Incentives for Advanced Abatement Technology Under National and International Permit Trading

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Abstract

We analyse the incentives for polluting firms to diffuse and adopt advanced abatement technology in two different frameworks, a national and an international one. In the first framework, the national government establishes a national permit market. In the second one, governments negotiate an environmental agreement that establishes an international permit market. In both scenarios we consider three different variants of allocation procedures (auctioning, benchmarking and grandfathering).

We show that in the national as well as in the international scenario the incentives to diffuse and adopt the technology depend on the allocation rule. Whereas in the national scenario diffusion (if it occurs) always leads to socially optimal outcomes, diffusion may increase global environmental damages and reduce global welfare in the international scenario.

This paper extends the seminal analysis by Milliman/Prince (1989).

JEL classification: Q5

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1 Introduction

Long-term oriented environmental policy cannot be confined to induce polluters to make efficient use of existing abatement technology. Additionally, it must create proper incentives to invent and to disseminate superior technologies. There is a growing body of literature on these dynamic aspects of environmental policy. There, different stylizations of technical change are used. In most of the contributions, technical progress is taken to reduce total and marginal abatement costs for all levels of abatement (see, e.g., Downing & White 1986; Endres 2011; Milliman & Prince 1989 or Parry 2003). Some models have technical progress reducing total abatement costs for all levels, and reducing marginal abatement costs for some levels of abatement (see, e.g., Amir et al. 2008; Baker et al. 2008; Bauman et al. 2008; Endres &Friehe 2011b). A third strand of the literature stylizes technical change to reduce total and marginal environmental damage (see, e.g., Dari-Mattiacci & Franzoni 2014; Endres & Friehe 2012; Endres & Friehe 2013b; Jacob 2013)[1]. In the paper at hand, we use the traditional approach taken by the most part of the literature: Technical progress generates a downward shift in the total and marginal abatement cost curves for all levels of abatement.

An established distinction in the literature on technical change (in the environmental economics context and beyond) is the one between innovation and diffusion. Most of the literature deals with innovation, but it is generally acknowledged that diffusion is just as important in a policy context as well as theoretically interesting. The seminal paper in this context is the one by Milliman and Prince (1989). They were the first to compare the performance of alternative environmental policy instruments with respect to their ability to induce the development of superior abatement technologies and the diffusion of these technologies. Meanwhile, there are several papers analysing different aspects of the diffusion issue in different analytical frameworks (see, e.g., Jaffe & Stavins 1995; Requate & Unold 2001, 2003; Coria 2009; Endres & Friehe 2011a). A common feature of all of these analyses is that they are confined to a national setting. By contrast, we allow polluting firms to be located in different countries and governments to negotiate an environmental agreement. We

[1] A framework within which technical progress reduces total damage for all levels of abatement and marginal damage for some levels of abatement is an obvious extension. To the best of the authors´ knowledge, this particular combination of assumptions has not yet been used in the literature. It seems to be worthwhile to do that for the following reason: The literature cited earlier showed that changing the assumptions from technical progress reducing marginal abatement costs for all levels of abatement to technical progress changing marginal abatement costs for some levels of abatement has significant impact for the results of the models. Analogously, changing the assumption from technical progress reducing marginal damage for all levels of abatement to technical progress reducing marginal damage for some levels of abatement might lead to interesting new results, too.

compare the dynamic incentive effects of an important environmental policy instrument in the national setting to the incentives in the international setting. This instrument is the use of tradeable emission permits. Most of the papers cited above either do not consider permit trading at all (Jaffe & Stavins 1995 and Endres & Friehe 2011b) or do only compare auctioning with a free allocation of permits based on grandfathering ignoring benchmarking (Milliman & Prince 1989; Requate & Unold 2001, 2003). Requate & Unold (2001, 2003) and Coria (2009) analyse the incentives to adopt an innovative technology but do not analyse the incentives of the innovator to promote diffusion which are in the main focus of our paper. [2] With respect to the diffusion and adoption incentives in case of auctioning and grandfathering in the national scenario, our results are analogous to those of Milliman & Prince (1989) (in their scenario of ex post regulation).[3] To the best of the authors' knowledge, in the literature there has neither been an analysis of diffusion (and adoption) incentives of benchmarking in the national context; nor have the incentives for technology transfer under tradable discharge permits in an international setting been analysed before. The paper at hand is not the first one to consider induced technical change within an international context. There are some recent publications which have done that before. However, it must be noted that they deal with this issue in a completely different framework. Most of them either use macroeconomic growth models (see, e.g., Bosetti & Tavoni 2009; Gerlagh et al. 2009; Held et al. 2009; Löschel & Otto 2009; Otto et al. 2008), consider an exogenously given international environmental agreement (see, e.g., Golombek & Hoel 2005, 2008; Hagem 2009) or assume non-cooperative behaviour between governments (see, e.g., Golombek & Hoel 2004; Ulph & Ulph 1996, 2007). Opposed to that, in the paper at hand endogenous bargaining for an international environmental agreement is analysed. The formation of an international agreement is studied by Hong & Wang (2012). Their paper is concerned with how climate policy and learning about climate damages affect investment in abatement technology in small countries. Opposed to that, Endres & Rundshagen (2013) analyse technology transfer induced by environmental policy within a setting in which the results of international environmental negotiations depend on the diffusion (and adoption) decisions. However, that paper does not consider a permit regime but only negotiations about emission taxes and quotas.

[2] Note that in the literature the term „diffusion" often comprises the diffusion activity of the innovator as well as the adoption activity of the potential recipient. To have a clear terminology in our model we distinguish between *diffusion* incentives of the innovator and *adoption* incentives of the potential recipient. If and only if both incentives are positive, a *technology transfer* takes place.

[3] However, the model presented in the paper at hand is more general than the one by Milliman & Prince (1989). See footnote 8 for elaboration.

There is a last strand of literature to be mentioned, to which the paper at hand is related. This is the literature on endogenous formation of international environmental coalitions.[4] To distinguish the contributions to this literature from the paper at hand, it is important to note that this literature does not consider induced technical change. The contributions to this literature can be divided into two categories. They are distinguished by their assumptions on how the members of a coalition deal with each other. In the first subset of this literature, the members of a coalition are taken to maximize aggregate welfare of the coalition and to determine the corresponding equilibrium coalition structure (see, e.g., Breton et al. 2006; Carraro & Siniscalco 1993; Osmani & Tol 2009; Yi & Shin 2000). In the second subset of the literature, the somewhat optimistic assumption of joint welfare maximization is relinquished. It is deemed to be unfeasible in most cases since interests of involved countries are highly asymmetric. Consequentially, the equilibrium outcome of a given coalition structure is determined endogenously in these models. (See, e.g., Endres & Finus 2002; Endres & Rundshagen 2013; Espinola-Arredondo 2009; Finus et al. 2005; Hoel 1992). This is the approach taken in section 4 of the present paper, where we analyse diffusion and adoption incentives in an international scenario. There, consideration is given to the incentives for polluting firms to diffuse and adopt advanced abatement technology in a framework in which governments negotiate an international permit regime. In both scenarios, the national and the international one, the equilibrium outcomes depend on the permit allocation rule. We consider the following three variants: *auctioning, benchmarking* and *grandfathering*. In the international scenario, we assume that each government makes a proposal with respect to the uniform emission reduction. We call the country with the smallest proposal the “bottleneck country” and assume that the countries agree on the lowest common denominator, i.e., the proposal made by the bottleneck country.[5] We consider a three-stage game with one country in the national scenario (section 3) and two countries in the international scenario (section 4). We assume that there are two firms A and B, of which firm A uses a superior technology that would also be useful for firm B. In section 4, firm A and B are settled in different countries.

