Strategic Emission Fees: Entry Deterrence and Green Technology*

Ana Espínola-Arredondo†
School of Economic Sciences
Washington State University
Pullman, WA 99164

Felix Munoz-Garcia‡
School of Economic Sciences
Washington State University
Pullman, WA 99164

Boying Liu§
School of Economic Sciences
Washington State University
Pullman, WA 99164

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Abstract

We consider a sequential-move game in which a polluting monopolist chooses whether to acquire a green technology, and a potential entrant responds deciding whether to join the market and, upon entry, whether to invest in clean technology. Our paper compares two models: one in which environmental regulation is strategically set before firms' decisions; and another where regulation is selected after firms' entry and investment decisions. We show that a proactive regulation that strategically anticipates firms' behavior can implement different market structures. In particular, policy makers can choose emission fees to induce competition and/or investment in clean technology, giving rise to market structures that maximize social welfare.

Keywords: Green Technology Adoption; Market Structure; Emission tax; Strategic regulation.

JEL classification: H23; L12; Q58.

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†Address: 111C Hulbert Hall, Washington State University, Pullman, WA 99164. E-mail: anaespinola@wsu.edu.

‡Address: 101G Hulbert Hall, Washington State University, Pullman, WA 99164. E-mail: fmunoz@wsu.edu.

§Address: 315 Hulbert Hall, Washington State University, Pullman, WA 99164. E-mail: boying.liu@wsu.edu.

1 Introduction

Climate change has lead some countries to regard environmental policy as urgent.[1] However, such policy still raises opposition given its potential impact on firms' competitiveness and growth. As a consequence, environmental regulation should carefully consider market conditions and pollution. In particular, if the market structure changes as a result of regulation, a policy that does not anticipate such effects would yield suboptimal outcomes.[2] Instead, regulators should recognize the market dynamics that ensue due to environmental policy; especially given how dynamic market structures have become, both in terms of the number of competing firms and in their investment decisions in green technology. This paper shows that the traditional approach to environmental policy, where the regulator observes the current market structure and responds with regulation, yields to consistently lower welfare levels than a more strategic policy, where the regulator recognizes his active role in modifying future industry characteristics.[3]

In order to analyze the effects of strategic emission fees, we examine two models. First, we consider a setting with the following time structure: In the first stage, the regulator sets emission fees; in the second, an incumbent firm chooses whether to invest in green technology; in the third, a potential entrant decides whether to join the market and, if so, whether to acquire green technology; and in the last stage, firms choose their output levels. We compare equilibrium results with those of a second model in which the regulator acts in the third stage, thus taking the market structure as given. In particular, we analyze how the emergence of different market structures, and how firms' decision to acquire green technology, are affected by the time period in which the regulator sets emission fees.

Using backward induction in the first model, we find that the entrant's response depends on its entry costs and on the cost of acquiring the green technology. In particular, we identify cases in which the entrant stays out the market regardless of the incumbent's technology (blockaded entry), is deterred if the incumbent acquires green technology (deterred entry), or enters independent of the incumbent's technology. The incumbent anticipates the entrant's behavior in subsequent stages, and thus uses its investment in green technology as an entry-deterring tool when the cost of such technology are sufficiently low. Otherwise, the incumbent keeps its dirty technology since the cost of acquiring the green technology offsets its associated entry-deterring benefits; thus giving rise to a dirty duopoly. (We also show that mixed duopolies can emerge, with one firm choosing green technology while the other keeps its dirty technology, when entry costs are low and technology costs

[1] President Obama recognized the urgency of policies tackling climate change during the presentation of the revised Clean Power Plan in August 3, 2015, when he mentioned: "We are the first generation to feel the impacts of climate change, and the last generation to be able to do something about it."

[2] Finland was in 1990 the first country to enact a carbon tax. While Neste was the only oil company (refinery and distributor) active in Finland when the tax was enacted, the St1 oil company entered the industry in 1995 and started its operations in 1997. Although both companies have recently invested in bioethanol production, the carbon tax did not affect their investment decisions during the 1995-97 entry period.

[3] Several environmental regulations in the US are frequently revised according to current industry conditions. For instance, EPA (2001) indicates that wastewater discharge fees across most states have been raised approximately every year since 1986, exceeding the rate of inflation. Similarly, air emission fees in California have also experienced yearly changes since 1996.

take intermediate values.)[4]

These findings, however, are different in the second model, whereby the regulator chooses emission fees at the third stage of the game. In this setting, he cannot alter firms' subsequent entry and investment decisions. In contrast, a proactive regulation that strategically anticipates firms' behavior can now expand the set of market structures that a policy maker implements. In particular, he can choose emission fees to induce competition and/or investment in clean technology, giving rise to market structures that could not emerge otherwise, ultimately maximizing social welfare. Nonetheless, such policy decision is constrained since, for given entry and investment costs, the regulator cannot implement all market structures, but a subset of them, among which he chooses that yielding the highest social welfare (second best). If, however, he ignores entry threats and investment decisions in future stages (taking the current market structure as given), he would generate market outcomes that yield even lower welfare levels (third best).

Therefore, regulatory agencies should be especially aware about the presence of potential competitors in the industry in order to design regulation considering its effects on entry and investment as well as its profound consequences on social welfare. Our results, furthermore, suggest that even if regulatory agencies gather accurate information about market conditions and firms' costs, they would induce poor welfare outcomes if they ignore the strategic ramifications that unfold once environmental regulation is implemented. Our paper is especially relevant in developing economies where polluting industries are relatively concentrated, such as chemical, oil and other natural resource extraction, and where policy makers seek to address environmental damages through regulation. In these contexts, the design of proactive (rather than reactive) regulation could have significant effects on market structures and firms' decision to adopt green technologies.

Related literature. Several studies consider a given market structure and examine how environmental regulation affects firms' incentives to invest in abatement technologies, while other papers take firms' technology as given and analyze how environmental policy produces changes in the number of firms competing in the industry. Specifically, the first group of studies shows that environmental policy can stimulate the adoption of new technologies that reduce marginal emissions or save abatement costs (Porter and van der Linde 1995; Zhao 2003; Requate 2005a; Krysiak 2008; Perino and Requate 2012; and Storrøsten 2015). 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).[5] Among different environmental regulations, it is well known that market-based instruments are preferred by economists and widely implemented in many countries (Requate, 2005a). Specifically, emission fees are

[4] In particular, the incumbent's decision gives rise to different market structures: a dirty monopoly, in which entry and technology costs are sufficiently high; a green monopoly, in which entry costs are high but technology costs are low; a dirty (green) duopoly, if low (high) entry costs are accompanied by high (low) technology costs; and a mixed duopoly, which occurs when entry costs are low and technology costs take intermediate values.

[5] A traditional conclusion is that such incentives increase monotonically with regulation stringency (Requate and Unold 2003).

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). Similarly, our paper examines how an appropriate emission fee induces firms to adopt clean technology. However, unlike the previous literature, we focus on an entry-deterrence model rather than markets that do not face entry threats.

Our results are also connected with the second group of papers, as they suggest that stringent emission fees could affect 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 by Heyes (2009) also concludes that environmental regulation helps 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.[6] 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 allowing incumbent and entrant to invest in green technology. This approach allows us to identify cases in which the regulator sets emission fees that do not support entry deterrence and promote the acquisition of green technology. In addition, our results show that, relative to settings where investment in green technology is unavailable (or prohibitively expensive), allowing both firms to invest in this technology attracts the potential entrant under larger conditions on entry costs, ultimately hindering the incumbent's ability to deter entry.

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 when the regulator moves first, and section 4 studies the model in which the regulator sets emission fees in the third stage; section 5 discusses our results.

2 Model

Consider a market with 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 $p(Q) = a - bQ$, where a, $b > 0$ and Q is the aggregate output level. If firm 2 decides to enter it must incur a fixed entry cost, $F > 0$. 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. We assume that firms initially have a dirty technology and, hence, if they adopt a green technology they must pay a fixed cost $S > 0$. Technologies differ in terms of their emissions, which are assumed to be proportional to output. In particular, if firm i acquires a clean technology its total emission level is $E_i = \theta q_i$, where $\theta \in (0, 1)$ describes the efficiency of the new technology in

[6] Our paper also connects with the literature on the optimal timing of environmental policy, such as Requate (2005b) who analyzes a monopoly investing in R&D and selling abatement technology to other firms.

reducing emissions. Specifically, the green technology becomes more efficient with lower values of θ. However, if firm i keeps its dirty technology every unit of output generates one unit of emissions. 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 marginal environmental deterioration. Finally, in order to guarantee that emission fees are positive under all market structures we consider that the environmental damage is substantial, $d > \frac{a}{3\theta}$; but not too severe, i.e., $d < a$, as otherwise a zero output level would become socially optimal.

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.

We analyze a four-stage complete information game, with the following time structure:

- In the first period, the regulator sets an emission fee, τ.
- In the second period, the incumbent chooses its technology (dirty or green).
- 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 does not occur, the incumbent operates as a monopolist. If entry ensues, both firms compete a la Cournot game.

We derive the subgame-perfect Nash equilibrium. Specifically, in the following sections, we first investigate two different market structures in the fourth period (with and without entry), and then examine firm 2's decision over entry and technology in the third period. We next analyze the incumbent's technology choice in the second period, and finally study the regulator's optimal emission fee in the first period of the game. The time structure considers that the regulator chooses emission fees before firms choose their technology and whether to enter the industry, and thus he can strategically alter the conditions under which each market structure emerges. Alternatively, the regulator could take the market structure as given and respond to that with an optimal emission fee. For completeness, we explore this setting in section 4.

No regulation. As a benchmark the next lemma analyzes equilibrium behavior when regulation is absent.

Lemma 1. *When regulation is absent the incumbent does not invest in green technology under any parameter values. The entrant responds entering with dirty technology if and only if* $F < \frac{a^2}{9b}$.

Therefore, if entry costs are sufficiently low, $F < \frac{a^2}{9b}$, the entrant joins the industry and a dirty duopoly arises, while entry does not occur otherwise (and a dirty monopoly emerges). Hence, in the absence of regulation there are no incentives for firms to acquire green technology, whereas as we next show the introduction of an emission fee induces one or both firms to invest in clean technology.

