Environ Resource Econ (2013) 56:177–210
DOI 10.1007/s10640-012-9596-9

# Incentives to Diffuse Advanced Abatement Technology Under the Formation of International Environmental Agreements

**Alfred Endres · Bianca Rundshagen**

Accepted: 8 August 2012 / Published online: 28 August 2012


**Abstract** We analyse the incentives for polluting firms to diffuse and adopt advanced abatement technology in a framework in which governments negotiate an international environmental agreement. These incentives crucially depend on whether the underlying environmental policy instrument is an emission tax or an emission quota. The results for the international setting fundamentally differ from those for the national setting that have been elaborated upon in the earlier literature. In particular, equilibrium diffusion and adoption of advanced abatement technology are not necessarily optimal under the tax regime and may be even lower than those under the quota regime.

**Keywords** International environmental agreement · Induced technical change · Pollution abatement · Emission taxes · Emission quotas

**JEL Classification** Q5

## 1 Introduction

Technical progress, most pressingly with respect to technologies that abate pollution, is of outstanding importance in tackling climate change and other environmental challenges in

The authors are indebted to three anonymous referees as well as Joanna Poyago-Theotoky, Robert Waschik (both at the Economics Department of La Trobe University, Melbourne) and Michael Faure, Maastricht University, Faculty of Law, for their helpful comments on an earlier draft of this paper. The manuscript was completely revised while Alfred Endres was a visiting scholar at La Trobe University. This author is indebted to the Economics Department for its hospitality and to the University of Hagen for granting a sabbatical.

A. Endres · B. Rundshagen (✉)
Department of Economics, University of Hagen, Profilstr. 8, 58084 Hagen, Germany
e-mail: Bianca.Rundshagen@FernUni-Hagen.de

A. Endres
Department of Economics, University of Witten/Herdecke, Witten, Germany
e-mail: Alfred.Endres@FernUni-Hagen.de

a dynamically cost-effective manner. A standard characterization of technical progress is a downward shift in marginal abatement costs for all levels of abatement (see, e.g., Downing and White 1986; Endres 2011; Milliman and Prince 1989 or Parry 2003). This is the view of technical progress also taken in the paper at hand. Technical progress describes the overall process of innovation and diffusion of new technologies. Although the majority of the literature on induced technical change deals with innovation, diffusion is at least as important in improving both global and national average technology levels.[1] Milliman and Prince (1989) were the first to study the relative performance of alternative environmental policy instruments with respect to the overall process of innovation, and explicitly the role of diffusion. Several papers analysing diffusion in various settings followed (see, e.g., Jaffe and Stavins 1995; Requate and Unold 2001, 2003; Coria 2009; Endres and Friehe 2011). All these settings (explicitly or implicitly) assume a national context, where a single government decides on environmental regulation. By contrast, the focus of our paper is on a setting where the polluting firms are located in different countries and the governments negotiate an international environmental agreement. We also compare the results we obtain for the international setting to those for the more conventional national framework. Even though some recent publications do consider induced technical change within an international context, none of them discuss endogenous bargaining in order to reach an international environmental agreement. Instead, they either use macroeconomic growth models (see, e.g., Bosetti and Tavoni 2009; Gerlagh et al. 2009; Held et al. 2009; Löschel and Otto 2009; Otto et al. 2008), consider an exogenously given international environmental agreement (see, e.g., Golombek and Hoel 2005, 2008; Hagem 2009) or assume non-cooperative behaviour between governments (see, e.g., Golombek and Hoel 2004; Ulph and Ulph 1996, 2007). To the best of the present authors' knowledge, the current paper is the first to analyse technology diffusion induced by environmental policy in a setting in which the results of international environmental negotiations are endogenously determined.

This leads us to another strand of literature to which our paper refers, namely the literature on endogenous international environmental coalition formation.[2] This strand of literature, which does not consider induced technical change, can be separated into two categories. The first category assumes that the members of an environmental coalition maximize the aggregate welfare of the coalition and determine the corresponding equilibrium coalition structure (see, e.g., Breton et al. 2006; Carraro and Siniscalco 1993; Osmani and Tol 2009; Yi and Shin 2000). By contrast, the second category takes into account the fact that welfare maximization within a coalition is usually unfeasible, due to the asymmetric interests of countries. Therefore, the equilibrium outcome of a given coalition structure is, in these contributions, determined endogenously (see, e.g., Endres and Finus 2002; Espinola-Arredondo 2009; Finus et al. 2005; Hoel 1992). This is the approach taken in the following sections.

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 environmental agreement, with the results being compared to a corresponding national framework. The negotiation results are shown to depend on the environmental policy instrument chosen. From the portfolio of environmental policy instruments, we take emission taxes and quotas ("prices vs. quantities") to serve as the examples in our analysis. We assume that each government makes a proposal with respect to the uniform policy level, i.e., each

[1] See, e.g., Requate (2005) for a survey of the literature on induced technical change through environmental policy instruments.

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

country proposes a uniform tax rate or a uniform emission reduction, respectively. 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.[3] We consider a three-stage game with two firms, with stage one involving the firm with the superior abatement technology choosing the level of diffusion, and the firm with the inferior abatement technology choosing the adoption level. 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 abatement level. We analyse the game by backward induction.

As it transpires, the incentives to diffuse and adopt advanced abatement technology are not necessarily optimal under the tax regime (as they would be in a corresponding national framework). In case of asymmetric damage functions, they may even be lower under the tax regime than under the quota regime. In this case, and even in the case of identical damage functions, social welfare may be higher under the quota regime, depending on the parameter values.

We proceed as follows. So as to provide two reference points, we begin by deriving the socially optimal activity (diffusion and abatement) levels in Sect. 2 and the equilibrium activity levels within a national framework in Sect. 3. Sections 4 and 5, respectively characterize the international negotiation outcomes in the tax and quota scenarios. Section 6 compares the bargaining outcomes, with respect to global welfare in particular. In Sect. 7, we consider two extensions, an additional type of abatement cost function and a second variant of the quota regime. We conclude our analysis in Sect. 8.

Before presenting the formal analysis, the motivation of the paper might be clarified by the following remarks appealing to the reader's intuition.

It is an element of environmental economics folklore that the impact of regulation of technical advances in pollution control is "over the long haul, perhaps the single most important criterion on which to judge environmental policy" (Kneese and Schultze 1975) and "the key to an effective solution of environmental problems" (Orr 1976).

There are two alternative approaches to study how alternative environmental policy instruments affect the incentives for firms to innovate in pollution control technology. The first is to start the analysis with the policy maker deciding on the policy instrument to use (e.g., pollution taxes or command and control) and on the stringency with which it is applied (the level of the tax rate in the example of pollution taxes). After the policy has been designed, the firms are assumed to react in terms of pollution control technology and in terms of pollution abatement. A second approach (going back to Milliman and Prince 1989) takes a different view. Here, it is acknowledged that firms are able to influence the policymaker's choice of environmental policy design, and that they have an incentive to do so. The firms' leeway and incentives to manipulate the policies they are regulated with might vary across different policy instruments. Milliman and Prince (1989) have argued that a policy-relevant assessment of alternative means to regulate pollution must acknowledge these issues. We follow this approach and note that, to date, it has been exclusively applied to the national policy framework. The paper at hand attempts to extend the analysis to the international arena.

[3] 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), and Eyckmans (1999). 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 2012 and Dannenberg et al. 2010).

The reason for the fundamental differences between the national and the international policy context is intuitively understandable using the example of a pollution tax. We briefly present this intuition as an appetizer for the formal analysis given in the main part of the paper.

In the national setting, the rate of the pollution tax is set at the level of marginal aggregate damage in the socially optimal situation. This situation is characterized by the condition "aggregate marginal abatement cost equals aggregate marginal damage". Technical progress, in the form of innovation as well as of diffusion, lowers marginal abatement costs and therefore changes the level of pollution abatement meeting the aforementioned condition for social optimality. Marginal damage in the new socially optimal situation is always lower than it is in the old socially optimal situation. Accordingly, the pollution tax rate is lower in the situation after technical progress is introduced. It follows that, in this setting, a firm can always rely on changing the regulation to which it is subject in a favourable manner by introducing progress in abatement technology.

Of course, it is possible to imagine an international setting in which this fundamental result is maintained. A Coasean world is all we need. However, a more realistic view must acknowledge that the free rider problem is hard to overcome and that international negotiations trying to achieve this suffer from many distortions.[4] The idea of the international community agreeing upon the smallest common denominator implies that the "bottleneck country" effectively determines the result of the negotiations. This approach, which has been briefly explained above, is one of the many ways to stylize such distortions. In direct contrast to the national setting, the countries will not agree on the socially optimal tax rate in a distorted international setting. Instead, the equilibrium tax rate will turn out to be lower than the socially optimal one, due to incentive distortions in the bottleneck country. Consequently, to investigate the implications of technical advance on the tax rate with which firms have to cope, it is not the socially optimal rate on which the analysis has to focus. As against the national setting, it is the equilibrium tax rate determined in the international negotiations, which plays the focal role. Even though the socially optimal tax rate always goes down in the process of introducing technical advance, the propensity of the bottleneck country to accept a higher tax rate might go up. If so, the equilibrium tax rate increases. In this case, a firm introducing technical progress increases the burden of environmental regulations from which it suffers. Obviously, this is an incentive not to advance technology in the international setting.

## 2 Socially Optimal Abatement and Diffusion

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.[5,6] Firm $i$'s emissions are given by $E_i = E_{\max} - X_i$, with $X_i$ denoting the abatement level and $E_{\max}$ the upper emission limit, i.e., the emission level at which marginal abatement costs (which are assumed to

[4] There are many studies in pure and applied game theory supporting this view. E.g., see Finus (2008) for a survey.

[5] We use the assumption that there is one firm in each region/country, and so as to simplify notation we use the same indices A, B as the names of the firms and regions/countries. A generalisation of our model with $n \geq 1$ firms in each region/country would not affect the qualitative results, since in our model firms do not interact within the market place.

[6] In the main parts of the paper the firms are located in different countries. Only in Sect. 3 they are located in different regions that belong to one country with a single government.

be strictly decreasing in the emission level) equal zero. Hence, total emissions are given by $E = E_A + E_B = 2E_{\max} - X_A - X_B$. Environmental damage in each country is assumed to be given by $D_i(E)$ with $D_i' > 0$, $D_i'' > 0$, i.e., marginal damage is positive and strictly increasing. The state of the abatement technology is represented by $T_i \in [0, 1]$. 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 abatement levels $X_i$ but also on the effective transfer parameter $\gamma \in [0, 1]$, which describes the extent to which the technology spills over to firm $B$ ($T_B = T_B^0 + \gamma = \gamma$). Under decentralization, firm $A$ determines the technology share that may diffuse $\alpha \in [\alpha_{\min}, 1]$ with $\alpha_{\min} \geq 0$, and firm $B$ determines the extent to which it is willing to embrace the new technology $\beta \in [0, 1]$.[7] The effective transfer parameter is then given by $\gamma = \min\{\alpha, \beta\}$. For simplicity we assume that diffusion and adoption are costless.[8] The abatement level $X_i$ corresponds to abatement costs $C(X_i, T_i)$. Marginal abatement costs are positive and strictly increasing ($C_X > 0, C_{XX} > 0$). The state of the technology used affects abatement costs, with an improvement in the abatement technology lowering abatement costs ($C_T < 0$) at a constant or diminishing rate ($C_{TT} \geq 0$). Furthermore, we assume that technical change lowers marginal abatement costs for all abatement levels ($C_{XT} < 0$).[9]

The social planner minimizes social costs associated with pollution. These costs are composed of abatement costs and expected damages. Hence, the optimization problem faced by the social planner is given by

$$\min_{\gamma \in [0,1], X_A \in [0, E_{\max}], X_B \in [0, E_{\max}]} SC = C(X_A, 1) + C(X_B, \gamma) + \sum_{i \in \{A,B\}} D_i(2E_{\max} - X_A - X_B). \tag{1}$$

The corresponding first-order conditions are

$$SC_{X_A} = C_X(X_A, 1) - \sum_{i \in \{A,B\}} D_i'(2E_{\max} - X_A - X_B) = 0, \tag{1a}$$

$$SC_{X_B} = C_X(X_B, \gamma) - \sum_{i \in \{A,B\}} D_i'(2E_{\max} - X_A - X_B) = 0, \tag{1b}$$

$$SC_\gamma = C_T(X_B, \gamma) < 0. \tag{1c}$$

[7] Note that $\alpha_{\min}$ is exogenously given for firm A. Its value is positive if firm A cannot completely prevent diffusion. Additionally, note that firm B can only influence its technology by the choice of $\beta$ if $\alpha_{\min} > 0$ or $\alpha > \alpha_{\min} = 0$ holds. If $\alpha = \alpha_{\min} = 0$, the value of $\beta$ is irrelevant for the resulting technology level.

[8] See also Milliman and Prince (1989) The assumption of costless diffusion and adoption implies that the socially optimal transfer parameter equals one and hence 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 both instruments, which results in lower equilibrium transfer levels for sufficiently high costs of diffusion. However, for sufficiently high costs of diffusion the socially optimal effective transfer level would also be reduced.

[9] Recent publications have acknowledged the existence of some kinds of technical change 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 and Adu-Bonnah 2008; Baker et al. 2008; Baumann et al. 2008 and Endres and Friehe 2011). Another way to stylize technical change is that it decreases emissions per unit of output (see, e.g., Ulph and Ulph 2007). However, 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.

With respect to the abatement levels, we focus on interior solutions and thereby consider only cases in which the social planner seeks to induce positive abatement levels from both firms. The conditions (1a) and (1b) state that the optimal levels of abatement are obtained if marginal abatement costs equal aggregate marginal damage.

Equation (1c) directly implies the following statement:

**Proposition 1** (Socially optimal effective technology transfer level) *The socially optimal effective transfer level is given by* $\gamma^{**} = 1$.

Since aggregate social costs are decreasing in the technology levels of the firms, the social planner seeks to encourage firm B to use the state-of-the-art technology type $T = 1$ as well, and hence sets $\gamma^{**} = 1$, which implies that $\alpha^{**} = \beta^{**} = 1$.

