Signaling environmental quality to green consumers and the incentive to invest in cleaner technology: Effect of environmental regulation

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Abstract

I consider an imperfectly competitive industry where firms signal the environmental attribute of their production technology through prices to environmentally conscious consumers that are not informed about the environmental damage caused by firms but are willing to pay more for "cleaner" products. I analyze the effect of changes in the level of environmental regulation on signaling behavior of firms and their incentive to develop cleaner technology. While cleaner firm types charge higher prices when regulation is weak, higher price does not signal better environmental performance when regulation is sufficiently stringent. With weak regulation, a monopolist has absolutely no incentive to invest in the development of a potentially less damaging technology even though consumers are willing to pay more for the product. This incentive is positive when regulation is strong enough. In a more competitive market structure (duopoly with price competition), firms may have strategic incentive to invest even when regulation is weak.

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1 Introduction

The willingness of environmentally conscious or "green" consumers to pay more for goods produced with lower environmental damage[1], and the market incentives it generates for firms, have received considerable attention in recent years. One can view this as an important social mechanism that disciplines the negative environmental externalities created by rent seeking firms and therefore, complementary to environmental regulation by public authorities. The efficacy of consumer consciousness is, however, constrained by the fact that consumers often do not have sufficient information about the environmental attributes of the production technology of firms. Some information is provided through ecolabeling[2] and other certification intermediaries as well as the fact that firms are in compliance with government regulations; it is, however, fair to say that such information often pertains to only certain specific kinds of environmental damage and remains significantly limited relative to the environmental concerns of consumers. Even if regulatory authorities succeed in gathering better information about the actual environmental performance of firms and make it publicly accessible,[3] such information may not always percolate down to individual consumers. This gap between consumer concern and the availability of information is likely to increase in the future with increase in environmental consciousness. It is, therefore, important to understand the role of product prices and other market variables in signaling the environmental performance of firms. However, the signaling incentives of firms are influenced by public environmental regulations such as taxes, emission permits, liability for actual damage etc., that add to the production cost of firms that cause greater environmental damage. Indeed, like consumer consciousness (and perhaps related to it), the stringency of such public regulation has been increasing over time. In this paper, we focus on the extent and manner in which prices set by rent seeking firms reveal their environmental performance to conscious consumers, and analyze the effect of increase in the level of environmental regulation on the signaling outcomes. We treat regulation as exogenous and abstract from information problems between the regulator and the firms.[4] We use this framework to understand how changes in regulation may influence the incentive of firms to invest in the development of less damaging

[1] The recent theoretical literature in environmental economics considers environmental friendliness as a vertical attribute of a product and shows that environmentally conscious (green) consumers pay a price premium for an environment-friendly product (See Cremer and Thisse (1999), Arora and Gangopadhyay (2003), Bansal and Gangopadhyay (2003)). Teisl et al. (2002) find that introduction of "dolphin-safe" labels increases the market share of canned tuna. Galarraga and Markandya (2004) show that consumers in the UK pay significant price premium for organic and fair trade coffee. Casadesus-Masanell et al. (2009) find that consumers are willing to pay more for sportswear made of organic cotton that involves lower use of pesticides and fertilizers.

[2] See Karl and Orwatt (2000), Dosi and Morretto (2001), Sedjo and Swallow (2002), Mason (2006), Grolleau and Ibanez (2008).

[3] See Sartzetakis, Xepapadeas, and Petrakis (2005, 2008) and Uchida (2007). Rege (2000) argues that government can provide information about environmental quality of a firm by imposing penalty on the non-compliant firm.

[4] Antelo and Loureiro (2009) discuss the incomplete information problem where firms signal environmental performance to the regulator, and then the regulator decides on the optimal policy.

environmental production processes.

In particular, we consider an imperfectly competitive industry where environmentally conscious consumers are uninformed about the environmental damage caused by firms. (Even if public regulation takes the form of emission permit or tax, information about the actual trades or tax payments by individual firms is not available to consumers.) Firms signal the environmental attribute of their production technology which is either *clean* or *dirty* to uninformed green consumers through prices.[5] We consider the case where the industry is a monopoly as well as the situation where the market is a duopoly with firms competing in prices.

In the absence of any environmental regulation, Mahenc (2007, 2008) shows that in case of a monopoly, if the marginal production cost is relatively higher for a clean type firm then better environmental quality is signaled by higher price. In this paper, we show that this holds in the case of a monopoly as well as duopoly when regulation is weak. However, under significantly higher level of environmental regulation, we find that *lower* price may signal better environmental performance of a firm since the post-regulation marginal cost of a clean firm is lower than that of the dirty firm.[6]

The signaling game in our analysis is closely related to Bayesian games considered in the industrial organization literature where firms signal their product quality to uninformed consumers through prices. In their seminal paper, Bagwell and Riordan (1991) show that in a market with a single seller when consumers are unaware of product quality, high price signals high quality. Since the low quality (type of the) seller has lower marginal cost and earns sufficient rent by selling larger quantity at lower price, it does not have any incentive to imitate the high quality type. In the presence of competition, Daughety and Reinganum (2007, 2008) show that if consumers are heterogeneous in terms of their valuation of a given quality of a product (*horizontal product differentiation*) then in the unique separating equilibrium firms signal superior product quality by higher prices. Janssen and Roy (2009) argue that even in the absence of any horizontal product differentiation or other friction, firms can signal product quality through prices, though the equilibrium involves randomization over prices. Unlike much of this literature, in our model, the effective marginal cost of production depends on the level of exogenously given environmental regulation, and for significantly higher level of regulation, the clean firm has lower post-regulation marginal cost of production compared to the dirty firm, and thus, lower price may signal better "quality".[7]

[5] Tiesl et al. (2005) find that consumers use price as a signal of the quality of genetically modified food (corn, bread, and egg).

[6] Under complete information framework, in a market with green consumers, Deltas, Harrington, and Khanna (2008) analyze the role of environmental regulation on the choice of environmental quality of products by duopolists.

[7] The closest result to this, in the existing literature, is provided by Daughety and Reinganum (1995). They show that in case of a monopoly, lower price signals a safer product when marginal cost of risk per unit output sold is significantly high.

We examine whether firms initially endowed with dirty technology have any incentive to invest in the development of a cleaner production technology where the outcome of investment is intrinsically uncertain; the latter may reflect uncertainty about the success of the project or the environmental impact of the new technology. Investment is observed publicly but not the realized technology (or the environmental attribute of the technology i.e., whether it is clean or dirty). In the next stage, firms with private information about their technology set prices.

This investment game is somewhat similar to that in Daughety and Reinganum (1995) where a monopolist invests in research and development for product design that, in turn, determines the safety level of a product, and this is signaled to unaware consumers through prices. In our model firms are initially endowed with *dirty production technology,* they decide whether to invest to develop a *cleaner technology of production*, and this makes the return structure on investment somewhat different from a product development game.

To the best of our knowledge, the existing literature contains no analysis of the relationship between environmental regulation, signaling of environmental attribute of technology to green consumers through prices, and their relation to the incentive of firms to invest in cleaner technology. We show that even though green consumers are willing to pay more for the product of a *clean* firm, a monopolist does not have any incentive to invest in cleaner technology when regulation is not strong enough. However, more stringent regulation increases the effectiveness of consumer consciousness and creates incentive to invest in the development of potentially cleaner technology. Note that this supports the principal claim of the celebrated Porter Hypothesis i.e., "stringent regulation can actually produce greater innovation" (Porter (1991); Porter and van der Linde (1995)). In the case of duopoly with price competition, incomplete information allows firms to gain market power and thus soften price competition. We show that in the presence of competition, firms may have strategic incentive to invest even when regulation is weak, as firms invest not only to reduce the burden of regulation but also to change the information structure in the market (as consumers observe investment) that, in turn, alters the intensity of competition and allows the firms to gain market power; this connection between investment in technology and market power in competitive markets is an important contribution yielded by our analysis.

The remainder of the paper is organized as follows. Section 2 describes the signaling game and how environmental regulation affects the nature of separating equilibrium under monopoly and duopoly. In section 3, we discuss a case where a monopolist may invest in cleaner technology in the first stage and analyze the effect of an increase in the level of environmental regulation on the incentive to invest. Section 4 illustrates how environmental regulation affects signaling behavior of firms and the effect of competition on the incentive to invest. Section 5 concludes.

