$$

The terms in the brackets are positive as $\bar{\omega}_{ii}^i, \bar{\omega}_{ij}^i < 0$ and $|\bar{\omega}_{ii}^i| > |\bar{\omega}_{ij}^i|$. Moreover, we also see from (24) and (25) that $[\bar{\omega}_{ah}^a - \bar{\omega}_{aa}^a] = [\bar{\omega}_{ha}^h - \bar{\omega}_{hh}^h]$. Furthermore, the two first terms on the right-hand side of (30) are positive, and it can be shown that the sum of the two first terms on the right-hand side of (31) is positive.¹⁷ Since $[\bar{e}_h - e_h^*] = -[\bar{e}_a - e_a^*]$, then $\bar{\omega}_{hk_i}^h + \bar{\omega}_{ak_i}^a > 0$, which implies that $\frac{\partial \bar{e}_h^N}{\partial k_a} + \frac{\partial \bar{e}_a^N}{\partial k_a} > 0$, and $\frac{\partial \bar{e}_h^N}{\partial k_h} + \frac{\partial \bar{e}_a^N}{\partial k_h} > 0$.

Appendix 4: Proof of Proposition 6

The derivative $\frac{\partial \bar{\omega}^a}{\partial k_a}$, given by (23), can be rearranged by using (21) and that $-\left[\bar{e}_a^N - e_a\right] = [\bar{e}_h^N - e_h]$:

$$\frac{\partial \bar{\omega}^a}{\partial k_a} = t \left[\frac{\partial \bar{e}_h^N}{\partial k_a} + \frac{\partial \bar{e}_a^N}{\partial k_a} \right] + |c'_{ak}| - p_a$$

We know from section “Proof of proposition 3” of Appendix that the sum of the terms in the bracket is positive. Hence, the condition $|c'_{ak}| \geq p_a$ is sufficient for $\frac{\partial \bar{\omega}^a}{\partial k_a} \geq 0$, but not necessary. Since some R&D investment is profitable from a cost minimizing point of view, the equation $|c'_{ak}| = p_a$ yields a positive k_a . Thus, k_a^* must be positive.

References

- Baker E, Clarke L, Shittu E (2008) Technical change and the marginal cost of abatement. *Energy Econ* 30(6):2799–2816
- Barrett S (1999) A theory of full international cooperation. *J Theor Polit* 11(4):519–541
- Bauman Y, Lee M, Seeley K (2008) Does technological innovation really reduce marginal abatement costs? Some theory, algebraic evidence, and policy implications. *Environ Resour Econ* 40(4):507–527
- Buchholz W, Konrad KA (1994) Global environmental problems and the strategic choice of technology. *J Econ* (Springer Science & Business, Media B.V.) 60:299–321
- Carbone JC, Helm C, Rutherford TF (2009) The case for international emission trade in the absence of cooperative climate policy. *J Environ Econ Manag* 58(3):266–280

¹⁷ We have $-\frac{\partial t^*}{\partial k_j} + \frac{\partial t^*}{\partial \bar{e}_i} \frac{\partial e_i^*}{\partial k_j} = -c''_{iek} \left(\frac{c''_j}{c''_h + c''_a} \right)^2 > 0$.

- Chander P, Tulkens H (1995) A core-theoretic solution for the design of cooperative agreements on transfrontier pollution. *Int Tax Public Financ* 2(2):279–293
- Cohen WM, Levinthal DA (1989) Innovation and learning: the two faces of R&D. *Econ J* 99(397):569–596
- Copenhagen Accord (2009) <http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf>
- Finus M (2003) Stability and design of international environmental agreements: the case of transboundary pollution. In: Folmer H, Tietenberg T (eds) *International yearbook of environmental and resource economics* 2003/4. Edward Elgar, Cheltenham, UK, Chap 3, pp 82–158
- Gersbach H, Winkler R (2011) International emission permit markets with refunding”. *Eur Econ Rev* 55(6):759–773
- Golombek R, Hoel M (2004) Unilateral emission reductions and cross-country technology spill-overs. *Adv Econ Anal Policy* 4(2): Article 3
- Goulder LH, Mathai K (2000) Optimal CO₂ abatement in the presence of induced technological change. *J Environ Econ Manag* 39(1):1–38
- Helm C (2003) International emissions trading with endogenous allowance choices. *J Public Econ* 87(12):2737–2747
- Hoel M (1991) Global environmental problems: the effects of unilateral actions taken by one country. *J Environ Econ Manag* 20(1):55
- Hoffert MI, Caldeira K, Benford G, Criswell DR, Green C, Herzog H, Jain AK, Kheshgi HS, Lackner KS, Lewis JS, Lightfoot HD, Manheimer W, Mankins JC, Mauel ME, Perkins LJ, Schlesinger ME, Volk T, Wigley TML (2002) Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* 298(5595):981–987
- Pizer WA (2002) Combining price and quantity controls to mitigate global climate change. *J Public Econ* 85:409–434
- Rosendahl KE, Strand J (2009) Simple model frameworks for explaining inefficiency of the clean development mechanism. Policy Research Working Paper 4931, The World Bank
- Schneider L (2009) Assessing the additionality of CDM projects: practical experiences and lessons learned. *Clim Policy* 9:242–254
- Stranlund JK (1996) On the strategic potential of technological aid in international environmental relations. *J Econ (Springer Science & Business, Media B.V.)* 64:1–22
- Stranlund JK (1999) Sunk capital and negotiated resolutions of environmental conflicts. *Land Econ Univ Wisconsin Press* 75:142–155
- Tirole J (1988) *The theory of industrial organisation*. The MIT Press, Massachusetts, Cambridge
- UNFCCC (2009) Expert group on technology transfer—five years of work. <http://unfccc.int/2860.php>
- Wara M (2007) Is the global carbon market working? *Nature* 445(7128):595–596