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Abstract

In this paper, we analyze technology transfers (TT) and tradable emission rights, which are core issues of the ongoing climate negotiations. Subsidizing TT leads to the adoption of better abatement technologies in developing countries, thereby reducing the international permit price. This is beneficial for industrialized countries as long as they are permit buyers, and as long as they can target subsidies to "additional" investments. We also consider how TT affects countries' non-cooperative choices of permit endowments and find that it reduces overall emissions. Finally, a simple numerical simulation model illustrates some results and explores some further comparative statics.

Keywords: emissions trading, technology transfer, international climate policy.

JEL-classification: D62, D78, H41, O38, Q58

1 Introduction

The "Cancun Agreements", which were signed at the UN Climate Change Conference in December 2010, highlighted technology transfers (TT) as a central element of international climate policies. In particular, governments decided to establish a "Technology Mechanism" which is expected to enhance technology development and transfer. Moreover, industrialized countries made substantial financial pledges, committing themselves to providing funds amounting to USD 100 billion per year by 2020 to support concrete mitigation actions

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by developing countries.[1] In this paper, we analyze the incentives of industrialized countries to finance TT, and the incentives of developing countries to enhance their abatement technologies. Our focus is on the interaction between abatement technologies and an international system of tradable emission rights. Moreover, we examine how TT affect countries' choices of greenhouse gas emission targets.

Within the context of climate change, new technologies that improve energy efficiency and advance alternative ways of energy production play a central role. For example, (Levinson, 2009) finds that from 1987 to 2001 manufacturing output in the US grew by 24%, while emissions decreased by 25%. According to his empirical study, technology accounted for the majority of this improvement. Similar changes took place in Europe and Asia.[2] Although there has also been substantial progress in developing countries, their CO_2 emissions intensity is still higher. For example, using the standardized measure of emission intensity (measured in kg of CO_2 per PPP $ of GDP) China exhibits a ratio of 0.88, while the US has only 0.41. Looking at aggregate data, the ratio equals 0.34 for high income countries (World Bank classification) and 0.57 for low and middle-income countries together (Mundial, 2011).

These figures show that there is not only a need for R&D of new technologies, but also for a better transfer of such technologies to developing countries. Without specific measures this process is often very slow. For example, Comin and Hobija (2010) show that, on average, countries have adopted technologies 45 years after their invention.[3] Similarly, using patent data Dechezleprêtre et al. (2011) find that innovation of low-carbon technologies in Japan, Germany and the USA accounts for 60% of global inventions. Moreover, they estimate that 73% of all exports of climate-mitigation innovation occur between OECD countries, while only 22% go to non-OECD countries.

The Intergovernmental Panel on Climate Change (IPCC) defines technology transfer as "a broad set of processes covering the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders" (Metz et al., 2007, 158). For modeling purposes, we have to adopt a more narrow perspective and focus on subsidies as the most obvious candidate for measures aimed at international TT (Hoekman et al., 2005). Our focus on permit trading reflects that establishing a price on CO_2 emissions is often seen as "the single most important policy for encouraging the innovation that might bring about advanced technology development"

[1]See, e.g., http://cancun.unfccc.int.

[2]See King (2004) for similar results for the UK and China.

[3]In their paper, the authors consider a sample of 15 technologies, spanning the period from 1820 to 2003.

(Aldy et al., 2010, 25). The authors also note that cap-and-trade systems are more popular than taxes and, therefore, an international application might be easier to implement.

We consider a model with two regions, sometimes referred to as industrialized countries ("North") and developing countries ("South"). This restriction is often used in the literature that considers asymmetric games of international cooperation so as to keep the analysis tractable (see, e.g., Barrett, 2001). We begin by analyzing a scenario in which the initial permit endowments are exogenously given. Therefore, subsidies have no effect on climate change damages, which allows us to focus on strategic considerations related to the permit market. In the first stage of the game, the North chooses the subsidy level that is paid per unit of technologies that reduce abatement costs in the South. In the second stage, firms in the South decide on the level of abatement technologies that they want to adopt. In the third stage, firms trade their initial permit endowments on a competitive international permit market.

Subsidies reduce the price of abatement technologies; hence firms in the South will choose a higher adoption level. This lowers the costs of abatement, leading to more emission reductions in the South and a lower permit price. Hence, if the North is a permit buyer, it benefits because it can substitute its own expensive emission reductions by the purchase of cheaper permits. This is the main motive for subsidizing TT in our paper.

Obviously, the North will want to restrict subsidies to those technology investments that would not have taken place without subsidies. This resembles the additionality problem in the context of the Clean Development Mechanism (CDM), where certified emission reduction units (CERs) are gained only for "reductions in emissions that are additional to any that would occur in the absence of the certified project activity" (Kyoto Protocol, Article 12(5c)). However, in both cases the determination of additionality is difficult because it requires knowing the business-as-usual scenario, which is only a counterfactual. Indeed, some studies on CDM projects cast doubt on the additionality of the emission reductions for which CERs have been obtained.[4] In our model we take this into account by allowing for different degrees of additionality. If the North is a permit buyer and if it is able to restrict subsidies to "additional" investments, then it will always choose a positive subsidy level. Moreover, if

[4]For example, Zhang and Wang (2011) utilize the relationship that CO_2 and SO_2 are co-pollutants of fossil-fuel combustion to indirectly assess additionality of the CDM. For China, the largest recipient of CDM projects, their econometric estimates suggest that certified emission reductions would have happened anyway. Similarly, Schneider (2009) evaluates 93 registered CDM projects and concludes that there is still need for substantial improvement in the tools for demonstrating additionality.

the South is a permit seller, it will always choose a higher level of technology adoption than in a regime without permit trading. Thus, permit trading tends to strengthen incentives in the North to transfer technologies as well as incentives in the South to adopt them.

