Climate Policy with Technology Transfers and Permit Trading

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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 the South, thereby reducing the international permit price. This is beneficial for the North as long as it is a permit buyer; hence it chooses to subsidize TT. By contrast, the permit selling South suffers from the lower permit price and its welfare usually deteriorates, despite receiving subsidies. We also consider how TT affects countries' non-cooperative choices of permit endowments and find that it tends to reduce 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, additionality, subsidies.

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

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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 by developing countries.[1] In this paper, we analyze the incentives of industrialized countries to finance TT, and the incentives of firms in developing countries to invest in 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 – kg of CO_2 per PPP \$ of GDP – in 2008 China and the US had ratios of 0.86 and 0.38, respectively. Looking at aggregate data, the ratio equaled 0.32 for high income countries (World Bank classification) and 0.54 for low and middle-income countries (Mundial, 2011).

In a recent empirical study, Douglas and Nishioka (2012) find that such differences in emission intensities are primarily driven by differences in production techniques rather than by trading and specialization patterns. Consequently, they recommend technology transfers as an effective instrument to reduce emission intensities for developing countries.

Without such specific measures, the process of technology diffusion 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 technol-

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[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.

ogy 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. In their analysis of national and international policy options to encourage the international transfer of technology (ITT), Hoekman et al. (2005, 1594) conclude that: “Turning to specific measures aimed at ITT, fiscal incentives or subsidies are the most obvious candidates.” In line with this suggestion we will model ITT as a subsidy that is paid per unit of technologies transferred from industrialized to developing countries. Hence the subsidy reduces the price of the technology. Alternative instruments such as subsidized loans or fiscal incentives would have a similar effect.

Our focus on permit trading reflects that establishing a price on greenhouse gas (GHG) emissions is often seen as “the single most important policy for encouraging the innovation that might bring about advanced technology development” (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, referred to as industrialized countries (“North”) and developing countries (“South”). This restriction on the number of players 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. 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 technology level. This lowers the costs of abatement, leading to more emission reductions in the South and a lower permit price. 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 otherwise would not have taken place. 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 counter-factual. 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 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.

While this seems to be positive news, it does not imply welfare gains for both regions. In particular, the subsidy level is chosen by the government in the North. Assuming that it aims to maximize welfare in the North, a positive subsidy level must be associated with a welfare improvement. By contrast, we assume that technology adoption decisions in the South are undertaken by its firms, which purchase subsidized technologies on the world market. Moreover, we assume that the permit market is competitive. Accordingly, any individual firm takes the permit price as given and neglects that it will fall if all firms adopt a better technology. Hence the level of technology adoption will be too high from the perspective of welfare in the permit-selling South.

Indeed, if there exists no distortion on the market for abatement technologies, then the subsidy itself would constitute a distortion and, therefore, reduce overall welfare. As a consequence, the welfare increase in the North must be accompanied by an even larger welfare decrease in the South. In this scenario, technology subsidies turn out to be a "poisoned present".

However, policy discussions of TT are often motivated by the implicit assumption that there are obstacles of technology diffusion so that the technology level in the South is inefficiently low. Among the reasons that are discussed in the literature are DUP (Directly Unproductive, Profit-Seeking) activities (Bhagwati, 1982), capital constraints (Böhringer et al., 2003) and a limited absorptive capacity (Glass and Saggi, 1998). In such a scenario technology subsidies can help to correct a market failure and, therefore, improve welfare in the South as well.

Moreover, until now we have taken the overall emissions level as exogenously given. However, permit trading fundamentally changes countries incentives when they decide about their level of emission rights (Helm, 2003).[5] Therefore,

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[4] For example, Zhang and Wang (2011) utilize the relationship that CO_2 and SO_2 are copollutants 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.

[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.

we also consider the scenario where both regions simultaneously choose their initial permit endowments. We find that, in general, subsidies for TT lead to the choice of less permit endowments. The reason is that subsidies result in 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), the government in the North determines investments in abatement technologies "at home" and in the South. Thereafter, both regions choose their permit endowments, which are then traded on an international permit market. In our paper, the Northern government makes no investment decisions itself, but subsidizes the investments of private firms. These firms do not account for the environmental effects of their technology investments; hence their objective function differs from that of their governments. Moreover, Southern firms can invest in abatement technologies even without subsidies. This leads to the problem of "additionality" because the North wants to restrict its 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 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 in order to induce them choosing 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

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[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.

our paper because firms invest in technologies after governments have chosen endowments of tradable emission rights.

The paper is structured as follows. In section 2, we present the model that 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 as well as the resulting welfare effects. In section 4, we also endogenize the endowment choices. Finally, section 5 concludes.

2 Preliminaries

There are two regions, indexed N (the "North") and S (the "South") respectively. In each region $i = N, S$, production causes emissions, $x_i \in \mathbb{R}^+$, that are associated with welfare costs $v_i(x)$, where $x \equiv x_N + x_S, v_i'(x) > 0$, and $v_i''(x) \geq 0$. As it is common in the climate change literature, we sometimes refer to $v_i(x)$ simply as 'damage'. However, given the differences in preferences and wealth across regions, the same level of physical damage may be associated with different welfare costs. Hence it is more appropriate to interpret $v_i(x)$ as a region's willingness to pay (WTP) for emissions abatement. We assume that for all levels of aggregate emissions the North has a higher marginal WTP, i.e., $v_N'(x) > v_S'(x)$ for all x.[7]

