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Diffusion and adoption of advanced emission abatement technology induced by permit trading

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Abstract

This paper analyzes firm incentives to diffuse and adopt advanced abatement technology for three different regimes of tradeable emission permits (auctioning, benchmarking, and grandfathering). We particularly consider technical change that decreases marginal abatement costs (MACs) only at high emission levels, whereas it increases them at low firm emissions. We establish that the desirability of the different regimes of allocating permits to firms is critically influenced by how MACs are changed by technological improvements.

1 | INTRODUCTION

1.1 | Motivation and main results

A key role of environmental policy lies in the creation of incentives for firms to innovate, diffuse, and adopt more advanced abatement technologies. The relative performance of different instruments of environmental policy has attracted great attention (e.g., D'Amato & Dijkstra, 2018; Requate, 2005a). Market-based instruments such as tradeable permits are usually among the best performing instruments. In these analyses, it is commonly assumed that technical change lowers the marginal abatement cost curve at all levels of emission. This assumption has come under attack. Some contributors argue that technical change alters marginal abatement costs (MAC) in a way that depends on the level of emissions such that there will be a decrease for some and an increase for other levels of emissions (e.g., Amir, Germain, & van Steenberghe, 2008; Baker, Clarke, & Shittu, 2008; Bauman, Lee, & Seeley, 2008; Bréchet & Jouvét, 2008; Dijkstra & Gil-Moltó, 2018; Perino & Requate, 2012). For example, Amir et al. (2008) show that only innovation in end-of-pipe technology leads to a uniform

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downward shift of the MAC curve, whereas MACs may increase for high levels of abatement for other types of innovation. Perino and Requate (2012) explain that MACs increase for high levels of abatement when emissions are proportional to output and technological progress reduces emissions per output. Empirically, Bauman et al. (2008) estimate MACs for sulfur dioxide in Korea. Their regression results confirm that production process innovations did raise MACs.

This paper considers the incentives of polluting firms to diffuse and adopt a more advanced abatement technology in a regime with tradeable emission permits. We follow Baker et al. (2008), Bréchet and Jouvet (2008), Dijkstra and Gil-Moltó (2018), and Perino and Requate (2012), among others, in assuming that the advanced technology implies lower (higher) MACs for large (low) emission levels. More precisely, following Dijkstra and Gil-Moltó (2018), we assume that there exists a critical emission level such that marginal technical change starting from the current state increases (decreases) MACs at emission levels lower (higher) than that critical level.¹ Regarding the tradeable emission permit scheme, we distinguish auctioning, benchmarking, and grandfathering.

We analyze a simple framework to focus on selected mechanisms. Specifically, we analyze a model in which one firm is endowed with advanced abatement technology and may diffuse this technology to other firms (as in Endres & Friehe, 2011). The firms are interdependent because they are active in the market for permits, but firms are not interacting on product markets. In the market for permits, all firms—including the technology leader—are price-takers. However, by deciding about the diffusion of the advanced abatement technology, the technology leader critically influences the other firms' abatement technology and thus the other firms' conduct in the market for permits. Accordingly, the firm with the advanced abatement technology can influence the permit price via technology diffusion. While presumably no exact match exists for our framework in reality, our simplified setup allows us to clearly work out the firms' diffusion and adoption incentives under the three allocation regimes—auctioning, grandfathering, and benchmarking—stemming from the firms' concern about their own abatement costs and permit-market expenditures/receipts.

We find that the performance of the different regimes of permit allocation is decisively affected by the way in which technical change influences the MACs. In all regimes, the firm with the advanced abatement technology at hand will consider the repercussions of technology transmission for the permit price in equilibrium. For example, under auctioning, every firm must purchase the permits it needs to cover the emissions that are privately optimal. Accordingly, all firms have an interest in low permit prices. In a setup with generalized technical change, letting the advanced abatement technology diffuse to other firms can either decrease or increase the permit price because it may either lower or raise MACs. Therefore, under auctioning, allowing diffusion of the advanced abatement technology will be privately optimal to the firm with the superior technology only when the MACs of other firms are thereby shifted downward in the relevant range of emissions.

We contribute to the literature by investigating three different tradeable permit regimes and how diffusion and adoption incentives depend on whether technical change influences MACs in a traditional way (i.e., lowers MACs) or in a nontraditional way (i.e., increases MACs). Our analysis highlights that the adoption incentive under auctioning and benchmarking is always positive, whereas it may be negative under grandfathering. The diffusion incentive crucially depends on the sign of the price effect. Whereas a price decrease is advantageous for the

¹Thus, the standard textbook stylization with technical change lowering MAC in the whole emission range is nested by having the critical emission level fixed at zero for all possible technological states.

technology leader under auctioning it is disadvantageous under benchmarking. In an extension, we incorporate that the technology leader may charge a license fee. Here, we find a greater tendency toward full diffusion under both auctioning and benchmarking, and that both allocation rules dominate grandfathering.

The different procedures for the initial allocation of tradeable discharge permits are politically very relevant, which is clear from the fact that all of these procedures were and are widely used in the practice of emission trading systems (ETS) around the world.² Examples for *grandfathering* include the first (2005–2007) and second (2008–2012) period of the EU ETS,³ the Swiss ETS in the voluntary phase (2008–2012), the Tokyo Cap-and-Trade Program, the Saitama ETS, the Korean ETS, the Beijing (pilot) ETS, the Chongqing (pilot) ETS, the Guangdong (pilot) ETS, and the Shanghai (pilot) ETS. Examples for *benchmarking* include the first, second, and third (2013–2020) phase of the EU ETS, the Swiss ETS in the mandatory phase (2012–2020), the California Cap-and Trade-Program, the Korean ETS, the Beijing (pilot) ETS, the Guangdong (pilot) ETS, and the Shanghai (pilot) ETS. Examples for *auctioning* include the first, second, and third period of the EU ETS,⁴ the Swiss ETS in the mandatory phase, the Regional Greenhouse Gas Initiative,⁵ the California Cap-and Trade-Program, the Québec Cap-and-Trade-System, and the Korean ETS.⁶

In addition to the relevance in actual environmental policy, insights into the properties of the three allocation mechanisms may be helpful in future policy discussions. This is all the more the case if tradable discharge permits will be used in the policy formulation following the Paris Agreement on greenhouse gas reduction. The same is true for other international environmental agreements, such as the consolidated statement of continuing International Civil Aviation Organization policies and the United Nations Environment Programme (see International Civil Aviation Organization, 2016, and United Nations Environment Programme, 2016).

1.2 | Related literature

This paper is related to contributions dealing with the diffusion and adoption of more advanced technology. The seminal paper in this context is provided by Milliman and Prince (1989), which presents the foundation of later analyses by Jaffe and Stavins (1995) and Requate and Unold (2003), for instance.⁷ The present study focuses on tradeable permits as an environmental policy instrument. Endres and Friehe (2011) study liability law, Endres and Rundshagen (2013) elaborate on international agreements, for example. In our analysis, we will assume that there is compliance with the regulation, whereas Arguedas, Camacho, and Zofio (2010) consider dynamic incentives when there is imperfect compliance. The emphasis of our paper is on being inclusive with respect to how technical change influences the MAC curve (e.g., Bauman

²All of our examples presented below are taken from ICAP (2017).

³The EU ETS comprises EU member states and Norway, Iceland, and Liechtenstein.

⁴From Phase 1 to Phase 3, the share of permits allocated by grandfathering is going down as the share of allocation by benchmarking and auctions is going up. See http://ec.europa.eu/clima/policies/ets/allowances_en.

⁵Members of this program are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont.

⁶The share of auctioned allowances increases from 0 in the first phase (2015–2017), to 3% in the second phase (2018–2020), to more than 10% in the third phase (2021–2025).

⁷For a survey, refer to Requate (2005a).

et al., 2008). In that regard, the present paper departs from Endres and Rundshagen (2017), in which permit trading is considered under the traditional assumption regarding technical change.

Perino and Requate (2012) are interested in adoption incentives when the generalized technical change applies and the stringency of the policy is varied, analyzing different environmental policy instruments. In our paper on the tradeable permits regime, we are dealing with both the incentives to let advanced technology diffuse and the adoption choice under three permit allocation regimes. Both Perino and Requate (2012) and our paper abstract from interactions between the firms considered in the analysis on product markets. Bréchet and Meunier (2014), instead, explore adoption incentives when the stringency is varied and there is a market-based interaction between firms.

André and Arguedas (2018) analyze a setting with endogenous technology adoption in which each firm decides upon its investment into the level of an environmentally friendly technology, knowing that there exists market power in the emission permits market. In contrast to the paper at hand, there is no technology leader in their model deciding upon diffusion and no technology followers deciding upon adopting the leader's technology. Moreover, the authors do not compare alternative permit allocation modes and neither do they allow for a general stylization of technical change, both of which the present paper does.