3 Subgame Perfect Nash Equilibrium

3.1 Fourth stage

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. Firm 1 produces strictly positive output levels if the emission fee satisfies $\tau < a$ in the case of dirty technology, and $\tau < \frac{a}{\theta}$ in the case of green technology (as confirmed in the optimal emission fees found in the third stage of the game). We consider a nonnegative emission tax throughout the paper and thus assume $\tau \geq 0$. Profits are decreasing in the dirtiness of the green technology, θ, and its associated cost, S.

Table 1. Output levels and profits under monopoly

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

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 jk represents firm 1 (incumbent) choosing technology j and firm 2 (entrant) selecting 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 of every pair 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 considers that firm 2 keeps its dirty technology while in the right-hand column it adopts green technology.

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

Firm 2's type	**D**	**G**
Output[7]	$q_i^{d,DD} = \frac{a-\tau}{3b}$	$q_1^{d,DG} = \frac{a-\tau(2-\theta)}{3b}$ $q_2^{d,DG} = \frac{a-\tau(2\theta-1)}{3b}$
Profit	$\pi_1^{d,DD} = \frac{(a-\tau)^2}{9b}$ $\pi_2^{d,DD} = \frac{(a-\tau)^2}{9b} - F$	$\pi_1^{d,DG} = \frac{[a-\tau(2-\theta)]^2}{9b}$ $\pi_2^{d,DG} = \frac{[a-\tau(2\theta-1)]^2}{9b} - (F+S)$

Table 2 shows that firms' output and profits decrease in emission fees, when both have dirty technology. However, under a (D,G)-duopoly the green entrant's output and profits increase in emission fees if its technology is sufficiently clean, i.e., $\theta < \frac{1}{2}$. Finally, the incumbent's output in the (D,G)-duopoly is smaller than the entrant's, since emission fees more severely impact the dirty than the green firm. As a consequence, the green firm captures a larger market share than that

[7] If both firms keep their dirty technology, case (D, D), they produce strictly positive ouput levels if $\tau < a$. However, when only the entrant acquires green technology, (D, G), both firms produce a positive output if $\tau < \frac{a}{2-\theta}$.

keeping its dirty technology. Table 3 analyzes the case in which firm 1 decides to acquire a green technology, i.e., (G, D) and (G, G).

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

Firm 2's type	**D**	**G**
Output[8]	$q_1^{d,GD} = \frac{a-\tau(2\theta-1)}{3b}$ $q_2^{d,GD} = \frac{a-\tau(2-\theta)}{3b}$	$q_i^{d,GG} = \frac{a-\tau\theta}{3b}$
Profit	$\pi_1^{d,GD} = \frac{[a-\tau(2\theta-1)]^2}{9b} - S$ $\pi_2^{d,GD} = \frac{[a-\tau(2-\theta)]^2}{9b} - F$	$\pi_1^{d,GG} = \frac{(a-\tau\theta)^2}{9b} - S$ $\pi_2^{d,GG} = \frac{(a-\tau\theta)^2}{9b} - (F+S)$

Similar intuitions to those in table 2 apply when the incumbent is a green type, whereby output and profits decrease in τ unless the green technology is sufficiently clean.

3.2 Third stage

In this stage of the game, firm 2 decides whether or not to enter and, upon entry, its technology type, taking the emission fee as given. The next lemma analyzes the entrant's optimal responses.

Lemma 2. *When firm 1 is a dirty (green) type and $\tau < \frac{a}{2-\theta}$, firm 2: (1) enters and adopts green technology if entry costs satisfy $F \leq \bar{F}^{DG}$ ($F \leq \bar{F}^{GG}$ and $S \leq \widetilde{S}$); (2) enters and keeps its dirty technology if $\bar{F}^{DD} \geq F > \bar{F}^{DG}$; and (3) does not enter if $F > \bar{F}^{DD}$ ($F > \bar{F}^{GD}$, respectively), where the entry costs cutoffs for a dirty incumbent are $\bar{F}^{DG} \equiv \frac{[a-\tau(2\theta-1)]^2}{9b} - S$, and $\bar{F}^{DD} \equiv \frac{(a-\tau)^2}{9b}$, while those for a green incumbent are $\bar{F}^{GG} \equiv \frac{(a-\tau\theta)^2}{9b} - S$, $\widetilde{S} \equiv \frac{4\tau(1-\theta)(a-\tau)}{9b}$, and $\bar{F}^{GD} \equiv \frac{[a-\tau(2-\theta)]^2}{9b}$.*

Figure 1a identifies the entrant's responses when the incumbent keeps its dirty technology, while figure 1b depicts its responses when the incumbent adopts a green technology. Intuitively, when F and S are sufficiently low (close to the origin in figure 1), firm 2 chooses to enter with green technology irrespective of the incumbent's technology, as firm 2's profits satisfy $\pi_2^{d,KG} \geq \pi_2^{d,KD} > 0$ for every $K = \{D, G\}$. However, when investment costs, S, are relatively high, firm 2 enters with a dirty technology since its profits are higher than otherwise, i.e., $\pi_2^{d,KG} < 0 < \pi_2^{d,KD}$. Finally, when entry costs are higher than $\bar{F}^{DD}$, firm 2 does not enter given that its profits would be negative under all technologies, $\pi_2^{d,KG} < \pi_2^{d,KD} < 0$. (Note that cutoff $\bar{F}^{DD}$ is constant in S, and originates above cutoff $\bar{F}^{DG}$ since $\tau < \frac{a}{2-\theta}$.)

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

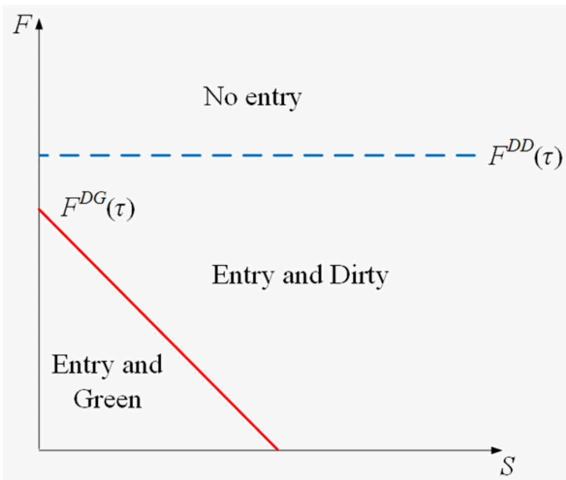

Fig 1a. Responses to a dirty incumbent.

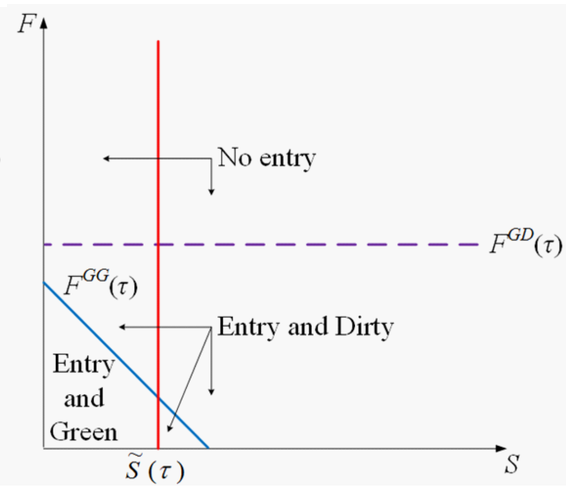

Fig 1b. Responses to a green incumbent.

In addition, a comparison of the cutoffs across figures yields $\bar{F}^{GD} < \bar{F}^{DD}$, which entails that firm 2 enters with a dirty technology under larger conditions when it faces a green than a dirty incumbent. Hence, the entrant anticipates that it will face less stringent emission fees when competing against a green incumbent. Furthermore, $\bar{F}^{DG} > \bar{F}^{GG}$ which implies that, when firm 2 enters, it invests in green technology under a smaller set of $(F, S)-$pairs when its rival is green than when it is dirty.

The following Lemma 3 summarizes the entrant's responses after the incumbent adopts a dirty or a green technology. Interestingly, in some cases the entrant's behavior is unaffected by the incumbent's technology, in other cases the entrant responds choosing the opposite technology, or stays out when the incumbent invests in green technology.

Lemma 3. *The entrant responds to the incumbent's technology decision as follows:*

I. *No entry regardless of the incumbent's technology choice if* $F > \bar{F}^{DD}$.

II. *No entry when the incumbent is green, but entry when the incumbent is dirty in which case the entrant chooses:*

   (a) *Dirty technology if* $\bar{F}^{DD} \geq F > \max\left\{\bar{F}^{GD}, \bar{F}^{DG}\right\}$.

   (b) *Green technology if* $\bar{F}^{DG} \geq F > \bar{F}^{GD}$.

III. *Dirty technology regardless of the incumbent's technology choice if* $\bar{F}^{GD} \geq F > \bar{F}^{DG}$.

IV. *Choosing the opposite technology than the incumbent if: (i)* $\min\{\bar{F}^{DG}, \bar{F}^{GD}\} \geq F > \bar{F}^{GG}$, *and if (ii)* $F < \bar{F}^{GG}$ *and* $S > \widetilde{S}$.

V. *Green technology regardless of the incumbent's technology choice if* $F < \bar{F}^{GG}$ *and* $S \leq \widetilde{S}$.

Figure 2 depicts all cutoffs from figures 1a and 1b, and thus divides the (F, S)-quadrant into regions I-V, each corresponding to an entrant's response described Lemma 3. In region I, entry costs are sufficiently high to blockade entry regardless of the incumbent's technology decision. In region II, however, the incumbent's choice of a green technology can deter entry (in region IIa), but keeping its dirty technology cannot deter entry (in region IIb) which is responded with investment in green technology by the entrant given its relatively low cost. However, in region III the incumbent's technology choice has no effect on firm 2's entry decision, nor on its technology choice. Finally, in region IV, the entrant joins and chooses the opposite technology than the incumbent. In the case that the incumbent invests in green technology, the entrant finds it too costly to acquire such a technology. In other words, the intermediate cost of S exceeds the competitive disadvantage of operating in a (G,D)-duopoly. If in contrast, the incumbent keeps its dirty technology, the entrant becomes green and benefits from a competitive advantage in the (G,D)-duopoly.