## 3 Diffusion and Adoption in a National Framework

As a second reference scenario (additional to the social optimum), we now assume that the two firms are located in the same country, i.e., $2D(2E_{\max} - X_A(t) - X_B(\gamma, t))$ represents national damages. As mentioned in the introduction, under both policy regimes we consider a three-stage game, which is solved by backward induction.

### 3.1 The National Tax Regime

*Stage 3:*

Firm $i$ minimizes private costs with respect to abatement, given the abatement technology, the tax level, and the abatement level of the other firm,[10]

$$\min_{X_i} PC_i^t = C(X_i, T_i) + t(E_{\max} - X_i). \tag{2}$$

The first-order condition is given by

$$PC_{X_i}^t = C_X(X_i, T_i) - t = 0 \quad \Rightarrow \quad C_X(X_i, T_i) = t. \tag{2a}$$

Each firm chooses the abatement level that equalizes marginal abatement costs and the tax level. We denote the equilibrium abatement levels at stage 3 by $X_A(t)$ and $X_B(\gamma, t)$.[11]

Note that, given the tax level $t$ and the abatement technologies $T_i$, the abatement levels are not only individually optimal but also optimal from the point of view of the social planner, since marginal abatement costs are equalized between the firms.

Comparative static analysis reveals that

$$\frac{dX_i}{dt} = \frac{1}{C_{XX}(X_i, T_i)} > 0 \tag{3}$$

and

$$\frac{dX_B}{d\gamma} = -\frac{C_{XT}(X_B, \gamma)}{C_{XX}(X_B, \gamma)} > 0, \tag{4}$$

i.e., the abatement levels are increasing in the tax rate. Additionally, the abatement level of firm B is increasing in the effective transfer level.

[10] We use the upper index $t$ for the tax and $q$ for the quota regime.

[11] The abatement level of firm B not only depends on the tax level but also on the effective transfer parameter.

*Stage 2:*
The optimization problem faced by the government is given by

$$\min_t SC^t = C(X_A(t), 1) + C(X_B(\gamma, t), \gamma) + \sum_{i\in\{A,B\}} D_i(2E_{\max} - X_A(t) - X_B(\gamma, t)) \quad (5)$$

with the last summand representing national damages.

The first-order condition is given by

$$\begin{aligned} dSC^t/dt &= C_X(X_A, 1)\frac{dX_A}{dt} + C_X(X_B, \gamma)\frac{dX_B}{dt} \\ &\quad - \left(\frac{dX_A}{dt} + \frac{dX_B}{dt}\right) \sum_{i\in\{A,B\}} D_i'(2E_{\max} - X_A(t) - X_B(\gamma, t)) = 0. \end{aligned} \quad (5a)$$

Using (2a), the expression may be simplified to

$$t = \sum_{i\in\{A,B\}} D_i'(2E_{\max} - X_A(t) - X_B(\gamma, t)). \quad (6)$$

Hence, the government chooses the tax level that equalizes marginal (aggregate) abatement costs and aggregate marginal damages.
*Stage 1:*
The optimal effective transfer level from the point of view of firm A (B) follows from the optimization problems

$$\min_\gamma PC_A^t = C(X_A, 1) + t(E_{\max} - X_A) \text{ and } \min_\gamma PC_B^t = C(X_B, \gamma) + t(E_{\max} - X_B). \quad (7)$$

Using (2a), the corresponding first-order conditions may be simplified as

$$dPC_A^t/d\gamma = \frac{dt}{d\gamma}(E_{\max} - X_A) \text{ and} \quad (7a)$$

$$dPC_B^t/d\gamma = C_T + \frac{dt}{d\gamma}(E_{\max} - X_B) \quad (7b)$$

Comparative static analysis reveals

$$\frac{dt}{d\gamma} = -\left(\frac{dX_B}{d\gamma}\sum_{i\in\{A,B\}} D_i''\right) \Big/ \left(1 + \left(\frac{dX_A}{dt} + \frac{dX_B}{dt}\right)\sum_{i\in\{A,B\}} D_i''\right) < 0. \quad (8)$$

Hence $PC_A^t$ as well as $PC_B^t$ are strictly decreasing in $\gamma$. For firm A, this is due to the decreasing tax level. We call this effect, which is positive (in the sense of decreasing private cost) for both firms, the *tax effect.* Additionally, for firm B there is an (also positive) *abatement cost effect:* an increase in $\gamma$ decreases firm B's abatement costs. Since for both firms the optimal effective transfer level is given by $\gamma^t = 1$, they choose $\alpha^t = \beta^t = 1$.

That is, under the national tax regime both firms choose the socially optimal levels of diffusion and adoption. Additionally, they choose the socially optimal levels of abatement (see also Milliman and Prince 1989).

## 3.2 The National Quota Regime

In the national quota regime at stage 2, the government chooses an upper emission limit $\bar{E}$ that holds for each region (or equivalently for each firm).

*Stage 3:*
At stage 3, firm $i$ minimizes private costs $PC_i^q = C(X_i, T_i)$ with respect to abatement $X_i$ under the constraint $X_i \geq E_{\max} - \bar{E}$. Since the abatement costs are increasing in the abatement level, the firms choose $X_i = E_{\max} - \bar{E}$.
*Stage 2:*
At stage 2, the optimization problem faced by the government is given by

$$\min_{\bar{E}} SC^q = C(E_{\max} - \bar{E}, 1) + C(E_{\max} - \bar{E}, \gamma) + \sum_{i \in \{A,B\}} D_i(2\bar{E}). \tag{9}$$

The first-order condition is given by

$$dSC^q/d\bar{E} = -C_X(E_{\max} - \bar{E}, 1) - C_X(E_{\max} - \bar{E}, \gamma) + 2 \sum_{i \in \{A,B\}} D_i'(2\bar{E}) = 0. \tag{9a}$$

Hence, the government chooses the upper emission limit that equalizes the sum of marginal abatement costs and aggregate marginal damages.
*Stage 1:*
Under the quota regime, the optimal effective transfer level from the point of view of firm A (B) follows from the optimization problems

$$\min_{\gamma} PC_A^q = C(E_{\max} - \bar{E}, 1) \text{ and } \min_{\gamma} PC_B^q = C(E_{\max} - \bar{E}, \gamma). \tag{10}$$

The corresponding first-order conditions are given by

$$dPC_A^q/d\gamma = -\frac{d\bar{E}}{d\gamma} C_X \quad \text{and} \tag{10a}$$

$$dPC_B^t/d\gamma = C_T - \frac{d\bar{E}}{d\gamma} C_X \tag{10b}$$

Comparative static analysis reveals that

$$\frac{d\bar{E}}{d\gamma} = \frac{C_{XT}(E_{\max} - \bar{E}, \gamma)}{C_{XX}(E_{\max} - \bar{E}, 1) + C_{XX}(E_{\max} - \bar{E}, \gamma) + 4 \sum_{i \in \{A,B\}} D_i''(2\bar{E})} < 0. \tag{11}$$

A higher value of $\gamma$ decreases the abatement costs of firm B and hence also the sum of the two firms' abatement costs for a given abatement norm. Hence, the higher the value of $\gamma$, the stricter the emission norm. Due to this negative *target effect,* $PC_A^q$ is strictly increasing in $\gamma$. Hence firm A chooses $\alpha^q = \alpha_{\min}$. This implies that under the national quota the equilibrium level of diffusion is lower than in the social optimum (see also Milliman and Prince 1989).

In the case of $\alpha^q = \alpha_{\min} = 0$, it directly follows that $\gamma^q = 0$. In particular, firm B cannot influence the effective transfer level via its choice of $\beta$.[12]

Hence, in the following we consider the case of $\alpha^q = \alpha_{\min} > 0$. That is, firm B's choice with respect to $\beta$ is consequential. The situation for firm B is, therefore, as follows. First, there is the negative *target effect,* $d\bar{E}/d\gamma < 0$, as described previously. Additionally, for firm B there is the positive *abatement cost effect*. Hence, firm B chooses $\beta^q = 1$ if the abatement cost effect overcompensates the target effect (irrespective of $\gamma$). Which effect is stronger

[12] Here and in the following we assume that there is no Coasean bargaining between firms A and B (with compensation payments from firm B to firm A for the choice of a higher diffusion level) because transaction costs are too high.

depends on the ratio of environmental damage to abatement costs. The higher the environmental damage (relative to abatement costs), the stricter the abatement target, increasing the weight of the abatement cost effect.

To illustrate (and derive some of) our results of this and the subsequent sections, we consider the following abatement cost and damage functions:

$$C_A = cX_A^2, C_B = \left(1 + \frac{1-\gamma}{3}\right) cX_B^2, D_i = d_i(E_A + E_B)^2, \ i \in \{A, B\}. \tag{12}$$

For the functions of type (12), the equilibrium effective transfer parameter is given by $\gamma^q = 0$ in the case of $\delta_A + \delta_B < -1/4 + \sqrt{3}/6 \approx 0.0387$, $\gamma^q \in \{0, \ \alpha_{\min}\}$ (depending on the value of $\alpha_{\min}$) in the case of $0.0387 \approx -1/4 + \sqrt{3}/6 < \delta_A + \delta_B < 1/12 \approx 0.0833$ and $\gamma^q = \alpha_{\min}$ in case of $\delta_A + \delta_B > 1/12 \approx 0.0833$ with $\delta_i := d_i/c, \quad i \in \{A, B\}$.[13]

### 3.3 Welfare Comparison

Proposition 2 summarizes the main results of the two preceding subsections and shows their implications for global welfare.

**Proposition 2** (*a*) *In a national framework, for the equilibrium effective transfer levels, it holds that $\gamma^t = \gamma^{**} = 1$ under the tax regime, and $\gamma^q \leq a_{\min}$ under the quota regime.*
(*b*) *Social welfare is strictly higher under the tax than under the quota regime.*

*Proof* (a) See Sects. 3.1 and 3.2.
(b) Follows directly from the fact that in the national scenario, the firms choose the socially optimal diffusion, adoption, and abatement levels under the tax regime. Under the quota regime, the diffusion level differs from the optimal one, resulting in different marginal abatement cost functions for the firms. Hence the symmetric division of the abatement levels between the two firms is not cost-effective. □

## 4 Decentralization Using Emission Taxes in an International Framework

We now assume that the two firms are located in different countries. It turns out that, in contrast with the national framework, our results crucially depend on whether the countries have identical damage functions or not. We therefore divide this and the following two sections in two subsections, with identical damage functions in the first and differing damage functions in the second subsection.

### 4.1 Countries with Symmetric Damage Functions

Assume that the two firms A, B are located in two countries A, B with identical damage functions $D_A(E) = D_B(E) = D(E)$.
*Stage 3:*
Given the tax rate and technology levels the equilibrium abatement choice of the firms is implicitly defined by Eq. (2a), and is identical to the one of the national tax scenario.

[13] See Appendix A.

*Stage 2:*

At stage 2, the governments negotiate an internationally uniform tax level and agree on the lowest common denominator of their tax proposals by assumption. The tax proposals of the two countries follow from their optimization problems:

$$\begin{aligned}\min_{t_A} SC_A^t &= C(X_A(t), 1) + D(2E_{\max} - X_A(t) - X_B(\gamma, t)) \text{ and}\\ \min_{t_B} SC_B^t &= C(X_B(t), \gamma) + D(2E_{\max} - X_A(t) - X_B(\gamma, t)).\end{aligned} \tag{13}$$

with corresponding first-order conditions

$$\frac{dSC_A^t}{dt_A} = C_X(X_A(t_A), 1)\frac{dX_A}{dt_A} - D_E(2E_{\max} - X_A(t_A) - X_B(\gamma, t_A))\left(\frac{dX_A}{dt_A} + \frac{dX_B}{dt_A}\right) = 0, \tag{13a}$$

$$\frac{dSC_B^t}{dt_B} = C_X(X_B(t_B), \gamma)\frac{dX_B}{dt_B} - D_E(2E_{\max} - X_A(t_B) - X_B(\gamma, t_B))\left(\frac{dX_A}{dt_B} + \frac{dX_B}{dt_B}\right) = 0. \tag{13b}$$

Using (2a), the tax proposals are implicitly defined by

$$t_A\frac{dX_A}{dt_A} - D_E(2E_{\max} - X_A(t_A) - X_B(\gamma, t_A))\left(\frac{dX_A}{dt_A} + \frac{dX_B}{dt_A}\right) = 0 \text{ and} \tag{13c}$$

$$t_B\frac{dX_B}{dt_B} - D_E(2E_{\max} - X_A(t_B) - X_B(\gamma, t_B))\left(\frac{dX_A}{dt_B} + \frac{dX_B}{dt_B}\right) = 0. \tag{13d}$$

Before we enter the formal discussion of the properties of the equilibrium tax rate we would like to approach reader intuition with some brief introductory remarks.

It should be noted that the arrangement of having the same tax rate for the two countries carries fundamental distributional consequences. The firms adjust their levels of pollution abatement according to the equilibrium condition “marginal abatement cost equals the tax rate” [see Eq. (2a)]. Therefore, the firm with the lower and flatter marginal abatement cost curve increases pollution abatement by a higher extent by adjusting to any predetermined increase in the tax rate than the firm with the higher and steeper marginal abatement cost. Consider a very small increase in the tax rate as an example. Suppose that in the very small range of the firms’ reactions to this marginal increase in terms of emission reduction levels, the slope of the marginal abatement cost curve of firm A is half of what it is for firm B. Then, A, in reaction to the marginal increase in the tax rate, reduces emissions by twice, the level reduced by B, the firm with the higher abatement cost. So, if country A agrees to this increase in the tax rate it accepts that two-thirds of total emissions reductions are attained as a result of its own firm and only one third is contributed by the firm in the other country. Country A accepts a “buy-two-get-one-free” arrangement. On the other hand, country B enters a “buy one-get-two-free” arrangement by endorsing the increase in the tax rate.

Notably, the fact that the tax rate is identical for the two countries leads to an asymmetric distribution of the burden of aggregate pollution reduction between these countries. In this arrangement, the country with the flatter marginal abatement cost subsidises the other country. This *subsidization effect* increases with increasing asymmetry in the marginal abatement costs of the two countries. On the other hand, since diffusion reduces the asymmetry in the marginal abatement costs of the two countries, it also reduces the subsidization effect.