1.3 | Plan of the paper

Section 2 lays out the model and the social optimum. Section 3 describes our analysis for the three different regimes of permit allocation. Section 4 presents a brief extension to the model dealing with license fees for the advanced technology, before Section 5 concludes.

2 | THE MODEL AND SOCIAL OPTIMUM

2.1 | The model

We consider firms of three different kinds and follow the notation used by Perino and Requate (2012) when it comes to representing abatement and MACs. Firm L has an advanced abatement technology at its disposal that implies own abatement costs $C_L(e_L)$ at emission level e_L which are decreasing in emissions at a diminishing rate (i.e., $C'_L < 0 < C''_L$) when $e < e_L^{\max}$. MACs of firm L are $MAC_L(e_L) = -C'_L(e_L) > 0$ and are zero at e_L^{\max} (i.e., $C'_L(e_L^{\max}) = 0$). To be able to make precise assertions below, we will consider specific abatement cost functions which are taken from Dijkstra and Gil-Moltó (2018), but slightly adjusted to our framework.⁸ We assume that

$$C_L(e_L) = \frac{1}{2} \frac{a^2}{b} - 2ae_L + 2be_L^2, \quad (1)$$

$$MAC_L(e_L, T) = 2(a - 2be_L), \quad (2)$$

⁸Dijkstra and Gil-Moltó (2018) consider MAC functions of type $MAC(e, \varepsilon) = \frac{P}{\varepsilon} - \frac{ce}{\varepsilon^2}$, $\varepsilon \in \mathbb{R}^+$. Substituting $\varepsilon = \frac{1}{T+1} \in [0.5, 1]$, $P = a$, and $c = b$ leads to (4) with $T \in [0, 1]$.

implying

$$e_L^{\max} = \frac{a}{2b}.$$

Firm L may diffuse the advanced technology to m other firms with abatement costs $C_M(e_M, T)$, provided that the firms of type M want to adopt the offered technology.⁹ For simplicity, we assume in our main analysis that diffusion and adoption costs are zero (as in Endres & Friehe, 2011; Endres & Rundshagen, 2013; Milliman & Prince, 1989). In Section 4, we outline a model in which firm L may charge a license fee for accessing the advanced abatement technology and provide both simulation and limit results.

Firm L controls the diffusion of its technology, choosing to what extent it is diffused to other firms by selecting $\alpha \in [0, 1]$. Firms of type M may either adopt the technology made available (at no cost) by selecting $\beta = 1$ or keep the old technology by selecting $\beta = 0$. The final technology level is $T = \alpha\beta$. Thus, $T = 1$ means that both firm L allowed diffusion and firms of type M adopted the offered technology. $T = 0$ results when either firm L would not diffuse its technology or when firms of type M would not adopt the technology made available. An intermediate level $T \in (0, 1)$ results when firm L and firms of type M are principally willing to diffuse (adopt) the new technology but either firm L is not willing to diffuse completely or firms of type M are not willing adopt completely, which is taken into account by firm L when it makes its offer to firms of type M . More advanced technology implies lower abatement costs as $\partial C_M(e_M, T)/\partial T < 0$ and $\partial^2 C_M(e_M, T)/\partial T^2 > 0$. With respect to marginal effects, we follow Dijkstra and Gil-Moltó (2018) and assume that a marginal technology improvement implies lower (higher) MACs $MAC_M(e_M, T) = -\partial C_M(e_M, T)/\partial e_M$ for $e_M > (<) e_c(T)$ with $de_c/dT < 0$.¹⁰ We thus have $\partial MAC_M/\partial T := -\frac{\partial^2 C_M}{\partial e_M \partial T} < (>) 0$ when $e_M > (<) e_c(T)$. Again, we assume that the level of abatement costs is decreasing in emissions at a diminishing rate (i.e., $MAC_M > 0 > \partial MAC_M/\partial e_M$) when $e < e_M^{\max}(T)$, where $e_M^{\max}(T)$ defines the emission level at which MACs are zero with $de_M^{\max}(T)/dT \leq 0$. With respect to firms of type M , we consider

$$C_M(e_M, T) = \frac{1}{2} \frac{a^2}{b} - a(T + 1)e_M + \frac{1}{2} b(T + 1)^2 e_M^2, \tag{3}$$

$$MAC_M(e_M, T) = a(T + 1) - b(T + 1)^2 e_M, \tag{4}$$

which leads to

$$\frac{\partial MAC_M}{\partial T} = a - 2b(T + 1)e_M, \quad e_c(T) = \frac{a}{2b(T + 1)}, \quad \text{and} \quad e_M^{\max}(T) = \frac{a}{b(T + 1)} = 2e_c(T).$$

Finally, there are r firms of type R with abatement cost function $C_R(e_R)$, leading to a level and change of MACs $-C'_R = MAC_R > 0 > MAC'_R$.¹¹ The advanced technology of firm L is not relevant for firms from this industry. This assumption reflects that participants in emission

⁹Firms of type M will always behave in a symmetric fashion, such one firm's willingness to adopt implies it for the other firms.

¹⁰In Dijkstra and Gil-Moltó (2018), an increase of the emission-to-output ratio ϵ corresponds to an increase of the technology level T in our model.

¹¹This residual industry is necessary to formalize a plausible benchmarking regime. Under benchmarking, the assigned number of permits is not directly linked to the emission target, that is, a tightening of the emission target reduces the permit allocation of the residual industry only.

permit trading regimes are heterogeneous.¹² With respect to firms of type M , we specifically assume that

$$C_R(e_R) = \frac{1}{2} \frac{a^2}{b} - ae_R + \frac{be_R^2}{2}, \quad (5)$$

$$MAC_R(e_R) = a - be_R, \quad (6)$$

implying

$$e_R^{\max} = \frac{a}{b}.$$

Unabated emissions have adverse social consequences. Total emissions $E = e_L + me_M + re_R$ create environmental harm amounting to $D(E)$, the level of which is increasing at an increasing rate with the level of total emissions (i.e., $D' > 0$ and $D'' > 0$). With respect to environmental harm, we specify

$$D(E) = \frac{d}{2}E^2, \quad (7)$$

with $d > 0$.

Our analysis is concerned with firm L 's diffusion and type M firms' adoption incentives. Firm L and firms of type M are actors in the market for permits. They may either buy or sell permits. For our general assertions, we assume that all single firms (i.e., firm L and firms of type M) are too small to noticeably change the permit price via variations in private supply or demand of permits.¹³ However, firm L 's diffusion choice impacts on the permit market because type M firms' behavior as permit-market actors depends on their abatement technology. This channel shapes firm L 's diffusion incentives. It will take into account how diffusion influences permit demand and thereby the permit price.

Below, we will consider results for the functions specified above for a wide range of parameter combinations. Specifically, we will consider $(m, r) \in [2, 100]^2$ and $b \in [0.1, 100]$.

The timing of the model is as follows:¹⁴

- (1) Firm L first decides about diffusion and firms of type M next choose whether or not to adopt when firm L diffuses the advanced technology.
- (2) The policy maker implements a level of total emissions E in response to the state of technology used by type M firms. This level is independent of the specific regime. The

¹²With respect to the EU ETS, for example, large shares of total emissions stem from the cement, steel, glass, and paper industries, which presumably use different emission abatement technologies. Therefore, one and the same pollutant can be generated by very different industries, say X and Y , and an advancement of abatement technology may only be relevant for industry X but not for industry Y .

¹³In our numerical simulations, the impact on the permit price is taken into account.

¹⁴We study the strategic aspects of diffusion and adoption. For that purpose, we consider a scenario where the diffusion decision takes place before the details of environmental policy are determined while policy maker behavior is perfectly anticipated via backward induction. Poyago-Theotoky (2007) as well as D'Amato and Dijkstra (2015) consider a similar game structure in which firms move in the first stage that involves innovation. D'Amato and Dijkstra (2015) additionally consider an alternative sequence in which the regulator moves first. Requate (2005b) focuses on the influence of timing on the level of research and development.

allocation of permits may follow the rules of either auctioning, benchmarking, or grandfathering, the details of which will be explained below.

- (3) Firms choose emission levels and buy/sell permits accordingly.

The sequence we consider is not the only one worth scrutiny. Nevertheless, it stylizes important issues in real-world policy making: Environmental policy is often *reactive* in the sense that policy makers tailor environmental requirements to the state of technology used by regulated firms. For example, in the US environmental policy, firms using older equipment had to meet the requirements of *reasonably available control technology* (ract) while firms using new equipment had to meet the standards of *best available control technology* (bact). There are many examples for this kind of reactive regulation. In Germany, policy makers distinguish between *Stand der Technik* (analogous to bact) and *allgemein anerkannte Regeln der Technik* (analogous to ract). Another example for the reactive approach from a different policy area is that in some variants of emission trading, “benchmarking” is used. Some of the regulations intend that these values “will be updated” reflecting technical progress (ICAP, 2017, p. 29, Column 1).