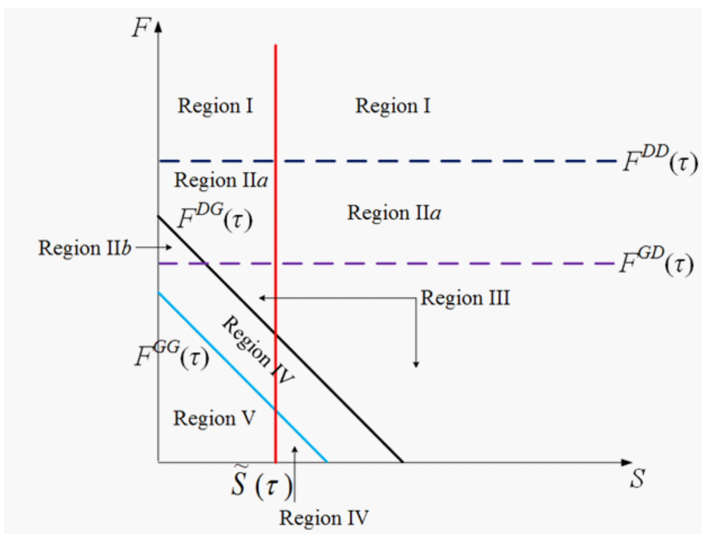

Fig 2. Entrant's responses.

The cutoffs on F and S identified in Lemmas 2-3 are a function of τ, implying that the regions under which firm 2 decides to enter (and its technology choice upon entry) is affected by the regulator's choice of τ at the first period of the game. That is, regions I-V expand/shrink depending on the specific fee selected by the regulator.

3.3 Second stage

Anticipating the entrant's responses in the third stage, firm 1 selects its own technology; as the next lemma describes.

Lemma 4. *In region $i = \{I, IIa, IIb, III\}$ the incumbent chooses a green technology if its cost satisfies $S < S_i$, where $S_I \equiv \frac{\tau(1-\theta)(2a-\tau(1+\theta))}{4b}$, $S_{IIa} \equiv \frac{5a^2-2\tau a(9\theta-4)+\tau^2(9\theta^2-4)}{39b}$, $S_{IIb} \equiv$*

$\frac{5a^2-2\tau a(13\theta-8)+\tau^2\left[5\theta^2-16(1-\theta)\right]}{39b}$, *and* $S_{III} = \frac{4\tau(1-\theta)(a-\tau\theta)}{9b}$. *In regions IV and V, the incumbent adopts green technology under all parameter values.*

The incumbent's technology choice in the second stage exhibits, hence, a similar pattern as that of the entrant in the third stage, since the incumbent decides whether to invest in green technology based on cutoffs of S that also depend on fee τ.

3.4 First stage

Let us finally analyze the first stage of the game. Define the set of market structures as $M = \{D, G, DD, GG, DG, GD\}$ indicating, respectively, a dirty monopoly, a green monopoly, a dirty duopoly, a green duopoly, and the two types of mixed duopolies. For a given emission fee, τ, let $M^*(\tau) \subset M$ be the set of implementable market structures, i.e., those that emerge in stages 2-3 of the game when firms face fee τ and a given $(F,S)-$pair. Intuitively, starting from any $(F,S)-$pair in Figure 2, a marginal change in fee τ shifts the position of all cutoffs for F and S, ultimately giving rise to one or more market structures in $M^*(\tau)$. Therefore, the model cannot be solved analytically. We next provide a formal description of the regulator's decision rule in the first stage of the game, and subsequently offer a numerical example.

The regulator chooses the emission fee τ that solves

$$\max \ \left\{W\left(\tau^*(m_1)\right), W\left(\tau^*(m_2)\right), ..., W\left(\tau^*(m_N)\right)\right\} \tag{1}$$

where all market structures in profile $(m_1, m_2, ..., m_N)$ are implementable, i.e., $m_i \in M^*(\tau)$ for every $i = \{1, 2, ..., N\}$; and the optimal fee in market m_i, $\tau^*(m_i)$, solves

$$W\left(\tau^*(m_i)\right) \equiv \max_{\tau \geq 0} \ W\left(\tau(m_i)\right) \tag{2}$$

In words, the regulator's decision follows a two-step approach (starting from problem (2) and moving to (1)):

1. First, for every implementable market structure, $m_i \in M^*(\tau)$, the regulator chooses the welfare-maximizing emission fee $\tau^*(m_i)$ among all taxes that implement such a market m_i, yielding $W\left(\tau^*(m_i)\right)$.

2. Second, the regulator compares the maximal welfare that each implementable market structure generates, i.e., $W\left(\tau^*(m_i)\right)$ for all $m_i \in M^*(\tau)$, and selects the fee that induces the market with the highest welfare.

Importantly, since the set of implementable market structures $M^*(\tau)$ does not necessarily include all elements in M, i.e., $M^*(\tau) \subset M$, the regulator's choice is constrained in terms of the markets he can implement, and thus could lead to a second best. We next provide a numerical example to illustrate the regulator's decision in the first stage of the game.

Example: Consider parameter values $a = b = 1$, $d = 0.8$, $\theta = 0.45$, and costs $F = 0.01$ and $S = 0.02$. In this context, the conditions for positive output levels described in section 2 entail $\tau < \frac{a}{\theta} = \frac{1}{0.45} = 2.22$ and $\tau < \frac{a}{2-\theta} = \frac{1}{2-0.45} = 0.64$. (We thus restrict our attention to fees satisfying $\tau < 0.64$.) In this case, only two market structures can be implemented by variations on τ: the (G,G)-duopoly with fees $\tau \in [0.09, 0.64)$, and the (G,D)-duopoly for fees $\tau < 0.09$. Specifically, the $(F, S) = (0.01, 0.02)$ pair lies in the region of admissible parameters that support a (G,G)-duopoly when τ is relatively high. When τ decreases, however, such a region shrinks, leaving the $(0.01, 0.02)$ pair outside the (G,G) region, and inside the area that sustains the (G,D)-duopoly. (For more details, see Appendix 1.) Furthermore, if the regulator sets fees in the first stage but ignores the second and third stage (as if the market structure was not affected by fees), he would set a fee of $\tau^{m,D} = 0.6$ to the initial dirty monopoly, which would still induce a (G,G)-duopoly since $\tau \in [0.09, 0.64)$, yielding an even lower social welfare of $W^{GG}(0.6) = 0.01$.

Hence, the set of implementable market structures is $M^*(\tau) = \{GG, GD\}$. Next, the regulator chooses the welfare-maximizing emission fee $\tau^*(\theta)$ within the interval of τ's that implements every market structure, as follows:[9]

$$\tau^*(GG) = 0.09 \text{ solves } \max_{\tau \in [0.09, 0.64)} W^{GG}(\tau) = \frac{695 + 9\tau(45\tau - 146)}{4500}$$

and

$$\tau^*(GD) = 0 \text{ solves } \max_{\tau \in [0, 0.09)} W^{GD}(\tau) = \frac{1000 + \tau(13855\tau - 8752)}{36000}$$

Figure 3 illustrates $W^{GG}(\tau)$ and $W^{GD}(\tau)$ for all $\tau < 0.64$. For low values of τ, the (G,D)-duopoly can be implemented, while for high values of τ the (G,G)-duopoly arises.

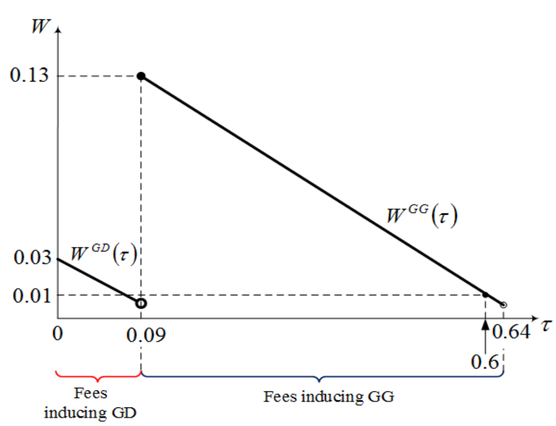

Fig 3. Comparison of $W^{GG}(\tau)$ and $W^{GD}(\tau)$.

[9] Both welfare functions $W^{GG}(\tau)$ and $W^{GD}(\tau)$ are monotonically decreasing in τ for the admissible range of emission fees, $\tau \in [0, 0.64)$.

Finally, the regulator compares the welfare that arises from optimal fees $\tau^*(m)$ in these implementable market structures, obtaining

$$W^{GG}(0.09) = 0.13 \text{ and } W^{GD}(0) = 0.03,$$

thus, selecting a fee of $\tau^*(GG) = 0.09$ that induces a green duopoly.

Our results hold under other parameter values. For instance, a more damaging pollution ($d = 0.9$) does not affect the cutoffs for F and S that give rise to different market structures in the (F, S)-quadrant. As a consequence, the intervals of emission fees that the regulator can use are also unaffected, i.e., (G,D) and (G,G) still arise under the same values of τ; and thus the same optimal fees in each market structure apply, $\tau^*(GD) = 0$ and $\tau^*(GG) = 0.09$. However, a more harmful pollution lowers the social welfare for all market structures, graphically shifting $W^{GG}(\tau)$ and $W^{GD}(\tau)$ downwards in figure 3, which entails a lower welfare in equilibrium $W^{GG}(0.09) = 0.10$.

4 Regulator moving in the third stage

In previous sections, we assume that the regulator acts before observing the market structure and investments decisions by all firms. How would our results change if the regulator sets emission fees in the third stage of the game (before firms choose their output levels)? In this setting, the order of play would be the following: in the first stage the incumbent chooses whether to invest in green technology; in the second stage firm 2 responds choosing to enter and, if so, whether to acquire green technology; in the third stage, the regulator sets an emission fee given the entry and investment patterns emerging from the previous stages; and in the fourth stage firm 1 chooses its output as a monopolist (if entry does not occur) or competes with firm 2 (if entry ensues).

Third stage. Solving the game by backward induction, we focus on the third stage since in the fourth stage firms' output and profits coincide with those in section 3. In the third stage, the regulator sets the optimal fees identified in the following Lemma.

Lemma 5. *Depending on the market structure that ensues from the second stage, the regulator chooses an optimal emission fee: (1) Dirty monopoly:* $\tau^{m,D} = 2d - a$*; (2) Green monopoly:* $\tau^{m,G} = 0$*; (3) Dirty duopoly:* $\tau^{d,DD} = \frac{3d-a}{2}$*; (4) Green duopoly:* $\tau^{d,GG} = \frac{3d\theta-a}{2\theta}$*; and (5) (G,D) and (D,G)-duopoly:* $\tau^{d,GD} = \tau^{d,DG} = \frac{3d\theta-a}{1+\theta}$.

