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Design Standards and Technology Adoption: Welfare Effects of Increasing Environmental Fines when the Number of Firms is Endogenous

Florian Baumann*   Tim Friehe†

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Abstract

This paper examines the consequences of an increase in the expected fine for non-compliance with an environmental design standard for an industry with Cournot competition and free entry. Our analysis is quite timely, given recent policy proposals to raise environmental fines. We describe the range in which changes in the environmental fine have no consequences, and detail the various other effects that emerge. It is established that an increase in the expected fine for non-compliance may have adverse welfare consequences, while it always serves the purpose of inducing a greater share of firms to adopt the prescribed technology.

Keywords: pollution, regulation, design standard, endogenous number of firms, environmental fines

JEL-Classification: D62, Q55, Q58

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1 Introduction

1.1 Motivation and main results

The damage to the environment caused by industry is a widespread problem of great importance. One recent UN-backed study estimated the monetary value of the global environmental damage caused by human activity in 2008 at $6.6 trillion (equivalent to 11% of global GDP), attributing $2.15 trillion to the top 3,000 public companies alone.[1] In the search for the potential causes of this harm, it is often argued that environmental policy suffers from a serious underdeterrence problem (e.g., Faure 2009). The recent policy initiatives by the European Commission that propose the intensified criminalization of offences against the environment are thus logical and widely embraced responses to this crisis. The ratification of EU directive 2008/99/EC introduced a general policy criminalizing environmental offenses in the European Union. The rationale for this development is that criminal prosecution provides access to the full sanctioning regime of criminal law, in contrast to standard regulatory procedures. This access may be beneficial by application of the classic economic theory of deterrence: Increasing the level of the expected sanction for harmful activities reduces their attractiveness, thereby reducing the level of harm (Goeschl and Jürgens forthcoming).

This paper analyzes policy initiatives that create harsher sanctions for environmental damages, exploring the associated welfare repercussions in a setting with imperfect product market competition and free entry into the industry. The consideration of a market setting is warranted because corporations are the predominant actors in the context of offences against the environment (e.g., Faure 2009). More specifically, we study market outcomes for an industry in which firms are engaged in Cournot competition and are subject to a design standard – that is, a prescription regarding the production technology employed by the firm. Despite the fact that much of the environmental economics literature focuses on emission taxes and tradeable permits, the real-world regulation of environmental risk continues to be dominated by the use of standards (Endres 2011, Hueth and Melkonyan 2009). In many industries and for many products, environmental standards in the form of performance and design standards are applied as the main policy instrument. Performance standards directly control pollution

[1] See the press release 'Putting a price on global environmental damage' by Principles for Responsible Investment, issued October 6, 2010.

by regulating its total allowable level (i.e., by imposing a cap for emissions). In contrast, design standards, the focus of the present paper, demand the fulfillment of specific technological requirements (such as the use of at least a minimum level of emission-control inputs) without defining a maximum allowable level of pollution. A prominent example of a design standard is the European Union council directive 96/61/EC, which regulates plant licenses for most industries, mandating that a license should only be granted when the plant makes use of the best available technology. Similar regulations referring to the state of the art can also be found in Germany, the UK, and the USA (Endres 2011, p. 109). In our setup, one technology is regarded as the *best* among those available and is therefore mandated by the environmental protection agency. This *green* technology is associated with less pollution for a given level of output when compared to a *brown* alternative, but has higher adoption costs and incurs potentially higher marginal production costs. The design standard is enforced by a fine for non-compliance, imposed only probabilistically because perfect monitoring of technology adoption is prohibitively expensive. This implies that firms may adopt the brown technology when the benefits from doing so overcompensate the profit repercussions resulting from the expected fine. In addition to firms' decisions regarding the kind of production technology to use and the level of output to produce, we allow for an endogenous number of firms. Our analysis contributes in (at least) two different ways to the literature. First, we explore the imperfect compliance of firms with a design standard. Second, we consider the adoption decision in conjunction with firm interaction in an imperfectly competitive market, comparing the effects on scenarios with exogenous and endogenous numbers of firms.[2]

We analyze a scenario in which the policy maker's chief instrument is the expected fine for non-compliance with the design standard. In the context of environmental policy, administrative authorities generally have a significant influence on such regulations are formulated, interpreted, and enforced (e.g., Faure 2009). For example, the USA's Environmental Protection Agency has considerable discretion regarding the penalties assessed under the Clean Air Act Amendments of 1977 (Besanko 1987). We consider Cournot competition between firms producing a homogenous product with constant marginal costs. Production implies socially harmful pollution, where the relationship between output and pollution depends on the kind

[2]See Requate (2005) for a relatively recent survey of the literature on the dynamic incentives induced by different environmental policy instruments.

of production technology used. Firms differ in their costs for adopting the green technology and will incur marginal costs based on the kind of technology adopted. Participation in the industry is determined by the fact that firms face fixed market entry costs.

Our main finding is that a marginal increase in the level of the expected fine need not be welfare-increasing. Indeed, for an illustrative example, we establish that there is a broad range of levels of the expected fine in which welfare falls in response to an increase in the expected fine. The reason for this counter-intuitive finding is that the level of the expected fine affects not only on the share of compliant firms in equilibrium, but also both the output levels and the number of firms in the industry. However, we show that the narrower policy goal of inducing a greater share of adopting firms is always attained by a stricter enforcement. This follows from the fact that the direct effect – a higher level of the fine motivates more firms to adopt the green technology – dominates the potentially counteracting indirect effect based on the number of firms in the industry. For this indirect effect, it holds that when the higher level of the expected fine results in fewer firms in the industry, the share of green firms will decrease. This follows from the fact that a reduction in the number of firms in the industry makes the lower marginal costs associated with the brown technology more profitable. We also find that there is a critical strictly positive level of the expected fine that must be surpassed in order to induce the first firm to switch to compliance, i.e., there is a range of levels of the expected fine for which the rate of adoption of the green technology is zero. Moreover, our example also clearly shows that a marginal increase in the level of the expected fine may imply an increase in the harm done to the environment, as brown firms will increase their output in response to a possible decrease in the number of firms.

Based on our results, although a basic economic theory of crime perspective would seem to support the recent policy initiatives that raise the possibility of increased environmental sanctions, they should perhaps be regarded more skeptically. The consideration of industrial organization aspects blurs the picture, making it more difficult to ensure the beneficial nature of simple prescriptions.

1.2 Related literature

Our paper is related to contributions to the literature that study standards, as well as those that explore the repercussions of imperfect compliance with environmental policy.

Our framework builds on the model proposed by Besanko (1987), who similarly focuses on standards in the environmental context. Whereas that study compares perfectly enforced design and performance standards, the present analysis considers imperfectly enforced design standards; our main interest is the comparative-statics analysis of the effects of the expected fine implemented to support the design standard. Like Besanko (1987), Helfand (1991) seeks to compare the relative merits of different kinds of standards. A more recent contribution is provided by Hueth and Melkonyan (2009), who consider regulation by standards when there is asymmetric information between firms and regulators regarding the cost and efficacy of different technologies. Somewhat more closely related to the focus of our paper, Farzin (2003) studies the repercussions of increasing the emission standard, meaning that firms must abate a greater proportion of their emissions. As in the present paper, his framework is one in which firms compete in quantities and there is free market entry. Farzin's main argument is that a stricter enforcement standard may induce more firms to enter the industry – in contrast to what many industrialists would claim – when the demand shifts outside with the strictness of the emission standard. To the best of our knowledge, the consideration of imperfect compliance with a design standard is new to the literature.