Before we characterize the equilibrium for the three different allocation regimes, we briefly elaborate on the first-best outcome.

2.2 | The social optimum

The policy maker seeks to minimize social costs by deciding about technology transmission and emission levels. The problem thus is to

$$\min_{T, e_L, e_M, e_R} SC = C_L(e_L) + mC_M(e_M, T) + rC_R(e_R) + D(E) \tag{8}$$

with $E = e_L + me_M + re_R$. Assuming an interior solution, this minimization yields the following conditions for the optimal levels:

$$MAC_L(e_L^*) = MAC_M(e_M^*, T^*) = MAC_R(e_R^*) = D'(E^*), \tag{9}$$

$$\partial C_M(e_M^*, T^*) / \partial T < 0, \tag{10}$$

where $T^*=1$.

The total level of emissions is split among the different kinds of firms such that the MACs at socially optimal firm-level emissions are symmetric across firm L and firms of type M and R . With respect to technology transmission, we find that $T = \alpha\beta = 1$ should hold (see (10)) for our setup in which there are only benefits and no costs from letting firms of type M produce with the more advanced technology (as we abstract from diffusion and adoption costs).

3 | THE ANALYSIS

We consider a setup that comprises three stages. We solve the game by backward induction. The treatment of stages 2 and 3 does not depend on the specific allocation method in the permit

market. Thus, when describing the analysis of stages 2 and 3, we do not yet have to condition on the specific regime.

3.1 | Stage 3: Choice of firm-level emissions by firms

Firms will choose emissions in view of the permit price and their abatement cost function that is fixed at this stage. Taking the price p as given, firms emit such that MACs are equal to the permit price.¹⁵ Thus, we obtain

$$MAC_L(e_L) = MAC_M(e_M, T) = MAC_R(e_R) = p, \quad (11)$$

which will also hold for sellers of permits as they consider the opportunity costs of using the permits they can spare for their own emissions. This feature of tradeable permits is well known and one key motive for their implementation (e.g., Endres, 2011).

The equilibrium permit price p equals aggregate MACs,

$$p = MAC(E, T) \quad (12)$$

with $MAC(E, T) := MAC_M(e_M, T)$, where the dependence of aggregate MACs on total emissions stems from $MAC_M(e_M, T) = MAC_L(e_L) = MAC_R(e_R)$ and $E = e_L + me_M + re_R$. Graphically, the aggregate MAC function can be determined by the horizontal aggregation of the individual MAC functions.

3.2 | Stage 2: Choice of the number of permits by the policy maker

The policy maker seeks to minimize social costs by deciding about total emissions for the abatement technologies as she finds them (as they are determined in Stage 1 by the diffusion and adoption decisions of firm L and firms of type M). The policy maker's problem yields the condition

$$MAC(E^*(T), T) = D'(E^*(T)). \quad (13)$$

The corresponding firm specific equilibrium emission levels under permit trading with emission cap $E^*(T)$ meet

$$MAC_L(e_L^*(T)) = MAC_M(e_M^*(T), T) = MAC_R(e_R^*(T)) = D'(E^*(T)). \quad (14)$$

The optimal levels that solve (14) are denoted e_L^* , e_M^* , and e_R^* and all depend on the technology level T of firms of type M (i.e., determined by firms in Stage 1). It is of key importance to understand how the policy maker's optimum changes with a successful transmission of the advanced abatement technology from firm L to firms of type M . For that purpose, we consider how a marginal increase in the level of T influences the policy

¹⁵Again, we assume an interior solution.

maker's solution for the number of permits. We arrive the following results (which are established in the appendix):

Lemma 1.

- (i) *When MACs decrease with more advanced technology (i.e., when $\partial \text{MAC}_M(e_M^*(T), T)/\partial T < 0$), the emission levels e_L^* and e_R^* increase when more of the advanced abatement technology is transmitted to firms of type M , whereas e_M^* decreases. Total emissions, environmental harm, and the permit price decrease.*
- (ii) *When MACs increase with more advanced technology (i.e., when $\partial \text{MAC}_M(e_M^*(T), T)/\partial T > 0$), the emission levels e_L^* and e_R^* decrease when more of the advanced abatement technology is transmitted to firms of type M , whereas e_M^* increases. Total emissions, environmental harm, and the permit price increase.*

The results in Lemma 1. (i) summarize the findings for the standard case, while the results in Lemma 1. (ii) reflect the possibility of technical change increasing MACs. When technology transmission reduces the MACs of firms of type M in the relevant range of emissions, then e_M^* should fall, a very intuitive result. In contrast, when technology transmission implies higher MACs in the relevant part of the MAC curve, then firms of type M should emit more in the minimum of social costs, a counterintuitive result. The higher level of e_M raises the marginal environmental harm and thus gives reasons for lowering the emissions of firm L and those of firms of type R . However, firms of type M dominate with regard to the level of total emissions, meaning that total emissions increase despite the more widespread use of advanced abatement technology.

The possibility that technical change of the nontraditional kind may not induce an overall lower level of emissions was highlighted in the previous literature (e.g., Bauman et al., 2008; Bréchet & Meunier, 2014). In our framework, we have firms of different types. In Lemma 1., we explain how the different firm-level emissions respond to the transmission of advanced abatement technology to a subset of firms when the overall supply of permits responds to the technologies used by firms.

Having described how the policy maker responds to a change in the abatement technologies used by firms of type M , we are now in the position to consider firm L 's diffusion and type M firms' adoption incentives in the first stage.

3.3 | Stage 1: Choice about diffusion by firm L and adoption by firms of type M

The incentives of firm L with respect to diffusion and the incentives of firms of type M regarding adoption are shaped by the way that permits are allocated, as we will describe in the subsequent parts. The decisions about α and β are made sequentially by firm L and firms of type M .

3.3.1 | Auctioning

Under auctioning, all firms purchase the permits that they need to cover unabated emissions in Stage 3. In Stage 1, firms of type M select the extent β to which they welcome any abatement

technology spillover α from firm L . The choice of whether or not to adopt the advanced abatement technology of each single type M firm has a negligible effect on the permit price. Hence, in deciding about adoption, firms of type M consider the effect of adoption on the level of private costs

$$C_M(e_M, T) + pe_M. \quad (15)$$

Since e_M is optimally chosen in view of the relevant technological state, the effect comprises only the direct effect which is unambiguously signed, $\partial C_M / \partial T < 0$. Firms of type M have a dominant action in $\beta = 1$. The more advanced abatement technology promises lower costs even if the emissions were kept at the level that is optimal for $T = 0$. In other words, firms of type M would always welcome the opportunity to adopt more advanced abatement technology. The remaining question is whether firm L allows the diffusion.

Under auctioning, firm L is a buyer of permits and hence prefers a low permit price. In Stage 1, firm L decides about the extent of diffusion. This presents a mechanism for firm L to influence the equilibrium on the permit market, given that type M firms chose $\beta = 1$. Firm L decides about diffusion by considering the repercussion for its private costs given by

$$TC_L^A(T) = C_L(e_L^*(T)) + p^*(T) \cdot e_L^*(T). \quad (16)$$

The only channel via which diffusion bears on firm L 's costs is the permit price. The price need not decrease or increase with more advanced abatement technology for all technology levels because the sign of $\partial MAC_M(e_M^*(T), T) / \partial T$ (and hence also the sign of dp^* / dT) need not be identical for all values of T . This is due to the fact that the critical emission level is itself a function of the technology level (specifically, $e_c(T)$ is assumed to be decreasing in T). This fact is illustrated in Figure 2 below.

