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## Does more stringent environmental regulation induce or reduce technology adoption? When the rate of technology adoption is inverted u-shaped

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Christian-Albrechts-Universität zu Kiel

Department of Economics

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does more stringent environmental regulation  
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by Grischa Perino and Till Requate

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# **Does more stringent environmental regulation induce or reduce technology adoption?**

When the rate of technology adoption is inverted U-shaped

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## **Abstract**

We show that for a broad class of technologies the relationship between policy stringency and the rate of technology adoption is inverted U-shaped. This happens when the marginal abatement cost (MAC) curves of conventional and new technologies intersect, which invariably occurs when emissions are proportional to output and technological progress reduces emissions per output. This outcome does not result from policy failure. On the contrary, in social optimum, the relationship between the slope of the marginal damage curve and the rate of technology adoption is also inverted U-shaped. Under more general conditions, these curves can look even more complicated (e.g. such as inverted W-shaped).

Keywords: induced diffusion, environmental policy

JEL codes: Q55, Q52, Q58, H23, O33

## 1 Introduction

A key insight from the environmental economics literature is that, when appropriately designed, environmental policy can strongly affect both technological progress and the diffusion of less pollution-intensive or less cost-intensive abatement technologies.<sup>1</sup> The intuitive nature of the relationship between policy stringency and incentives to develop and adopt ‘green’ technologies is positive and monotonic, i.e. stricter policy raises both R&D and the diffusion of abatement technologies. Such monotonicity results are derived for instance, by Requate and Unold (2001, 2003) for the case of diffusion and by Requate (2005b) for R&D incentives. A monotonic relationship is also commonly assumed in empirical tests of induced innovation/diffusion hypotheses (see e.g. Jaffe and Palmer 1997, Newell 1999, Popp 2002, Kerr and Newell 2003, Brunnermeier and Cohen 2003, Carrión-Flores and Innes 2010).

For the case of R&D incentives there are however a couple of contributions questioning monotonic relationship between the stringency of environmental regulation and innovation incentives. For example, Ulph (1997) establishes an ambiguous relationship between the level of a tax on emissions and R&D spending for an imperfectly competitive polluting industry. Similar results have been established in models with international Cournot oligopolies (e.g. Simpson and Bradford 1996). Baker et al. (2008) conjecture that, if high abatement levels are required, technologies featuring increased MAC for high levels of abatement will be replaced by backstop-type technologies. In contrast to the present paper, their argument relies on the availability of three distinct technologies and is not formally proven. Denicolò (1999), Farzin and Kort (2000) and Baker and Shitu (2006) derive related results for non-monotonicity in R&D incentives (Denicolò 1999 and Baker and Shitu 2006) and investment into an abatement capital stock (Farzin and Kort 2000).

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<sup>1</sup> See Jaffe et al. (2002), Löschel (2002) and Requate (2005a) for excellent reviews of this literature.

Our aim here is to examine the relationship between the stringency of environmental policy and the rate of technology adoption. We look at a simple model with many (small) firms characterized by their short-term (marginal) abatement cost (MAC) curves. Each firm can adopt an advanced technology that induces a new MAC curve. However, instead of making the typical assumption that R&D shifts down the MAC curves<sup>2</sup>, we assume that the MAC curves of the old and the new technology intersect each other. The possibility and relevance of such a representation of technological change has recently been pointed out by several authors (see Amir et al. 2008, Baker et al. 2008, Baumann et al. 2008, Brechet and Jouvét 2008). Amir et al. (2008) even show that technological progress induced by the reduction of emission coefficients within a neoclassical production function necessarily leads to decreasing MACs for high emission levels but increasing MACs when the targeted emission level is sufficiently low. The intuition for the arising of such a pattern is straightforward in the case where the only way to reduce emissions (other than adopting the new technology) is reducing output and MACs of the old ‘technology’ are strictly downward sloping. Adopting a technology that reduces the emission coefficient clearly reduces unregulated emissions. However, any further emission reduction requires sacrificing more units of output than with the conventional technology exactly because the emission coefficient has been reduced. An important insight of these contributions is that there exists a broad, and widely used class of green technologies<sup>3</sup> for which the MAC curves of the old and new technology intersect.

To complement previous theoretical monotonicity results and check their robustness, we consider environmental technological progress that triggers such intersecting MAC curves.

We ask how much technology adoption is optimal, given a particular marginal damage (MD)

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<sup>2</sup> Jaffe et al. (2002) state that “technology diffusion presumably lowers the aggregate marginal abatement cost function” (p. 54), and this assumption is also made by Milliman and Prince (1989), Jung et al. (1996), Goulder and Schneider (1999), Fischer et al. (2003), Requate and Unold (2001, 2003), Rosendahl (2004), Requate (2005b) and others.

<sup>3</sup> Papers using clean technologies of this type include Denicolò (1999), Baudry (2000), Nordhaus (2002), and Perino (2010). Baker et al. (2008) provide additional references.

function, and how much adoption will occur given a particular stringency level for a policy instrument (e.g., a tax rate, tradable permits, uniform emission standard). We show that the relationship between the slope of the MD function and the degree of technology adoption shows an inverted U- (or tunnel-) shape. For low MD, society optimally manages emission reductions by conventional measures without switching technologies. For intermediate slopes of the MD function, partial or full technology adoption is desirable, while for sufficiently high MD, society will switch back to traditional measures. The reason for this is twofold. Firstly, the abatement cost reduction from adopting the new technology is non-monotonic in the level of abatement. Hence, for more severe environmental problems, the cost advantage is decreasing in the level of abatement. Secondly, for extremely hazardous pollutants (i.e. those causing substantial damage at the margin), adoption of a cleaner technology would induce an increase in aggregate emissions. The associated rise in damages from pollution offsets some or all of the abatement cost reductions that would be realized by adoption.

Looking at adoption patterns under different pollution control policies, we find the same pattern. If the firms' technologies are ex ante symmetric, the adoption rate as a function of the policy instrument's stringency has also an inverted U-shape. The intersecting relationship between the MAC curves of conventional and new technology does not create any major policy problems. If firms are sufficiently small and have only a marginal impact on total emissions and thus on marginal damage, the Pigouvian rule still induces the first best rate of adoption.

If firms are not symmetric with respect either to their conventional or their advanced technologies, the relationship between policy stringency and technology adoption can be even more complex, e.g. inverted W-shaped. However, one robust finding is that the rate of

technology adoption is always weakly increasing (decreasing) for sufficiently low (high) ranges of policy stringency.

Calel (2011) and Brechet and Meunier (2012) have independently derived non-monotonic relationships between environmental regulation and technology adoption. In contrast to us, they both explicitly model output markets and focus exclusively on taxes and tradable permits. They do not consider the effects of heterogeneous firms.

Note that switching back on technology as a response to increasing prices was also found early on in macroeconomic growth models. After Levhari (1965) had incorrectly claimed that reswitching of technologies is impossible in an indecomposable Leontief-Sraffa system, Samuelson (1966) and Levhari and Samuelson (1966) corrected this error, triggering the so-called Robinson-Samuelson controversy summarized in Robinson (1975) and Samuelson (1975).

