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The Impact of Environmental Taxes on Firms' Technology and Entry Decisions

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The Impact of Environmental Taxes on Firms' Technology and Entry Decisions*

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Abstract

This paper investigates conditions under which the regulator can strategically set an emission fee as a tool to induce firms to adopt a green technology and, also, promote (or hinder) entry deterrence. We consider a market in which a monopolistic incumbent faces the threat of entry, and firms can choose between a dirty and a green technology. Our results show that, despite the fact of facing a polluting incumbent, an entrant might find it profitable to join the market and acquire a clean technology if the environmental tax is stringent enough and the technology is effective eliminating pollution. We also demonstrate that a duopoly, in which all firms acquire green technology, is socially optimal if the technology cost is low and the environmental damage is sufficiently high. However, if the environmental damage is low, a partially clean duopoly (in which only one firm adopts the green technology) is socially optimal under less restrictive conditions on the cost of clean technology.

KEYWORDS: Technology Adoption; Market Structure; Emission tax.
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1 Introduction

An increasing concern for the negative effects of pollution has induced governments and firms to consider the adoption of clean technologies (also referred as green technologies).[1] Environmental regulation in this matter is a keystone tool for the development and acquisition of this type of technology. Hence, the analysis and understanding of policy schemes that promote the investment in clean technologies are of great importance for the solution of several environmental problems. For instance, Popp (2002) argues that emission fees can promote the development of less costly pollution control technologies. Stern (2007) also suggests that carbon pricing provides incentives to invest in new abatement technologies. However, the setting of environmental policies could generate several distortions; such as hindering domestic firms' competitiveness or deter entry. As a consequence, the regulator must take into account those effects when designing an optimal regulation. Only few studies, nevertheless, have analyzed environmental regulation when firms are considering the adoption of a new technology and, in addition, they face the threat of entry.

We study an entry-deterrence model where a regulator sets an environmental tax and an incumbent and an entrant decide their type of technology. Specifically, we investigate the case in which two different technologies are available: an environmentally friendly (green) technology and a dirty technology. The clean technology is assumed to have different degrees of effectiveness in reducing pollution. This setting is relevant, for example, to the coal mining industry which often faces the dilemma of acquiring new equipment to make their plants less polluting or keeping the conventional technology, while being regulated for its emissions.[2]

The paper, hence, analyzes a four-stage complete information game. In the first and the second period, the regulator sets an emission tax and the incumbent responds selecting a type of technology, respectively. In the third period the potential entrant, after observing the regulator's and incumbent's action, decides whether to join the market and its technology. Finally, if entry ensues, both firms compete in a Cournot game; otherwise the incumbent continues to operate as a monopolist. We first examine how entry decisions and entrant's technology are affected by the emission tax and the incumbent's type of technology. In particular, if the incumbent keeps its dirty technology, emission fees are more likely to deter entry when the clean technology available to the potential entrant is not sufficiently effective eliminating pollution. Hence, an environmental regulation accompanied by an early-stage green technology may help the incumbent to keep its monopolistic position. However, an environmental tax does not promote entry deterrence when the technology available is in an

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[1] For instance, the Clinton administration established the Environmental Technology Initiative in 1993 in order to promote green technology adoption and more competitive businesses.

[2] This industry must comply with, among others, the Clean Air Act, the Clean Water Act and the Toxic Substances Control Act. In addition, according to IBISWorld analyst, B. Bueno, the industry concentration has increased over the past five years (PRWEB, July 06, 2012).

advanced stage of development and, hence, it is able to capture a significant proportion of pollutants. In this case, despite facing a dirty incumbent, the entrant is more likely to join the market and acquire a clean technology.

If the incumbent has a green technology, it is more likely to deter entry when an environmental regulation is in place. Although stringent emission fees can support entry deterrence under certain cases, it does not necessarily induce the entrant to acquire a green technology. In fact, the entrant's decision about adopting a clean technology depends on its effectiveness in reducing emissions and, also, its cost. Moreover, we find that the adoption of a green technology by the incumbent triggers the acquisition of such a technology by its competitor. That is, a potential entrant that has decided to join the market is more likely to adopt a clean technology when it faces a green incumbent than otherwise.

We also evaluate social welfare under different contexts of environmental deterioration. Our welfare comparisons suggest that when the environmental damage is sufficiently high and the cost of a partially clean technology is low, the entry of a clean competitor is always welfare improving. Our findings, hence, indicate that the presence of a potential entrant that can be induced by the environmental regulation to acquire a green technology makes the regulator less willing to facilitate the incumbent's entry-deterring practices. In addition, if the environmental damage is relatively low, a partially green duopoly is socially preferred than a completely dirty duopoly. Intuitively, the reduction of the moderate environmental damage by one green firm compensates the loss in producer surplus, since the incumbent adopts a green technology. Therefore the regulator should evaluate emission fees and, in particular, their effects on the market structure and the acquisition of clean technologies, depending on how severe the environmental damage is.

Studies over the last decades have analyzed firms' incentives to invest in abatement technologies, due to environmental regulations. A well-designed environmental policy can stimulate the adoption of new technologies that reduce marginal emissions or save abatement costs (Porter and van der Linde 1995; Requate 2005; Perino and Requate 2012). Several authors have demonstrated that firms' incentives to adopt clean technology differ across market structures and policy instruments. They have also analyzed the optimal environmental policy scheme that generates the most incentives (see Katsoulacos and Xepapadeas 1996; Montero 2002; and Requate and Unold 2003). The incentives to acquire clean technologies are also affected by the stringency of the environmental policy. A traditional conclusion is that such incentives increase monotonically with regulation stringency (Requate and Unold 2003). However, Perino and Requate (2012) point out that there exists an inverted U-shaped relationship between the policy stringency and the rate of clean technology adoption. Among different environmental regulations, it is well known that market-based instruments are preferred by economists and widely implemented in many countries (Requate, 2005). Specifically, emission fees are an effective instrument in providing incentives to acquire a new abatement technology in perfectly competitive markets (Parry 1998) as well as in oligopolistic markets (Montero 2002). Amacher and Malik (2002) analyze pollution taxes when firms face discrete technology choices. Similarly, our paper examines how an appropriate emission fee induces firms to adopt a clean technology. However, unlike the previous literature, we focus on an entry-deterrence model rather than markets that do not face entry threats.

Environmental regulation, in an entry-deterrence game, strategically affects firms' entry decision and, hence, market structure. From the regulator's perspective, environmental policy is a tool that can create barriers to entry. Early studies have examined how a stringent emission quota acts as an effective instrument in leading to cartelization (Buchanan and Tullock 1975; Maloney and McCormick 1982; Helland and Matsuno 2003). An article survey conducted by Heyes (2009) also concludes that environmental regulations help incumbents to discourage entry and thus reduce market competition. However, few papers have analyzed entry deterrence in the case of an emission tax. Schoonbeek and de Vries (2009) examine the effects of emission fees on firms' entry in a complete information context and Espínola-Arredondo and Muñoz-García (2013) analyze a setting of incomplete information. Both studies identify conditions under which the regulator protects a monopolistic market by setting an emission fee that deters entry.[3] However, they consider technology as given. Our paper is not only concerned about the role of emission fees hindering competition, but also examines firms' technology choices by considering that there is a green technology available to both the incumbent and the entrant. This approach allows us to identify cases in which the regulator sets emission fees that do not support entry deterrence.

The paper is organized as follows. Section 2 describes the model and the structure of the game; section 3 examines the equilibrium of the game and section 4 investigates social welfare under different contexts; section 5 concludes and discusses extensions.

2 Model

Consider a market in which there is a monopolistic incumbent (firm 1) and a potential entrant (firm 2). Both firms produce a homogeneous good. The output level of firm i is denoted as q_i, where $i = 1, 2$. The inverse demand function is assumed to be $p(Q) = a - bQ$, where a, $b > 0$ and Q is the aggregate output level. If firm 2 decides to enter it must incur a strictly positive fixed entry cost, F. For simplicity assume that production is costless.

Two different types of technology are available for both firms: a dirty (D) and a green (G) technology. Each firm can be a "dirty" type or a "green" type based on its technology decision. We assume that firms currently have a dirty technology and, hence, if they adopt a green technology they must pay a fixed cost equal to $S \in \mathbb{R}_+$. Technologies differ in terms of their emissions,

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[3] Mason and Swanson (2002) investigate a model in which the incumbent possesses patents and faces the possibility of entry under a MAC-PSB regulation. They show that a patent-holding incumbent can take advantage of such regulation to deter entry.

which are assumed to be proportional to output levels.[4] In particular, if firm i acquires a clean technology its total emission level is $E_i = \theta e q_i$, where $e \in (0, \infty^+)$ and $\theta \in (0,1)$ describes the efficiency of the new technology in reducing emissions. Specifically, the green technology becomes more efficient with lower values of θ, and it is completely free of pollution when $\theta = 0$. However, if firm i keeps its dirty technology then $\theta = 1$ and $E_i = eq_i$. Environmental damage, Env, is assumed to be a linear function of aggregate emissions, that is $Env = d \sum_{i=1,2} E_i$, where $d > 0$ captures the environmental deterioration.

