# Competitive Investment in Clean Technology and Uninformed Green Consumers.

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**Abstract**

In a market where consumers are not fully informed about the actual production technology or environmental performance of firms that engage in strategic competition, I study the effect of environmental consciousness of consumers on the incentive to invest in cleaner technology. Firms compete in prices and may signal their environmental performance to uninformed consumers through prices. I also analyze the effect of environmental regulation of firms in this setting. Compared to full information incomplete information generates higher strategic incentive to invest in cleaner technology particularly when consciousness and/or regulation is not too high which appears to fit the current reality in many industries. Thus, requiring mandatory disclosure of technology or environmental performance may discourage such investment. Even though consumers are uninformed, competition has a positive effect (relative to monopoly) on the incentive to invest. The fact that (in contrast to full information) under incomplete information higher environmental consciousness and/or regulation may reduce the incentive to invest in clean technology has important implication for public policy design as well as for environmental activists'campaign to increase green consciousness.

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**Key-words**: Duopoly; Environmental consciousness; Environmental regulation; Incomplete information; Investment; Mandatory disclosure; Signaling.

# 1 Introduction

Environmental consciousness among consumers is an important market force that can create incentives for firms to invest in the development and adoption of cleaner technology. Environmental groups often argue that the efficacy of green consumer consciousness as a device to discipline the environmental performance of firms is sharply limited by the availability of information; in particular, the fact that consumers are largely uninformed about the actual production technology or process and therefore, the actual environmental performance of firms, implies that profit maximizing firms may mostly ignore the implications of green consciousness. This is particularly relevant in markets where there are no reliable mechanisms (such as eco-labelling or credible third party certification) that enable at least partial disclosure of the actual technology or environmental performance of firms. This would appear to suggest that public dissemination of information about technology or production process used by firms (for instance, by requiring mandatory disclosure, or through activities of voluntary organizations that collect and publish such information) ought to promote investment in cleaner technology. This paper is an attempt to critically examine the theoretical basis of this claim.

While consumers may not have direct access to information about the nature of actual technology or production process used by firms, as rational agents they may *infer* such information from the observed conduct of firms in the market such as pricing. Indeed, the possibility of such inference creates incentives for firms to signal their private information (in a credible manner) and the incentive to signal, in turn, modifies the market behavior of firms and the market outcome relative to that in a world of full information. When firms evaluate their profit from investment in cleaner technology, they may not assume that consumers will have no information about their actual production technology; rather, they may foresee the signaling outcome in the market in the post-investment phase, and evaluate the profits generated in that outcome. The efficacy of consumer consciousness on technological change under incomplete information of consumers is then based on the signaling outcome. In order to argue for or against mandating direct disclosure of information, we need to compare the investment outcome under full information to that generated in a market where uninformed consumers infer the information from the observable behavior of firms.

The main contribution of this paper is to argue that when firms engage in strategic competition and signaling in the market, the incentive to invest in cleaner technology is generally *higher* when consumers are *ex ante* uninformed compared to that under full information. In other words, the lack of information about firms' actual production technology may not inhibit and in fact, may enhance the efficacy of consumer consciousness in inducing greener technological change. From this point of view, the paper suggests that there is not much of a case for mandatory disclosure law.

In addition to consumer consciousness, economic instruments of environmental regulation such as taxes, pollution permit requirements, liability laws etc. that impose costs on firms for their environmental externality also create incentives for investment in cleaner technology. Such regulations often affect the profitability of different types of technology, and the incentive of dirty firms to

pretend to be clean by imitating the actions of clean firms in the market place. All of these, in turn, affect the signaling outcomes in the market resulting from any profile of investment decisions by firms. The second contribution of this paper is that it offers an analysis of the interaction between environmental regulation and consumer consciousness when consumers are uninformed, and the circumstances under which they are complementary in inducing technological change.[1]

I consider an imperfectly competitive industry where two firms compete in prices. A fraction of consumers are environmentally conscious and are willing to pay more for the product produced at lower emission intensity. Consumers are uninformed about the actual emission caused or technology used by firms. Firms are also subject to public environmental regulation in the form of an emission permit requirement or emission tax. Regulation is assumed to be exogenous. Further, even though the public authority has information about the actual emissions (from actual permit trading or tax payments) of individual firms, such information is not directly available to consumers. Firms are initially endowed with a dirty technology and may invest in the development of a cleaner production technology where the outcome of investment i.e., whether the realized production process is clean or dirty, 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. In the next stage, firms with private information about their realized technology set prices competitively. In particular, firms may signal the environmental attribute of their production technology to uninformed consumers through prices.

The signaling and market competition stage of the model in this paper is closely related to models of signaling product quality in the presence of price competition in an oligopoly (Daughety and Reinganum (2007) , (2008) ; Janssen and Roy (2010)).[2] The underlying competitive signaling game in this paper draws on the specific model of Janssen and Roy (2010), but introduces a specific type of heterogeneity among consumers. Note that the focus of this paper is on the incentive to invest in technological change generated when firms signal private information about technology rather than the possibility of signaling. Further, unlike the quality signaling literature that often assumes symmetry between firms, analyzing the incentive to invest requires evaluation of market outcomes in asymmetric situations where one firm invests and the other does not.

There is a large theoretical literature on the effect of consumer consciousness on production technology and environmental performance of firms when there is no information problem between consumers and firms.[3] A few papers have studied the problem in the context of markets where consumers are uninformed but all of them confine attention to the case of a single seller and abstract from issues of strategic competition. Cavaliere (2000) studies the impact of consciousness on choice

[1] Eriksson (2004) illustrates the existence of complementarity between environmental regulation and consciousness even when consumers are aware of the environmental performance of firms.

[2] Unlike much of this literature, in this 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 type has lower effective marginal cost of production compared to the dirty type, and thus, lower price may signal better "quality".

[3] See among others Cremer and Thisse (1999), Moraga-Gonzalez and Padron-Fumero (2002), Arora and Gangopadhyay (2003), Bansal and Gangopadhyay (2003)) Anton, Deltas, and Khanna (2004), Conrad (2005), Deltas, Harrington, and Khanna (2008), Garcia-Gallego and Georgantzís (2009) , and Clemenz (2009).

of environmental performance by a monopolist when the latter is not observed and the possibility of reputation overcoming the moral hazard problem. Sengupta (2010) contains an analysis of a monopoly version of this paper; it is shown that even though green consumers are willing to pay more for the product of a clean firm, under incomplete information a firm does not have any incentive to invest in cleaner technology unless regulation is excessively high (so that the clean technology is cheaper to use).

To the best of my knowledge, this paper is the first comprehensive analysis of the strategic incentive to invest in clean technology in the presence of competition and incomplete information.[4] I find that when both firms invest, incomplete information allows firms to gain market power and thus softens price competition; in fact, unlike markets with complete information, when consumers are uninformed, increase in environmental consciousness among consumers may increase the market power and profitability of not only the clean type but also the dirty type. In contrast to the monopoly case in Sengupta (2010), I show that in the presence of competition, firms have strategic incentive to invest even when regulation is weak. 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 competitive market power is an important contribution yielded by this analysis which implies that in order to promote green technological change anti-competitive policies should be discouraged.