[4] For an overview see, e.g., Finus (2008).

[5] The assumption that the countries bargain over uniform policy levels and agree on the lowest common denominator is a simplification frequently used in the literature: see, for example, Altamirano-Cabrera et al. (2008), Endres (1997), Endres & Rundshagen (2013), Eyckmans (1999) and Finus & Rundshagen (1998). It is quite common in real world international negotiations (see Barrett 2003) and is also used in the design of economic experiments analysing the formation of coalitions to provide public goods (see Dannenberg, Lange & Sturm 2014 and Kesternich, Lange & Sturm 2012).

Further, we assume that in each country (in the international setting, chapter 4) or region (in the national setting, chapter 3) there is a *residual industry*, for which the superior technology is of no interest, but which also participates in emission trading.

At *stage one*, the firm with the superior abatement technology determines its preferred level of diffusion, and the firm with the inferior abatement technology decides whether it wants to adopt the better technology. At the *second stage*, the governments negotiate the global environmental policy level in case of the international framework. In the national framework, the single government chooses its optimal policy level. At the *third stage*, the firms choose their emission levels. We analyse the game by backward induction.

It turns out that in the national as well as in the international scenario the incentives to diffuse and adopt depend on the allocation rule. In the national scenario, equilibrium emissions and welfare are always at their socially optimal levels, in case there is an equilibrium technology transfer. Opposed to that, equilibrium technology transfer may increase global damages and thereby reduce global welfare in the international scenario.

We proceed as follows. To provide a reference point, we begin by deriving the socially optimal technology transfer level in section 2. In section 3, we analyse the national framework, whereas section 4 characterizes the international negotiation outcomes under alternative permit allocation rules. In section 5, we conclude and discuss issues for future research.

2 Socially Optimal Emissions and Technology Transfer

We consider a model with two polluting firms, $i \in \{A, B\}$. Each firm is located in a corresponding country or region (*A*, *B*), respectively.[6,7] Firm *i*'s emissions are given by E_i, and total emissions of the global pollutant are given by $E = E_A + E_B + E_R$ with $E_R = E_{RA} + E_{RB}$ denoting the aggregate emissions of the residual industries in country (or region) *A*, *B*, respectively. Environmental damage in each country (or region) is assumed to be given by $D^i(E) = d_i E^2$, i.e., marginal damages are positive and strictly increasing. The emission level E_i ($i \in \{A,B\}$) corresponds to benefits $B^i(E_i, T_i)$, where $B_E > 0$ for $E_i < E_i^{\max}(T)$ and $B_{EE} < 0$ holds, i.e., marginal benefits from emissions are positive and strictly decreasing in

[6] We use the assumption that there is one firm in each region/country that (may) use the superior abatement technology, and so as to simplify notation we use the same indices A, B for the names of the firms as well as for the regions/countries. A generalisation of our model with $n \geq 1$ firms in each region/country, more region/countries or additional polluters would not affect the qualitative results, but complicate the analysis.

[7] In section 3 the firms are located in different regions that belong to one country with a single government. In section 4 the firms are located in different countries.

the relevant range $0 < E_i < E_i^{\max}(T)$.[8] T_i represents the state of the technology in use. A higher technology level increases the benefit level ($B_T > 0$).[9] Additionally, we assume that marginal benefits from emissions and hence marginal abatement costs are decreasing with regard to the state of the technology used ($B_{ET} < 0$).[10] These assumptions together imply that $dE_i^{\max} / dT < 0$ holds. Firm *A* has advanced abatement technology at its disposal ($T_A = 1$), while the status quo abatement technology of firm *B* is inferior to that of firm *A* ($T_B^0 = 0$). In the social optimum (as a reference scenario), the social planner not only decides on the emission levels E_i but also on the technology transfer parameter $\gamma \in \{0,1\}$, which describes whether the technology spills over to firm *B* ($T_B = T_B^0 + \gamma = \gamma$). Under decentralization, the technology transfer only occurs if diffusion is preferable for the technology-providing firm A and adoption is preferable for the technology receiving firm B. For simplicity, we assume that diffusion and adoption are costless. Moreover we have the benefit functions $B^{Ri}(E_{Ri})$ of the residual industries *RA, RB* with $B_E > 0$ for $E_i < E_{Ri}^{\max}$ and $B_{EE} < 0$.

The social planner seeks to maximize the expected welfare associated with pollution. This welfare comprises the benefits from emissions minus expected damages. Hence, the optimization problem faced by the social planner is given by

(1) $$\max_{\gamma, E_A, E_B, E_{RA}, E_{RB}} W = B^A(E_A,1) + B^B(E_B,\gamma) + B^{RA}(E_{RA}) + B^{RB}(E_{RB}) - \sum_{i\in\{A,B\}} D^i(E_A + E_B + E_{RA} + E_{RB}) .$$

The corresponding first-order conditions are

(1.a) $$W_{E_A} = B_E^A(E_A,1) - \sum_{i\in\{A,B\}} D^{i\prime}(E) = 0 , \quad W_{E_B} = B_E^B(E_B,\gamma) - \sum_{i\in\{A,B\}} D^{i\prime}(E)$$

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[8] In contrast, Milliman & Prince (1989) assume that $E_i^{\max}$ is independent of the technology level. Moreover, they do not consider a residual industry that takes part in emission trading. These two distinctions imply that our setting is more general and comes closer to reality in the following sense: i) In reality innovation not only changes the slope of the emission benefit curve, it also quite frequently changes the emission level, which would be optimal in the absence of regulation. ii) One and the same pollutant can be caused by very different industries X, Y, such that an emission abatement technology that can be used by industry X is of no use for industry Y. Moreover the residual industry is necessary to formalize a plausible benchmarking scenario. Under benchmarking the assigned permit number is not directly linked to the emission target, i.e., a tightening of the emission target reduces the permit allocation of the residual industry only.

[9] Below, we only consider discrete border case levels for the technology parameter $(T_i \in \{0,1\})$, i.e., in equilibrium there is either total or no transfer of the superior technology. Still, we assume that the benefit functions are defined and sufficiently differentiable in the whole range $T_i \in [0,1]$.

[10] This is the standard assumption used in most of the research literature and (as far as the authors are aware of) used in all textbooks. However, recent publications have acknowledged the empirical observation that some kinds of technical change exist that are associated with a reduction in marginal abatement costs only for a sub-range of abatement levels, while for another range marginal abatement costs are increasing (see e.g. Baker & Adu-Bonnah 2008; Baker et al. 2008; Bauman et al. 2008 and Endres & Friehe 2011a, 2012, 2013a). Another way to stylize technical change is that it decreases emissions per unit of output (see, e.g., Ulph & Ulph 2007). For simplicity, we confine our analysis to the case in which technical progress induces an overall reduction of marginal abatement costs and ignore all other modelling possibilities.