The regulator sets a tax rate per unit of emission. In particular, it selects an emission fee τ that maximizes overall social welfare denoted as $W = PS + CS + T - Env$, where PS and CS are the producer and consumer surplus, respectively, and T is the total tax revenue. Firms' technology choices are influenced by the emission fee. Hence, each firm faces the trade-off between the cost of the tax (which is higher when a firm uses the dirty technology) and the fixed investment in green technology.

We solve a four-stage complete information game, in which the time structure is as follows:

- In the first period, the regulator sets an optimal tax.
- In the second period, the incumbent chooses its technology.
- In the third period, the potential entrant decides whether or not to enter and, if it enters, which technology to use.
- In the fourth period, if entry is deterred, the incumbent operates as a monopolist. If entry occurs, however, both firms play a Cournot game.

We derive the subgame-perfect Nash equilibrium. Specifically, in the following sections, we first investigate two different market structures and output levels in the fourth period, we then examine firm 2's decision over entry and technology in the third period. We also discuss the incumbent's technology choice and, finally, we analyze the first period game by identifying the optimal emission fee as well as the resulting social welfare.

3 Subgame Perfect Nash Equilibrium

3.1 Fourth stage

Let us first examine the case in which the potential entrant stays out of the market.

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[4] Porter and van der Linde (1995) demonstrate that environmental technologies basically have two forms: (1) the type of technology that deals with polluting emissions more efficiently and effectively and thus reduces compliance costs when regulation is imposed; and (2) the technological innovation that not only solves the environmental problem but also improves productivity. We here focus on the first form of technology.

3.1.1 No entry

If entry does not ensue, firm 1's equilibrium output level is denoted by $q_1^{m,j}$, where superscript m represents monopoly and $j = D, G$ is the firm's technology. Table 1 describes the equilibrium results for this case.

Table 1. Output levels and profits under monopoly

Firm 1's type	**D**	**G**
Output	$q_1^{m,D} = \frac{a-\tau e}{2b}$	$q_1^{m,G} = \frac{a-\tau\theta e}{2b}$
Profit	$\pi_1^{m,D} = \frac{(a-\tau e)^2}{4b}$	$\pi_1^{m,G} = \frac{(a-\tau\theta e)^2}{4b} - S$

In order to guarantee that firm 1 produces strictly positive output levels the emission fee must be $\tau < \frac{a}{e}$ if it keeps its dirty technology, and $\tau < \frac{a}{\theta e}$ if firm 1 acquires a green technology. Note that we consider a nonnegative emission tax all through the paper and thus assume $\tau \geq 0$. It is apparent that imposing an emission tax reduces output levels and profits. However, a green monopolist produces more units than a dirty one and its profits depend on the characteristics of the clean technology.

3.1.2 Entry

Let $q_i^{d,jk}$ denote the equilibrium output level of firm i when both firms compete. The superscript d denotes a duopoly market and the superscript jk represents the case in which firm 1 chooses technology j and firm 2 decides to use technology k, where $j, k = \{D, G\}$. Four possible cases can arise (D, D), (D, G), (G, D) and (G, G), in which the first (second) term denotes the technology choice of firm 1 (firm 2, respectively). We separately analyze two groups according to the technology acquired by firm 1: {(D, D), (D, G)} and {(G, D), (G, G)}. Equilibrium results for the case in which firm 1 uses a dirty technology are presented in table 2, where the left-hand column analyzes the case in which firm 2 keeps its dirty technology, while in the right hand column it adopts a clean technology.

Table 2. Output levels and profits under duopoly - Firm 1 keeps its dirty technology

Firm 2's type	**D**	**G**
Output[5]	$q_i^{d,DD} = \frac{a-\tau e}{3b}$	$q_1^{d,DG} = \frac{a+\tau\theta e-2\tau e}{3b}$ and $q_2^{d,DG} = \frac{a-2\tau\theta e+\tau e}{3b}$
Profit	$\pi_1^{d,DD} = \frac{(a-\tau e)^2}{9b}$ $\pi_2^{d,DD} = \frac{(a-\tau e)^2}{9b} - F$	$\pi_1^{d,DG} = \frac{(a+\tau\theta e-2\tau e)^2}{9b}$ $\pi_2^{d,DG} = \frac{(a-2\tau\theta e+\tau e)^2}{9b} - (F+S)$

Table 2 shows that the effects of the emission tax on output levels and profits depend on the entrant's technology. While firms produce the same output level

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[5] If both firms keep their dirty technology, case (D, D), they produce strictly positive ouput levels if $\tau < \frac{a}{e}$. However, when only the entrant acquires green technology, (D, G), it produces a positive amount if $\tau < \frac{a}{(2\theta-1)e}$ and the dirty incumbent requires $\tau < \frac{a}{(2-\theta)e}$. For more details see appendix 6.1.

when they both use a dirty technology, the entrant's profit is lower than that for the incumbent since it has to incur a fixed entry cost. In contrast, if firm 2 acquires a green technology, its output level is higher than that of the incumbent. Moreover, the impact of environmental taxes on firm 2's output and profit relies on the emission-reducing efficiency of the clean technology. In particular, if the non-polluting technology is relatively effective eliminating pollution, i.e., $\theta \in (0, \frac{1}{2}]$, $q_2^{d,DG}$ and $\pi_2^{d,DG}$ are positively affected by the emission tax.

Let us now analyze the case in which firm 1 decides to acquire a green technology, i.e., (G, D) and (G, G). Table 3 presents the equilibrium results.

Table 3. Output levels and profits under duopoly - Firm 1 adopts a green technology

Firm 2's type	**D**	**G**
Output[6]	$q_1^{d,GD} = \frac{a-2\tau\theta e+\tau e}{3b}$ and $q_2^{d,GD} = \frac{a+\tau\theta e-2\tau e}{3b}$	$q_i^{d,GG} = \frac{a-\tau\theta e}{3b}$
Profit	$\pi_1^{d,GD} = \frac{(a-2\tau\theta e+\tau e)^2}{9b} - S$ $\pi_2^{d,GD} = \frac{(a+\tau\theta e-2\tau e)^2}{9b} - F$	$\pi_1^{d,GG} = \frac{(a-\tau\theta e)^2}{9b} - S$ $\pi_2^{d,GG} = \frac{(a-\tau\theta e)^2}{9b} - (F+S)$

Similar intuitions to those in table 2 apply when the incumbent is a green type. That is, if only one firm chooses a green technology then its output level and profit increase in the emission fee when θ is sufficiently low. However, if both firms acquire a green technology that completely eliminates pollution, i.e., $\theta = 0$, their profits coincide with those in a duopoly market with zero marginal costs. But if the technology is partially clean, $\theta > \frac{1}{2}$, then the emission fee reduces firms' profits.

3.2 Third stage

In this stage of the game, firm 2 decides whether or not to enter and its technology type. Firm 2 enters if its profit is nonnegative. In addition, it acquires the technology that generates the highest profit given the emission fee, the incumbent's type, and the characteristics of green technology (θ and S).

3.2.1 Firm 2's entry and technology decisions when firm 1 is dirty

Entry is profitable if the net benefit from adopting a type of technology is weakly positive, i.e., $max\left\{\pi_2^{d,DG}, \pi_2^{d,DD}\right\} \geq 0$. In addition, the entrant decides to acquire a green technology if tax savings exceed the cost of new technology. Hence, firm 2 joins the market and becomes a green type obtaining profits

$$\pi_2^{d,DG} = \frac{(a - 2\tau\theta e + \tau e)^2}{9b} - (F + S),$$

which are positive if the entry cost satisfies $F \in (0, \bar{F}^{DG}]$, where $\bar{F}^{DG} \equiv \frac{(a-2\tau\theta e+\tau e)^2}{9b} - S$. In contrast, if firm 2 enters and keeps its dirty technology, it

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[6] In order to ensure strictly positive output levels emission taxes satisfy $\tau < \frac{a}{(2-\theta)e}$ for the case (G, D) and $\tau < \frac{a}{\theta e}$ when both firms acquire the green technology, (G, G).

receives profits

$$\pi_2^{d,DD} = \frac{(a-\tau e)^2}{9b} - F,$$

which are positive if $F \leq \bar{F}^{DD} \equiv \frac{(a-\tau e)^2}{9b}$. Lemma 1 summarizes firm 2's decisions when facing a dirty incumbent.