However, permit trading fundamentally changes countries incentives when they choose their level of emission rights (Helm, 2003).[5] Therefore, we also consider the scenario where permit endowments are endogenous. In particular, at stage one of the game both regions now simultaneously choose their permit endowments. We then analyze how the possibility of subsidizing TT affects the regions's endowment choices. Our results suggest that, in general, technology transfers will induce countries to choose less permit endowments, thereby reducing total emissions. The reason is that subsidies lead to the adoption of better technologies, which makes abatement cheaper.

Some other papers have analyzed the incentives of industrialized countries to transfer advanced abatement technologies to developing countries. Using the RICE model, Yang (1999) and Yang and Nordhaus (2006) have focused on the associated environmental benefits. In particular, unilateral TT reduce abatement costs in the South, which, therefore, chooses more abatement. Thus the level of externality flows from the South is reduced.

Greaker and Hagem (2010) analyze the effects of permit trading on the incentives to invest in climate-friendly technologies, which is also a crucial element in our paper. However, there are substantial differences. In Greaker and Hagem (2010), industrialized countries invest in abatement technologies "at home" and in developing countries. Thereafter, the regions choose their permit endowments, which are then traded on an international permit market. In our paper the industrialized countries do not invest themselves, but subsidize the investments of private firms. These firms do not account for the environmental effects of their investment decisions, hence their objective function differs from that of their governments. Moreover, firms in developing countries can invest in abatement technologies even without subsidies. This leads to the problem of "additionality" because industrialized countries want to restrict their subsidies to additional investments. This problem does not arise in Greaker and Hagem (2010) as they abstract away from developing countries' own investments. Furthermore, our timing is reversed to that in Greaker and Hagem (2010). Countries first choose their abatement targets and investments

[5]See also see Carbone et al. (2009); Gersbach and Winkler (2011). Alternative approaches to analyze international climate policies are cooperative and non-cooperative coalition theory (e.g., Carraro and Siniscalco (1993); Chander and Tulkens (1997)). However, in these models coalition members choose their emissions cooperatively. Hence there is no role for permit trading, which is at the core of the present paper.

take place only thereafter. Especially in our framework where firms invest, this timing is more natural because investments in abatement technologies are usually a response to government regulation.[6]

The reversed timing is crucially related to the different focus in Greaker and Hagem (2010). They build upon a literature that examines the strategic usage of abatement technologies so as to affect countries' incentives for emissions abatement. For example, Stranlund (1996) shows that industrialized countries may want to transfer advanced technologies to developing countries so as to induce them to choose more ambitious abatement targets. According to Buchholz and Konrad (1994), the same can be achieved if countries adopt a technology with high costs of emission reductions at home. This serves as a commitment device to not reducing emissions in the future, which shifts the burden of abatement to other countries. Golombek and Hoel (2004) examine how technology spillovers from R&D investment in industrialized countries affect emission choices in developing countries. Such aspects are missing in our paper because we abstract from the technology choice in the industrialized countries, and because investments take place after endowments of tradable emission rights have been chosen.

The paper is structured as follows. In section 2, we present the model, which will be solved subsequently under two regimes. In section 3, we take endowments of tradable emission rights as exogenously given and focus on the choice of subsidies and technology. In section 4, we also endogenize the endowment choices. Section 5 provides a numerical simulation which illustrates the results and discusses some further comparative statics. Finally, section 6 concludes.

2 The model

There are two regions, indexed 1 (the "North") and 2 (the "South") respectively. In each region production causes emissions, $x_i \in \mathbb{R}^+$, that are associated with welfare costs $v_i(x)$,where $x \equiv x_1 + x_2, v_i'(x) > 0$, and $v_i''(x) \geq 0$. As it is common in the climate change literature, we often refer to $v_i(x)$ simply as 'damage'. However, given the differences in preferences and wealth across countries, the same level of physical damage may be associated with different welfare costs. Hence it is more appropriate to interpret $v_i(x)$ as the countries' willingness to pay (WTP) for emissions abatement. We assume that for

[6]Another difference is that Greaker and Hagem (2010) assume specific functional forms which enables them to calculate closed form solutions. By contrast, we only make assumptions about the sign of first- and second-order derivatives.

all levels of aggregate emissions the North has a higher marginal WTP, i.e., $v_1'(x) > v_2'(x)$ for all x.[7]