Similar as in Buchanan (1969), emission fees are more stringent in duopoly than in monopoly for a given technology, i.e., $\tau^{d,KK} > \tau^{m,K}$ for all $K = \{D, G\}$. In addition, fees are stricter in a green than dirty monopoly, that is $\tau^{m,D} > \tau^{m,G}$; and a similar ranking arises under a duopoly in which both firms choose the same technology, $\tau^{d,DD} > \tau^{d,GG}$. Note that in the case of a green monopoly the incumbent would only invest in green technology when receiving a subsidy.[10]

[10] For the remainder of this section we focus on green technologies that have a significant impact at reducing emissions, $\theta < 1/2$.

Second stage. We next analyze the entrant's responses to the incumbent's technology decision in the second stage of the game. Unlike in section 3, the entrant can now anticipate the optimal fee that the regulator sets for each market structure in the subsequent stage, and decides whether to enter and invest in green technology if its associate costs F and S are sufficiently low. We find that in some cases the entrant's behavior is unaffected by the incumbent's technology, in other cases the entrant responds choosing the opposite technology, or stays out when the incumbent invests in green technology. (For compactness, all cutoffs of Lemma 6 are defined in its proof.)

Lemma 6. *The entrant responds to the incumbent's technology decision as follows:*

I. *No entry regardless of the incumbent's technology choice if* $F > \max\{F^A, F^D\}$.

II. *No entry when the incumbent is green (dirty), but entry when the incumbent is dirty (green) in which case the entrant chooses green (dirty) technology if* $F^A \geq F > \max\{F^C, F^D\}$ ($F^D \geq F > \max\{F^A, F^B\}$*, respectively).*

III. *Green (Dirty) technology regardless of the incumbent's technology choice if* $F \leq F^C$ *and* $S \leq S_B$ *(if* $F \leq F^B$ *and* $S > S_A$*, respectively).*

IV. *Choosing the opposite technology than the incumbent if* $S_A \geq S > S_B$ *and* $\min\{F^A, F^D\} \geq F$*.*

Figure 4 identifies the four types of entrant's responses of Lemma 6 in regions I-IV. In region I, entry costs are sufficiently high to blockade entry regardless of the incumbent's technology decision. In region II, in contrast, the incumbent's choice of a green technology can deter entry (in region IIa), but entry ensues if the incumbent keeps its dirty technology (in region IIb). In this case, the entrant responds investing in green technology given its relatively low cost. However, in region III the incumbent's technology choice has no effect on firm 2's entry decision, nor on its technology choice. In particular, in region IIIa (IIIb) costs from entering and acquiring green technology, the sum of F and S, are low (high), inducing the entrant to choose a green (dirty, respectively) technology regardless of the incumbent's decision. Finally, in region IV, the entrant joins and chooses the opposite technology than the incumbent. In the case that the incumbent invests in green technology, the entrant finds it too costly to acquire such a technology. In other words, the intermediate cost of S exceeds the competitive disadvantage of operating in a (G,D)-duopoly. If in contrast, the incumbent keeps its dirty technology, the entrant becomes green and benefits from a competitive advantage in the (D,G)-duopoly.

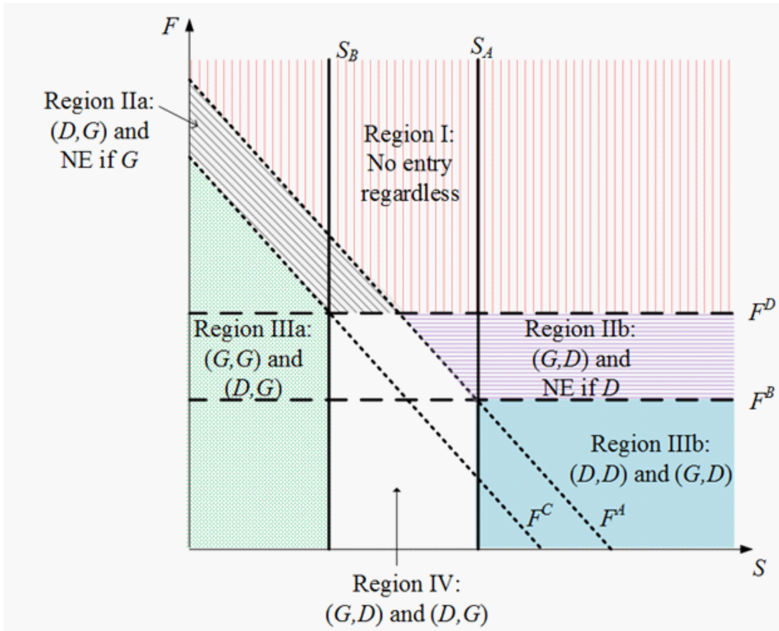

Fig 4. Entrant's responses when the regulator acts third.

First stage. The next proposition analyzes firm 1's technology decision.

Proposition 1. *The incumbent chooses the following technologies:*

- *In region I, green technology if* $S \leq S_I = \frac{(a-2d)(2d-3a)}{4b}$*, entailing a green monopoly. Otherwise, a dirty monopoly arises.*
- *In region IIa, green technology for all parameter values, entailing a green monopoly.*
- *In region IIb, green technology under all parameter values if* $a > \frac{d[(2+3\theta)-\sqrt{\theta(4+\theta(2\theta-3)(1+2\theta))}]}{2(1+\theta)}$*, entailing a (G,D)-duopoly. Otherwise, the incumbent chooses dirty technology if and only if* $S > S_{IIb} \equiv \frac{d\theta^2[a+d(1-2\theta)]-(a-d)^2(1+\theta)}{b(1+\theta)}$ *and a dirty monopoly emerges.*
- *In region IIIa (IIIb), green (dirty) technology under all parameter values, entailing a green (dirty) duopoly.*
- *In region IV, green technology if* $S \leq 2S_B$*, entailing a (G,D)-duopoly. Otherwise, a (D,G)-duopoly arises.*

Figure 5 summarizes the market structures that arise in each region. Specifically, in region I and IIa a green monopoly emerges. In region I entry is blockaded under all parameter values and the incumbent invests in green technology if its cost is sufficiently low. Intuitively, firm 1 compares the savings in emission fees against the cost of acquiring green technology, and chooses the latter if S is relatively low. In region IIa, the incumbent is threatened by entry and deters it by investing in green technology. Similarly, in region IIb the incumbent is threatened, but can deter entry by keeping is dirty technology, which is profitable if the cost of the green technology is sufficiently high. In this case, the incumbent expects small savings in emission fees from investing in green technology which, in addition, is followed by entry. In region IIIa (IIIb) the cost of investing in green technology is very low (high), inducing both incumbent and entrant to choose green (dirty) technology. Finally, in region IV the incumbent compares the benefits from acquiring green technology (capturing a larger market share) against its associated costs: (1) the technology cost S; and (2) the cost from taxes which despite having identical emission fees in both market structures, $\tau^{d,GD} = \tau^{d,DG}$, becomes larger under the (G,D)-duopoly given that the incumbent produces a larger output level. Hence, when S is sufficiently low, the benefit from green technology offsets its two costs.

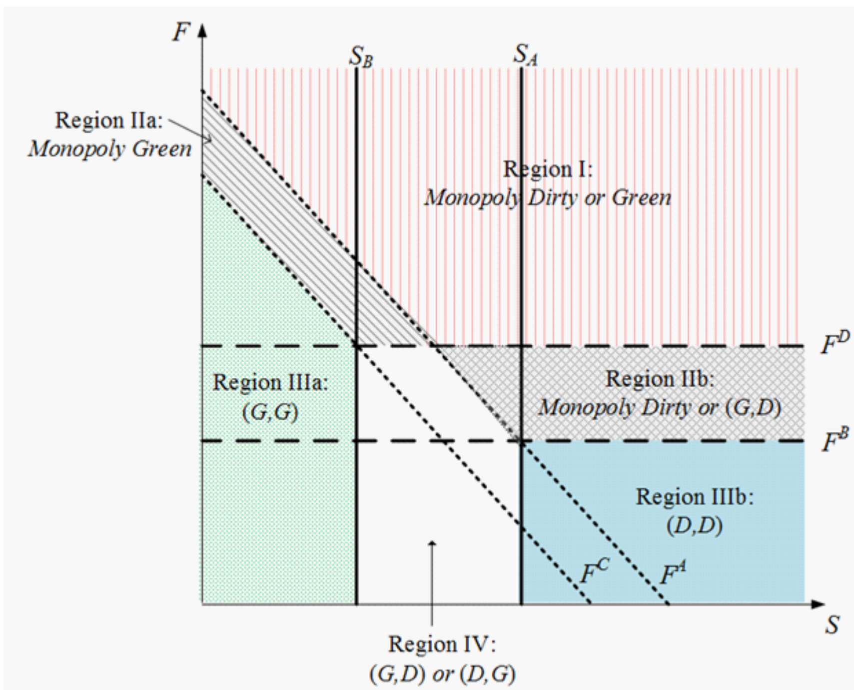

Fig 5. Summary of market structures.

Unlike in section 3 (where the regulator acts first), firms can now evaluate their profits from investing/not investing in green technology (and from entering/not entering for firm 2) at the optimal emission fee that the regulator will set in the fourth stage of the game. As a consequence, the cutoffs for F and S that yield different market structures in the (F, S)-quadrant are now evaluated at equilibrium fees; as opposed to those in section 3 whereby the regulator could alter the position of these cutoffs by varying τ in order to induce different market structures.

We next extend the previous numerical example, evaluate the welfare that arises when the regulator acts in the third stage of the game, and compare it against that when he acts first.

Example (cont'd). When the regulator acts in the third stage of the game, the $(F, S) = (0.01, 0.02)$ pair lies in region IV of figure 5, where a (G,D)-duopoly arises.[11] In this context, the optimal emission fee (from Lemma 5) is $\tau^{GD} = 0.055$, yielding a social welfare of $W^{GD} = 0.015$. Therefore, the regulator cannot implement the green duopoly when acting third, and social welfare becomes lower than when he acts first (where $W^{GG}(0.09) = 0.13$, as shown in the previous example).

In summary, if the regulator had the ability to directly choose the number of firms in the industry and their technology, our numerical example shows that the green monopoly would yield the highest social welfare (such market structure would be the first best). However, a green monopoly is not an implementable market structure. When we focus on implementable markets, the regulator can only use τ in order to induce firms to enter and/or invest in green technologies. In that context, the green duopoly becomes the best implementable market (second best). Finally, when he acts in the third stage of the game, a (G,D)-duopoly emerges (third best).