When environmental consciousness and/or regulation is low, if the rival does not invest then a firm has higher strategic incentive to invest in order to soften price competition under incomplete information compared to the full information. Therefore, even if consumers are not informed about the actual production technology of firms at least one firm invests in equilibrium given that the fixed cost of investment is not prohibitive; however, this *unilateral incentive* to invest decreases with increase in the level of consciousness and/or regulation. Interestingly, in this case the non-investing firm enjoys positive externality because of the incomplete information about the type of its rival which in fact goes away with higher level of environmental consciousness and/or regulation. Thus, if consciousness and/or regulation is moderately high, then there is sufficient incentive to invest if rival firm invests, but insufficient incentive to do so if rival does not invest. Thus, there exist multiple equilibrium with high and zero investment in clean technology with high consciousness and/or regulation; however, the equilibrium where both firms invest is Pareto dominant. This implies that there is a scope for industry level effort to resolve the coordination problem.

The remainder of the paper is organized as follows. Section 2 describes the model. In Section 3, I examine the strategic incentive of a firm to invest in cleaner technology under full information. Section 4 illustrates how competing firms signal their environmental performance through prices when consumers and rival firm are not aware of the actual technology of the firm. In section 5, I study the strategic incentive to invest in cleaner technology under incomplete information and

[4] There is a large literature on strategic interaction between firms and regulator (under both complete and incomplete information) where firms invest in technology adoption to reduce its own burden of compliance cost and increase rivals' cost.

compare the investment behavior of firms with that of under full information. Section 6 concludes.

## 2 Model

I consider a market where the production process of two firms that compete in prices cause environmental damage. The production technology of each firm can be of two potential types: *dirty* ($D$) and *clean* ($C$); a firm produces $\beta_C$ units of emission per unit of output if it is *clean*, and a firm emits $\beta_D$ per unit of output if it is *dirty* where

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

Each firm produces at constant unit cost, and the unit production cost of a clean type (defined by $m_C$) is greater than that of a dirty type (defined by $m_D$) i.e.,

$$0 < m_D < m_C.$$[5]

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 $t$. Here emission is a proxy for any kind of environmental damage, and the emission price represents any expected cost that a firm may have to incur 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 legal liability, and the emission price would then capture the future expected payments under liability.[6] Let

$$X_C = m_C + t\beta_C \text{ and } X_D = m_D + t\beta_D$$

be the effective marginal cost of a clean and dirty type 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. A fraction, say $\alpha \in [0, 1]$ of consumers are environmentally conscious whereas $(1 - \alpha)$ proportion of the consumers are not environmentally conscious. Consumers that are not environmentally conscious have equal valuation (maximum willingness to pay) $V$ for a unit of the product of the clean type as well as of the dirty type. However, the environmentally conscious consumers are willing to pay a premium, $\Delta > 0$, for a unit of the clean type's product; in other words, all environmentally conscious consumers have identical valuation $V$ for a unit of the dirty product and $(V + \Delta)$ for a unit of a clean product. I assume that $V > X_C$ and $V > X_D$. Observe that the proportion of conscious consumers $\alpha$ and the premium $\Delta$ are two dimensions of the extent of environmental consciousness of consumers.

[5] The case where cleaner technology is more cost effective i.e., $m_C < m_D$ is discussed in the Appendix.

[6] It is important to clarify that I do not ask the normative question of optimal regulation, and it is beyond the scope of this framework to check whether the existing level of regulation is socially optimal as there is no emission or damage function explicitly modelled.

Firms are initially endowed with a dirty production technology i.e., each produces $\beta_D$ units of emission per unit of output and incurs an effective marginal cost of $X_D$. In the first stage, firms simultaneously decide whether or not to invest a fixed amount $f > 0$ in the development of clean technology. The actions chosen by each firm at this stage i.e., whether or not it has invested is 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 the realized production technology is pure private information - unknown to the rival firm as well as to consumers. The realizations of production technology after investment are independent across firms. If a firm attains a clean technology as a result of investment then the firm emits $\beta_C < \beta_D$ per unit of output and incurs an effective marginal cost of $X_C$. In the next stage, firms choose prices simultaneously to signal the environmental performance to consumers. Finally, consumers observe the prices charged by the firms, update their beliefs, decide whether to buy, and from which firm to buy.

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

$$t^R = \frac{m_C - m_D}{\beta_D - \beta_C}.$$

I assume that regulation is not too stringent i.e., $t \leq t^R$ where the effective marginal cost of a clean type is higher than that of a dirty type. If $t > t^R$ the relative cost structure gets reversed; this case is discussed in the Appendix.

The *strategic incentive* of a firm to invest in cleaner technology is given by the difference between the *ex ante* expected profit of the firm if it invests (ignoring fixed cost $f > 0$ of investment) and the expected profit when it does not invest. Note that the strategic incentive to invest differs between situations where the rival firm does not invest and the rival invests. I study the incentive to invest in each of these two situations; more specifically, I examine whether a firm has *unilateral incentive* ($UI$) to invest when the rival does not invest as well as whether the firm has *reciprocal incentive* ($RI$) to invest in cleaner technology given that the rival has invested too. Further, if the strategic incentive is strictly positive then the firm will invest as long as the fixed cost of investment is less than the strategic incentive to invest; in other words, the strategic incentive is the highest value of fixed cost that the firm is willing to pay to invest in cleaner technology. In particular, if $UI \geq f$ then at least one firm invests otherwise no firm invests and moreover if $RI \geq f$ then both firms invest in the equilibrium; there exists multiple equilibrium i.e., either no firm invests or both firms invest when $UI < f < RI$.

# 3 Benchmark: incentive to invest under full information

Under mandatory disclosure law the firms are required to report their true environmental attributes to the regulatory authorities; otherwise regulatory authorities can also on their own acquire infor-

mation about actual environmental performance of firms and disseminate the information among public. As a result, the actual environmental performance of firms eventually becomes a common knowledge among rival firms and consumers. In this section, I consider a two stage game where in the first stage firms (initially endowed with dirty technology) simultaneously decide whether to invest in cleaner technology. The action chosen by firms are observed by both firms and consumers. If a firm does not invest it remains dirty with probability one whereas if it invests then it successfully adopts the cleaner technology with probability $\mu$ and fails with probability $(1-\mu)$. Firms either disclose the actual outcome of the investment or regulatory authorities acquire the information and make it public. Finally, the consumers decide to buy. The following Lemma illustrates the full information equilibrium of the second stage pricing game after the investment decisions are made and the outcome of the investment is made public. Suppose that under full information the clean type and the dirty type charge prices $p_C^{FI}$ and $p_D^{FI}$ respectively. Observe that at any emission price $t \leq \bar{t} = t^R - \frac{\Delta}{\beta_D - \beta_C}$ the dirty type generates higher surplus than the clean type i.e., $V - X_D \geq V + \Delta - X_C$ whereas the opposite holds true when the emission price is high enough i.e., $t \geq \bar{t}$.