This article is organized as follows: In the next section we set up the model. In section 3 we characterize the socially optimal adoption rate contingent on a damage parameter determining the slope of the MD function. In section 4 we look at the relationship between the stringency of policy instruments and the rate of adoption and show that decentralization of the first-best allocation does not cause problems under market-based instruments, notably emission taxes and tradable permits. In section 5 we take a brief look at the case of ex-ante asymmetric firms. In section 6 we sum up and draw a number of conclusions.

## **2 The Model**

We consider a continuum of polluting firms indexed by  $i \in [0,1]$ . Firms are endowed with some initial technology 0 and can invest to adopt a new technology  $I$ . Both technologies are

the same for each firm. Firms, however, differ in the fixed investment cost  $F(i) \geq 0$  they incur by adopting the new technology. We assume firms to be sorted according to their adoption costs, with  $F' > 0$ , i.e. the higher the firm index  $i$ , the more costly adoption.<sup>4</sup> We write  $F(0) = \underline{F} > 0$  and  $F(1) = \bar{F} > 0$  for the lower and upper bound of adoption costs. In section 5 we outline how this model can be extended to the case of technological heterogeneity in firms.

The firms' technologies are represented by their abatement cost functions  $C_j(e) > 0$  where  $j = 0, I$ .<sup>5</sup> Since the choice of emissions depends solely on the technology, we can write  $C_j(e_j) > 0$ . The abatement cost functions satisfy the following properties:  $C_j(e) > 0$ ,  $-C'_j(e) > 0$ , and  $C''_j(e) > 0$  for all  $e < e_j^{\max}$ , i.e. (marginal) abatement costs are continuous, positive, and strictly convex for emissions not exceeding some unregulated emission level  $e_j^{\max}$ , where  $C_j(e) = 0$  for all  $e \geq e_j^{\max}$ ,  $j = 0, I$ .<sup>6</sup> The two technologies are related as follows:  $e_I^{\max} \leq e_0^{\max}$ , i.e. the unregulated maximal emissions of the new technology do not exceed those of the conventional technology. Moreover, there is some emission level  $e^c$  where the marginal abatement cost curves of the two technologies intersect. More precisely, we make the following assumption:

**Assumption 1 (Single Crossing Property):** There exists an emission level  $e^c$  such that

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<sup>4</sup> For convenience we assume that  $F(i)$  is continuous and differentiable in  $i$ . However, all non-monotonicity results hold if firms can be ordered such that  $F(i)$  is weakly monotonously increasing in  $i$ .

<sup>5</sup> Amir et al. (2008), Bauman et al. (2008) and Brechet and Jouvét (2008) all explicitly model input and output adjustments in their derivation of the particular pattern of crossing MACs used here. For the sake of simplicity we suggest the reduced form approach focusing on MAC curves only. Results are robust to explicit consideration of output.

<sup>6</sup> Most of our results hold also for weakly convex abatement functions (e.g. those with constant marginal abatement costs). Exceptions are Propositions 2d) and 5d) that concern the optimality of Pigouvian taxes. While the social optimum will still be an equilibrium under taxes, the equilibrium will no longer be unique if the abatement cost function is not strictly convex in the relevant range. However, this is a well known phenomenon not specific to the contribution of this paper. It also holds if there is only one technology and adoption is not an issue.



$$-C'_I(e^c) = -C'_0(e^c),$$

$$-C'_I(e) < -C'_0(e) \text{ for all } e \text{ with } e^c < e < e_0^{\max} \text{ and}$$

$$-C'_I(e) > -C'_0(e) \text{ for all } e < e^c.$$

This assumption, which ensures that the MAC curves of the conventional and the new technology intersect in a way derived by Amir et al. (2008), Baker et al. (2008), Bauman et al. (2008) and Brechet and Jouvét (2008), implies the following auxiliary result:

***Lemma 1***

*i) The cost advantage of technology I over 0 is maximal and strictly positive at  $e^c$ .*

*ii) There exists some emission level  $e^b < e^c$  such that  $C_I(e) < C_0(e)$  for all  $e > e^b$ .*

*iii) If  $-C'_0(e_0) = -C'_I(e_I)$ , then*

$$a) e_0 = e_I = e^c \text{ for } -C'_j(e_j) = -C'_j(e^c), \text{ for } j=0, I$$

$$b) e_0 > e_I \text{ for } -C'_j(e_j) < -C'_j(e^c), \text{ for } j=0, I$$

$$c) e_0 < e_I \text{ for } -C'_j(e_j) > -C'_j(e^c), \text{ for } j=0, I$$

The proof is given in the Appendix. The intuition for all results is straightforward. The intersection point of the two MACs represents a global maximum of the cost difference between the two technologies. The non-monotonicity in the cost advantage is the key driver of all non-monotonicity results presented below. The cost difference is strictly positive at  $e^c$  since marginal abatement costs of the new technology are strictly lower for all  $e^c < e < e_0^{\max}$ .

With a strictly positive cost difference at  $e^c$  and continuity of both marginal abatement cost functions, it follows that there is a neighborhood around  $e^c$  where cost differences are strictly positive. If the equimarginal principle holds, emissions from the new technology are below

those of the old one in the region where the old technology's marginal abatement costs are higher, and vice versa. As a direct consequence, sufficiently stringent tax policies (with tax rates above  $-C'_j(e^c)$ ) will lead to an increase in aggregate emissions whenever there is at least some diffusion of the new technology. Hence, adoption of a cleaner technology can result in increased emissions, all else being equal.

We use  $n$  to denote the index of the marginal firm adopting the new technology. Accordingly,  $n$  is also the share of firms that adopt technology  $I$ . Total emissions are then given by  $E = n \cdot e_I + (1 - n) \cdot e_0$  where  $e_0$  ( $e_I$ ) is a firm's emission level when using the old (new) technology.

The damage from pollution is assumed to depend on aggregate emissions only. Therefore the damage function is denoted by  $D(E, \beta) > 0$ , where  $\beta \geq 0$  is an exogenous scale parameter. We assume  $D(0, \beta) = 0$  for all  $\beta > 0$ , and  $D_E(E, 0) = 0$ . Moreover,  $D(E, \beta) > 0$ ,  $D_E(E, \beta) > 0$ ,  $D_\beta(E, \beta) > 0$ , and  $D_{E\beta}(E, \beta) > 0$  for all  $E > 0, \beta > 0$ .<sup>7</sup> The parameter  $\beta$  therefore leads to an increase of both damage and marginal damage from emissions.

### 3 The Social Optimum

First we derive the socially optimal diffusion rate for the new technology as a function of the damage parameter  $\beta$ . Social costs are given by the sum of the abatement costs for both technologies, the costs of adopting the new technology, and pollution damages:

$$SC(e_0, e_I, n) = n \cdot C_I(e_I) + \int_{i=0}^n F(i) di + (1 - n) \cdot C_0(e_0) + D(E, \beta). \quad (3.1)$$

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<sup>7</sup> Here we use  $D_x$  and  $D_{xy}$  to denote the first and second (cross) derivative of  $D$  with respect to  $x$ , and  $x$  and  $y$ , respectively.