2 Signaling environmental quality through price

2.1 Monopoly

Consider a market where the production process of a monopolist causes environmental damage. We assume that depending on its current production technology, the monopolist could be of two types: *clean* (C) or *dirty* (D); a firm produces β_C units of emission per unit of output if it is *clean*, and a firm emits β_D per unit of output if it is *dirty* where

$$0 < \beta_C < \beta_D.$$

The firm produces output at constant unit cost, and the unit production cost of a clean firm is greater than that of a dirty type i.e.,

$$0 < c_D < c_C.$$

Emission in the industry is regulated with the firm being required to purchase emission permit from a competitive emission permit market at an exogenously given price t. Here emission is a proxy for any kind of environmental damage, and emission price signifies any expected price that a firm may have to pay for the environmental damage caused by the production process. For example, under liability rule, if a firm's production process causes significant environmental damage over time then in the long run, it might be subjected to litigation in a court of law, and the emission price would capture the future expected liability. Let

$$X_C = c_C + t\beta_C \text{ and } X_D = c_D + t\beta_D$$

be the post-regulation marginal cost of a clean and dirty firm respectively.

There is a unit mass of risk neutral consumers in the market. Consumers have unit demand i.e., each consumer buys at most one unit of the good. The valuation (maximum willingness to pay) of a consumer for a unit of the product depends on the firm's actual emission e per unit of output and is given by:

$$V(e, \rho) = \theta + \rho(A - \frac{e}{\beta_D}) \tag{1}$$

where $\theta > 0$, $1 < A < 2$, and ρ is a consumer specific environmental consciousness index that is distributed *uniformly* on an interval $[0, \overline{\rho}]$. Observe that for any ρ,

$$V(\beta_C, \rho) = \theta + \rho(A - \frac{\beta_C}{\beta_D}) > V(\beta_D, \rho) = \theta + \rho(A - 1);$$

further, we assume that $V(\beta_C, \rho) > X_C$ and $V(\beta_D, \rho) > X_D$. Consumers are not aware of the actual environmental performance of a firm and the trades in emission permit market. *Ex ante,* consumers believe that the firm is of clean (C) type with probability $\mu \in (0,1)$ and of dirty (D) type with probability $(1-\mu)$. Observe that the true demand for a product is

$$\begin{aligned} Q &= 1 + \frac{\theta - p}{\overline{\rho}(A - \frac{\beta_C}{\beta_D})} \text{ where } p \in \left[\theta, \theta + \overline{\rho}(A - \frac{\beta_C}{\beta_D})\right] \text{ if the firm is clean,} \\ &= 1 + \frac{\theta - p}{\overline{\rho}(A-1)} \text{ where } p \in [\theta, \theta + \overline{\rho}(A-1)] \text{ if the firm is dirty.} \end{aligned} \tag{2}$$

The demand for the dirty firm's product is more elastic than that of the clean one. In the *full information equilibrium,* both types of firms charge their respective monopoly prices i.e.,

$$P_C^m = \frac{1}{2}\left[\theta + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) + X_C\right] \text{ and } P_D^m = \frac{1}{2}\left[\theta + \overline{\rho}(A-1) + X_D\right]. \tag{3}$$

For simplicity, we normalize θ to 1.

We consider a two stage Bayesian game. In the first stage, nature draws the type (*clean* or *dirty*) of the firm from a distribution that assigns probability $\mu \in (0,1)$ to *clean* type and probability $(1-\mu)$ to *dirty* type. This move of nature is observed only by the firm. After observing its realized type, the firm chooses its price. Finally, consumers observe the price charged by the firm, update their beliefs, and decide whether to buy. The basic solution concept used in this section is that of *Perfect Bayesian Equilibrium (PBE)* that satisfies Cho-Kreps (1987) intuitive criterion.

2.1.1 Low emission price: Clean firm has higher effective cost of production

Let t^R be the critical emission price at which the post-regulation marginal cost of a clean firm (X_C) is exactly equal to that of the dirty firm (X_D) i.e.,

$$t^R = \frac{c_C - c_D}{\beta_D - \beta_C}.$$

For any emission price $t \leq t^R$, the post-regulation marginal cost of a clean firm is strictly higher than that of a dirty firm $(X_C \geq X_D)$, and we find that in the unique separating equilibrium high price signals environment friendly production process.

Proposition 1 *Suppose that $t \leq t^R$ i.e., the emission price is low (weak regulation) so that the post-regulation marginal cost is lower for the dirty firm. Then, the unique separating equilibrium that satisfies the intuitive criterion is one where higher price signals better environmental performance (clean type). Further, in this equilibrium, the dirty type always charges its full information monopoly price whereas the clean type may charge a price equal to or higher than its* *own full information monopoly price.*[8]

In a separating equilibrium, a dirty firm always charges its unique full information monopoly price. Note that for any emission price $t \leq t^R$, the full information monopoly price of a dirty firm is lower than that of the clean firm. Under significantly lower emission price, the post-regulation marginal cost difference between the clean and the dirty firm is quite high. The clean type charges its full information monopoly price. If the dirty type imitates the clean type's action i.e., charges full information monopoly price of the clean type then because of the downward sloping demand curve the dirty type (with relatively lower post-regulation marginal cost) sells lower quantity and earns lower profit. In other words, the dirty type does not have any incentive to imitate the clean type. Increase in the level of emission price reduces the gap between the post-regulation marginal costs of both types which implies that the difference between full information monopoly prices of the clean type and the dirty type becomes smaller; this, in turn, increases the incentive of the dirty type to imitate the clean type. Therefore, in order to deter the dirty type from imitating its higher price-lower quantity combination, the clean type charges a higher price than its own full information monopoly price (upward signaling distortion).

The equilibrium outcome described above is supported by the following out-of-equilibrium beliefs of consumers: if the price charged by a firm is above the equilibrium price of the clean type then consumers believe that it is a clean firm with probability one, otherwise consumers believe that it is a dirty firm with probability one. It is easy to verify that given these out-of-equilibrium beliefs of consumers, a firm whether it is clean or dirty has no incentive to charge any out-of-equilibrium price. Following the argument in Bagwell and Riordan's (1991) paper, it can be shown that these out-of equilibrium beliefs satisfy intuitive criterion.

2.1.2 High emission price: Clean firm has lower effective cost of production

At a significantly higher level of emission price $t \geq t^R = \frac{c_C - c_D}{\beta_D - \beta_C}$, the post-regulation marginal cost of a clean firm is relatively lower than that of the dirty firm $(X_C \leq X_D)$; this contradicts the standard assumption (i.e., a clean firm has higher marginal cost).

Proposition 2 *Suppose that $t \geq t^R$ i.e., the emission price is high (stringent regulation) so that the post-regulation marginal cost is lower for the clean firm. Then, in the unique separating equilibrium, lower price signals better environmental performance (clean type). The dirty type always charges its full information monopoly price whereas the clean type may charge a price equal to or lower than its own full information monopoly price. Incomplete information may reduce the market power of a firm.*[9]

[8] See proposition 1* in Appendix.

[9] See proposition 1* in Appendix.

As mentioned in Section 1, in the absence of any environmental regulation, Mahenc (2007, 2008) shows that higher price signals better environmental quality of a firm. Proposition 2 shows that this does not hold if the level of regulation is significantly high. In particular, since the post-regulation marginal cost of a dirty firm is more than that of a clean firm ($X_D \geq X_C$), a clean firm cannot reveal its type by charging a higher price relative to the price charged by the dirty type. In fact, when the post-regulation marginal cost difference is not significantly high, and the difference between the full information monopoly prices of the clean type and the dirty type is small, then the dirty type has an incentive to imitate the clean type. In this case, a clean firm prefers to sell a higher quantity by charging a price lower than its own full information monopoly price (downward signaling distortion). On the other hand, when the post-regulation effective cost difference between the clean type and the dirty type of the firm is quite high then the firm, if it is of clean type, charges its full information monopoly price (which is lower than that of the full information monopoly price of a dirty firm), and the dirty type does not have any incentive to imitate the clean type's action i.e., to charge lower price and sell higher quantity.