The fact that firms may not comply with environmental policies has been considered in a number of studies such as Keeler (1991), Malik (1990), Rousseau and Proost (2005, 2009), and Sandmo (2002). For example, in a scenario with tradeable emissions permits, non-compliance also implies interesting feedback effects via the permit price, a theoretical finding validated by laboratory experiments (Murphy and Stranlund 2006). How policies ought to optimally respond when actors could be non-compliant has been discussed, for example, in Montero (2002) and Macho-Stadler and Perez-Castrillo (2006). The potential importance of imperfect compliance for dynamic incentives (that is, incentives concerning R&D and technology adoption) has only recently been taken up. Villegas and Coria (2010) and Arguedas et al. (2010) provide related analyses on the adoption incentives of firms when there is imperfect compliance with environmental policy, in frameworks in which firms act in perfectly competitive product markets. Complementing the aforementioned papers, we provide the first exploration of imperfect compliance with a design standard, focusing on the marginal influence of an increase in the penalty for non-compliance on market outcomes and welfare. Moreover, previous analyses of imperfect compliance and many studies on technology adoption have abstracted from industry aspects, whereas we explicitly take into account the interaction of firms in a setting characterized by Cournot competition and free entry.[3]

Finally, our contribution is related to papers that study the design of optimal environmental taxation under conditions of imperfect competition and free entry. In this literature, it has been shown that the optimal environmental tax is less than marginal external harm in an industry with a fixed number of firms (to account for the restriction of output); the tax may be greater than marginal external harm when there is an endogenous number of firms in the industry (see, e.g., Katsoulacos and Xepapadeas 1995, Lee 1999). In our analysis, the policy maker will similarly choose a different level for the expected fine for non-compliance when the number of firms in the industry results from decentralized decision-making.

The rest of the paper is structured as follows. We present the framework used for our analysis in Section 2 and the social optimum as a benchmark scenario in Section 3. The outcome that emerges under decentralized decision-making is discussed in Section 4 for relatively general functional forms. Section 5 imposes more structure, which yields clear predictions regarding the effects of increases in the level of the expected fine for non-compliance with the design standard. Section 6 concludes.

2 The model

Our analysis uses the oligopoly set-up described in Besanko (1987), albeit extended to the scenario of an endogenous number of firms, n. Firm i produces output x_i and emits pollution $f(x_i, e_i)$, where e_i is the quantity of an emissions-control input and $f(0, e) = 0$, $\partial f/\partial x > 0 > \partial f/\partial e$, and $\partial^2 f/\partial x \partial e < 0 \leq \partial^2 f/\partial x^2$. The function $f(x_i, e_i)$ is a reduced-form pollution production function. The emissions-control input may also be understood as representing a state of the production technology based on its emission-intensity. Total emissions are given by $E = \sum_{i=1}^{n} f(x_i, e_i)$ and cause environmental harm $D(E)$, where D is strictly convex in the level of total pollution. Firm i's variable cost function is given by $C(e_i, x_i) = c(e_i)x_i$, where $c(e_i)$ is the constant per unit cost of output. Marginal costs are weakly increasing in the emissions-control input; thus, it is weakly more costly to produce output using a cleaner technology (i.e., we assume that $c' \geq 0$). Firms can choose between two technology options.

[3]For classic contributions in the technology adoption literature, see Requate and Unold (2003) and the survey presented by Requate (2005).

The brown technology uses e^B of the emissions-control input, whereas the green technology uses e^G, $e^G > e^B$. The adoption of the brown technology implies fixed costs normalized to zero. In contrast, the adoption of the green technology entails firm-specific costs α, where α is uniformly distributed on $[\underline{\alpha}, \bar{\alpha}] = [0, 1]$.[4] In the following discussion, firms and their outputs will be indicated by a B or a G depending on the technology adopted.

Firms compete in quantities, serving the inverse demand function $P(X)$, where $X = \sum_{i=1}^{n} x_i$ is total output and both $P' < 0$ and $P''X + P' \leq 0$ are assumed for any X.[5] Entry into the industry is associated with fixed costs K. Firms are subject to environmental regulation that manifests as a design standard (i.e., a prescription regarding the production technology to be used). The environmental agency requires that firms implement the green production technology since this is the *best available technology.* Whether or not firms actually implement the green technology can only be ascertained by costly monitoring undertaken by the environmental protection agency. When a firm is inspected and found to be using the brown production technology, a penalty is assessed. The product of this penalty and the monitoring probability yields the expected fine F that firms associate with non-compliance with the design standard.[6] The quantity purchased by each individual consumer is small, such that the influence on overall pollution is negligible. As a consequence, consumers do not discriminate between firms using the brown technology and firms using the green one.[7] Furthermore, we assume that the regulatory agency cannot perfectly observe any single firm's total output and that adoption costs are private information; otherwise, this would allow deductions on the part of the agency regarding the technology utilized by firms in our stylized setting (due to the difference in marginal costs).

[4] It is standard procedure to consider exogenous adoption costs in the technology adoption literature. However, there are other contributions that explicitly address the innovation sector and firms investing in R&D (see, e.g., the survey by Requate 2005).

[5] The latter assumption ensures that the reaction function of firm i is downward sloping in the output of all other firms.

[6] For example, the Dutch Criminal Code sets out a hierarchy of monetary fines depending on the category of the offense. For a survey of criminal sanctions, see, for instance, 'Criminal Penalties in EU Member States Environmental Law' available at *ec.europa.eu/environment/legal/crime/*.

[7] This may also be rationalized by assuming that consumers prefer free-riding to contributing to the public good represented by high environmental quality.

3 The social optimum

In this section, we assume that there is a benevolent policy maker capable of determining the number of firms in the industry, the share of firms in the industry that adopt the green technology, and firms' quantity levels. This is a benchmark scenario that will help us to evaluate the outcome under decentralized decision-making. In later sections, we will consider a policy maker who is unable to unilaterally define all relevant variables and instead utilizes the expected fine for non-compliance with the design standard in order to ameliorate the consequences therefrom.