Both regions can reduce their emissions. The associated abatement costs, $c_i(x_i, k_i), i = N, S$, depend on the levels of emissions and abatement technologies, $k_i \in \mathbb{R}^+$. 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 are decreasing convex in the technology level. 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. Specifically, $c_i'(x_i) \equiv \partial c_i(x_i, k_i)/\partial x_i$, $c_i'(k_i) \equiv \partial c_i(x_i, k_i)/\partial k_i$, $c_i''(k_i) \equiv \partial^2 c_i(x_i, k_i)/\partial k_i^2$ and $c_i''(x_i, k_i) \equiv \partial^2 c_i(x_i, k_i)/\partial x_i \partial k_i$.[8] For the cross-partial derivatives we adopt the standard assumption that investments in abatement technologies reduce the marginal costs of abatement. Noting that more abatement means less emissions, it follows that $c_i''(x_i, k_i) > 0$.[9]

In order to address the issue of additionality, we have to specify the technology level that existed prior to the introduction of the policy measures – permit trading and technology subsidies – that we analyze. As the baseline scenario

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[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] Using this notation, the assumptions about the cost functions are $c_i'(k_i) < 0, c_i''(k_i) > 0$, and $c_i'(x_i) < 0, c_i''(x_i) > 0; i = N, S$.

[9] See, e.g., Greaker and Hagem (2010) and Golombek and Hoel (2004). For example, this assumption is satisfied for a multiplicative specification $f(k_i)\, c_i(x_i)$, where $f'(k_i) < 0$ (see Montero (2002)). Baker et al. (2008) contains a more general discussion of marginal abatement cost and technical change, which also includes other assumptions.

we use the situation of no international climate policy and denote the ensuing technology level as $\underline{k}_i$. Specifically, $\underline{k}_i$ follows from the game where regions non-cooperatively choose their emissions and, thereafter, the representative firms in each region choose their technology level.

We assume that disinvestment is costly (for economic and political reasons) so that firms' technology choices in the scenario with an international climate policy are restricted to levels $k_i \geq \underline{k}_i$, $i = N, S$.[10] Finally, to assure interior solutions of emissions and a finite technology level we assume $\lim_{x_i \to 0} c_i'(x_i) = -\infty$, and $\lim_{x_i \to \infty} c_i'(x_i) = \lim_{k_i \to \infty} c_i'(k_i) = 0$, $i = N, S$.

Occasionally, we will use a simple numerical example to illustrate results or to explore comparative statics that are difficult to evaluate without imposing more specific assumptions about functional forms. It is based on the following specification of damage and abatement cost functions:

$$\begin{array}{ll} c_i(k_i, x_i) = \frac{\beta_i}{k_i x_i}, & \text{where } \beta_N = 5, \ \beta_S = 2, \\ v_i(x) = \alpha_i x, & \text{where } \alpha_N = 5, \ \alpha_S = 1. \end{array} \tag{1}$$

Here, $\beta_N > \beta_S$ implies that with the same technology and the same emissions target, abatement costs would be higher in the North. Moreover, the technology price before subsidies is set at $t = 3$. Using this specification, the solution in the baseline scenario of no climate policy is $\{\omega_N, \omega_S, \underline{k}_N, \underline{k}_S\} = \{0.84, 1.82, 1.41, 0.61\}$.

3 Technology transfer with exogenous emission targets

We want to analyze the effects of emissions trading on technology adoption and on the incentives of the North to subsidize TT to the South. In this section, we take the initial permit allocation, $\omega_i \in \mathbb{R}$, as exogenously given. Accordingly, there are no environmental reasons for TT.

We assume that firms in regions $i = N, S$ can buy k_i units of technology at a constant price t on the world market. Technology transfers to the South are modeled as a subsidy, σ_S, that is paid by the North. Hence, for firms in the South the price after subsidies per unit of technologies is $\pi_S = t - \sigma_S$. Given the focus of our paper on TT we do not consider the possibility that governments in the North may also subsidize their own firms. Accordingly, we set $\sigma_N = 0$ (specifying σ_N although it is neglected in the analysis will facilitate the notation later on).

The timing of the game is as follows: First, the North chooses the subsidy σ_S for TT. Then the representative firms in the two regions choose their technology level k_i. Finally, firms choose emissions, which determines the trading

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[10] The assumption is not crucial for our results. Actually, it makes the analysis slightly more complicated because it introduces the possibility of corner solutions. However, it seems hard to imagine an international climate policy at which, for instance, some regions replace their existing gas-fired by more pollutive coal-fired power plants.

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:

$$\max_{x_i} \; p^*(\omega_i - x_i) - c_i(x_i, k_i). \tag{2}$$

The equilibrium conditions of profit maximization and market clearing are

$$c_i'(x_i) + p = 0, \qquad i = N, S, \tag{3}$$

$$x_N + x_S - \omega = 0. \tag{4}$$

Note that $c_i'(x_i)$ depends on k_i. Hence this system implicitly defines after-trade equilibrium emissions, $x_i^*(k_N, k_S, \omega)$, and the permit price, $p^*(k_N, k_S, \omega)$, as functions of the technology levels k_N, k_S and the overall permit endowment $\omega \equiv \omega_N + \omega_S$.

3.2 Technology choice

Turning to technologies, we assume that these are chosen simultaneously by the representative firms in regions $i = N, S$ so as to maximize their income on the permit market minus abatement and technology costs. In the South, the latter depend on the subsidy, and on the restriction 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 $\max\{k_S - \tilde{k}_S; 0\}$, where $\tilde{k}_S \in [\underline{k}_i, k_S^0]$, and k_S^0 is the technology level of the South that is implemented for $\sigma_S = 0$. Accordingly, $\tilde{k}_S = \underline{k}_i$ is the case where all technology investments as compared to the reference scenario of no climate policy are subsidized. By contrast, $\tilde{k}_S = k_S^0$ is the other extreme where the subsidy is restricted to additional investments that would not have taken place without it.