The equilibrium outcome is supported by the following out-of-equilibrium beliefs of consumers: if the price charged by a firm is greater than equal to the price charged by the dirty type then consumers believe that it is a dirty firm with probability one, otherwise consumers believe that the firm is a clean type with probability one. Given this out-of-equilibrium beliefs of consumers, a firm whether it is clean or dirty has no incentive to charge any out-of-equilibrium price. As before, following the argument in Bagwell and Riordan's (1991) paper, it can be easily verified that these out-of-equilibrium-beliefs satisfy intuitive criterion.

2.1.3 Effect of environmental regulation on signaling distortion

From the above discussion one can conclude that a monopolist signals its environmental performance to consumers through prices, and the choice of signaling equilibrium price depends on the level of emission price. The following proposition summarizes the effect of increase in the level of emission price on the signaling behavior of a monopolist.

Proposition 3 *(i) Suppose that $t < t^R$ i.e., the post-regulation marginal cost of the clean type is higher than that of the dirty type. Then, there exists a critical emission price t^U such that for $t \in (t^U, t^R]$, the clean type charges a higher price compared to its own full information monopoly price to signal its environmental performance (i.e., there is* upward signaling distortion*).*
(ii) Suppose that $t > t^R$ i.e., the post-regulation marginal cost of the clean type is lower than that of the dirty type. Then, there exists a critical emission price t^D such that $t \in [t^R, t^D)$, a clean firm charges a lower price compared to its own full information monopoly price to signal its environmental performance (i.e., there is downward signaling distortion*).*
(iii) If $t \leq t^U$ or $t \geq t^D$, then there is no signaling distortion, and the market outcome is as

under full information.

Proof. See Appendix.[10] ■

Let Δ be the measure of signaling distortion i.e., the difference between signaling distortion price and full information monopoly price; when $\Delta > 0$ then there is *upward signaling distortion*, and $\Delta < 0$ implies that there is *downward signaling distortion*. For any $t \leq t^R$, $\Delta > 0$, and the value of Δ increases with increase in the level of emission price; whereas, for any $t \in [t^R, t^D)$, $\Delta < 0$, and the absolute value of Δ decreases with increase in the level of emission price (see Figure 2 in Appendix).

Proposition 4 *When the emission price is low $\left(t < t^R \text{ i.e., weak regulation}\right)$, then the extent of upward signaling distortion (the absolute value of Δ) in the separating equilibrium increases with an increase in emission price (i.e., increase in regulation). Whereas when the emission price is high $\left(t > t^R \text{ i.e., strong regulation}\right)$, then the extent of downward signaling distortion (the absolute value of Δ) in the separating equilibrium decreases with an increase in emission price (i.e., increase in regulation).*

2.2 Duopoly

In this section, we consider a market with two firms that compete in prices. The production technology of each firm can be of two potential types: *dirty* (D) and *clean* (C); a firm produces β_C units of emission per unit of output if it is *clean*, and a firm emits β_D per unit of output if it is *dirty* where

$$0 < \beta_C < \beta_D.$$

As before, each firm produces at constant unit cost, and the unit production cost of a clean firm is greater than that of a dirty firm i.e.,

$$0 < c_D < c_C.$$

Emission in the industry is regulated with each firm being required to purchase emission permit from a competitive emission permit market at an exogenously given price t. Let

$$X_C = c_C + t\beta_C \text{ and } X_D = c_D + t\beta_D$$

be the post-regulation marginal cost of a clean and dirty firm respectively.

There is a unit mass of risk-neutral consumers in the market. Consumers have unit demand i.e., each consumer buys at most one unit of the good. The valuation (maximum willingness to

[10] Figure 1 in Appendix illustrates proposition 3.

pay) of a consumer for a unit of the product depends on his environmental consciousness and on the firm's actual emission e per unit of output. To maintain tractability of our model, we assume that *consumers are identical in terms of their environmental consciousness.* In other words, all consumers have identical valuation V_C for a unit of a clean product and V_D for a unit of a dirty product where

$$V_C = 1 + \widetilde{\rho}(A - \frac{\beta_C}{\beta_D}) > V_D = 1 + \widetilde{\rho}(A - 1),$$

and $\widetilde{\rho}$ is the common environmental consciousness of all consumers. Further, we assume that $V_C > X_C$ and $V_D > X_D$.

Here we consider a two stage Bayesian game. In the first stage, nature draws the type (*clean* or *dirty*) of each firm independently from a common distribution that assigns probability $\mu \in (0, 1)$ to *clean* type and probability $(1 - \mu)$ to *dirty* type. A firm observes its realized type; however, its rival firm and consumers remain unaware of the realized type of the firm. In the next stage, firms choose prices simultaneously. Finally, consumers observe the prices charged by the firms, update their beliefs, decide whether to buy, and from which firm to buy. The basic solution concept used in this section is that of *Perfect Bayesian Equilibrium (PBE)* that satisfies Cho-Sobel (1990) D1 criterion which is stronger than the intuitive criterion.

2.2.1 Low emission price: Cleaner firm has higher effective cost of production

Under lower level of emission price i.e., for any emission price $t < t^R = \frac{c_C - c_D}{\beta_D - \beta_C}$, the post-regulation marginal cost of a clean firm is more than that of a dirty firm ($X_C > X_D$); in this case, the problem is equivalent to the signaling game considered by Janssen and Roy (2009). Following the construction in their paper we get the following result:

Proposition 5 (Janssen and Roy (2009)**)** *For $t < t^R$ (weak regulation), in any symmetric separating perfect Bayesian equilibrium, a clean firm charges a deterministic price p_C which is higher than any price charged by a dirty firm; dirty firms follow a mixed pricing strategy with support $\left[\underline{P}_D, \overline{P}_D\right]$ and a continuous distribution function $F_D(p)$, where*

$$\overline{P}_D = p_C - \widetilde{\rho}(1 - \frac{\beta_C}{\beta_D}) \text{ and } \underline{P}_D = \mu\left[p_C - \widetilde{\rho}(1 - \frac{\beta_C}{\beta_D})\right] + (1 - \mu) X_D.$$

If $V_C - X_D \leq 2(V_D - X_D)$, then there exists a unique symmetric separating D1 equilibrium[11] *where a clean firm charges a deterministic price $p_C = \max\{X_C, X_D + 2(V_C - V_D)\}$ which is*

[11] This strong refinement criterion is originally developed by Cho and Sobel (1990) in the context of pure signaling games with one sender. Janssen and Roy (2009) modify and adapt D1 criterion in their model with multiple senders (firms).

lower than its full information monopoly price; all consumers buy with probability one.
If $V_C - X_D > 2(V_D - X_D)$, then in the unique symmetric separating D1 equilibrium, the price charged by a clean firm is a deterministic price equal to its full information monopoly price V_C; all consumers may not buy with probability one.

Note that there does not exist any separating equilibrium in pure strategies. When a dirty firm wants to reveal its type by charging a lower price than its rival then it can earn a strictly positive rent in the state where the rival is of clean type, but in a state where the rival is of dirty type, it does not earn sufficient positive profit as a dirty rival (with lower marginal cost) can always undercut its price.

In the symmetric separating perfect Bayesian equilibrium, dirty firms follow a common probability distribution $F_D(p)$ whose support is an interval $\left[\underline{P}_D, \overline{P}_D\right]$, and the clean firms charge a common deterministic price p_C which is always higher than the price charged by the dirty firms. At the upper bound of the support $\left(\overline{P}_D\right)$, a consumer is indifferent between buying from a clean firm at p_C and from a dirty firm at $\overline{P}_D$ i.e.,

$$\overline{P}_D = p_C - (V_C - V_D).$$

The probability distribution function $F_D(p)$ of dirty firm has no mass point at $\overline{P}_D$. As a dirty firm charges a price less than $\overline{P}_D$ almost surely, a clean firm can only sell in the state when the rival is of clean type. The equilibrium expected profit of the dirty firm for charging any price $p \in \left[\underline{P}_D, \overline{P}_D\right]$ is given by

$$\pi_D^* = [\mu + (1-\mu)(1-F_D(p))](p - X_D). \tag{4}$$

In a state where its rival is a clean firm, a dirty firm can charge $\overline{P}_D$, sell to all consumers, and earns a strictly positive profit equal to

$$\left(\overline{P}_D - X_D\right)\mu = \left(p_C - \widetilde{\rho}(1 - \frac{\beta_C}{\beta_D}) - X_D\right)\mu \tag{5}$$

which is identical to the equilibrium expected profit of the dirty firm π_D^*. The lower bound of the support $(\underline{P}_D)$ is the lowest price that the dirty firm wants to undercut, given that it is going to capture entire market irrespective of the type of its rival; it earns strictly positive expected profit which is equal to π_D^* i.e.,

$$\underline{P}_D - X_D = \pi_D^* = \left(p_C - \widetilde{\rho}(1 - \frac{\beta_C}{\beta_D}) - X_D\right)\mu.$$