We assume that the policy maker seeks to maximize the sum of producer and consumer surplus less environmental harm under the restriction that the share of adopting firms can only take values between zero and one. The constrained objective function can thus be stated as

$$W = \int_0^X P(v)dv - n\left[\sum_{j=B,G} \gamma^j c^j x^j + \int_0^{\gamma^G} \alpha d\alpha\right] - D(E) - nK + \lambda(1-\gamma^G) + \mu\gamma^G \qquad (1)$$

where γ^j denotes the share of firms in the industry choosing technology j, with $\gamma^B = 1 - \gamma^G$, $X = n\sum_{j=B,G} \gamma^j x^j$, and $E = n\sum_{j=B,G} \gamma^j f^j$ (using $f(x^j, e^j) = f^j$). The first-order conditions are as follows:

$$\frac{\partial W}{\partial x^j} = n\gamma^j\left[P(X) - c^j - D'(E)\frac{\partial f^j}{\partial x}\right] = 0, \quad j = B, G \qquad (2)$$

$$\frac{\partial W}{\partial \gamma^G} = n\left[P(X)(x^G - x^B) - \left[c^G x^G - c^B x^B + \gamma^G\right] - D'(E)(f^G - f^B)\right] - \lambda + \mu = 0 \qquad (3)$$

$$\frac{\partial W}{\partial n} = P(X)X/n - \left[\sum_{j=B,G} \gamma^j c^j x^j + \int_0^{\gamma^G} \alpha d\alpha\right] - D'(E)E/n - K = 0 \qquad (4)$$

$$\frac{\partial W}{\partial \lambda} \geq 0, \quad \lambda \geq 0, \quad \frac{\partial W}{\partial \lambda}\lambda = 0 \quad \frac{\partial W}{\partial \mu} \geq 0, \quad \mu \geq 0, \quad \frac{\partial W}{\partial \mu}\mu = 0. \qquad (5)$$

The socially optimal output level for a firm using technology j requires that the willingness to pay (as measured by P) be equal to the social marginal costs, which consist of the marginal production costs and the marginal harm due to the increase in the level of pollution. Condition (2) mandates output levels that ensure that social marginal costs are equalized:

$$c^G + D'\frac{\partial f^G}{\partial x} = c^B + D'\frac{\partial f^B}{\partial x}, \qquad (6)$$

meaning that $\partial f^B/\partial x > \partial f^G/\partial x$ must hold when $c' > 0$.

In evaluating the condition for the share of firms adopting the green technology given by (3), we find that the policy maker takes into account the difference in technology-specific first-best output levels, the levels of costs incurred by the respective firm types, and – importantly – the level of environmental harm. Restating the bracket in (3) as

$$D'(E)\left(f^B - f^G\right) + (P - c^G)x^G - (P - c^B)x^B - \gamma^G \tag{7}$$

shows that inducing an additional firm to adopt the green technology reduces environmental harm when $f^B > f^G$; it also implies a change in surplus and additional adoption costs.

With regard to the number of firms, condition (4) may be reformulated using condition (2) as

$$\gamma^G D'(E)\left[\frac{\partial f^G}{\partial x}x^G - f^G\right] + (1-\gamma^G)D'(E)\left[\frac{\partial f^B}{\partial x}x^B - f^B\right] = K + \frac{(\gamma^G)^2}{2}, \tag{8}$$

where $\int_0^{\gamma^G} \alpha d\alpha = (\gamma^G)^2/2$. Given constant marginal costs and positive market entry costs, the only societal advantage from increasing the number of firms results from the reduction in environmental harm when firm-specific pollution is strictly convex. For a linear f^j, the left-hand side of (8) is zero, negating the possibility of a socially optimal number of firms greater than one.

Realistically, policy makers are not as omnipotent as we have assumed in this section. In the next section, we will consider the scenario in which the policy maker can set the expected fine for non-compliance with the design standard, based on assumptions about how firms will make decisions on issues of interest to the policy maker. However, as is standard, we maintain the assumption that policy makers are omniscient in that they know the demand function and the cost functions of firms employing the two types of technology.

4 The market equilibrium

In this section, firms are actors in a market economy subject to regulation by the policy maker. For the policy maker, we consider an expected fine for non-compliance with the technology standard as the policy instrument. The timing of the decentralized decision-making is as follows.

1. The policy maker determines the expected fine for non-compliance with the technology standard $F \geq 0$.

2. Firms decide whether or not to enter the industry.

3. Idiosyncratic adoption costs α are realized for the firms in the industry.

4. Firms in the industry choose whether to adopt the green production technology or the brown one.

5. Firms in the industry determine output contingent on the production technology adopted in stage 4.

The game will be solved by backward induction.

4.1 Stage 5: Determination of output

The profit of a firm with adoption costs α that uses technology j can be stated as

$$\pi_i^j = P(X)x_i^j - c^j x_i^j - (1 - \Sigma_j)\alpha - \Sigma_j F, \tag{9}$$

where $\Sigma_B = 1$ and $\Sigma_G = 0$.

The first-order condition that defines the privately optimal equilibrium output contingent on the firm's technology and the total output of other firms is given by

$$P'(X)x^j + P(X) - c^j = 0, \tag{10}$$

where $x_i^j = x^j$ for firms using technology j. When $c' = 0$, green and brown firms produce the same level of output.[8] When $c' > 0$, the output of brown firms exceeds that of green ones. The difference in output levels implicitly depends on the difference in marginal costs and the shape of demand thus:

$$x^B - x^G = \frac{c^B - c^G}{P'} \geq 0. \tag{11}$$

Firms do not take environmental repercussions into account; consequently, obtaining a ranking in which green firms produce more than brown firms is impossible in the market setting. This may stand in a sharp contrast to the socially optimal configuration.

Turning to a comparative-statics analysis of privately optimal output levels, we first note that the profit-maximizing quantity level is not determined by the level of the expected fine due to the fixed-cost nature. However, privately optimal output is a function of the share of

[8] Recall that $c' = 0$ requires that brown firms produce less than green ones in the social optimum.

firms adopting the green technology and the number of firms, $x^j = x^j(\gamma^G, n)$, such that:

$$\frac{\partial x^j}{\partial \gamma^G} = H^{-1} n(x^B - x^G)(P'' x^j + P') \geq 0 \tag{12}$$
$$\frac{\partial x^j}{\partial n} = H^{-1} X/n(-1)(P'' x^j + P') < 0, \tag{13}$$

with $H = (n+1)P' + P''X < 0$. Intuitively, we find that an increase in the share of firms using the green technology increases output per firm when $c' > 0$, as green firms produce less (which contracts total output). In contrast, a higher number of firms for a given γ^G lowers output per firm; this is a standard result in oligopolistic settings.

Condition (12) provides information about the changes in output of green and brown firms when their respective proportions in the totality of firms are modified. It is also of interest to determine what this change means for total output. Starting from the definition of total output, the impact of a change in γ^G on total output for a given number of firms can be stated as

$$\frac{\partial X}{\partial \gamma^G} = n \left[(x^G - x^B) + \sum_{j=B,G} \frac{\partial x^j}{\partial \gamma} \gamma^j \right]. \tag{14}$$

Using (12), we obtain

$$\frac{\partial X}{\partial \gamma^G} = -\frac{nP'(x^B - x^G)}{(n+1)P' + P''X} \leq 0. \tag{15}$$

This signifies that the direct effect of a marginal firm producing only x^G instead of x^B dominates the indirect effect whereby both firm types increase their outputs.

Similarly, the sign of dX/dn may be determined by applying (13):

$$\frac{\partial X}{\partial n} = \frac{P'X/n}{(n+1)P' + P''X} > 0. \tag{16}$$

With regard to the influence of a change in the number of firms on industry output, the direct effect indicates an increase in total output, whereas the indirect effect points in the opposite direction. Condition (16) informs us that the total effect is unambiguous under the current assumptions.