The equilibrium emission and permit price levels are determined by

$$MAC(E^*(T), T) = D'(E^*(T)) = p^*(T), \quad (17)$$

with the aggregate MAC function MAC defined as the *horizontal* aggregation of the individual MAC functions. Below, we separate the MAC curve of a firm of type M from the residual MAC function. To do this, we note that the equilibrium permit price fulfills $MAC^{-1}(p^*(T), T) = D'^{-1}(p^*(T))$.¹⁶ Since the inverse MAC function equals the *vertical* aggregation of the inverse individual MAC functions, we may write

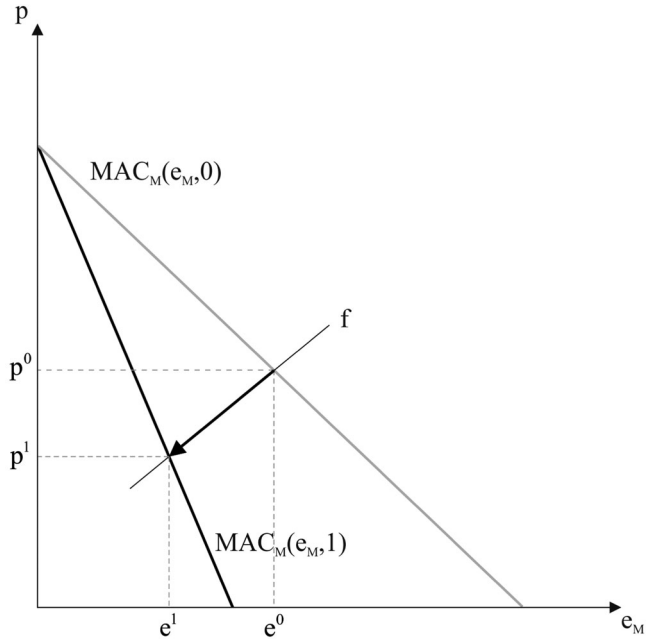
$$MAC_L^{-1}(p^*(T)) + m MAC_M^{-1}(p^*(T), T) + r MAC_R^{-1}(p^*(T)) = D'^{-1}(p^*(T)) \quad (18)$$

or equivalently

$$MAC_M^{-1}(p^*(T), T) = g(p^*(T)) := \frac{D'^{-1}(p^*(T)) - MAC_L^{-1}(p^*(T)) - r MAC_R^{-1}(p^*(T))}{m} \quad (19)$$

¹⁶Note that in this simplifying notation, the inversion only refers to the first variable of the MAC curve, whereas the second variable T is held fixed.

FIGURE 1 MACs of a firm of type M for different levels of T when technical change lowers MACs everywhere. MAC, marginal abatement cost



and hence

$$MAC_M(e_M^*(T), T) = f(e_M^*(T)) = p^*(T) \tag{20}$$

with

$$f(e_M^*(T)) = g^{-1}(e_M^*(T)). \tag{21}$$

From $D'' > 0$ and $\partial^2 C_i / \partial e_i^2 > 0$, it follows that $f' > 0$.¹⁷

Graphically, the equilibrium permit price can be determined by the intersection of the strictly increasing function $f(e_M^*)$ and the strictly decreasing function $MAC_M(e_M^*(T), T)$. In Figure 1, we consider the graphical illustration of the scenario with the traditional kind of technical change, that is, the case in which $\partial MAC_M(e_M^*(T), T) / \partial T < 0$ applies for all positive emission levels. In this example, the MAC curve pivots down such that marginal cost savings from more advanced abatement technology are greater at lower levels of abatement. The equilibrium permit price is unambiguously decreasing in T , as indicated by the direction of the

¹⁷For the specific functional forms for the MACs and marginal environmental harm introduced in Section 2.1, we receive

$$g(p^*(T)) = \frac{p^*(T)/d - (2a - p^*(T))/4b - r(a - p^*(T))/b}{m} = -\frac{a(1 + 2r)}{2bm} + \frac{4b + d + 4rd}{4bdm} p^*(T)$$

and

$$f(e_M^*(T)) = \frac{4bdm}{4b + d + 4rd} \left(e_M^*(T) + \frac{a(1 + 2r)}{2bm} \right).$$

For a given T , the intersection of MAC_M and f occurs at

$$e_M^* = \frac{a(4Tdr + 4Tb + Td + 4b - d)}{b((T + 1)^2(4dr + 4b + d) + 4dm)},$$

$$p^* = \frac{2a(T + 1)d((T + 1)(2r + 1) + 2m)}{(T + 1)^2(4dr + 4b + d) + 4dm}.$$

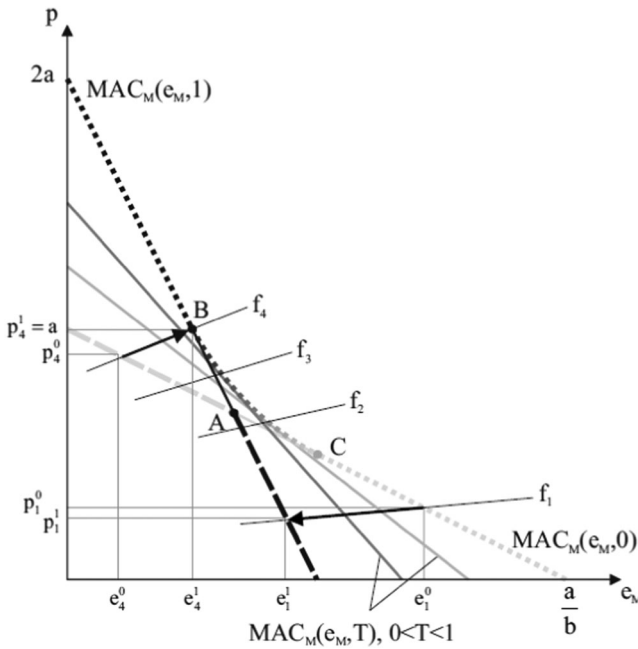


FIGURE 2 MACs of a firm of type *M* for different levels of *T* when technical change may lower or increase MACs. MAC, Marginal Abatement Cost

arrow. In Figure 1, we represent the MAC functions and the equilibrium levels for the permit price and resulting emissions for the cases $T = 0$ and $T = 1$.

Next, in Figure 2, we consider our general scenario in which MACs decrease at low abatement levels but increase at high abatement levels. The figure includes the MAC function of firms of type *M* at four different levels of *T*. These curves differ in their shade of grey: the darker the curve, the higher is the technology level. As in Dijkstra and Gil-Moltó (2018), an increase in the technology level pivots the MAC curve clockwise, with the pivot point $e_c(T)$ being always halfway between 0 and $e_M^{max}(T)$, and thus moving northwest in the figure.

Figure 2 also includes four possible courses of the function f , f_1 to f_4 , using the parameters $a = 10 = m = r$ and $b = 1/2$. An increase of the damage parameter d implies that the f -curve is shifted upward. For that reason, the curve f_1 corresponds with the lowest damage parameter (out of the four considered) and curve f_4 corresponds with the highest one. In Figure 2, the lower index of e and p identifies the corresponding curve f and the upper index denotes the equilibrium value of T . In addition, we have illustrated three locations in the (e_M, p) -space for referencing, namely $A = (a/(3b), 2a/3)$, $B = (a/(4b), a)$, and $C = (a/(2b), a/2)$.

- (1) When function f_1 applies, a marginal increase of the technology level *decreases* the equilibrium permit price for all technology levels. The pivot point is always on the left-hand side above the intersection of $MAC_M(e_M, T)$ and f_1 . Since the permit price is minimal for $T^*=1$, this is the equilibrium technology level under auctioning. The corresponding equilibrium emission level of a type *M* firm is $e_M^* = e_1^1$. The equilibrium permit price equals p_1^1 . A function of type f_1 results for sufficiently small levels of the marginal environmental harm, that is, when $d < \underline{d} = \frac{b}{m+r+3/4}$.
- (2) When function f_4 applies instead, a marginal increase of the technology level *raises* MACs of the type *M* firm for all levels of *T*. Hence, the demand for permits and thus the equilibrium permit price increases, which runs against the interests of firm *L* under auctioning.

For $T < 1$, the pivot point is always on the right-hand side below the intersection of $MAC_M(e_M, T)$ and $f(T)$. For $T = 1$, it coincides with the intersection. Since the permit price is minimal for $T^*=0$, this is the equilibrium technology level under auctioning. The corresponding equilibrium emission level of a type M firm is $e_M^* = e_4^0$. The equilibrium permit price equals $p^* = p_4^0$. A function of type f_4 results if $d = d_{\max} = \frac{4b}{m+1}$, where

$$d_{\max} := \max\left\{d \mid \min\{e_L^*(T), e_M^*(T), e_R^*(T)\} \geq 0\right\} \tag{22}$$

denotes the maximal damage parameter for which all emission levels are nonnegative, that is, for the parameter range $d \in (0, d_{\max})$ our assumption with respect to an interior solution is fulfilled.

- (3) When either f_2 or f_3 applies, a marginal increase of the technology level first *raises* the equilibrium permit price and then *decreases* it. Starting from $T = 0$, the pivot point is first on the right-hand side below and then on the left-hand side above the intersection of $MAC_M(e_M, T)$ and $f(T)$. A function of type f_2 results if $\underline{d} < d < \bar{d} = \frac{2b}{m+r+1}$ and features points of intersection lying between points A and C. In contrast, a function of type f_3 results if $\bar{d} < d < d_{\max}$ and features points of intersection lying between points A and B.