(1.b) $W_{E_{Ri}} = B_E^{Ri}(E_{Ri}) - \sum_{i\in\{A,B\}} D^{i'}(E) = 0$, $i \in \{A,B\}$

(1.c) $W_\gamma = B_T^B(E_B,\gamma) > 0$.

With respect to the emission levels, we focus on interior solutions and thereby consider only cases in which the social planner seeks to induce positive emission (and positive emission abatement) levels from both firms and the residual industries. The conditions (1.a) and (1.b) state that the optimal emission levels are obtained if marginal benefits equal aggregate marginal damage. Equation (1.c) directly implies the following statement:

Proposition 1: *Socially optimal technology transfer level*
The socially optimal technology transfer level is given by , "complete technology transfer".[11]

3 Permit Trading in a National Framework

3.1 The three-stage game

In this section, we consider a national scenario where we assume that the firms and the residual industries are located in the same country, i.e., $D = D^A + D^B = (d_A + d_B)E^2 =: dE^2$ represents national damages. As mentioned in the introduction, for each allocation procedure we consider a three-stage game which is solved by backward induction.

Stage 1: Diffusion (and adoption) decision of firm A (and B)
Stage 2: Choice of emission target (= number of permits) (and initial permit allocation)
Stage 3: Choice of emission levels (and permit trade)

Whereas stages 2 and 3 can be analysed independently from the underlying permit allocation rule, the outcome of type 1 depends on it. Hence, we analyse stage 1 of the game for three permit allocation rules: a) auctioning, b) benchmarking and c) grandfathering.
With respect to stages 1 and 2, note the following remarks: At stage 1, firm B only has to decide whether it wants to adopt the technology if firm A has a positive diffusion incentive, i.e., if firm A offers the new technology to firm B. To determine the optimal emission target at stage 2, the regulator calculates the equilibrium firm-specific emission levels for any possible

[11] Since the optimal transfer parameter equals one (complete technology transfer) we have a clear reference scenario from which deviations can be easily measured. The introduction of costs for technology diffusion and/or adoption would reduce the incentives to diffuse and/or adopt the better technology under each permit allocation rule, which results in the equilibrium technology transfer level $\gamma^* = 0$ for sufficiently high technology transfer costs. However, for sufficiently high costs the socially optimal technology transfer level would also be reduced to $\gamma^{**} = 0$.

emission target. Different from the initial permit allocation, this equilibrium allocation is independent of the permit allocation rule.

Stage 3:

Independent from the allocation rule, at stage 3 marginal benefits are equalized between the firms, i.e., the equilibrium emission levels are determined by

(2) $$B_E^A(E_A,1) = B_E^B(E_B,\gamma) = B_E^{RA}(E_{RA}) = B_E^{RB}(E_{RB}) \;\wedge\; E_A + E_B + E_{RA} + E_{RB} = \bar{E}^\gamma ,$$

with $\bar{E}^\gamma$ denoting the aggregate permit endowment, given the technology transfer level γ (see stage 2).

Stage 2:

Also the chosen emission target at stage 2 does not depend on the allocation rule. Given the technology transfer γ, the optimal emission levels $E_{(R)i}^{\gamma *} := E_{R(i)}^{*}(\gamma)$ are implicitly determined by equations (1.a) and (1.b). The aggregate optimal permit endowment $\bar{E}^\gamma = E^{\gamma *}$ is determined by the intersection of the aggregate marginal abatement cost curve *MAC* and the marginal damage curve *MD*. The aggregate marginal abatement cost curve can be derived by the horizontal aggregation of the individual marginal abatement cost curves. However, these are identical to the marginal benefits from emissions. Due to $B_{ET} < 0$ a technology transfer shifts the marginal abatement cost curve of firm B ($MAC^B = B_E^B$) and hence also the aggregated abatement cost curve MAC downwards, from which $\bar{E}^1 < \bar{E}^0$ follows. (See Figure 1 for a graphical illustration.)

Moreover, for the equilibrium marginal damages and marginal abatement costs we have $D'(\bar{E}^1) < D'(\bar{E}^0)$. Thus from $D'(\bar{E}^\gamma) = B_E^A(E_A,1) = B_E^B(E_B,\gamma) = B^{Ri}(E_{Ri})$ it follows $E_A^{1*} > E_A^{0*}$ and $E_{Ri}^{1*} > E_{Ri}^{0*}$. That means a technology transfer leads to a reduction of the optimal emission level of firm B only ($E_B^{1*} < E_B^{0*}$), whereas the equilibrium levels for firm A and the residual firms increase. The aggregate equilibrium permit level decreases ($\bar{E}^1 < \bar{E}^0$) as well as the equilibrium permit price ($p_1 < p_0$ with $p_\gamma := p(\gamma)$).

Note, that in the national scenario the equilibrium allocation equals the socially optimal one, given that the outcome of the first stage is $\gamma = 1$. Hence, in the national framework a permit allocation rule leads to the socially optimal welfare levels if, and only if, it results in a transfer of the superior technology. In particular, permit allocation rules with equilibrium technology transfer produce higher welfare than allocation rules without equilibrium technology transfer.[12]

[12] As we will see in section 4, below, this assertion does not hold for the international scenario.

To be able to derive analytical solutions, in the following we consider the benefit functions:[13]

$$(3) \qquad B^i(E_i,T_i) = aE_i - b(T_i+1)E_i^2 + \frac{a^2(T+1)}{4b}, \quad B^{Ri}(E_{Ri}) = aE_{Ri} - 2bE_{Ri}^2 + \frac{a^2}{2b}$$

Solving (2) leads to the equilibrium emission levels (under each kind of permit regime):

$$(4) \qquad E_A^{\gamma*} = E_{RA}^{\gamma*} = E_{RB}^{\gamma*} = \frac{1}{2}\frac{a(\gamma+1)}{2b(\gamma+1)+d(3\gamma+5)}, \quad E_B^* = \frac{a}{2b(\gamma+1)+d(3\gamma+5)}.$$

Note, that $E_B^{1*} < E_B^{0*}$ (and the other assertions stated above hold) and for the concrete functions we get $E_B^* > (=) E_A^*$ if, and only if, $\gamma < (=) 1$ holds.

Stage 1:

Whereas it turned out that stages 2 and 3 could be analysed independently from the permit allocation procedure, the diffusion and adoption incentives on stage 1 crucially depend on the allocation rule, as is shown below.

3.2 Alternative Allocation Rules

3.2.1 Auctioning

To see whether the firms involved are interested in technology transfer, we first have to analyse the relevant effects of diffusion and adoption from the points of view of firm A and B, respectively. However, only if the aggregate diffusion incentive for firm A is positive, the sign of the adoption incentive of firm B is relevant for the equilibrium outcome. In case of a negative diffusion incentive of firm A, no technology transfer takes place in equilibrium even if firm B would like to adopt the better technology. For firm A, the only consequence of technology transfer is the *permit price effect*: Due to the downward shift of the aggregate marginal abatement cost curve in case of technology transfer, the equilibrium permit price decreases. This effect is advantageous for firm A. Hence firm A has a positive diffusion incentive.