A social planner minimizes these costs w.r.t.  $e_0$ ,  $e_I$ , and  $n$  subject to non-negativity constraints  $n \geq 0$  and  $1-n \geq 0$ . Applying the Kuhn-Tucker calculus, the first-order conditions are

$$C'_0(e_0) + D_E(E, \beta) = 0 \quad (3.2)$$

$$C'_I(e_I) + D_E(E, \beta) = 0 \quad (3.3)$$

$$C_I(e_I) + F(n) - C_0(e_0) + (e_I - e_0) \cdot D_E(E, \beta) - \lambda_0 + \lambda_1 = 0 \quad (3.4)$$

where  $\lambda_i$  are the Kuhn-Tucker multipliers of the non-negativity constraints on  $n$  and  $(1 - n)$ .

We can now study how the damage parameter  $\beta$  impacts on the optimal share of adopting firms. For an interior solution, i.e. for  $\lambda_0 = \lambda_1 = 0$ , one can show (see Appendix) that

$$\frac{\partial n}{\partial \beta} = \frac{-D_{E\beta} C''_0 C''_I \cdot [e_I - e_0]}{C''_0 C''_I \left[ F_n + (e_I - e_0)^2 D_{EE} \right] - n \cdot (1-n) F_n D_{EE}} \quad (3.5)$$

The numerator is positive if  $e_0 > e_I$ , it is zero for  $e_0 = e_I$ , and negative otherwise. The denominator is positive whenever the solution is a cost minimum. Next, we define the critical damage parameter  $\hat{\beta}$  for which the socially optimal emission level for both technologies is equal to  $e^c$  i.e.:

$$D_E(e^c, \hat{\beta}) = C'_j(e^c), \quad j = 0, I \quad (3.6)$$

We are now ready to characterize the optimal share of adopting firms as a function of the damage parameter  $\beta$ .

**Proposition 1**

*Assuming the second-order conditions for a social optimum are met, then*

- *the optimal share of adopting firms is weakly monotonically increasing in  $\beta$  for all  $\beta \leq \hat{\beta}$  and weakly monotonically decreasing in  $\beta$  for all  $\beta > \hat{\beta}$ ;*
- *full diffusion is optimal for some interval of damage parameters  $[\underline{\beta}, \overline{\beta}]$  containing  $\hat{\beta}$  if  $\overline{F} \leq C_0(e^c) - C_1(e^c)$ ;*
- *for  $\beta$  sufficiently large, no firm will adopt the abatement technology in the social optimum if  $\underline{F} \geq \lim_{e \rightarrow 0} C_0(e) - C_1(e)$ .*

The proof is given in the Appendix. The proposition indicates that the relationship between  $\beta$  and the share of adopting firms is inverted U- (or tunnel-) shaped as shown in Figure 1. This shape is driven by non-monotonicity in the new technology's cost advantage. For low levels of  $\beta$ , marginal damages are low, and the cost advantage of the new technology is still increasing in the level of abatement. Moreover, firm-level emissions are weakly decreasing in adoption. Starting from a relatively flat damage function a marginal increase in  $\beta$  makes abatement more desirable, hence increasing the new technology's cost advantage. The trade-off between incurring adoption cost  $F(n)$  and realizing lower aggregate abatement costs favors the reduction of abatement costs.

However, once the threshold level  $\hat{\beta}$  is passed, the new technology's cost advantage decreases in additional abatement, and firm-level emissions weakly increase as a result of adoption. A marginal increase in  $\beta$  still makes abatement more desirable but decreases the new technology's cost advantage. Society becomes less willing to incur adoption costs, and the socially optimal share of the new technology decreases in  $\beta$ .

Note further that (a) the tunnel shape includes zero adoption for very small and (under the condition specified in Proposition 1) for very large  $\beta$  (see Figure 1), and that (b) full diffusion may or may not occur for intermediate levels of  $\beta$ . The upper panel in Figure 1 displays two

possible shapes of the  $(\beta, n)$  diagram. For both examples no adoption is optimal for small levels of  $\beta$  since adoption costs are strictly positive for all firms. In the example represented by curve  $n_1$  full diffusion is desirable for some range of damage parameters while for sufficiently high damage parameters no firm should adopt. Curve  $n_2$  represents a case where neither full diffusion nor full re-switching to the conventional technology for high damage parameters is optimal. Other combinations of these features are possible as well. The lower panel in Figure 1 presents aggregate emissions for the two examples. The dotted line indicates aggregate emissions if only the old technology is available. To the right of  $\hat{t}_1(\hat{t}_2)$  aggregate emissions are strictly higher whenever at least one firm uses the new technology compared to a situation where only the old technology is available. Once the industry is perfectly clean, changes in the damage parameter  $\beta$  (or the tax rate  $t$ ) have no further effect on the allocation.

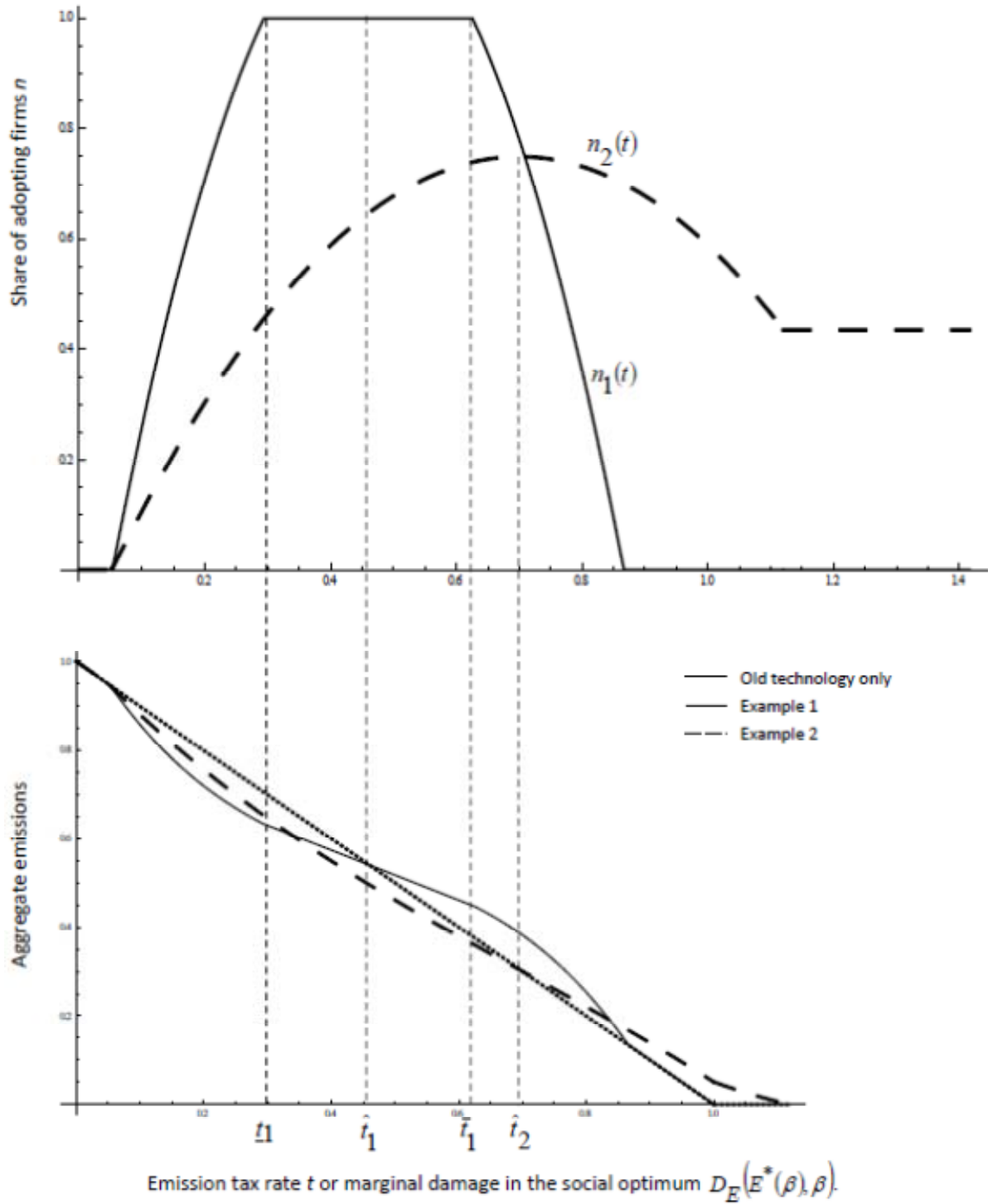
#### **4 Diffusion and Regulatory Stringency**