An alternative expression for the phenomenon described above is “terms of trade effect”. Under the tax scheme, the difference between the slopes of the marginal abatement cost curves of the two countries determines how many units of emission reduction a country gets back from the other country for each individually achieved unit of reduction. The number of these units increases for the country with the superior technology in the process of diffusion and decreases for the country with the inferior technology. So diffusion improves the "terms of trade" for country A and makes them worse for country B.

It is intuitively clear that due to the subsidization (terms of trade) effect, the propensity of country A to accept higher tax rates in the negotiations increases with the extent of diffusion (provided that diffusion reduces the slope of the marginal abatement cost curve of country B and hence improves the terms of trade, see Assumption 1 below). For country B the reversed relationship holds true.[14]

After these introductory remarks, relying on plausibility we now proceed with the formal analysis of stage 2.

For all $\gamma < 1$ it holds that $\partial C_B/\partial X = \partial C(X,\gamma)/\partial X > \partial C(X,1)/\partial X = \partial C_A/\partial X$ because $C_{XT} < 0$. To avoid case-by-case analysis, we use the following additional assumption:

**Assumption 1** An improvement in abatement technology lowers the slope of the marginal abatement cost function for any given level of marginal abatement costs. I.e., for all technology levels $T_1 > T_2$, it holds that:

$$C_X(X_1, T_1) = C_X(X_2, T_2) \Rightarrow C_{XX}(X_1, T_1) < C_{XX}(X_2, T_2).$$ [15]

Note that an equivalent formulation of Assumption 1 is given by $\frac{\partial C_X^{-1}}{\partial y}(y, T_1) > \frac{\partial C_X^{-1}}{\partial y}(y, T_2)$ for all technology levels $T_1 > T_2$, i.e., the slope of the inverse marginal abatement cost function is increasing in the technology level.[16]

**Lemma 1** (Bottleneck country under the tax regime) *For $\gamma < 1$ country A is the bottleneck country under the tax bargaining regime under Assumption 1 (and in case of identical damage functions), i.e., with regard to the tax proposals of the two countries', it holds that $t_A < t_B$.*[17]

*Proof* To prove that country A is the bottleneck country, we first show that starting from an (arbitrary) initial tax rate $t$, an increase of the tax rate to the level $t + \Delta$ leads to larger additional aggregate abatement costs for firm A than for firm B.

First, note that from $\frac{dX_B}{d\gamma} > 0$ and $X_B(t) = X_A(t)$ for $\gamma = 1$, it follows that $X_A(t) > X_B(t)$ for all $\gamma < 1$. Additionally, from Assumption 1 and $C_X(X_A(\tau), 1) = C_X(X_B(\tau), \gamma)$, it follows that $C_{XX}(X_A(\tau), 1) < C_{XX}(X_B(\tau), \gamma)$ or equivalently $\frac{\partial C_X^{-1}}{\partial \tau}(\tau, 1) > \frac{\partial C_X^{-1}}{\partial \tau}(\tau, \gamma)\; \forall \tau \in [t, t+\Delta]$. That is, in the whole range $\tau \in [t, t+\Delta]$ a marginal increase of the tax rate leads to a higher increase in the abatement level by firm A than by firm B. However, this implies that $X_A(t+\Delta) - X_A(t) > X_B(t+\Delta) - X_B(t)$ and

[14] However, the subsidization effect is not the only one at work here. A full appraisal of the effects, extending the analysis to a countervailing "marginal damage effect", is presented below.

[15] Note that Assumption 1 is fulfilled if (i) the marginal abatement cost function is linear ($C_{XXX} = 0$) or alternatively (ii) the marginal abatement cost function is weakly concave ($C_{XXX} \leq 0$) and additionally $C_{XXT} < 0$ holds, i.e., an improvement of the abatement technology lowers the slope of the marginal abatement cost function for all abatement levels. However, Assumption 1 is also fulfilled for a subset of strictly convex marginal abatement cost functions.

[16] Note that the upper index "-1" denotes the inverse with respect to the first variable of $C_X$ for an exogenously given technology level.

[17] In Appendix B, it is shown that in case of identical damage functions, country B may turn out to be the bottleneck country under the tax regime if Assumption 1 is not fulfilled.

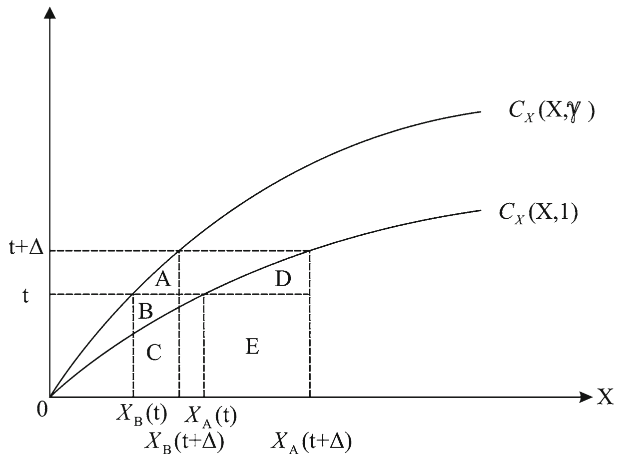


**Fig. 1** Marginal abatement costs under the tax regime

$$\int_{X_A(t)}^{X_A(t+\Delta)} C_X(X,1)dX = t\,(X_A(t+\Delta) - X_A(t)) + \int_t^{t+\Delta} X_A(t+\Delta) - C_X^{-1}(\tau,1)d\tau$$
$$> t\,(X_B(t+\Delta) - X_B(t)) + \int_t^{t+\Delta} X_A(t+\Delta) - C_X^{-1}(\tau,1)d\tau$$
$$> t\,(X_B(t+\Delta) - X_B(t)) + \int_t^{t+\Delta} X_B(t+\Delta) - C_X^{-1}(\tau,\gamma)d\tau$$
$$= \int_{X_B(t)}^{X_B(t+\Delta)} C_X(X,\gamma)dX.$$

Hence, an increase in the tax rate is more attractive for country B than for country A, since it "forces" the industry of country A to bear the largest portion of the costs of global emission reduction, whereas the benefits (in terms of reduction of environmental damages, $D(2E_{\max} - X_A(t) - X_B(t)) - D(2E_{\max} - X_A(t+\Delta) - X_B(t+\Delta))$ are, by assumption, equal for both countries. Thus, country A's tax proposal is smaller than country B's. □

Figure 1 illustrates the cost effects of an increase in the tax rate from $t$ to $t+\Delta$ for an arbitrary value $\gamma < 1$. The additional aggregate abatement costs incurred by firm A are represented by the areas D and E, while those of firm B are represented by the areas A, B, and C.

*Stage 1:*

Since country A is the bottleneck country at stage 2, the optimal effective transfer level from the point of view of firm A (B) follows from the optimization problems

$$\min_{\gamma} PC_A^t = C(X_A, 1) + t_A(E_{\max} - X_A) \text{ and } \min_{\gamma} PC_B^t = C(X_B, \gamma) + t_A(E_{\max} - X_B). \tag{14}$$

Using (2a), the corresponding first-order conditions may be simplified as

$$dPC_A^t/d\gamma = \frac{dt_A}{d\gamma}(E_{\max} - X_A) \text{ and} \tag{14a}$$

$$dPC_B^t/d\gamma = C_T + \frac{dt_A}{d\gamma}(E_{\max} - X_B). \tag{14b}$$

In contrast with the national framework, the sign of $dt_A/d\gamma$ is undetermined. From Eq. (13c), it follows that an increase in $\gamma$ has two opposing (indirect) effects for country A.

(1) *Subsidization effect:* Starting from a given tax level $t$, an increase in this tax level up to $t + \Delta$ becomes more attractive for country A, since due to Assumption 1, the additional emission reduction of the foreign firm B increases in $\gamma$, i.e., $\frac{d^2 X_B}{dt_A d\gamma} > 0$. This is the formal expression of the effect dealt with using plausibility arguments at the end of Sect. 1, above. If firms with different marginal abatement cost functions are subject to the same pollution tax, the extent of the emission reduction by the firm with the lower and flatter marginal abatement cost, A, depends on the increase in the tax rate, and is higher than the adjustment quantity of the other firm, B. Thereby, if the two firms are located in two different countries, and these countries cooperatively agree to increase the pollution tax rate they are using, then country A subsidizes country B, since it contributes a higher share to the joint product of aggregate pollution reduction than does B. This effect attenuates A's enthusiasm to agree to increases in the tax rate. Since the extent of the subsidisation effect is reduced by technology diffusion, increasing the tax rate becomes more attractive to A in the process of diffusion. The formal language for this result is $dt_A/d\gamma > 0$.

However, this is not the only effect present. There is a second effect at work that has not been alluded to in the introductory exposition addressing reader intuition, above.

(2) *Marginal damage effect:* From $\frac{dX_B}{d\gamma} > 0$ it follows that for a given tax level $t$, the marginal damages decrease in $\gamma$ due to $D_{EE} > 0$. Since the optimal tax proposal $t_A$ is determined by the equalization of marginal abatement costs and reduction in marginal damages, this effect works in favor of $dt_A/d\gamma < 0$.

Both effects together imply that the sign of $dt_A/d\gamma$ is indeterminate. The more elastic firm B's reaction to an increase in the tax rate, the stronger is the subsidization effect and hence the more probable it is that firm A decides against diffusion and chooses $\alpha^t = \alpha_{\min}$. The larger the slope of the marginal damage function, the stronger is the marginal damage effect and hence the more probable it is that firm A promotes diffusion of the new technology and chooses $\alpha^t = 1$.

Hence, the higher the damage cost/abatement cost ratio $\delta = d/c$ the greater the weight given to the marginal damage effect relative to the subsidization effect. That is, $dt_A/d\gamma < 0$ holds for high values of $\delta$ and $dt_A/d\gamma > 0$ holds for small values of $\delta$.

In the case of $\alpha = \alpha_{\min} = 0$, it directly follows that $\gamma = 0$.

The presence of the two aforementioned effects (the subsidization and the marginal damage effect) is the key to understanding why equilibrium diffusion may be different in the international and national context. In the latter, there is no subsidization effect between two countries, by definition. It is only the marginal damage effect that exists nationally, and this effect always runs in the direction of equilibrium tax rate decreasing in the level of diffusion. In the absence of any countervailing effect, the firm with the superior technology is always happy to diffuse in the national context.

In case of $\alpha^t > 0$ the situation for firm B is as follows. First, there is the indeterminate influence on the tax level $dt_A/d\gamma$, described previously discussing the subsidization and the marginal damage effect. Additionally, for firm B there is the unambiguously positive *abatement cost effect*: that is, an increase in $\gamma$ decreases the firm's abatement costs. Hence, the optimal value of $\gamma$ from the point of view of firm B tends to be higher than the optimal value for firm A.

**Proposition 3** (*a*) *Under an international tax bargaining regime with identical damage functions, firms A and B choose* $\alpha^t \in [0, 1]$ *and* $\beta^t \in [0, 1]$. *It follows that* $\gamma^t \in [0, 1]$ *(with both border cases possible for each parameter* $\alpha, \beta, \gamma$*).*

(*b*) *The equilibrium under the tax regime coincides with the social optimum if and only if* $\gamma^t = 1$.

*Proof* (a) See the example below.

(b) Follows from the fact that (only) in the case of $\gamma^t = 1$ the marginal abatement costs are equalized between the firms and due to identical damage both countries make the socially optimal tax proposals.

□

Note that the results strongly differ from those of the corresponding national model analyzed in Sect. 3, where the tax regime produced socially optimal incentives for diffusion and adoption.

To improve intuition, let us briefly disentangle the set of equilibrium tuples $(\alpha^t, \beta^t)$ written in Proposition 3 using compact formal language.

According to Proposition 3, $\alpha^t$ may take either the values 0 or 1.[18] Consider $\alpha^t = 0$ first. This is the equilibrium diffusion level if the subsidization effect overcompensates the marginal damage effect. It is compatible with this situation that firm B would like to adopt, just as it is with that that B would not like to adopt. In the former case, the subsidization effect overcompensates not only the marginal damage effect but also the sum of the marginal damage and the abatement cost effect. In the latter case, the sum of marginal damage and abatement cost effects overcompensates the subsidisation effect. However, even in the latter case, B does not adopt (even though he would like to). Adoption required diffusion as an "input" and there is none if $\alpha^t$ is at 0. So if $\alpha^t = 0$, $\gamma^t = 0$ follows.

Now turn to the case of $\alpha^t = 1$. This is the equilibrium level of diffusion if the marginal damage effect overcompensates the subsidization effect. B wants to adopt if the sum of the marginal damage and abatement cost effects overcompensate the subsidization effect. Since the abatement cost effect is always positive, it follows that B always wants to adopt in the case of $\alpha^t = 1$. So in the case of A deciding to fully diffuse ($\alpha^t = 1$) this is completely effective ($\gamma^t = 1$), because B decides in favour of full adoption ($\beta^t = 1$).

Let us now consider the functions of type (12) with $d_A = d_B$.[19] The set of all possible parameter values can be divided into three subsets ("regions"), where each is characterized by its specific pattern of equilibrium diffusion, adoption (and thereby effective transfer) values.[20]

(a) $\delta \geq \frac{16}{49}$: The marginal damage effect is stronger than the subsidization effect, i.e., $\frac{\partial t_A}{\partial \gamma} < 0$. Hence firm A promotes diffusion, $\alpha^t = 1$. For firm B there is the additional abatement cost effect $\Rightarrow \beta^t = \gamma^t = 1$. For this parameter range the tax equilibrium coincides with the social optimum.

[18] As it will turn out below for the functions of type (12), firm A's equilibrium level of diffusion is always one of these border types. However, for other functions an interior solution might be possible.

[19] To guarantee inner solutions with respect to the emission levels we assume $\delta < 16/7$ with $\delta := d/c$.

[20] See Appendix A.