The array of MAC curves $MAC_M(e_M, T)$ has a lower boundary (plotted as the dashed curve in Figure 2), which is composed of two parts: the light grey dashed line as part of $MAC_M(e_M, 0)$ for small values of e_M , and the black-dashed line as part of $MAC_M(e_M, 1)$ for large values of e_M . Depending on whether f intersects the light grey or the black part of this boundary, the equilibrium level of T under auctioning is either 0 or 1. If f intersects the curve at the corner point, firm L is indifferent between full diffusion and no diffusion at all.

Using Lemma 1., our results regarding auctioning may be summarized as follows:

Proposition 1. *Assume that auctioning applies. Firms of type M always want to adopt the advanced abatement technology. (i) Marginally increasing the diffusion of the advanced abatement technology lowers firm L 's total costs locally if and only if $\partial MAC_M(e_M^*(T), T)/\partial T < 0$. (ii) Firm L chooses complete diffusion when*

$$\int_0^1 \frac{\partial MAC_M(e_M^*(T), T)}{\partial T} dT < 0 \Leftrightarrow p^*(1) < p^*(0).$$

(iii) *Given the functions (1), (3), (5), and (7), we obtain $T^* = 1$ ($T^* = 0$) under auctioning when*

$$d \leq (>) \bar{d} = \frac{2b}{m+r+1}.$$

Proof. Claims (i) and (ii) were established above, noting that a boundary solution with respect to T is clearly privately optimal. Claim (iii) is derived in the Supporting Information Material. □

According to Proposition 1., the circumstances under which firm L prefers not to diffuse the advanced abatement technology can be described by a marginal damage parameter in excess of

\bar{d} which increases (decreases) in b (m and r). Remember from our description in Section 2.1, we know that a high level of b ensures that MACs will decrease in response to technical change already at relatively low emission levels.

3.3.2 | Grandfathering

Under grandfathering, emission permits are allocated to firms on the basis of their past record of emissions. In our analysis, we distinguish between two situations, one *before* the permit policy is introduced and one *after*. We assume that in the “before”-phase, no other environmental policy is applied. One commonly voiced concern with grandfathering is that firms strategically distort their conduct to influence how they will be affected by an *anticipated* change of regulation (e.g., Damon, Cole, Ostrom, & Sterner, 2019). We want to accommodate this possibility and for that reason use the following timing: In Stage 1 (which is in the “before” phase), firm L decides about diffusion and firms of type M about adoption anticipating that the reference point for grandfathering depends on the technology at the end of Stage 1. In Stage 2 (which initiates the “after” phase), the policy maker implements a level of total emissions and, in Stage 3, firm-level permit purchases are executed.¹⁸ The equilibrium emissions of firms in a setting without any environmental policy are called “preregulation” emissions. These equilibrium emissions serve as the “past emission levels” when we model the basis for the allocation of emission rights under grandfathering.

We specify this regime by assuming that each firm receives a share δ of its preregulation emissions. Without environmental regulation, firms chose emission levels that do not generate abatement costs. These emission levels are given by e_i^{\max} . Since the number of permits must add up to $E^*(T)$, the share of preregulation emissions each firm receives is given by

$$\delta(T) = \frac{E^*(T)}{e_L^{\max} + me_M^{\max}(T) + re_R^{\max}}. \quad (23)$$

By using $\delta(T)$, the policy maker seeks to impose a similar contraction of emissions across firms. In the regime of grandfathering, the decision about diffusion thus also carries implications for the number of permits each firm obtains. This *quantity effect* is absent in the two other regimes auctioning and benchmarking.

Firms of type M receive $\delta(T)e_M^{\max}(T)$, a level of permits that depends on the technology level $T = \alpha\beta$ that results from the diffusion decision of firm L and the adoption decision of firms of type M . When m is sufficiently high, the adoption decision of any single firm of type M only has a negligible effect on $\delta(T)$.¹⁹ From this line of reasoning, we obtain the result that the *quantity effect* for any single type of firm M is determined by $de_M^{\max}(T)/dT$ for which we assumed $de_M^{\max}(T)/dT \leq 0$. In other terms, the *quantity effect* discourages firms of type M from adopting the more advanced abatement technology. However, the direct effect on the level of abatement costs pulls in the other direction and will dominate the *quantity effect* when $|de_M^{\max}/dT|$ is sufficiently small.

¹⁸This timing is a shortcut for having a sequence where firms first decide about diffusion/adoption, then emit “preregulation” emissions during a regulation-free period, and then become subject to the grandfathering regime with the policy maker’s decision-making before firms decide.

¹⁹In our calculations for the specific functions, we take this effect into account.

Firm L obtains $\delta(T)e_L^{\max}$. The *quantity effect* is thus a motive for firm L to let its technology diffuse when $d\delta/dT > 0$. With respect to the denominator of $\delta(T)$, we know that $de_M^{\max}/dT \leq 0$ from our assumptions regarding technical change. As a result, $d\delta/dT$ is unambiguously positive when the total level of emissions increases after (additional) technology transmission, that is, when $dE^*/dT > 0$. This holds—according to Lemma 1.—when $\partial MAC_M/\partial T > 0$ in the relevant range of the MACs. In other terms, when MACs of firms of type M are increasing with the state of the technology, then firm L favors a marginal increase of the diffusion level when taking only the *quantity effect* into account. For our specific framework (specified by functions (1), (3), (5), and (7) and the parameter range), $d\delta/dT > 0$ always results. However, for other functions, the quantity effect may be negative when $|de_M^{\max}/dT|$ is sufficiently small and $\partial MAC_M/\partial T < 0$ holds in the relevant range.

To arrive at a decision, firm L will also consider how diffusion influences the permit price. Firm L 's concern will thus be to

$$\min_{\alpha} TC_L^G = C_L(e_L) - \left[\delta(\alpha\beta)e_L^{\max} - e_L \right] p(\alpha\beta). \tag{24}$$

The evaluation of any permit price change depends on whether firm L acts as a buyer or seller of permits. The influence on the permit price in equilibrium in turn is critically affected by the kind of technical change, as described above.

The quantity effect and the price effect described by $dp/dT > (<) 0$ in case of $\partial MAC_M/\partial T > (<) 0$ leads us to the following proposition:

Proposition 2. *Assume that grandfathering applies. (i) Firms of type M prefer the advanced abatement technology when $|de_M^{\max}/dT|$ is sufficiently small. (ii) The permit price increases with more diffusion when $\partial MAC_M(e_M^*(T), T)/\partial T > 0$, such that firm L prefers to locally increase T when it is a seller of permits. In the other instances (i.e., when $\partial MAC_M(e_M^*(T), T)/\partial T < 0$ and/or the firm is a buyer), the quantity effect and the price effect (may) work in opposite directions. (iii) Given the functions (1), (3), (5), and (7), we obtain that TC_L^G is minimized by $T = 1$ when*

$$d \leq \min \{ \tilde{d}, d_{\max} \},$$

where

$$\tilde{d} = b \frac{8m^2 + 36mr + 28r^2 + 11m + 16r + 3 + 3\sqrt{(6m + 6r + 1)(m + 2r + 1)(m + 6r + 1)(2m + 2r + 1)}}{(m^2 + (9r + 1)m + 8r^2 + 2r)(m + r + 1)}$$

and by $T = 0$ when $\tilde{d} < d \leq d_{\max}$. However, due to the possibly negative adoption effect for firms of type M , an interior level of T may result in equilibrium.

Proof. Claims (i) and (ii) were established above. Claim (iii) is derived in the Supporting Information Material. □

Despite $\tilde{d} > \bar{d}$, equilibrium diffusion under grandfathering may be lower than under auctioning due to a potentially negative adoption effect for firms of type M . Consider, for example,

the case in which $a = m = 10$, $r = 50$, $b = 0.1$, and $d = 0.001$. It results that the adoption incentive is positive (negative) for $T \leq (>) 0.04757$, such that T^* results at that threshold level since TC_L^G is strictly decreasing in T for all $T \in [0, 1]$. In contrast, auctioning induces $T^* = 1$ for this parameter combination.