**Lemma 1** *When no firm invests then both remain dirty for sure, involve in aggressive price competition, charge a price equal to the dirty type's effective marginal cost i.e.,* $p_D^{FI} = X_D$*, and lose all market power in the full information equilibrium.*

*When at least one firm invests then*
*(i) at any emission price* $t \leq \bar{t}$ *i.e., when dirty type generates higher surplus than the clean type, the clean type charges its own effective marginal cost i.e.,* $p_C^{FI} = X_C$ *and the dirty type charges a price at which a consumer is indifferent between buying from the clean and the dirty type (viz.,* $p_D^{FI} = X_C - \Delta$*) if the rival is of clean type (whereas it charges its effective marginal cost i.e.,* $p_D^{FI} = X_D$ *if the rival is of dirty type too).*
*(ii) at any emission price* $t \geq \bar{t}$*, i.e., when clean type generates higher surplus than the dirty type then the clean type charges a price at which a consumer is indifferent between buying from the clean and the dirty type (viz.* $p_C^{FI} = X_D + \Delta$*) if the rival is of dirty type (whereas it charges its own effective marginal cost i.e.,* $p_C^{FI} = X_C$ *if the rival is of clean type too), and the dirty type charges its effective marginal cost (*$p_D^{FI} = X_D$*).*[7]

Following proposition illustrates the full information equilibrium of the investment game.

**Proposition 1** *When consumers are fully aware of the actual environmental performance of firms, under weak regulation* $\left(t \leq \bar{t}\right)$ *no firm invests even if the fixed cost of investment is zero whereas when the regulation is strong* $\left(t \geq \bar{t}\right)$ *at least one firm invests if the unilateral incentive to invest*

[7] Further, as long as the price charged by the clean type is not above the willingness to pay for a unit by the consumers who are not environmentally conscious (i.e., $X_D + \Delta \leq V$ which implies that $t \leq \frac{V - \Delta - m_D}{\beta_D}$) the clean type captures the entire market in the state where the rival is of dirty type; otherwise, only $\alpha$ fraction of consumers buy from the clean type whereas the rival dirty type sells to the rest of the consumers (i.e., $(1-\alpha)$ fraction of total consumers) that are not environmentally conscious.

$(UI_{FI})$ *is greater than the fixed cost of investment* $(f)$ *and both firms invest if the reciprocal incentive* $(RI_{FI})$ *is higher than the fixed cost* $(f)$.

## 4 Signaling environmental quality through price

Consider the incomplete information multi-stage investment game described in Section 2. In the first stage firms decide whether to invest a fixed amount in cleaner technology. Though the rival firm and the consumers observe the investment decision, but the outcome of the investment i.e., the realized technology of the investing firm remains private knowledge. In the next stage, firms with private information about their actual technology decide on prices to reveal their environmental performance to consumers. In this section, I study this second stage subgame.

I denote the firm that invests as firm $I$ and the firm that does not invest as firm $NI$. There are three different possible situations: (1) both firms do not invest $(NI, NI)$, (2) one invests and other does not $(I, NI)$, and (3) both firms invest $(I, I)$.

In the first case, since both firms decide not to invest both remain dirty for sure, and the second stage pricing game degenerates to a standard full information symmetric Bertrand price competition game. For any emission price, both firms charge a common price equal to the effective marginal cost of production of the dirty type $(X_D)$, and both earn zero profit.

A more interesting case arises under the second situation i.e., when only one firm invests. Here, in the second stage I have a one sided incomplete information game; the firm that invests (firm $I$) becomes clean $(C)$ with probability $\mu$ and remains dirty $(D)$ with probability $(1-\mu)$, while a firm that does not invest (firm $NI$) stays dirty $(D)$ for sure. If the investing firm truly becomes clean then it tries to convince the consumers that it is of clean type by choosing a very high price (as the effective marginal cost of the clean type is higher than that of the dirty type) that is not optimal for the dirty type. In other words, even if the dirty type fools the consumers into believing that it is of clean type it is not profitable for the dirty type to imitate the clean type's price. I argue that there exists a unique separating equilibrium of the one sided incomplete information pricing game where the investing firm charges a higher price when it is of clean type than when it is dirty since clean type has more incentive to charge higher price because of its relatively higher effective marginal cost. However, the clean type does not earn any positive expected profit as it charges a price equal to its own effective marginal cost whereas the dirty type of the investing as well as the non-investing firm manage to earn strictly positive rent. Note that the dirty type must earn sufficient rent so as not to have any incentive to imitate the clean type. The solution concept used in the signaling game is that of Perfect Bayesian Equilibrium which is supported by the out-of-equilibrium beliefs that satisfy Cho-Sobel (1990) D1 Criterion.[8]

[8] This implies that for every possible investment outcome (in the first stage) I consider the D1 equilibrium of the pricing game in the second stage. 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). An out-of-equilibirum belief staisfies D1 criterion if consumers believe that the off equilibirum price is charged by the type which has relatively higher incentive to deviate to that price (given the equilibrium strategy of the rival) compared to the other type.

**Lemma 2** *If only one firm invests, at any emission price $t \leq \bar{t}$ i.e., when the dirty type generates higher surplus than that of the clean type, there exists a unique separating D1 equilibrium in the second stage pricing game. A clean type charges a price equal to its effective marginal cost $X_C$ earning zero expected profit while a firm that does not invest as well as a firm that invests but remains dirty choose randomized price (mixed strategy) with identical support $[\underline{p}_D, \overline{p}_D]$ where*

$$\overline{p}_D = X_C - \Delta \text{ and } \underline{p}_D = \mu \overline{p}_D + (1-\mu) X_D$$

*and thus earn strictly positive expected profit.*

The above lemma implies that when only one firm invests there does not exist any separating equilibrium in pure strategies under weak regulation (i.e., $t \leq \bar{t}$). Recall that for any emission price $t \leq \bar{t}$ the dirty type has a competitive advantage over the clean type since the dirty type generates higher surplus than that of the clean type. Thus, the non-investing firm $NI$ that remains dirty for sure enjoys market power and steals the business in the state when the rival (investing) firm is of clean type, but also has an incentive to undercut the rival in case it is of dirty type. Thus, in the separating equilibrium the non-investing firm randomizes over an interval (mixed strategy) to balance these incentives. It is indeed interesting to note that the non-investing firm enjoys a kind of positive externality due to its rival's decision to invest in cleaner technology.

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 (off equilibrium) price other than the effective marginal cost of the clean type i.e., $p > X_C$ or $p < X_C$ then consumers believe that the firm is of clean or dirty type respectively with probability one. Given these out-of-equilibrium beliefs, no firm has an incentive to unilaterally deviate to any off equilibrium price. It can be argued that these out-of-equilibrium beliefs satisfy the D1 refinement; the set of quantities for which it is profitable for a clean type to deviate to any price $p > X_C$ is larger than that of the dirty type, and since a clean type will never deviate to any price $p < X_C$ D1 refinement is trivially satisfied in this case.

However, under relatively higher emission price $t$ (i.e., $\bar{t} \leq t \leq t^R$) the condition for existence (*i.e.*, $\Delta \leq X_C - X_D$) of the separating equilibrium described in Lemma 2 does not hold.

**Lemma 3** *For any emission price $\bar{t} \leq t \leq t^R$, if only one firm invests then in the unique D1 separating equilibrium the dirty type charges a price equal to its effective marginal cost $X_D$, and all consumers buy from the dirty type with probability one whereas the clean type charges a higher price*

$$p_C = X_D + \Delta$$

*and sells zero.*

Interestingly even though the clean type yields higher surplus than the dirty type (as $\Delta \geq X_C - X_D$) the clean type can never sell in the equilibrium. In the separating equilibrium the

non-investing dirty type sells with probability one in the state where the rival investing firm is of clean type; if the clean type happens to sell with a strictly positive probability then the dirty type of the investing firm will always have an incentive to imitate the clean type. Thus, in this pure strategy unique separating equilibrium the clean type as well as the dirty type earn zero profit.