Therefore, the lower bound of the support is

$$\underline{P}_D = \mu \left[p_C - \widetilde{\rho}(1 - \frac{\beta_C}{\beta_D}) \right] + (1-\mu)\, X_D.$$

Note that the equilibrium price distribution i.e., $\left[\underline{P}_D, \overline{P}_D\right]$ and the expected profit π_D^* of the dirty firm depend on the deterministic price charged by the clean firm. At every price $p \in \left[\underline{P}_D, \overline{P}_D\right]$, the dirty firm can sell to all consumers as long as the rival of dirty type does not undercut, and its expected profit at p is equal to

$$\left[\mu + (1-\mu)(1 - F_D\left(p\right))\right](p - X_D)$$

This is equal to π_D^* for every price $p \in \left[\underline{P}_D, \overline{P}_D\right]$ as long as

$$\left[\mu + (1-\mu)(1 - F_D\left(p\right))\right](p - X_D) = \left(p_C - \widetilde{\rho}(1 - \frac{\beta_C}{\beta_D}) - X_D \right) \mu$$

(from (4) and (5)) which implies that

$$F_D\left(p\right) = 1 - \frac{\mu}{(1-\mu)} \left(\frac{p_C - \widetilde{\rho}(1 - \frac{\beta_C}{\beta_D}) - X_D}{p - X_D} - 1 \right)$$

where $F_D\left(p\right)$ is continuous on $\left[\underline{P}_D, \overline{P}_D\right]$, $F_D\left(\underline{P}_D\right) = 0$, and $F_D\left(\overline{P}_D\right) = 1$.

In this perfect Bayesian separating equilibrium, a clean firm can sell only in the state where its rival is clean too, and they equally divide the market among themselves as consumers are indifferent between firms. In that case, either all consumers buy from the clean firms with probability one, or some of them do not buy i.e., randomize between buying a clean product and not buying at all. If the state in which all consumers buy with probability one from the clean firms exists, then the strategies and the out-of-equilibrium beliefs described above constitute a perfect Bayesian equilibrium which satisfies the incentive compatibility constraints of the clean and the dirty firms iff

$$V_C - X_D \leq 2\left(V_D - X_D\right). \tag{6}$$

Under this unique separating equilibrium, the price p_C charged by the clean firm is lower than its full information monopoly price V_C; in particular, for emission price $t \leq t^R - 2\frac{\widetilde{\rho}}{\beta_D}$ the clean type charges its post-regulation marginal cost X_C such that the firm loses its market power. If (6) does not hold then only a fraction, say α, of consumers buy from the clean firms; note that in this equilibrium, a clean firm charges a price equal to its full information monopoly price V_C since a consumer is indifferent between buying from a clean firm and not buying at all.

The symmetric Bayesian equilibrium described above can be supported by the following out-of-equilibrium beliefs of consumers: if the price p charged by a firm is such that $p \neq p_C$

and $p \notin [\underline{P}_D, \overline{P}_D]$, then consumers believe that the firm is of dirty type with probability one. Given these out-of-equilibrium beliefs, no firm has an incentive to unilaterally deviate to any out-of-equilibrium price.

It can be argued that these out-of-equilibrium beliefs satisfy the D1 refinement.[12] Consider any out-of-equilibrium price; observe that for any level of quantity, if it is profitable for a clean firm to deviate to the out-of-equilibrium price then the dirty type also finds it strictly profitable to deviate to such a price.

2.2.2 High emission price: Clean firm has lower effective cost of production

Under higher level of emission price i.e., for any emission price $t > t^R = \frac{c_C - c_D}{\beta_D - \beta_C}$, the post-regulation marginal cost of a clean firm is lower than that of a dirty firm $(X_C < X_D)$. In this case, we find the following unique symmetric Bayesian equilibrium:

Proposition 6 *For any emission price $t > t^R$, there exists a unique symmetric separating D1 equilibrium where the dirty firm charges a deterministic price $p_D = X_D$, and the clean firm follows the mixed strategy with support $[\underline{P}_C, X_D)$ and a continuous distribution function $F_C(p)$, where $\underline{P}_C = \mu X_C + (1-\mu) X_D$ and $F_C(p) = 1 - \frac{1-\mu}{\mu}\left(\frac{X_D - X_C}{p - X_C} - 1\right)$. Thus, under strong regulation, lower price signals better environmental performance (clean type).*

Note that it can be easily established that there does not exist any separating equilibrium in pure strategies. When a clean firm wants to reveal its type by charging a lower price than its rival then it can earn a strictly positive rent in the state where the rival is of dirty type, but in a state where the rival is of clean type, it does not earn sufficient positive rent as a clean rival (with lower post-regulation marginal cost) can always undercut its price.

In the symmetric perfect Bayesian equilibrium, the dirty firms always charge a deterministic price, say p_D, whereas, the clean firms follow a common probability distribution $F_C(p)$ whose support is an interval $[\underline{P}_C, X_D)$. As $p \to X_D$, the expected profit earned by the clean firm is given by

$$\pi_C^* = (1-\mu)(X_D - X_C),$$

and for any price $p \in [\underline{P}_C, X_D)$, a clean firm's expected profit is equal to π_C^*. The lower bound $\underline{P}_C$ is the price below which a clean firm does not have any incentive to undercut its rival clean firm, and at this price a clean firm's expected profit is equal to π_C^*. This implies that

$$\underline{P}_C = \mu X_C + (1-\mu) X_D.$$

[12] For a formal proof see Janssen and Roy (2009).

At every $p \in [\underline{P}_C, X_D)$, the clean firm sells to all consumers as long as it is not undercut by rival clean firm, and its expected profit at price p is given by

$$[(1-\mu) + \mu(1 - F_C(p))](p - X_C)$$

which is equal to π_C^*. From this we can derive that

$$F_C(p) = 1 - \frac{1-\mu}{\mu}\left(\frac{X_D - X_C}{p - X_C} - 1\right)$$

where $F_C(p)$ is continuous on $p \in [\underline{P}_C, X_D)$, $F_C(X_D) = 1$, and $F_C(\underline{P}_C) = 0$.

The symmetric Bayesian equilibrium described above can be supported by the following out-of-equilibrium beliefs of consumers: if a firm charges any price $p > X_D$ then consumers believe that the firm is dirty type with probability one, whereas if a firm charges a price $p < \underline{P}_C$ then consumers believe that it is clean type with probability one. Given these out-of-equilibrium beliefs, no firm has an incentive to unilaterally deviate to any out-of-equilibrium price.

It can be argued that these out-of-equilibrium beliefs satisfy the D1 refinement. Consider any out-of-equilibrium price; observe that for any level of quantity, if it is profitable for a clean firm to deviate to the out-of-equilibrium price then the dirty type also finds it strictly profitable to deviate to such a price.

3 Effect of environmental regulation on the incentive to invest: Monopoly

Suppose that a firm is initially endowed with a dirty production technology i.e., it produces β_D units of emission per unit of output and incurs a post-regulation marginal cost of $X_D = c_D + t\beta_D$, where c_D is the unit cost of production, and t is the exogenously given emission price. Before going in to production, the firm decides whether to invest in development of cleaner technology. For simplicity, we assume that a firm invests either zero or an exogenously fixed amount $f > 0$. The realized outcome of investment is a *clean* production technology with probability $\mu \in (0, 1)$ and a *dirty* one with probability $(1-\mu)$. If a firm does not invest then it remains *dirty.* If investment leads to clean technology, the firm emits $\beta_C < \beta_D$ per unit of output incurring a post-regulation marginal cost of $X_C = c_C + t\beta_C$, where c_C is the unit cost of production. We assume that if the realized outcome is a clean production technology then the firm always uses that technology.[13] As described in section 2.1, there is a unit mass of risk neutral consumers

[13] Observe that after firms invest to develop a cleaner technology, if firms are again allowed to choose the production technology to be used, then if dirty technology is cheaper, a firm may discard the realized clean technology as the dirty firm may earn higher profit. In this case, consumers will infer that any firm that invests is a dirty firm with probability one, and therefore, in equilibrium no firm invests.

with unit demand; the valuation of a consumer for per unit of the product, true demand for the product are given by (1) and (2) respectively.