Lemma 1. *When firm 1 is a dirty type and* $\tau < \frac{a}{(2-\theta)e}$*, firm 2 enters and keeps its dirty technology if* $F \leq \bar{F}^{DD}$ *and* $S > \widehat{S} \equiv \frac{4\tau e(1-\theta)(a-\tau\theta e)}{9b}$*. However, firm 2 adopts the green technology if* $F \leq \bar{F}^{DG}$ *and* $S \leq \widehat{S}$*. Finally, if* $F > \max\{\bar{F}^{DD}, \bar{F}^{DG}\}$*, firm 2 does not enter.*

Hence, firm 2 enters and acquires a green technology when F and S are sufficiently low[7]. We next examine whether the emission fee can affect the market structure by influencing the cutoff of entry costs.

Lemma 2. *When firm 1 keeps its dirty technology, an increase in emission taxes facilitates entry,* $\frac{d\bar{F}^{DG}}{d\tau} \geq 0$*, when firm 2 acquires a relatively efficient green technology, i.e.,* $\theta \in (0, \frac{1}{2}]$*. Otherwise, raising emission taxes could deter entry.*

The above lemma indicates that strict emission fees accompanied by a green technology that is sufficiently clean enlarge the set of entry costs for which firm 2 chooses to enter the industry. However, if the clean technology does not significantly ameliorate pollution, or if firm 2 keeps its dirty technology, high emission fees are likely to deter entry.

3.2.2 Firm 2's entry and technology decisions when firm 1 is green

We now analyze firm 2's entry and technology choices when firm 1 adopts a green technology. Similar to the previous discussion, firm 2 decides to enter if profits satisfy $max\left\{\pi_2^{d,GD}, \pi_2^{d,GG}\right\} \geq 0$. Firm 2 enters the market and adopts a green technology obtaining profits

$$\pi_2^{d,GG} = \frac{(a-\tau\theta e)^2}{9b} - (F+S) \geq 0,$$

which require an entry cost $F \in (0, \bar{F}^{GG}]$, and $\bar{F}^{GG} \equiv \frac{(a-\tau\theta e)^2}{9b} - S$. If, in contrast, firm 2 keeps its dirty technology, its profits are

$$\pi_2^{d,GD} = \frac{(a+\tau\theta e-2\tau e)^2}{9b} - F$$

which are positive if $F \leq \bar{F}^{GD} \equiv \frac{(a+\tau\theta e-2\tau e)^2}{9b}$. The following lemma summarizes our findings.

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[7] Note that an emission fee $\tau < \frac{a}{(2-\theta)e}$ guarantees strictly positive output levels.

Lemma 3. *When firm 1 is a green type and* $\tau < \frac{a}{(2-\theta)e}$*, firm 2 enters and keeps its dirty technology if* $F \leq \bar{F}^{GD}$ *and* $S > \widetilde{S} \equiv \frac{4\tau e(1-\theta)(a-\tau e)}{9b}$*. However, firm 2 adopts the green technology if* $F \leq \bar{F}^{GG}$ *and* $S \leq \widetilde{S}$*. Finally, if* $F > \max\{\bar{F}^{GD}, \bar{F}^{GG}\}$*, firm 2 does not enter.*

Therefore, both firms acquire a green technology if its cost is sufficiently low. Note that firm 2 stays out of the market under larger conditions when it faces a green than a dirty incumbent. We next discuss the effect of the emission fee on the entry cost cutoffs.

Lemma 4. *When firm 1 is a green type, an increase in emission taxes raises entry barriers, i.e.,* $\frac{d\bar{F}^{GK}}{d\tau} < 0$*, regardless of the technology* $K = \{D, G\}$ *that firm 2 chooses.*

Hence, entry is more likely to be deterred when a green incumbent operates in the market and strict emission fees are in place. If we compare the admissible technology costs for an entrant facing a dirty, $\widehat{S}$, and a green incumbent, $\widetilde{S}$, we observe that $\widehat{S} > \widetilde{S}$. Therefore, the entrant's decision on technology adoption is also affected by the incumbent's type. That is, the entrant is more willing to pay the fixed cost of acquiring a green technology when the incumbent is dirty than when it is green, since $\widehat{S} > \widetilde{S}$. Finally, we next investigate the impact of the emission fee on potential entrant's technology adoption.

Lemma 5. *When firm 1 is a dirty type, an increase in emission taxes induces firm 2 to adopt a green technology if and only if* $\theta \in (0, \frac{2}{3}]$*. However,* when *firm 1 is a green type, an increase in emission fees induces firm 2 to become green if the fee is lower than* $\frac{a}{2e}$*, independent of* θ*.*

Hence, higher emission fees are more likely to induce the acquisition of green technology by an entrant facing a dirty incumbent if such a technology is able to effectively eliminate pollution (low values of θ). However, if the technology is in a preliminary stage and, as a consequence, its capacity to capture emissions is unsatisfactory then higher emission fees do not necessarily induce the acquisition of this type of technology. In addition, when the incumbent is green, a more stringent environmental tax makes the adoption of green technology more attractive, independent of its capacity to eliminate pollution if the emission fee is lower than $\tau < \frac{a}{2e}$.

3.3 Second stage

3.3.1 Firm 1's technology decisions

In the second stage, firm 1 now decides whether or not to acquire a green technology. It is obvious that, without environmental regulation, firms have no incentives to invest in a clean technology. However, it is meaningful to investigate the incumbent's technology choices with regulation and entry threats.

In the absence of entry threats, firm 1 chooses the technology associated with higher profits. In particular, it adopts the clean technology if $S \leq \overline{S}$, where $\overline{S} \equiv \frac{\tau e(1-\theta)(2a-\tau e-\tau\theta e)}{4b}$. Since we consider a complete information game, the incumbent can fully anticipate the entrant's responses in the third and the fourth stage. Hence, the incumbent can maintain its monopolistic power acquiring the green technology if $S \leq \overline{S}$.

If, however, firm 1 foresees that entry can occur then its decision on whether to become a green type coincides with that of the entrant since both firms are symmetric except by the fact that firm 2 has to incur a fixed entry cost F. Specifically, when the incumbent anticipates that the entrant keeps its dirty technology, then it acquires a green technology if $S \leq \widehat{S}$. In contrast, if it anticipates that the entrant will adopt the green technology, firm 1 also becomes a green type if $S \leq \widetilde{S}$. Lemma 6 summarizes the above discussions.

Lemma 6. *Firm 1's technology choices can be summarized as follows:*

- No entry: *when* $\tau < \frac{a}{e}$ *and entry does not occur,* $F > \max\{\bar{F}^{GD}, \bar{F}^{GG}\}$, *firm 1 becomes a green type if* $S \leq \overline{S}$*;*
- Entry: *when* $\tau < \frac{a}{(2-\theta)e}$ *and firm 2 enters keeping its dirty technology,* $F \leq \bar{F}^{GD}$, *firm 1 becomes a green type if* $S \leq \widehat{S}$*;*
- Entry: *when* $\tau < \frac{a}{(2-\theta)e}$ *and firm 2 enters,* $F \leq \bar{F}^{GG}$, *adopting a green technology, firm 1 also becomes a green type if* $S \leq \widetilde{S}$.

Specifically, an incumbent that does not face the threat of entry acquires a green technology if the emission fee and the technology cost are relatively low. In addition, if the clean technology is effective reducing emission ($\theta \rightarrow 0$), then the set of admissible values of $\overline{S}$ expands and, hence, the incumbent is more likely to acquire the technology. Notice that the effects of imposing emission fees on firm 1's technology adoption follow the same intuitions discussed in Lemma 5. Let us now examine the impact of entry threats on firm 1's technology choices.

Lemma 7. *In the absence of entry threats firm 1 acquires a green technology under larger conditions than when it faces a potential entrant if* $\tau < \frac{a}{(9-7\theta)e}$. *However, if the emission fee satisfies* $\frac{a}{(9-7\theta)e} \leq \tau < \frac{a}{(2-\theta)e}$, *firm 1 acquires the green technology under more restrictive conditions in the absence of entry threats than when it faces a potential dirty entrant.*

Hence, when firm 1 faces the threat of entry of a dirty firm, it acquires the green technology under larger conditions than when entry threats are absent if the emission fee is sufficiently stringent.

3.4 First Stage

3.4.1 Regulator's emission tax choice if firm 1 is dirty

As discussed in lemma 6, the incumbent becomes a dirty type if the cost of green technology is sufficiently high. Specifically, when there is no entry $S > \overline{S}\left(\tau^{m,D}\right)$ evaluated in the optimal emission fee, and when entry ensues $S > \widehat{S}\left(\tau^{d,DD}\right)$ and $S > \widetilde{S}\left(\tau^{d,DG}\right)$ for the case of a dirty and a green entrant, respectively. The following proposition identifies the optimal environmental tax.