In the following, we investigate how regulatory stringency affects the rate of diffusion. Using the technologies specified in section 2, we will derive inverted U-shaped relationships between the stringency of three common policy instruments (emission taxes, tradable permits, and uniform emission standards) and the equilibrium rate of diffusion. This complements the monotonicity results obtained by Requate and Unold (2001, 2003) for a broad class of technologies (Amir et al., 2008; Baker et al., 2008; Bauman et al., 2008, Brechet and Jouvet 2008). It also challenges the generality of the induced-diffusion hypothesis by showing (a) that stricter environmental regulation can also reduce – and not only induce – adoption of a given clean technology, and (b) that sufficiently high levels of stringency may prevent the technology from being used at all.

##### **4.1 Taxes**

We assume that firms' emissions are subject to a uniform and linear emission tax schedule, where we use  $t$  to denote the emission tax rate. Profit maximization requires that firms choose emissions such that marginal abatement costs equal the tax rate  $t$  regardless of the technology used, i.e.

$$-C'_j(e_j) = t \text{ for } j = 0, I. \tag{4.1}$$



**Figure 1:** Two examples of diffusion rates of the new technology (upper panel) and aggregate emissions (lower panel) as functions of the marginal damage parameter  $\beta$  and the emission tax rate. Specifications of the functional forms are given in the appendix.

Furthermore, in any equilibrium with an interior solution in the share of adoption, the marginal firm  $n$  is indifferent between adopting and non-adopting, i.e.

$$C_I(e_I) + F(n) - C_0(e_0) + t \cdot (e_I - e_0) = 0. \quad (4.2)$$

If (4.1) and (4.2) hold, the relationship between  $n$  and  $t$  is given by

$$\frac{\partial n}{\partial t} = \frac{e_0 - e_I}{F'} \quad (4.3)$$

which is positive if  $e_0 > e_I$ , (i.e. if  $t < -C'_j(e^c)$ ), zero for  $e_0 = e_I$ , and negative otherwise.

This produces the following proposition characterizing the relationship between the tax rate and the rate of adoption. For this purpose we define the critical tax rate  $\hat{t}$  as

$$\hat{t} = C'_j(e^c) \quad j=0, I. \quad (4.4)$$

**Proposition 2**

- a) *The share of adopting firms is weakly monotonically increasing in  $t$  for all  $t < \hat{t}$  and weakly monotonically decreasing in  $t$  for all  $t > \hat{t}$ .*
- b) *Full diffusion is optimal for an interval of tax rates  $[\underline{t}, \bar{t}]$  containing  $\hat{t}$  if  $\bar{F} \leq C_0(e^c) - C_I(e^c)$ .*
- c) *For sufficiently large tax rates  $t$ , no firm will adopt the abatement technology if  $\underline{F} \geq \lim_{e \rightarrow 0} C_0(e) - C_I(e)$ .*
- d) *For each damage parameter  $\beta$ , the socially optimal allocation can be implemented by the Pigouvian tax rate, i.e.  $t = D_E(E^*, \beta)$ , where  $E^*$  denotes the first-best emission level.*

The proof is given in the Appendix. We see that the induced-diffusion hypothesis holds only for sufficiently low tax rates. Above the point where the marginal abatement cost curves intersect, the effect of an increase in stringency is reversed, and further increases in the tax



rate reduce adoption incentives. Note that this is not a result of a market or policy failure. A tax set equal to the marginal damage of pollution evaluated at the socially optimal level of pollution always implements the first-best outcome. Again, non-monotonicity rests exclusively on the fact that marginal abatement costs cross in the way specified in Section 2, and hence on the circumstance that the cost advantage of the new technology is non-monotonic in the level of abatement (Lemma 1). The examples presented in Figure 1 also represent the rate of diffusion (upper panel) and aggregate emissions (lower panel) for emission taxes. The curve  $n_I(t)$  depicted in Figure 1 presents an example where both conditions b) and c) of Proposition 2 on  $F$  hold. Note that  $n_2(t)$  is based on linear MAC curves. Accordingly, once the emission tax rate is higher than the MAC of the new technology at zero emissions, the cost advantage and hence the rate of diffusion are independent of  $t$ .

## 4.2 Tradable permits

If the government sets an emission cap  $\bar{E}$  and issues a corresponding number of tradable permits to internalize the pollution externality, aggregate emissions will be constrained by

$$n \cdot e_I + (1 - n) \cdot e_0 \leq \bar{E}. \quad (4.5)$$

Profit maximization requires firms to choose emissions such that marginal abatement costs equal the price of permits  $\rho$  regardless of the technology used, i.e.

$$-C'_j(e_j) = \rho \text{ for } j = 0, I. \quad (4.6)$$

Again, for equilibria with interior shares of adoption the marginal firm  $n$  is indifferent between adopting and non-adopting, i.e.

$$C_I(e_I) + F(n) - C_0(e_0) + \rho \cdot (e_I - e_0) = 0. \quad (4.7)$$

The share of adopting firms  $n$  adjusts to changes in the permit quantity as follows:

$$\frac{\partial n}{\partial \bar{E}} = \frac{C_0'' C_1'' \cdot [e_1 - e_0]}{F'(nC_0'' - (1-n)C_1'') + (e_1 - e_0)^2 C_0'' C_1''}. \quad (4.8)$$

The numerator is negative if  $e_0 > e_1$ , zero for  $e_0 = e_1$ , and positive otherwise. The denominator is positive whenever a second-best permit quantity exists.