We summarize the findings from above in Lemma 1.

Lemma 1 *1) Individual output is decreasing with the number of firms in the industry, whereas industry output increases.*
2) When $c' = 0$, individual and total output is unaffected by the share of green firms. When $c' > 0$, individual output is increasing with the share of green firms in the industry, whereas

industry output decreases.

3) Neither individual nor total output is directly influenced by the expected fine for non-compliance with the technology standard.

4.2 Stage 4: Production technology choice

The firms in the industry choose either the green or the brown production technology. For each firm, this selection will be critically influenced by both the level of realized firm-specific adoption costs α and the level of the expected fine for non-compliance with the design standard.

Firms arrive at their technology choice by comparing their anticipated profits under the two alternatives; thus, the difference in profits Δ that results from choosing the brown technology instead of the green one is of critical importance, where

$$\Delta(F, \alpha) = (P - c^B)x^B - F - \left[(P - c^G)x^G - \alpha\right]. \tag{17}$$

We obtain an interior equilibrium adoption rate when $\Delta(F, \alpha) = 0$ for some $\alpha \in (0, 1)$. In this case, the level of adoption costs for the indifferent firm is equal to γ^G, defining the share of green firms. Full adoption would be indicated by $\Delta(F, 1) \leq 0$, such that even firms with the highest possible adoption costs would find it more profitable to produce using the green technology. No adoption would follow from $\Delta(F, 0) > 0$: Even firms with the lowest possible adoption costs would find it more profitable to produce using the brown technology. Note that $\Delta(F, \alpha) = 0$ for $\alpha = F = \gamma^G$ when $c' = 0$. It is also noteworthy that the adoption of the green technology cannot be preferable for firms (implying zero adoption) when $c' > 0$ and F is close to zero, since $(P - c^B)x^B > (P - c^G)x^G$ is always fulfilled for $c' > 0$. This finding leads us to Lemma 2.

Lemma 2 *1) A positive adoption rate requires the imposition of an expected fine such that* $F > F_0$*, where*

$$F_0 = (P(X(F_0)) - c^B)x^B(F_0) - (P(X(F_0)) - c^G)x^G(F_0).$$

Full adoption is obtained for $F \geq F_c$*, where*

$$F_c = (P(X(F_c)) - c^B)x^B(F_c) - (P(X(F_c)) - c^G)x^G(F_c) + 1.$$

2) It holds that $F_c - F_0 \neq 1 = \bar{\alpha}$ because individual and total output is an indirect function of the level of the expected fine.

3) The equilibrium adoption rate is unique.

Proof. Regarding 3): From (17), using (10), it follows for $\alpha = \gamma^G$ that

$$\frac{\partial \Delta(F, \gamma^G)}{\partial \gamma^G} = P' \frac{\partial X}{\partial \gamma^G}(x^B - x^G) - P' \left(x^B \frac{\partial x^B}{\partial \gamma^G} - x^G \frac{\partial x^G}{\partial \gamma^G} \right) + 1 > 1. \tag{18}$$

The ranking follows from application of (12):

$$\frac{\partial \Delta(F, \gamma^G)}{\partial \gamma^G} = -\frac{n(P')^2(x^B - x^G)^2}{(n+1)P' + P''X} \left[1 + \frac{P''}{P'} x^B + 1 + \frac{P''}{P'} x^G \right] + 1, \tag{19}$$

where the signing of the first term uses $P' + P''x^j < 0$. In other words, the greater the share of green firms in equilibrium, the more attractive choosing the brown technology is for the marginal firm. This rules out strategic complementarity. With regard to 2), this claim uses the argument presented in Lemma 1. ■

Part 1 of Lemma 2 means that an increase in the level of the expected fine such that $F < F_0$ after the increase is inconsequential for the equilibrium adoption rate. Firms are not prepared to accept the reduction in profits that the adoption of the green technology entails. The level F_0 mirrors this difference in profits (for $\gamma^G = 0$); at this level firms whose adoption costs are zero are indifferent between the two technologies. Similarly, an increase in the level of the expected fine where $F > F_c$ before and after the increase is inconsequential for the adoption rate, as all firms have already opted for the green technology at the lower level of the expected fine. Part 3 of Lemma 2 states that there is no possibility of multiple equilibrium adoption rates, because the profitability of adopting the brown technology is increasing in the adoption rate.

Turning to a comparative-statics analysis of the equilibrium adoption rate, we note that it is generally a function of the level of the expected fine and the number of firms in the industry, $\gamma^G = \gamma^G(F, n)$. How these relationships unfold is described starting from $\Delta(F, \gamma^G) = 0$ as follows:

$$\frac{\partial \gamma^G}{\partial F} = A^{-1} > 0 \tag{20}$$

$$\frac{\partial \gamma^G}{\partial n} = A^{-1} \frac{-P'(x^B - x^G)}{(n+1)P' + P''X} \frac{X}{n} \left[2P' + P''(x^G + x^B) \right] \geq 0 \tag{21}$$

where $A = \partial \Delta(F, \gamma^G) / \partial \gamma^G > 0$.

We summarize our results in:

Lemma 3 *1) For $c' > 0$, the share of firms in the industry that adopt the green technology γ^G is (weakly) increasing in the level of the expected fine and in the number of firms.*
2) For $c' = 0$, the share of firms in the industry that adopt the green technology γ^G is (weakly) increasing in the level of the expected fine, whereas it is independent of the number of firms in the industry.

The basic rationale for the introduction of a positive expected fine for firms convicted of producing with the brown technology is that it will induce more firms to opt for the green technology. This intuition is confirmed by condition (20). The influence of the number of firms for the scenario in which $c' > 0$ is also intuitive. More firms in the industry means smaller market shares for both brown and green firms. As a result, the price-cost margin benefit that results for brown firms is of less importance.[9] This latter factor has repercussions on the critical levels of the expected fine as follows:

Lemma 4 *Both critical fines F_0 and F_c are decreasing in the number of firms when $c' > 0$.*

Proof. This claim follows from an argument similar to that put forward in the proof of Lemma 2 when evaluating, for example, $dF_0/dn = P'\partial X/\partial n(x^B - x^G) - P'(x^B \partial x^B/\partial n - x^B \partial x^B/\partial n) < 0$. There is not an additional influence of n via γ^G, because the two fines apply to both $\gamma^G = 0$ and $\gamma^G = 1$. ■

Lemma 4 states that the policy instrument of an expected fine for non-compliance with the design standard is effective even at lower levels when there are more firms in the industry. In other words, policy makers must take into account the fact that the expected fine may be less effective in scenarios with fewer competitors.