Proposition 1. *The optimal emission fee for a dirty incumbent is:*

- *No entry:* $\tau^{m,D} = 2d - \frac{a}{e}$ *if* $\frac{a}{2e} \leq d < \frac{a}{e}$ *and firm 2 stays out since* $F > \max\{\bar{F}^{DD}(\tau^{m,D}), \bar{F}^{DG}(\tau^{m,D})\}$.
- *Entry (D,D):* $\tau^{d,DD} = \frac{3}{2}d - \frac{a}{2e}$ *if* $\frac{a}{3e} \leq d < \frac{a}{e}$ *and firm 2 enters since* $F \leq \bar{F}^{DD}(\tau^{d,DD})$*, and does not adopt the green technology, i.e.,* $S > \widehat{S}\left(\tau^{d,DD}\right)$.
- *Entry (D,G):* $\tau^{d,DG} = \frac{6(\theta^2-\theta+1)}{(1+\theta)^2}d - \frac{a}{(1+\theta)e}$ *if* $\underline{d} \leq d < \overline{d}$, where $\underline{d} \equiv \frac{a(1+\theta)}{6e(\theta^2-\theta+1)}$ and $\overline{d} \equiv \frac{a(1+\theta)}{2e(2-\theta)(\theta^2-\theta+1)}$. *Firm 2 enters since* $F \leq \bar{F}^{DG}(\tau^{d,DG})$*, but adopts the green technology, i.e.,* $S \leq \widehat{S}\left(\tau^{d,DG}\right)$.

The optimal emission fee in the case of a dirty monopolist is lower than that in the case of a dirty duopoly, a result in line of Buchanan (1969), for any environmental damage between $\frac{a}{2e} \leq d < \frac{a}{e}$, and also lower than the emission fee under a partially dirty duopoly, (D,G), for the environmental damage $d \in [\frac{a}{2e}, \overline{d})$.[8] In addition, a partially dirty duopoly faces more stringent emission fee than a completely dirty duopoly if the environmental damage is between $\frac{a(1+\theta)}{9e(1-\theta)} \leq d < \overline{d}$. [9]

3.4.2 Regulator's emission tax choice if firm 1 is green

We next examine the case in which the incumbent adopts a green technology. Lemma 6 discusses the range of S for which the incumbent becomes a green type. That is, the incumbent adopts a green technology when entry does not ensue if $S \leq \overline{S}\left(\tau^{m,G}\right)$. In addition, if a green (dirty) entrant joins the market, the incumbent acquires green technology if $S \leq \widetilde{S}\left(\tau^{d,GG}\right)$ ($S \leq \widehat{S}\left(\tau^{d,GD}\right)$, respectively). The optimal environmental taxes for this case are identified in the following proposition.

Proposition 2. *The optimal emission fee for a green incumbent is:*

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[8] In order to compare the optimal emission fee in cases (D) and (D,G) we first need to identify a range of environmental damage for which these two cases coexist. Specifically, emission fees are supported for any value of $\frac{a}{2e} \leq d < \overline{d}$ since $\underline{d} < \frac{a}{2e}$ and $\overline{d} < \frac{a}{e}$.

[9] Cases (D,D) and (D,G) coexist when $\frac{a}{3e} \leq d < \overline{d}$ (or $\underline{d} \leq d < \overline{d}$) and $\theta \in (0, \frac{1}{2}]$ (or $\theta \in (\frac{1}{2}, 1)$).

- *No entry:* $\tau^{m,G} = 2d - \frac{a}{\theta e}$ *if* $\frac{a}{2\theta e} \leq d < \frac{a}{\theta e}$ *and firm 2 stays out since* $F > \max\{\bar{F}^{GD}\left(\tau^{m,G}\right), \bar{F}^{GG}\left(\tau^{m,G}\right)\}$.
- *Entry (G,G):* $\tau^{d,GG} = \frac{3}{2}d - \frac{a}{2\theta e}$ *if* $\frac{a}{3\theta e} \leq d < \frac{a}{\theta e}$, *and firm 2 enters since* $F \leq \bar{F}^{GG}\left(\tau^{d,GG}\right)$ *and adopts the green technology, i.e.,* $S \leq \widetilde{S}\left(\tau^{d,GG}\right)$.
- *Entry (G,D):* $\tau^{d,GD} = \frac{6(\theta^2-\theta+1)}{(1+\theta)^2}d - \frac{a}{(1+\theta)e}$ *if* $\underline{d} \leq d < \overline{d}$ *and firm 2 enters since* $F \leq \bar{F}^{GD}(\tau^{d,GD})$, *but keeps its dirty technology, i.e.,* $S > \widetilde{S}\left(\tau^{d,GD}\right)$.

The regulator selects a lower optimal emission fee when a green monopolist operates in the market than in the case of a completely (or partially) green duopoly ((G,G) and (G,D)) if the environmental damage $d \in [\frac{a}{2\theta e}, \overline{d})$ and $\theta > \frac{1}{2}$.[10] In addition, the optimal emission fee in case (G,D) is higher than that in case (G,G) when the environmental damage is between $d \in [\frac{a}{3\theta e}, \overline{d})$ and the green technology is inefficient. Finally, the optimal emission tax in a green monopoly is lower than that of a dirty monopoly for any environmental damage $\frac{a}{2\theta e} \leq d < \frac{a}{e}$.

For comparison purposes, let us use figure 1.[11] The figure indicates that the regulation is not urgent when the environmental damage is sufficiently low. For a relatively low environmental damage, $\frac{a}{3e} \leq d < \frac{2a}{3e}$, the partially clean market faces the highest emission fee. However, regulation for a market consisting of two dirty firms becomes more stringent under a medium level of environmental damage $d \in [\frac{2a}{3e}, \frac{a}{e})$. Finally, when emissions have grievous consequences, $\frac{a}{e} \leq d < \frac{2a}{e}$, the regulator imposes the highest emission fee on a green duopoly that has a partially clean technology.

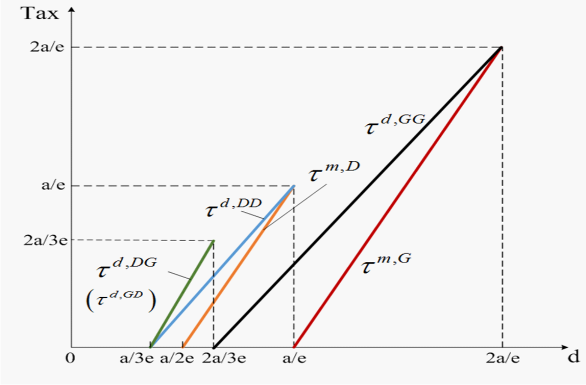

Figure 1. Comparisons between optimal emission fees.

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[10] Cases (G,G) and (G,D)cannot coexist if $\theta \leq \frac{1}{2}$ since $\overline{d} \leq \frac{a}{3\theta e}$. When $\theta > \frac{1}{2}$, the admissible range of d is $\frac{a}{3\theta e} \leq d < \overline{d}$ since $\underline{d} < \frac{a}{3\theta e}$ and $\overline{d} < \frac{a}{\theta e}$. Thus, the admissible range of d for cases (G), (G,D), and (G,G) is $d \in [\frac{a}{2\theta e}, \overline{d})$.

[11] For presentation purposes we assume $\theta = \frac{1}{2}$.

4 Welfare Analysis

In order to facilitate our comparisons we consider a green technology with moderate efficiency level, i.e. $\theta = \frac{1}{2}$, which simplifies social welfare analysis while still provides useful intuitions.

Proposition 3. *The social welfare when fees induce firm 1 to keep its dirty technology is,*

- *No entry:* $W^{m,D} = \frac{(a-ed)^2}{2b}$
- *Entry (D,D):* $W^{d,DD} = \frac{(a-ed)^2}{2b} - F = W^{m,D} - F$
- *Entry (D,G):* $W^{d,DG} = \frac{3a^2-5aed+3(ed)^2}{6b} - (F+S) = W^{m,D} + \frac{aed}{6b} - (F+S)$

First, in the case in which firms do not choose the green technology, social welfare under no entry is higher than under entry, (D,D), given $\frac{a}{2e} \leq d < \frac{a}{e}$. Intuitively, it is socially desirable having a dirty monopolist than two dirty duopolists generating a higher environmental damage which is not compensated by an increase in consumer surplus. Therefore, the regulator can raise entry costs, F, to obtain a welfare improvement since outcome (D) occurs under a higher range of F than outcome (D,D).[12] In addition, social welfare in outcome (D,G) is always higher than (D,D) for all admissible environmental damages, i.e., $d \in [\frac{a}{3e}, \frac{2a}{3e})$ for which both emission fees are supported.[13] In this case, the entry of a green firm is socially desirable. Finally, the social welfare of a partially green duopoly is higher than a dirty monopoly only when both fixed costs (F and S) are sufficiently low, that is, $F + S < \frac{aed}{6b}$, for a moderate range of the environmental damage $d \in [\frac{a}{2e}, \frac{2a}{3e})$. Under this situation, the regulator could help the emergence of (D,G) by reducing fix entry costs or partially subsidizing the clean technology.[14] Otherwise, the entry of a green competitor is socially undesirable.