For firm B, the permit price effect is advantageous for the same reason as it is for firm A. However, for firm B, there is an additional effect in that B´s (total) benefits for a given emission level increase with the new technology. This *technology effect* ($B_T > 0$) is always advantageous for firm B.[14] Hence, the aggregate adoption incentive of firm B is positive since

[13] Note that the benefit functions have the conventional properties, that are postulated in section 2. E.g, marginal benefits from emissions are positive and decreasing, which implies that marginal abatement cost are positive and increasing (see, e.g., Milliman & Prince 1989).

[14] The statement that the technology effect is advantageous for firm B holds independent from the permit allocation rule.

it is composed of two positive effects. Summarizing what has been said about the incentives of the two firms involved, it follows that technology is transferred in equilibrium.

Formally, the (aggregate) incentives for technology transfer are given by the change of the profit levels for firms A and B, respectively:[15]

(5) $$\Delta_A^{nat,auct} = \left(B^A(E_A^{1*},1) - p_1 E_1^{1*}\right) - \left(B^A(E_A^{0*},1) - p_0 E_A^{0*}\right) > 0,$$
$$\Delta_B^{nat,auct} = \left(B_B(E_B^{1*},1) - p_1 E_B^{1*}\right) - \left(B^B(E_B^{0*},0) - p_0 E_B^{0*}\right) > 0.$$

For the functions of type (3) we receive $\Delta_A^{nat,auct} = \frac{1}{8}\frac{a^2 db(4b+9d)}{(2b+5d)^2(b+2d)^2} > 0$ and

$$\Delta_B^{nat,auct} = \frac{1}{8}\frac{a^2\left(4b^4 + 60b^3 d + 235b^2 d^2 + 360bd^3 + 200d^4\right)}{b(2b+5d)^2(b+2d)^2} > 0 .$$

3.2.2 Free allocation of permits based on benchmarking

Under benchmarking, firms do not have to reduce their emissions provided that they use the most efficient technology.[16] In our model this is formalized as follows: firm A receives the amount of permits that equals the emission level firm A would choose (resp. has chosen) in the absence of environmental policy regulation. This amount $E_A^{\max}$ is determined by $B_E^A(E_A^{\max},1) = 0$. Analogously, firm B receives the amount of permit $E_B^{1,\max}$ that is determined by $B_E^B(E_B^{1,\max},1) = 0$, irrespective of whether firm B is using the benchmark technology ($\gamma = 1$) or not ($\gamma = 0$).

As for the auctioning scenario, we have to analyse the incentives for diffusion and adoption of firms A and B, respectively. We do so by elaborating on the effects of diffusion and adoption for firms A and B as well as the "signs" of these effects, meaning whether they are advantageous or detrimental. In case of more than one effect, we investigate the signs of the net effect for each firm under consideration.

Since technology transfer does not affect the permit endowment of firm A, for this firm there is only a *permit price effect* (as in the auctioning case). However, in contrast to the situation under auctioning, the permit price effect is detrimental for firm A under benchmarking. This is due to the following reasoning. From $B_E^A(E_A^{\max},1) = 0$ it follows that in the initial allocation marginal abatement costs of firm A are lower than the (positive) permit price. This holds in the technology transfer just as well as in the non-transfer case. Hence, in both cases firm A

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[15] The superscripts in this equation (and subsequently) indicate both, the national or international scenario, respectively, and the permit allocation rule (here: auctioning).

acts as a permit seller, which implies that a price reduction is detrimental for this firm. Since there are no further effects, the aggregate diffusion incentive is negative for firm A.

For firm B, the situation is somewhat more complicated. Again, we have two effects: the unambiguously advantageous *technology effect* and a *permit price effect*. Whether the latter effect is advantageous for firm B depends upon firm B's part in the permit market in the case of $\gamma = 0$. Whereas in the case of technology transfer ($\gamma = 1$) B acts as a permit seller, just as firm A does, in the opposite case, in which no technology is transferred in the equilibrium situation ($\gamma = 0$) two subcases arise. These subcases are defined by the relationship between firm B´s marginal abatement cost in the starting point situation and the equilibrium permit price. In the first subcase $B_E^B(E_B^{1,\max},0) > p_0$, firm B acts as a permit buyer. In the second subcase $B_E^B(E_B^{1,\max},0) < p_0$, firm B acts as a permit seller. In the first subcase, the permit price effect and also the aggregate adoption incentive is unambiguously positive.[17] In the second subcase, the permit price effect is disadvantageous and the aggregate adoption incentive may be either positive or negative. Summarizing, for the aggregate diffusion and adoption incentives of the two firms, we have

(6) $$\Delta_A^{nat,\,benchm} = \left(B^A(E_A^{1*},1) + p_1(E_A^{\max} - E_A^{1*})\right) - \left(B^A(E_A^{0*},1) + p_0(E_A^{\max} - E_A^{0*})\right) < 0,$$
$$\Delta_B^{nat,\,benchm} = \left(B^B(E_B^{1*},1) + p_1(E_B^{1,\max} - E_B^{1*})\right) - \left(B^B(E_B^{0*},0) + p_0(E_B^{1,\max} - E_B^{0*})\right) <,>,= 0.$$

For the functions of type (3) we receive $E_A^{\max} = E_B^{1,\max}\frac{1}{4}\frac{a}{b}$,

$$\Delta_A^{nat,\,benchm} = -\frac{1}{8}\frac{a^2d^2(9b+20d)}{(2b+5d)^2(b+2d)^2 b} < 0 \text{ and}$$
$$\Delta_B^{nat,\,benchm} = \frac{1}{8}\frac{a^2(4b^4+56b^3d+217b^2d^2+340bd^3+200d^4)}{(2b+5d)^2(b+2d)^2 b} > 0.$$

Since the diffusion incentive of firm A is unambiguously negative, there is no equilibrium technology transfer under benchmarking.

[16] E.g., in the third trading period of the EU emissions trading system for the determination of benchmark values, "the Commission has used as a starting point the arithmetic average of the greenhouse gas performance of the 10% most greenhouse gas efficient installations in 2007 and 2008 for which data has been collected." (See Commission Decision 2011/278/EU (8).)

[17] Note that, strictly speaking, in the first subcase the positive effect might better be called *trade effect*, since in case of diffusion the role of firm B in the permit market changes from *buyer* to *seller*, which is advantageous. However given $\gamma = 1$ and the role of firm B as *seller* a price decline is negative.

3.2.3 Free allocation of permits based on grandfathering

Under grandfathering we assume that the government takes those emission levels as baseline that are chosen after the technology transfer decision but before environmental policy regulation takes place, that is the baseline emission levels are given by $E_A^{\max}$, $E_B^{\gamma,\max}$ and $E_{Ri}^{\max}$. Hence, the total baseline emission level is given by $E^{\gamma,\max} := E_A^{\max} + E_B^{\gamma,\max} + E_{RA}^{\max} + E_{RB}^{\max}$. For the functions of type (3) these levels are given by $E_A^{\max} = E_{Ri}^{\max} = \frac{1}{4}\frac{a}{b}$ and $E_B^{\gamma,\max} = \frac{1}{2}\frac{a}{b(\gamma+1)}$. Since, given γ, under grandfathering (as well as under any other allocation rule) the aggregate permit number is given by $\bar{E}^{\gamma}$, the emission reduction level r_{γ} is given by $r_{\gamma} = 1 - \bar{E}^{\gamma} / E^{\gamma,max}$ and each firm receives the share $1 - r = \bar{E}^{\gamma} / E^{\gamma,\max}$ of its initial emission level $E_{(R)i}^{(\gamma,)\max}$.