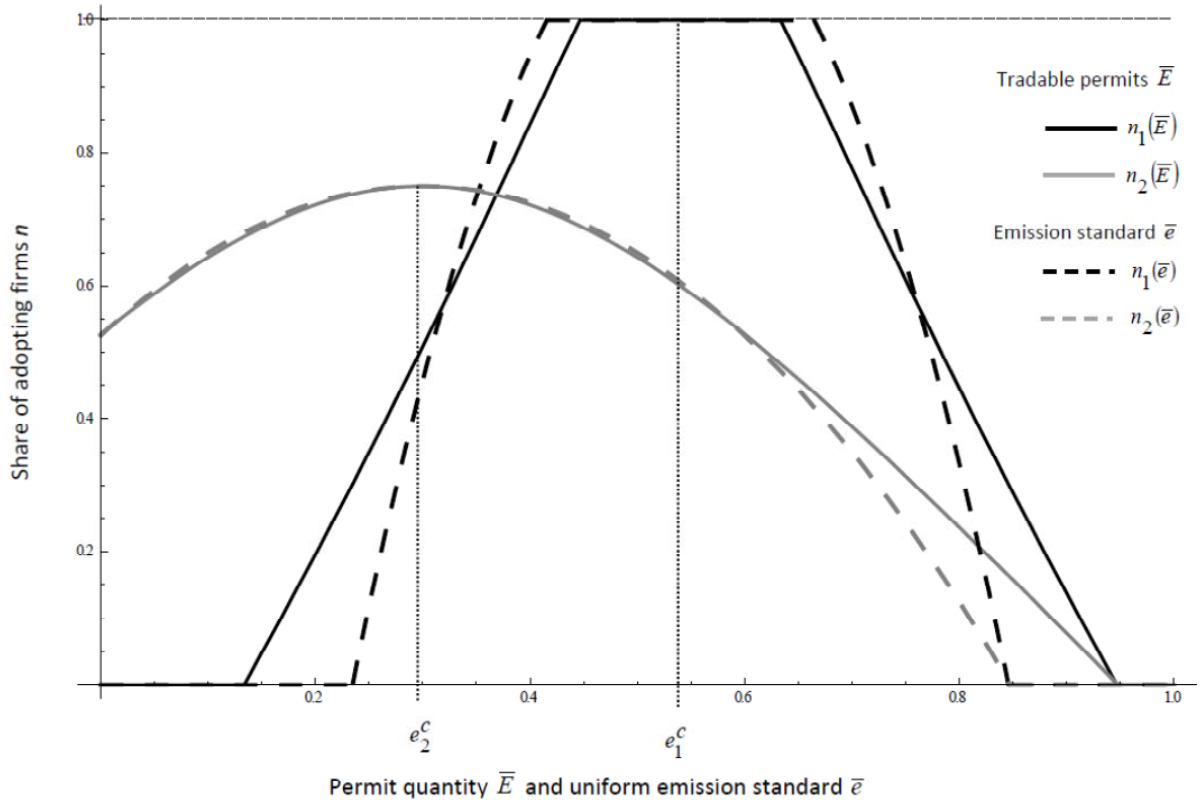
The next result characterizes the adoption rate contingent on the total emission cap  $\bar{E}$  set by the regulator. Note that the mass of firms is normalized to unity. The total emission level resulting when all firms emit the critical emission level  $e^c$  is therefore written as  $\hat{E} = e^c$ .

**Proposition 3**

- a) *The share of adopting firms is weakly monotonically increasing in  $\bar{E}$  for all  $\bar{E} < \hat{E}$  and weakly monotonically decreasing in  $\bar{E}$  for all  $\bar{E} > \hat{E}$ .*
- b) *Full diffusion is optimal for some interval of emission caps  $[\underline{\bar{E}}, \bar{\bar{E}}]$  containing  $\hat{E} = e^c$  if  $\bar{F} \leq C_0(e^c) - C_1(e^c)$ .*
- c) *For a sufficiently small emission cap  $\bar{E}$ , no firm will adopt the abatement technology if  $\bar{F} \geq \lim_{e \rightarrow 0} C_0(e) - C_1(e)$ .*
- d) *For each damage parameter  $\beta$ , the socially optimal allocation can be implemented by issuing tradable permits with an emission cap of  $\bar{E} = E^*$ , where  $E^*$  denotes the first-best aggregate emission level.*

The proof is given in the Appendix. The result is illustrated in Figure 2. The continuous lines represent two possible inverted U-shaped relationships between the aggregate emission cap  $\bar{E}$  and the share of adopting firms  $n$ , where we employed the same functional forms and

parameters as in the examples shown in Figure 1. Note that a higher emission cap implies a laxer policy. Thus emission caps close to zero correspond to high damage parameters or high tax rates, respectively, and vice versa. The intuition for this result is exactly the same as for taxes. Indeed, the share of adopting firms under both instruments will be the same if the equilibrium permit price equals the tax rate.



**Figure 2:** Two examples of diffusion as a function of the aggregate emission cap (continuous lines) and uniform emission standard (dashed).

### 4.3 Uniform emission standard

A uniform emission standard imposes a binding upper bound  $\bar{e}$  on a firm's emissions. Since firms are ex-ante symmetric, this policy could achieve the first-best allocation if technology 0 were the only one available. If both technologies are available, the marginal firm  $n$  is indifferent between adopting and non-adopting if

$$C_1(\bar{e}) + F(n) - C_0(\bar{e}) = 0. \quad (4.8)$$

For equilibria with interior solutions in  $n$ , the relationship between  $\bar{e}$  and  $n$  is derived by totally differentiating (4.8), yielding

$$\frac{\partial n}{\partial \bar{e}} = \frac{C'_0(\bar{e}) - C'_I(\bar{e})}{F'} \quad (4.9)$$

Due to Assumption 1, the above expression is positive for  $\bar{e} < e^c$ , negative for  $\bar{e} > e^c$  and zero if  $\bar{e} = e^c$ . The following result characterizes the rate of adoption contingent on a uniform emission standard:

**Proposition 4**

- a) *The share of adopting firms is weakly monotonically increasing in  $\bar{e}$  for all  $\bar{e} < e^c$  and weakly monotonically decreasing in  $\bar{e}$  for all  $\bar{e} > e^c$ .*
- b) *Full diffusion is optimal for an interval of standards  $[\underline{e}, \bar{e}]$  containing  $e^c$  if  $\bar{F} \leq C_0(e^c) - C_I(e^c)$ .*
- c) *For sufficiently small standards  $\bar{e}$ , no firm will adopt the abatement technology if  $\underline{F} \geq \lim_{e \rightarrow 0} C_0(e) - C_I(e)$ .*
- d) *The first-best allocation cannot be implemented by a uniform emission standard if partial adoption is optimal.*

The proof is given in the Appendix. In Figure 2 the dashed lines display the relationship between the emission standard  $\bar{e}$  and the share of adopting firms  $n$  for the same parameter values used for tradable permits (solid lines in Figure 2). This allows a direct comparison of the diffusion rates under the two policy regimes. We observe that emission standards result in smaller diffusion rates than tradable permits for low and high levels of policy stringency while the opposite holds for intermediate levels. This is not by coincidence. For any level of aggregate emissions the adoption incentives for the first firm that considers adopting are no larger under uniform standards than under tradable permits since in the latter case the firm can

realize additional gains from trading permits if it adopts. For the last firm, however, adoption incentives under permits are weakly smaller under uniform standards because the permit price has adjusted as a result of other firms adopting the new technology. A more detailed discussion of this effect can be found in Requate and Unold (2003).