Formally, we have a multi-stage Bayesian game. In the first stage, a firm decides whether to invest in development of cleaner production technology; consumers observe firm's investment decision, but they do not know the realized outcome (in case the firm invests). Then, Nature draws the type of an investing firm from a distribution that assigns probability $\mu \in (0,1)$ to the clean type and probability $(1-\mu)$ to the dirty type. This move of nature is only observed by the firm. Next, the firm chooses its price, and finally, consumers decide whether to buy.

If post-regulation effective marginal cost is lower for the dirty firm i.e., $X_D < X_C$ then in the signaling equilibrium the dirty type earns higher profit relative to the clean type, and thus, a firm has no incentive to invest in clean technology. Whereas if $X_D > X_C$, then the clean firm who has lower effective marginal cost of production earns higher profit in the separating equilibrium. Therefore, a firm endowed with dirty technology has an incentive to invest in cleaner technology. Observe that for any $t > t^R$ (which implies $X_D > X_C$) as emission price increases, the difference between profits earned by a clean type and a dirty type firm decreases.

Proposition 7 *(i) If the emission price* $t \leq t^R = \frac{c_C - c_D}{\beta_D - \beta_C}$ *i.e., regulation is weak, a firm does not invest in cleaner technology.*
(ii) At any emission price $t > t^R = \frac{c_C - c_D}{\beta_D - \beta_C}$ *i.e., if regulation is strong, and in addition,* f *is not too large, then the firm invests in development of clean production technology.*

4 Effect of environmental regulation on the incentive to invest: Duopoly

In this section, we consider a market with two firms that compete in prices. Suppose that firms are initially endowed with a dirty production technology i.e., each produces β_D units of emission per unit of output and incurs a post-regulation marginal cost of $X_D = c_D + t\beta_D$, where c_D is the unit cost of production and t is the exogenously given emission price. Before going into production, firms simultaneously decide whether to invest in development of clean technology. As before, we assume that each firm may either invest zero or an exogenously fixed amount $f > 0$. Investment leads to the development of clean technology with probability $\mu \in (0,1)$ and if this occurs, each firm emits $\beta_C < \beta_D$ per unit of output and incurs a post-regulation marginal cost of $X_C = c_C + t\beta_C$, where c_C is the unit cost of production. As in the duopoly model analyzed in section 2.2, there is a unit mass of risk neutral consumers with unit demand, and further, consumers are identical in terms of their environmental consciousness i.e., all consumers have identical valuation V_C for a unit of a clean product and V_D for a unit of a dirty product where

$$V_C = 1 + \widetilde{\rho}(A - \frac{\beta_C}{\beta_D}) > V_D = 1 + \widetilde{\rho}(A - 1),$$

and $\widetilde{\rho}$ is the common environmental consciousness of all consumers.

Formally, we have a multi-stage Bayesian game. In the first stage, firms simultaneously decide whether to invest in development of clean technology. The actions chosen by both firms at this stage are observed by both firms and consumers. If it does not invest, a firm remains dirty with probability one, and this is known to all. If it invests then the realized production technology is clean with probability $\mu \in (0, 1)$ and dirty with probability $1-\mu$, but their realized production technology is pure private information - unknown to the rival firm as well as to consumers. However, the realizations of production technology after investment are independent (and identically distributed) across firms that choose to invest, and the distribution function that assigns probability $\mu \in (0, 1)$ to cleaner technology and probability $1 - \mu$ to dirty technology is common knowledge. In the next stage, firms choose prices simultaneously to signal the environmental performance to consumers, and finally, consumers make their purchase decisions.

4.1 Possible subgames

Consider the second stage subgame beginning after investment decisions are made. There are essentially three different situations: (1) both firms invest (I, I), (2) both firms do not invest (NI, NI), and (3) one invests and other does not (I, NI). In section 2.2, we have already discussed the signaling game under the first situation i.e., when both firms invest in the development of clean technology. In situation (2), since both firms decide not to invest, the second stage game degenerates to a standard full information symmetric Bertrand price competition game.

Proposition 8 *When both firms do not invest then for any emission price, both firms charge a common price equal to the post-regulation marginal cost of production of the dirty firm* (X_D), *and both earn zero profit.*

A more interesting case arises under the last situation i.e., *when only one firm invests*; we have a game of one sided incomplete information. The firm that invests (say, firm I) becomes clean (C) with probability μ and dirty (D) with probability $1 - \mu$, while a firm that does not invest (say firm NI) remains dirty (D) with probability one.

For a low emission price i.e., $t < t^R = \frac{c_C - c_D}{\beta_D - \beta_C}$, the post-regulation marginal cost of a clean firm is higher compared to the dirty firm $(X_C > X_D)$; in this case if *only one firm invests* then we find the following unique separating equilibrium:

Proposition 9 *When only one firm invests, at any emission price* $t \leq t^R - \frac{\widetilde{\rho}}{\beta_D}$ (*weak regulation*), *there exists a unique separating D1 equilibrium in the second stage pricing game. In this equilibrium, a clean firm charges a price equal to its post-regulation marginal cost* X_C (*earning zero expected profit*), *and a firm that does not invest as well as a firm that invests but remains dirty, play mixed strategies with different distribution functions but identical support* $[\underline{p}_D, \overline{p}_D]$

$$\overline{p}_D = V_D - [V_C - X_C] \text{ and } \underline{p}_D = \mu\overline{p}_D + (1-\mu)X_D$$

(*earning strictly positive expected profit*)*. Thus, for any emission price* $t \leq t^R - \frac{\widetilde{\rho}}{\beta_D}$ (*low emission price*), *if only one firm invests then higher price signals better environmental performance* (*clean type*).

In the symmetric perfect Bayesian separating equilibrium, firm I of type C charges a deterministic price p_C, and firm NI as well as firm I of type D randomize price over an identical support $[\underline{p}_D, \overline{p}_D]$ but with different probability distributions, $F_{NI}(p)$ and $F_I(p)$ respectively (that we describe below).[14] At the upper bound of the support, a consumer is indifferent between buying from a clean firm at p_C and from a dirty firm at price $\overline{p}_D$. Note that since firm I of type C always charges a higher price than its rival firm NI who is a dirty firm for sure, it sells zero with probability one and earns zero profit in the equilibrium. Therefore, in the separating equilibrium a clean firm should charge a price as low as its post-regulation marginal cost X_C such that it does not have any incentive to imitate the dirty firm's action.

To guarantee the existence of this separating equilibrium, the upper bound of price support of the dirty firm (i.e., $\overline{p}_D = V_D - [V_C - X_C]$) has to be greater than the post-regulation effective marginal cost of the dirty firm i.e.,

$$V_C - X_C \leq V_D - X_D. \tag{7}$$

which is satisfied as long as the emission price $t \leq t^R - \frac{\widetilde{\rho}}{\beta_D}$. Since at price $\overline{p}_D$ firm I of type D undercuts firm NI with probability one, at price $\overline{p}_D$ firm NI sells only in the state where the rival firm I is of type C, and the equilibrium expected profit of firm NI is given by:

$$\pi^*_{NI} = \mu[\overline{p}_D - X_D];$$

for any price $p \in [\underline{p}_D, \overline{p}_D]$, the dirty firm earns the same expected profit. This yields the lower bound of the mixed strategy price support i.e.,

$$\underline{p}_D = \mu\overline{p}_D + (1-\mu)X_D.$$

[14] It is easy to check that there is no separating equilibrium in pure strategies.