5 Discussion

A regulator that does not consider entry threats and potential investments in green technology would run the risk of setting emission fees that induce suboptimal market structures. Hence, environmental regulation will benefit from setting emission fees before entry and investment decisions are made. Such early policy would provide regulators with a wider set of market structures to implement, ultimately helping them reach a larger social welfare.

In addition, our results suggest that, even when the regulator acts first, if he ignores entry threats and investment decisions in future stages, he would set a emission fee corresponding to the existing dirty monopoly, $\tau^{m,D}$. In this case, he would inadvertently induce a market structure yielding lower welfare levels than even those achieved when he acts third. Therefore, regulatory agencies should be especially aware about the presence of potential competitors in the industry, their investment decisions after the policy, and design regulation taking into account that it can affect entry and the adoption of clean technology.

Furthermore, if the green duopoly is one of the implementable market structures, $M^*(\tau)$, the use of emission fees can help the regulator achieve such a market when he acts first, while he can only take the market structure as given when acting third.

Our paper could be extended to consider that firms, rather than incurring a fixed cost to acquire green technology, face a continuum of investment choices which increase in the cleanliness of the technology. In addition, we considered that the regulator is perfectly informed, but in a different setting he could be unable to observe the cost of clean technology. In this context, the position of the (F, S)-pair would be probabilistic, thus potentially inducing different market structures (each with an associated probability). It would be interesting to study how the optimal emission fee is

[11] It is straightforward to evaluate the cutoffs of Lemma 5-6 and Proposition 1 in these parameter values, yielding $F^A = 0.12 - S$, $F^B = 0.08$, $F^C = 0.11 - S$, $F^D = 0.10$, $S^A = 0.04$, $S^B = 0.0054$, $S_I = 0.36$, $S_{IIb} = 0.08$, $S_{IV} = 0.011$. Hence, the $(F, S) = (0.01, 0.02)$ pair lies in a region IV of figure 5.

set in this context, and whether uncertainty reduces the regulator's incentives to move first.

6 Appendix

6.1 Appendix 1 - Numerical example

For parameter values $a = b = 1$, $d = 0.8$, $\theta = 0.45$, the cutoffs for F and S become

$$\begin{aligned} \bar{F}^{DD}(\tau) &= \frac{(1-\tau)^2}{9},\ \bar{F}^{GD}(\tau) = \frac{1}{9}\left[\frac{20-31\tau}{20}\right]^2,\ \bar{F}^{DG}(\tau) = \frac{(10+\tau)^2}{900} - S, \\ \bar{F}^{GG}(\tau) &= \frac{1}{9}\left[\frac{20-9\tau}{20}\right]^2 - S,\ \widetilde{S} = \frac{11(1-\tau)}{45},\ \widehat{S} = S_{III} = \frac{11\tau(20-9\tau)}{900} \\ S_I &= \frac{11\tau}{80}\left[\frac{40-29\tau}{20}\right],\ S_{IIa} = \frac{2000-\tau(40+871\tau)}{14,400},\ S_{IIb} = \frac{(4+7\tau)(100-89\tau)}{2880} \end{aligned}$$

Let us check if the $(F, S) = (0.01, 0.02)$ pair lies in Region I-IV of Figure 2. First, it cannot lie in Region I, as for that we would need $F > \overline{F}^{DD}(\tau)$, which in this context implies $0.01 > \frac{(1-\tau)^2}{9}$, or $\tau > 0.7$, violating the initial condition on τ, i.e., $\tau < 0.64$. Hence, the regulator cannot implement the market structures that arise in Region I with any value of τ.

Second, the $(F, S) = (0.01, 0.02)$ pair cannot lie in Region IIa either, since for that we would need $F > \overline{F}^{DG}(\tau)$. In order to show that such a condition does not hold, note that cutoff $\overline{F}^{DG}(\tau)$ passes through pair $(F, S) = (0.01, 0.02)$ when the vertical intercept of $\overline{F}^{DG}(\tau)$ becomes 0.03. As a consequence, for condition $F > \overline{F}^{DG}(\tau)$ to be satisfied, we need that vertical intercepts satisfy $0.03 > \frac{(10+\tau)^2}{900}$. However, solving for τ in this inequality we obtain $\tau < -4.8$, which cannot hold by definition.

In addition, the $(F, S) = (0.01, 0.02)$ pair can lie in Region IIb. In particular, the (G,G)-duopoly emerges in this region when (1) $S < S_{IIb}$, (2) $F > \overline{F}^{GD}(\tau)$, and (3) $F < \overline{F}^{DG}(\tau)$, which in this parameter example entail, respectively,

$$0.02 < \frac{(4+7\tau)(100-89\tau)}{2880}$$

or $623\tau^2 - 344\tau - 342.4 < 0$, which holds for all admissible fees, $\tau < 0.64$; (2) $0.01 > \frac{1}{9}\left(1 - \frac{31\tau}{20}\right)^2$ or $\tau > 0.45$; and (3) $0.03 < \frac{(10+\tau)^2}{900}$, or $\tau > -4.8$ (as shown in our discussion of Region IIa above). Therefore, the regulator can implement the (G,G)-duopoly in Region IIb with emission fees in the interval $\tau \in [0.45, 0.64)$. The (D,G)-duopoly that also arises in Region IIb (when condition (1) is violated, but (2) and (3) hold) cannot be sustained since, as discussed above, $S > S_{IIb}$ would imply $\tau > 0.64$.

Third, the $(F, S) = (0.01, 0.02)$ pair cannot lie in Region III. Specifically, for the (G,D)-duopoly to arise, we need $S < \widehat{S}$, $F > \overline{F}^{DG}(\tau)$, and $F < \overline{F}^{GD}(\tau)$. However, condition $F > \overline{F}^{DG}(\tau)$ cannot hold since, from our above discussion of Region IIa, we know that it entails $\tau < -4.8$, which does not hold by definition. A similar argument applies to the (D,D)-duopoly, which arises when $S > \widehat{S}$, $F > \overline{F}^{DG}(\tau)$, and $F < \overline{F}^{GD}(\tau)$, thus still requiring $\tau < -4.8$.

Fourth, the $(F, S) = (0.01, 0.02)$ pair can lie in Region IV. Recall that for the (G,G)-duopoly to emerge we need: (1) $F < \overline{F}^{GG}(\tau)$, or $0.01 < \frac{1}{9}\left(1 - \frac{9\tau}{20}\right)^2$, which yields $\tau < 1.068$, a condition that holds given that emission fees are restricted to $\tau < 0.64$; and (2) $S < \widetilde{S}$, or $0.02 < \frac{11\tau(1-\tau)}{45}$, which holds for all $\tau \in [0.09, 0.91]$. Hence, since τ must satisfy $\tau < 0.64$, the regulator can implement the (G,G)-duopoly of Region IV by selecting a fee in the interval $\tau \in [0.09, 0.64)$. In contrast, the (G,D)-duopoly cannot be implemented with any fee τ as, for this market to emerge, we need $\overline{F}^{GG}(\tau) < F$, or $\frac{1}{9}\left(1 - \frac{9\tau}{20}\right)^2 < 0.01$, which yields $\tau > 1.068$, a condition that cannot hold given that emission fees are restricted to $\tau < 0.64$.

Finally, the $(F, S) = (0.01, 0.02)$ pair can lie in Region V since for that we need: (1) $S > \widetilde{S}$, or $0.02 > \frac{11\tau(1-\tau)}{45}$, which simplifies to $-11\tau^2 + 11\tau - 0.9 > 0$, a condition that holds for all $\tau < 0.09$ and $\tau > 0.91$; and (2) $F < \overline{F}^{GG}(\tau)$ or $\frac{1}{9}\left(1 - \frac{9\tau}{20}\right)^2 > 0.01$, which yields $\tau < 1.068$, a condition that holds given that emission fees are restricted to $\tau < 0.64$. Therefore, the regulator can implement the (G,D)-duopoly with emission fees satisfying $\tau < 0.09$.

Summarizing, a (G,D)-duopoly can be implemented with fee $\tau < 0.09$ (see Region V), and a (G,G)-duopoly can be induced with fee $\tau \in [0.09, 0.64)$ (see Regions IIb and IV).

6.2 Proof of Lemma 1

Optimal response to dirty incumbent. When the incumbent keeps its dirty technology, firm 2's profits from responding with green technology are positive if

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

which entails $F \leq \frac{a^2}{9b} - S \equiv F_{NR}^A$, where NR denotes no regulation. If, instead, firm 2 responds choosing a dirty technology its profits are positive if

$$\pi_2^{d,DD} = \frac{a^2}{9b} - F \geq 0$$

which implies $F \leq \frac{a^2}{9b} \equiv F_{NR}^B$. Clearly, $F_{NR}^B \geq F_{NR}^A$ for all values of S. Hence, when $F \leq F_{NR}^A$ both profits are positive, when $F_{NR}^A \geq F > F_{NR}^B$ only profits from dirty technology are positive, while when $F > F_{NR}^B$ profits from all technologies are negative.

When both profits are positive, i.e., $F \leq F_{NR}^A$, firm firm 2 has incentives to adopt a green technology if $\pi_2^{d,DG} \geq \pi_2^{d,DD}$, entailing $S < 0$, which cannot hold, thus implying that the entrant enters with dirty technology. When $F_{NR}^A \geq F > F_{NR}^B$ the profits from green technology are negative while those of dirty technology are positive, implying that firm 2 chooses to enter and keep its dirty technology. Finally, when $F > F_{NR}^B$ firm 2 does not enter.

Optimal response to green incumbent. When the incumbent invests in green technology, firm

2's profits from responding with green technology are positive if

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

which entails $F \leq \frac{a^2}{9b} - S \equiv F_{NR}^A$. If, instead, firm 2 responds choosing a dirty technology its profits are positive if

$$\pi_2^{d,GD} = \frac{a^2}{9b} - F \geq 0$$

which also implies $F \leq \frac{a^2}{9b} \equiv F_{NR}^B$. Since $F_{NR}^B \geq F_{NR}^A$ for all values of S, similar responses emerge than when the incumbent keeps its dirty technology. Hence, the same three regions as above arise.