Our focus are TT from the North to the South. Therefore, we abstract from the technology choice in the North and specify its abatement costs of reducing emissions to the level x_1 simply as[8]

$$c_1(x_1). \tag{1}$$

By contrast, the South can reduce its abatement costs by investing in advanced technologies $k \in \mathbb{R}^+$. Its abatement costs are

$$c_2(x_2, k). \tag{2}$$

For both regions, abatement costs are decreasing convex in emissions, which reflects that higher emissions require less abatement and that abatement gets increasingly costly as emissions are reduced further. Moreover, abatement costs in region 2 are decreasing convex in technology investments. In order to keep the notation compact, we indicate derivatives by primes which are followed (in brackets) only by those variables with respect to which the differentiation takes place. In particular, $c_2'(x_2) \equiv \partial c_2(x_2,k)/\partial x_2$, $c_2'(k) \equiv \partial c_2(x_2,k)/\partial k$, $c_2''(k) \equiv \partial^2 c_2(x_2,k)/\partial k^2$ and $c_2''(x_2,k) \equiv \partial^2 c_2(x_2,k)/\partial x_2 \partial k$.[9] For the cross-partial derivatives we adopt the standard assumption that investments in abatement technologies reduce the marginal costs of abatement.[10] Noting that more abatement means less emissions, it follows that $c_2''(x_2,k) > 0$. Finally, in order to assure interior solutions we assume $\lim_{x_i \to 0} c_i'(x_i) = \lim_{k \to 0} c_2'(k) = -\infty$, and $\lim_{x_i \to \infty} c_i'(x_i) = \lim_{k \to \infty} c_2'(k) = 0$, $i = 1, 2$.

3 Technology transfer with exogenous emission targets

We want to analyze the effects of emissions trading on technology adoption in region 2 and technology subsidization by region 1. In this section, we take the

[7]The assumption could easily be dropped, but some of the following results would then require a case distinction – a complication that we want to avoid.

[8]Accordingly, all information about the given abatement technologies are subsumed under the functional form $c_1(.)$.

[9]Using this notation, the assumptions about the cost functions are $c_2'(k) < 0, c_2''(k) > 0$, and $c_i'(x_i) < 0, c_i''(x_i) > 0; i = 1, 2$.

[10]See, e.g., Greaker and Hagem (2010) and Golombek and Hoel (2004). Baker et al. (2008) contains a more general discussion of marginal abatement cost and technical change, which also includes other assumptions.

initial permit allocation, $\omega_i \in \mathbb{R}$, as exogenously given. Accordingly, there are no environmental reasons for TT.

We assume that firms in region 2 can buy technologies k at a constant price t on the world market. Technology transfers are modeled as a subsidy, s, that is paid by region 1. Hence the price after subsidies per unit of technologies is $\pi = t - s$. The timing of the game is as follows: First, region 1 chooses the subsidy s for TT. Then the representative firm in region 2 chooses the technology level k. Finally, firms choose emissions, which also determines the trading of allowances on the international permit market. To find the subgame-perfect Nash equilibrium we solve the game by backwards induction.

3.1 Permit market

We assume that a system of international emissions trading exists. Specifically, each region has a permit endowment ω_i, which it passes to its firms so that trading will be competitive. Let p^* denote the equilibrium price for permits. Given p^*, the representative firm in each region i chooses emissions so as to maximize income on the permit market less the cost for emission abatement:

$$\max_{x_i} \; p^*(\omega_i - x_i) - c_i(.). \tag{3}$$

The equilibrium conditions of profit maximization and market clearing are

$$c_i'(x_i) + p = 0, \qquad i = 1, 2 \tag{4}$$

$$x_1 + x_2 - \omega = 0. \tag{5}$$

Remembering that $c_2'(x_2)$ depends on k, this system implicitly defines after-trade equilibrium emissions, $x_i^*(k, \omega)$, and the permit price, $p^*(k, \omega)$, as functions of the technology level k and the overall permit endowment $\omega \equiv \omega_1 + \omega_2$.

3.2 Technology choice

Turning to the choice of k, the representative firm in region 2 maximizes income on the permit market minus abatement and technology costs. The latter depend on the subsidy, and on the limitation of subsidies to those technology investments that are undertaken *in addition* to their level without subsidies. In the introduction we discussed the problems to determine additionality, hence we allow for different degrees to which this is feasible. In particular, we assume that subsidies are only paid on $\max\{k - \tilde{k}; 0\}$, where $\tilde{k} \in [0, k_0]$ and k_0 is the technology level that is implemented for $s = 0$. Accordingly, $\tilde{k} = 0$ is the case where all technology investments are subsidized, while $\tilde{k} = k_0$ is the other extreme where only additional investments are subsidized.

Intuitively, subsidies raise the level of technology investments, which we formally show further below (see eq. 12). Hence $\max\{k - \tilde{k}; 0\} = k - \tilde{k}$ for all $s \geq 0$ so that technology costs of the representative firm in region 2 are $-tk + s(k - \tilde{k}) = -\pi k - s\tilde{k}$. In conclusion, its technology choice problem is

$$\max_{k} \ p\left[\omega_2 - x_2\left(k\right)\right] - c_2(x_2\left(k\right), k) - \pi k - s\tilde{k}, \tag{6}$$

where the notation $x_2\left(k\right)$ emphasizes that a firm's emission choice on the permit market depends on the technology level k that it has implemented (from 4). By contrast, an individual firm's technology choice has no effects on the permit price, due to our assumption of competitive trading. In conclusion, the first-order condition of (6) is

$$-px_2'(k) - c_2'(k) - c_2'(x_2)x_2'(k) - \pi = 0. \tag{7}$$

Using (4) this simplifies to

$$-c_2'(k) - \pi = 0. \tag{8}$$

Intuitively, the firm balances the marginal benefit of k (the reduction of abatement costs) with the marginal cost π. The second-order condition is

$$-c_2''(k) - c_2''\left(x_2, k\right)x_2'(k) < 0. \tag{9}$$

From the above discussion, the firm takes the permit price as given when evaluating $x_2'(k)$. Therefore, it follows by implicit differentiation of (4) that

$$x_2'(k) = -\frac{c_2''\left(x_2, k\right)}{c_2''\left(x_2\right)} < 0. \tag{10}$$