The above unique separating equilibrium can be supported by the following out-of-equilibrium beliefs of consumers: if a firm charges any off equilibrium price $p < X_D + \Delta$ or $p > X_D + \Delta$ then consumers believe that the firm is of dirty or clean type respectively with probability one. Note that for any level of quantity if it is profitable for a clean type to deviate to any price $p < X_D + \Delta$ then the dirty type also finds it profitable to deviate, whereas for any level of quantity if it is profitable for the dirty type to deviate to a price $p > X_D + \Delta$ then the clean type finds it strictly profitable to deviate as well; thus, the out-of-equilibrium beliefs satisfy the D1 Criterion.

Next, I define the following range of emission prices and refer them as different region in the rest of the paper:

**Region A:** $t < \max\{\frac{V-m_C}{\beta_C}, \frac{V-2\Delta-m_D}{\beta_D}\}$

**Region B:** $\min\{\frac{V-m_C}{\beta_C}, \frac{V-\frac{2\Delta}{(2-\alpha)}-m_D}{\beta_D}\} < t \leq \frac{V-\frac{(2-\alpha)\Delta}{\alpha}-m_D}{\beta_D}$

if $\min\{\frac{V-m_C}{\beta_C}, \frac{V-\frac{2\Delta}{(2-\alpha)}-m_D}{\beta_D}\} < \frac{V-\frac{(2-\alpha)\Delta}{\alpha}-m_D}{\beta_D}$

**Region C:** $t \geq \max\{\frac{V-\frac{(2-\alpha)\Delta}{\alpha}-m_D}{\beta_D}, \min\{\frac{V-m_C}{\beta_C}, \frac{V-\frac{2\Delta}{(2-\alpha)}-m_D}{\beta_D}\}\}$

**Region D:** $\max\{\frac{V-m_C}{\beta_C}, \frac{V-2\Delta-m_D}{\beta_D}\} \leq t \leq \min\{\frac{V-m_C}{\beta_C}, \frac{V-\frac{2\Delta}{(2-\alpha)}-m_D}{\beta_D}\}$

If both firms invest then the market competition of this analysis is almost similar to the signaling game considered by Janssen and Roy (2009); however note that unlike their model I assume the consumers are heterogeneous i.e., a fraction of consumers that are environmentally conscious pay a price premium for the product produced by clean technology. Following the construction in their paper, I get the following results:

**Lemma 4** *For $t \leq t^R$ (weak regulation), if both firms invest then in any symmetric separating perfect Bayesian equilibrium that is supported by the out-of-equilibrium beliefs that satisfy D1 criterion, a clean type charges a deterministic price $p_C$ which is higher than any price charged by a dirty type; the dirty type follows a mixed pricing strategy with support $\left[\underline{P}_D, \overline{P}_D\right]$ and a continuous distribution function $F_D(p)$, where*

$$\overline{P}_D = p_C - \Delta \text{ and } \underline{P}_D = \mu\left[p_C - \Delta\right] + (1-\mu)\, X_D.$$

*In Region A a clean type charges a price which is lower than the dirty type's full information monopoly price $V$ i.e., $p_C = \max\{X_C, X_D + 2\Delta\}$, and all consumers buy with probability one.*

*In Region B a clean type charges a deterministic price $p_C$ which is higher than dirty type's full*

*information price $V$ but lower than its own full information monopoly price $V+\Delta$ i.e., $p_C = \max\{X_C, \frac{2\Delta}{(2-\alpha)} + X_D\}$, and all environmentally conscious consumers (i.e., $\alpha$ fraction of the consumers) buy with probability one*

*In Region C the clean type charges its own full information monopoly price i.e., $p_C = V + \Delta$, and all environmentally conscious consumers may not buy with probability one.*

*In Region D a clean type charges a price equal to the full information monopoly price of the dirty type i.e., $p_C = V$.*

Note that there does not exist any separating equilibrium in pure strategies. In the separating equilibrium, the dirty type (with lower effective marginal cost) ought to earn sufficient positive rent otherwise it will imitate clean type's equilibrium price. If the rival is of clean type (with higher effective marginal cost), a dirty type can earn a strictly positive rent by charging a lower price and does not have any incentive to imitate the clean type's higher price. However, in a state where the rival is of dirty type, it has an incentive to undercut the dirty rival (with the same effective marginal cost). Therefore, the dirty type (with lower effective marginal cost) involves in price dispersion i.e., plays mixed strategy. Lack of information about the actual environmental attributes of firms allows not only the clean type but also the dirty type to enjoy stochastic market power even when there are consumers who are willing to pay more for the products of the cleaner type.

The symmetric Bayesian equilibrium 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 $p \notin \left[\underline{P}_D, \overline{P}_D\right]$, 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.[9] Consider any out-of-equilibrium price; observe that for any level of quantity, if it is profitable for a clean type to deviate to the out-of-equilibrium price then the dirty type also finds it strictly profitable to deviate to such a price.

From the above proposition, one can identify that there are two major sources of signaling distortion. One stems from the fact that all environmentally conscious consumers though they are willing to pay more for the product produced by the cleaner technology, in the equilibrium, buy from the dirty type except when both firms are of clean type. Moreover, even when both firms are clean, all environmentally conscious consumers may not buy as the clean type charges a very high price which is equal to its own full information monopoly price; this creates additional signaling distortion.

Rise in the level of environmental consciousness among consumers is measured by the increase in the premium that consumers are willing to pay ($\Delta$) for the cleaner product or by the increase in the proportion of conscious consumers ($\alpha$); this in turn yields higher rent for the clean as well as for the dirty type.

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

**Proposition 2** *Consider the moderate range of regulation* $\frac{V-\frac{2\Delta}{(2-\alpha)}-m_D}{\beta_D} < t < \frac{V-2\Delta-m_D}{\beta_D}$*. In this range, increase in the environmental consciousness among consumers increases the market power and profit of both clean and dirty type.*

At a significantly lower level of regulation $\left(t \leq t^R - \frac{2\Delta}{(\beta_D-\beta_C)}\right)$ the difference in the effective marginal cost is large which implies that the incentive of a dirty type to imitate the clean type is relatively low; thus, the clean type can charge the lowest possible price i.e., its effective marginal cost in the separating equilibrium without getting imitated by the dirty type. Recall that in the separating equilibrium the price distribution of the dirty type depends on the deterministic price charged by the clean type; in particular, for a given price of the clean type the price distribution shifts downward as the premium increases.[10] Therefore, in this range of emission price the price distribution and thus the strictly positive profit of the dirty type go down as the premium paid by the conscious consumers goes up. However, the dirty type earns sufficient rent such that the incentive compatibility constraint is not binding i.e., the dirty type does not have an incentive to imitate the clean type's price. Beyond a critical level of emission price, the incentive of the dirty type to imitate becomes significantly strong such that the clean type's price goes up with the premium which in turn increases the positive profit earned by the dirty type (see (9) and (16)). In other words, under a moderately high emission price $t \in \left(\frac{V-\frac{2\Delta}{(2-\alpha)}-m_D}{\beta_D}, \frac{V-2\Delta-m_D}{\beta_D}\right)$ the dirty type enjoys higher stochastic market power with the increase in the premium paid by the conscious consumers for the cleaner product. Similar argument can be made for the increase in the proportion of the environmentally conscious consumers i.e., $\alpha$. In the situation where only the fraction of the conscious consumers buy from the clean type (in the state where the rival is of clean type too) increase in the number of conscious consumers positively affects the clean type's profit (see (14)). As a result it becomes more lucrative for the dirty type to imitate the clean type's price and thus in the separating equilibrium the dirty type will earn higher profit too (see (16)).