3.3.3 | Benchmarking

A fundamental criticism raised in the discussion of the EU ETS is that—under grandfathering—heavy polluters are privileged rather than firms that already have invested in CO₂-efficient production processes. To make amends, the benchmark scheme was developed to “reward operators that have taken early action to reduce greenhouse gases and give stronger incentives to reduce emissions, as allocation would no longer depend on historical emissions” (European Commission, 2008). In the benchmarking system within EU ETS, emission rights are allocated on the basis of “the average of GHG emission performance of the 10% best performing installations (for a given product) in 2007–2008 in the EU” (Borghesi, Montini, & Barreca, 2016; European Commission, 2011).²⁰ The performance of this “avant-garde” group of firms defines the benchmark technology. A firm using an inferior technology receives a number of permits calculated as if the firm would use the benchmark technology. In our paper, only two types of firms, L and M , may use the advanced abatement technology. As a result, we cannot apply the 10% rule used in the EU. In our setting, the benchmark technology is defined by the type L firm using the superior of the two technologies modelled in our paper. Consequently, we assume that, under benchmarking, firms do not have to reduce their emissions provided that they use the most efficient technology. Firm L receives the number of permits that equals the level of emissions it would choose without environmental regulation, that is, the level fulfilling $MAC_L(e_L^{\max}) = 0$ (as the advanced technology is the benchmark technology and in use at firm L). This permit endowment is independent of whether or not advanced technology diffuses to firms of type M . However, for firms of type M , the endowment follows from the benchmark technology (i.e., the $e_M^{\max}(1)$, where $MAC_M(e_M^{\max}(1), 1) = 0$), independent of whether firms of type M actually utilize it. Since MACs decrease for $e > e_c(T)$, it follows that $e_M^{\max}(1) \leq e_M^{\max}(0)$. Firms of type R are not benchmarked (as they do not have access to a superior technology) and receive (not necessarily free of charge) what remains of $E(T)$ after the allocation to firm L and firms of type M .

Independent of whether firms of type M are permit buyers or sellers in Stage 3, the effect of the adoption decision of a single type M firm on the equilibrium permit price is negligible. Hence, as under auctioning, the direct marginal effect on the level of abatement costs, $\partial C_M / \partial T < 0$, is relevant for the adoption decision of type M firms. Type M firms are ready to adopt whatever share α firm L will diffuse, that is, firms of type M choose $\beta = 1$.

Firm L is endowed with e_L^{\max} and will thus be a permit seller in Stage 3 under benchmarking. Using that $\beta = 1$ results from the decision-making of firms of type M , firm L 's decision about diffusion follows from:

$$\min_{\alpha} C_L(e_L) - (e_L^{\max} - e_L)p(\alpha). \quad (25)$$

²⁰Zetterberg et al. (2012, p. 27), note: “The general principal was that the allocation should be based on best available technology (BAT).”

It is thus again key how diffusion will influence the price of permits. Referring to the discussion of the auctioning regime, we will have a permit price increasing with technology transmission when MACs of firms of type M are increasing with the level of the technology T . The impact on MACs of firms of type M translates into an upward shift of the demand for permits. The increase in the number of permits—as $dE^*/dT > 0$ in this scenario—is not sufficient to compensate the change in demand, implying an increase in the equilibrium price. The marginal impact of technical change on firm L 's diffusion incentive is opposite to that under auctioning. This is intuitive as firm L is a seller in the present regime whereas it was a buyer under auctioning.

Proposition 3. *Assume that benchmarking applies. Firms of type M prefer to adopt the advanced abatement technology. (i) Firm L prefers to marginally increase T if and only if $\partial MAC_M(e_M^*(T), T)/\partial T > 0$. (ii) Firm L chooses full diffusion when $\partial MAC_M(e_M^*(1), 1)/\partial T > 0$ and partial diffusion otherwise. (iii) Given the functions (1), (3), (5), and (7), we obtain $T^* = 1$ ($T^* = 0$) under benchmarking when*

$$d = d_{\max} = \frac{4b}{m + 1} \left(d < \underline{d} = \frac{4b}{4m + 4r + 3} \right).$$

For $d \in (\underline{d}, d_{\max})$, $0 < T^* < 1$ results.

Proof. Claims (i) and (ii) were established above. Claim (iii) is derived in the Supporting Information Material. □

The assertion of Proposition 3. with respect to firm L directly follows from $dp^*/dT < (>)0 \Leftrightarrow \partial MAC_M(e_M^*(T), T)/\partial T < (>)0$ (see Lemma 1.). As the MACs may either increase or decrease throughout or increase at first and decrease at higher levels of diffusion, the qualification is due.

We conclude our discussion of benchmarking by returning to Figure 2. Since the technology leader now prefers the highest possible permit price, the intersection of f with the upper boundary of the array of MAC curves determines the equilibrium technology level under benchmarking. Whereas the lower boundary consists of two parts, for the upper boundary three parts have to be distinguished: the black dotted line as part of $MAC_M(e_M, 1)$ for small values of e_M , the light grey dotted line as part of $MAC_M(e_M, 0)$ for large values of e_M , and the envelope curve changing its color from light grey to black for intermediate values of e_M . This part of the curve is restricted by the two pivot points $e_c(0)$ (painted in light grey) and $e_c(1)$ (painted in black) and contains any other pivot point $e_c(T)$, $0 < T < 1$. The equilibrium technology T^* under benchmarking is determined by the intersection of f and this dotted border line. If the intersection lies in the black area, we get $T^* = 1$ (as in case of f_4 with corresponding equilibrium emission level $e_M^* = e_4^1$ of a type M firm and equilibrium permit price $p^* = p_4^1$). If the intersection lies in the light-grey area, we get $T^* = 0$ (as in case of f_1 with corresponding equilibrium emission level $e_M^* = e_1^0$ of a type M firm and equilibrium permit price $p^* = p_1^0$). If the intersection lies in the envelope section of the curve, we get $0 < T^* < 1$ (as in case of f_2 and f_3).

4 | EXTENSION: FIRM L MAY CHARGE A LICENSE FEE

In Section 3, we assumed that firm L either lets the advanced abatement technology diffuse to other firms free of charge or prevents its transfer completely (when diffusion is

not in firm L 's interest). In reality, technology leaders may charge other firms license fees in exchange for access to advanced technology. In this section, we discuss the consequences of such an extension to the model, again considering the functions (1)–(5) and (7). To describe private incentives, we use simulations based on the parameter set introduced in Section 2 and present analytical limit results. With respect to the latter, note that by considering the case in which $d \rightarrow 0$ ($d \rightarrow d_{\max}$), we can ensure that the (non-traditional) representation of technical change applies everywhere. The proofs are contained in the Supporting Information Material.

Let us assume that firm L offers only one specific technology level T to potential adopters at a license fee (price) F .²¹ From the social planner's standpoint, the license fee is a welfare-neutral transfer payment. As a result, the social optimum is characterized by complete diffusion of the advanced technology.²²

The timing of the model is:

- (0) Firm L decides about which technology level T to offer and which price F to charge.
- (1) Firms of type M decide about buying the offered technology level T .
- (2) The policy maker determines the number of permits and their initial allocation.
- (3) Firms choose emission levels and buy/sell permits accordingly.

The outcomes of the Stages 2 and 3 of the model with license fees correspond with those of Stages 2 and 3 of the model without license fee (in Section 3). Hence, we only have to take a closer look at Stages 0 and 1 of the model with license fees. As it will turn out, again, equilibrium actions on both stages depend on the underlying allocation rule.

4.1 | Auctioning

4.1.1 | Stage 2: Purchasing decision of firms of type M

If an individual firm i of type M decides to buy the technology T at price F , given that all other firms of type M buy T , its costs are given by

$$TC_i^{A,F}(T) = F + p^*(T)e_M^*(T) + C_M(e_M^*(T), T). \quad (26)$$

If firm i instead chooses the technology level 0, its costs are given by

$$TC_i^{A,F}(0) = p^*(T)e_M^*(0) + C_M(e_M^*(0), 0), \quad (27)$$

where $e_M^*(0)$ denotes the equilibrium demand of firm i given the permit price $p^*(T)$ and its own technology Level 0.²³

²¹In our setup, firm L cannot do better by concentrating the offer to a selected group of firms only. There are diminishing returns to increasing T and firms are not in market relationship (such that gaining a competitive advantage relative to a competitor or similar concerns do not play a role here).

²²In contrast, since Requate and Unold (2003) assume fixed set-up costs for potential adopters, they obtain partial adoption in the social optimum.

²³Again, we assume that firm i 's decision has a negligible effect on the equilibrium permit price. However, in our calculations for the specific functions, we take this slight effect into account.

If

$$F \leq F_{\max}^A(T) = p^*(T)e_M^*(0) + C_M(e_M^*(0), 0) - \left(p^*(T)e_M^*(T) + C_M(e_M^*(T), T) \right) \quad (28)$$

holds, then firm i is willing to buy the better technology, given that the other firms of type M adopt the better technology. Hence, adoption by each firm of type M is a Nash equilibrium. For our specification from (1), (3), (5), and (7) and our parameter set, we obtain $F_{\max}^A(T) > 0$ and $dF_{\max}^A(T)/dT > 0$ for all $T \in [0, 1]$.