Upon substitution into (9) and rearranging, the second-order condition becomes

$$\frac{-c_2''(k)c_2''\left(x_2\right) + c_2''\left(x_2, k\right)^2}{c_2''\left(x_2\right)} < 0, \tag{11}$$

which we assume to be satisfied.[11]

[11] In general, we assume that second-order conditions are satisfied, which will often depend in a non-trivial way on third-order derivatives. For parsimony, we state them only when they are used in the subsequent analysis.

We want to compare the technology choice without permit trading ($x_2 = \omega_2$), and with permit trading ($x_2 = x_2^*(\omega)$). From the first-order condition (8) and our assumption that marginal abatement costs are decreasing in the technology level, lower emissions of region 2 are associated with a higher technology level k.[12] Moreover, region 2's after-trade emissions are lower than its emissions without trading if and only if it is a permit seller. Accordingly, the effects of permit trading on the incentives in the South to invest in advanced abatement technologies depends on its position on the permit market.

Proposition 1 *Permit trading raises the technology level k in region 2 if it is a permit seller, and reduces k if it is a permit buyer.*

Intuitively, permit trading reduces emissions by a permit seller and requires him to undertake more abatement. This makes a better abatement technology more valuable. The opposite happens for a permit buyer.

We now summarize the outcome of stages 2 and 3 of the game. For any technology price π, it follows from the equilibrium conditions on the permit and technology market. Specifically, equation system (4), (5) and (8) defines k, x_1, x_2 and p as a function of π and ω. The resulting comparative statics follow from applying the implicit function theorem to this equation system. In particular,

$$\begin{pmatrix} k'(\pi) \\ x_1'(\pi) \\ x_2'(\pi) \\ p'(\pi) \end{pmatrix} = \frac{1}{y} \begin{pmatrix} c_2''(x_2) + c_1''(x_1) \\ c_2''(x_2, k) \\ -c_2''(x_2, k) \\ -c_2''(x_2, k)\, c_1''(x_1) \end{pmatrix} \begin{cases} < 0 \\ < 0 \\ > 0 \\ > 0 \end{cases}, \tag{12}$$

where

$$y \equiv c_2''(x_2, k)^2 - c_2''(k)\left[c_2''(x_2) + c_1''(x_1)\right] < 0. \tag{13}$$

Note that y is smaller than the numerator of the second-order condition (11); hence it must be negative. The signs then follow straightforwardly from the curvature assumptions. In particular, $k'(\pi) < 0$ because firms buy less technology if it becomes more expensive. Moreover, for a given permit endowment one gets $-x_1'(\pi) = x_2'(\pi) > 0$. Intuitively, as region 2 uses a worse technology (due to the higher price π) that makes abatement more expensive, it will increase emissions and demand more permits. Hence the permit price

[12] Formally, implicit differentiation of (8) yields

$$\frac{dk}{dx_2} = -\frac{c_2''(x_2, k)}{c_2''(k)} < 0.$$

rises, i.e., $p'(\pi) > 0$. This makes abatement in region 1 more attractive so that it will reduce emissions.

3.3 Subsidy choice

We now turn to the previous stage of the game, at which region 1 chooses whether to subsidize technology adoption in region 2. For parsimony, we assume that technologies are produced at constant marginal costs which are equal to the price before subsidies, t. Hence, subsidies have no effect on the profits of firms that sell technologies k. Accordingly, welfare of region 1, denoted W_1, consists of payments on the permit market and the costs of emission abatement, technology subsidies and environmental damages:

$$W_1 = p(\omega_1 - x_1) - c_1(x_1) - s(k - \tilde{k}) - v_1(\omega). \tag{14}$$

Remember that $\pi = t - s$, where t is exogenous so that $d\pi = -ds$. Accordingly, choosing s is equivalent to choosing the technology price π. Moreover, region 1's subsidy decision accounts for the effects of changes in π at the subsequent stages of the game. These were summarized by the comparative statics at the end of the preceding section. Hence the welfare maximizing s must satisfy the first-order condition

$$-p'(\pi)(\omega_1 - x_1) + px_1'(\pi) + c_1'(x_1)x_1'(\pi) - (k - \tilde{k}) + sk'(\pi) \leq 0, \tag{15}$$

where the equality is strict for interior solutions. Using (4), this simplifies to

$$-p'(\pi)(\omega_1 - x_1) - (k - \tilde{k}) + sk'(\pi) \leq 0. \tag{16}$$

Intuitively, raising s has the following effects. First, it raises subsidy costs due to the higher subsidy rate that is paid per unit of $k - \tilde{k}$, and because a higher level of k is implemented. Second, the higher k makes abatement cheaper such that the permit price falls. This is beneficial for a permit buyer and we obtain the following result.