## 5 More General Forms of Cost Heterogeneity

In this section we relax the assumption that firms have identical marginal abatement costs curves under the old and the new technology. As a result, more complex patterns of non-monotonicity may arise. The reason is that, while for each firm adoption incentives are still akin to an inverted U-shape, the peaks will generally differ between firms. So at a given level of policy stringency, some firm  $i$  may have already passed its peak, and it may no longer be profitable to adopt the new technology, while another firm  $k$  requires an even stricter level before adoption becomes attractive.

To extend our simple model we now represent the firms' technologies by firm-specific abatement cost functions  $C_j(e; i)$  where  $j = 0, I$  and  $i \in [0, 1]$  indexes firms. Firms also differ in the fixed investment cost  $F(i) \geq 0$  they incur by adopting the new technology. The abatement cost functions satisfy the same properties as in the symmetric case:  $-C'_j(e; i) > 0$ , and  $C''_j(e; i) > 0$  for all  $e < e_j^{\max}(i)$ , where derivatives refer to emissions and  $e_j^{\max}(i)$  is the technology-specific unregulated emission level of firm  $i$  with technology  $j = 0, I$ . For each firm  $i$ , the two technologies satisfy Assumption 1.

We now re-order firms on the unit interval according to the level of marginal abatement costs at  $e^c(i)$  such that  $-C'_j(e^c(i); i)$  is weakly monotonically increasing in  $i$ . Clearly Lemma 1 still holds for each firm.

Since firms' marginal abatement cost functions intersect at different emission levels and at different marginal abatement costs, Lemma 1 does not extend to industry level. However, for both emission taxes and tradable permits we obtain the following result:

**Proposition 5**

- a) *The share of adopting firms  $n$  is weakly increasing in  $t$  (in  $\bar{E}$ , respectively) for all  $t < -C'_0(e^c(0);0)$  (for all  $\bar{E} < e^c(1)$ ), weakly decreasing in  $t$  (in  $\bar{E}$ ) for all  $t > -C'_0(e^c(1);1)$  (for all  $\bar{E} > e^c(0)$ ) and may behave non-monotonically for all levels of stringency in between.*
- b) *Each firm will adopt for at least one level of stringency if  $F(i) \leq C_0(e^c(i);i) - C_I(e^c(i);i)$  for all firms  $i$ .*
- c) *If  $F(i) \geq \lim_{e \rightarrow 0} C_0(e;i) - C_I(e;i)$  for all firms  $i$ , then no firm will adopt for sufficiently stringent environmental regulation.*
- d) *For each damage parameter  $\beta$ , the socially optimal allocation can be implemented by charging the Pigouvian tax rate, i.e.  $t = D_E(E^*, \beta)$ , or by issuing tradable emission permits with an emission cap  $\bar{E} = E^*$ , where  $E^*$  is the first-best emission level.*

The proof is analogous to those of Propositions 2 and 3.

For uniform emission standards, we have to re-order firms according to  $e^c(i)$  such that  $e^c(i)$  is weakly monotonically increasing in  $i$ . We then obtain the following result:

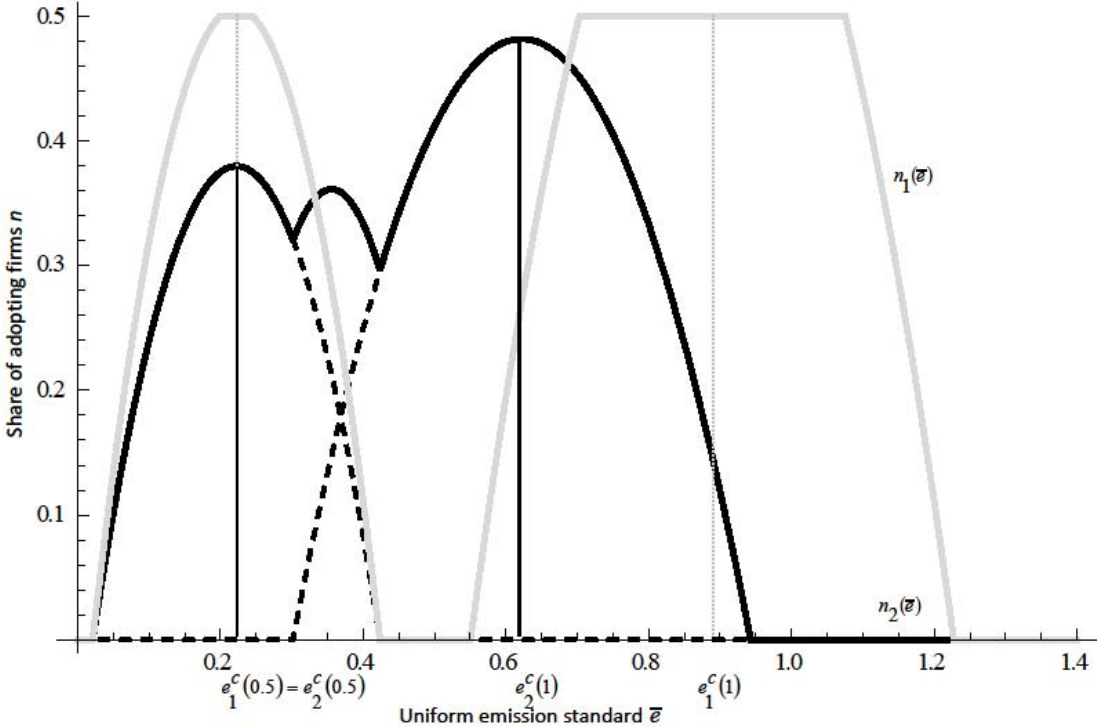
**Proposition 6**

- a) *The share of adopting firms  $n$  is weakly increasing in  $\bar{e}$  for all  $\bar{e} < e^c(0)$ , weakly decreasing for all  $\bar{e} > e^c(1)$  and can behave non-monotonically for all levels of stringency in between.*
- b) *Each firm will adopt for at least one level of stringency if  $F(i) \leq C_0(e^c(i); i) - C_I(e^c(i); i)$  for all firms  $i$ .*
- c) *If  $F(i) \geq \lim_{e \rightarrow 0} C_0(e; i) - C_I(e; i)$  for all firms  $i$ , then no firm will adopt for sufficiently stringent environmental regulation.*

The proof is analogous to that of Proposition 4. The issue of non-monotonicity intensifies considerably if firms are heterogenous in their marginal abatement cost functions. The range of stringencies for which an increase in stringency induces more diffusion can be substantially reduced. For intermediate levels of stringency, the direction of the stringency effect on diffusion can change several times.