## 5 Incentive to invest under incomplete information

Firms initially endowed with dirty production technology decide whether or not to incur a fixed cost $f$ in the adoption of cleaner technology. Though the rival firm and the consumers observe the firm's decision to invest but the outcome of the investment i.e., whether the firm could successfully adopt clean technology remains a private knowledge to the firm. In this section, I investigate whether firms have any strategic incentive to invest in cleaner technology under incomplete information and how environmental consciousness and the level of environmental regulation affect this incentive. Further, I examine whether the strategic incentive to invest increase or decrease if all consumers became informed; in other words, I compare firms' incentive to invest in cleaner technology under

[10] Observe that this interdependence between the deterministic price charged by the clean type and the price distribution of the dirty type is a unique feature of the separating equilibrium under incomplete information. In other words, in case of full information (discussed in Section 5) the price and the profit of the dirty type do not increase with increase in the environmental consciousness of consumers.

incomplete information and full information.

Even if the rival does not, a firm invests to adopt cleaner technology when the unilateral incentive of the firm is at least as high as the fixed cost of investment. Moreover, both firms invest in equilibrium if the reciprocal incentive to invest (strategic incentive when the rival invests) in cleaner technology exceeds the fixed cost of investment. It may happen that for certain values of fixed cost either no firm invests or both firms invest in the Nash equilibrium; in this case, the fixed cost is more than the unilateral incentive to invest but less than the reciprocal incentive.

Prior to realization of environmental quality of production technology, the expected profit of each firm is always zero if both firms do not invest in cleaner technology. When only one firm invests, at any emission price $t \leq \bar{t}$ the clean type of the investing firm earns zero profit as it is always undercut by the non-investing rival; in other words, the non-investing rival which is of dirty type for sure enjoys stochastic monopoly power. The investing firm can earn strictly positive rent only in the state where it is of dirty type. However, for any emission price $t \geq \bar{t}$, both clean and dirty type earn zero profit When one firm invests, the ex ante (prior to realization of their types) equilibrium profit of a firm that invests and that does not invest are given by $\pi_I^*$ and $\pi_{NI}^*$ respectively. At any emission price $t \leq \bar{t}$, the *ex ante* expected profits of investing and non-investing firms are strictly positive i.e., $\pi_I^* = (1-\mu)[X_C - X_D - \Delta]$ and $\pi_{NI}^* = \mu[X_C - X_D - \Delta]$ respectively; whereas under moderately higher level of emission price $\left(\text{ i.e., } \bar{t} \leq t \leq t^R\right)$ the investing as well as the non-investing firm earn zero profit. This implies that at a lower level of regulation $\left(t \leq \bar{t}\right)$ even if the fixed cost of investment is zero, a non-investing rival gains more compared to an investing firm i.e., $\pi_{NI}^* > \pi_I^* > 0$ if the probability of a successful investment is high i.e., $\mu \geq \frac{1}{2}$; it is a major strategic externality. This, in turn, implies that increase in the probability of a successful investment (viz. probability of being clean) $\mu$ has a disincentive effect on investment. The strategic externality enjoyed by the non-investing firm increases with increase in $\mu$. Further, note that the rise in environmental consciousness among consumers (viz. the premium ($\Delta$) paid by the conscious consumers for the product of the clean type) decreases the price ($\overline{p}_D = X_C - \Delta$) at which a consumer is indifferent between buying from the clean type and the dirty type, and increase in the level of regulation increases the effective marginal cost of the dirty type more than that of the clean type. Therefore, increase in consciousness and regulation reduce the profit of the non-investing firm as well as the profit of the dirty type of the investing firm.

Beyond a critical level of emission price ($t \geq \bar{t}$), in particular, when clean type generates more surplus than the dirty type then the investing firm of the clean type cannot sell in the equilibrium otherwise its own dirty type will always imitate its clean type's price. Aggressive competition by the non-investing firm brings down the price of the dirty type to its own effective marginal cost. In other words, it is not possible to create rent for the dirty type of the investing firm and at the same time take away market from the non-investing firm. As a result, no firm can sustain strictly positive rent.

First consider the case where rival does not invest in cleaner technology. Let $UI_{II}$ be the *unilateral incentive to invest* under incomplete information; it is the difference between the *ex ante*

expected profit of a firm if it invests given that the rival does not and the expected profit earned by the firm if it does not invest (thus remains dirty with probability one). Proposition 3 illustrates the unilateral incentive of a firm when rival does not invest under incomplete information and how this incentive changes with respect to environmental consciousness (in this case premium that a conscious consumer pays for a unit product of the clean type i.e., $\Delta$) and the level of regulation. Recall that unilateral incentive to invest is the maximum fixed cost that a firm would pay in order to invest in cleaner technology when the rival does not invest; in other words, at least one firm invests in the equilibrium if the unilateral incentive to invest is at least as high as the fixed cost of investment.

**Proposition 3** *Consider the situation where the rival does not invest.*
*At any emission price* $t \leq \bar{t}$ *at least one firm invests if the unilateral incentive to invest* (*i.e.,* $UI_{II} = (1-\mu)(X_C -$ *in cleaner technology is higher than the fixed cost of investment* $(f)$ *whereas if* $\bar{t} \leq t \leq t^R$ *then no firm invests in the equilibrium even if the fixed cost of investment is zero.*

*Increase in environmental consciousness, in particular premium* $(\Delta)$ *paid by the conscious consumers for the clean type shrinks the range of regulation* $(t \leq \bar{t})$ *over which a firm has an incentive to invest and also decreases the gain from investment of a firm.*

At a lower emission price $(t \leq \bar{t})$ if a firm decides not to invest and thus remains dirty for sure then it earns zero profit because of the aggressive price competition with the non-investing rival. However, if the firm invests then it has a strictly positive ex ante expected profit because of the stochastic monopoly power enjoyed by the non-investing firm; this in turn implies that a firm does have a unilateral incentive to invest in clean technology. In other words, the gain from investment which is a measure of unilateral incentive to invest depends on the profit earned by the dirty type. In this range of emission price increase in environmental consciousness $(\Delta)$ and regulation $(t)$ reduce the *ex ante* expected profit of a firm and also the gain from investment when the rival firm does not invest. Moreover, beyond a critical level of emission price $\left(t > \bar{t}\right)$, it is not possible to earn strictly positive rent for any firm which implies that no firm invests in the Nash equilibrium of the first stage investment game even at zero cost of investment.

Next consider the case when rival invests. Table $1-4$ (in Appendix) depict the reciprocal incentive to invest $(RI_{II})$ i.e., the maximum fixed cost of investment for which both firms find it profitable to invest to adopt cleaner technology in the equilibrium, and the effect of environmental consciousness (premium $(\Delta)$ as well as the proportion of environmentally conscious consumers $(\alpha)$) and the level of regulation on this reciprocal incentive. Note that the reciprocal incentive to invest in cleaner technology under incomplete information is negative when the clean type charges its effective marginal cost to reveal its actual environmental performance; otherwise, a firm has a positive incentive to invest when the rival invests. *When consumers and rival firm are not aware of the actual environmental performance of a firm then both firms invest in the equilibrium if the reciprocal incentive to invest* $(RI_{II})$ *is higher than the fixed cost of investment* $(f)$.Observe that

unlike the monopolist[11] 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.