Proposition 2

(i) If region 1 is a permit seller or if there is no permit trading, it will not subsidize TT.

(ii) If region 1 is a permit buyer and it is able to restrict subsidies to additional technology investments (i.e., $\tilde{k} = k_0$), then it always chooses $s > 0$.

(iii) If region 1 is a permit buyer but it is not able to restrict subsidies to additional investments, then it subsidizes only if the associated cost savings on the permit market exceed the subsidy costs.

Proof. See appendix.

Accordingly, region 1's decision to subsidize TT depends on the existence of a tradable permits market, and on its position on this market. In particular, only a permit buyer benefits from technology transfers because this reduces the permit price. However, if region 1 cannot determine whether a technology investment would have taken place even without a subsidy, then it cannot restrict subsidies to additional technology investments. This constitutes a kind of fixed cost that is associated with a subsidy system. If it is too large, even a permit buyer may choose $s = 0$. By contrast, without this additionality problem, subsidies are always strictly positive.

4 Technology transfer with endogenous endowment choices

In the previous section we analyzed the effects of emissions trading on abatement technologies. These effects are positive if region 1 (the North) is a permit buyer. In this case, the permit-selling region 2 invests in better technologies, independently of subsidies. Moreover, depending on the degree of additionality, emissions trading induces region 1 to subsidize TT. This leads to further technology improvements. In the analysis, the permit endowments were taken as exogenously given. We now extend the above model by letting countries choose their initial endowment of tradable emission rights strategically. This allows us to analyze the interaction between technology and endowment choices.

In the current climate negotiations, abatement targets and TT are negotiated simultaneously. In line with this, we assume that at the first stage of the game both countries choose their permit endowment and region 1 also chooses the technology subsidy s. The following two stages of the game at which the regions choose the technology and emissions levels proceed as in the preceding section. Moreover, when regions choose their permit endowments, they account for the effects on technology and emissions. These are determined in the same way as the above comparative statics w.r.t. π by applying the implicit function theorem to equation system (4), (5) and (8). Doing so yields

$$\begin{pmatrix} k'(\omega) \\ x_1'(\omega) \\ x_2'(\omega) \\ p'(\omega) \end{pmatrix} = \frac{1}{y} \begin{pmatrix} c_2''(x_2,k)\, c_1''(x_1) \\ c_2''(x_2,k)^2 - c_2''(x_2)\, c_2''(k) \\ -c_2''(k)\, c_1''(x_1) \\ -c_1''(x_1)\left[c_2''(x_2,k)^2 - c_2''(x_2)\, c_2''(k)\right] \end{pmatrix} \begin{cases} <0 \\ >0 \\ >0 \\ <0 \end{cases}. \qquad (17)$$

Remember that y and $c_2''(x_2,k)^2 - c_2''(x_2)\, c_2''(k)$ are both negative from the second-order condition (11) and the discussion after (13). The signs then follow straightforwardly from the curvature assumptions. Intuitively, if there are more permits, their equilibrium price falls and emissions increase in both regions. The resulting lower abatement costs make technology investments less attractive. We can now turn to stage 1 of the game.

4.1 Choices of permit endowments and subsidies

Welfare of region 2, denoted W_2, consists of the profits of the representative firm (see 6) and the costs of environmental damages:

$$W_2 = p(\omega_2 - x_2) - c_2(x_2,k) - \pi k - s\tilde{k} - v_2(\omega). \qquad (18)$$

In a Nash equilibrium of the stage 1 game, region 2 chooses ω_2 so as to maximize its welfare, taking endowment choices of the other region and the technology subsidy as given. However, the region takes into account how its endowment choice will affect permit price, emissions and technology in the subsequent stages of the game, as given by (17). Accordingly, using (4) and (8) the welfare maximizing ω_2 must satisfy the first-order condition

$$p'(\omega)(\omega_2 - x_2) + p - v_2'(\omega) = 0. \qquad (19)$$

Welfare of region 1 is given by (14). The first-order condition w.r.t. its permit endowments, ω_1, is (using 4)

$$p'(\omega)(\omega_1 - x_1) + p - sk'(\omega) - v_1'(\omega) = 0. \qquad (20)$$

The first-order condition w.r.t. subsidies, s, has already been calculated and is given by (16). In conclusion, the solution of the first stage of the game, denoted $\omega_1^c, \omega_2^c, s^c$, is determined by equation system (16), (19) and (20).

The results with exogenous endowment choices did depend on the regions' position on the permit market. It turns out that endogenous endowment choices lead to a clear pattern of permit buyers and sellers.

Proposition 3 *If permit endowments are chosen endogenously, then region 1 is a permit buyer and region 2 is a permit seller, i.e.,* $x_1^c > \omega_1^c$ *and* $x_2^c < \omega_2^c$*.*

Proof. See appendix.

Intuitively, subsidies are only provided by a permit buyer who benefits from the lower permit price. Hence, if region 1 subsidizes abatement technologies then it must be a permit buyer. Alternatively, we may have a boundary solution in which region 1 chooses not to pay subsidies. Nevertheless, the assumption that region 1 has a higher marginal willingness to pay for abatement implies that it has a stronger incentive to reduce its endowment choice than region 2. This puts the region in the position of a permit buyer (see Helm (2003)).