Firm NI assigns probability mass μ to the upper bound $\overline{p}_D$ of its price support as it knows that the rival firm I is of type C with probability μ. At every price $p \in [\underline{p}_D, \overline{p}_D]$, firm NI can sell to all consumers as long as it is not undercut by the rival firm I of type D, and its expected profit at p is equal to π^*_{NI} i.e.,

$$[\mu + (1-\mu)(1 - F_I(p))](p - X_D) = (p_D - X_D)\,\mu.$$

This yields the probability distribution function of firm I of type D i.e.,

$$F_I(p) = 1 - \frac{\mu}{1-\mu}\left[\frac{\overline{p}_D - X_D}{p - X_D} - 1\right], p \in [\underline{p}_D, \overline{p}_D]$$

where $F_I(p)$ is a continuous distribution function with no probability mass at any point, $F_I(\underline{p}_D) = 0$, and $F_I(\overline{p}_D) = 1$. Similarly, at every price $p \in [\underline{p}_D, \overline{p}_D]$ firm I of type D can sell to all consumers as long as it is not undercut by the rival firm NI, and its expected profit at p is equal to π^*_{NI} i.e.,

$$(p - X_D)(1 - F_{NI}(p)) = (p_D - X_D)\,\mu;$$

this yields the probability distribution function of firm NI i.e.,

$$F_{NI}(p) = 1 - \mu\frac{\overline{p}_D - X_D}{p - X_D}$$

where $F_{NI}(\overline{p}_D) = 1 - \mu$ and $F_{NI}(\underline{p}_D) = 0$.

The one sided incomplete information Bayesian equilibrium described above can be supported by the following out-of-equilibrium beliefs of consumers: if a firm charges any price $p > X_C$ then consumers believe that the firm is clean type with probability one; if $p < X_C$ then consumers believe that the firm is of dirty type with probability one. Given these out-of-equilibrium beliefs, no firm has an incentive to unilaterally deviate to any out-of-equilibrium price.

It can be argued that these out-of-equilibrium beliefs satisfy the D1 refinement. Consider any out-of-equilibrium price $p > X_C$; observe that for any level of quantity, if it is profitable for a dirty firm to deviate to any price $p > X_C$ then the clean type also finds it strictly profitable to deviate.

However, *when only one firm invests under a high emission price* i.e., $t > t^R - \frac{\widetilde{\rho}}{\beta_D}$, then the separating equilibrium described in proposition 9 does not exist. In particular, the condition for existence of such a separating equilibrium does not hold i.e., $V_C - X_C > V_D - X_D$; this along with relatively higher post-regulation marginal cost of the clean firm ($X_C > X_D$) imply that the emission price t lies within the following interval $\left(t^R - \frac{\widetilde{\rho}}{\beta_D}, t^R\right)$. In this case, both firms charge a price equal to the post-regulation marginal cost of the clean firm i.e., X_C.

One can easily check that when one firm invests then, for any emission price $t \geq t^R$, there does not exist any separating equilibrium; in this case, both firms charge a price equal to the post-regulation marginal cost of the dirty firm i.e., X_D. Note that since both firms are charging the same price in these (pooling) equilibrium, a firm that does not invest sells zero, and an investing firm captures the entire market as consumer's expected valuation of the investing firm's product is always higher.

Proposition 10 *Consider the situation where only one firm invests. (i) If* $t^R - \frac{\widetilde{\rho}}{\beta_D} < t < t^R$ *(low emission price), there does not exist any separating equilibrium. In the unique D1 pooling equilibrium, both firms charge a price equal to the post-regulation marginal cost of the clean firm i.e.,* X_C*; a firm that does not invest sells zero whereas a firm that invests in cleaner technology always gets the entire market.*
(ii) If $t \geq t^R$ *(high emission price), there does not exist any separating equilibrium. In the unique D1 pooling equilibrium, both firms charge a price equal to the post-regulation marginal cost of the dirty firm i.e.,* X_D*; a firm that has invested in cleaner technology captures the entire market and earns strictly positive expected profit.*

4.2 Subgame perfect Nash equilibrium of the investment game

In this sub-section, we investigate whether firms initially endowed with dirty technology have any incentive to invest in cleaner technology under the following two situations : (1) emission price is significantly low i.e., $t \leq t^R$ such that clean firm has higher post-regulation marginal cost of production $(X_C \geq X_D)$, and (2) emission price is high, in particular $t > t^R$, such that clean firm has lower post-regulation marginal cost of production $(X_C < X_D)$. Note that for any emission price, prior to realization of environmental quality of production technology, the expected profit of each firm is zero if both firms do not invest in cleaner technology.

4.2.1 Low emission price $t \leq t^R$

When **one firm** i.e., firm I **invests,** and the other firm NI does not then for any emission price $t \leq t^R - \frac{\widetilde{\rho}}{\beta_D}$, in the unique separating D1 equilibrium, firm I of type C sells zero with probability one and earns zero profit. Since firm NI assigns probability mass μ to the upper bound $\overline{p}_D$, firm I of type D earns equilibrium profit equal to $\mu[\overline{p}_D - X_D]$. As firm I undercuts firm NI at $\overline{p}_D$ with probability one, at price $\overline{p}_D$, firm NI sells only in the state where firm I is of type C, and the equilibrium profit of a firm that does not invest i.e., firm NI is given by:

$$\widehat{\pi}_{NI} = \mu[\overline{p}_D - X_D].$$

The *ex ante* expected equilibrium profit (before realization of types) of a firm that invests (here, firm I) is given by

$$\widehat{\pi}_I = (1-\mu)\mu[\overline{p}_D - X_D].$$

Note that even if the fixed cost of investment is zero, a non-investing rival gains more compared to an investing firm i.e., $\widehat{\pi}_{NI} > \widehat{\pi}_I > 0$. This is a major strategic externality.[15] From part (i) of proposition 10, we can easily check that at any emission price $t \in \left(t^R - \frac{\widetilde{\rho}}{\beta_D}, t^R\right)$, a firm that does not invest always earns zero profit in the equilibrium whereas, a firm who invests earns a strictly positive expected profit of $(1-\mu)\mu[X_C - X_D]$.

When both firms invest[16] then in the unique symmetric separating equilibrium that meets D1 refinement, the expected profit of a clean firm is

$$\begin{aligned}
\pi_C^* &= \frac{\mu}{2}(p_C - X_C) \\
&= 0, \text{ if } t \leq t^R - 2\frac{\widetilde{\rho}}{\beta_D} \\
&= \mu[(V_C - V_D) - \frac{X_C - X_D}{2}], \text{ if } t^R - 2\frac{\widetilde{\rho}}{\beta_D} < t \leq t^R,
\end{aligned}$$

and the expected profit of a dirty firm is

$$\begin{aligned}
\pi_D^* &= \mu(p_C - (V_C - V_D) - X_D) \\
&= \mu\left[(V_D - X_D) - (V_C - X_C)\right], \text{ if } t \leq t^R - 2\frac{\widetilde{\rho}}{\beta_D} \\
&= \mu(V_C - V_D), \text{ if } t^R - 2\frac{\widetilde{\rho}}{\beta_D} < t \leq t^R.
\end{aligned}$$

Thus, in this equilibrium, the *ex ante* expected profit of any firm in the first stage game is

$$\begin{aligned}
\pi^* &= \mu\pi_C^* + (1-\mu)\pi_D^* \\
&= (1-\mu)\mu\left[(V_D - X_D) - (V_C - X_C)\right], \text{ if } t \leq t^R - 2\frac{\widetilde{\rho}}{\beta_D}, \\
&= \mu\{(V_C - V_D) - \mu(\frac{X_C - X_D}{2})\}, \text{ if } t^R - 2\frac{\widetilde{\rho}}{\beta_D} < t \leq t^R
\end{aligned}$$

where $\overline{p}_D = V_D - [V_C - X_C]$.

There exist critical values of fixed cost of investment that depend on the level of emission

[15] It could be related to a type of vertical product differentiation, but since in this model consumers are identical, so the usual product differentiation story does not apply.

[16] For sake of simplicity, we consider the equilibrium where the clean firm charges a price which is less than its full information monopoly price, and all consumers buy with probability one; in other words, we assume that $V_C - X_D \leq 2(V_D - X_D)$ (see Proposition 5).

price $f_1(t), f_3(t)$, and $f_4(t)$ respectively where

$$f_1(t) = (1-\mu)\mu(\overline{p}_D - X_D),$$

$$f_3(t) = (V_C - V_D) - \mu(\frac{X_C - X_D}{2}),$$

$$\text{and } f_4(t) = (1-\mu)\mu(X_C - X_D).$$

The following two propositions illustrate the subgame perfect Nash equilibrium of the investment game, for any emission price $t \leq t^R$.