(b) $\frac{1}{4} < \delta < \frac{16}{49} : \frac{\partial t_A}{\partial \gamma} > 0$ if $\gamma < \bar{\gamma}$ and $\frac{\partial t_A}{\partial \gamma} < 0$ if $\gamma > \bar{\gamma}$ with $\bar{\gamma} \in (0, 1)$ implicitly defined by $\delta = (4 - \bar{\gamma})^2/(7 - \bar{\gamma})^2$. Hence, firm A chooses one of the border solutions $\alpha^t \in \{\alpha_{\min}, 1\}$. Since, for the whole range $\partial PC_B/\partial \gamma < 0$ holds, we have $\beta^t = 1$ and hence $\gamma^t = \alpha^t \in \{\alpha_{\min}, 1\}$. I.e., for firm B, the sum of the abatement cost and marginal damage effects outweigh the subsidization effect in the whole parameter range. The critical ratio $\delta$ for which firm A is indifferent between $\alpha = \alpha_{\min}$ and $\alpha = 1$ depends on the level of $\alpha_{\min}$. For example, in case of $\alpha_{\min} = 0$ we obtain $\alpha^t = \gamma^t = 1$ in case of $\frac{2}{7} \leq \delta_A < \frac{16}{49}$ and $\alpha^t = \gamma^t = 0$ in case of $1/4 < \delta_A < 2/7$.[21]

(c) $\delta \leq \frac{1}{4} : \frac{\partial t_A}{\partial \gamma} > 0, \alpha^t = \alpha_{\min}$. For firm B we get

$$\frac{\partial PC_B}{\partial \gamma} > 0 \Leftrightarrow (4 - \gamma)^3 - \delta(7 - \gamma)(4 - \gamma)(13 - \gamma) - 2\delta^2(7 - \gamma)^3 > 0.$$

For example, in case of $\delta = 1/5$ we have $\partial PC_B/\partial \gamma < 0 \quad \Rightarrow \beta^t = 1$, i.e., firm A chooses $\alpha^t = \alpha_{\min}$ since the subsidization effect overcompensates for the marginal damage effect. However, for firm B the sum of marginal damage and abatement cost effects overcompensates for the marginal damage effect.

In case of $\delta = 1/10$ we have $\partial PC_B/\partial \gamma > 0 \Rightarrow \beta^t = 0$. That is, the subsidization effect now overcompensates for the sum of marginal damage and abatement cost effects as well.

## 4.2 Countries with Asymmetric Damage Functions

We now consider the more general case of asymmetric countries with respect to environmental damage.[22] Since there might be different kinds of asymmetries that most particularly influence the role of the bottleneck country, general results are no longer possible. Hence, we restrict our attention to the functions of type (12). Additionally, to avoid making the analysis too complex, we assume $\alpha_{\min} = 0$ in both this section and the corresponding section, 5.2.[23]

In the case of asymmetric countries, each country may take the role of the bottleneck country, depending on the ratio between the damage factors. More precisely, country A is the bottleneck country (i.e., $t_B \geq t_A$), if $d_B/d_A \geq 3/(4-\gamma)$ or equivalently $\gamma \leq (4\delta_B - 3\delta_A)/\delta_B$ holds, i.e., if its damages are sufficiently low relative to the damages suffered in country B.[24,25] This result implies that the choice of the diffusion and adoption levels may also determine which country takes the role of the bottleneck country. With respect to the influence of $\gamma$ on the tax proposals, we obtain: $\partial t_A/\partial \gamma > 0 \Leftrightarrow \delta_A < (4 - \gamma)^2/(7 - \gamma)^2$, i.e., the optimal tax proposal is decreasing in $\gamma$ for a large damage/abatement cost relationship in country A. The reasoning is the same as in case of identical countries. The tax proposal

[21] Here, and in the following, we assume that if firm A is indifferent between different levels of $\alpha$, it chooses the maximum of these levels. This maximal level happens to coincide with the socially optimal level. We make it easy on ourselves (and on the readers) by using the aforementioned assumption as a "tie-breaker" in the case of indifference. In more complicated models, the tie-breaker could be instead endogenous. For example, the consideration of sales revenues would increase the diffusion incentive, whereas the consideration of competition between the firms would reduce it.

[22] E.g., in the context of climate change, for the functions of type (12) the case $d_B > d_A$ could represent the situation of a developing country B with ex ante inferior technology and higher environmental damage compared to the industrialized country A.

[23] The case of $\alpha_{\min} > 0$ would not produce notable, additional insights, since as in case of identical countries the optimal transfer parameter for the adopting firm B is at least as high as the optimal transfer parameter for the diffusing firm A. This is due to the additional positive abatement cost effect of the adopting firm. For one parameter region, this is exemplarily demonstrated in Appendix A (see case T.2.a, there).

[24] A derivation of this and the following results is presented in Appendix A.

[25] Note that for $d_A = d_B$ the condition is equivalent to $\gamma \leq 1$ and hence fulfilled.

**Table 1** Effective transfer parameters under the tax regime

| Case | Effective transfer level | Equilibrium tax proposal (bottleneck country) | Parameter range |
|---|---|---|---|
| A | $\gamma^t = 1$ | $t = t_B$ | $\delta_B \leq \frac{3}{4}\delta_A$ |
| | | | $\frac{3}{4}\delta_A < \delta_B < \frac{14\delta_A}{16-7\delta_A}$ and $\delta_A \leq \frac{1}{4}$ |
| | | | $\frac{3}{4}\delta_A < \delta_B < \min\left\{\frac{14\delta_A}{16-7\delta_A}, \delta_A\right\}$ and $\frac{1}{4} < \delta_A < \frac{16}{49}$ |
| | | | $\frac{3}{4}\delta_A < \delta_B < \delta_A$ and $\delta_A \geq \frac{16}{49}$ |
| B | $\gamma^t = 1$ | $t = t_A$ | $\delta_B \geq \delta_A$ and $\delta_A \geq \frac{2}{7}$ |
| C | $\gamma^t = 0$ | $t = t_A$ | $\delta_B \geq \frac{14\delta_A}{16-7\delta_A}$ and $\delta_A < \frac{2}{7}$ |

of country B is unambiguously decreasing in $\gamma$, $\partial t_B/\partial\gamma < 0$. The optimal tax proposal of country B equates marginal abatement costs of firm B with the reduction in marginal damages due to the emission reduction in both countries. Since an increase in $\gamma$ moves the marginal abatement cost curve downwards, the optimal tax rate is decreasing. Both results together imply that firm A avoids the diffusion of the new technology if the damages in country A are low relative to country B. This suggests that country A is the bottleneck country and that, taking abatement costs into account, the tax proposal of country A is increasing in the technology level since the subsidization effect outweighs the marginal damage effect. The corresponding parameter ranges are summarized in Table 1.

Note that in case of $d_A \neq d_B$, even if $\gamma^t = 1$ holds, the tax proposal of the bottleneck country differs from the socially optimal one. Thereby, equilibrium pollution abatement differs from socially optimal abatement. This in turn implies that in case of asymmetric damages social costs under the tax regime are always higher than in the social optimum.

## 5 Decentralization Using Emission Quotas in an International Framework

### 5.1 Countries with Symmetric Damage Functions

Whereas under the tax regime the negotiated uniform tax rate does not depend on an initial activity level, under the quota regime the negotiated uniform emissions reduction entails a uniform percentage reduction starting from the initial emission level. We assume that in the initial situation there is either no regulation at all (i.e., the ex ante emissions levels are given by $E_i = E_{\max}$) or the ex ante environmental standard is given by the emission level $E_i = \bar{E}_0$, which is optimal, given the old technology, and defined by $C_X(E_{\max} - \bar{E}_0, 0) = 2D_E(2E_{\max} - 2\bar{E}_0)$. Since, in both cases, the initial emissions levels are symmetric, the choice between these two assumptions influences only the percentage emission reduction quota, and not the corresponding equilibrium emission levels.[26] Correspondingly, in the following we may take the upper emission limit $\bar{E}$ as the choice variable of the government(s) (as in the national scenario).

[26] Note that, due to the uniform starting point in this section, bargaining over a uniform absolute emission reduction is equivalent to bargaining over a uniform relative emission reduction. In Sect. 7, we consider a second variant of the quota regime that starts from asymmetric Nash equilibrium emission levels.

*Stage 3:*
As in the national scenario at stage 3, given $\bar{E}$, firm $i$ chooses $X_i = E_{\max} - \bar{E}$.
*Stage 2:*
At stage 2 the governments negotiate an internationally uniform abatement level and agree on the lowest common denominator among their abatement proposals (or equivalently on the highest common denominator of their emission standard proposals), by assumption. The corresponding optimization problems of the two countries are given by

$$\min_{\bar{E}_A} SC_A^q = C(E_{\max} - \bar{E}_A, 1) + D(2\bar{E}_A) \text{ and } \min_{\bar{E}_b} SC_b^q = C(E_{\max} - \bar{E}_B, \gamma) + D(2\bar{E}_B). \quad (15)$$

The corresponding first-order conditions are

$$dSC_A^q/d\bar{E}_A = -C_X(E_{\max} - \bar{E}_A, 1) + 2D'(2\bar{E}_A) = 0 \text{ and} \quad (15a)$$

$$dSC_B^q/d\bar{E}_B = -C_X(E_{\max} - \bar{E}_B, \gamma) + 2D'(2\bar{E}_B) = 0. \quad (15b)$$

Hence, the government chooses the upper emissions limit that equalizes the country-specific marginal abatement and marginal damage costs.

In analogy to what we did for the tax regime in Sect. 4.1, we would like to precede the analysis of stage 2 for the quota regime with a few introductory remarks appealing to intuition. Above, we have emphasized the distributional implications of the tax regime. It must be noted that changing from this regime to the quota regime fundamentally changes the mechanism according to which the burdens of aggregate pollution reduction are shared between the two countries. It does so to the pleasure of country A. In contrast with the asymmetric burden sharing under the tax regime, the quota regime considered in the main part of this paper is defined by each country paying half of the environmental protection bill.[27] For any unit of aggregate pollution reduction agreed upon in the international negotiations, each of the two countries contributes half. They both enter a "buy-one-get-one-free" arrangement negotiating quotas.

Consequently, investigating the implications of changing from the tax to the quota regime in terms of abatement and diffusion means investigating the allocative implications of a change in the distributional arrangement.

**Lemma 2** (Bottleneck country under the quota regime) *For $\gamma < 1$ country B is the bottleneck country under the quota bargaining regime, i.e., with regard to the two countries' quota proposals, it holds that $\bar{E}_B > \bar{E}_A$.*

*Proof* Starting from an initial emission standard $\bar{E}$, an increase in the abatement obligations from $\bar{X}$ to $\bar{X} + \Delta$ for an arbitrary value $\gamma < 1$ leads to an identical emission reduction for both firms, by definition. The corresponding additional aggregate abatement costs for firm B (given by $\int_{\bar{X}}^{\bar{X}+\Delta} C_X(X, \gamma)dX$) are higher than the corresponding additional aggregate abatement costs of firm A (given by $\int_{\bar{X}}^{\bar{X}+\Delta} C_X(X, 1)dX$) because $C_{XT} < 0$. Hence, an increase in the abatement norm is more attractive for country A than for country B. The reason is that this increase "forces" the industry of country B to bear the largest portion of the costs of global emission reductions, whereas the benefits (in terms of decreasing environmental damage, $D(2E_{\max} - 2\bar{X}) - D(2E_{\max} - 2(\bar{X} + \Delta))$) are equal for both countries, by assumption. Thus, country B's proposal is smaller than that of country A, for all $\gamma < 1$. □

Figure 2 illustrates the cost effects of an increase in abatement obligations. The additional aggregate abatement costs of firm A are represented by the area A, while those of firm B are represented by the areas A and B.

[27] A different variant of the quota regime is discussed in Sect. 7.2.3.

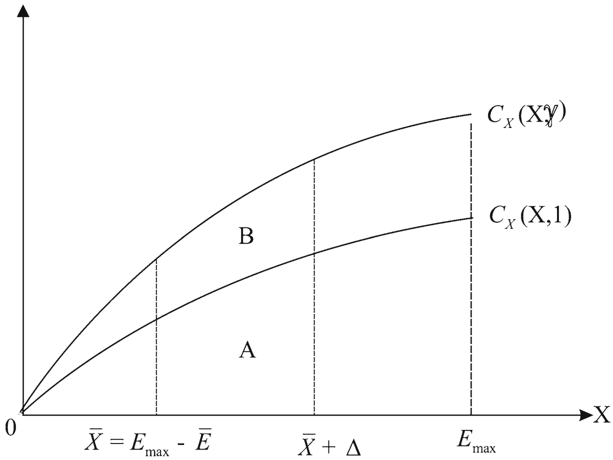


**Fig. 2** Marginal abatement costs under the quota regime

*Stage 1:*
Since country B is the bottleneck country at stage 2, the optimal effective transfer level from the point of view of firm A (B) follows from the optimization problems

$$\min_{\gamma} PC_A^q = C(E_{\max} - \bar{E}_B, 1) \text{ and } \min_{\gamma} PC_B^q = C(E_{\max} - \bar{E}_B, \gamma). \tag{16}$$

with corresponding first-order conditions

$$dPC_A^q/d\gamma = -\frac{d\bar{E}_B}{d\gamma} C_X \text{ and} \tag{16a}$$

$$dPC_B^q/d\gamma = C_T - \frac{d\bar{E}_B}{d\gamma} C_X. \tag{16b}$$

Comparative static analysis reveals

$$\frac{d\bar{E}_B}{d\gamma} = \frac{C_{XT}(E_{\max} - \bar{E}_{B,\gamma})}{C_{XX}(E_{\max} - \bar{E}_{B,\gamma}) + 4D_{EE}(2\bar{E}_B)} < 0. \tag{17}$$

Hence, as in the national scenario and due to analogous reasoning, the *target effect* under the quota regime is unambiguously negative. This implies that $PC_A^q$ is strictly increasing in $\gamma$, from which it follows that $\alpha^q = \alpha_{\min}$. As in the national quota scenario for firm B, there are two opposing effects: the positive *abatement cost effect* and the negative *target effect*. Hence, firm B's optimal level of adoption depends on the parameter values.