Intuitively, subsidies (weakly) raise the level of technology investments.[11] Hence $\max\{k_S - \tilde{k}_S; 0\} = k_S - \tilde{k}_S$ for all $\sigma_S \geq 0$ so that technology costs of the representative firm in the South are $-tk_S + \sigma_S(k_S - \tilde{k}_S) = -\pi_S k_S - \sigma_S \tilde{k}_S$. For the firm in the North, technology costs are simply tk_N. Using $\sigma_N = 0$ which

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[11] Formally, this will be shown further below (see eq. 11)

implies $\pi_N = t - \sigma_N = t$, we can state the technology choice problem for both regions as

$$\max_{k_i \geq \underline{k}_i} \; p\left[\omega_i - x_i\left(k_i\right)\right] - c_i(x_i\left(k_i\right), k_i) - \pi_i k_i - \sigma_i \tilde{k}_i. \tag{5}$$

Here the notation $x_i\left(k_i\right)$ emphasizes that a firm's emission choice on the permit market depends on the technology level k_i that it has implemented (from 3). By contrast, an individual firm's technology choice has no effects on the permit price, due to our assumption of competitive trading. In conclusion, interior solutions $k_i > \underline{k}_i$ follow from the first-order condition of (5):

$$-\, p x_i'(k_i) - c_i'(k_i) - c_i'(x_i) x_i'(k_i) - \pi_i = 0. \tag{6}$$

Using (3) this simplifies to

$$-\, c_i'(k_i) - \pi_i = 0, \qquad i = N, S. \tag{7}$$

Intuitively, firms balance the marginal benefit of k_i, the reduction of abatement costs, with the marginal cost, π_i. The second-order condition is

$$-\, c_i''(k_i) - c_i''\left(x_i, k_i\right) x_i'(k_i) < 0. \tag{8}$$

From the above discussion, firms take the permit price as given when evaluating $x_i'(k_i)$. Therefore, it follows by implicit differentiation of (3) that

$$x_i'(k_i) = -\frac{c_i''\left(x_i, k_i\right)}{c_i''\left(x_i\right)} < 0. \tag{9}$$

Upon substitution into (8) and rearranging, the second-order condition becomes

$$\frac{-c_i''(k_i) c_i''\left(x_i\right) + c_i''\left(x_i, k_i\right)^2}{c_i''\left(x_i\right)} < 0, \tag{10}$$

which we assume to be satisfied.[12]

We now compare the technology choice without permit trading ($x_i = \omega_i$), and with permit trading ($x_i = x_i^*\left(k_N, k_S, \omega\right)$). For interior solutions, the first-order condition (7) and our assumption that marginal abatement costs are decreasing in the technology level imply that lower emissions of a region i are associated with a higher technology level k_i in that region.[13] Moreover, each

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[12] 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.

[13] Formally, implicit differentiation of (7) yields

$$\frac{dk_i}{dx_i} = -\frac{c_i''\left(x_i, k_i\right)}{c_i''\left(k\right)} < 0.$$

region'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 to invest in abatement technologies depend on a region's position on the permit market. Taking into account that k_i may remain unchanged in the case of a boundary solution, we obtain the following result.

Proposition 1 *(Exogenous emission targets.) Permit trading leads to a (weakly) higher technology level, k_i, in the region that is a permit seller, and a (weakly) lower k_i in the region that is a permit buyer.*

Permit trading reduces emissions of a permit seller and requires him to undertake more abatement. Intuitively, 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 prices, it follows from the equilibrium conditions on the permit and technology market. Specifically, for interior solutions equation system (3), (4) and (7) defines k_N, k_S, x_N, x_S and p as a function of π_N, π_S and ω. The resulting comparative statics follow from applying the implicit function theorem to this equation system. In particular, the effects of a subsidy that reduces the technology price in the South follow from

$$\begin{pmatrix} k'_N(\pi_S) \\ k'_S(\pi_S) \\ x'_N(\pi_S) \\ x'_S(\pi_S) \\ p'(\pi_S) \end{pmatrix} = \frac{1}{c''_N(k_N)\lambda_S + c''_S(k_S)\lambda_N} \begin{pmatrix} c''_N(x_N, k_N)\, c''_S(x_S, k_S) \\ -\lambda_N - c''_N(k_N) c''_S(x_S) \\ -c''_N(k_N) c''_S(x_S, k_S) \\ c''_N(k_N) c''_S(x_S, k_S) \\ \lambda_N c''_S(x_S, k_S) \end{pmatrix} \left\{ \begin{matrix} > 0 \\ < 0 \\ < 0 \\ > 0 \\ > 0 \end{matrix} \right. , \tag{11}$$

where

$$\lambda_i \equiv c''_i(k_i)\, c''_i(x_i) - c''_i(x_i, k_i)^2 > 0 \tag{12}$$

by the second-order condition (10). The signs then follow straightforwardly from the curvature assumptions. Intuitively, the representative firm in the South buys less technology if it becomes more expensive ($k'_S(\pi_S) < 0$). This makes abatement more costly and the firm in the South will increase its emissions ($x'_S(\pi_S) > 0$). Ceteris paribus, the permit price rises, which makes abatement and, therefore, technology investments in the North more attractive. Accordingly, $k'_N(\pi_S) > 0$ and $x'_N(\pi_S) = -x'_S(\pi_S) < 0$, where the equality reflects that the overall permit endowment is exogenously fixed. Obviously, this has a moderating effect on the permit price. Nevertheless, the overall effect of a higher technology price is that marginal abatement costs and, therefore, the permit price increase ($p'(\pi_S) > 0$).