Proposition 11 *For $t \leq t^R - \frac{\widetilde{\rho}}{\beta_D}$, at least one firm invests if the fixed cost of investment $f \leq f_1(t)$ where $f_1(t) = (1-\mu)\mu(\overline{p}_D - X_D)$; for $t^R - \frac{\widetilde{\rho}}{\beta_D} \leq t \leq t^R$, at least one firm invests in equilibrium if the fixed cost of investment $f \leq f_4(t)$ where $f_4(t) = (1-\mu)\mu(X_C - X_D)$.*

Observe that unlike in the case of monopoly discussed in the previous section, here at least one firm invests in cleaner technology even when regulation is weak (provided the fixed cost of investment is small enough). In other words, in the presence of competition, firms may have strategic incentive to invest in the cleaner technology. The intuition is as follows. Firms invest not only to reduce the burden of regulation but also to change the information structure in the market (as consumers observe investment decision) that, in turn, changes the intensity of competition and allows them to gain market power. If no firm invests then each firm earns zero profit due to Bertrand price competition whereas, when at least one firm invests each earn strictly positive profit; though investing firm may earn lower profit.

Moreover, if the fixed cost of investment is sufficiently low then in the equilibrium both firms may invest in cleaner technology.

Proposition 12 *For $t \leq t^R - 2\frac{\widetilde{\rho}}{\beta_D}$, both firms never invest; for $t^R - 2\frac{\widetilde{\rho}}{\beta_D} \leq t \leq t^R$ there exists a critical fixed cost of investment $f_3(t) = (V_C - V_D) - \mu(\frac{X_C - X_D}{2})$ such that for any fixed cost $f \leq f_3(t)$ both firms invest. Further, $f_3(t)$ is increasing in t i.e., an increase in the level of regulation increases the incentive to invest.*

4.2.2 High emission price $t > t^R$

In this case, the post-regulation marginal cost of a clean firm is less relative to the post-regulation cost of the dirty firm ($X_D > X_C$). From proposition 6, we know that if **both firms invest,** then in the unique separating D1 equilibrium, the expected profit of the non-investing firm (NI) is always zero whereas, the expected profit of the investing firm (I) is $\mu(1-\mu)(X_D - X_C)$. Both firms, initially endowed with dirty technology, have an incentive to invest in cleaner technology if *ex ante* expected profit of the investing firm is at least as high as the fixed cost of investment, i.e.,

$$f \leq \mu (1-\mu) (X_D - X_C) .$$

This implies that at any emission price $t \geq t^R + \frac{f}{\mu(1-\mu)(\beta_D - \beta_C)}$, both firms invest in cleaner technology.

Similarly, when one firm invests, then from part (*ii*) of proposition 10, one can easily check that a firm that invests has a strictly positive expected profit of $\mu (X_D - X_C)$, and a firm that does not invest earns zero. Therefore, at least one firm finds it profitable to invest if the expected profit of an investing firm is large enough to compensate for the fixed cost of investment i.e.,

$$f \leq \mu (X_D - X_C) ,$$

which implies that for any emission price $t \geq t^R + \frac{f}{\mu(\beta_D - \beta_C)}$, at least one firm invests. The following proposition summarizes the equilibrium investment behavior of firms under significantly higher emission price.

Proposition 13 *For $t^R \leq t \leq t^R + \frac{f}{\mu(\beta_D - \beta_C)}$, no firm invests; one firm invests if $t^R + \frac{f}{\mu(\beta_D - \beta_C)} \leq t < t^R + \frac{f}{\mu(1-\mu)(\beta_D - \beta_C)}$, and at any emission price $t \geq t^R + \frac{f}{\mu(1-\mu)(\beta_D - \beta_C)}$, both firms invest. Thus, with increase in the level of regulation the incentive to invest in cleaner technology increases.*

5 Conclusion

In an imperfectly competitive industry where environmentally conscious consumers are not informed about the environmental damage (emissions) caused by firms, and firms signal the environmental attributes of their production technology through prices, I analyze the effect of environmental regulation on signaling behavior of firms as well as their incentive to invest in the development of cleaner technology. I consider a multi-stage Bayesian game where in the first stage, each firm (initially endowed with a "dirty" technology) decides whether or not to invest in process innovation, that can stochastically lead to the development of a relatively "cleaner" technology. Consumers observe the investment decision of each firm but not the realized outcome of innovation process nor the actual emissions of the firm. Firms are required to buy emission permits, but consumers are uninformed about trades in emission permit market. In the next stage, firms with private information about their technology set prices; we focus on the unique symmetric separating equilibrium at this stage. I show that if the post-regulation marginal cost is lower for the dirty firm (regulation is weak), then in the signaling equilibrium the dirty type earns higher profit; in this situation, a monopolist has no incentive to invest in clean technology. However, higher levels of regulation (where the post-regulation marginal cost is lower for the clean type), a firm always has an incentive to invest; in this case, the clean type signals its environmental attribute by charging a lower price. If the industry is a duopoly where firms compete in prices, there is always a strategic incentive to invest in order to soften price competition through incomplete information. I characterize the effect of increasing stringency of environmental regulation on the signaling behavior of firms and their incentive to invest in cleaner technology.

6 Appendix

Proposition 1^* **:** For any $t \leq t^R$, the unique separating equilibrium prices satisfying the intuitive criterion are

$$P_D = P_D^m \text{ and } P_C = \max\{P_C^m, P_C^{D+}\}$$

where P_D and P_C are the equilibrium price charged by the dirty type and the clean type respectively, and

$$P_C^{D+} = \frac{1}{2}\left[1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) + X_D\right] + \sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^m - X_D\right)^2}$$

For any $t \geq t^R$ there exists a separating equilibrium that satisfies the intuitive criterion

$$P_D = P_D^m \text{ and } P_C = \min\{P_C^m, P_C^{D-}\} \tag{8}$$

where

$$P_C^{D-} = \frac{1}{2}\left[1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) + X_D\right] - \frac{1}{2}\sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^m - X_D\right)^2}$$

Proof: A clean type has no incentive to mimic the dirty type if it charges a price P_C in the equilibrium such that $\pi\left(C, 1, P_C\right) > \pi\left(C, 0, P_D^m\right)$[17] i.e., the clean firm does not earn higher profit when it imitates a dirty firm, and this is possible when clean firm charges a price P_C such that $P_C^{C-} \leq P_C \leq P_C^{C+}$ (incentive compatibility constraint of a clean type) where

$$\begin{aligned} P_C^{C-} &= P_C^m - \sqrt{\left[P_C^m - X_C\right]^2 - \frac{(A - \frac{\beta_C}{\beta_D})}{(A-1)}\left(P_D^m - X_C\right)\left(P_D^m - X_D\right)} \text{ and} \\ P_C^{C+} &= P_C^m + \sqrt{\left[P_C^m - X_C\right]^2 - \frac{(A - \frac{\beta_C}{\beta_D})}{(A-1)}\left(P_D^m - X_C\right)\left(P_D^m - X_D\right)}. \end{aligned} \tag{9}$$

[17] Profit of a firm is written as a function of type of the firm, the probability that it is a clean type, and the price charged by the firm.

Observe that the incentive compatibility constraint for clean type is always satisfied at $P_C = P_C^m$ when $X_D < X_C$. Similarly, a dirty type has no incentive to imitate the clean type i.e., $\pi(D, 0, P_D^m) > \pi(D, 1, P_C)$ if clean type charges a price P_C such that either

$$\begin{aligned}
P_C \quad &\geq \quad P_C^{D+} = \frac{1}{2}\left[1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) + X_D\right] \\
&\quad + \frac{1}{2}\sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^m - X_D\right)^2} \\
\textit{or } P_C \quad &\leq \quad P_C^{D-} = \frac{1}{2}\left[1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) + X_D\right] \\
&\quad - \frac{1}{2}\sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^m - X_D\right)^2} \qquad (10)
\end{aligned}$$