Interestingly, at any emission price $t \in \left[\bar{t}, t^R\right]$ there are multiple Nash equilibrium; in particular, either both firms invest or neither firm invests as the fixed cost of investment is less than the reciprocal incentive to invest but more than the unilateral incentive to invest i.e., $UI_{II} < f < RI_{II}$. This implies that there exists a strategic complementarity among firms as far as their decision to invest in clean technology is concerned. However, presence of multiple equilibrium leads to the coordination problem and this in turn, calls for additional social intervention in order to trigger both firms to decide to invest in clean technology. Note that strictly positive investment by both firms Pareto dominates (with respect to profit earned by each firm) no investment equilibrium as both firms earn zero if neither invests. Further, increase in environmental consciousness (specifically the premium paid by the conscious consumers for the product of the clean type) expands the range for which both firms invest in the equilibrium as well as the range where either both firms invest or neither firms invests. In other words, with high level of regulation and consciousness both firms are more likely to invest in clean technology.

**Proposition 4** *When the rival firm invests, increase in the premium paid by the environmentally conscious consumers for a unit of the clean product* $(\Delta)$ *expands the range of emission price along which both firms always invest. The gain from investment goes up with increase in the premium except in Region D when* $t \in \left[\bar{t}, t^R\right]$.
*Moreover, as more consumers become environmentally consciousness* (*i.e.,* $\alpha$ *increases*) *the reciprocal incentive of a firm to invest in cleaner technology goes up.*

For a given price of the clean type, increase in the premium reduces the price at which consumers are indifferent between buying from the clean type and the dirty type. This in turn reduces the profit of a firm's own dirty type as well as the rival's dirty type and increases the incentive of the dirty type to imitate the clean type's price. In order to prevent the dirty type from imitating if the firm reduces its price of the clean type then it further increases the incentive of the dirty type to imitate. Therefore, a firm increases the price of its clean type which pushes up the dirty type's profit and ex ante expected profit of an investing firm which in turn, creates positive incentive to invest in cleaner technology. However, in Region D at an emission price $t \in \left[\bar{t}, t^R\right]$, the clean type's price is fixed at the common valuation $V$ of all consumers and thus, in this case the unilateral incentive to invest in clean technology does not go up with increase in environmental consciousness.

[11] In Sengupta (2010), I find that a single seller does not have any incentive to invest in cleaner technology under weak regulation $\left(t \leq t^R\right)$ as the dirty type always earns higher expected profit than the clean type.

**Proposition 5** *The reciprocal incentive of a firm to invest (in particular the gain from investment) in clean technology increases with the level of environmental regulation* $\left(\frac{\partial RI_{II}}{\partial t} > 0\right)$ *except in Region C and Region D under a significantly higher level of regulation (i.e.,* $\bar{t} \leq t \leq t^R$*).*

Note that at a higher level of regulation when the clean type charges a fixed price (insensitive to emission price) even though a firm has a unilateral incentive to invest in clean technology the gain from investment goes down with increase in the level of regulation. The intuition is as follows. In this range of regulation the gain from investment is equal to the ex ante expected profit of any firm when both firms invest, and this expected profit (see (28) and (29)) goes down with increase in regulation. Moreover, regulation enhances the efficacy of environmental consciousness (*i.e.*, $\frac{\partial RI_{II}}{\partial \alpha}$ is increasing in $t$) in Region B. For significant range of parameters (in Region C and Region D) there is a complementarity between regulation and price premium $\Delta$ paid by the environmentally conscious consumers in promoting green technological change.

One of the main objectives of this paper is to compare the strategic incentive of a firm to invest in cleaner technology under incomplete information with the situation where rival firm and consumers are aware of the actual environmental performance of the firm.

**Proposition 6** *The unilateral incentive to invest in clean technology is higher in case of incomplete information compared to the full information when emission price is below a critical level* $\left(i.e.,\ t \leq \bar{t}\right)$.

**Proposition 7** *Under weak environmental regulation* $\left(t \leq t^R\right)$, *a firm has higher reciprocal incentive to invest in cleaner technology under incomplete information compared to full information.*

This implies that mandatory disclosure law or public dissemination of information about actual environmental performance of firms is likely to discourage investment in the adoption of cleaner technology. Unlike in the situation where firms reveal their true environmental performance under mandatory disclosure law, a firm enjoys stochastic monopoly power if at least one firm invests in the presence of incomplete information. This in turn generates a higher strategic incentive to invest in cleaner technology under incomplete information.

## 6 Conclusion

This paper focuses on firms' strategic incentive to invest in clean technology in a market where firms compete in prices and some consumers are environmentally conscious (willing to pay more for the cleaner product) but uninformed about the actual production process of the firms. Though investment is publicly observed, the outcome of investment is uncertain and observed only by the firm. Firms may signal their private information about the realized technological outcome of investment through product prices. I find that lack of information of conscious consumers about the actual technology used by firms and their environmental performance often leads to higher incentive to invest in cleaner technology when firms compete strongly in the market. In

fact, incomplete information generates higher investment compared to full information particularly when consciousness and/or regulation is not too high which appears to fit the current reality in many industries. Therefore, mandatory disclosure law or public dissemination of information may indeed reduce investment in cleaner technology. However, incomplete information also generates higher market power and may imply that a dirty firm serves the market even though it does not generate higher surplus. Under incomplete information, competition generates higher incentive to invest relative to monopoly power. Further, in contrast to full information, under incomplete information, higher consciousness and/or regulation may reduce the incentive to invest. Note that the analysis has important significance for public policy design as well as for environmental activists' campaign to increase green consciousness. I also find multiple equilibrium at higher level of consciousness and/or regulation under incomplete information with high investment being better (i.e., yields higher pay-off) for firms; thus, there is a scope for industry level effort to resolve this coordination problem.

# 7 Appendix

**Proof of Proposition 1** Under weak regulation i.e., $t \leq \bar{t}$ the expected profit of a firm in the first stage

$$\pi^{FI} = \mu (1-\mu)(X_C - \Delta - X_D)$$

if both firms invest,

$$\pi^{FI} = \mu (X_C - \Delta - X_D)$$

if the firm does not invest whereas the rival does, and $\pi^{FI} = 0$ if the firm invests but the rival does not or neither firm invests. Therefore, the unilateral and reciprocal incentive to invest under full information are

$$UI_{FI} = -\mu (X_C - \Delta - X_D)$$

and

$$RI_{FI} = -\mu^2 (X_C - \Delta - X_D)$$

respectively; this implies that no firm invests in the full information equilibrium when regulation is weak. For any emission price $t \geq \bar{t}$ the *ex ante* expected profit of any firm will be

$$\begin{aligned} \pi^{FI} &= \mu (1-\mu)(X_D + \Delta - X_C) \text{ when } t \leq \frac{V - \Delta - m_D}{\beta_D} \\ &= \mu (1-\mu) \alpha (X_D + \Delta - X_C) \text{ when } t \geq \frac{V - \Delta - m_D}{\beta_D} \end{aligned}$$

if both firms invest,

$$\pi^{FI} = \mu\left(X_D + \Delta - X_C\right) \text{ when } t \leq \frac{V - \Delta - m_D}{\beta_D}$$
$$= \mu\alpha\left(X_D + \Delta - X_C\right) \text{ when } t \geq \frac{V - \Delta - m_D}{\beta_D}$$

if the firm invests but its rival does not, and $\pi^{FI} = 0$ both in the case where the firm does not invest but its rival does and neither of the firms invests. In this case, the unilateral incentive of a firm is given by

$$UI_{FI} = \mu\left(X_D + \Delta - X_C\right) \text{ when } t \leq \frac{V - \Delta - m_D}{\beta_D}$$
$$= \mu\alpha\left(X_D + \Delta - X_C\right) \text{ when } t \geq \frac{V - \Delta - m_D}{\beta_D}$$

whereas the reciprocal incentive of a firm to invest is

$$RI_{FI} = \mu\left(1 - \mu\right)\left(X_D + \Delta - X_C\right) \text{ when } t \leq \frac{V - \Delta - m_D}{\beta_D}$$
$$= \mu\left(1 - \mu\right)\alpha\left(X_D + \Delta - X_C\right) \text{ when } t \geq \frac{V - \Delta - m_D}{\beta_D}.$$