Finally, let us briefly consider boundary solutions. The case $k_S = \underline{k}_S$ would mean that there are no technology transfers. Hence this case is uninteresting in the context of our paper and we exclude it in the remaining. This is not a strong simplification because $k_S = \underline{k}_S$ can only occur if emissions in South are higher than in the scenario of no climate policy. By contrast, $k_N = \underline{k}_N$ does arise in the simulations that we present below. It reflects that the North is a permit buyer which reduces the attractiveness of technology investments. In such a boundary solution, $k_N'(\pi_S) = 0$, while the signs of the other comparative statics in (11) remain unchanged.[14]

3.3 Subsidy choice of the North

We now turn to the previous stage of the game, at which the North chooses whether to subsidize technology adoption in the South. 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_i. Accordingly, welfare of the North, denoted W_N, consists of payments on the permit market and the costs of emission abatement, technology subsidies and environmental damages:

$$W_N = p(\omega_N - x_N) - c_N(x_N, k_N) - tk_N - \sigma_S(k_S - \tilde{k}_S) - v_N(\omega). \tag{13}$$

Remember that $\pi_S = t - \sigma_S$, where t is exogenous so that $d\pi_S = -d\sigma_S$. Moreover, the subsidy decision of the North accounts for the effects of changes in π_S at the subsequent stages of the game. These were summarized by the comparative statics at the end of the preceding section. Using (3) and (7), the welfare maximizing σ_S must satisfy the first-order condition

$$-p'(\pi_S)(\omega_N - x_N) - (k_S - \tilde{k}_S) + \sigma_S k_S'(\pi_S) \leq 0, \tag{14}$$

where the equality is strict for interior solutions. Intuitively, raising σ_S has the following effects. First, it raises subsidy costs due to the higher subsidy rate that is paid per unit of $k_S - \tilde{k}_S$, and because a higher level of k_S is implemented. Second, the reduction in technology costs makes abatement cheaper so that the permit price falls. Thus, the decision of the North to subsidize TT hinges on the existence of a tradable permits market, and on its position on this market as a permit buyer. We obtain the following result.

Proposition 2 *(Exogenous emission targets.)*

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

(ii) If the North is a permit buyer and can restrict subsidies to additional technology investments (i.e., $\tilde{k}_S = k_S^0$), then it always chooses $\sigma_S > 0$.

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

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[14] The exact expressions change, of course. They follow from setting $k_N = \underline{k}_N$ and applying the implicit function theorem to the remaining equation system.

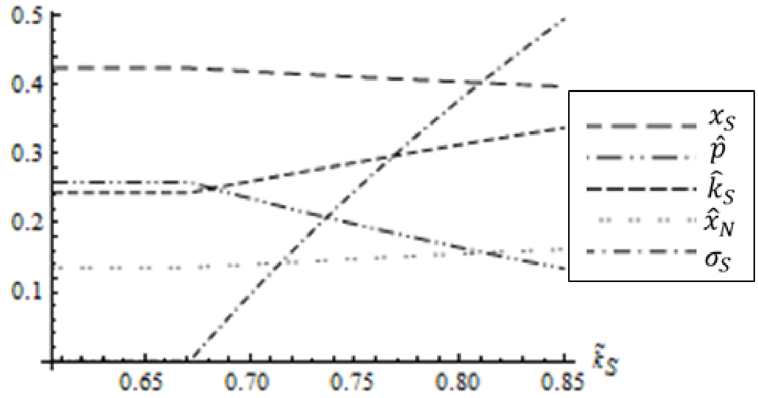

Figure 1: Effects of changing additionality

Proof. See appendix.

Based on specification (1) and an initial permit endowment $\{\omega_N, \omega_S\} = \{0.27, 1.79\}$, figure 1 illustrates the results so far.[15] The horizontal axis depicts the additionality parameter $\tilde{k}_S \in [\underline{k}_S, k_S^0]$. The shown range starts at the technology level in the reference scenario of no climate policy, $\underline{k}_S = 0.61$, and ends at the technology level that would be implemented without subsidies, $k_S^0 = 0.85$. Accordingly, the difference $k_S^0 - \underline{k}_S > 0$ only results from the introduction of permit trading and the South' associated emission reductions as a permit seller.

If the North can not 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 $\sigma_S = 0$. This happens in the leftist part of figure 1.[16] For higher levels of additionality, subsidies increase. This has the effects as summarized in (11). Firms in the South raise their technology investments, which lowers their costs of emissions abatement. As a consequence, they abate more and the permit price falls. Given that the overall permit number is fixed, emissions in the North must increase. This reduces the attractiveness of investing in abatement technology, yielding a corner solution $k_N = \underline{k}_N$ over the whole interval (thus k_N is not shown in the figure).

3.4 Welfare effects with exogenous endowments

We now turn to the welfare effects of subsidizing abatement technologies in the South. Naturally, we focus on interior solutions with $\sigma_S > 0$, for which the South must be a permit seller (by proposition 2).

The North chooses the subsidy so as to maximize its welfare. Hence it selects a positive subsidy level if and only if this raises its welfare. The South benefits from the cheaper abatement technologies. However, there is also a

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[15] The initial permit distribution is the one that arises endogenously if there are no subsidies and each region non-cooperatively chooses its own endowment level (see section 4 below).