**Proposition 4** (*a*) *Under an international quota bargaining regime with identical damage functions, firms A and B choose* $\alpha^q = \alpha_{\min}$ *and* $\beta^q \in [0, 1]$, *from which it follows that* $\gamma^q \in [0, \alpha_{\min}]$ *(with both border cases possible for both parameters* $\beta, \gamma$*).*
(*b*) *The equilibrium under the quota regime always differs from the social optimum.*

*Proof* (a) See the example below.
(b) Follows from $\gamma^q < 1$. □

For the functions of type (12), we obtain for firm B:
$\partial PC_B/\partial\gamma > 0 \Leftrightarrow \delta < (4-\gamma)/12 \Leftrightarrow \gamma < 4-12\delta$. For example, in the case of $\delta > 1/3$ we obtain $\beta^q = 1$, whereas for $\delta < 1/4$ we obtain $\beta^q = 0$. As in the national framework, a high damage/abatement cost ratio leads to a strict abatement target and hence a relative strong abatement cost effect, which results in a positive adoption incentive.

Note that in contrast with the tax regime, the general structure of technology choice equilibria is the same under the national and global quota regimes.

In addition to the formal analysis, the incentives to diffuse and adopt under the quota regime are explained below using intuitive terms. We start with the comparison of the situation under the quota regime to the one under the tax regime explained above.

When the firms calculate the consequences of their technology decisions on the outcome of the international negotiations, they focus on their impact on the bottleneck's willingness to accept a more stringent environmental policy. This is so because the bottleneck country determines the result of the negotiations. It is important to note that the role of the bottleneck country depends upon the policy regime. Under the tax regime, A is the bottleneck country, whereas under the quota regime the role is taken up by B.[28] So, in the present context it is only country B upon which the firms focus when deciding upon diffusion and adoption.

Since the marginal abatement costs of firm B decrease in the process of technical progress, the willingness of country B to accept higher reduction quotas (lower emission quotas) in the negotiations increases as the superior technology is introduced. This has immediate consequences for the outcome of the negotiations in that the equilibrium quota becomes more restrictive. This *target effect* is the only consequence of technical progress for the potentially diffusing firm, A. Of course, it is an unpleasant one from the point of view of that firm. Accordingly, A will avoid diffusing as much as possible. We allow two interpretations of "as much as possible". In the first case, A is able to fully avoid diffusion, $\alpha^{\min} = 0$, whereas in the second A cannot completely prevent diffusion i.e. there is some involuntary diffusion, $\alpha^{\min} > 0$.

For firm B, the situation is somewhat more complicated. On the one hand, a decision to adopt would lead to the unpleasant target effect mentioned above. However, for firm B there is a countervailing effect in that B's marginal abatement costs go down in the process of adoption, the *marginal abatement cost-effect*. Obviously, B would like to adopt if the marginal abatement cost effect overcompensates the target effect, and vice versa.

In the case that A cannot fully avoid diffusion, $\alpha^{\min} > 0$, and that the marginal abatement cost effect overcompensates the target effect, B adopts what it can get, meaning the effective technology transfer is at $\gamma^q = \alpha^{\min} > 0$. However, if the target effect is stronger than the marginal abatement cost effect, B ignores the chance to adopt what A involuntarily diffuses and (much to the relief of A) effective technology transfer is zero, $\gamma^q = 0$.

Of course, if A can fully avoid diffusion, $\alpha^{\min} = 0$, then it does not matter how the two aforementioned effects relevant to B relate to each other. Whether or not B would like to adopt, effective diffusion is zero, $\gamma^q = 0$, because adoption requires diffusion as an input, which is not provided in the case we refer to here.

## 5.2 Countries with Asymmetric Damage Functions

Again, we restrict our attention to the case $\alpha_{\min} = 0$.

As under the tax regime, in the case of asymmetric countries each country may take the role of the bottleneck country. Country B is the bottleneck country, if

[28] It will be apparent in the next section that things are somewhat more complicated if we deviate from the simplifying assumption that the two countries have identical damage functions.

**Table 2** Effective transfer parameters under the quota regime

| Case | Effective transfer level | Equilibrium quota proposal (bottleneck country) | Parameter range |
|---|---|---|---|
| D | $\gamma^q = 1$ | $\bar{E} = \bar{E}_A$ | $\delta_A \leq \frac{3}{4}\delta_B$ |
| E | $\gamma^q = 0$ | $\bar{E} = \bar{E}_B$ | $\delta_A > \frac{3}{4}\delta_B$ |

$\bar{E}_B - \bar{E}_A > 0 \Leftrightarrow d_B/d_A \leq (4-\gamma)/3 \Leftrightarrow \gamma \leq (4\delta_A - 3\delta_B)/\delta_A$ holds.

With respect to the influence of $\gamma$ on the emission norm proposals, we obtain: $d\bar{E}_A/d\gamma = 0$ and $d\bar{E}_B/d\gamma < 0$. I.e., if country A is the bottleneck country, the abatement norm is independent of $\gamma$. We assume that in this case firm A chooses the socially optimal diffusion level $\alpha^t = 1$.[29] If country B is the bottleneck country we obtain $\alpha^t = \alpha_{\min}$ as in the case of symmetric countries.

Both results together imply that firm A avoids diffusion of the new technology if the damages in country A are rather high relative to country B and hence country B is the bottleneck country. The set of all possible parameter values can be divided into two subsets ("regions"), where each is characterized by its specific pattern of bottleneck country assignment and equilibrium diffusion as well as adoption (and thereby effective transfer) values. The corresponding parameter ranges are presented in Table 2.

Note that when $d_A \neq d_B$ even if $\gamma^q = 1$ holds, the quota proposal of the bottleneck country differs from the socially optimal one. Therefore, equilibrium pollution abatement is different from socially optimal abatement. This in turn implies that in the case of asymmetric damage social costs under the quota regime are always higher than in the social optimum.

## 6 Welfare Comparison

### 6.1 Countries with Symmetric Damage Functions

Proposition 5 compares global welfare and the effective transfer parameters under the two policy regimes for the functions of type (12) with symmetric damages $d_A = d_B = d$.

**Proposition 5** *For the functions of type (12) with $d_A = d_B = d$*

(*a*) *the effective transfer parameter under the tax regime is no smaller than under the quota regime, $\gamma^t \geq \gamma^q$ and*

(*b*) *social costs are lower under the tax regime than under the quota regime, $SC^t \leq SC^q$.*

*Proof* (a) Follows from $\gamma^t \geq \alpha_{\min}$ for $\delta \geq 1/4$ (see Sect. 4.1) and from $\gamma^q = 0$ for $\delta < 1/4$ and $\gamma^q \leq \alpha_{\min}$ for $\delta \geq 1/4$ (see Sect. 5.1).

(b) Follows from $SC^t(E^t(\gamma^t) \overset{(1)}{\leq} SC^t(E^t(\gamma^q)) \overset{(2)}{<} SC^t(E^q(\gamma^q)) \overset{(3)}{<} SC^q(E^q(\gamma^q))$ due to the following reasoning:

(1) Under the tax regime global welfare is strictly decreasing in $\gamma$ [see Eq. (1c)].

(2) For each given effective transfer level $\gamma$, aggregate abatement under the tax regime is higher than under the quota regime (see Appendix A), i.e., $E^q(\gamma^q) > E^t(\gamma^q) > E^t(\gamma^{**} = 1)$.

[29] See footnote 21.

(3) The division of the aggregate abatement target is not cost-effective under the quota regime since marginal abatement costs in country B are higher due to $E_A^q = E_B^q$ and $\gamma^q < 1$. □

The intuition behind Proposition 5 is that under the tax regime the effective transfer level and the aggregate abatement level come closer to the socially optimal value and, additionally, the division of the aggregate abatement target is cost-effective, which is not the case under the quota regime.

## 6.2 Countries with Asymmetric Damage Functions

Proposition 6 shows that in the case of asymmetric damage functions the result of Proposition 5 is not valid.

**Proposition 6** *For the functions of type* (12) *with $d_A \neq d_B$ under the tax regime*

(*a*) *the effective transfer parameter may be lower and*
(*b*) *social costs may be higher*

*than under the quota regime.*

*Proof* See Table 3 below. □

For the functions of type (12) Table 3 compares the equilibria under the two policy regimes for the intersections of the relevant parameter ranges A, B, and C of the tax and D and E of the quota regime. In each cell, the first line describes the relevant parameter range and the second line the bottleneck proposals. The third to seventh lines compare the effective transfer parameters (line 3), total emissions (line 4), individual abatement levels (line 5), marginal abatement costs (line 6), and aggregate social costs (line 7) under the assumption $\alpha_{\min} = 0$.[30]

In the intersections A/E and B/E the effective transfer level under the tax regime equals the socially optimal one, whereas under the quota regime there is no diffusion at all. Correspondingly, the tax regime is welfare superior but differs from the social optimum in case of $d_B \neq d_A$ (which holds in the whole parameter range of case A).

In the intersection B/D due to the identical bottleneck assignment under both regimes (country A) and the symmetric marginal abatement cost functions ($\gamma = 1$), both instruments lead to the same outcome. However, if the damages (and hence also the abatement proposal) of the bottleneck country A are strictly lower than those of country B, social costs are higher than in the social optimum.

In the intersection C/D the effective transfer level and the abatement levels are higher under the quota regime than under the tax regime. This *size effect* overcompensates for the *cost-ineffectiveness* of the quota regime. I.e., the quota is welfare superior.[31]

In the intersection C/E we obtain $\partial(SC^q - SC^t)/\partial\delta_B < 0$. Moreover, for $\delta_B$ sufficiently low[32] the tax regime is welfare superior, while for $\delta_B$ sufficiently high the quota regime is welfare superior. The reason is that for $\delta_B \to (4/3)\delta_A$ total abatement is higher under the quota regime and, as in the case of C/D, this size effect overcompensates for the cost-ineffectiveness of the quota regime.

30 See Appendix A for the individual values.

31 Note that in the whole parameter range of C/D the damages are asymmetric.

32 A sufficient but not necessary condition is given by $\delta_B \leq (49/48)\delta_A$. Hence, also in the intersection C/E identical damage functions imply the welfare superiority of the tax regime.

**Table 3** Comparison of the equilibrium outcomes under the two policy regimes

| | D | E |
|---|---|---|
| A | No intersection of the parameter ranges[a] | Whole parameter range of Case A,<br>$t = t_B, \bar{E} = \bar{E}_B$<br>$\gamma^t = 1 > \gamma^q = 0,$<br>$E^q > E^t > E^{**},$<br>$X_A^t = X_B^t > X_A^q = X_B^q,$<br>$C_B'^q > C_A'^t = C_B'^t > C_A'^q,$[b]<br>$SC^q > SC^t > SC^{**}$ |
| B | $\delta_A \leq \frac{3}{4}\delta_B$ and $\delta_A \geq \frac{2}{7},$<br>$t = t_A, \bar{E} = \bar{E}_A$<br>$\gamma^t = \gamma^q = 1,$<br>$E^q = E^t (>, = E^{**} \Leftrightarrow d_A <, = d_B),$<br>$X_A^t = X_B^t = X_A^q = X_B^q,$<br>$C_A'^t = C_B'^t = C_A'^q = C_B'^q,$<br>$SC^q = SC^t (> SC^{**} \Leftrightarrow d_A \neq d_B)$ | $\frac{3}{4}\delta_B < \delta_A \leq \delta_B$ and $\delta_A \geq \frac{2}{7},$<br>$t = t_A, \bar{E} = \bar{E}_B$<br>$\gamma^t = 1 > \gamma^q = 0,$<br>$E^q > E^t (>, = E^{**} \Leftrightarrow d_B >, = d_A),$<br>$X_A^t = X_B^t > X_A^q = X_B^q$<br>$C_B'^q > C_A'^t = C_B'^t > C_A'^q,$<br>$SC^q > SC^t (> SC^{**} \Leftrightarrow d_A \neq d_B)$ |
| C | $\delta_A \leq \frac{3}{4}\delta_B$ and $\delta_A < \frac{2}{7},$<br>$t = t_A, \bar{E} = \bar{E}_A$<br>$\gamma^t = 0 < \gamma^q = 1$<br>$E^t > E^q > E^{**},$<br>$X_A^q = X_B^q > X_A^t > X_B^t,$<br>$C_A'^q = C_B'^q > C_A'^t = C_B'^t,$<br>$SC^t > SC^q (> SC^{**} \Leftrightarrow d_A \neq d_B)$ | $\frac{14\delta_A}{16-7\delta_A} \leq \delta_B < \frac{4}{3}\delta_A$ and $\delta_A < \frac{2}{7},$<br>$t = t_A,\ \bar{E} = \bar{E}_B$<br>$\gamma^t = \gamma^q = 0,$<br>$E^t > E^q \Leftrightarrow \delta_B > \frac{49}{48}\delta_A, E^q > E^{**}, E^t > E^{**},$<br>$X_A^t > X_i^q \Leftrightarrow 56\delta_A + 21\delta_A\delta_B - 48\delta_B > 0, X_B^t < X_i^q, X_A^t$<br>$C_A'^t > C_A'^q \Leftrightarrow X_A^t > X_A^Q, C_B'^q > C_A'^t = C_B'^t, C_A'^q,$<br>$SC^q > (<, =) SC^t \Leftrightarrow \delta_B < (>, =) \bar{\delta}(\delta_A) \in \left(\frac{49}{48}\delta_A, \frac{4}{3}\delta_A\right)$ |

[a]In particular, note that $14\delta_A/(16 - 7\delta_A) < (4/3)\delta_A$ holds in case of $\delta_A \leq 1/4$
[b]E.g., $C_A'^q$ is the abbreviated notation for $\frac{\partial C}{\partial X}(X_A^q)$

In Sect. 6, we have shown that the quota regime may be welfare superior to the tax regime despite its cost-ineffectiveness. For the functions of type (12) this case only occurred in parameter regions with asymmetric damage functions. However, in Sect. 7.1 we will show that for a different type of abatement cost functions than that specified in (12) the quota regime may be welfare superior to the tax regime also in the case of identical damage functions.