4.3 Stage 2: Firms decide whether or not to enter the industry

Firms determine whether or not to enter the industry without knowing their level of adoption costs α. This feature of the model reflects some real-world issues; for example, understanding the training requirements for implementing a more advanced production technology requires the acquisition of knowledge specific to the industry. These costs may be firm-specific due to differences in location, which could (via the regional labor market) affect firms in an imperfectly predictable manner. Firms will enter the industry up to the point at which the expected profits

[9] This effect does not exist for $c' = 0$.

are equal to the entry costs. As a result, the following condition defines the equilibrium number of firms:

$$\Pi = \gamma^G \left[P(X)x^G - c^G x^G\right] - \int_0^{\gamma^G} \alpha d\alpha + (1-\gamma^G)\left[P(X)x^B - c^B x^B - F\right] = K, \tag{22}$$

where γ^G either solves $\Delta = 0$ or is equal to one (zero) when $\Delta(F,1) < 0$ ($\Delta(F,0) > 0$).

The endogenous number of firms determined by (22) is influenced by changes in the level of the expected fine. This relationship can be described by

$$\frac{dn}{dF} = -\frac{\partial\Pi/\partial F}{\partial\Pi/\partial n}, \tag{23}$$

where

$$\frac{\partial\Pi}{\partial n} = P'\left(\frac{\partial X}{\partial n} + \frac{\partial X}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial n}\right)\frac{X}{n} - \sum_{j=B,G} P' x^j \gamma^j \left(\frac{\partial x^j}{\partial n} + \frac{\partial x^j}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial n}\right) \tag{24}$$

$$\frac{\partial\Pi}{\partial F} = -(1-\gamma^G) + P'\frac{\partial X}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial F}\frac{X}{n} - \sum_{j=B,G} P' x^j \gamma^j \frac{\partial x^j}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial F}. \tag{25}$$

The expected profits of a potential entrant decrease in the number of firms, which can be shown as follows. Total output increases in n, since

$$\frac{\partial X}{\partial n} + \frac{\partial X}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial n} = \frac{P'X}{n\left(P''X + P'(n+1) - nP'(x^B - x^G)^2(2P' + P''(x^B + x^G))\right)} > 0. \tag{26}$$

When total output increases due to a higher number of firms, individual output must decrease (according to the requirement imposed by the firms' first-order conditions). As a result, a higher number of firms in the industry implies lower expected profits (i.e., term (24) is negative). In contrast, the influence of the level of the expected fine on the level of firms' expected profits is ambiguous. The direct effect is negative and is more important for low levels of γ^G. The indirect effect means that a higher share of green firms will increase expected profits (i.e., make entry more attractive) due to the implied lower level of total output. A variation in the level of the expected fine will have repercussions that depend greatly on the level of the fine, as described in the following lemma.

Lemma 5 *1) For $F \in [0, F_0)$, the number of firms decreases in the level of the expected fine for non-compliance with the design standard.*
2) For $F \in [F_0, F_c)$, it is unclear whether or not the number of firms in the industry decreases

when the expected fine increases.

3) For $F \geq F_c$, the number of firms does not respond to changes in the level of the expected fine.

Proof. The claim uses (23) and the fact that (22) is independent of F when $\gamma^G = 1$. ■

It is interesting to compare Lemma 5 to Lemma 2. Whereas the adoption of the technology cannot be incentivized unless the expected fine is at least as high as F_0, the number of firms is depressed by a marginal increase in F even at very low levels of the expected fine.

4.4 Stage 1: Policy maker sets the level of the expected fine

The policy maker determines the circumstances under which decentralized decision-makers interact. In the present setting, the policy maker announces the level of the expected fine that will be assessed should a firm opt to employ the brown technology. The firms then decide upon entry, technology adoption, and output levels. With regard to firms' decisions, the previous analysis allows the following compact statement of equilibrium levels for different values of the expected fine:

$$n = n(F) \tag{27}$$

$$\gamma^G = \gamma^G(F, n(F)) \tag{28}$$

$$x^j = x^j(\gamma^G(F, n(F)), n(F)). \tag{29}$$

Regarding the signs, Lemma 5 stated that dn/dF cannot be signed for intermediate levels of the expected fine, which might be expected to have repercussions on signing the total effects for the other variables of interest as well:

$$\frac{d\gamma^G}{dF} = \underbrace{\frac{\partial \gamma^G}{\partial F}}_{(+)} + \underbrace{\frac{\partial \gamma^G}{\partial n}}_{(+)} \frac{dn}{dF} \tag{30}$$

$$\frac{dx^j}{dF} = \underbrace{\frac{\partial x^j}{\partial \gamma^G}\frac{\partial \gamma^G}{\partial F}}_{(+)} + \left[\underbrace{\frac{\partial x^j}{\partial \gamma^G}\frac{\partial \gamma^G}{\partial n}}_{(+)} + \underbrace{\frac{\partial x^j}{\partial n}}_{(-)} \right] \frac{dn}{dF}. \tag{31}$$

The overall effect of a change in the level of the expected fine on the share of firms adopting the green technology consists of a positive direct effect and a second (potentially negative) indirect effect that acts via the number of firms. When a higher expected fine for non-compliance decreases the number of firms in the industry, this represents a disincentive for adoption of the green technology. Making use of the terms derived above, we can state

$$\frac{d\gamma^G}{dF} = \frac{x^G\left(2P' + x^G P''\right)}{2P'\frac{X}{n} + \left((x^B)^2(1-\gamma^G) + (x^G)^2\gamma^G\right)P''} > 0, \tag{32}$$

such that a higher expected fine always induce a greater share of firms to adopt the green technology.

The privately optimal level of output is not directly affected by the level of the expected fine for a given choice of technology. However, the optimal output of all firms is clearly influenced by the number of firms in the industry and the share of green firms (which is also affected by the number of firms); both of these factors change with the level of the expected fine. Making use of the terms derived above, we can state

$$\frac{dx^j}{dF} = -\frac{\gamma^j\left(P' + x^j P''\right)}{P'\left(2P'\frac{X}{n} + \left((x^B)^2(1-\gamma^G) + (x^G)^2\gamma^G\right)P''\right)} > 0, \tag{33}$$

such that a higher expected fine always induces higher output levels by a firm of type j.

We summarize in Lemma 6.

Lemma 6 *An increase in the expected fine induces a greater share of firms to adopt the prescribed technology and an increase in output per firm.*

Proof. The claims follow directly from (32) and (33). ■

Next, we turn to optimal policy in the current setting. The policy maker sets the level of the expected fine, where a change in the level of the expected fine influences the level of welfare thus:

$$\frac{dW}{dF} = \frac{\partial W}{\partial \gamma^G}\frac{d\gamma^G}{dF} + \frac{\partial W}{\partial n}\frac{dn}{dF} + \sum_{j=B,G}\frac{\partial W}{\partial x^j}\frac{dx^j}{dF} - \psi'(F) \tag{34}$$

where $\psi' \geq 0$, $\psi'(0) = 0$ represents marginal enforcement costs and the partial derivatives of welfare are found in (2)-(4).[10]

For $F \in \mathcal{F} = [F_0, F_c)$, we can evaluate this derivative at the equilibrium levels of the number of firms in the industry described by (22), the equilibrium technology adoption rate that follows

[10] We assume that the fine is pure redistribution, following the standard assumption of the economics of crime (see, e.g., Polinsky and Shavell 2007).

from (17), and the privately optimal levels of output as determined by (10) to obtain

$$\frac{dW}{dF} = \underbrace{\left[D'(f^B - f^G) - F\right]}_{(i)} \frac{d\gamma^G}{dF} + \underbrace{\left[(1-\gamma^G)F - D'(E)E/n\right]}_{(ii)} \frac{dn}{dF}$$
$$+ \sum_{j=B,G} \underbrace{\left[-P'x^j - D'(E)\frac{\partial f^j}{\partial x}\right]}_{(iii)} \frac{dx^j}{dF} - \psi'(F). \tag{35}$$

The restriction regarding $F \in \mathcal{F}$ is relevant for (35) because we substitute using $\Delta = 0$, which does not apply outside of this interval.