[16] For all figures, we subtract a constant from the solution of some variables in order to facilitate their presentation in a single diagram. For this diagram: $\hat{k}_S = k_S - \underline{k}_S$, $\hat{p} = p - 2.5$.

cost because the permit price falls (see 11). As discussed in section 3.2, the individual firms neglect the latter effect in their technology choice due to our assumption of a competitive permit market. Accordingly, they will choose a technology level that is too high from a welfare perspective of the South.

More generally, the subsidy constitutes a distortion. In addition, it cannot contribute to balance the externalities in the regions' emissions choices because their overall level is taken as exogenous. Therefore, overall welfare and – given the gains in the North – welfare in the South must fall.

However, in the introduction we have argued that the technology level in the South is often considered to be inefficiently low due to obstacles to technology adoption. The simplest way to model this idea is to introduce a price distortion (or transaction cost) $\gamma_S \geq 0$ on the technology market. Specifically, we now assume that in the South the representative firm's cost per unit of technology are $\bar{\pi}_S = t - \sigma_S + \gamma_S$, while the social cost per unit of technology are only $t - \sigma_S$.[17]

Replacing π_S by $\bar{\pi}_S$ in the above analysis, it is straightforward to see that all equations (and results) remain unchanged apart from this substitution. Moreover, welfare of the South is

$$W_S = p(\omega_S - x_S) - c_S(x_S, k_S) - (t - \sigma_S)\, k_S - \sigma_S \tilde{k}_S - v_S(\omega). \tag{15}$$

Hence, using (3),

$$\begin{aligned} \frac{dW_S}{d\sigma_S} &= -p'\left(\bar{\pi}_S\right)\left(\omega_S - x_S\right) + \left[t - \sigma_S + c_S'(k_S)\right] k_S'\left(\bar{\pi}_S\right) + (k_S - \tilde{k}_S) & (16) \\ &= -p'\left(\bar{\pi}_S\right)\left(\omega_S - x_S\right) - \gamma_S k_S'\left(\bar{\pi}_S\right) + (k_S - \tilde{k}_S), & (17) \end{aligned}$$

where the last step follows from $t - \sigma_S + \gamma_S + c_S'(k_S) = 0$ according to (7) after replacing π_S by $\bar{\pi}_S$. Here, the term $-\gamma_S k_S'\left(\pi_S\right) > 0$ represents the welfare improvement that arises from the subsidy because it balances the inefficiently low technology level which was caused by the price distortion γ_S.

Turning to overall welfare, $W \equiv W_N + W_S$, the marginal effect of raising the technology subsidy is (using (7) and $x_N'\left(\bar{\pi}_S\right) = -x_S'\left(\bar{\pi}_S\right)$)

$$\frac{dW}{d\sigma_S} = \left(\sigma_S - \gamma_S\right) k_S'(\pi_S). \tag{18}$$

This expression reflects that subsidy costs and the effects on the permit market cancel out in the aggregate. From (11), it is positive if and only if $\gamma_S > \sigma_S$, i.e. if the transaction cost parameter γ_S is sufficiently large compared to the subsidy. Moreover, it follows straightforwardly from (18) that the subsidy level which maximizes global welfare just corrects the technology price distortion that existed in the original situation, i.e. that satisfies $\sigma_S = \gamma_S$. We summarize these results in the following proposition.

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[17] For example, γ_S maybe a rent that has to be paid to the bureaucracy. Alternatively, the difference between the private and social costs of technology investments may result from technology spillovers to other local firms.

Proposition 3 *(Exogenous emission targets.)*

(i) If the original technology level is efficient, then subsidizing TT increases welfare in the North, but reduces welfare in the South as well as overall welfare.

(ii) If the original technology level in the South has been inefficiently low, then subsidizing TT may raise welfare in both regions.

4 Technology transfer with endogenous endowment choices

In the previous section we have analyzed the effects of emissions trading on abatement technologies, on incentives to subsidize them and on welfare. However, the analysis was based on the restrictive assumption that the level of permit endowments is exogenously given. We now extend the above model by letting the regions choose their initial endowment of tradable emission rights strategically. This allows us to analyze the interaction between technology, subsidy and endowment choices. To the extent that technology subsidies reduce overall emissions, this should also lead to a more optimistic assessment of their welfare effects: First, due to the direct effect of less pollution; and second, because lower emissions raise the optimal level of abatement technologies, which increase in subsidies.

In current climate negotiations, abatement targets and TT are negotiated simultaneously. In line with this, we now assume that at the first stage of the game both countries choose their permit endowment and the North also chooses the technology subsidy σ_S. The subsequent two stages of the game, at which the regions choose their technology and emission 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 with respect to π_S. In particular, for interior solutions applying the implicit function theorem to equation system (3), (4) and (7) yields

$$\begin{pmatrix} k'_N(\omega) \\ k'_S(\omega) \\ x'_N(\omega) \\ x'_S(\omega) \\ p'(\omega) \end{pmatrix} = \frac{1}{c''_N(k_N)\lambda_S + c''_S(k_S)\lambda_N} \begin{pmatrix} -c''_N(x_N,k_N)\lambda_S \\ -c''_S(x_S,k_S)\lambda_N \\ c''_N(k_N)\lambda_S \\ c''_S(k_S)\lambda_N \\ -\lambda_N\lambda_S \end{pmatrix} \begin{cases} <0 \\ <0 \\ >0 \\ >0 \\ <0 \end{cases}, \quad (19)$$

where the signs follow straightforwardly from $\lambda_i > 0$ and 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.

Finally, if the technology level reaches its lower bound, $k_i = \underline{k}_i$, a corner solution obtains. This implies $k_i'(\omega) = 0$, but does not affect the signs of the other comparative statics in (19).