Incumbent. When $F \leq F_{NR}^B$ the entrant responds with dirty technology regardless of the incumbent's decision (which holds true both when $F \leq F_{NR}^A$ and when $F_{NR}^A \geq F > F_{NR}^B$). Therefore, the incumbent acquires green technology if $\pi_1^{d,GD} \geq \pi_1^{d,DD}$, which entails

$$\frac{a^2}{9b} - S \geq \frac{a^2}{9b} \Leftrightarrow S \leq 0$$

Hence, the incumbent keeps its dirty technology in this region. Finally, when $F > F_{NR}^B$ firm 2 stays out of the industry regardless of the incumbent's technology, implying that the incumbent chooses green technology if $\pi_1^{m,G} \geq \pi_1^{m,D}$, which entails $\frac{a^2}{4b} - S \geq \frac{a^2}{4b}$, or $S \leq 0$. Therefore, the incumbent keeps its dirty technology in this region as well. ■

6.3 Proof of Lemma 2

Dirty incumbent. If $\tau < \frac{a}{2-\theta}$ both firms produce strictly positive output levels if the incumbent is dirty. Firm 2's profits when choosing green technology are positive if

$$\pi_2^{d,DG} = \frac{[a - \tau(2\theta - 1)]^2}{9b} - (F + S) \geq 0$$

which entails $F \leq \frac{[a-\tau(2\theta-1)]^2}{9b} - S \equiv \bar{F}^{DG}$. In addition, firm 2 profits when choosing a dirty technology are positive if

$$\pi_2^{d,DD} = \frac{(a - \tau)^2}{9b} - F \geq 0$$

which implies $F \leq \frac{(a-\tau)^2}{9b} \equiv \bar{F}^{DD}$. Furthermore, $\bar{F}^{DG} < \bar{F}^{DD}$ since $\theta < \frac{1}{2}$ by definition. Therefore, both profits are positive if $F \leq \bar{F}^{DG}$. However, if $\bar{F}^{DD} \geq F > \bar{F}^{DG}$ firm 2's profits from acquiring green technology are negative while those of keeping its dirty technology are positive. Finally, if $F > \bar{F}^{DD}$ both profits are negative. We next analyze each case separately.

When both profits are positive, i.e., $F \leq \bar{F}^{DG}$, firm 2 has incentives to adopt a green technology if

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

Therefore, firm 2 enters with green technology if $S \leq \widehat{S}$ and $F \leq \bar{F}^{DG}$. In addition, cutoff $\widehat{S}$ satisfies $\widehat{S} > \frac{[a-\tau(2\theta-1)]^2}{9b}$ since $a > \tau$ by definition, entailing that the only condition required for firm 2 to adopt the green technology is $F \leq \bar{F}^{DG}$.

When $\bar{F}^{DD} \geq F > \bar{F}^{DG}$ the profits from the green technology are negative while those of the dirty technology are positive, implying that firm 2 chooses to enter and keep its dirty technology. Finally, if $F > \bar{F}^{DD}$ firm 2 does not enter as its profits from the green and dirty technologies are both negative.

Green incumbent. If $\tau < \frac{a}{2-\theta}$ both firms produce strictly positive output levels if the incumbent is green type. Firm 2's profits when choosing a green technology are positive if

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

which entails $F \leq \frac{(a-\tau\theta)^2}{9b} - S \equiv \bar{F}^{GG}$. In addition, firm 2 profits when choosing a dirty technology are positive if

$$\pi_2^{d,GD} = \frac{[a-\tau(2-\theta)]^2}{9b} - F \geq 0$$

which implies $F \leq \frac{[a-\tau(2-\theta)]^2}{9b} \equiv \bar{F}^{GD}$. Furthermore, $\bar{F}^{GG} < \bar{F}^{GD}$ since $\theta < \frac{1}{2}$ by definition. Therefore, both profits are positive if $F \leq \bar{F}^{GG}$. However, if $\bar{F}^{GD} \geq F > \bar{F}^{GG}$ profits from the green technology are negative while those of the dirty technology are positive. Finally, if $F > \bar{F}^{GD}$ both profits are negative. We next analyze each case separately.

When both profits are positive, i.e., $F \leq \bar{F}^{GG}$, firm 2 has incentives to adopt a green technology if

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

Therefore, firm 2 enters with green technology if $S \leq \widetilde{S}$ and $F \leq \bar{F}^{GG}$. In addition, cutoff $\widetilde{S}$ satisfies $\widetilde{S} < \frac{(a-\tau\theta)^2}{9b}$ since $\widetilde{S} - \frac{(a-\tau\theta)^2}{9b} = -\frac{[a-\tau(2-\theta)]^2}{9b} < 0$, which implies that in the (F, S) quadrant cutoff $\widetilde{S}$ lies to the left-hand side of the horizontal intercept of cutoff $\bar{F}^{GG}$. Therefore, we need both conditions $S \leq \widetilde{S}$ and $F \leq \bar{F}^{GG}$ for firm 2 to adopt a green technology. If condition $F \leq \bar{F}^{GG}$ holds but $S \leq \widetilde{S}$ does not, then firm 2 enters with a dirty technology.

When $\bar{F}^{GD} \geq F > \bar{F}^{GG}$ the profits from adopting a green technology are negative while those of the dirty technology are positive, implying that firm 2 chooses to enter and keep its dirty technology. Finally, if $F > \bar{F}^{GD}$ firm 2 does not enter since its profits from both green and dirty technologies are negative. ■

6.4 Proof of Lemma 3

If $F > \bar{F}^{DD}$ entry does not occur when the incumbent is dirty. In addition, since $\bar{F}^{DD} > \bar{F}^{GD}$ entry does not occur when the incumbent is green either.

If $\bar{F}^{DD} \geq F > \bar{F}^{GD}$ entry does not occur when the incumbent is green since $F > \bar{F}^{GD}$, but entry ensues when the incumbent is dirty since $\bar{F}^{DD} \geq F$. Upon entry, firm 2 chooses a dirty technology if $F > \bar{F}^{DG}$ but a green technology if $\bar{F}^{DG} \geq F$.

If $\bar{F}^{GD} \geq F > \bar{F}^{DG}$ the entrant chooses to enter with a dirty technology both when the incumbent is dirty since, $F > \bar{F}^{DG}$, and when the incumbent is green, given that $F > \bar{F}^{GG}$, where $\bar{F}^{GG} > \bar{F}^{DG}$.

If $\min\{\bar{F}^{DG}, \bar{F}^{GD}\} \geq F > \bar{F}^{GG}$ firm 2 enters and adopts a green technology when the incumbent is dirty since $F < \bar{F}^{DG}$ holds, but choose a dirty technology when the incumbent is green since $F > \bar{F}^{GG}$ holds. In addition, a similar response by firm 2 occurs when $F < \bar{F}^{GG}$ and $S > \widetilde{S}$. In particular, when the incumbent is dirty the entrant responds entering with a green technology since $F < \bar{F}^{DG}$; while when the incumbent is green the entrant chooses dirty technology given that $F < \bar{F}^{GG}$ and $S > \widetilde{S}$.

If $F < \bar{F}^{GG}$ and $S \leq \widetilde{S}$ firm 2 enters with a green technology, both when the incumbent is dirty, since $F < \bar{F}^{DG}$ (where $\bar{F}^{DG} > \bar{F}^{GG}$), and when the incumbent is green, since $F < \bar{F}^{GG}$ and $S \leq \widetilde{S}$. ■

6.5 Proof of Lemma 4

Let us separately analyze the incumbent's technology choice for each of the entrant's responses identified in regions I-V.

Region I. In this region the entrant stays out of the industry regardless of the incumbent's technology, implying that the latter adopts a green technology if and only if

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

In addition, cutoff S_I satisfies $S_I > \widetilde{S}$ since their difference

$$S_I - \widetilde{S} = \frac{\tau(1-\theta)\left[2a - \tau(9\theta - 7)\right]}{36b}$$

is positive if $\tau < \frac{2a}{9\theta-7}$. However, since $\frac{2a}{9\theta-7} > \frac{a}{2-\theta}$, then the condition for positive output levels $\tau < \frac{a}{2-\theta}$ implies $\tau < \frac{2a}{9\theta-7}$, thus guaranteeing that $S_I > \widetilde{S}$ holds for all admissible values. Furthermore, cutoff S_I also satisfies $S_I > \widehat{S}$ since

$$S_I - \widehat{S} = \frac{\tau(1-\theta)\left[2a - \tau(9-7\theta)\right]}{36b}$$

is positive for all $\tau < \frac{2a}{9-7\theta}$. However, since $\frac{2a}{9-7\theta} > \frac{a}{2-\theta}$, then the condition for positive output levels $\tau < \frac{a}{2-\theta}$ implies $\tau < \frac{2a}{9-7\theta}$, thus guaranteeing that $S_I > \widehat{S}$ holds for all admissible values. Finally, cutoff $\widehat{S}$ lies to the right-hand side of the horizontal intercept of F^{DG} since $a > \tau$. Therefore, given that $S_I > \widehat{S}$, cutoff S_I also lies to the right-hand side of F^{DG}.

Region IIa. In this region, the entrant stays out if the incumbent is green but enters with a dirty technology otherwise. The incumbent, hence, adopts a green technology if and only if

$$\begin{aligned} \pi_1^{m,G} \quad &\geq \quad \pi_1^{d,DD}, \text{ or } \frac{(a-\tau\theta)^2}{4b} - S \geq \frac{(a-\tau)^2}{9b} \\ \iff \quad &S \leq \frac{5a^2 - 2\tau a(9\theta - 4) + \tau^2(9\theta^2 - 4)}{36b} \equiv S_{IIa} \end{aligned}$$

Region IIb. In this region, the entrant stays out if the incumbent is green but enters with green technology otherwise. The incumbent, thus, adopts a green technology if and only if

$$\begin{aligned} \pi_1^{m,G} \quad &\geq \quad \pi_1^{d,DG}, \text{ or } \frac{(a-\tau\theta)^2}{4b} - S \geq \frac{\left[a - \tau(2-\theta)\right]^2}{9b} \\ \iff \quad &S \leq \frac{5a^2 - 2\tau a(13\theta - 8) + \tau^2\left[5\theta^2 - 16(1-\theta)\right]}{36b} \equiv S_{IIb} \end{aligned}$$

Region III. In this region, the entrant enters with dirty technology regardless of the incumbent's choice. The incumbent, thus, adopts green technology if and only if

$$\begin{aligned} \pi_1^{d,GD} \quad &\geq \quad \pi_1^{d,DD}, \text{ or } \frac{\left[a - \tau(2\theta - 1)\right]^2}{9b} - S \geq \frac{(a-\tau)^2}{9b} \\ \iff \quad &S \leq S_{III} \end{aligned}$$

where cutoff $S_{III} = \widehat{S}$. Since cutoff $\widehat{S}$ lies to the right-hand side of the horizontal intercept of F^{DG}, region III is divided into two subareas: one in which the incumbent invests in green technology if $S \leq \widehat{S}$, and another in which it keeps its dirty technology if $S > \widehat{S}$.