Note that $UI_{FI} > RI_{FI}$. When $f > UI_{FI}$ then no firm invests, $UI_{FI} \geq f > RI_{FI}$ only one firm invests, and if $UI_{FI} > RI_{FI} \geq f$ then both firms invest in the equilibrium.

**Formal Characterization of the equilibrium in Lemma 2** In the perfect Bayesian separating equilibrium, investing firm that becomes clean charges a deterministic price $p_C$, and the non-investing firm as well as the investing firm that remained dirty 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 I describe below). At $\overline{p}_D$ i.e., the upper bound of the support, a consumer is indifferent between buying from a clean type at $p_C$ and from a dirty type at price $\overline{p}_D$. Note that since the clean type cannot charge a lower price than its non-investing rival firm, it sells zero with probability one and earns zero profit in the equilibrium. Therefore, in the separating equilibrium a clean type ends up charging a price as low as its effective marginal cost i.e., $X_C$. The existence of this separating equilibrium is guaranteed since the upper bound of the price support of the dirty type ( $\overline{p}_D = X_C - \Delta$) is greater than its effective marginal cost i.e., $\Delta \leq X_C - X_D$. Since at price $\overline{p}_D$ the dirty type of the investing firm undercuts non-investing firm with probability one, at price $\overline{p}_D$ non-investing firm sells only in the state where the rival investing firm is of the clean type, and the equilibrium expected profit of the non-investing firm is given by:

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

for any price $p \in [\underline{p}_D, \overline{p}_D]$, and the dirty type of investing firm earns the same expected profit.

This yields the lower bound of the mixed strategy price support i.e.,

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

The non-investing firm assigns probability mass $\mu$ to the upper bound $\overline{p}_D$ of its price support as it knows that the rival investing firm becomes clean with probability $\mu$. At every price $p \in [\underline{p}_D, \overline{p}_D]$, the non-investing firm can sell to all consumers as long as it is not undercut by the dirty type of the rival investing firm, and its expected profit at $p$ is equal to $\pi^*_{NI}$ i.e.,

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

This yields the probability distribution function of the dirty type of the investing firm 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 $p \in [\underline{p}_D, \overline{p}_D]$ the dirty type of the investing firm can sell to all consumers as long as it is not undercut by the rival non-investing firm, and its expected profit at $p$ is equal to $\pi^*_{NI}$ i.e.,

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

this yields the probability distribution function of the non-investing firm 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 $F_{NI}(\underline{p}_D) = 0$.

**Formal characterization of the equilibrium described in Lemma 4** When both firms invest, in the symmetric separating perfect Bayesian equilibrium the dirty type follows a common probability distribution $F_D(p)$ whose support is an interval $\left[\underline{P}_D, \overline{P}_D\right]$, and the clean type charges a common deterministic price $p_C$ which is always higher than the price charged by the dirty type. At the upper bound of the support $\left(\overline{P}_D\right)$, a consumer is indifferent between buying from a clean type at $p_C$ and from a dirty type at $\overline{P}_D$ i.e.,

$$\overline{P}_D = p_C - \Delta.$$

The dirty type charges a price less than $\overline{P}_D$ almost surely since otherwise the rival dirty type can undercut to earn higher rent. This, in turn, implies that a clean type can only sell in the state when the rival is of clean type. The equilibrium expected profit of the dirty type for

charging any price $p \in \left[\underline{P}_D, \overline{P}_D\right]$ is given by

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

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

$$\left(\overline{P}_D - X_D\right)\mu = (p_C - \Delta - X_D)\,\mu \tag{2}$$

which is identical to the equilibrium expected profit of the dirty type $\pi_D^*$. The lower bound of the support $(\underline{P}_D)$ is the lowest price that the dirty type 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 $\pi_D^*$ i.e.,

$$\underline{P}_D - X_D = \pi_D^* = (p_C - \Delta - X_D)\,\mu.$$

Therefore, the lower bound of the support is

$$\underline{P}_D = \mu\left[p_C - \Delta\right] + (1-\mu)\,X_D. \tag{3}$$

Note that the equilibrium price distribution i.e., $\left[\underline{P}_D, \overline{P}_D\right]$ and the expected profit $\pi_D^*$ of the dirty type depend on the deterministic price charged by the clean type. At every price $p \in \left[\underline{P}_D, \overline{P}_D\right]$, the dirty type 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

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

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

$$\left[\mu + (1-\mu)(1 - F_D(p))\right](p - X_D) = (p_C - \Delta - X_D)\,\mu$$

(from (1) and (2)) which implies that

$$F_D(p) = 1 - \frac{\mu}{(1-\mu)}\left(\frac{p_C - \Delta - X_D}{p - X_D} - 1\right) \tag{4}$$

where $F_D(p)$ is continuous on $\left[\underline{P}_D, \overline{P}_D\right]$, $F_D(\underline{P}_D) = 0$, and $F_D\left(\overline{P}_D\right) = 1$.
Consider Region A. In the perfect Bayesian separating equilibrium, a clean type 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 this case, all consumers buy from the clean type with probability one. 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 type iff

$$\frac{V - X_D}{V + \Delta - X_D} \geq \frac{1}{2}. \tag{5}$$

where

$$p_C \geq 2\Delta + X_D \text{ and } p_C \leq 2\Delta + X_C$$

are the incentive compatibility constraints of the dirty and clean type respectively. Note that (5) is always satisfied under $t < \max\{\frac{V-m_C}{\beta_C}, \frac{V-2\Delta-m_D}{\beta_D}\}$. In this unique separating equilibrium, the price $p_C$ charged by the clean type is lower than its full information monopoly price $V + \Delta$; in particular, when $t \leq t^R - \frac{2\Delta}{(\beta_D - \beta_C)}$ then the clean type charges its effective marginal cost $X_C$ such that the firm loses its market power whereas if $t^R - \frac{2\Delta}{(\beta_D-\beta_C)} \leq t \leq t^R$ then clean type charges $X_D + 2\Delta$. Further, the expected profit of a clean type is

$$\begin{aligned}
\pi_C^* &= \frac{\mu}{2}(p_C - X_C) \\
&= 0, \text{ if } t \leq t^R - \frac{2\Delta}{(\beta_D - \beta_C)} && (6) \\
&= \mu[\Delta - \frac{X_C - X_D}{2}], \text{ if } t^R - \frac{2\Delta}{(\beta_D - \beta_C)} \leq t \leq t^R, && (7)
\end{aligned}$$

and the expected profit of a dirty type is

$$\begin{aligned}
\pi_D^* &= \mu(p_C - \Delta - X_D) \\
&= \mu\left[X_C - X_D - \Delta\right], \text{ if } t \leq t^R - \frac{2\Delta}{(\beta_D - \beta_C)} && (8) \\
&= \mu\Delta, \text{ if } t^R - \frac{2\Delta}{(\beta_D - \beta_C)} \leq t \leq t^R && (9)
\end{aligned}$$