The share of green firms γ^G, which may be considered the primary policy target of an expected fine for non-compliance with a design standard, is unaffected by changes in the expected fine as long as the expected fine is smaller than F_0. In this range, a marginal increase in F implies that the number of firms decreases, which in turn implies that the output per firm increases (while total output decreases).

The policy maker who determines the expected fine (focusing only on the firms' decisions with respect to the adoption of the green technology) will choose $F_1 = D'(E)(f^B - f^G)$ when $F_1 \in \mathcal{F}$. This is the level of the expected fine that implies that the term (i) is equal to zero, such that the expected fine mirrors the externality arising from a firm's decision between the two technologies (given by the increase in environmental harm due to $f^B > f^G$).

As long as $F \leq F_c$, the level of the expected fine is also an instrument that directly influences the number of firms, as random adoption costs ensure that each potential entrant considers the possibility of disobeying the design standard (see term (ii)). Our framework considers Cournot competition with homogeneous goods; consequently, we can expect the number of firms to be excessive when $F = 0$ (Mankiw and Whinston 1986). When $dn/dF < 0$, the policy maker focusing only on the number of firms in the industry for given levels of the other variables would have to set $F_2 = D'(E)E/n(1-\gamma^G)^{-1}$ when $F_2 \in \mathcal{F}$. An additional firm imposes more pollution on society, a harm that the firm does not internalize. However, the firm incorporates the expected fine with the ex-ante probability for non-compliance $(1-\gamma^G)$; thus, the fine may be used to influence the firm's decision-making. Note that $F_1 \leq F_2$ holds.[11] Consequently, term (i) is positive and (ii) is negative when $F \in [F_0, F_1)$. It is difficult to relate F_1 and F_2 to the level of F_c (which implies full adoption and therefore nullifies the influence of the fine on the equilibrium number of firms), as the external harm is completely unrelated to firms' decisions.

[11] $F_1 \leq F_2$ simplifies to $f^G \geq 0$.

The level of the expected fine does not have a direct bearing on the levels of output selected by brown and green firms. However, there is an indirect influence as detailed in (31). The privately optimal level of output differs from the socially optimal one contingent on the technology selected for two reasons (as has already been elaborated for the case of the monopolistic polluter in Barnett 1980). First, firms have market power and consider marginal revenue to differ from the marginal willingness to pay (i.e., due to $P'x^j < 0$). Second, firms do not incorporate the adverse societal repercussions of the increase in environmental harm that results from higher output. These two influences are decisive in term (iii). The role of the two influences will depend on a firm's type (green or brown), given that both x^G and x^B as well as $\partial f^G/\partial x$ and $\partial f^B/\partial x$ are different. When the distortion due to market power is more critical, then the policy maker seeks to induce an increase in the level of output. Alternatively, when the distortion due to pollution is more critical, then the policy maker seeks to induce a decrease in the level of output. Given the sign established in (33), this objective may call for either a low or high expected fine.

Proposition 1 *Assume that $[F_1, F_2] \subseteq \mathcal{F}$ and $dn/dF < 0$. Then, increasing the level of the expected fine in the range $[F_0, F_1)$ to $F_1 = D'(f^B - f^G)$ yields welfare benefits with respect to the number of firms in the industry and the number of firms adopting the green technology. Increasing F in the range $[F_1, F_2)$ yields welfare benefits with respect to the number of firms in the industry, while implying a decrease in welfare resulting from the excessive number of firms induced to adopt the green technology. Any increase in the expected fine above F_2 is costly with respect to both n and γ^G (up to $F = F_c$).*

Proof. The claims follow from (35). ■

In the above analysis, the policy maker has utilized one policy instrument only, despite having different policy targets in mind. Tinbergen (1952) argues that each policy target usually requires its own instrument, although this is often infeasible in practice. Accordingly, we now give the policy maker a second instrument; this allows us to briefly compare the above scenario to a setting in which the policy maker can determine both the level of the environmental fine and the number of firms (e.g., via licenses for participation in the industry). We obtain

$$\gamma^G = \gamma^G(F, n) \tag{36}$$

$$x^j = x^j(\gamma^G(F, n), n), \tag{37}$$

where $\partial\gamma^G/\partial F > 0$, $\partial\gamma^G/\partial n > 0$, and

$$\frac{dx^j}{dF} = \underbrace{\frac{\partial x^j}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial F}}_{(+)} \tag{38}$$

$$\frac{dx^j}{dn} = \underbrace{\frac{\partial x^j}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial n}}_{(+)} + \underbrace{\frac{\partial x^j}{\partial n}}_{(-)} \tag{39}$$

for an interior adoption rate. Similar to our previous statement for dx^j/dF, the change is unambiguous when the policy maker determines both the fine and the number of firms. The effect of an increase in the number of firms regarding output of a firm using technology j is negative, i.e., the direct effect dominates the indirect effect that works via the adoption rate. This follows from the argument presented for (23).

The policy maker must consider the following marginal influences on welfare when determining the level of the expected fine and the number of firms in the industry:

$$\frac{dW}{dF} = \frac{\partial W}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial F} + \sum_{j=B,G}\frac{\partial W}{\partial x^j}\frac{dx^j}{dF} - \psi'(F) \tag{40}$$

$$\frac{dW}{dn} = \frac{\partial W}{\partial\gamma^G}\frac{\partial\gamma^G}{\partial n} + \sum_{j=B,G}\frac{\partial W}{\partial x^j}\frac{dx^j}{dn} + \frac{\partial W}{\partial n}, \tag{41}$$

with the partial derivatives of welfare found in (2)-(4).

When we evaluate (40) and (41) for $F \in \mathcal{F}$ at the equilibrium technology adoption rate that follows from (17) and the privately optimal levels of output as determined by (10), we obtain

$$\frac{dW}{dF} = \underbrace{\left[D'(f^B - f^G) - F\right]}_{(i)}\frac{\partial\gamma^G}{\partial F} + \sum_{j=B,G}\underbrace{\left[-P'x^j - D'(E)\frac{\partial f^j}{\partial x}\right]}_{(ii)}\frac{dx^j}{dF} - \psi'(F) \tag{42}$$

$$\begin{aligned}\frac{dW}{dn} &= \underbrace{\left[D'(f^B - f^G) - F\right]}_{(i)}\frac{\partial\gamma^G}{\partial n} + \sum_{j=B,G}\underbrace{\left[-P'x^j - D'(E)\frac{\partial f^j}{\partial x}\right]}_{(ii)}\frac{dx^j}{dn} \\ &\quad + \underbrace{\left[(1-\gamma^G)F - D'(E)\Big(\sum_{j=B,G}\gamma^j f^j\Big)\right]}_{(iii)}.\end{aligned} \tag{43}$$

In this setting, the policy maker has two policy instruments. However, there are still more policy targets than instruments. As becomes clear from (42), the policy maker will choose the level of the expected fine based on its impact on both the adoption rate and the private output choice. The level that best serves the policy maker's objective when there is direct control over the number of firms in the industry will generally differ from the policy maker's optimal level when the number of firms results from decentralized choices. The condition (43) illustrates the fact that the policy maker also uses the number of firms in the industry in order to address the other policy targets; the adequate use of the green technology (see term (i)) and output per firm (see term (ii)).