## 7 Extensions

### 7.1 Marginal Abatement Costs Revisited

In Sect. 6, it turned out that for the functions of type (12) the damage functions had to be asymmetric in order to obtain the result of a welfare superior quota regime. However, this is not a necessary requirement for all types of abatement cost functions satisfying Assumption 1. As an example, consider the following abatement cost and damage functions:

$$C_A = cX_A^{3/2}, C_B = \left(1 + \frac{1-\gamma}{3}\right) cX_B^{3/2}, D_i = d(E_A + E_B)^2.^{33} \quad (18)$$

For $c = E_{\max} = 10{,}000$ and $d = 10$ we obtain $\gamma^t = \gamma^q = 0$.

The aggregate emission reduction is given by $X^q = 2460.95$ under the quota regime and by $X^t = 2158.69$ under the tax regime, whereas the socially optimal aggregate abatement level would be given by $X^{**} = 3753.80$. Hence, aggregate abatement under both regimes is lower than the socially optimal level. However, the aggregate abatement level under the quota regime comes closer to the socially optimal level than the level under the tax regime. As in a sub-region of the intersection C/E (as seen in Sect. 6.2), this positive *size effect* overcompensates for the cost-ineffectiveness effect of the quota regime. Thus, the quota regime leads to lower social costs than the tax regime ($SC^q = 7.1595 \times 10^9$, $SC^t = 7.1686 \times 10^9$).

This example has shown that in the case of identical damage functions the quota regime results in higher global welfare than the tax regime if (i) the incentives for technology diffusion are also suboptimal under the tax regime (because otherwise the tax equilibrium equals the social optimum) and (ii) global abatement is higher under the quota regime and this *size effect* dominates the *cost-ineffectiveness effect*.

## 7.2 Bargaining Starting from Nash Equilibrium

In the following we assume that in the initial situation before international bargaining takes places the national governments have chosen the Nash equilibrium policy levels given the new technology in country A and the old technology in country B. That is, differing from the former analyses, we now assume that the governments have already responded to the improved technology in country A. In this section, we restrict our attention to the case of identical countries and proceed as follows: in Sect. 7.2.1 we derive the Nash equilibrium emission levels and discuss potential consequences for the bargaining regimes in Sect. 7.2.2 (tax regime) and Sect. 7.2.3 (quota regime). In Sect. 7.2.4, we compare global welfare under both bargaining regimes.

### *7.2.1 Nash Equilibrium*

In the Nash equilibrium the government of country A (B) minimizes national pollution costs given the abatement level of country B (A). Hence the optimization problems of countries A and B may be written as

$$\min_{X_A} SC_A^N = C(X_A, 1) + D(2E_{\max} - X_A - X_B) \text{ and} \tag{19}$$
$$\min_{X_B} SC_B^N = C(X_B, 0) + D(2E_{\max} - X_A - X_B).$$

The Nash equilibrium abatement levels, $X_A^N, X_B^N$, are implicitly defined by the first-order conditions given by

$$C_X(X_A^N, 1) = C_X(X_B^N, 0) = D_E(2E_{\max} - X_A^N - X_B^N). \tag{19a}$$

These activity levels can be implemented by, for example, a corresponding national tax

$$t_A^N = t_B^N = D_E(2E_{\max} - X_A^N - X_B^N) \tag{20}$$

as well as by a corresponding emissions quota

$$\bar{E}_A^N = E_{\max} - X_A^N, \bar{E}_B^N = E_{\max} - X_B^N. \tag{21}$$

[33] Note that the abatement cost functions specified in (15) satisfy Assumption 1 but differ from the abatement cost functions specified in (12).

**Lemma 3** (Nash equilibrium emission levels) *The Nash equilibrium emission level of country A is lower than that of country B, $E_A^N < E_B^N$.*

*Proof* From $C_X(X_A^N, 1) = C_X(X_B^N, 0), C_{XX} > 0$ and $C_{XT} < 0$ it directly follows that $X_A^N > X_B^N$ or equivalently $E_A^N < E_B^N$ holds. □

### *7.2.2 Decentralization Using Emission Taxes*

Since the corresponding Nash equilibrium tax levels are identical for both countries (due to the assumption of identical environmental damage), the results of Sect. 4.1 are not affected by the change of the initial situation.

### *7.2.3 Decentralization Using Emission Quotas*

The situation is different under the quota regime. Here, unlike the situation of Sect. 5.1, the initial emissions quota is stricter for country A (see Lemma 3). This has the following consequences for the international bargaining game:
*Stage 2:*
At stage 2, the governments negotiate an internationally uniform emissions reduction quota $\Delta$, with the corresponding emission norms given by $\bar{E}_i = (1-\Delta)E_i^N$ and the corresponding abatement levels as

$$\bar{X}_i = E_{\max} - (1-\Delta)E_i^N = X_i^N + \Delta E_i^N. \tag{22}$$

The optimization problems faced by the two countries are given by

$$\min_{\Delta_A} SC_A^q = C(E_{\max} - (1-\Delta_A)E_A^N, 1) + D((1-\Delta_A)(E_A^N + E_B^N)) \text{ and} \tag{23}$$
$$\min_{\Delta_B} SC_B^q = C(E_{\max} - (1-\Delta_B)E_B^N, \gamma) + D((1-\Delta_B)(E_A^N + E_B^N))$$

with corresponding first-order conditions

$$E_A^N \cdot C_X(E_{\max} - (1-\Delta_A)E_A^N, 1) - (E_A^N + E_B^N)D_E((1-\Delta_A)(E_A^N + E_B^N)) = 0 \text{ and} \tag{23a}$$

$$E_B^N \cdot C_X(E_{\max} - (1-\Delta_B)E_B^N, \gamma) - (E_A^N + E_B^N)D_E((1-\Delta_B)(E_A^N + E_B^N)) = 0. \tag{23b}$$

Lemma 4 shows that the change of the initial situation under the quota regime does not affect the role allocation for sufficiently low values of $\gamma$.

**Lemma 4** (Bottleneck country under the quota regime starting from Nash) *Under Assumption 1, for $\gamma \to 0$ country B is the bottleneck country under the quota bargaining regime starting from Nash equilibrium emission levels ($\Delta_B < \Delta_A$).*

*Proof* (a) We prove the first part of the assertion by considering the border case $\gamma = 0$. Starting from the Nash equilibrium emission levels $E_i^N$ a reduction of the emission levels to $\bar{E}_i = (1-\Delta)E_i^N$ corresponds with an increase in the abatement levels from $X_i^N$ to $\bar{X}_i = X_i^N + \Delta E_i^N$. Because of $E_A^N < E_B^N$ the increase is larger for country B than for country A. Hence, to prove that the additional aggregate abatement costs for firm B are higher than

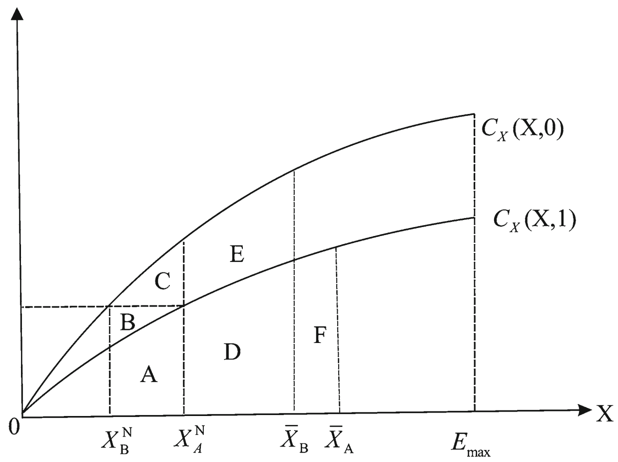


**Fig. 3** Marginal abatement costs under the quota regime starting from Nash

for firm A, it suffices to show that for arbitrary levels of $\Delta \in (0, 1)$ the following holds: $C_X(\bar{X}_B, 0) - C_X(\bar{X}_A, 1) > 0$. This, however, follows from

$$\begin{aligned} C_X(\bar{X}_B, 0) - C_X(\bar{X}_A, 1) &> C_X(\bar{X}_B, 0) - C_X(\bar{X}_B + (X_A^N - X_B^N), 1) \\ &\underset{Ass.1}{>} C_X(X_B^N, 0) - C_X(X_B^N + (X_A^N - X_B^N), 1) \\ &= C_X(X_B^N, 0) - C_X(X_A^N, 1) = 0. \end{aligned}$$

From Assumption 1, we have $\frac{\partial C_X^{-1}}{\partial \tau}(\tau, 1) > \frac{\partial C_X^{-1}}{\partial \tau}(\tau, 0)$, which implies that the distance between $C_X^{-1}(\tau, 1)$ and $C_X^{-1}(\tau, 0)$ is increasing in the level of marginal abatement cost $\tau$, from which the assertion above follows.

Hence, as in Sect. 5.1, an increase in the abatement norm is more attractive for country A than for country B since for a given benefit (in terms of reduction of environmental damage, $D(2E_{\max} - X_A^N - X_B^N) - D(2E_{\max} - \bar{X}_A - \bar{X}_B)$) the increase in abatement costs is higher for country B. Thus, country B's proposal is smaller than that of country A. □

Figure 3 illustrates the cost effects of an increase in the abatement obligations for the border cases $\gamma = 0$ and $\gamma = 1$. The additional aggregate abatement costs of firm A are represented by the areas D and F, while those of firm B are represented by the areas A, B, C, D, and E in the case of $\gamma = 0$ and A and D in case of $\gamma = 1$. This implies that in the case of $\gamma = 1$ the ratio between A and F determines which country bears the greatest proportion of additional abatement costs.

*Stage 1:*

At the first stage, the firms consider how $\gamma$ influences the bargaining outcome of the governments. Since, depending on the parameter values, both countries may take the role of the bottleneck country, we consider both proposals: from Eq. (23) it follows that the optimization problem of country A does not depend on $\gamma$ at all. Hence we have $d\Delta_A/d\gamma = 0$. From (23b), it follows that

$$\frac{d\Delta_B}{d\gamma} = -\frac{E_B^N \cdot C_{XT}}{(E_B^N)^2 \cdot C_{XX} + (E_A^N + E_B^N)^2 D_{EE}} > 0. \tag{24}$$

Since firm A (as well as firm B) prefers a weaker emissions reduction target, firm A chooses $\alpha^q = \alpha_{\min}$ (as in Sect. 5.1). If $\alpha_{\min} = 0$, it directly follows that $\gamma^q = 0$.

In case of $\alpha_{\min} > 0$, at stage 1, the optimization problem faced by firm B under the quota regime is given by

$$\min_{\beta} PC_B^q = C(E_{\max} - (1 - \Delta)E_B^N, \alpha\beta) \tag{25}$$

from which it follows that

$$\frac{dPC_B^q}{d\beta} = \underbrace{\underbrace{C_X}_{>0}\underbrace{E_B^N \alpha \frac{d\Delta}{d\gamma}}_{\geq 0}}_{\geq 0} + \alpha \underbrace{C_T}_{<0}. \tag{25a}$$

Hence, for firm B, we have the two countervailing effects already known from Sect. 5.1. An increase in $\gamma$ reduces abatement costs but decreases the emission limit (as long as country B takes the role of the bottleneck country).

Again, firm B's optimal level of adoption depends on the parameter values. Hence, Proposition 4 is also valid for the quota regime starting from Nash equilibrium emission levels.

### *7.2.4 Welfare Comparison*

Using a numerical example, we demonstrate that global welfare may be higher under the quota regime than under the tax regime also for the second variant of the quota regime, where bargaining starts from Nash equilibrium emission levels.

As an example, consider the cost functions and damage functions of type (18) with $c = E_{\max} = 10{,}000$ and $d = 10$.

The Nash equilibrium abatement levels are given by $X_A^N = 641.61$ and $X_B^N = 360.91$.

Under the quota regime starting from the Nash equilibrium the role of the bottleneck country depends on the level of $\gamma$. For $0 \leq \gamma \leq 0.88$ the bottleneck country is country B, while for $0.89 \leq \gamma \leq 1$ the bottleneck country is country A. As under the tax regime and the first variant of the quota regime, we obtain $\gamma^q = 0$ under the quota regime starting from Nash. The technology level $\gamma^q = 0$ corresponds with $\Delta = \Delta_B = 0.084$. The corresponding abatement costs for firm B are given by $C_B(1175, 0) = 5.37 \times 10^8$.[34] The aggregate emissions reduction for the equilibrium levels $\gamma^q = 0$ and $\Delta = \Delta_B = 0.084$ is given by $X^q = 2607.13$ and hence higher than under the tax regime ($X^t = 2158.69$). In addition, social costs are lower under the second variant of the quota regime than under the tax regime ($SC^q = 7.1292 \times 10^9$, $SC^t = 7.1686 \times 10^9$).

## 8 Conclusion

In this paper we have analysed the incentives to diffuse and adopt superior pollution abatement technology in an international setting. The results were compared to those obtained for the national setting in the earlier literature. The comparison was performed for two environmental policy instruments, pollution taxes and non-tradable pollution quotas. In the national context, the results are clear cut: diffusion is socially optimal in the tax regime but not in

[34] Note that Firm B's optimal value of $\gamma$ within the range $0.89 \leq \gamma \leq 1$ is given by $\gamma = 1$ with corresponding abatement costs $C_B(1713, 1) = 7.09 \times 10^8 > C(1175, 0)$.

the quota regime. Things turn out to be more complicated in the international arena. Here, even in the tax regime, incentives to diffuse and adopt may be too weak, compared to the social optimum. The reason is that diffusion and adoption lower the marginal abatement cost in the technology receiving country, and that this generates a tendency of making higher tax rates more acceptable in the international negotiations. If this effect dominates countervailing effects present in this setting, firms refuse to diffuse and adopt.

There is another result, distinguishing the international arena from the national one. Under certain conditions, the equilibrium in terms of pollution abatement as well as technology diffusion and adoption may be welfare superior in the quota regime compared to the tax regime. The reason is that the equilibrium emissions reduction might be higher in the case of the countries negotiating quotas instead of taxes. If this effect dominates other effects (all working in the direction of the welfare superiority of the tax), then the counter-intuitive result materializes.