4.1.2 | Stage 1: Technology leader chooses offered technology level and its price

Given that the technology leader L offers the technology level T , it will demand the license price $F(T) = F_{\max}^A(T)$, that is, the willingness to pay of type M firms. Hence, firm L chooses which technology level to offer according to

$$\min_T TC_L^{A,F} = p^*(T)e_L^*(T) + C_L(e_L^*(T)) - mF_{\max}^A(T). \quad (29)$$

In our simulations (explained in the Supporting Information Material), we obtain $dTC_L^{A,F}/dT < 0 \forall T \in [0, 1]$. Firm L thus offers $T^*=1$. This results from a positive revenue effect ($dF_{\max}^A(T)/dT > 0$) that is either added to a positive permit price effect or dominates any possible negative permit price effect.

Corollary 1. *Under auctioning with license fees, given the functions (1), (3), (5), and (7), full diffusion results.*

Proof. See the Supporting Information Material. □

4.2 | Grandfathering

4.2.1 | Stage 2: Purchasing decision of firms of type M

Given that all other firms of type M buy the offered technology level T and an individual firm i of type M also decides to buy the technology, its costs are given by

$$TC_i^{G,F}(T) = F + p^*(T)\left(e_M^*(T) - \delta(T)e_M^{\max}(T)\right) + C_M(e_M^*(T), T). \quad (30)$$

If firm i instead chooses the technology Level 0, its costs are given by²⁴

$$TC_i^{G,F}(0) = p^*(T)\left(e_M^*(0) - \delta(T)e_M^{\max}(0)\right) + C_M(e_M^*(0), 0). \quad (31)$$

²⁴Corresponding to our assumption with respect to the permit price, we assume that firm i 's decision also has a negligible effect on the equilibrium share δ . In the calculations for the specific function, this slight effect has been taken into account.

Hence, firm i is willing to adopt technology level T , given that the other firms adopt the better technology, if

$$F \leq F_{\max}^G(T) = \left(p^*(T) \left(e_M^*(0) - \delta(T) e_M^{\max}(0) \right) + C_M \left(e_M^*(0), 0 \right) \right) - \left(p^*(T) \left(e_M^*(T) - \delta(T) e_M^{\max}(T) \right) + C_M \left(e_M^*(T), T \right) \right). \quad (32)$$

In contrast to our results for auctioning, under grandfathering, firm i 's willingness to pay may be negative. The reason lies in the possibly negative quantity effect. Hence, in case of a negative adoption incentive, the license fee $F(T)$ becomes negative, that is, the technology leader has to subsidize type M firms if it wants to enforce the technology level T .

4.2.2 | Stage 1: Technology leader chooses offered technology level and its price

Given that the technology leader L offers the technology level T , it will ask for the price $F(T) = F_{\max}^G(T)$, which corresponds with the willingness to pay of type M firms (and may be negative as argued above). Hence, firm L chooses which technology level to offer according to

$$\min_T TC_L^{G,F} = p^*(T) \left(e_L^*(T) - \delta(T) e_L^{\max} \right) + C_L \left(e_L^*(T) \right) - m F_{\max}^G(T). \quad (33)$$

Our results may be summarized as follows:

Corollary 2. *Under grandfathering with license fees, given the functions (1), (3), (5), and (7), it is possible that either full, partial, or no diffusion results.*

Proof. See the Supporting Information Material. No diffusion obtains, for example, when $a = 1$, $m = 50$, $r = 10$, $b = 30$, and $d = 0.9d_{\max}$. Partial diffusion results, for example, when $a = 10$, $m = 50$, $r = 10$, $b = 1/10$, and $d = 0.1d_{\max}$. Full diffusion results, for example, when $a = 10$, $m = 10$, $r = 500$, $b = 1/2$, and $d = 0.1d_{\max}$. \square

The socially optimal technology level $T = 1$ does not always result in equilibrium, which is mainly due to the fact that the willingness to pay for the better technology may be negative under grandfathering.

4.3 | Benchmarking

4.3.1 | Stage 2: Purchasing decision of firms of type M

Given that all other firms of type M buy the offered technology level T and an individual firm i of type M also decides to buy the technology, its costs are given by

$$TC_i^{B,F}(T) = F + p^*(T) \left(e_M^*(T) - e_M^{\max}(1) \right) + C_M \left(e_M^*(T), T \right). \quad (34)$$

If firm i instead chooses not to buy, its costs are given by

$$TC_i^{B,F}(0) = p^*(T)(e_M^*(0) - e_M^{\max}(1)) + C_M(e_M^*(0), 0). \tag{35}$$

Since in both expressions, compared to the corresponding costs under auctioning, only the identical term $p^*(T)e_M^{\max}(1)$ is deducted, i 's willingness to pay for a technology level T equals the one under auctioning, that is, $F_{\max}^B(T) = F_{\max}^A(T)$ holds.

4.3.2 | Stage 1: technology leader chooses offered technology level and its price

Given that the technology leader L offers the technology level T , it will demand the price $F(T) = F_{\max}^B(T)$. Hence, firm L chooses which technology level to offer according to

$$\min_T TC_L^{B,F} = p^*(T)(e_L^*(T) - e_L^{\max}) + C_L(e_L^*(T)) - mF_{\max}^B(T). \tag{36}$$

As is true under auctioning, we have $dTC_L^{B,F}/dT < 0 \forall T \in [0, 1]$ as a result of a dominant revenue effect.

Corollary 3. *Under benchmarking with license fees, given the functions (1), (3), (5), and (7), full diffusion results.*

4.4 | Comparison of allocation rules for the case in which firm L licenses advanced abatement technology

The equilibrium outcome under auctioning is equivalent to the one under benchmarking when firm L charges a license fee. Both allocation rules lead to the socially optimal allocation for both the scenario in which technical change lowers the MACs and the one in which it increases them. Under grandfathering, the socially optimal allocation may not result. However, we have to note that we assumed that firm L bears no cost in providing the better technology, which is a simplifying assumption. Hence, it might be of interest to know under which allocation rule the technology leader has the strongest diffusion incentive.

As a measure for this diffusion incentive under auctioning/benchmarking/grandfathering, we use $\Delta^{J,F} = TC_L^{J,F}(0) - TC_L^{J,F}(1)$, $J = A, B, G$. Since the license fees which the technology leader may charge are identical for the allocation rules auctioning and benchmarking, only the permit price effect is relevant for the comparison of diffusion incentives under auctioning and benchmarking. We find $\Delta^{A,F} > (<)\Delta^{B,F}$ for $d < \bar{d}_\Delta$ with²⁵

$$\bar{d}_\Delta = \frac{2b}{m + r + 1}.$$

²⁵Remember that MACs increase (decrease) in case of diffusion of the better technology when the marginal environmental damage is high (low).

With respect to the diffusion incentive under grandfathering, we have to keep in mind that, under grandfathering, the socially optimal technology level $T = 1$ may not result in equilibrium. Moreover the parameter simulations show that diffusion incentives under both auctioning and benchmarking always dominate those under grandfathering.

5 | CONCLUSION AND AVENUES FOR FUTURE RESEARCH

To combat serious environmental problems such as climate change, arriving at better technology and diffusing it are key policy challenges. Accordingly, the incentives created by environmental policy instruments in this realm are critical for the overall performance of these institutions. Tradeable permits are a policy instrument with many desirable features. We show that the incentives created for diffusion and adoption of advanced abatement technology depend on the way that permits are allocated to firms and, importantly, on how technical change shapes MACs. For example, whereas benchmarking performs poorly in this regard when MACs are lower after the technical change at the relevant levels of emissions, this judgment is reversed when the relevant part of the MAC curve is shifted upward. When the policy maker who is interested in the diffusion and adoption of superior technology understands how the MACs are influenced by technical progress, he may either use auctioning or benchmarking. According to our analysis, incentives for diffusion and adoption that emerge under the grandfathering regime point less clearly toward technology transmission. In our framework, the regimes influence directly the diffusion and adoption choices, and overall emissions are then assessed against the background of the state of the technology used. In other words, in our setting, all welfare implications are related to diffusion and adoption choices alone.

The present paper supports the emphasis on the importance of distinguishing different types of technical change. We show that the social desirability of environmental policy instruments may hinge on the initial level of emissions. Our contribution is focused on deriving this insight, using a very simple model.