Firm-level heterogeneity can also give rise to non-standard patterns like an inverted W-shape of the stringency-diffusion relationship (see  $n_1(\bar{e})$  in Figure 3) or even saw-blade shapes like  $n_2(\bar{e})$  in Figure 3. Note that both examples presented in Figure 3 are based on only two firm types (in terms of their MAC), i.e. in each example there are only two critical levels  $e^c(i)$ . Nevertheless,  $n_2(\bar{e})$  features three local maxima in the rate of diffusion. The dashed lines in Figure 3 indicate the diffusion rate for each type of firm contributing to  $n_2(\bar{e})$ . Note that in Figure 3 the rate of diffusion never exceeds 50% and that none of the firms adopting at the first peak of the diffusion rate (at  $e_1^c(0.5)$  and  $e_2^c(0.5)$ ) would adopt at the last peak (at  $e_1^c(1)$ )

and  $e_2^c(1)$ ) and vice versa. As illustrated by example  $n_1(\bar{e})$  in Figure 3, another interesting feature can arise with heterogeneous firms. It is possible that a level of stringency exists for each and every firm at which that firm will adopt. At the same time, there may be no level of stringency at which all firms will adopt. The intuition for this pattern is straightforward and rests on two key ingredients. The first is the inverted U-shape of adoption incentives at the firm level for each policy instrument which has been established in Lemma 1. The second is the heterogeneity between firms and the feature that the intervals of stringencies for which firms adopt may be disjoint. Therefore full diffusion is not guaranteed even if all firms adopt for some level of stringency.



**Figure 3:** Two examples of diffusion of a new technology as a function of a uniform emission standard if firms are heterogeneous in their marginal abatement costs. Exact specifications are given in the appendix.



## 6 Conclusions

Recent research on technological innovation has pointed out that marginal abatement cost curves induced by new emission-saving technologies can cross the marginal abatement cost curve resulting from conventional technologies. Accordingly, we have investigated the consequences for both optimal technology adoption and firms' response to more stringent environmental policy. We find that, under sufficient symmetry between firms, the relationship between the rate of advanced technology adoption and the stringency of environmental policy is inverted U-shaped. We further point out that this is by no means a result of market or policy failure. On the contrary, the celebrated Pigouvian rule works well with respect to technology adoption. The reason is that the relationship between the slope of the marginal damage function, on the one hand, and the rate of technology adoption, on the other, is also inverted U-shaped if marginal abatement cost curves resulting from conventional and advanced technology intersect. Matters may be different if R&D firms have market power and regulators set their policies *ex post* rather than *ex ante*. It has to be left to further research to determine whether inverted U- or W-shaped relationships between stringency of environmental policy and both the rate of adoption and R&D effort are likely to trigger lock-in or hysteresis effects when large R&D firms can impact the level of policy stringency.

Our findings also have important implications for empirical tests of the induced diffusion and innovation hypotheses. The predicted relationship between policy stringency and adoption or R&D effort can be (highly) non-monotonic for a broad class of technologies. So far, empirical literature has commonly assumed a monotonic relationship. Our results call for caution when extrapolating the results of such studies as the marginal effect of stringency on technology diffusion might differ from the average effect of a past policy change not only in size but also in direction. Future empirical tests of the induced diffusion hypothesis should explicitly take into account the possibility of non-monotonicity.

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## Appendix

### Proof of Lemma 1

i) Maximizing  $C_0(e) - C_I(e)$  yields the first-order condition  $C'_0(e) - C'_I(e) = 0$ , which by Assumption 1 is satisfied for  $e = e^c$ . The second-order condition is  $C''_0(e^c) - C''_I(e^c) < 0$ . Assumption 1 and continuity of  $C'_I(e)$  imply that the second-order condition is satisfied. The cost difference does indeed adopt a maximum at  $e = e^c$ .

To see ii), observe that  $e_I^{\max} \leq e_0^{\max}$  and  $-C'_I(e) < -C'_0(e)$  for all  $e^c < e < e_0^{\max}$ . It follows that  $C_I(e) < C_0(e)$  for all  $e \geq e^c$ . By continuity this is also true for some  $e < e^c$ .

iii) By Assumption 1 we have  $-C'_I(e) < -C'_0(e)$  for all  $e^c < e < e_0^{\max}$ . This implies that for all emission levels  $e_0$  and  $e_I$  with  $-C'_0(e_0) = -C'_I(e_I) < -C'_j(e^c)$  it holds that  $e_0 > e_I$  and, accordingly, that for all emission levels  $e_0$  and  $e_I$  with  $-C'_0(e_0) = -C'_I(e_I) > -C'_j(e^c)$  it holds that  $e_0 < e_I$ , where  $j = 0, I$ .

### Derivation of the first-best allocation and equation (3.5)

The Lagrangian of this problem is

$$L = n \cdot C_I(e_I) + \int_{i=0}^n F(i) di + (1-n) \cdot C_0(e_0) + D(E, \beta) - \lambda_0 n - \lambda_1 (1-n)$$

where  $\lambda_i$  are the Kuhn-Tucker multipliers of the non-negativity constraints on  $n$  and  $(1-n)$ .

If an interior solution exists ( $\lambda_0 = \lambda_1 = 0$ ), applying the implicit function theorem to system (3.2) – (3.4) gives the influence of  $\beta$  on  $n$ , which is (3.5).

To verify that the denominator is positive, note that the denominator is the determinant of the Hessian Matrix, which has to be positive for a cost minimum (as part of the positive definiteness condition).

### Proof of Proposition 1

For interior solutions of  $n$ , the proof for the first part of Proposition 1 follows from (3.5). For corner solutions  $n = 1$ , the shadow price  $\lambda_1$  indicates the marginal increase in social welfare of the last firm adopting. Applying the implicit function theorem to (3.3) and making use of the envelope theorem gives

$$\frac{\partial \lambda_1}{\partial \beta} = -(e_I - e_0) \cdot D_{E\beta}(E, \beta)$$

which is positive for all  $\beta \leq \hat{\beta}$  and negative for all  $\beta > \hat{\beta}$  where  $\hat{\beta} : D_E(e^c, \hat{\beta}) = C'_j(e^c)$ . The proof for  $n = 0$  is analogous.

Using (3.4), the last firm adopts in the social optimum if  $\bar{F} \leq C_0(e_0) - C_I(e_I) - (e_I - e_0) \cdot D_E(E, \beta)$ . Maximizing this threshold over  $\beta$  yields the first-order condition  $-(e_I - e_0) \cdot D_{E\beta}(E, \beta) = 0$  which yields  $\beta = \hat{\beta}$ . The second-order condition for a maximum is satisfied.

Using (3.4) again, environmental regulation ceases to create adoption incentives for sufficiently high values of  $\beta$  if  $\underline{F} \geq C_0(e_0) - C_I(e_I) - (e_I - e_0) \cdot D_E(E, \beta)$  for some  $\beta > 0$ . A sufficient (but not necessary) condition for this to hold is  $\underline{F} \geq \lim_{e \rightarrow 0} C_0(e) - C_I(e)$  since for all  $\beta > \hat{\beta}$ ,  $-(e_I - e_0) \cdot D_E(E, \beta)$  is non-positive.

### Proof of Equation (4.3)

Applying the implicit function theorem and differentiating conditions (4.1) and (4.2) w.r.t.  $t$  yields (4.3).