These numerous channels and our interest in keeping our model relatively general has meant that some of the results from the analysis detailed above remain ambiguous. In the next section, we follow the lead of Besanko (1987) and simplify our setting by imposing some standard assumptions regarding, for instance, demand. This allows us to arrive at more concrete conclusions.

5 Results for a functional specification

In this section, for illustrative purposes, we provide a concrete example by applying standard simplifying assumptions. Regarding demand, we consider a linear schedule given by $P(X) = a - X$. With respect to the two technologies available and their respective impacts on pollution, we assume $f^G = (x^G/10,000)^2$ and $f^B = (2x^B)^2$. This specification ensures a sizable difference in the implied level of pollution when the green technology is selected. The total level of pollution $E = n\sum_{j=B,G}\gamma^j f^j$ translates into environmental harm according to $D(E) = E^2/10$.

5.1 Stage 5: Determination of output

The profit maximization of firms at stage 5 yields the following output levels

$$x^G = \frac{a - c^G - n(1-\gamma^G)\Delta c}{n+1} \tag{44}$$

$$x^B = \frac{a - c^B + n\gamma^G\Delta c}{n+1}, \tag{45}$$

where $\Delta c = c^G - c^B$; thus, brown firms produce more when $c' > 0$, where the difference $x^B - x^G$ reduces to $c^G - c^B$ (i.e., this difference is independent of the number of firms and the share of green firms, as demand is linear in total output). Moreover, we obtain the intuitive predictions that we have already established in the general analysis, namely, $\partial x^j/\partial n < 0$ and, for the case of $c' > 0$, $\partial x^j/\partial \gamma^G > 0$.

5.2 Stage 4: Production technology choice

In stage 4, firms can choose between compliance and non-compliance with the design standard, i.e., between adopting the green or the brown production technology. The critical term for a firm's trade-off is

$$\Delta(F,\alpha) = \frac{2\Delta c(a - n\sum_{j=B,G} c^j\gamma^j)}{n+1} - F + \alpha \tag{46}$$

When $c' = 0$, the trade-off between adopting the brown technology and the green one thus simplifies to the difference between adoption costs and the expected fine. A firm with realized adoption costs γ^G is indifferent between the two technologies when $\Delta(F,\gamma^G) = 0$. The adoption rate that solves $\Delta(F,\gamma^G) = 0$ is given by

$$\gamma^G = \frac{(c^G)^2 - (c^B)^2 - 2a\Delta c + F + ((\Delta c)^2 + F)\,n}{1 + (1 + 2(\Delta c)^2)\,n}, \tag{47}$$

such that the critical levels of the expected fine for no adoption and full adoption become

$$F_0 = \frac{\Delta c(2a + (n-1)c^B - (n+1)c^G)}{n+1} \tag{48}$$

$$F_c = 1 + \frac{\Delta c(2a + (n-1)c^G - (n+1)c^B)}{n+1}. \tag{49}$$

This clearly indicates that $F_c - F_0 \neq 1$ for $c' > 0$.

We obtain the following comparative-statics results for the adoption rate when starting from $\Delta = 0$:

$$\frac{\partial\gamma^G}{\partial F} = \left[1 + \frac{2(\Delta c)^2 n}{n+1}\right]^{-1} > 0 \tag{50}$$

$$\frac{\partial\gamma^G}{\partial n} = \frac{2\Delta c(a - \sum_{j=B,G} c^j\gamma^j)}{(n+1)\{1 + n(1 + 2(\Delta c)^2)\}} \geq 0. \tag{51}$$

5.3 Stage 2: Firms decide whether or not to enter the industry

In stage 2, firms facing fixed entry costs K and the distribution of adoption costs determine whether or not to enter the industry. For the present example, we obtain

$$\Pi = \frac{\gamma^G(a - c^G - \Delta c(1-\gamma^G)n)^2}{(n+1)^2} - \frac{(\gamma^G)^2}{2} + \gamma^B\left[\frac{(a - c^B + \Delta c\gamma^G n)^2}{(n+1)^2} - F\right] = K. \tag{52}$$

When we insert the γ^G defined in (47) into this equation, we can derive the total effect of changes in the level of the expected fine for the equilibrium number of firms:

$$\frac{dn}{dF} = \frac{\left(1 + \left(1 + 2(\Delta c)^2\right)n\right)\left((c^G)^2 - (c^B)^2 - 2a\Delta c - 1 + F - \left(1 + (\Delta c)^2 - F\right)\{2n + \left(1 + 2(\Delta c)^2\right)n^2\}\right)}{2\left(c^B - a\left(1 + 2(\Delta c)^2\right) + \Delta c\left((c^G)^2 - (c^B)^2 + F\right)\right)^2}. \tag{53}$$

This cannot be unambiguously signed in the present example, as was true in our general analysis. (We will present a graphical depiction of n as a function of F for specific parameter values below; see Figure 2.) This obviously contrasts with the scenario in which there are no adopting firms; in such a case, the influence of a higher level of the expected fine would clearly be negative.

5.4 Stage 1: Policy maker sets the level of the expected fine

The policy maker decides on the level of the one policy instrument available (i.e., the level of the expected fine for non-compliance with the design standard), thereby potentially affecting the decisions made by firms regarding whether or not to enter the industry, which technology to adopt, and how much output to produce.

With regard to the level of social welfare, we can simplify the expression using condition (22). A firm's expected profits are equal to its entry costs K, where expected profits include the deduction of $(1-\gamma^G)F$. The latter does not represent social costs, as we maintain the commonly used assumption that fines are pure transfers. As a result, we can state welfare as consumer surplus less environmental harm, adding expected fine revenue (thereby correcting for its subtraction from firms' expected profits):

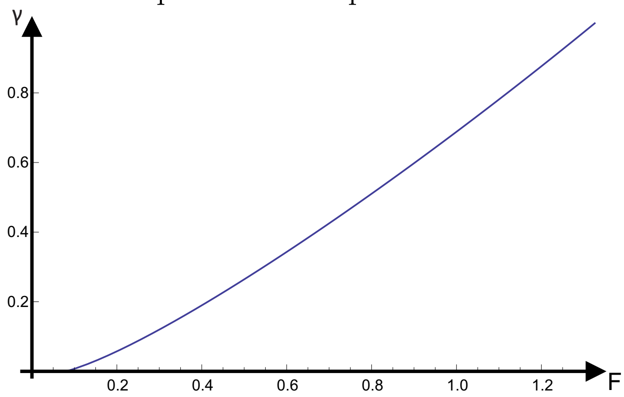
$$W = \frac{X^2}{2} - D(E) + n(1-\gamma^G)F. \quad (54)$$

For simplicity, we abstract from enforcement costs ψ.