4.2 Effects of subsidies on endowment choices

The focus of the Kyoto Protocol lies on binding emission targets. The ongoing negotiations of a Post-Kyoto agreement have put TT as a second central element on the agenda. We want to examine how this broadening of the negotiation agenda affects the prospects of achieving an agreement that leads to substantial emission reductions.

Obviously, the choices of endowments and subsidies will affect each other. Subsidies lead to better abatement technologies in the South. For a given level of permit endowments, this reduces the permit price. Hence the value of a permit endowment falls, which should induce the regions to choose lower endowment levels. The following result shows that this intuition is generally true, despite the feedback effects of the lower endowments on the incentives to subsidize and to invest in abatement technologies.

Proposition 4 *Consider endogenous choices of permit endowments. Subsidizing TT reduces overall emissions if* $p''(\pi)$ *and* $k''(\omega)$ *are not too small (e.g. non-negative).*

Proof. See appendix.

5 Numerical simulations and discussion

In the previous sections we have derived several general results regarding the strategic choices of subsidies, technology, and emission endowments. However, there are some further comparative statics that are difficult to evaluate without imposing more specific assumptions about functional forms.[13] Therefore, we

[13]In particular, this is the case for effects that include the optimal choice of subsidies s, because the first-order condition (16) depends on $p'(\pi)$ and $k'(\pi)$. From the above analysis

now examine these issues using numerical simulations that are based on the following specifications of damage and abatement cost functions:

$$c_i(.) = \frac{\beta_i}{k_i x_i}, \qquad \text{where } \beta_1 = 20,\ \beta_2 = 10,\ k_1 = 4,\ k_2 = k;$$
$$v_i(x) = \alpha_i x, \qquad \text{where } \alpha_1 = 5,\ \alpha_2 = 1.$$

These specifications satisfy the general assumptions from section 2 about the functional forms and the WTP for emissions abatement. Moreover, $\beta_1 > \beta_2$ implies that with the same technology and the same emissions target, abatement costs would be higher in the North. Finally, k_1 and the technology price before subsidies, $t = 3$, were chosen such that the North always employs a better technology in equilibrium than the South.

5.1 Simulations for exogenous endowment choices

In our first set of simulations we consider the case of exogenous endowment choices for which the solution follows from the system of equations (4), (5), (8) and (16). In particular, we examine how subsidies and the other choice variables are affected by changes in the endowment levels.[14] We distinguish two cases. First, suppose that the overall endowment level is fixed, but the distribution of endowments across regions varies. Specifically, let d denote the level of endowments that is shifted from the South to the North, leading to endowments $\omega_1 + d$ and $\omega_2 - d$ in the respective regions. Figure 1 depicts the resulting equilibrium values for subsidies s , technology $\hat{k}$, and the permit price $\hat{p}$ as a function of d.[15]

As the North gets more endowments, its need for purchasing permits decreases. Hence its interest in reducing this price by TT wanes, and subsidies decline. This leads to a worse technology, and a higher permit price. An increase in the endowments of the South has exactly the opposite effect. Moreover, as s reaches the corner solution of zero, more endowments for the North

these are non-trivial expressions which involve second-order conditions. Hence the comparative statics that follow from applying the implicit function theorem depend in a complex way on third-order conditions.

[14] As the starting point we chose the endowment level that arises in the model with endogenous choices, which we discuss in the next section ($\omega_1 = 0.25, \omega_2 = 2.49$). Moreover, we assume that only additional investments are subsidized, which leads to $\tilde{k} = k_0 = 1.5$. In the next section we vary the degree of additionality.

[15] For all figures, we subtract a constant from the solution of the following variables in order to facilitate their presentation in a single diagram: $\hat{k} = k - 1$, $\hat{p} = p - 2$, and $\hat{\omega} = \omega - 2$.

Figure 1: Effects of changing distribution of endowments

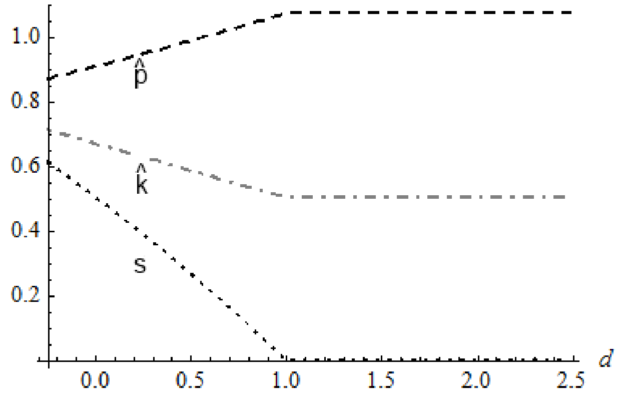
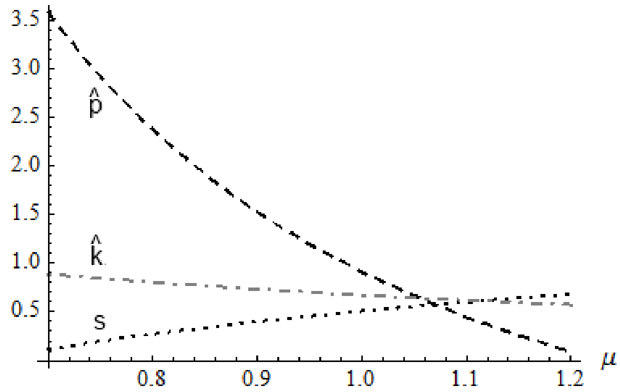


Figure 2: Effects of changing overall endowments



have no effect on the equilibrium. This illustrates the crucial role of TT in our model.