The present paper is thus only a first exploration of the matter and leaves many possible extensions for future research. One interesting avenue would concern the scenario in which firms are also interacting in product markets. For example, the optimality of allowing diffusion under auctioning when the MACs decrease with transmission may be questioned due to the influence on rivals' costs. Moreover, we abstracted from potential costs of diffusing or adopting the advanced technology (the latter are considered in Perino & Requate, 2012, e.g.). Such costs may introduce *zones of inaction* as a cost advantage (stemming from the technology itself) is dominated by a cost disadvantage (stemming from diffusion and/or adoption costs). In addition, the permit market was considered to be approximately perfectly competitive in the sense that no single firm had a nonnegligible influence on the market equilibrium via its supply or demand choices. Obviously, our model can be extended to allow for various stylizations of market power.²⁶

²⁶ Among the papers dealing with market power in permit markets are the seminal articles by Hahn (1984) and Montero (2009) as well as the recent ones by Hintermann (2017), and Alvarez and André (2016). However, these papers do not deal with the diffusion and adoption of new technologies. André and Arguedas (2018) analyze technical change with market power in permit markets. However, as explained in the introduction, the focus of this paper is different from the one of the present one.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

- Alvarez, F., & André, F. J. (2016). Auctioning emission permits with market power. *B.E. Journal of Economic Analysis & Policy*, 16, 28. <https://doi.org/10.1515/bejeap-2015-0041>
- Amir, R., Germain, M., & van Steenberghe, V. (2008). On the impact of innovation on the marginal abatement cost curve. *Journal of Public Economic Theory*, 10, 985–1010.
- André, F. J., & Arguedas, C. (2018). Technology adoption in emission trading programs with market power. *The Energy Journal*, 39, 145–175.
- Arguedas, C., Camacho, E., & Zofio, J. L. (2010). Environmental policy instruments: Technology adoption incentives with imperfect compliance. *Environmental and Resource Economics*, 47, 261–274.
- Baker, E., Clarke, L., & Shittu, E. (2008). Technical change and the marginal cost of abatement. *Energy Economics*, 30, 2799–2816.
- Bauman, Y., Lee, M., & Seeley, K. (2008). Does technological innovation really reduce marginal abatement costs? Some theory, algebraic evidence, and policy implications. *Environmental and Resource Economics*, 39, 507–527.
- Borghesi, S., Montini, M., & Barreca, A. (2016). *The European emission trading system and its followers - comparative analysis and linking perspectives*. Berlin: Springer International Publishing.
- Bréchet, T., & Jouvet, P.-A. (2008). Environmental innovation and the cost of pollution abatement revisited. *Ecological Economics*, 65, 262–265.
- Bréchet, T., & Meunier, G. (2014). Are clean technology and environmental quality conflicting policy goals? *Resource and Energy Economics*, 38, 61–83.
- D'Amato, A., & Dijkstra, B. R. (2015). Technology choice and environmental regulation under asymmetric information. *Resource and Energy Economics*, 41, 224–247.
- D'Amato, A., & Dijkstra, B. R. (2018). Adoption incentives and environmental policy timing under asymmetric information and strategic firm behavior. *Environmental Economics and Policy Studies*, 20, 125–155.
- Damon, M., Cole, D. H., Ostrom, E., & Sterner, T. (2019). Grandfathering: Environmental uses and impacts. *Review of Environmental Economics and Policy*, 13, 23–42.
- Dijkstra, B. R., & Gil-Moltó, M. J. (2018). Is emission intensity or output U-shaped in the strictness of environmental policy? *Journal of Public Economic Theory*, 20, 177–201.
- Endres, A. (2011). *Environmental Economics—Theory and Policy*. Cambridge: Cambridge University Press.
- Endres, A., & Friehe, T. (2011). Incentives to diffuse advanced abatement technology under environmental liability law. *Journal of Environmental Economics and Management*, 62, 30–40.
- Endres, A., & Rundshagen, B. (2013). Incentives to diffuse advanced abatement technology under the formation of environmental agreements. *Environmental and Resource Economics*, 56, 177–210.
- Endres, A., & Rundshagen, B. (2017). Spreading the green—How international emission permit markets can help. *Strategic Behavior and the Environment*, 5, 249–287.
- European Commission. (2008). Questions and answers on the commission's proposal to revise the EU emissions trading system. MEMO 08–35, Brussels, 23 January 2008.

- European Commission. (2011). Decision 2011/278/EU on determining Union-wide rules for harmonised free emission allowances pursuant to Article 10a of Directive 2003/87/EC. Official Journal of the European Union, 2011/278/EU.
- Hahn, R. (1984). Market power and transferable property rights. *Quarterly Journal of Economics*, 99, 753–765.
- Hintermann, B. (2017). Market power in emission permit markets: Theory and evidence from the EU ETS. *Environmental and Resource Economics*, 66, 89–112.
- International Carbon Action Partnership. (2016). *Emissions Trading Worldwide: Status Report 2016*. Berlin.
- International Civil Aviation Organization. (2016). Consolidated statement of continuing ICAO policies and practices related to environmental protection—Global Market-based Measure (MBM) Scheme, part of the Resolutions Adopted by the Assembly, Assembly—39th Session, Provisional Edition October 2016. Retrieved from http://icao.int/Meetings/a39/Documents/Resolutions/a39_res_prov_en.pdf
- Jaffe, A. B., & Stavins, R. N. (1995). Dynamic incentives of environmental regulations: The effects of alternative policy instruments on technology diffusion. *Journal of Environmental Economics and Management*, 29, 43–63.
- Milliman, S. R., & Prince, R. (1989). Firm incentives to promote technical change in pollution control. *Journal of Environmental Economics and Management*, 17, 247–265.
- Montero, J. (2009). Market power in pollution permit markets. *Energy Journal*, 30, 115–142.
- Perino, G., & Requate, T. (2012). Does more stringent environmental regulation induce or reduce technology adoption? When the rate of technology adoption is inverted U-shaped. *Journal of Environmental Economics and Management*, 64, 456–467.
- Poyago-Theotoky, J. A. (2007). The organization of R&D and environmental policy. *Journal of Economic Behavior & Organization*, 62, 63–75.
- Requate, T. (2005a). Dynamic incentives by environmental policy instruments—A survey. *Ecological Economics*, 54, 175–195.
- Requate, T. (2005b). Timing and commitment of environmental policy, adoption of new technology, and repercussions on R&D. *Environmental and Resource Economics*, 31, 175–199.
- Requate, T., & Unold, W. (2003). Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? *European Economic Review*, 47, 125–176.
- United Nations Environment Programme (2016). Countries agree to curb powerful greenhouse gases in the largest climate breakthrough since Paris, 15 October 2016. Department of Public Information. Retrieved from <http://unep.org/newscentre/Default.aspx?DocumentID=27086&ArticleID=36283&l=en>
- Zetterberg, L., Wråke, M., Sterner, T., Fischer, C., & Burtraw, D. (2012). Short-run allocation of emissions allowances and long-term goals for climate policy. *Ambio*, 41, 23–32.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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APPENDIX: PROOF OF LEMMA 1

Totally differentiating (14) with respect to T gives

$$\begin{pmatrix} C_L'' + D'' & mD'' & rD'' \\ D'' & \partial^2 C_M / \partial e_M^2 + mD'' & rD'' \\ D'' & mD'' & C_R'' + rD'' \end{pmatrix} \begin{pmatrix} \frac{de_L}{dT} \\ \frac{de_M}{dT} \\ \frac{de_R}{dT} \end{pmatrix} = \begin{pmatrix} 0 \\ -\partial^2 C_M / \partial e_M \partial T \\ 0 \end{pmatrix} \tag{A1}$$

where H ,

$$H = (C_L'' + D'')\partial^2 C_M / \partial e_M^2 C_R'' + C_L'' D'' (\partial^2 C_M / \partial e_M^2 r + C_R'' m) > 0 \tag{A2}$$

denotes the determinant of the 3×3 matrix on the left-hand side in our subsequent argumentation.

This implies that the endogenous variables change as follows with a change in T :

$$\frac{de_L}{dT} = C_{eT}^M \frac{C_R'' m D''}{H}, \tag{A3}$$

$$\frac{de_M}{dT} = -C_{eT}^M \frac{[C_R'' (C_L'' + D'') + C_L'' r D'']}{H}, \tag{A4}$$

$$\frac{de_R}{dT} = C_{eT}^M \frac{C_L'' m D''}{H}, \tag{A5}$$

$$\frac{dE}{dT} = \frac{de_L}{dT} + m \frac{de_M}{dT} + r \frac{de_R}{dT} = -\frac{\partial^2 C_M}{\partial e_M \partial T} \frac{m C_L'' C_R''}{H}. \tag{A6}$$

We deduce that the level of emissions from firms of type M and total emissions are moving in one direction, while emissions by firm L and firms R are changing in the other direction. Specifically, $C_{eT}^M > 0$ will induce a decrease (increase) in e_M and E (e_L and e_R). In contrast, an increase in the level of marginal abatement costs, that is, $C_{eT}^M < 0$, will induce an increase (decrease) in e_M and E (e_L and e_R).

Finally, the claims about the change in environmental harm directly follow from $D'(E) > 0$, and the claims about the change in permit price directly follow from $p = D'(E)$ and $D'' > 0$.