4.1 Choices of permit endowments and subsidies

In a Nash equilibrium of the stage 1 game, the South chooses ω_S so as to maximize its welfare as given by (15), 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, which are summarized in (19). As in section 3.4, we allow for the possibility that the original technology level in the South is inefficiently low. Accordingly, we replace $\pi_S = t - \sigma_S$ by $\bar{\pi}_S = t - \sigma_S + \gamma_S$ in the above analysis and, in particular, in expression (7). Using this and (3), maximizing welfare W_S with respect to ω_S yields the first-order condition

$$p'(\omega)(\omega_S - x_S) + p + \gamma_S k_S'(\omega) - v_S'(\omega) = 0. \tag{20}$$

Similarly, welfare of the North is given by (13), and the first-order condition with respect to ω_N is (using 3 and 7)

$$p'(\omega)(\omega_N - x_N) + p - \sigma_S k_S'(\omega) - v_N'(\omega) = 0. \tag{21}$$

Finally, the first-order condition with respect to subsidies, σ_S, has already been calculated and is given by (14). In conclusion, the solution of the first stage of the game, denoted $\omega_N^c, \omega_S^c, \sigma^c$, is determined by equation system (14), (20) and (21).

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

Proposition 4 *(Endogenous emission targets.) If the price distortion γ_S is not too large, then the North is a permit buyer and the South is a permit seller.*

Proof. See appendix.

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

However, from (20) we see that a higher γ_S reduces the welfare gains of raising ω_S. Intuitively, raising ω_S reduces the technology level, which is bad if this level is inefficiently low due $\gamma_S > 0$. Only if this effect is strong enough to dominate the outcome, the positions of permit buyer and seller may be reversed.

4.2 Effects of subsidies on endowment choices

The focus of the Kyoto Protocol lay on binding emission targets. The ongoing negotiations of a Post-Kyoto agreement have put TT as a second central element on the agenda. We now examine the feed-back effects of this broadening of the negotiation agenda on the choices of emission targets.

For any given level of permit endowments, technology subsidies reduce the permit price (see 11). 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 5 *(Endogenous emission targets.) Subsidizing TT reduces overall emissions if $p''(\pi)$ is not too small and γ_S is not too large (e.g. $p''(\pi) \geq 0$ and $\gamma_S \leq \sigma_S^c$).*

Proof. See appendix.

From (11), the expression for $p'(\pi)$ includes only second order derivatives of the cost functions. Hence the proposition says that adding TT to the negotiation agenda reduces emissions unless third order effects or price distortions on the technology market dominate the outcome.

For the functional specification (1) and $\gamma_S = 0$, figure 2 illustrates the effects of TT on the choices of permit endowments.[18] As in figure 1, we depict the additionality parameter $\tilde{k}_S$ on the horizontal axis because it affects the subsidy, but has no direct effects on the choice of emissions, technology and permit endowments. Therefore, these variables remain constant until $\tilde{k}_S$ is large enough to trigger a positive subsidy.

The specification yields $p''(\pi) \geq 0$.[19] Accordingly, consistent with proposition 5 we find that higher subsidies reduce overall emissions. Also the main effects on individual endowments are quite intuitive. First, for any subsidy level, higher endowments reduce the technology level in the South (by 19). The higher the subsidy, the stronger are the incentives for the North to exploit this effect so as to lower the quantity on which it has to pay the subsidy. Second, for given endowments, a higher subsidy reduces the emissions level in the South (by 11). Consequently, the South sells more permits. Hence it reduces its endowment level in order to drive up the permit price. For the North the

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[18] For this diagram, $\hat{x}_N = x_N - 1$ $\hat{\omega}_S = \omega_S - 1$, $\hat{\omega} = \omega - 1$ and $\hat{W}^{en} = W^{en} + 25.5$.

[19] In the current specification the sign depends solely on the cost functions parameters $\beta_i, i = N, S$. While $p''(\pi)$ is decreasing in β_i, even for very high values of β_i (e.g. 1,000) it is still slightly positive.

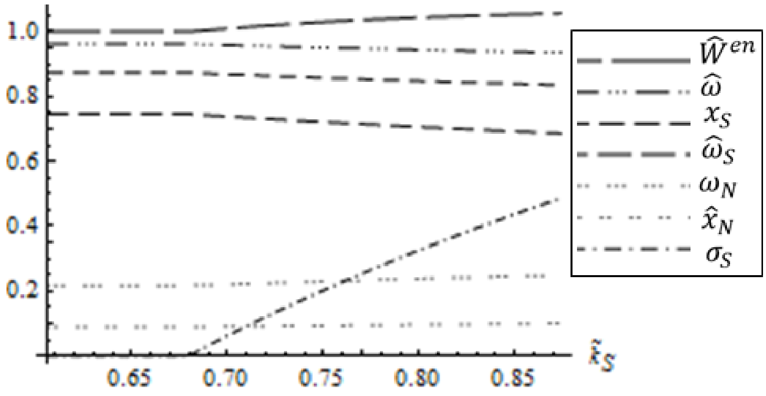

Figure 2: Effects of changing additionality

effect is reversed. It buys more permits and, therefore, has a stronger incentive to lower the permit price by raising its endowment level.[20]

4.3 Welfare effects with endogenous endowments

We now turn to the welfare effects of subsidizing technology transfers. In comparison to the corresponding section with exogenous endowments, the analysis is substantially more complex because a variation of the subsidy has feed-back effects on the regions' endowment choices. Taking these into account makes the general analysis intractable. Therefore, we explore this issue using the functional specification (1).