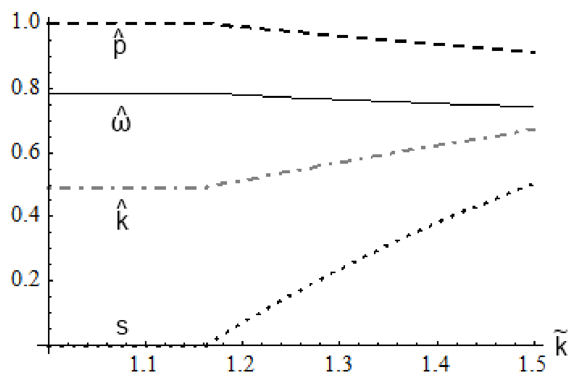
Next, we look at the effect of changes in the overall endowment level. Specifically, let $\mu > 0$ be a scalar that deflates or inflates the individual endowments to $\mu\omega_1$ and $\mu\omega_2$ in the respective regions.

Figure 2 shows the results. Intuitively, more endowments reduce the price of permits, making them a cheaper substitute for abatement. This makes investments in technologies to reduce abatement costs less attractive for the South. The North tries to counter this effect by raising subsidies, but not enough to prevent technology investments k from falling. Thus, the lower the South' own incentives to invest in abatement technologies, the higher the subsidies that the North is choosing.

5.2 Simulations for endogenous endowment choices

We now turn to the case of endogenous endowment choices, where the solution

Figure 3: Effects of changing additionality



follows from the system of equations (4), (5), (8), (16), (19) and (20). We present the equilibrium values of the choice variables as a function of $\tilde{k}$, which allows us to investigate the effects of different degrees of additionality too. In Figure 3, we thus vary $\tilde{k}$ and observe the effects on equilibrium. The range of $\tilde{k}$ follows from our assumption that $\tilde{k} \in [0, k_0]$, where k_0 is the technology level that is implemented for $s = 0$. Hence from the figure we obtain $k_0 = \hat{k}_0 + 1 = 1.5$ (see footnote 15).

For low levels of additionality, i.e., when the North is financing most of the South's technology investments, a corner solution with $s = 0$ obtains. For higher levels of additionality, subsidies increase, the South undertakes more technology investments and the permit price decreases. Given the lower value of a permit endowment, the regions reduce their endowment choice and overall emissions fall.

This negative correlation of subsidies and emissions is interesting because in the case of exogenous endowments s and ω have been complements. In particular, for exogenous reductions of endowment levels, the North reduces the subsidy level (see figure 2). This is different in the endogenous case. Here s and ω act as strategic substitutes, i.e., increases in the subsidy level are accompanied by lower endowment choices (figure 3). This confirms the claim in proposition 4 that the possibility of subsidizing TT generally reduces overall emissions. Moreover, TT also raise welfare, although this effect is small in our simulations.[16] Intuitively, the North can never be worse off with TT because it would choose $s = 0$ otherwise, and the South benefits from a positive subsidy.

[16]Using (14) and (18), overall welfare $W = W_1 + W_2$ is -29.54 in the scenario with $s = 0$, and -29.46 in the scenario with $s = s^* = 0.5$.

6 Concluding remarks

Technology transfers have become a central element of ongoing climate negotiations. Our analysis suggests that this should be conducive to the negotiation of greenhouse gas reduction targets. In particular, unless the additionality problem becomes too large, the North has an incentive to subsidize TT, which leads to improved abatement technologies in the South. Given the lower abatement costs, the regions choose lower permit endowments.

The main motive of the North for TT is the resulting lower permit price, which reduces its costs of achieving a given abatement target. This effect would be missing if countries used a system of CO_2 taxes, rather than permits. The extensive literature that compares these instruments usually focuses on firms' technology adoption decisions (e.g. Requate and Unold, 2003). While we also examine this, our main focus lies on the incentives for TT, i.e., on the supply side rather than on the demand side. From this perspective, permits seem to be more conducive for achieving technology improvements than taxes.

Our analysis was based on the assumption that the regions behave non-cooperatively in their interaction. Within this modeling framework, Carbone et al. (2009) have shown that extending countries' action set by including the possibility of agreeing on an international permit market may lead to substantial emission reductions as compared to the standard non-cooperative choice of emissions. In this paper we have gone one step further and also included the possibility of TT. Again the result was that countries choose more ambitious emission reductions. Hence, even if one is pessimistic about countries' ability to agree on cooperative action, a well designed negotiation process that puts the right issues on the agenda may still achieve a lot.