In order to present a numerical illustration, we assume that $c^G = 1/5$ and $c^B = 0$, and set a to 100. In the following example, we describe how welfare and key variables respond to changes in the level of the expected fine.

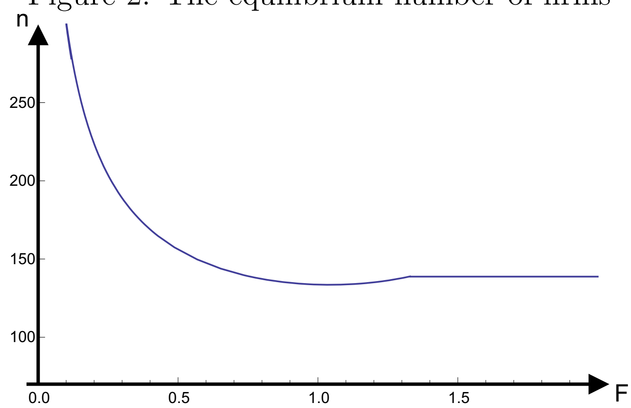
As argued above, low levels of the expected fine for non-compliance with the design standard cannot motivate adoption. In our numerical example, the expected fine can be increased up to $F_0 = 2/25$ before any firms will start to use the green technology. Even though the increase in the expected fine in this range has no impact on the share of green firms (which is equal to zero), it changes the industry outcome via its influence on *de facto* entry costs. When the expected fine is sufficiently low, all firms plan to disregard the design standard, such that *de facto* entry costs consist of K plus F. Next, there is a range in which an interior adoption rate results (as shown in Figure 1). All firms in the industry will adopt the green technology when the expected fine is at least as high as $F_c = (26+\sqrt{51})/25 > 1$. From there onwards, an increase in the expected fine does not change the market outcome. The equilibrium adoption rate is illustrated in Figure 1.

Figure 1: The equilibrium adoption rate in the range $\mathcal{F}$



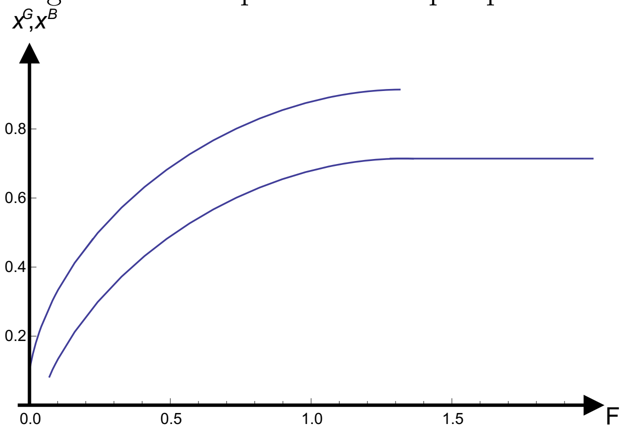
The number of firms is decreasing with the level of the expected fine when all firms in the industry choose non-compliance with the design standard. This is a necessary outcome for marginal changes in F where the expected fine still remains below F_0. Figure 2 shows that starting at F about equal to one, the number of firms is indeed increasing with the level of the expected fine. As our general analysis indicated, this can be attributed to the output contraction resulting from the higher share of green firms.

Figure 2: The equilibrium number of firms



Total output is decreasing everywhere with the level of the expected fine until F_c is reached. In contrast, individual output is increasing with the level of the fine (see Figure 3). Initially, this is only due to the decreasing number of firms in the industry. At F_0, some firms start producing only x^G instead of x^B. This reinforces the dampening effect on total output already present via the channel of firms in the industry. At F_c, the level of x^G is equal to the level of firm output that is applicable for all higher levels of the expected fine as well. Figure 3 illustrates x^B (the upper curve) and x^G, where applicable.

Figure 3: The equilibrium output per firm

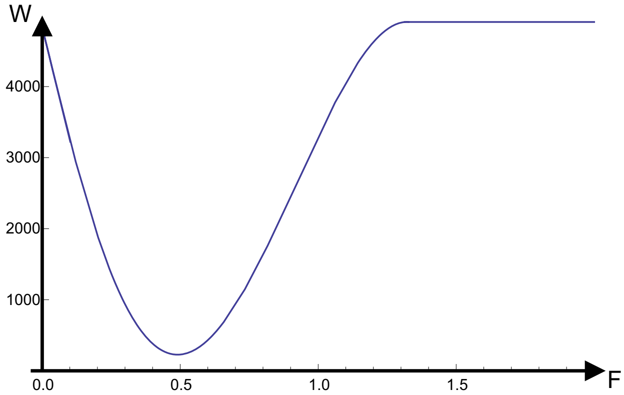


All things considered, we find that inducing adoption of the green technology by all firms is preferable for the policy maker in our example (see Figure 4). The policy maker still prefers to induce adoption of the green technology when the implementable adoption rate is high. However, when this cannot be achieved (e.g., because such fines are not possible for some legal reason), we find that the scenario in which the level of the expected fine remains at zero is desirable. Indeed, there is a range of levels for F in which a marginal increase in the level of the expected fine is harmful to society. This finding can be traced back to the fact that initially consumer surplus decreases and environmental harm increases in response to marginal increases in F. Whereas the influence on consumer surplus is a direct consequence of the downward trend in total output, the implied change in the level of environmental harm is more complex, resulting from the convexity of the level of firm pollution. The increase in F lowers n; thus, total output is split up among fewer firms leading to higher pollution.

6 Conclusion

Firms continue to harm the environment on a grand scale. Recent policy initiatives in the European Union seek to allow for an increase in the level of fines that a policy maker can impose. The present paper considers the consequences of increasing the expected fine for non-compliance with a design standard in a framework with Cournot competition, technology adoption, and free entry. In such a setting, the welfare consequences of marginal increases

Figure 4: The level of welfare as a function of the expected fine for non-compliance



in the level of the expected fine are complex and may in reality be difficult to predict. The relationships between the level of the fine and the number of firms in the industry, the share of compliant firms, and the output levels of both compliant and non-compliant firms may result in potentially counterintentional repercussions, such as an increase in the level of environmental harm and a decrease in the overall level of welfare.

This paper presents a first exploration of the results of a comparative-statics analysis of the expected fine for non-compliance with an environmental standard in an admittedly simple framework. For example, we consider consumers who do not distinguish between firms based on their production technology. While presumably this is true for the majority of consumers, there is an increasing awareness among some consumers of the conditions under which firms produce. In another regard, our analysis simplifies by assuming that the environmental protection agency does not use market data to tailor its enforcement policy. If that were the case, firms employing the brown technology might have to obscure this by choosing a level of output other than the profit-maximizing level. Such factors may aid enforcement as well as improve environmental quality. These and other interesting considerations are left for future research. Needless to say, adding such complexities to the framework will make it even more difficult to judge whether or not a marginal increase in environmental fines can be expected to be welfare-increasing.

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