From our results we do not derive the policy conclusion that quotas should be applied instead of taxes in the international setting. Instead, we point out that the general superiority theorem regarding taxes does not carry over from the national to the international setting. Here, incentives are more complicated, and it all depends on the parameters (of the involved abatement cost and damage cost functions).

An obvious suggestion is to solve the problems of the tax in the international setting (and perhaps the distortions of the quota regime, too) by using an additional policy instrument. A likely candidate is a subsidy on diffusion (and another on adoption in the cases where adoption is refused, as specified in the paper). After all, it has been shown that allocative problems in terms of diffusion and adoption may be solved using technology subsidies in the national setting, under certain circumstances (see, for example, Katsoulacos and Xepapadeas 1996).[35] However, it is far from being obvious that these results carry over from the national to the international setting. Incentives for a country to unilaterally introduce national subsidies might be distorted because of the international spillover effect. Of course, the countries might try to make amends, negotiating technology subsidies in addition to pollution tax rates (or emission reduction quotas). However, this program might be threatened by distortions that prevent a socially optimal allocation, analogous to the ones explained in this paper regarding the equilibrium level of tax rates (as well as quotas). In view of these possible complications, we perceive the allocative effect of combinations of policy instruments (like pollution taxes plus technology subsidies) to be a topic of its own, and one that ought to be pursued in future research.

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. Of those, some pertinent might be the discussion of alternative stylizations of technical progress and of the international negotiation process, the issue of competition between involved firms in output markets, as well as the expansion of the set of policy regimes. Further extensions are costly diffusion and adoption as well as patented discoveries.

## Appendix A

Equilibrium analysis for abatement costs and damage functions of type (12).

[35] An analogous result to the one derived by Katsoulacos and Xepapadeas (1996) for the combination of taxes and technology subsidies is derived in Endres et al. (2012) for the combination of different forms of environmental liability law with a technology subsidy.

A.1 Social Optimum

$$\gamma^{**}=1,\quad X_A^{**}=X_B^{**}=\frac{2E_{\max}(\delta_A+\delta_B)}{1+2(\delta_A+\delta_B)},\; SC^{**}=\frac{4cE_{\max}^2(\delta_A+\delta_B)}{1+2(\delta_A+\delta_B)}\text{ with}$$
$$\delta_i:=d_i/c,\quad i\in\{A,B\}.$$

A.2 National Tax Regime

For a given tax rate the abatement levels of firms A and B are given by

$$X_A=\frac{1}{2}\frac{t}{c},\; X_B=\frac{3}{2(4-\gamma)}\frac{t}{c},$$

which leads to the equilibrium tax rate

$$t^*=\frac{4(4-\gamma)E_{\max}(d_A+d_B)}{4-\gamma+(7-\gamma)(\delta_A+\delta_B)},\; dt^*/d\gamma<0,$$
$$\Rightarrow (X_B^t\le)X_A^t<E_{\max}\Leftrightarrow \delta_A+\delta_B<\frac{4-\gamma}{1-\gamma}.$$

To guarantee an inner solution we assume that $\delta_A+\delta_B\le\min_{\gamma\in[0,1]}\frac{4-\gamma}{1-\gamma}=4$ holds, from which it follows that $\frac{\partial PC_A^t}{\partial\gamma}<0$. Additionally, we have $\frac{\partial PC_B^t}{\partial\gamma}<0$. Hence, $\gamma^t=\alpha^t=\beta^t=1$, $SC^t=SC^{**}=\frac{4cE_{\max}^2(\delta_A+\delta_B)}{1+2(\delta_A+\delta_B)}$.

A.3 National Quota Regime

The equilibrium norm is given by

$$\bar{E}=\frac{E_{\max}(7-\gamma)}{7-\gamma+12(\delta_A+\delta_B)},\quad \frac{\partial\bar{E}}{\partial\gamma}<0\quad\Rightarrow\alpha=\alpha_{\min}.$$

Inserting this norm into the private cost function of firm B reveals

$$\frac{\partial PC_B}{\partial\gamma}=\frac{48cE_{\max}^2(\delta_A+\delta_B)^2(1-\gamma-12(\delta_A+\delta_B))}{(7-y+12(\delta_A+\delta_B))^3}>0\Leftrightarrow\delta_A+\delta_B<\frac{1-\gamma}{12}.$$

Hence, for $\delta_A+\delta_B>\frac{1}{12}$ we get $\frac{dPC_B^q}{d\gamma}<0$, from which $\beta^q=1$ and hence $\gamma^q=\alpha_{\min}$ follows.

For $\delta_A+\delta_B<\frac{1}{12}\approx0.0833$ we obtain $\frac{dPC_B^q}{d\gamma}>0$ for $\gamma<1-12(\delta_A+\delta_B)$ and $\frac{dPC_B^q}{d\gamma}<0$ for $\gamma>1-12(\delta_A+\delta_B)$. Since the private cost function of firm B is single-peaked, firm B chooses one of the border solutions with corresponding effective transfer levels $\gamma^q=\alpha_{\min}$ or $\gamma^q=0$.

We obtain $PC_B^q(\gamma=0)<PC_B^q(\gamma=1)\Leftrightarrow\delta_A+\delta_B<-\frac{1}{4}+\frac{1}{6}\sqrt{3}\approx0.0387$. I.e., in the case of $\delta_A+\delta_B<0.0387$ it follows from $PC_B^q(\gamma=0)<PC_B^q(\gamma=1)$ that $PC_B^q(\gamma=0)<PC_B^q(\gamma=\alpha_{\min})$ and hence $\gamma^q=\beta^q=0$. For $0.0387<\delta_A+\delta_B<0.0833$ it depends on the value of $\alpha_{\min}$, whether firm B prefers $\gamma^q=0$ or $\gamma^q=\alpha_{\min}$.

A.4 International Tax Regime

To guarantee an inner solution ($X_A(t_A) < E_{\max}$) we assume

$$\delta_A < \min_{\gamma\in[0,1]} \frac{(4-\gamma)^2}{7-8\gamma+\gamma^2} = \frac{16}{7}.$$

Then, the tax proposals of country A and B are given by

$$t_A = \frac{4d_A E_{\max}(7-\gamma)(4-\gamma)}{(4-\gamma)^2+(7-\gamma)^2\delta_A} \quad \text{and} \quad t_B = \frac{4d_B E_{\max}(7-\gamma)(4-\gamma)}{12-3\gamma+(7-\gamma)^2\delta_B},$$

from which we see

$$t_B \geq t_A \Leftrightarrow \frac{d_B}{d_A} \geq \frac{3}{4-\gamma} \Leftrightarrow \gamma \leq \Gamma(\delta) := \frac{4\delta_B - 3\delta_A}{\delta_B}, \text{ with } \Gamma(\delta) \geq 1 \Leftrightarrow \delta_B \geq \delta_A \text{ and}$$

$\Gamma(\delta) \leq 0 \Leftrightarrow \delta_B \leq \frac{3}{4}\delta_A$.

With respect to the influence of $\gamma$ on the tax proposals, we obtain: $\frac{\partial t_B}{\partial \gamma} < 0$,

$$\frac{\partial t_A}{\partial \gamma} > 0 \Leftrightarrow \delta_A < T(\gamma) := \frac{(4-\gamma)^2}{(7-\gamma)^2} \text{ with}$$
$$\partial T/\partial\gamma < 0 \; \forall\gamma \in [0,1], T(0) = 16/49, T(1) = 1/4.$$

Hence, we can distinguish the following cases:
T.1) $\delta_B \leq \frac{3}{4}\delta_A : t = t_B$ (B is bottleneck country independent of $\gamma$),

$$\frac{\partial t_B}{\partial \gamma} < 0 \Rightarrow \alpha^t = \beta^t = \gamma^t = 1, SC^t = \frac{4cE_{\max}^2(8\delta_B^2+\delta_A+\delta_B)}{(1+4\delta_B)^2}$$

T.2.a) $\delta_B \geq \delta_A$ and $\delta_A \leq \frac{1}{4} : t = t_A$, $\frac{\partial t_A}{\partial \gamma} > 0 \Rightarrow \alpha = \alpha_{\min}$.
For firm B, we obtain

$$\frac{dPC_B(t_A(\gamma),\gamma)}{d\gamma} > 0$$
$$\Leftrightarrow \Delta(\delta_A,\gamma) := (4-\gamma)^3 - \delta_A(7-\gamma)(4-\gamma)(13-\gamma) - 2\delta_A^2(7-\gamma)^3 > 0,$$

with $\partial\Delta/\partial\delta_A < 0$, $\Delta(\delta_A,\gamma) > 0 \; \forall\delta_A \leq 0.10$, $\Delta(\delta_A,\gamma) < 0 \; \forall\delta_A \geq 0.14$ (irrespective of $\gamma$). In the range $\delta_A \in [0.11, 0.13]$ we obtain $\Delta(\delta_A,\gamma) > 0$ for sufficiently low values of $\gamma$). $\Rightarrow \beta \in \{0, \alpha_{\min}\}$, with $\beta = \alpha_{\min}$, if $PC_B(\gamma = \alpha_{\min}) \leq PC_B(\gamma = 0)$. [36]
Summarizing, we obtain $\gamma^t \in \{0, \alpha_{\min}\}$.

T.2.b) $\delta_B \geq \delta_A$ and $\frac{1}{4} < \delta_A < \frac{16}{49} : t = t_A$
Let $\bar{\gamma} \in (0,1)$ be implicitly defined by $\delta_A = \frac{(4-\bar{\gamma})^2}{(7-\bar{\gamma})^2}$.Then we obtain

$$\frac{\partial t}{\partial \gamma} = \frac{\partial t_A}{\partial \gamma} > 0 \Leftrightarrow \gamma < \bar{\gamma} \text{ and } \frac{\partial t}{\partial \gamma} = \frac{\partial t_A}{\partial \gamma} < 0 \Leftrightarrow \gamma > \bar{\gamma} \quad \Rightarrow \alpha^t \in \{\alpha_{\min}, 1\}.$$

In the case of $\alpha^t = 1$ we obtain $\gamma^t = \beta^t = 1$.
In the case of $\alpha^t = \alpha_{\min}$ for firm B, we have the two opposing effects as analyzed in case

[36] Note that if $PC_B(\gamma = 1) \leq PC_B(\gamma = 0) \leq PC_B(\gamma = \alpha_{\min})$ holds, firm B chooses $\beta = 0$ instead of $\beta = 1$, because in the case of $\alpha = \alpha_{\min}$, the choice $\beta = 1$ would result in the effective transfer parameter $\gamma = \alpha_{\min}$.

T.2.a).
In case of $\alpha_{\min} = 0$ we obtain

$\frac{1}{4} < \delta_A < \frac{2}{7} \Rightarrow PC_A(t = t_A, \gamma = 1) > PC_A(t = t_A, \gamma = 0) \Rightarrow \gamma^t = 0$ (case T.2.b.1) and
$\frac{2}{7} \leq \delta_A < \frac{16}{49} \Rightarrow \gamma^t = 1$ (case T.2.b.2).

T.2.c) $\delta_B \geq \delta_A$ and $\delta_A \geq \frac{16}{49} : t = t_A, \partial t_A/\partial\gamma < 0 \Rightarrow \alpha^t = \beta^t = \gamma^t = 1$.
T.3.a) $\frac{3}{4}\delta_A < \delta_B < \delta_A$ and $\delta_A \leq \frac{1}{4}$ :

$$\frac{\partial t}{\partial\gamma} = \frac{\partial t_A}{\partial\gamma} > 0 \Leftrightarrow \gamma \leq \frac{4\delta_B - 3\delta_A}{\delta_B} \text{ and } \frac{\partial t}{\partial\gamma} = \frac{\partial t_B}{\partial\gamma} < 0 \Leftrightarrow \gamma > \frac{4\delta_B - 3\delta_A}{\delta_B}.$$
$$\Rightarrow \alpha^t \in \{\alpha_{\min}, 1\}.$$

In case of $\alpha_{\min} = 0$ we obtain

$$PC_A(t = t_B, \gamma = 1) > PC_A(t = t_A, \gamma = 0) \Leftrightarrow \delta_B > \frac{14\delta_A}{16 - 7\delta_A},$$

i.e.:

$$\frac{14\delta_A}{16 - 7\delta_A} < \delta_B < \delta_A \Rightarrow \gamma^t = \alpha^t = 0 \text{ (case T.3.a.1)},$$
$$\frac{3}{4}\delta_A < \delta_B < \frac{14\delta_A}{16 - 7\delta_A} \Rightarrow \gamma^t = \alpha^t = 1 \text{ (case T.3.a.2)}$$

T.3.b) $\frac{3}{4}\delta_A < \delta_B < \delta_A$ and $\frac{1}{4} < \delta_A < \frac{16}{49}$:

$$\frac{\partial t}{\partial\gamma} = \frac{\partial t_A}{\partial\gamma} > 0 \Leftrightarrow \gamma < \min\left\{\bar{\gamma}, \frac{4\delta_B - 3\delta_A}{\delta_B}\right\} \text{ and}$$
$$\frac{\partial t}{\partial\gamma} < 0 \Leftrightarrow \gamma > \min\left\{\bar{\gamma}, \frac{4\delta_B - 3\delta_A}{\delta_B}\right\}, \text{ with } t = t_B \text{ for } \gamma = 1.$$
$$\Rightarrow \alpha^t \in \{\alpha_{\min}, 1\}.$$

In case of $\alpha_{\min} = 0$ we obtain

$$PC_A(t = t_B, \gamma = 1) > PC_A(t = t_A, \gamma = 0) \Leftrightarrow \delta_B > \frac{14\delta_A}{16 - 7\delta_A}\left(< \delta_A \Leftrightarrow \delta_A < \frac{2}{7}\right),$$

i.e.:

$$\frac{14\delta_A}{16 - 7\delta_A} < \delta_B < \delta_A \Rightarrow \gamma^t = 0 \text{ (case T.3.b.1)},$$
$$\frac{3}{4}\delta_A < \delta_B < \min\left\{\frac{14\delta_A}{16 - 7\delta_A}, \delta_A\right\} \Rightarrow \gamma^t = 1 \text{ (case T.3.b.2)}.$$