Having said so, we should remark that some of the assumptions that we employed to keep the model tractable are restrictive, of course. This also sets the stage for possible extensions to the model. First, we have considered only two regions. While an extension to n countries would not affect the basic mechanisms in the model, it would add free-rider incentives at the subsidy stage. In particular, a country that subsidizes technology transfers would have to share the benefits of a lower permit price with all permit buyers. Second, we have assumed a competitive technology market, which neglects the fact that new technologies are often protected by patent rights. As a result, the price of technologies would be too high, which provides a further rationale for subsidizing them. Third, we have abstracted from the North's technology choice. Technology transfers reduce the permit price and, thereby, the costs of achieving a given emissions target. Therefore, one would expect lower incentives of investing in abatement technologies in the North. Implementing these extensions in an analytical model would conflict with the aim of keeping it tractable. Therefore, one might explore these issues using a calibrated numerical simulation model as in Carbone et al. (2009).

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Appendix

A1: Proof of Proposition 2

From the comparative statics at the end of section 3.2, $p'(\pi) > 0$ and $k'(\pi) < 0$. Accordingly, if region 1 is a permit seller or does not trade, then the left-hand side of (16) is non-positive and we have a boundary solution with $s = 0$.

By contrast, if region 1 is a permit buyer, then $-p'(\pi)(\omega_1 - x_1) > 0$ so that a subsidy reduces its costs on the permit market. The subsidy payments depend on the degree of additionality. First, consider the case where subsidies can be fully restricted to additional investments, i.e., $\tilde{k} = k_0$. By contradiction to statement (ii), suppose that $s = 0$; hence $k = k_0$ by definition of k_0. In this case $k - \tilde{k} + sk'(\pi) = 0$ so that the left-hand side of (16) is strictly positive. Hence $s = 0$ can not be an optimal solution. Turning to statement (iii), suppose that region 1 is not able to restrict subsidies to additional investments, i.e., $\tilde{k} < k_0$. In this case $k - \tilde{k} > 0$ even at $s = 0$. If this term is sufficiently large compared to the other terms in (16), then we may have a boundary solution with $s = 0$. ■

A2: Proof of Proposition 3

For interior solutions with $s^c > 0$, the first-order condition for subsidies is

$$-p'(\pi^c)(\omega_1^c - x_1^c) = k^c - \tilde{k} - s^c k'(\pi^c). \tag{21}$$

The right-hand side is positive and $p'(\pi^c) > 0$ so that $\omega_1^c < x_1^c$. Turning to boundary solutions with $s^c = 0$, remember that $v_1'(\omega^c) > v_2'(\omega^c)$ by assumption. Together with the first-order conditions for endowment choices, (20) and (19), it follows that

$$\begin{aligned} p'(\omega^c)(\omega_1^c - x_1^c) + p &> p'(\omega^c)(\omega_2^c - x_2^c) + p \\ \Longleftrightarrow \qquad \omega_1^c - x_1^c &< \omega_2^c - x_2^c. \end{aligned}$$

Given that $\omega_1^c + \omega_2^c = x_1^c + x_2^c$, the two sides must have different signs. Accordingly, the left-hand side must be negative and $\omega_1^c < x_1^c$. ■

A3: Proof of Proposition 4

We want to show that $\omega(s^c) - \omega(0) < 0$, where $\omega(s^c)$ and $\omega(0)$ are endowment choices that arise in the regimes with subsidies ($s = s^c$) and with no TT

($s = 0$). Given the lack of closed form solutions we can not directly compare these endowment levels. However,

$$\omega\left(s^{c}\right) - \omega\left(0\right) = \int_{0}^{s^{c}} \omega'\left(s\right) ds, \tag{22}$$

where $\omega'\left(s\right)$ can be determined using the implicit function theorem. In particular, we treat s as an exogenous variable and then track how ω evolves as subsidies rise from $s = 0$ to the equilibrium value s^{c}.

To determine $\omega'\left(s\right)$, summation of the first-order conditions for endowment choices, equations (19) and (20), yields

$$2p - sk'\left(\omega\right) - v_1'(\omega) - v_2'(\omega) = 0, \tag{23}$$

which implicitly defines ω as a function of s. Implicit differentiation yields (remember that $d\pi/ds = -1$)

$$\frac{d\omega}{ds} = \frac{2p'\left(\pi\right) + k'\left(\omega\right) - s\frac{\partial k'(\omega)}{\partial \pi}}{2p'\left(\omega\right) - sk''\left(\omega\right) - v_1''(\omega) - v_2''(\omega)}, \tag{24}$$

where the derivatives account for the effects of endowment choices and subsidies at the subsequent stages of the game. From the comparative statics (12) and (17) we have $k'\left(\omega\right) = -p'\left(\pi\right)$ so that

$$2p'\left(\pi\right) + k'\left(\omega\right) = \frac{-c_2''\left(x_2, k\right) c_1''\left(x_1\right)}{c_2''\left(x_2, k\right)^2 - c_2''\left(k\right)\left[c_2''\left(x_2\right) + c_1''\left(x_1\right)\right]} > 0, \tag{25}$$

and $-\frac{\partial k'(\omega)}{\partial \pi} = p''\left(\pi\right)$. Accordingly, the numerator of (24) is positive for all s if $p''\left(\pi\right)$ is not too small (e.g., positive). Similarly, the denominator is negative for all s if $k''\left(\omega\right)$ is not too small (e.g., positive). ■

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