Region IV. In this region, the entrant enters and adopts the opposite technology of the incumbent. The incumbent, hence, adopts a green technology if and only if

$$\begin{aligned} \pi_1^{d,GD} \quad &\geq \quad \pi_1^{d,DG}, \text{ or } \frac{\left[a - \tau(2\theta - 1)\right]^2}{9b} - S \geq \frac{\left[a - \tau(2-\theta)\right]^2}{9b} \\ \iff \quad &S \leq \frac{\tau(1-\theta)(2a - \tau(1+\theta))}{3b} \equiv S_{IV} \end{aligned}$$

In addition, cutoff S_{IV} satisfies $S_{IV} > S_I$, entailing that all (F, S)-pairs in which region IV exists, the incumbent chooses a green technology.

Region V. In this region, the entrant enters and adopts a green technology regardless of the incumbent's choice. The incumbent, thus, adopts a green technology if and only if

$$\pi_1^{d,GG} \geq \pi_1^{d,DG}, \text{ or } \frac{(a-\tau\theta)^2}{4b} - S \geq \frac{[a-\tau(2-\theta)]^2}{9b}$$
$$\iff S \leq S_V$$

where cutoff $S_V = \widetilde{S}$. Therefore, since cutoff $\widetilde{S}$ is the upper bound of region V, for all (F, S)-pairs in which region V exists, the incumbent chooses a green technology. ■

6.6 Proof of Lemma 5

Dirty Monopoly: The incumbent keeps its dirty technology and the entrant stays out of the market. The regulator identifies the optimal output level that maximizes social welfare

$$\frac{1}{2}bq_1^2 + (a - bq_1)q_1 - dq_1$$

which is $q_1^* = \frac{a-d}{b}$. Equalizing q_1^* to the monopoly output function of a dirty incumbent, $q_1^{m,D} = \frac{a-\tau}{2b}$ (see table 1), we obtain the optimal emission fee $\tau^{m,D} = 2d - a$, which is positive since $a < 3d\theta$ implies $a < 2d$, and yields a social welfare

$$W^{m,D} = \frac{(a-d)(3a-5d)}{2b}$$

Green Monopoly: In this case the incumbent chooses a green technology and entry does not ensue. The regulator identifies the optimal output level that maximizes social welfare

$$\frac{1}{2}bq_1^2 + (a - bq_1)q_1 - S - d\theta q_1$$

which is $q_1^* = \frac{a-d\theta}{b}$. Equalizing q_1^* to the monopoly output function of a green incumbent, $q_1^{m,G} = \frac{a-\tau\theta}{2b}$, and solving for τ, we obtain the optimal emission fee $\tau^{m,G} = \frac{2d\theta-a}{\theta}$, which is negative since $a > d$ by definition, leading the regulator to set a zero emission fee, $\tau^{m,G} = 0$.

Dirty Duopoly: The incumbent and the entrant choose a dirty technology. The regulator identifies the optimal output level that maximizes

$$\frac{1}{2}bQ^2 + (a - bQ)Q - dQ$$

where $Q = q_1 + q_2$, and it is solved at $Q^* = \frac{a-d}{b}$. Equalizing Q^* to the aggregate duopoly output of two dirty firms, $2q_i^{d,DD}$ (see table 1), we obtain the optimal emission fee $\tau^{d,DD} = \frac{3d-a}{2}$, which yields a social welfare

$$W^{d,DD} = \frac{a^2 - d(3a-2d)}{b} - F$$

Green Duopoly: The incumbent and the entrant choose a green technology. The regulator identifies the optimal output level that maximizes

$$\frac{1}{2}bQ^2 + (a - bQ)Q - dQ$$

where $Q = q_1 + q_2$, and it is solved at $Q^* = \frac{a-d\theta}{b}$. Equalizing Q^* to the aggregate duopoly output of two green firms, $2q_i^{d,GG}$ (see table 1), we obtain the optimal emission fee $\tau^{d,GG} = \frac{3d\theta - a}{2\theta}$, which yields a social welfare

$$W^{m,D} = \frac{(a - 2d\theta)(a - d\theta)}{b} - (F + 2S)$$

(D,G)-Duopoly: In this case the incumbent keeps its dirty technology and the entrant acquires a green technology. The regulator identifies the optimal output level that maximizes

$$\frac{1}{2}bQ^2 + (a - bQ)Q - F - S - d(q_1 + \theta q_2)$$

In this case the regulator induces a corner solution where only green output is produced at $q_2 = \frac{a-d\theta}{b}$. Equalizing q_2 to the aggregate duopoly output (D,G), $q_1^{d,DG} + q_2^{d,DG}$ (see table 1), we obtain the optimal emission fee $\tau^{d,DG} = \frac{3d\theta - a}{1+\theta}$.

(G,D)-Duopoly: in this case the incumbent chooses green technology and the entrant chooses dirty technology. The regulator identifies the optimal output level that maximizes

$$\frac{1}{2}bQ^2 + (a - bQ)Q - S - F - d(\theta q_1 + q_2)$$

In this case the regulator induces a corner solution where only green output is produced at $q_1 = \frac{a-d\theta}{b}$ and equalizing it to the aggregate duopoly output (G,D), $q_1^{d,GD} + q_2^{d,GD}$, we obtain the optimal emission fee $\tau^{d,GD} = \frac{3d\theta - a}{1+\theta}$. ■

6.7 Proof of Lemma 6

In the second stage of the game, we separately analyze the response of the entrant to a dirty incumbent, and to a green incumbent, and subsequently combine our results.

Lemma A1 (Dirty incumbent). *When firm 1 is dirty, (1) firm 2 enters and adopts green technology if entry costs satisfy $F \leq F^A$ and $S \leq S_A$; (2) enters and keeps its dirty technology if $F \leq F^B$ and $S > S_A$; and (3) does not enter if $F > \max\{F^A, F^B\}$, where*

$$F^A \equiv \frac{[a - d(2\theta - 1)]d\theta^2}{b(1 + \theta)} - S, \quad F^B \equiv \frac{(a - d)\,d}{2b} \text{ and } S_A \equiv \frac{d(1 - \theta)[d - (1 + 2\theta)(a - 2d\theta)]}{2b(1 + \theta)}$$

Proof. Firm 2's profits when choosing green technology are positive if

$$\pi_2^{d,DG} = \frac{[a - d(2\theta - 1)]d\theta^2}{b(1 + \theta)} - (F + S) \geq 0$$

which entails

$$F \leq \frac{[a - d(2\theta - 1)]d\theta^2}{b(1+\theta)} - S \equiv F^A$$

In addition, firm 2 profits when choosing a dirty technology are positive if

$$\pi_2^{d,DD} = \frac{(a-d)d}{2b} - F \geq 0$$

which implies

$$F \leq \frac{(a-d)d}{2b} \equiv F^B$$

Furthermore, the vertical intercept of F^A lies above F^B since $\theta < \frac{1}{2}$. Therefore, both profits are positive if $F \leq \min\{F^A, F^B\}$, see figure 4. However, if $F^B \geq F > F^A$ the profits from the green technology are negative while those of the dirty technology are positive. A similar pattern arises if $F^A \geq F > F^B$ whereby only profits from the green technology are positive. Finally, if $F > \max\{F^A, F^B\}$ both profits are negative. We next analyze each case separately.

When both profits are positive, i.e., $F \leq \min\{F^A, F^B\}$, firm 2 has incentives to adopt a green technology if

$$\begin{aligned}
\pi_2^{d,DG} &\geq \pi_2^{d,DD} \\
\frac{[a - d(2\theta - 1)]d\theta^2}{b(1+\theta)} - (F+S) &\geq \frac{(a-d)d}{2b} - F \\
S &\leq \frac{d(1-\theta)\left[2 - (1+2\theta)(a - 2d\theta)\right]}{2b(1+\theta)} \equiv S_A
\end{aligned}$$

Therefore, firm 2 enters with a green technology if $S \leq S_A$ and $F \leq \min\{F^A, F^B\}$. In addition, cutoff S_A is to the right-hand side of the crossing point between F^A and F^B, which we denote as $\widehat{S} \equiv \frac{2[a-d(2\theta-1)]d\theta^2 - (a-d)(1+\theta)}{2b(1+\theta)}$, since $\widehat{S} - S_A = (a-d)(1-d)(1+\theta) < 0$ given that $a \in (0,1)$ and $a > d$. If $S > S_A$ and $F \leq \min\{F^A, F^B\}$ then firm 2 enters with a dirty technology.

When $F^B \geq F > F^A$ the profits from the green technology are negative while those of the dirty technology are positive, implying that firm 2 chooses to enter and keep its dirty technology. If instead $F^A \geq F > F^B$ the profits from the dirty technology are negative while those of the green technology are positive, implying that firm 2 chooses to enter and invest in the green technology. Finally, if $F > \max\{F^A, F^B\}$ firm 2 does not enter as its profits from both the green and dirty technology are negative.

Finally, note that F^A originates above cutoff F^B given that $a < 3d\theta$ by definition. In addition, cutoff S_A coincides with the crossing point between F^A and F^B. ■

Lemma A2 (Green incumbent). *When firm 1 is green, (1) firm 2 enters and adopts a green technology if* $F \leq F^C$ *and* $S \leq S_B$*; (2) enters and keeps its dirty technology if* $F \leq F^D$ *and*

$S > S_B$; (3) and does not enter if $F > \max\{F^C, F^D\}$, where

$$F^C \equiv \frac{(a - d\theta)d\theta}{2b} - S,\ F^D \equiv \frac{[a - d\theta\,(2 - \theta)]\,d\theta}{b(1+\theta)} \textit{ and } S_B \equiv \frac{d\theta(1-\theta)(3d\theta - a)}{2b(1+\theta)}$$

Proof. Firm 2's profits when choosing a green technology are positive if

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

which entails

$$F \leq \frac{(a - d\theta)d\theta}{2b} - S \equiv F^C$$

In addition, firm 2 profits when choosing a dirty technology are positive if

$$\pi_2^{d,GD} = \frac{[a - d\theta(2-\theta)]d\theta}{b(1+\theta)} - F \geq 0$$

which implies

$$F \leq \frac{[a - d\theta(2-\theta)]d\theta}{b(1+\theta)} \equiv F^D$$

Furthermore, the vertical intercept of F^C lies above F^D since $a < 3d\theta$. Therefore, both profits are positive if $F \leq \min\{F^C, F^D\}$, see figure 4. However, if $F^D \geq F > F^C$ the profits from the green technology are negative while those of the dirty technology are positive. A similar pattern arises if $F^C \geq F > F^D$ whereby only the profits from the green technology are positive. Finally, if $F > \max\{F^C, F^D\}$ both profits are negative. We next analyze each case separately.