Proposition 4 describes social welfare when the incumbent acquires a green technology.

Proposition 4. *The social welfare when fees induce firm 1 to acquire the green technology is,*

- *No entry:* $W^{m,G} = \frac{(2a-ed)^2}{8b} - S$

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[12] Specifically, the case (D) requires $F > \overline{F}^{*D}$, while the case (D,D) requires $F \leq \overline{F}^{*DD}$. Notice that $\overline{F}^{*D} > \overline{F}^{*DD}$. In addtion, $S > \widehat{S}^{*DD}$ supports both cases in terms of the fixed costs for green technology. See the proof of Proposition 3 in the appendix.

[13] Notice that condition of fixed entry costs $F \leq \overline{F}^{*DG}$ supports both case (D,D) and (D,G). Moreover, the requirements for the fixed costs of green technology are compatible when $\widehat{S}^{*DD} < S \leq \widehat{S}^{*DG}$. See the proof of Proposition 3 in the appendix.

[14] Cases (D) and (D,G) requires $\max\{\overline{S}^{*D}, \widetilde{S}^{*DG}\} < S \leq \widehat{S}^{*DG}$. However, the case (D) always requires higher fixed entry costs since $\overline{F}^{*D} > \overline{F}^{*DG}$. See the proof of Proposition 3 in the appendix.

- *Entry (G,G):* $W^{d,GG} = \frac{(2a-ed)^2}{8b} - (F+2S) = W^{m,G} - (F+S)$
- *Entry (G,D):* $W^{d,GD} = W^{d,DG}$

Comparing these welfare levels, we observe that the social welfare under no entry is always higher than when entry ensues and firm 2 is also a green type for $\frac{a}{e} \leq d < \frac{2a}{e}$. However, the fixed entry costs that assures the green monopolistic market is always higher than that supporting the green duopolistic market.[15] Since optimal emission fees cannot be modified in order to guarantee the emergence of a particular market structure, the regulator could promote, for instance, the existence of a green monopoly market when the environmental damage is high throughout entry costs. That is, making entry more expensive to potential entrants. Moreover, notice that when the clean technology is moderately efficient, a partially green duopolistic market with a green incumbent, (G,D), occurs for a relatively low range of the environmental damage. However, a green monopoly or green duopoly are supported only under sufficiently high environmental damage limiting our comparisons.[16] We next examine under which conditions the social welfare in the case of a green incumbent is higher than when the incumbent has a dirty technology.

Lemma 8. *Social welfare when the incumbent is a green type is higher than when it is dirty under the following conditions:*

- *Entry:* $W^{d,GG} > W^{d,DD}$ *for* $d \in [\frac{2a}{3e}, \frac{a}{e})$, *if* $S < \frac{(4a-3ed)ed}{16b}$.
- *Entry:* $W^{d,GD} > W^{d,DD}$ *for* $d \in [\frac{a}{3e}, \frac{2a}{3e})$.

Hence, a higher social welfare is obtained under a clean duopoly market, (G,G), than a completely dirty duopoly, (D,D), if the environmental damage is sufficiently high and the clean technology has a low cost. This result suggests that a green market is socially preferred when pollution can have disastrous consequences on the environment and an inexpensive moderately clean technology is available to firms. In this case, it is socially optimal to induce the incumbent or both firms to adopt the environmentally friendly technology, if entry is not deterred. Therefore, any complementary policy that expands the set of admissible values of S would favor the emergence of this type of market. However, if the environmental damage is low a partially dirty duopoly, in which only the incumbent adopts the green technology, is socially preferred than two dirty firms in the market.

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[15] Cases (G) requires $F > \overline{F}^{*G}$, while the case (G,G) requires $F \leq \overline{F}^{*GG}$. Notice that $\overline{F}^{*G} > \overline{F}^{*GG}$. Moreover, the condition of fixed costs for green technology is compatible when $S \leq \min\{\overline{S}^{*G}, \widetilde{S}^{*GG}\}$. See proof of Proposition 4 in the appendix.

[16] See proof of Proposition 4 in the appendix.

5 Conclusions

This paper examines under which conditions an emission tax can be used to induce firms to adopt a green technology and, also, to deter entry. Our results show that a stringent emission fee does not necessarily induce the entrant to acquire a green technology. The entrant's decision about becoming a green type depends on the efficiency of the clean technology reducing emissions and its cost. However, once the entrant has decided to join the market and emission fees are sufficiently high, this firm is more likely to adopt the green technology when there is a green incumbent operating in the market than otherwise. In addition, we find that entry is more plausible to be deterred by a green incumbent when there is a strict emission fee in place.

We also provide comparisons of optimal environmental taxes and social welfare under different contexts. In particular, when the environmental damage is sufficiently low, a partially green duopoly is socially desirable than a dirty duopoly. In addition, when the environmental damage is relatively high, a green duopoly is welfare improving than a dirty duopoly, if the green technology cost is sufficiently low. Our results suggest that the regulator should evaluate emission fees and, in particular, their effects on the market structure and the adoption of environmentally friendly technologies, depending on how severe the environmental damage is. Hence, if the environmental damage is relatively low, emission fees that support entry of a green firm, are socially preferred than an environmental tax that hinders entry. However, a severe environmental damage calls for policies that promote a clean monopoly or duopoly market.

Our paper can be extended in different ways. For instance, we assume that the environmentally friendly technology does not affect marginal production costs. However, it may be interesting to analyze a setting in which the green technology not only partially reduces pollution but is also able to modify marginal costs. Moreover, our model does not allow the regulator to be uninformed about the cost of clean technology. However, we should expect to observe different equilibrium results under a context of incomplete information. Finally, it would be worthwhile to analyze a different game structure in which the incumbent produces in the second and fourth stage of the game and the regulator is able to adjust its regulation if entry ensues.

6 Appendix

6.1 Strictly Positive Output Levels

Let us analyze the case (D, G). Firm 1's output level is strictly positive, $q_1^{d,DG} > 0$, if $a + \tau\theta e - 2\tau e > 0$ or

$$\tau < \frac{a}{(2-\theta)e} \text{ where } 2-\theta > 0 \text{ since } \theta \in (0,1)$$

and firm 2's output level is strictly positive, $q_2^{d,DG} > 0$, if $a - 2\tau\theta e + \tau e > 0$

or

$$\tau < \frac{a}{(2\theta - 1)e} \text{ where } 2\theta - 1 > 0 \text{ if } \theta > \frac{1}{2}$$

However, if $0 < \theta \leq \frac{1}{2}$, any non-negative emission tax ensures $q_2^{d,DG} > 0$. It is immediate to check that $\frac{a}{(2-\theta)e} < \frac{a}{(2\theta-1)e}$. Hence, for the case (D, G), the emission tax has to satisfy $\tau < \frac{a}{(2-\theta)e}$ for all θ. Note that the same conditions are required for the case (G,D).■

6.2 Proof of Lemma 1

If $\tau < \frac{a}{(2-\theta)e}$ both firms produce strictly positive output levels in cases (D, D) and (D, G). Firm 2 has incentives to adopt a green technology, when facing a dirty incumbent, if

$$\begin{aligned} \pi_2^{d,DG} &\geq \pi_2^{d,DD} \\ \frac{(a - 2\tau\theta e + \tau e)^2}{9b} - (F + S) &\geq \frac{(a - \tau e)^2}{9b} - F \\ S &\leq \frac{4\tau e(1-\theta)(a - \tau\theta e)}{9b} \equiv \widehat{S} \end{aligned}$$

Hence, firm 2 chooses the green technology and enters if

$$\begin{aligned} \pi_2^{d,DG} &= \frac{(a - 2\tau\theta e + \tau e)^2}{9b} - (F + S) \geq 0 \\ F &\leq \frac{(a - 2\tau\theta e + \tau e)^2}{9b} - S \equiv \bar{F}^{DG} \end{aligned}$$

However, firm 2 prefers the dirty technology if $S > \widehat{S}$ and entry occurs if

$$\begin{aligned} \pi_2^{d,DD} &= \frac{(a - \tau e)^2}{9b} - F \geq 0 \\ F &\leq \frac{(a - \tau e)^2}{9b} \equiv \bar{F}^{DD} \end{aligned}$$

■

6.3 Proof of Lemma 2

We now check the effect of emission taxes on the entry cost cutoffs.