Obviously, under grandfathering, technology transfer will have permit price and technology effects. We will elaborate on those arguing analogously to how we did for the rules of auctioning and benchmarking, above. Before we do, we turn to a consequence of technology transfer under grandfathering which has no analogon under the two other rules. This consequence is the *quantity effect*, which relates to both firms. This effect refers to the fact that the initial permit allocation under grandfathering depends upon whether technology is transferred in equilibrium or not. Under the two allocation modes analysed earlier, initial permit allocation is always independent from equilibrium technology transfer. The quantity effect relates to both firms. It is disadvantageous if the initial permit allocation of a firm decreases in case of technology transfer. For firm B this unambiguously holds because of $(1-r_1)E_B^{1,\max} < (1-r_0)E_B^{0,\max}$.[18] For firm A, the *quantity effect* may be either advantageous or detrimental. It is advantageous if $(1-r_1)E_A^{\max} > (1-r_0)E_A^{\max}$ or equivalently $r_1 < r_0$ holds. Since $dE^{\gamma,max} / d\gamma = dE_B^{\gamma,max} / d\gamma < 0$ and $d\bar{E}^{\gamma} / d\gamma < 0$ (see section 3.1) holds, the sign of $dr_{\gamma} / d\gamma = -d(\bar{E}^{\gamma} / E^{\gamma,max}) / d\gamma$ is undetermined, which implies that the quantity effect of firm A may be either advantageous or detrimental. To illustrate this point, we take a look at Figures 1a and 1b.

[18] This can be easily proven by contradiction. Assume $(1-r_1)E_B^{1,\max} > (1-r_0)E_B^{0,\max}$. From $E_B^{1,\max} < E_B^{0,\max}$ it follows $r_1 < r_0$. However, this implies $(1-r_1)(E_A^{\max} + E_B^{1,\max} + E_{RA}^{\max} + E_{RB}^{\max}) > (1-r_0)(E_A^{\max} + E_B^{0,\max} + E_{RA}^{\max} + E_{RB}^{\max})$, i.e., the aggregate number of permits would increase in case of technology transfer. This is a contradiction to the result of section 3.1.

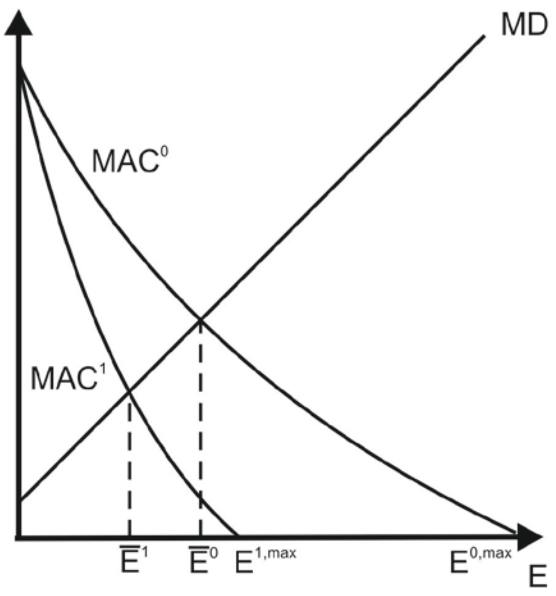

Figure 1a

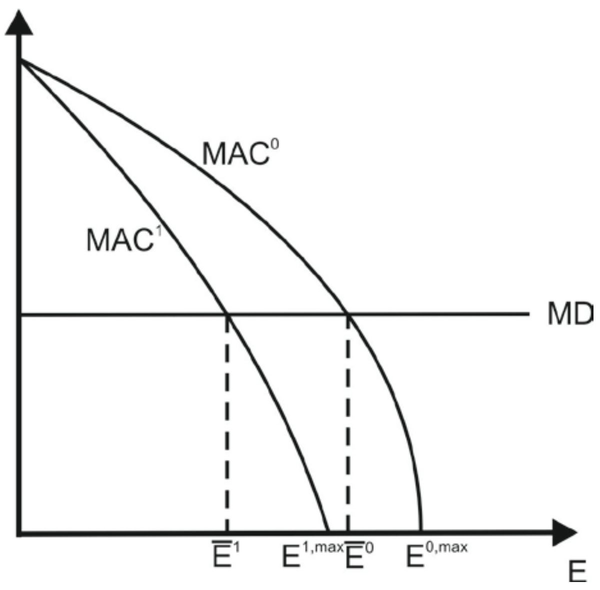

Figure 1b

Each figure plots a possible shape of the aggregate marginal damage curve (MD) and the aggregate marginal abatement cost curves in case of $\gamma = 0$ (MAC^0) and $\gamma = 1$ (MAC^1), respectively.

Whereas Figure 1a illustrates a case where (as for the type (3) functions with linear marginal abatement costs) $r_1 = 1 - \bar{E}^1 / E^{1,\max} < r_0 = 1 - \bar{E}^0 / E^{0,\max}$ holds, Figure 1b illustrates the opposite case, i.e., $r_1 > r_0$. From the figures we can see that convexity of the marginal benefit functions and increasing marginal damages work in favour of an advantageous quantity effect for firm A. In the boundary case with constant marginal damage function (as shown in figure 1b), technology transfer does not influence the permit price and the optimal emission level of firm A, i.e., $E_A^{1*} = E_A^{0*}$. In this case the sign of the aggregate diffusion effect equals the one of the quantity effect. More precisely we have $\Delta_A^{national,grandf} = p(r_0 - r_1)E_A^{\max}$ with $p := p_1 = p_0$.

For the functions of type (3) we receive $r_1 = 2d/(b+2d)$ < $r_0 = 5d/(2b+5d)$, i.e., the quantity effect is advantageous for firm A.

In case of increasing marginal damages beside the quantity effect, we additionally have to consider the *price effect.* To analyse this effect in the following we restrict our attention to the border case $r_1 = r_0$, i.e., we assume that the quantity effect for firm A equals zero. In this case technology transfer reduces the worth of firm A's permit endowment in case it acts on the permit market as permit seller. On the other hand, the price decline is advantageous when firm A acts as a permit buyer. Summarizing, the quantity effect as well as the price effect may be either advantageous or detrimental and hence may work in favour of or against diffusion from the point of view of firm A.