(incentive compatibility constraint of a dirty type). For any emission price $t < t^R$ ($\implies X_D < X_C$), $P_C^{D+} < P_C^{C+}$ and $P_C^{D-} < P_C^{C-}$; this implies that if a clean type charges a price P_C such that $P_C^{C-} \leq P_C < P_C^{D+}$ then a dirty type has an incentive to imitate the clean type. On the other hand, if a clean type charges a price below P_C^{D-} then incentive compatibility constraint of a clean type implies that the clean type finds it profitable to imitate the dirty type as $P_C^{D-} < P_C^{C-}$. Therefore, a clean firm cannot reveal its type by charging a lower price than P_C^{D+}. In particular, if $P_C^m \geq P_C^{D+}$ then in the separating equilibrium a clean firm charges P_C^m; whereas, if $P_C^m < P_C^{D+}$ then it charges P_C^{D+} (which is also the minimum upward signaling distortion price) in order to deter the dirty type from imitating its higher price-lower quantity combination. The out-of-equilibrium beliefs of consumers is specified as follows: if the price charged by a firm is greater than equal to P_C then consumers believe that it is a clean firm with probability one whereas, if the equilibrium price is strictly less than P_C then green consumers believe that the firm is a dirty (D) type with probability one, where $P_C = \max\{P_C^m, P_C^{D+}\}$.
For any emission price $t > t^R$ ($\implies X_D > X_C$), $P_C^{D+} > P_C^{C+}$ and $P_C^{D-} > P_C^{C-}$; this implies that if a clean type charges a price above P_C^{D+} in order to deter dirty firm from imitating its action, it always has an incentive to imitate the dirty type's higher price-lower quantity combination. On the other hand, if a clean type charges a price P_C such that $P_C^{D-} < P_C \leq P_C^{C+}$ then a dirty type has an incentive to imitate the clean type's action Therefore, a clean cannot reveal its type by charging a higher price than P_C^{D-}. In particular, $P_C = \min\{P_C^m, P_C^{D-}\}$ where P_C^{D-} is the minimum (downward) signaling distortion price. The out-of-equilibrium belief is specified as follows: if the price charged by a firm is greater than equal to P_C then consumers believe that the firm is a dirty firm with

probability one, otherwise they believe that it is a clean firm with probability one.

Proof of proposition 3: From proposition 1^* we know that for any $t \leq t^R$ the clean firm charges a price $P_C = \max\{P_C^m, P_C^{D+}\}$ in the unique separating equilibrium that satisfies intuitive criterion. Now observe that $P_C^m \geq P_C^{D+}$ when $t \leq t^U$ and $t^U \leq 0$ if $\overline{\rho} \geq \rho^* = \sqrt{\frac{\left(1-\frac{\beta_C}{\beta_D}\right)(1-c_D)^2+(A-1)(c_C-c_D)^2}{\left(1-\frac{\beta_C}{\beta_D}\right)(A-1)\left(A-\frac{\beta_C}{\beta_D}\right)}}$. Therefore, if $\overline{\rho} \geq \rho^*$ then $P_C = P_C^{D+}$ whereas if $\overline{\rho} < \rho^*$ then for any $t \leq t^U$ $P_C = P_C^m$ and for any $t \in (t^U, t^R]$ $P_C = P_C^{D+}$. We also know that for any $t \geq t^R$ the clean firm charges a price $P_C = \min\{P_C^m, P_C^{D-}\}$ in the unique separating equilibrium that satisfies intuitive criterion. $P_C^m \gtreqless P_C^{D-} \implies t \lesseqgtr t^D$. Q.E.D.

Higher average environmental consciousness of consumers increases the true demand for the clean product, which in turn creates additional incentive for a dirty type to imitate the clean type. Therefore, under sufficiently *high* average environmental consciousness of consumers $(\overline{\rho} \geq \rho^*)$, for any emission price $t \leq t^R$, a clean firm charges a higher price than its full information monopoly price to deter a dirty type from imitating its action. On the other hand, when the average environmental consciousness is *not* sufficiently *high* $(\overline{\rho} < \rho^*)$ then for any emission price $t \leq t^U$, in the separating equilibrium, a clean firm charges its full information monopoly price whereas, for any emission price $t \in (t^U, t^R]$, it charges the upward signaling distortion price. Observe that at the critical emission price $t = t^U$, full information monopoly price of a clean firm is equal to the upward signaling distortion price.

It can be easily shown that for any emission price $t \in \left[t^R, t^D\right]$, a clean firm charges the downward signaling distortion price, as it is lower than the full information monopoly price; whereas, for any emission price $t \geq t^D$, a clean firm reveals its quality by its own full information monopoly price. Observe that at emission price $t = t^R$, the post-regulation marginal cost for a clean firm is equal to that of a dirty firm; in the separating equilibrium, a clean firm is indifferent between charging the upward distortion price and the downward distortion price.

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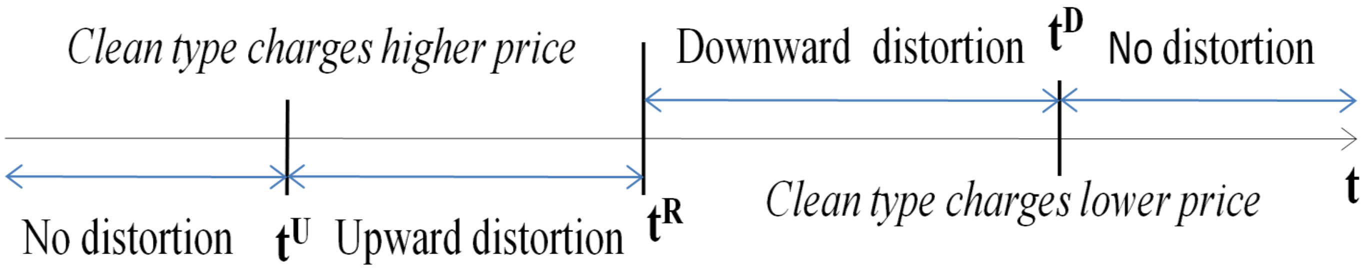

Figure 1

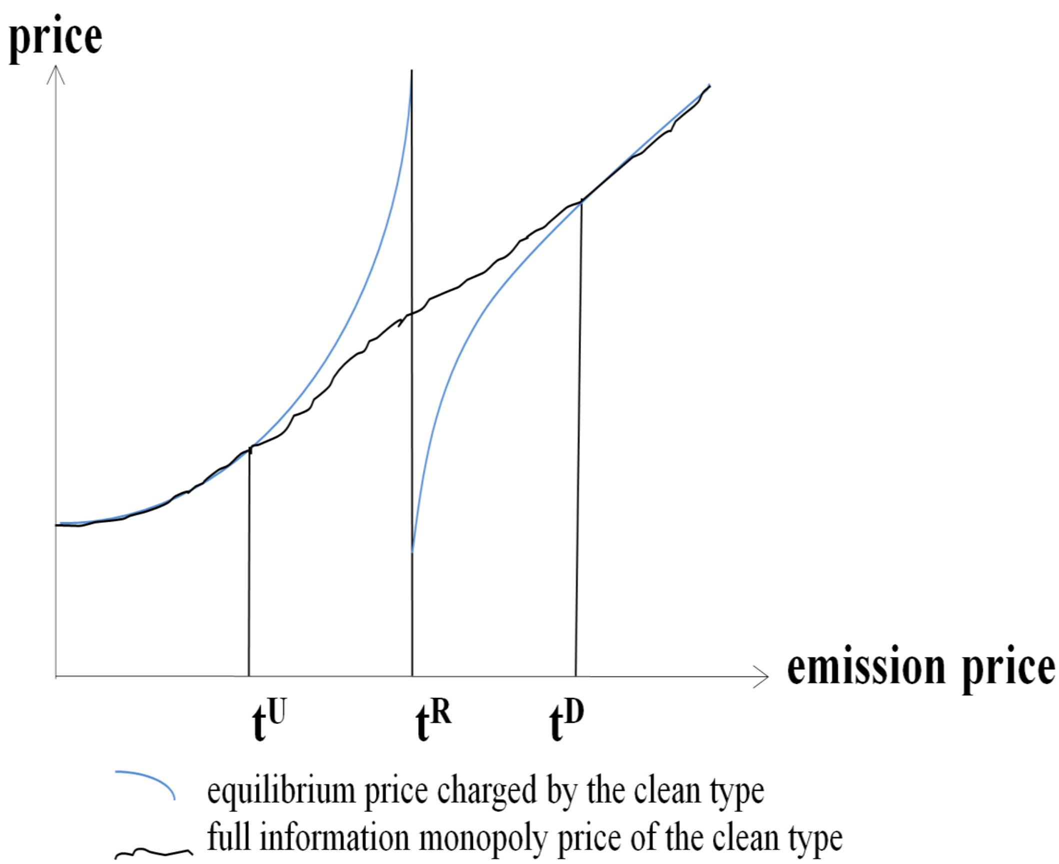

Figure 2