Case (D, G). $\frac{d\bar{F}^{DG}}{d\tau} = \frac{2e(a-2\tau\theta e+\tau e)}{9b}(1 - 2\theta)$. Since $\frac{2e(a-2\tau\theta e+\tau e)}{9b} > 0$, then $\frac{d\bar{F}^{DG}}{d\tau} \geq 0$ if $1 - 2\theta \geq 0$, which is equivalent to $0 < \theta \leq \frac{1}{2}$. However, $\frac{d\bar{F}^{DG}}{d\tau} < 0$ if $\frac{1}{2} < \theta < 1$.

Case (D,D). $\frac{d\bar{F}^{DD}}{d\tau} = \frac{-2e(a-\tau e)}{9b} < 0$ since $\frac{2e(a-\tau e)}{9b} > 0$.■

6.4 Proof of Lemma 3

Considering $\tau < \frac{a}{(2-\theta)e}$ and given that the incumbent is a green type, the entrant also chooses the clean technology if

$$\begin{aligned}
\pi_2^{d,GG} &\geq \pi_2^{d,GD} \\
\frac{(a-\tau\theta e)^2}{9b} - (F+S) &\geq \frac{(a+\tau\theta e-2\tau e)^2}{9b} - F \\
S &\leq \frac{4\tau e(1-\theta)(a-\tau e)}{9b} \equiv \widetilde{S}
\end{aligned}$$

Hence, firm 2 chooses the green technology and enters the market if

$$\begin{aligned}
\pi_2^{d,GG} &= \frac{(a-\tau\theta e)^2}{9b} - (F+S) \geq 0 \\
F &\leq \frac{(a-\tau\theta e)^2}{9b} - S \equiv \bar{F}^{GG}
\end{aligned}$$

However, firm 2 prefers the dirty technology if $S > \widetilde{S}$. Therefore, entry occurs if

$$\begin{aligned}
\pi_2^{d,GD} &= \frac{(a+\tau\theta e-2\tau e)^2}{9b} - F \geq 0 \\
F &\leq \frac{(a+\tau\theta e-2\tau e)^2}{9b} \equiv \bar{F}^{GD}
\end{aligned}$$

■

6.5 Proof of Lemma 4

Case (G, D). $\frac{d\bar{F}^{GD}}{d\tau} = \frac{2e(a+\tau\theta e-2\tau e)}{9b}(\theta-2) < 0$ since $\frac{2e(a+\tau\theta e-2\tau e)}{9b} > 0$ and $\theta - 2 < 0$. Similarly, it is straightforward to show that $\frac{d\bar{F}^{GG}}{d\tau} < 0$.■

6.6 Proof of Lemma 5

Let us first analyze the case in which the incumbent keeps its dirty technology. Then $\frac{d\widehat{S}}{d\tau} = \frac{4e(1-\theta)}{9b}(a-2\tau\theta e)$ is positive if $a - 2\tau\theta e \geq 0$ which is equivalent to $\tau \leq \frac{a}{2\theta e}$. In addition, comparing $\frac{a}{2\theta e}$ with the cutoff for strictly positive outputs, $\frac{a}{(2-\theta)e}$, we obtain $\frac{a}{2\theta e} \geq \frac{a}{(2-\theta)e}$ if $\theta \in (0, \frac{2}{3}]$. Hence, when $0 < \theta \leq \frac{2}{3}$ we have that $\frac{d\widehat{S}}{d\tau} \geq 0$ for any τ that supports strictly positive outputs. However, if $\frac{2}{3} < \theta < 1$, the $min\left\{\frac{a}{2\theta e}, \frac{a}{(2-\theta)e}\right\} = \frac{a}{2\theta e}$ and thus $\frac{d\widehat{S}}{d\tau} \geq 0$ if $\tau \geq \frac{a}{2\theta e}$, whereas $\frac{d\widehat{S}}{d\tau} < 0$ if $\frac{a}{2\theta e} < \tau < \frac{a}{(2-\theta)e}$.

If the incumbent is a green type, we obtain that $\frac{d\widetilde{S}}{d\tau} = \frac{4e(1-\theta)}{9b}(a-2\tau e) \geq 0$ if $a - 2\tau e \geq 0$, i.e., $\tau \leq \frac{a}{2e}$. Since $\frac{a}{2e} \leq \frac{a}{(2-\theta)e}$, hence, $\frac{d\widetilde{S}}{d\tau} \geq 0$ if $\tau \leq \frac{a}{2e}$, regardless of the efficiency of the green technology, whereas $\frac{d\widetilde{S}}{d\tau} < 0$ for $\frac{a}{2e} < \tau < \frac{a}{(2-\theta)e}$.■

6.7 Proof of Lemma 6

A monopolist has incentives to adopt a green technology if

$$\begin{aligned} \pi_1^{m,G} &\geq \pi_1^{m,D} \\ \frac{(a-\tau\theta e)^2}{4b} - S &\geq \frac{(a-\tau e)^2}{4b} \\ S &\leq \frac{\tau e(1-\theta)(2a-\tau e-\tau\theta e)}{4b} \equiv \overline{S} \end{aligned}$$

In addition, firm 1 becomes green if $S \leq \widetilde{S}$, when it anticipates that firm 2 enters and acquires green technology. However, firm 1 adopts the clean technology if $S \leq \widehat{S}$, when knowing entry can occur and firm 2 is a dirty type.

6.8 Proof of Lemma 7

We require that firms produce strictly positive output levels for cases (D),(G),(D,D), and (G,D) in order to compare $\overline{S}$, $\widetilde{S}$ and $\widehat{S}$, which is satisfied by $\tau < \frac{a}{(2-\theta)e}$. Let us first analyze $\overline{S}$ and $\widetilde{S}$.

$$\overline{S} - \widetilde{S} = \frac{\tau e(1-\theta)}{36b}(2a - 9\tau\theta e + 7\tau e) > 0$$

which is positive if $2a - 9\tau\theta e + 7\tau e > 0$, or equivalently $\tau < \frac{2a}{(9\theta-7)e}$. However, since $\frac{2a}{(9\theta-7)e} > \frac{a}{(2-\theta)e}$ then $\overline{S} > \widetilde{S}$ for all admissible values of τ. Now we compare $\overline{S}$ and $\widehat{S}$.

$$\overline{S} - \widehat{S} = \frac{\tau e(1-\theta)}{36b}(2a + 7\tau\theta e - 9\tau e) > 0$$

which is positive if $2a + 7\tau\theta e - 9\tau e > 0$, or equivalently $\tau < \frac{2a}{(9-7\theta)e}$. In addition, $\frac{2a}{(9-7\theta)e} - \frac{a}{(2-\theta)e} = \frac{5a(\theta-1)}{e(9-7\theta)(2-\theta)} < 0$ and thus $\frac{2a}{(9-7\theta)e} < \frac{a}{(2-\theta)e}$. Therefore, $\overline{S} > \widehat{S}$ if $\tau < \frac{2a}{(9-7\theta)e}$, whereas $\overline{S} \leq \widehat{S}$ if $\frac{2a}{(9-7\theta)e} \leq \tau < \frac{a}{(2-\theta)e}$.■

6.9 Proof of Proposition 1

No Entry. If firm 2 stays out of the market, the regulator solves the following maximization problem,

$$\max_{\tau} \quad W^{m,D} = \pi_1^{m,D} + CS^{m,D} + e(\tau - d)q_1^{m,D}$$

In particular, $\pi_1^{m,D} = \frac{(a-\tau e)^2}{4b}$, $CS^{m,D} = \frac{(a-\tau e)^2}{8b}$ and $q_1^{m,D} = \frac{a-\tau e}{2b}$. Then

$$W^{m,D} = \frac{3(a-\tau e)^2}{8b} + \frac{e(\tau-d)(a-\tau e)}{2b}.$$

Hence, the optimal emission fee is $\tau^{m,D} = 2d - \frac{a}{e}$ which is nonnegative if $d \geq \frac{a}{2e}$. In addition, $q_1^{m,D}(\tau^{m,D})$ is strictly positive if $d < \frac{a}{e}$, hence, combining both conditions we have $\frac{a}{2e} \leq d < \frac{a}{e}$. Moreover, given lemma 1, firm 2 does not enter if $F > \max\{\bar{F}^{DD}, \bar{F}^{DG}\}$. Substituting $\tau^{m,D}$ into $\bar{F}^{DD}$ and $\bar{F}^{DG}$, we obtain $F > \max\{\frac{4(a-ed)^2}{9b}, \frac{4(ed-2\theta ed+a\theta)^2}{9b} - S\}$. Finally, firm 1 does not adopt the green technology when $S > \overline{S}(\tau^{m,D}) = \frac{(1-\theta)(2ed-a)(3a-2ed+a\theta-2\theta ed)}{4b}$.