As for firm A, the sign of the *price effect* for firm B is undetermined. Additionally we have the disadvantageous *quantity effect* and the advantageous *technology effect*.
Summarizing the aggregate diffusion and adoption incentives of firms A and B are given by

(7)

$$\Delta_A^{nat,grandf} = \left(B^A(E_A^{1*},1) + p_1((1-r_1)E_A^{\max} - E_A^{1*})\right) - \left(B^A(E_A^{0*},1) + p_0((1-r_0)E_A^{\max} - E_A^{0*})\right) >,<,= 0\,,$$

$$\Delta_B^{nat,grandf} = \left(B^B(E_B^{1*},1) + p_1((1-r_1)E_B^{1,\max} - E_B^{1*})\right) - \left(B^B(E_B^{0*},0) + p_0((1-r_0)E_B^{0,\max} - E_B^{0*})\right) >,<,= 0.$$

For the functions of type (3) we receive

$$\Delta_A^{nat,grandf} = \frac{1}{8}\frac{a^2d^2(9b+20d)}{(2b+5d\ )^2(b+2d)^2} > 0 \text{ and}$$

$$\Delta_B^{nat,grandf} = \frac{1}{8}\frac{a^2(4b^4+36b^3d+155b^2d^2+300bd^3+200d^4)}{b(2b+5d\ )^2(b+2d)^2} > 0\,.$$

That is, the diffusion and adoption incentives are positive and technology transfer takes place in equilibrium.

3.3 Welfare Comparison

In the previous subsections we analysed the diffusion and adoption incentives and the corresponding equilibrium technology transfer levels under three permit allocation rules. It has been shown that under auctioning technology transfer always takes place at stage 1, whereas under grandfathering it depends on the functional forms. So far, the results of Milliman & Prince (1989) have been extended to our somewhat more general setting. Moreover, we have shown that under benchmarking no technology transfer takes place due to the negative diffusion incentives of firm A. Hence we are able to add to the ranking of allocation rules presented by Milliman & Prince (1989), as we do in Proposition 2.a. Moreover, we do not only compare the incentives for technology transfer but also the corresponding welfare effects in Proposition 2.b. Auctioning always leads to the socially optimal outcome and benchmarking leads to lower welfare due to the lack of technology transfer. However, for grandfathering the result is ambiguous again.

Proposition 2: Comparison of technology transfer and welfare in the national scenario

a) In the national scenario for the permit allocation rules auctioning, grandfathering and benchmarking holds
$1 = \gamma^{nat,auct} \geq \gamma^{nat,grandf} \geq \gamma^{nat,benchm} = 0$.[19]

b) In case of technology transfer emission levels are lower and welfare levels are higher than in case of non-transfer.
For the corresponding emission and welfare levels the following relations hold:
$E^{**} = E^{nat,auct} \leq E^{nat,grandf} \leq E^{nat,benchm}$ and $W^{**} = W^{nat,auct} \geq W^{nat,grandf} \geq W^{nat,benchm}$.

Proof:
a) See section 3.2.
b) Follows from two facts. First, for a given level of technology transfer the equilibrium outcomes with respect to aggregate emissions and welfare are identical under all three permit allocation rules. Second, only in case of $\gamma = 1$, these outcomes equal the socially optimal ones.

4 International permit market

4.1 The three-stage game

We now assume that the two firms and residual industries are located in different countries. That is, firm A and the residual industry RA are located in country A, whereas firm B and the residual industry RB are located in country B. In the following we mainly focus on the functions of type (3) since this type of benefit functions suffices to demonstrate the differences between the national and international scenario with respect to the resulting welfare effect of the different allocation rules. Additionally we describe the relevant effects for the general functions introduced in section 2. As in section 3 we have a three-stage game, which is solved by backward induction. Whereas stages 1 and 3 are identical to the national game, at stage 2 we replace the decision of the national government by a bargaining procedure between the governments of the two countries. We assume that the countries negotiate a uniform emission reduction level and agree on the lowest common denominator. Hence, we have the following three stage game:

[19] Since $\gamma \in \{0,1\}$ we either have $1 = \gamma^{nat,auct} = \gamma^{nat,grandf} > \gamma^{nat,benchm} = 0$ or $1 = \gamma^{nat,auct} > \gamma^{nat,grandf} = \gamma^{nat,benchm} = 0$.

Stage 1: Diffusion (and adoption) decision of firm A (and B)
Stage 2: Bargaining of the emission target (= number of permits) according to the smallest common denominator rule
Stage 3: Choice of emission levels (and permit trade)

After the bargaining decision at stage 2 each country distributes its permits according to the considered allocation rule. As in the national scenario we consider the allocation rules auctioning, benchmarking and grandfathering. In case of auctioning, permit revenues are assumed to remain in the seller country.[20] In case of the free permit distribution rules, all permits are distributed to the national industry.
As in section 3, we solve the game by backward induction.

Stage 3:
As in the national scenario, marginal benefits are equalized between the firms. I.e., the equilibrium emission levels are determined by (2). For a given aggregate emission reduction level r, and technology transfer level γ we denote the equilibrium emission levels by $E^{\gamma}_{(R)i}(r)$.

Stage 2:

At stage 2, the governments negotiate an internationally uniform abatement level and agree on the lowest emission reduction proposal, by assumption. In this context the country with the lowest emission reduction proposal is called "bottleneck country" and its proposal the "smallest common denominator".[21]
Note that in contrast to the national scenario, also in case of technology transfer ($\gamma = 1$), at stage 2 the bargained emission target generally differs from the socially optimal one due to asymmetric preferences of the two countries.

The corresponding optimization problems of the two countries are given by

(8)

$$\max_r W_A = B^A(E^{\gamma}_A, 1) + B^{RA}(E^{\gamma}_{RA}) + p_{\gamma}(r)\Big((1-r)(E^{\max}_A + E^{\max}_{RA}) - (E^{\gamma}_A + E^{\gamma}_{RA})\Big) + d_A(rE^{\gamma,\max})^2,$$

$$\max_r W_B = B^B(E^{\gamma}_B, \gamma) + B^{RB}(E^{\gamma}_{RB}) + p_{\gamma}(r)\Big((1-r)(E^{\gamma,\max}_B + E^{\max}_{RB}) - (E^{\gamma}_B + E^{\gamma}_{RB})\Big) + d_B(rE^{\gamma,\max})^2.$$

In the following we want to discuss how the optimal values of r for countries A and B (and hence their proposals r_A and r_B are influenced by technology transfer, and which country

[20] In contrast, Hong & Wang (2012) assume that permit fees are transferred from the country to the IEA (see Hong & Wang (2012), p. 396).
[21] See the literature cited in footnote 5.

takes the role of the bottleneck country. Therefore we first take a closer look at the optimization problem of country A.

For country A, first, there is the *environmental effect*. The baseline emission level of firm B ($E_B^{\gamma,\max}$) and hence also the aggregate emission level ($E^{\gamma,\max}$) decreases in case of technology transfer. This implies that (for a given level of r) marginal damages are decreasing ($2d_A((1-r)E^{1,\max}) < 2d_A((1-r)E^{0,\max})$. This effect works in favour of a lower emission reduction level r.

Additionally, there is a *permit price effect* the sign of which depends on the shape of firm B's marginal abatement cost in case of $\gamma = 1$ and $\gamma = 0$. To understand this point we take a look at Figures 1a and 1b again. However, we now interpret the plotted marginal abatement cost functions as the abatement costs of firm B under $\gamma = 1$ and $\gamma = 0$, respectively. (This implies that $E^{\gamma,\max}$ in the figure now represents $E_B^{\gamma,\max}$). If the marginal abatement cost functions of firm B are represented by the curves of Figure 1b, $MAC_B^1((1-r)E_B^{1\max}) < MAC_B^0((1-r)E_B^{0,\max})$ holds. That is for a given level of r initial marginal abatement cost of firm B and hence also the equilibrium permit price decrease in case of technology transfer. This is detrimental for country A if it is a net permit seller. In this case this effect also works in favour of a weaker emission target, that is a lower level of r. If, on the other hand, the marginal abatement cost functions of firm B are represented by Figure 1a, we have $MAC_B^1((1-r)E_B^{1\max}) > MAC_B^0((1-r)E_B^{0,\max})$. This is advantageous for country A if it is a net permit seller. In this case the permit price effect works in favour of a stricter emission target.[22]

For country B the situation is as follows: As for country A, there is the *environmental effect*, which works in favour of a weaker emission target. Whether this effect is stronger for country A or country B depends on the relation of the damage parameters d_A and d_B.