T.3.c) $\frac{3}{4}\delta_A < \delta_B < \delta_A$ and $\delta_A \geq \frac{16}{49}$ :

$$\frac{\partial t}{\partial\gamma} = \frac{\partial t_A}{\partial\gamma} < 0 \Leftrightarrow \gamma < \frac{4\delta_B - 3\delta_A}{\delta_B} \text{ and } \frac{\partial t}{\partial\gamma} = \frac{\partial t_B}{\partial\gamma} < 0 \Leftrightarrow \gamma > \frac{4\delta_B - 3\delta_A}{\delta_B}.$$
$$\Rightarrow \alpha^t = \beta^t = \gamma^t = 1.$$

A.5 International Quota Regime

The proposals of country A and B are given by

$$\bar{E}_A = \frac{E_{\max}}{1+4\delta_A}, \bar{E}_B = \frac{E_{\max}(4-\gamma)}{4-\gamma+12\delta_B} \text{ with}$$
$$\bar{E}_B - \bar{E}_A > 0 \Leftrightarrow \delta_B \leq \frac{1}{3}\delta_A(4-\gamma) \Leftrightarrow \gamma \leq \frac{4d_A - 3d_B}{d_A}.$$

With respect to the influence of $\gamma$ on the emission norm proposals we obtain: $\frac{\partial \bar{E}_A}{\partial \gamma} = 0$, i.e., if country A is the bottleneck country, the abatement norm is independent of $\gamma$. We assume that in this case firm A chooses the socially optimal diffusion level $\alpha^q = 1$. If country B is the bottleneck country, we obtain $\frac{\partial \bar{E}_B}{\partial \gamma} < 0$.
Hence, we can distinguish the following cases:
Q.1) $\delta_A \leq \frac{3}{4}\delta_B : \bar{E} = \bar{E}_A \Rightarrow \gamma^q = \alpha^q = \beta^q = 1$.
Q.2) $\delta_A \geq \delta_B : \bar{E} = \bar{E}_B \Rightarrow \alpha^q = \alpha_{\min}$. For firm B, we obtain:

$$\frac{\partial PC_B}{\partial \gamma} > 0 \Leftrightarrow \delta_B < \frac{4-\gamma}{12}.$$

Q.3) $\frac{3}{4}\delta_B < \delta_A < \delta_B$:

$$\Rightarrow \bar{E} = \bar{E}_B \Leftrightarrow \gamma \leq \frac{4\delta_A - 3\delta_B}{\delta_A} \quad \text{and} \quad \bar{E} = \bar{E}_A \Leftrightarrow \gamma > \frac{4\delta_A - 3\delta_B}{\delta_A}.$$

Under the assumption $\alpha_{\min} = 0$ firm A chooses $\gamma^q = \alpha^q = 0$ because

$$PC_A(\bar{E}_A, \gamma = 1) > PC_B(\bar{E}_B, \gamma = 0).$$

A.6 Welfare Comparison

Assumption: $\alpha_{\min} = 0$
Social optimum:

$$SC^{**} = \frac{4cE_{\max}^2(\delta_A+\delta_B)}{1+2\delta_A+2\delta_B}, X_A^{**} = X_B^{**} = \frac{2E_{\max}(\delta_A+\delta_B)}{1+2\delta_A+2\delta_B}, E^{**} = \frac{2E_{\max}}{1+2\delta_A+2\delta_B},$$
$$\frac{\partial C_A}{\partial X}(X_A^{**}) = \frac{\partial C_B}{\partial X}(X_B^{**}) = \frac{4cE_{\max}(\delta_A+\delta_B)}{1+2\delta_A+2\delta_B}$$

Tax regime:

$$\text{A) } SC^t(t=t_B, \gamma=1) = \frac{4cE_{\max}^2(8\delta_B^2+\delta_A+\delta_B)}{(1+4\delta_B)^2} (> SC^{**} \Leftrightarrow \delta_A \neq \delta_B),$$
$$X_A = X_B = \frac{4\delta_B E_{\max}}{1+4\delta_B},$$
$$E = \frac{2E_{\max}}{1+4\delta_B}, \ \frac{\partial C_A}{\partial X}(X_A) = \frac{\partial C_B}{\partial X}(X_B) = \frac{8c\delta_B E_{\max}}{1+4\delta_B}$$
$$\text{B) } SC^t(t=t_A, \gamma=1) = \frac{4cE_{\max}^2(8\delta_A^2+\delta_A+\delta_B)}{(1+4\delta_A)^2} (> SC^{**} \Leftrightarrow \delta_A \neq \delta_B),$$
$$X_A = X_B = \frac{4\delta_A E_{\max}}{1+4\delta_A},$$

$$E = \frac{2E_{\max}}{1+4\delta_A}, \frac{\partial C_A}{\partial X}(X_A) = \frac{\partial C_B}{\partial X}(X_B) = \frac{8c\delta_A E_{\max}}{1+4\delta_A}$$

$$\text{C) } SC^t(t = t_A, \gamma = 0) = \frac{16cE_{\max}^2(343\delta_A^2 + 64\delta_A + 64\delta_B)}{(16+49\delta_A)^2},$$

$$X_A = \frac{56\delta_A E_{\max}}{16+49\delta_A}, X_B = \frac{42\delta_A E_{\max}}{16+49\delta_A},$$

$$E = \frac{32E_{\max}}{16+49\delta_A}, \frac{\partial C_A}{\partial X}(X_A) = \frac{\partial C_B}{\partial X}(X_B) = \frac{112c\delta_A E_{\max}}{16+49\delta_A}$$

Quota regime:

$$\text{D) } SC^q(\bar{E} = \bar{E}_A, \gamma = 1) = \frac{4cE_{\max}^2(8\delta_A^2 + \delta_A + \delta_B)}{(1+4\delta_A)^2}, X_A = X_B = \frac{4\delta_A E_{\max}}{1+4\delta_A},$$

$$E = \frac{2E_{\max}}{1+4\delta_A}, \frac{\partial C_A}{\partial X}(X_A) = \frac{\partial C_B}{\partial X}(X_B) = \frac{8c\delta_A E_{\max}}{1+4\delta_A}$$

$$\text{E) } SC^q(\bar{E} = \bar{E}_B, \gamma = 0) = \frac{cE_{\max}^2(21\delta_B^2 + 4\delta_A + 4\delta_B)}{(1+3\delta_B)^2}, X_A = X_B = \frac{3\delta_B E_{\max}}{1+3\delta_B},$$

$$E = \frac{2E_{\max}}{1+3\delta_B}, \frac{\partial C_A}{\partial X}(X_A) = \frac{6c\delta_B E_{\max}}{1+3\delta_B}, \frac{\partial C_B}{\partial X}(X_B) = \frac{8c\delta_B E_{\max}}{1+3\delta_B}$$

## Appendix B

If Assumption 1 is not fulfilled, the marginal abatement cost functions could be represented by Fig. 4.

Assume that the tax proposal of country A is given by $t_A$. That is, for country A, the additional environmental damage if $t$ is reduced to $t_A - \varepsilon$ with $\varepsilon \to 0$ is just offset by the reduction in abatement costs, which is represented by the areas D and E. However, for country B, the abatement cost reducing effect would be represented by the areas A, B, and C and hence larger than that of country A. Hence, country B's optimal tax proposal would be smaller than $t_A$. I.e., for an appropriate marginal damage function (that leads to the tax proposal $t_A$ of country A), country B would be the bottleneck country under the tax regime.

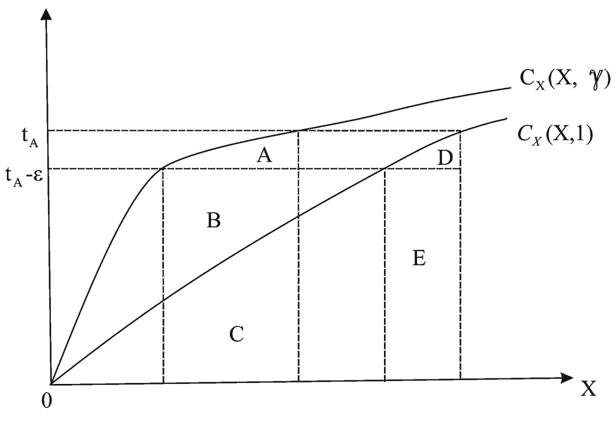


**Fig. 4** Marginal abatement costs under the tax regime if Assumption 1 is violated

## References

Altamirano-Cabrera J-C, Finus M, Dellink R (2008) Do abatement quotas lead to more successful climate coalitions. Manch Sch 76:104–129
Baker E, Adu-Bonnah K (2008) Investment in risky R&D programs in the face of climate uncertainty. Energy Econ 30:465–486
Baker E, Clarke L, Shittu E (2008) Technical change and the marginal cost of abatement. Energy Econ 30:2799–2816
Barrett S (2003) Environment and statecraft: the strategy of environmental treaty making. Oxford University Press, Oxford
Baumann Y, Lee M, Seeley K (2008) Does technological innovation really reduce marginal abatement costs? Some theory, algebraic evidence, and policy implications. Environ Resour Econ 39:507–527
Bosetti V, Tavoni M (2009) Uncertain R&D, backstop technology and GHGs stabilization. Energy Econ 31:S18–S26
Breton M, Fredj K, Zaccour G (2006) International cooperation, coalitions stability and free riding in a game of pollution control. Manch Sch 74:103–122
Carraro C, Siniscalco D (1993) Strategies for the international protection of the environment. J Public Econ 52:309–328
Coria J (2009) Taxes, permits, and the diffusion of a new technology. Resour Energy Econ 31:249–271
Dannenberg A (2012) Coalition formation and voting in public goods games. Strateg Behav Environ 2:83–105
Dannenberg A, Lange A, Sturm B (2010) On the formation of coalitions to provide public goods—experimental evidence from the lab. NBER Working Paper, NBER-WP 15967
Downing PB, White LJ (1986) Innovation in pollution control. J Environ Econ Manag 13:18–29
Endres A (1997) Negotiating a climate convention—the role of prices and quantities. Int Rev Law Econ 17:147–156
Endres A (2011) Environmental economics—theory and policy. Cambridge University Press, Cambridge
Endres A, Finus M (2002) Quotas may beat taxes in a global emission game. Int Tax Public Finance 9:687–707
Endres A, Friehe T (2011) Incentives to diffuse advanced abatement technology under environmental liability law. J Environ Econ Manag 62:30–40
Endres A, Friehe T, Rundshagen B (2012) It's all in the Mix!—Internalizing externalities with R&D subsidies and environmental liability. Discussion Paper No 479, University of Hagen
Espinola-Arredondo A (2009) Free-riding and cooperation in environmental games. J Public Econ Theory 11:119–158
Eyckmans J (1999) Strategy proof uniform effort sharing schemes for transfrontier pollution problems. Environ Resour Econ 14:165–189
Finus M (2008) Game theoretic research on the design of international environmental agreements: insights, critical remarks and future challenges. Int Rev Environ Resour Econ 2:1–39
Finus M, Altamirano-Cabrera J-C, Van Ierland EC (2005) The effect of membership rules and voting schemes on the success of international climate agreements. Public Choice 125:95–127
Gerlagh R, Kverndokk S, Rosendahl KE (2009) Optimal timing of climate change policy: interaction between carbon taxes and innovation externalities. Environ Resour Econ 43:369–390
Golombek R, Hoel M (2004) Unilateral emission reductions and cross-country technology spillovers. Adv Econ Anal Policy 4(2), Article 3
Golombek R, Hoel M (2005) Climate policy under technology spillovers. Environ Resour Econ 31:201–227
Golombek R, Hoel M (2008) Endogenous technology and tradable emission quotas. Resour Energy Econ 30:197–208
Hagem C (2009) The clean development mechanism versus international permit trading. Resour Energy Econ 31:1–12
Held H, Kriegler K, Edenhofer O (2009) Efficient climate policies under technology and climate uncertainty. Energy Econ 31:S50–S61
Hoel M (1992) International environmental conventions: the case of uniform reductions of emissions. Environ Resour Econ 2:141–159
Jaffe AB, Stavins RN (1995) Dynamic incentives of environmental regulations: the effects of alternative policy instruments on technology diffusion. J Environ Econ Manag 29:S43–S63
Katsoulacos Y, Xepapadeas A (1996) Environmental innovation, spillovers and optimal policy rules. In: Carraro C, Katsoulacos Y, Xepapadeas A (eds) Environmental policy and market structure, chap 8. Kluwer, Dordrecht, pp 143–150
Kneese AV, Schultze TL (1975) Pollution, prices and public policy. The Brookings Institution, Washington, DC

Löschel A, Otto VM (2009) Technological uncertainty and cost effectiveness of $CO_2$ emission reduction. Energy Econ 31:S4–S17
Milliman SR, Prince R (1989) Firm incentives to promote technological change in pollution control. J Environ Econ Manag 17:247–265
Orr L (1976) Incentive for innovation as the basis for effluent charge strategy. Am Econ Rev 66:441–447
Osmani D, Tol R (2009) Toward farsightedly stable international environmental agreements. J Public Econ Theory 11:455–492
Otto VM, Löschel A, Reilly J (2008) Directed technical change and differentiation of climate policy. Energy Econ 30:2855–2878
Parry IWH (2003) On the implications of technological innovation for environmental policy. Environ Dev Econ 8:57–76
Requate T (2005) Dynamic incentives by environmental policy instruments—a survey. Ecol Econ 54:175–195
Requate T, Unold W (2001) On the incentives created by policy instruments to adopt advanced abatement technology if firms are asymmetric. J Inst Theor Econ 157:536–554
Requate T, Unold W (2003) Environmental policy incentives to adopt advanced abatement technology: will the true ranking please stand up?. Eur Econ Rev 47:125–176
Ulph A, Ulph D (1996) Trade, strategic innovation and strategic environmental policy—a general analysis. In: Carraro C, Katsoulacos Y, Xepapadeas A (eds) Environmental policy and marktet structure, chap 10. Kluwer, Dordrecht, pp 181–208
Ulph A, Ulph D (2007) Climate change—environmental and technology policies in a strategic context. Environ Resour Econ 37:159–180
Yi S-S, Shin H (2000) Endogenous formation of research coalitions with spillovers. Int J Ind Organ 18: 229–256