Entry. Let us first analyze the case in which firm 2 also chooses to keep its dirty technology.

$$\max_{\tau} \;\; W^{d,DD} = \pi_1^{d,DD} + \pi_2^{d,DD} + CS^{d,DD} + e(\tau - d)(q_1^{d,DD} + q_2^{d,DD})$$

In particular, $\pi_1^{d,DD} + \pi_2^{d,DD} = \frac{2(a-\tau e)^2}{9b} - F$, $CS^{d,DD} = \frac{2(a-\tau e)^2}{9b}$ and $q_1^{d,DD} + q_2^{d,DD} = \frac{2(a-\tau e)}{3b}$. Then, social welfare function can be rewritten as

$$W^{d,DD} = \frac{4(a-\tau e)^2}{9b} + \frac{2e(\tau - d)(a - \tau e)}{3b} - F.$$

Hence the optimal environmental tax is $\tau^{d,DD} = \frac{3d}{2} - \frac{a}{2e}$, which is positive if $d \geq \frac{a}{3e}$. In addition, $q_i^{d,DD}(\tau^{d,DD})$ is strictly positive if $d < \frac{a}{e}$, hence, $\frac{a}{3e} \leq d < \frac{a}{e}$. Moreover, according to lemma 1, firm 2 enters and keeps its dirty technology if $F \leq \bar{F}^{DD}(\tau^{d,DD})$ and $S > \widehat{S}(\tau^{d,DD})$. Given the optimal emission tax, $\bar{F}^{DD}(\tau^{d,DD}) = \frac{(a-ed)^2}{4b}$ and $\widehat{S}(\tau^{d,DD}) = \frac{(1-\theta)(3ed-a)(2a+a\theta-3\theta ed)}{9b}$. Finally, notice that firm 1 also keeps its dirty technology when $S > \widehat{S}(\tau^{d,DD})$.

However, if the entrant adopts the green technology the optimal fee solves,

$$\max_{\tau} \;\; W^{d,DG} = \pi_1^{d,DG} + \pi_2^{d,DG} + CS^{d,DG} + (\tau - d)eq_1^{d,DG} + (\tau - d)\theta eq_2^{d,DG}$$

In particular, $\pi_1^{d,DG} + \pi_2^{d,DG} = \frac{(a+\tau\theta e-2\tau e)^2}{9b} + \frac{(a-2\tau\theta e+\tau e)^2}{9b} - (F+S)$, $CS^{d,DG} = \frac{(2a-\tau\theta e-\tau e)^2}{18b}$, $q_1^{d,DG} = \frac{a+\tau\theta e-2\tau e}{3b}$, $q_2^{d,DG} = \frac{a-2\tau\theta e+\tau e}{3b}$. Then social welfare can be expressed as follows,

$$\begin{aligned} W^{d,DG} \;\; = \;\; & \frac{(a+\tau\theta e-2\tau e)^2}{9b} + \frac{(a-2\tau\theta e+\tau e)^2}{9b} + \frac{(2a-\tau\theta e-\tau e)^2}{18b} \\ & + \frac{e(\tau-d)(a+\tau\theta e-2\tau e)}{3b} + \frac{\theta e(\tau-d)(a-2\tau\theta e+\tau e)}{3b} - (F+S). \end{aligned}$$

Therefore, the optimal emission fee is $\tau^{d,DG} = \frac{6(\theta^2-\theta+1)}{(1+\theta)^2} d - \frac{a}{(1+\theta)e}$, which is nonnegative if $d \geq \frac{a(1+\theta)}{6e(\theta^2-\theta+1)} \equiv \underline{d}$. In addition, $q_1^{d,DG}(\tau^{d,DG})$ and $q_2^{d,DG}(\tau^{d,DG})$ are strictly positive when $d < \frac{a(1+\theta)}{2e(2-\theta)(\theta^2-\theta+1)} \equiv \overline{d}$. Notice that $\underline{d} < \overline{d}$ is always satisfied.

From lemma 1 and using $\tau^{d,DG}$, we know that firm 2 enters the market and adopts the green technology if $F \leq \frac{[a+(1-2\theta)H]^2}{9b} - S$, where $H \equiv 6ed -$

$\frac{a+\theta(a+18ed)}{(1+\theta)^2}$, and $S \leq \varDelta[a(1+3\theta+2\theta^2)-6\theta ed(1-\theta+\theta^2)] = \widehat{S}(\tau^{d,DG})$, where $\varDelta \equiv \frac{4(1-\theta)H}{9b(1+\theta)^2}$. In addition, firm 1 does not become a green type if $S > \widetilde{S}(\tau^{d,DG})$, where $\widetilde{S}(\tau^{d,DG}) = \varDelta[a(2+3\theta+\theta^2)-6ed(1-\theta+\theta^2)]$.■

6.10 Proof of Proposition 2

No Entry. When firm 1 is a monopolist, the regulator selects the optimal emission fee solving,

$$\max_{\tau} \quad W^{m,G} = \pi_1^{m,G} + CS^{m,G} + (\tau - d)\theta e q_1^{m,G}$$

In particular, $\pi_1^{m,G} = \frac{(a-\tau\theta e)^2}{4b} - S$, $CS^{m,G} = \frac{(a-\tau\theta e)^2}{8b}$, and $q_1^{m,G} = \frac{a-\tau\theta e}{2b}$. Then, social welfare can be rewritten as,

$$W^{m,G} = \frac{3(a-\tau\theta e)^2}{8b} + \frac{\theta e(\tau-d)(a-\tau\theta e)}{2b} - S$$

and the optimal emission fee is $\tau^{m,G} = 2d - \frac{a}{\theta e}$. We require $\frac{a}{2\theta e} \leq d < \frac{a}{\theta e}$ to assure $\tau^{m,G} \geq 0$ and $q_1^{m,G} > 0$. Moreover, firm 1 adopts the green technology if $\overline{S}(\tau^{m,G}) = \frac{(1-\theta)(2\theta ed-a)(a+3a\theta-2\theta ed-2\theta^2 ed)}{4b\theta^2}$. From lemma 3, firm 2 does not enter when $F > max\{\frac{4(\theta^2 ed-2\theta ed+a)^2}{9b\theta^2}, \frac{4(a-\theta ed)^2}{9b} - S\}$.

Entry. We first analyze the case in which both firms adopt the green technology. The regulator solves

$$\max_{\tau} \quad W^{d,GG} = \pi_1^{d,GG} + \pi_2^{d,GG} + CS^{d,GG} + (\tau - d)\theta e(q_1^{d,GG} + q_2^{d,GG})$$

In particular, $\pi_1^{d,GG} + \pi_2^{d,GG} = \frac{2(a-\tau\theta e)^2}{9b} - (2S+F)$, $CS^{d,GG} = \frac{2(a-\tau\theta e)^2}{9b}$, $q_1^{d,GG} + q_2^{d,GG} = \frac{2(a-\tau\theta e)}{3b}$. Then

$$W^{d,GG} = \frac{4(a-\tau\theta e)^2}{9b} + \frac{2\theta e(\tau-d)(a-\tau\theta e)}{3b} - (2S+F)$$

The optimal emission fee is $\tau^{d,GG} = \frac{3d}{2} - \frac{a}{2\theta e}$, which is nonnegative if $d \geq \frac{a}{3\theta e}$. In addition, $q_i^{d,GG}(\tau^{d,GG}) > 0$ when $d < \frac{a}{\theta e}$. According to lemma 3, firm 2 enters being a green type if $F \leq \bar{F}^{GG}(\tau^{d,GG}) = \frac{(a-\theta ed)^2}{4b}$. Moreover, both firms adopt the green technology when $S \leq \widetilde{S}(\tau^{d,GG}) = \frac{(1-\theta)(3\theta ed-a)(a+2a\theta-3\theta ed)}{9b\theta^2}$.

Let us now examine the case in which the entrant keeps its dirty technology. Social welfare is the same as outcome (D,G) and thus the optimal emission tax $\tau^{d,GD} = \tau^{d,DG} = \frac{6(\theta^2-\theta+1)}{(1+\theta)^2}d - \frac{a}{(1+\theta)e}$. In addition, the requirement of the fixed costs of green technology coincides with (D,G). However, the admissible condition of fixed entry costs becomes $F \leq \frac{[a-(2-\theta)H]^2}{9b}$.■

6.11 Proof of proposition 3

We first analyze the cases in which firm 1 is a dirty type.
No Entry. Substituting $\tau^{m,D}\left(\theta=\frac{1}{2}\right)=2d-\frac{a}{e}$ into $W^{m,D}$, we obtain

$$W^{m,D}(\tau^{m,D})=\frac{(a-ed)^2}{2b}.$$

In addition, the fixed costs need to satisfy $F>\overline{F}^{*D}\equiv\max\{\frac{4(a-ed)^2}{9b},\frac{a^2}{9b}-S\}$ and $S>\overline{S}^{*D}\equiv\frac{(7a-6ed)(2ed-a)}{16b}$.