### Proof of Proposition 2

For interior solutions of  $n$ , the proof for the first part of Proposition 2 is contained in the main text as part of the discussion of Equation (4.3). To study corner solutions  $n = 0$  ( $n = 1$ ), we differentiate the left-hand side of (4.2), i.e. the cost advantage of adoption by the first (last) firm w.r.t.  $t$ , yielding

$$C'_I(e_I) \cdot \frac{\partial e_I}{\partial t} - C_0(e_0) \cdot \frac{\partial e_0}{\partial t} + (e_I - e_0) + \left( \frac{\partial e_I}{\partial t} - \frac{\partial e_0}{\partial t} \right) \cdot t = (e_I - e_0)$$

which is negative for all  $t \leq \hat{t}$  and positive for all  $t > \hat{t}$  with  $\hat{t} = C'_j(e^c)$ .

From (4.2) it follows that the last firm is indifferent between adoption and non-adoption if  $C_I(e_I) + \bar{F} - C_0(e_0) + t \cdot (e_I - e_0) = 0$ . Since adoption incentives are largest for  $\hat{t} = C'_j(e^c)$ , the condition for full diffusion is  $\bar{F} \leq C_0(e^c) - C_I(e^c)$ .

Using (4.2) again, emission taxes cease to create adoption incentives for sufficiently high values of  $t$  if  $\underline{F} \geq C_0(e_0) - C_I(e_I) - (e_I - e_0) \cdot t$  for some  $t > 0$ . A sufficient (but not necessary) condition for this to hold is  $\underline{F} \geq \lim_{e \rightarrow 0} C_0(e) - C_I(e)$ , since for all  $t > \hat{t}$ ,  $-(e_I - e_0) \cdot t$  is non-positive.

Conditions (4.1) and (4.2) coincide with the first-order conditions (3.2) – (3.4) of the social optimum if  $t = D_E(E^*, \beta)$ .



### Proof of Equation (4.8)

By eliminating  $\rho$  from (4.5) – (4.7), the equilibrium conditions become

$$C'_0(e_0) - C'_I(e_I) = 0$$

$$C_I(e_I) + F(n) - C_0(e_0) - C'_0(e_0) \cdot (e_I - e_0) = 0$$

$$n \cdot e_I + (1 - n)e_0 - \bar{E} = 0$$

Applying the implicit function theorem to interior solutions, the relationship between  $n$  and  $\bar{E}$  is given by (4.8). Note that the denominator is strictly positive if a socially optimal permit quantity exists.

### Proof of Proposition 3

For interior solutions of  $n$ , the proof for the first part of Proposition 3 is contained in the main text as part of the discussion of Equation (4.8). To study corner solutions  $n = 0$  ( $n = 1$ ), we again differentiate the left-hand side of (4.7), i.e. the cost advantage of adoption by the first (last) firm w.r.t.  $\bar{E}$ , yielding

$$C'_I(e_I) \cdot \frac{\partial e_I}{\partial \bar{E}} - C_0(e_0) \cdot \frac{\partial e_0}{\partial \bar{E}} + (e_I - e_0) \cdot \frac{\partial \rho}{\partial \bar{E}} + \left( \frac{\partial e_I}{\partial \bar{E}} - \frac{\partial e_0}{\partial \bar{E}} \right) \cdot \rho = (e_I - e_0) \cdot \frac{\partial \rho}{\partial \bar{E}}$$

which is negative for all  $\bar{E} < e^c$  and positive for all  $\bar{E} > e^c$  since  $\frac{\partial \rho}{\partial \bar{E}} < 0$ .

From (4.7) it follows that the last firm is indifferent between adoption and non-adoption if  $C_I(e_I) + \bar{F} - C_0(e_0) + \rho \cdot (e_I - e_0) = 0$ . Since adoption incentives are largest for  $\bar{E} = e^c$ , the condition for full diffusion is  $\bar{F} \leq C_0(e^c) - C_I(e^c)$ .

Using (4.7) again, tradable permits cease to create adoption incentives for sufficiently low values of  $\bar{E}$  if  $\bar{F} \geq C_0(e_0) - C_I(e_I) - (e_I - e_0) \cdot \rho$  for some  $\rho > 0$ . A sufficient (but not

necessary) condition for the latter to hold is  $\underline{F} \geq \lim_{e \rightarrow 0} C_0(e) - C_I(e)$ , since for all  $\bar{E} < e^c$ ,  $-(e_I - e_0) \cdot \rho$  is non-positive.

Conditions (4.6) and (4.7) coincide with the first-order conditions (3.2) – (3.4) of the social optimum if  $\rho = D_E(E^*, \beta)$ . Setting  $\bar{E} = E^*$  implements this.

#### **Proof of Proposition 4**

From (4.8) it follows that the last firm is indifferent between adoption and non-adoption if  $C_I(e_I) + \bar{F} - C_0(e_0) = 0$ . Since adoption incentives are biggest for  $\bar{e} = e^c$ , the condition for full diffusion is  $\bar{F} \leq C_0(e^c) - C_I(e^c)$ .

Again using (4.8), a uniform emission standard ceases to create adoption incentives for sufficiently low values of  $\bar{e}$  if  $\underline{F} \geq \lim_{e \rightarrow 0} C_0(e) - C_I(e)$ . Here the condition is both sufficient and necessary.

#### **Proof of Proposition 5 (d)**

The first-order conditions for the social optimum with heterogeneous firms are equivalent to (3.2) – (3.4) where (3.2) and (3.3) hold for each firm  $i$  individually. If  $t = D_E(E^*, \beta)$  or  $\bar{E} = E^*$  the equilibrium conditions under an emission tax (cap and trade) system will coincide with the first-order conditions for a social optimum.

## Specification of Examples

Figures 1 and 2:

$$\text{Functions: } C_j(e) = \frac{c_j}{2} (e_j^{\max} - e)^2, F(i) = f_{\text{int}} + f_{\text{slope}} \cdot i, D(E, \beta) = \frac{\beta}{2} E^2$$

Parameters:

$$n_1 : c_0 = 1, c_I = 1.77, e_0^{\max} = 1, e_I^{\max} = 0.8, f_{\text{int}} = 0.01, f_{\text{slope}} = 0.03$$

$$n_2 : c_0 = 1, c_I = 1.4, e_0^{\max} = 1, e_I^{\max} = 0.8, f_{\text{int}} = 0.01, f_{\text{slope}} = 0.08$$

Figure 3:

$n_1$  :

firm type 1:

$$\text{relative share 50\%, } c_0 = 1, c_I = 0.15625, e_0^{\max} = 1.4, e_I^{\max} = 1.12, f_{\text{int}} = 0.08, f_{\text{slope}} = 0.06$$

firm type 2:

$$\text{relative share 50\%, } c_0 = 2, c_I = 3.125, e_0^{\max} = 0.5, e_I^{\max} = 0.4, f_{\text{int}} = 0.06, f_{\text{slope}} = 0.08$$

$n_2$  :

firm type 1:

$$\text{relative share 50\%, } c_0 = 1, c_I = 0.15625, e_0^{\max} = 2, e_I^{\max} = 1.6, f_{\text{int}} = 0.19, f_{\text{slope}} = 0.045$$

firm type 2:

$$\text{relative share 50\%, } c_0 = 2, c_I = 3.125, e_0^{\max} = 0.5, e_I^{\max} = 0.4, f_{\text{int}} = 0.005, f_{\text{slope}} = 0.03$$