When both profits are positive, i.e., $F \leq \min\{F^C, F^D\}$, firm 2 has incentives to adopt a green technology if

$$\begin{aligned}
\pi_2^{d,GG} &\geq \pi_2^{d,GD} \\
\frac{(a - d\theta)d\theta}{2b} - (F + S) &\geq \frac{[a - d\theta(2-\theta)]d\theta}{b(1+\theta)} - F \\
S &\leq \frac{d\theta(1-\theta)\,(3d\theta - a)}{2b(1+\theta)} \equiv S_B
\end{aligned}$$

Therefore, firm 2 enters with green technology if $S \leq S_B$ and $F \leq \min\{F^C, F^D\}$. In addition, cutoff S_B coincides with the crossing point between F^C and F^D. If $S > S_B$ and $F \leq \min\{F^C, F^D\}$ then firm 2 enters with a dirty technology.

When $F^D \geq F > F^C$ the profits from the green technology are negative while those of the dirty technology are positive, implying that firm 2 chooses to enter and keep its dirty technology. If instead $F^C \geq F > F^D$ the profits from the dirty technology are negative while those of the green technology are positive, implying that firm 2 chooses to enter and invest in the green technology. Finally, if $F > \max\{F^C, F^D\}$ firm 2 does not enter as its profits from the green and dirty technologies are negative.

Finally, note that F^C originates above cutoff F^D given that $a < 3d\theta$ by definition. In addition, cutoff S_B coincides with the crossing point between F^C and F^D. In addition, comparing the cutoffs identified in Lemma A2 with those of Lemma A1, we find that the vertical cutoff S_A lies to the right hand side of S_B since $a < d(1+\theta)$ holds given that $a < 3d\theta$. However, S_A lies to the left hand side of the horizontal intercept of F^C only if $a \in [\bar{a}, 3d\theta]$ where $\bar{a} \equiv \frac{d\left[3\theta^2(1-\theta)+(1+\theta)\right]}{1+2\theta-\theta^2}$. Otherwise, S_A lies between the horizontal intercept of F^A and F^C. ■

We can now combine our above results from Lemmas A1-A2, providing the optimal responses of the entrant. If $F > \max\{F^A, F^D\}$ entry does not occur when the incumbent is dirty (since $F > \max\{F^A, F^B\}$ given that $F^D > F^B$) nor when it is green (since $F > \max\{F^C, F^D\}$ given that $F^A > F^C$).

If $F^A \geq F > \max\{F^C, F^D\}$ entry does not occur when the incumbent is green since $F > \max\{F^C, F^D\}$, but entry ensues when the incumbent is dirty since $F^A \geq F > F^B$. Upon entry, firm 2 chooses a green technology given that $F^A \geq F > F^B$.

If $F^D \geq F > \max\{F^A, F^B\}$ entry does not occur when the incumbent is dirty since $F > \max\{F^A, F^B\}$, but entry ensues when the incumbent is green since $F^D \geq F > F^C$. Upon entry, firm 2 chooses the dirty technology given that $F^D \geq F > F^C$.

If $F \leq F^C$ and $S \leq S_B$ the entrant chooses a green technology both when the incumbent is dirty since $S \leq S_A$ and $F \leq \min\{F^A, F^B\}$, and when the incumbent is green given that $S \leq S_B$ and $F \leq \min\{F^C, F^D\}$ or $F^C \geq F > F^D$.

If $F \leq F^B$ and $S > S_A$ the entrant chooses to enter with a dirty technology both when the incumbent is dirty since $F^B \geq F > F^A$ and when the incumbent is green given that $F^D \geq F > F^C$, or $F \leq \min\{F^C, F^D\}$ since $S > S_A > S_B$.

If $\min\{F^A, F^D\} \geq F$ and $S_A \geq S > S_B$ firm 2 enters and chooses a green technology when the incumbent is dirty since $F^A \geq F > F^B$ or $F \leq \min\{F^A, F^B\}$, but choose a dirty technology when the incumbent is green since $F^D \geq F > F^C$. ■

6.8 Proof of Proposition 1

Let us separately analyze the incumbent's technology choice for each of the entrant's responses identified in regions I-IV.

Region I. In this region the entrant stays out of the industry regardless of the incumbent's technology, implying that the latter adopts a green technology if and only if

$$\begin{aligned}\pi_1^{m,G} &\geq \pi_1^{m,D}, \text{ or } \frac{a^2}{4b} - S \geq \frac{(a-d)^2}{b} \\ S &\leq \frac{(a-2d)(2d-3a)}{4b} \equiv S_I\end{aligned}$$

which is positive since $a < 3d\theta$ implies that $a < 2d$, and $d < a$ implies that $2d < 3a$.

Region IIa. In this region, the entrant stays out if the incumbent is green but enters with a green technology otherwise. The incumbent, hence, adopts a green technology if and only if

$$\begin{aligned} \pi_1^{m,G} &\geq \pi_1^{d,DG}, \text{ or } \frac{a^2}{4b} - S \geq \frac{d\theta\left[a - d\theta\left(2-\theta\right)\right]}{b\left(1+\theta\right)} \\ S &\leq \frac{a^2(1+\theta) + 4d\theta\left[d\theta(2-\theta) - a\right]}{4b\left(1+\theta\right)} \equiv S_{IIa} \end{aligned}$$

In addition, S_{IIa} lies to the right-hand side of the crossing point between F^A and F^D denoted by $\widetilde{S} \equiv \frac{d\theta(1-\theta)(3d\theta-a)}{b(1+\theta)}$ for all $a > \frac{2d\theta\left[\theta+\sqrt{1-\theta-\theta^2}\right]}{1+\theta} \equiv \hat{a}$, where $\hat{a} - d = 2\theta^2 + 2\theta\sqrt{1-\theta-\theta^2} - 1 - \theta < 0$ for all $\theta < \frac{1}{2}$. Hence, the initial condition $a > d$ implies $a > \hat{a}$, entailing that for all (F, S)-pairs in which region IIa exists, the incumbent chooses a green technology.

Region IIb. In this region, the entrant stays out if the incumbent is dirty but enters with dirty technology otherwise. The incumbent, thus, adopts a green technology if and only if

$$\begin{aligned} \pi_1^{d,GD} &\geq \pi_1^{m,D}, \text{ or } \frac{d\theta^2\left[a + d\left(1-2\theta\right)\right]}{b\left(1+\theta\right)} - S \geq \frac{(a-d)^2}{b} \\ S &\leq \frac{d\theta^2\left[a + d\left(1-2\theta\right)\right] - \left(a-d\right)^2\left(1+\theta\right)}{b\left(1+\theta\right)} \equiv S_{IIb} \end{aligned}$$

Let us compare cutoff S_{IIb} with the crossing point between F^A and F^D, denoted as $\widetilde{S}$. In particular, $\widetilde{S} > S_{IIb}$ if $a > \frac{d[(2+3\theta)-\sqrt{\theta(4+\theta(2\theta-3)(1+2\theta))}]}{2(1+\theta)}$. In this case, all (F, S)-pairs of region IIb lie to the right-hand side of cutoff S_{IIb} implying that the incumbent chooses a dirty technology under all parameter values which deters entry. If instead, $a \leq \frac{d[(2+3\theta)-\sqrt{\theta(4+\theta(2\theta-3)(1+2\theta))}]}{2(1+\theta)}$ cutoff S_{IIb} divides region IIb into two areas: (i) one in which a dirty monopoly arises if $S > S_{IIb}$; and (ii) one in which a (G,D)-duopoly emerges if $S \leq S_{IIb}$.

Region IIIa. In this region, the entrant enters with a green technology regardless of the incumbent's choice. The incumbent, thus, adopts a green technology if and only if

$$\begin{aligned} \pi_1^{d,GG} &\geq \pi_1^{d,DG}, \text{ or } \frac{d\theta(a-d\theta)}{2b} - S \geq \frac{d\theta\left[a - d\theta\left(2-\theta\right)\right]}{b\left(1+\theta\right)} \\ S &\leq S_B \end{aligned}$$

Since region IIIa occurs to the left-hand side of cutoff S_B, all (F, S)-pairs in which this region exists imply that the incumbent chooses a green technology entailing a green duopoly.

Region IIIb. In this region, the entrant enters with a dirty technology regardless of the incumbent's choice. The incumbent, thus, adopts a green technology if and only if

$$\begin{aligned} \pi_1^{d,GD} &\geq \pi_1^{d,DD}, \text{ or } \frac{d\theta^2\left[a + d\left(1-2\theta\right)\right]}{b\left(1+\theta\right)} - S \geq \frac{d(a-d)}{2b} \\ S &\leq S_A \end{aligned}$$

Since region IIIb occurs to the right-hand side of cutoff S_A, all (F, S)-pairs in which this region exists imply that the incumbent chooses a dirty technology entailing a dirty duopoly.

Region IV. In this region, the entrant enters and adopts the opposite technology of the incumbent. The incumbent, hence, adopts a green technology if and only if

$$\begin{aligned} \pi_1^{d,GD} &\geq \pi_1^{d,DG}, \text{ or } \frac{d\theta^2\left[a+d\left(1-2\theta\right)\right]}{b\left(1+\theta\right)} - S \geq \frac{d\theta\left[a-d\theta\left(2-\theta\right)\right]}{b\left(1+\theta\right)} \\ S &\leq 2S_B \end{aligned}$$

Cutoff $2S_B$ lies to the left-hand side of S_A if $a < d + 2d\theta(1-\theta)$, which holds given that $a < 3d\theta$ and $a > d$ by definition. Then, region IV is divided into two subareas: one in which $S \leq 2S_B$ and the incumbent chooses a green technology and a (G,D) duopoly arises; and other where $S > 2S_B$ and the incumbent keeps its dirty technology and a (D,G)-duopoly emerges.■

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