Entry. If firm 2 also keeps its dirty technology, the social welfare evaluated at $\tau^{d,DD}\left(\theta=\frac{1}{2}\right)=\frac{3d}{2}-\frac{a}{2e}$ is

$$W^{d,DD}(\tau^{d,DD})=\frac{(a-ed)^2}{2b}-F=W^{m,D}-F.$$

Firm 2 enters and keeps its dirty technology if $F\leq\overline{F}^{*DD}\equiv\frac{(a-ed)^2}{4b}$ and $S>\widehat{S}^{*DD}\equiv\frac{(5a-3ed)(3ed-a)}{36b}$.

We now analyze the case in which firm 2 adopts the green technology. If $\theta=\frac{1}{2}$, the optimal emission fee becomes $\tau^{d,DG}\left(\theta=\frac{1}{2}\right)=2d-\frac{2a}{3e}$ and requires $\frac{a}{3e}\leq d<\frac{2a}{3e}$. Accordingly, the social welfare is

$$W^{d,DG}(\tau^{d,DG})=\frac{3a^2-5aed+3(ed)^2}{6b}-(F+S)=W^{m,D}+\frac{aed}{6b}-(F+S).$$

In addition, firm 2 enters and both firms adopt the green technology when $F\leq\overline{F}^{*DG}\equiv\frac{a^2}{9b}-S$ and $\widetilde{S}^{*DG}<S\leq\widehat{S}^{*DG}$, where $\widetilde{S}^{*DG}\equiv\frac{4(5a-6ed)(3ed-a)}{81b}$, and $\widehat{S}^{*DG}\equiv\frac{4(4a-3ed)(3ed-a)}{81b}$.

Social welfare comparisons. First, given proposition 1, $W^{m,D}$ and $W^{d,DD}$ can be supported if $\frac{a}{2e}\leq d<\frac{a}{e}$. It is straightforward to show that $W^{m,D}>W^{d,DD}$. In addition,

$$\overline{S}^{*D}-\widehat{S}^{*DD}=\frac{-(72(ed)^2-108aed+43a^2)}{144b}<0$$

Hence, the compatible condition for S is $S>\widehat{S}^{*DD}$. However, $\overline{F}^{*D}$ is always higher than $\overline{F}^{*DD}$ due to $\frac{4(a-ed)^2}{9b}>\frac{(a-ed)^2}{4b}$.

Next, let us compare $W^{d,DD}$ and $W^{d,DG}$. Both cases are supported in $\frac{a}{3e}\leq d<\frac{2a}{3e}$. Moreover,

$$\widehat{S}^{*DD}-\widetilde{S}^{*DG}=\frac{(35a-69ed)(a-3ed)}{324b}$$

of which sign depends on the value of d. Thus the requirement of S for both cases is $\max\{\widehat{S}^{*DD}, \widetilde{S}^{*DG}\} < S \leq \widehat{S}^{*DG}$. In addition, the condition for fixed entry costs is $F \leq \min\{\overline{F}^{*DD}, \overline{F}^{*DG}\}$. Then

$$W^{d,DG}(\tau^{d,DG}) - W^{d,DD}(\tau^{d,DD}) = \frac{aed}{6b} - S > 0$$

if $S < \frac{aed}{6b}$, which is higher than $\widehat{S}^{*DG}$. Hence, $W^{d,DG} > W^{d,DD}$ is always satisfied under the set of admissible conditions for S and F.

Finally, the comparison between $W^{m,D}$ and $W^{d,DG}$ requires that $\frac{a}{2e} \leq d < \frac{2e}{3a}$.

$$W^{d,DG}(\tau^{d,DG}) - W^{m,D}(\tau^{m,D}) = \frac{aed}{6b} - (F + S) > 0$$

if $F + S < \frac{aed}{6b}$. The conditions of S for both cases are compatible, i.e. $\max\{\overline{S}^{*D}, \widetilde{S}^{*DG}\} < S \leq \widehat{S}^{*DG}$. However, $\overline{F}^{*D} > \overline{F}^{*DG}$. ■

6.12 Proof of proposition 4

Now we analyze the cases when firm 1 adopts the green technology and $\theta = \frac{1}{2}$.

No Entry. When firm 1 operates as a green monopolist, the optimal emission fee is $\tau^{m,G}\left(\theta = \frac{1}{2}\right) = 2d - \frac{2a}{e}$, which requires $\frac{a}{e} \leq d < \frac{2a}{e}$. Hence,

$$W^{m,G}(\tau^{m,G}) = \frac{(2a - ed)^2}{8b} - S.$$

From proposition 2, firm 2 stays out if $F > \overline{F}^{*G} \equiv \max\{\frac{(4a-3ed)^2}{9b}, \frac{(2a-ed)^2}{9b} - S\}$, and firm 1 adopts the green technology for all $S \leq \overline{S}^{*G} \equiv \frac{(5a-3ed)(ed-a)}{4b}$.

Entry. Let us now analyze the case in which both firms adopt the green technology. The optimal emission fee becomes $\tau^{d,GG}\left(\theta = \frac{1}{2}\right) = \frac{3d}{2} - \frac{a}{e}$, which requires $\frac{2a}{3e} \leq d < \frac{2a}{e}$. Therefore,

$$W^{d,GG}(\tau^{d,GG}) = \frac{(2a - ed)^2}{8b} - (F + 2S) = W^{m,G} - (F + S).$$

Moreover, both firms adopt the green technology if $S \leq \widetilde{S}^{*GG} \equiv \frac{(4a-3ed)(3ed-2a)}{18b}$ and firm 2 enters when $F \leq \overline{F}^{*GG} \equiv \frac{(2a-ed)^2}{16b} - S$.

However, if firm 2 keeps its dirty technology, the optimal emission tax, social welfare, and the condition of fixed costs for green technology are the same as outcome (D,G). In addition, it also requires $\frac{a}{3e} \leq d < \frac{2a}{3e}$. The range of fixed entry costs becomes $F \leq \overline{F}^{*GD} \equiv \frac{(2a-3ed)^2}{9b}$.

Social welfare comparisons. Notice that outcomes (G) and (G,G) require that the environmental damage satisfies $\frac{a}{e} \leq d < \frac{2a}{e}$, while case (G,D) only occurs for a relatively low range of d, i.e. $\frac{a}{3e} \leq d < \frac{2a}{3e}$. Therefore it is only meaningful to compare $W^{m,G}$ with $W^{d,GG}$. It is straightforward to show that $W^{m,G} > W^{d,GG}$. In addition,

$$\overline{S}^{*G} - \widetilde{S}^{*GG} = \frac{-(9(ed)^2 - 36aed + 29a^2)}{36b} \gtrless 0,$$

depending on the value of d. Thus the compatible condition of S is $S < \min\{\overline{S}^{*G}, \widetilde{S}^{*GG}\}$. However, $\overline{F}^{*G} > \overline{F}^{*GG}$. ■

6.13 Proof of Lemma 8

No entry. Comparisons between $W^{m,G}$ and $W^{m,D}$ are not possible since they do not coexist within the range of admissible environmental damage.

Entry. Let us compare $W^{d,GG}$ and $W^{d,DD}$ for all $d \in [\frac{2a}{3e}, \frac{a}{e})$. The conditions of F that support both cases are $F \leq \min\{\overline{F}^{*DD}, \overline{F}^{*GG}\}$. In addition,

$$\widetilde{S}^{*GG} - \widehat{S}^{*DD} = \frac{-(9(ed)^2 - 18aed + 11a^2)}{36b} < 0.$$

Hence, $S < \widehat{S}^{*GG}$. Comparing social welfare for the two outcomes, we obtain

$$W^{d,GG} - W^{d,DD} = \frac{(2a - ed)^2}{8b} - \frac{(a - ed)^2}{2b} - 2S > 0$$

if $S < \frac{(4a - 3ed)ed}{16b}$, which is lower than $\widetilde{S}^{*GG}$.

Note that we cannot compare $W^{d,GG}$ with $W^{d,DG}$ since they occurs in different ranges of d. Finally, the comparison between $W^{d,GD}$ and $W^{d,DD}$ coincides with that of $W^{d,DG}$ and $W^{d,DD}$ in the proof of proposition 3. ■

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