In the model with exogenous permit endowments it turned out that subsidies have a negative effect on overall welfare, unless the price distortion on the technology market is large (see proposition 3). In the model with endogenous endowment choices, subsidies have an additional effect because they tend to reduce the overall endowment level (see proposition 5). This moderates the pollution externality and, therefore, improves welfare. In our numerical example, this effect dominates and overall welfare rises in the subsidy level even if the technology market is undistorted (see figure 2, which is based on $\gamma_S = 0$).

While this outcome strengthens the case for subsidizing TT, the corresponding political decisions will hinge on the welfare effects for the individual regions. These are depicted in figure 3, where we assume full additionality ($\tilde{k}_S = k_S^0$), but vary the parameter for the price distortion on the technology market, γ_S.[21]

Ceteris paribus, a stronger price distortion reduces the technology level in the South and, therefore, strengthens incentives of the North to subsidize TT. Accordingly, σ_S is increasing in γ_S for both cases of exogenous and endogenous endowments. To analyze the effects of TT, we compare the welfare at the depicted subsidy level that arises endogenously in the model, and the welfare

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[20] Formally, the first effect is driven by the term $\sigma_S k_S'(\omega)$ in equation (21), and the second by the terms $p'(\omega)(\omega_S - x_S)$ and $p'(\omega)(\omega_N - x_N)$ in equations (20) and (21).

[21] For this diagram, $\hat{\sigma}_S^{en} = \sigma_S^{en} - 0.4$ and $\hat{\sigma}_S^{ex} = \sigma_S^{ex} - 0.4$

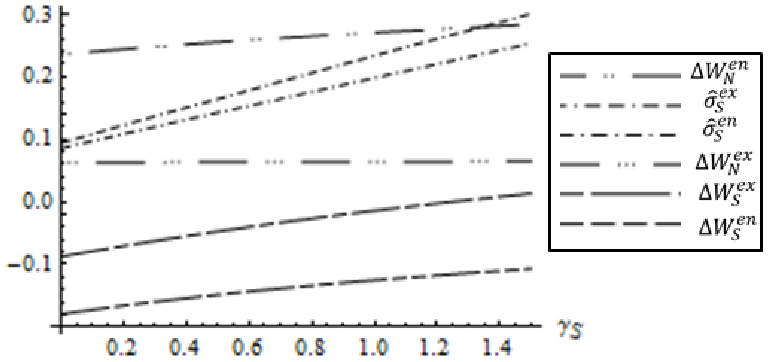

Figure 3: Welfare effects of changing price distortion γ_S.

that would obtain without subsidies. Accordingly, $\Delta W_i^{ex} = W_i^{ex}\big|_{\sigma_S=\sigma_S^{ex}} - W_i^{ex}\big|_{\sigma_S=0}$, $i = N, S$; and equivalently for endogenous endowment choices that are indicated by superscript ^{en}.

The welfare effects for exogenous endowments are in line with Proposition 3. The North always gains from subsidizing TT, while the South does so only if subsidies correct a price distortion on its technology market, i.e. if γ_S is sufficiently high. Turning to the case of endogenous endowments, additional effects arise. In particular, as discussed at the end of the preceding section, a higher subsidy goes along with the choice of more endowments by the North and less endowments by the South. This raises welfare in the North and reduces it in the South, thereby further accentuating the different welfare effects that already existed in the case of exogenous endowments. As a consequence, welfare in the South falls if technology subsidies are introduced over the whole range of depicted price distortions. This happens although the overall welfare effect of subsidies is positive and, in particular, higher than in the case of exogenous endowments.

5 Concluding remarks

Technology transfers have become a central element of ongoing climate negotiations. Nevertheless, they have rarely been integrated as a strategic decision variable in models of international environmental agreements (IEAs). We have tried to fill this gap. In our model, incentives of the North to subsidize TT crucially depend on the existence of a system of tradable permits. Moreover, subsidies leads to improved abatement technologies in the South. Given the lower abatement costs, the regions choose less 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 GHG 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.

Despite this positive assessment of a joint system of permit trading and TT, our analysis has also highlighted a fundamental conflict of interests. In particular, permit trading is crucial for the Northern incentives to subsidize TT, but the South benefits from TT only if there is no permit trading. This may help to understand that in ongoing climate negotiations the South is pressing for TT, but reluctant to overtake binding reduction targets, which are a prerequisite for a permit trading system. Nevertheless, at least in our numerical example both regions gain from a joint system of TT and permit trading, in comparison to the scenario of no international climate policy. This is due to the resulting lower emissions and the efficiency gains on the permit market. Hence the political prospects may not be that bad after all.

This is particularly true if one takes into account that we have imposed rather pessimistic assumptions about countries' ability to agree on cooperative action. They behaved completely non-cooperatively in all their decisions. If the North were willing to share some of its gains from technology subsidies with the South, this would moderate the asymmetric effects on the regions' welfare and improve the political acceptance.

Accordingly, a possible extension of the paper would be to allow for some degree of cooperative behavior or prosocial preferences and to systematically analyze their implications. Other assumptions that we have employed to keep the model tractable set the stage for further extensions. First, we have considered only two regions. The incorporation of more regions would not affect the basic mechanisms in the model, but it would add free-rider incentives at the subsidy stage. These arise because a region 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 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. This might also be a way to provide an explicit microfoundation for the price distortion parameter, γ_S, on the technology market.

Implementing such 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, $p'(\pi_S) > 0$ and $k_S'(\pi_S) < 0$. Accordingly, if the North is a permit seller or does not trade, then the left-hand side of (14) is non-positive and we have a boundary solution with $\sigma_S = 0$.