Additionally, there is the *permit price effect* the sign of which is opposed to the sign of the permit price effect of country A. In particular, as for country A, this effect may work in favour of a weaker as well as in favour of a stricter emission target. [23]

The aggregation of the country specific effects described above results in the equilibrium proposals r^A and r^B. For a sufficiently high value of d_A (in relation to d_B) country B is the bottleneck country, that is, it makes the less ambitious emission reduction proposal ($r^B < r^A$) and vice versa.

To be able to make more precise assertions, in the following we restrict our attention to the benefit functions of type (3). Since the corresponding marginal abatement cost curves are

[22] If country A is a net permit buyer, the signs of the trade effect are inverted.

[23] Note, that the *technology effect* for firm B ($B_T > 0$) reduces the baseline emission level ($E_B^{1,\max} < E_B^{0,\max}$), but does not directly affect the optimal choice of r.

linear with intercept a in the technology transfer as well as in the non-transfer case, we have $MAC_B^1((1-r)E_B^{1\max}) = MAC_B^0((1-r)E_B^{0,\max})$, which implies that for a given level of r the permit price effect equals zero, i.e., given r technology transfer has no effect on the permit price.

For the functions of type (3) the bottleneck countries, the absolute emission levels $\bar{E}^{\gamma i}$ (with the upper index *i* denoting the bottleneck country), the relative emission levels $r^{\gamma i}$, the equilibrium permit prices $p^{\gamma i}$ and their comparisons between the technology transfer and non-transfer case are displayed in Table 1. This information turns out to be useful for the analysis of stage 1 below.

	$\gamma = 1$	$\gamma = 0$	Comparison
$d_A < \frac{2}{3} d_B$	country A, $r_1^A = \frac{4d_A}{b+4d_A}$ $\bar{E}^{1A} = \frac{a}{b+4d_A}$ $p_1^A = \frac{4ad_A}{b+4d_A}$	country A, $r_0^A = \frac{25d_A}{4b+25d_A}$ $\bar{E}^{0A} = \frac{5a}{4b+25d_A}$ $p_0^A = \frac{25ad_A}{4b+25d_A}$	$r_0^A - r_1^A = \frac{9bd_A}{(b+4d_A)(4b+25d_A)}$ $\bar{E}^{0A} - \bar{E}^{1A} = \frac{a(b-5d_A)}{(4b+25d_A)(b+4d_A)}$ $p_0^A - p_1^A = \frac{9abd_A}{(4b+25d_A)(b+4d_A)}$
$\frac{2}{3} d_B < d_A < d_B$	country A, $r_1^A = \frac{4d_A}{b+4d_A}$ $\bar{E}^{1A} = \frac{a}{b+4d_A}$ $p_1^A = \frac{4ad_A}{b+4d_A}$	country B $r_0^B = \frac{25d_B}{6b+25d_B}$ $\bar{E}^{0B} = \frac{15a}{12b+50d_B}$ $p_1^B = \frac{25ad_B}{6b+25d_B}$	$r_0^B - r_1^A = \frac{b(25d_B - 24d_A)}{(b+4d_A)(6b+25d_B)}$ $\bar{E}^{0B} - \bar{E}^{1A} = \frac{1}{2}\frac{a(3b+60d_A-50d_B)}{(b+4d_A)(6b+25d_B)}$ $p_0^B - p_1^A = \frac{ab(25d_B-24d_A)}{(b+4d_A)(6b+25d_B)}$
$d_A > d_B$	country B, $r_1^B = \frac{4d_B}{b+4d_B}$ $\bar{E}^{1B} = \frac{a}{b+4d_B}$ $p_1^B = \frac{4ad_B}{b+4d_B}$	country B, $r_0^B = \frac{25d_B}{6b+25d_B}$ $\bar{E}^{0B} = \frac{15a}{12b+50d_B}$ $p_1^B = \frac{25ad_B}{6b+25d_B}$	$r_0^B - r_1^B = \frac{bd_B}{(b+4d_B)(6b+25d_B)}$ $\bar{E}^{0B} - \bar{E}^{1B} = \frac{1}{2}\frac{a(3b+10d_B)}{(b+4d_B)(6b+25d_B)}$ $p_0^B - p_1^B = \frac{abd_B}{(6b+25d_B)(b+4d_B)}$

Table 1: Bottleneck countries for payoff functions of type (3)

From Table 1 it can be seen that for $d_A / d_B < 2/3$ ($d_A / d_B > 1$) country A (country B) is the bottleneck country, irrespective of the technology transfer level. When d_A is only slightly lower than d_B, i.e., $2/3 < d_A / d_B < 1$ holds, country B is the bottleneck country only if its industry does not have the superior technology at its disposal. In this case the higher abatement costs of firm B overcompensate for the damage effect.

Comparing the bottleneck proposals in case of technology transfer and non-transfer shows that in contrast to the national case technology transfer not necessarily leads to lower global emission levels. Only if country B is bottleneck for $\gamma = 1$ and $\gamma = 0$ (which implies that the profit of the potential technology adopter is an integral part of the bottleneck country's welfare function in both cases), global emissions are reduced for any parameter constellation. In this case the welfare effects of a technology transfer for the bottleneck country are comparable to those of the national scenario. However, if country A takes the role of the bottleneck in case of non-transfer (and potentially also in case of technology transfer), $\bar{E}^{0i} - \bar{E}^{1A}$ may be negative. Accordingly, technology transfer may result in a higher aggregate emission level. In the following the reasoning behind this result is exemplarily explained for the case that country A takes the role of the bottleneck in case of technology transfer as well as in case of non-transfer.
Starting from the aggregate emission level which would be optimal from the point of view of country A in the non-transfer case ($\bar{E}^{0A}$) a marginal increase (dE) has the same (detrimental) environmental effect $D^{A\prime}(\bar{E}^{0A})dE$ in case of non-transfer as it has in case of technology transfer.[24] However, in case of technology transfer, the share of the aggregate emission increase that is allotted to firm A (given by $(1-dr_1)\cdot E_A^{\max}$) is higher than in case of non-transfer ($(1-dr_0)\cdot E_A^{\max}$).[25] This effect works in favour of $\bar{E}^{1A} > \bar{E}^{0A}$. However, on the other hand, starting from $\bar{E}^{0A}$ marginal benefits from emissions for country A are lower in case of technology transfer than in case of non-transfer due to the improved initial allocation. This *marginal benefit* effect works in favour of $\bar{E}^{1A} < \bar{E}^{0A}$. Table 1 reveals that for a sufficiently high ratio of county A's marginal damage and marginal benefit parameter ($d_A / b > 1/5$) the first effect outweighs the marginal benefit effect.