By contrast, if the North is a permit buyer, then $-p'(\pi_S)(\omega_N - x_N) > 0$ 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., $\tilde{k}_S = k_S^0$. By contradiction to statement (*ii*), suppose that $\sigma_S = 0$; hence $k_S = k_S^0$ by definition of k_S^0. In this case $k_S - \tilde{k}_S + \sigma_S k_S'(\pi_S) = 0$ so that the left-hand side of (14) is strictly positive. Therefore, $\sigma_S = 0$ can not be an optimal solution. Second, suppose that the North is not able to restrict subsidies to additional investments, i.e., $\tilde{k}_S < k_S^0$. In this case $k_S - \tilde{k}_S > 0$ even at $\sigma_S = 0$. If this term is sufficiently large compared to the other terms in (14), then we may have a boundary solution with $\sigma_S = 0$ (statement *iii*). ■

A2: Proof of Proposition 4

For interior solutions with $\sigma_S^c > 0$, it follows immediately from the first-order condition (14) for subsidies – or, equivalently, from Proposition 2(*i*) – that $\omega_N^c < x_N^c$. Turning to boundary solutions with $\sigma_S^c = 0$, remember that $v_N'(\omega^c) > v_S'(\omega^c)$ by assumption. Substituting from the first-order conditions for endowment choices, (21) and (20), thereby noting that $\omega_S^c - x_S^c = -(\omega_N^c - x_N^c)$, it follows that

$$2p'(\omega^c)(\omega_N^c - x_N^c) > \gamma_S k_S'(\omega^c). \tag{22}$$

Given that $p'(\omega^c) < 0$, this implies $\omega_N^c < x_N^c$ for γ_S sufficiently small (while the outcome is ambiguous for large γ_S due to $k_S'(\omega^c) \leq 0$). ■

A3: Proof of Proposition 5

We want to show that $\omega(\sigma_S^c) - \omega(0) < 0$, where $\omega(\sigma_S^c)$ and $\omega(0)$ are endowment choices that arise in the regimes with subsidies ($\sigma_S = \sigma_S^c > 0$) and with no TT ($\sigma_S = 0$). Given the lack of closed form solutions we can not directly compare these endowment levels. However,

$$\omega(\sigma_S^c) - \omega(0) = \int_0^{\sigma_S^c} \omega'(\sigma_S)\, d\sigma_S, \tag{23}$$

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

To determine $\omega'(\sigma_S)$, summation of the first-order conditions for endowment choices, equations (20) and (21), yields

$$2p - \sigma_S k_S'(\omega) + \gamma_S k_S'(\omega) - v_N'(\omega) - v_S'(\omega) = 0, \tag{24}$$

which implicitly defines ω as a function of σ_S. For high values of ω, we may have a boundary solution with $k_S = \underline{k}_S$ and $k_S'(\omega) = 0$. In this case, a marginal change in the subsidy level has no real effects and $\frac{d\omega}{d\sigma_S} = 0$.

By contrast, if ω is sufficiently low an interior solution with $k_S > \underline{k}_S$ obtains. For this case, implicit differentiation of (24) yields (remember that $d\pi_S/d\sigma_S = d\bar{\pi}_S/d\sigma_S = -1$)

$$\frac{d\omega}{d\sigma_S} = \frac{2p'(\pi_S) + k_S'(\omega) - (\sigma_S - \gamma_S)\frac{\partial k_S'(\omega)}{\partial \pi_S}}{2p'(\omega) - (\sigma_S - \gamma_S) k_S''(\omega) - v_N''(\omega) - v_S''(\omega)}, \tag{25}$$

where the derivatives account for the effects of endowment choices and subsidies at the subsequent stages of the game. From the comparative statics (11) and (19) we have $k_S'(\omega) = -p'(\pi_S)$ so that $2p'(\pi_S) + k_S'(\omega) = p'(\pi_S)$ and $-\frac{\partial k_S'(\omega)}{\partial \pi_S} = p''(\pi_S)$. Upon substitution into (25)

$$\frac{d\omega}{d\sigma_S} = \frac{p'(\pi_S) + (\sigma_S - \gamma_S) p''(\pi_S)}{2p'(\omega) - (\sigma_S - \gamma_S) k_S''(\omega) - v_N''(\omega) - v_S''(\omega)}, \tag{26}$$

Accordingly, the numerator of (25) is positive for all σ_S if $p''(\pi)$ is not too small and γ_S is not too large, e.g. if $p''(\pi) \geq 0$ and $\gamma_S \leq \sigma_S$. Moreover, the denominator is negative by the second-order conditions with respect to the regions' endowment choices. To see this, note that these conditions require that (using $d\omega/d\omega_i = 1$)

$$\frac{d}{d\omega}\left(\frac{dW_i}{d\omega}\right) < 0, \qquad i = N, S.$$

Hence, summation yields

$$\frac{d}{d\omega}\left(\frac{dW_N}{d\omega}\right) + \frac{d}{d\omega}\left(\frac{dW_S}{d\omega}\right) = \frac{d}{d\omega}\left(\frac{dW_N}{d\omega} + \frac{dW_S}{d\omega}\right) < 0.$$

In the above calculations, $\frac{dW_N}{d\omega} + \frac{dW_S}{d\omega}$ is given by the l.h.s. of (24). The denominator of (26) is the derivative of this term with respect to ω, i.e. $\frac{d}{d\omega}\left(\frac{dW_N}{d\omega} + \frac{dW_S}{d\omega}\right) < 0$. ■

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