Independent from who takes the role of the bottleneck country, the equilibrium permit price decreases unambiguously due to the decline of the aggregate marginal abatement cost in case of technology transfer.

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[24] Note, that whereas for the global welfare effect the global emission level is the relevant parameter, the firms are interested in the effect of technology transfer on their individual emissions. Hence above, we analysed the effects of technology transfer on the emission reduction level r, whereas for the welfare comparison we now consider the global emission level E.
[25] From $E_B^{1,\max} < E_B^{0,\max}$ and $dr_\gamma = 1 - dE / E^{\gamma,\max}$ follows $dr_1 < dr_0$, i.e., a given increase of the aggregate emission level results in a larger decrease of the emission reduction level in the technology transfer case.

Stage 1:

To analyse stage 1, we have to consider the different allocation rules separately again. This is so because the profits of firms A and B with and without technology transfer and hence also the diffusion and adoption incentives depend on the allocation rule.

4.2 Alternative Allocation Rules in Stage 1

4.2.1 Auctioning

We briefly discuss the diffusion and adoption incentives of firms A and B, respectively.

For firm A, there (only) is the *permit price effect*: Due to the downward shift of the aggregate marginal abatement cost curve in case of technology transfer, the equilibrium permit price decreases. This effect is advantageous for firm A (as well as for firm B). Hence, firm A's diffusion incentive is positive.

Firm B benefits from the advantageous *permit price effect* just as firm A does. Additionally, firm B is affected by the *technology effect* ($B_T > 0$). This effect is always advantageous, independent from the permit allocation rule. Hence, the aggregate adoption incentive of firm B is positive, since it is composed of two positive effects.

Drawing this together with what has been said for firm A, above, it follows that technology is transferred in equilibrium. This result holds irrespective of whether country A or B takes the role of the bottleneck in the technology transfer and non-transfer case. It is worth noting that this result which has been derived here is essentially the same as the result which had been derived for the national context, above.

4.2.2 Free allocation of permits based on benchmarking

As in the national model technology transfer does not affect the permit endowment of firm A (that is, the *quantity effect* equals zero), but reduces the permit price. Firm A acts as a permit seller, because of $B_A'(E_A^{\max}) = 0 < p_\gamma$ in the technology transfer as well as in the non-transfer case. Therefore, the *permit price effect* and hence also the aggregate diffusion incentive is detrimental to A. Even though the adoption incentive for firm B might be positive, no technology transfer takes place in equilibrium.

4.2.3 Free allocation of permits based on grandfathering

In section 3.2.3 it turned out that the diffusion and adoption incentives can be either positive or negative in general, whereas for the functions of type (3) they are always positive. Also in the international scenario for type (3) the diffusion and adoption incentives are positive irrespective of whether country A or B takes the role of the bottleneck country in the technology transfer and non-transfer case. In all three ranges from table 1, we have an advantageous *quantity effect* $r_1 < r_0$, that is, firm A receives a higher number of permits in case of technology transfer, which works in favour of a positive diffusion effect for firm A. However, the previous discussion of stage 2 revealed that, independent from which country takes the role of the bottleneck, the quantity effect may also be disadvantageous depending on the shape of the marginal abatement cost curves. Correspondingly also the diffusion incentive can be either positive or negative, as in the national scenario.

4.3 Welfare Comparison

In the previous subsections it has been shown that the ranking of the equilibrium technology transfer levels in the international scenario equals the one of the national scenario. That is, under auctioning technology transfer always takes place at stage 1, under grandfathering it depends on the shape of the benefit functions and under benchmarking no technology transfer takes place due to the negative diffusion incentives of firm A. However, this does not imply that also the ordering with respect to the global emission and welfare levels coincides with the national one. The underlying reasoning is that in the international scenario, in contrast to the national one, technology transfer may result in higher global emission levels, as has been shown in section 4.1.

In these cases benchmarking, that generates the lowest (= negative) diffusion incentive produces the lowest global emissions. This, however, implies that for sufficiently high values of global damages $d = d_A + d_B$ benchmarking produces the highest global welfare.

E.g. for $a = b = d_A = 10, d_B = 500$ country A is the bottleneck country in the technology transfer as well as in the non-transfer case. The global emission level is higher in case of technology transfer ($\bar{E}^{1A} = 1/5$) than in case of non-transfer ($\bar{E}^{0A} = 5/29$). Due to the high damage parameter of country B this effect overcompensates for the technology improvement of firm B ($W^1 = 7/5 < W^0 = 6635/1682$).

All in all, we arrive at the somewhat surprising result that in the international context technology transfer may produce globally welfare inferior outcomes. This is so, if the bottleneck country does not enjoy the technology improvement itself. This is the case where the potential recipients of the improved technology do not belong to the bottleneck country.

Our results are summarized in Proposition 3.

Proposition 3: ***Technology transfer levels and welfare comparison in the international scenario***

a) In the international scenario for the permit allocation rules auctioning, grandfathering and benchmarking holds

$1 = \gamma^{nat,auct} \geq \gamma^{nat,grandf} \geq \gamma^{nat,benchm} = 0$.[26]

b) In case of technology transfer global welfare may be lower and global emissions may be higher than in case of non-transfer.

Proof:

a) See section 4.2.

b) See the example above.

5 Conclusion

In this paper, we analysed the incentives to diffuse and adopt superior pollution abatement technology in a national and international permit setting. The comparison was performed for three permit allocation rules: auctioning, benchmarking and grandfathering. We thereby extended the literature on induced technical change by permit markets to benchmarking and international negotiations. Moreover, we did not only compare diffusion and adoption incentives but also analysed the resulting welfare effects.

In the national context, the results are rather clearly cut: if technology transfer takes place, it leads to the socially optimal outcomes. Since diffusion and adoption incentives are always positive under auctioning, this is the most preferable allocation rule. Under benchmarking, diffusion incentives are negative and under grandfathering they may be positive or negative. Things turn out to be more complicated in the international arena. Here, generally neither technology transfer nor non-transfer generate the socially optimal outcomes if countries are asymmetric with respect to environmental damages. Beyond that, transfer of a technology that makes emission abatement more profitable may even reduce global emission abatement and global welfare if the bottleneck country does not profit itself from the better technology. Only if the potential recipient of the new technology belongs to the bottleneck country, which is the case if environmental damages and/or environmental awareness are sufficiently high in the country with the superior technology compared to the country with the inferior technology, auctioning is unambiguously the allocation rule that results in highest global welfare. If this condition is not met, other allocation rules may be welfare-superior even though they generate weaker incentives for technology transfer. Obviously, there are additional questions that have not been dealt with in the present paper, but might be dealt with in future research using the framework we have developed. Particularly, the incentives for diffusion and adoption of

[26] Footnote 19 applies.

superior environmental technology might be analysed on the basis of a more sophisticated model than the most simple one we have used above. Elements of this more sophisticated fundamental framework may be alternative stylizations of technical progress and of the international negotiation process as well as (alternative forms) of competition between the involved firms in output (and/or input) markets. Further fruitful extensions are costly diffusion and adoption as well as patented discoveries. Moreover, in the international scenario the choice of the allocation rule could be endogenized.

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