In Region B the fraction of consumers that are not environmentally conscious refrains from buying the product of the clean type (even in the state where the rival firm is also of clean type); in this case the profit of the clean type is

$$\pi_C = \frac{\alpha\mu}{2}\left(p_C - X_C\right).$$

The dirty type does not have any incentive to imitate the clean type as long as

$$\frac{\alpha\mu}{2}\left(p_C - X_D\right) \leq \mu\left(p_C - \Delta - X_D\right)$$

which implies that

$$p_C \geq \frac{2\Delta}{(2 - \alpha)} + X_D. \tag{10}$$

Similarly, the clean type does not have any incentive to imitate the dirty type iff

$$\frac{\alpha\mu}{2}\left(p_C - X_C\right) \geq \mu\left(p_C - \Delta - X_C\right)$$

and this incentive compatibility constraint of the clean type yields

$$p_C \leq \frac{2\Delta}{(2-\alpha)} + X_C \tag{11}$$

The strategies along with the out of equilibrium beliefs constitute a perfect Bayesian equilibrium if and only if the price of the clean type $p_C \in [X_C, V+\Delta]$ satisfies the incentive compatibility constraints i.e., if

$$\max\{X_C, \frac{2\Delta}{(2-\alpha)} + X_D\} \leq p_C \leq \min\{\frac{2\Delta}{(2-\alpha)} + X_C, V+\Delta\}$$

Following the analysis of Janssen and Roy (2009) it can be easily shown that in the separating D1 equilibrium, if

$$\frac{V - X_D}{V + \Delta - X_D} \geq \frac{(2-\alpha)}{2} \tag{12}$$

(i.e., $t \leq \frac{V - \frac{(2-\alpha)\Delta}{\alpha} - m_D}{\beta_D}$) then the clean type charges a price $p_C = \max\{X_C, \frac{2\Delta}{(2-\alpha)} + X_D\}$ which is lower than its own full information price, all environmentally conscious consumers (i.e., $\alpha$ fraction of the consumers) buy with probability one, the equilibrium profits of the clean type

$$\begin{aligned} \pi_C^* &= \frac{\alpha\mu}{2}\left(p_C - X_C\right) \\ &= 0 \text{ when } t \leq t^R - \frac{2\Delta}{(2-\alpha)\left(\beta_D - \beta_C\right)} \qquad (13) \\ &= \frac{\alpha\mu}{2}\left(\frac{2\Delta}{(2-\alpha)} + X_D - X_C\right) \text{ when } t^R - \frac{2\Delta}{(2-\alpha)\left(\beta_D - \beta_C\right)} \leq t \leq t^R \qquad (14) \end{aligned}$$

and of the dirty type

$$\begin{aligned} \pi_D^* &= \mu\left(p_C - \Delta - X_D\right) \\ &= \mu\left(X_C - \Delta - X_D\right) \text{ when } t \leq t^R - \frac{2\Delta}{(2-\alpha)\left(\beta_D - \beta_C\right)} \qquad (15) \\ &= \mu\frac{\alpha}{2-\alpha}\Delta \text{ when } t^R - \frac{2\Delta}{(2-\alpha)\left(\beta_D - \beta_C\right)} \leq t \leq t^R \qquad (16) \end{aligned}$$

respectively. Further, when $t^R - \frac{2\Delta}{(2-\alpha)(\beta_D - \beta_C)} \leq t \leq t^R$ the profit of the clean type and the dirty type increase with increase in the proportion of environmentally conscious consumers i.e., $\alpha$ and also as $\Delta$ i.e., the difference between the valuation of the clean type and the dirty type increases.

On the other hand, if $\frac{V - X_D}{V+\Delta-X_D} \leq \frac{(2-\alpha)}{2}$ (i.e.,.$t \geq \frac{V - \frac{(2-\alpha)\Delta}{\alpha} - m_D}{\beta_D}$) then the clean type charges its full information monopoly price i.e., $p_C = V + \Delta$ and all environmentally conscious consumers

may not buy with probability one. The incentive compatibility constraint of the dirty type is

$$\frac{\alpha\mu\eta}{2}\left(V+\Delta-X_D\right)\leq\mu\left(V-X_D\right)$$

where $\eta$ is the fraction of environmentally conscious consumers that buy from the clean type. This implies that the equilibrium value of $\eta$ is

$$\eta^*=\frac{2\left(V-X_D\right)}{\alpha\left(V+\Delta-X_D\right)}, \tag{17}$$

the equilibrium profit of the clean type and dirty type are

$$\pi_C^*=\frac{\mu\left(V-X_D\right)\left(V+\Delta-X_C\right)}{\left(V+\Delta-X_D\right)} \tag{18}$$

and

$$\pi_D^*=\mu\left(V-X_D\right)$$

respectively. Next consider the Region D. Observe that when $p_C=\max\{X_C,\frac{2\Delta}{(2-\alpha)}+X_D\}$ then the consumers ($(1-\alpha)$ fraction of all consumers) that are not environmentally conscious may not buy from the clean type whereas if $p_C=\max\{X_C,2\Delta+X_D\}$ then all consumers buy the product from the clean type with probability one. Therefore, in the separating equilibrium the clean type charges a price which is exactly equal to the common valuation of the consumers that are not environmentally conscious i.e., $p_C=V$, and even though all environmentally conscious consumers will buy from the clean type with probability one (in the state where the rival is of clean type) $(1-\alpha)$ fraction of the consumers (who are not environmentally conscious) are indifferent between buying from the clean type and not buying at all. In this case, the profit of the clean type is given by

$$\pi_C=\frac{\left(\alpha+\lambda\left(1-\alpha\right)\right)\mu}{2}\left(V-X_C\right)$$

and that of the dirty type is

$$\pi_D=\mu\left(V-\Delta-X_D\right)$$

where $\lambda$ denotes the proportion of the consumers that are not environmentally conscious but buy from the clean type. The dirty type has no incentive to imitate the clean type iff

$$\frac{\left(\alpha+\lambda\left(1-\alpha\right)\right)\mu}{2}\left(V-X_D\right)\leq\mu\left(V-\Delta-X_D\right)$$

which implies

$$\lambda\leq\frac{\left(2-\alpha\right)\left(V-X_D\right)-2\Delta}{\left(1-\alpha\right)\left(V-X_D\right)}$$

and similarly the clean type has no incentive to imitate the dirty type iff

$$\lambda\geq\frac{\left(2-\alpha\right)\left(V-X_C\right)-2\Delta}{\left(1-\alpha\right)\left(V-X_C\right)}$$

Therefore, in a symmetric perfect Bayesian equilibrium a clean type can charge a price which is equal to the full information monopoly price of the dirty type iff

$$\max\{0, \frac{(2-\alpha)(V-X_C)-2\Delta}{(1-\alpha)(V-X_C)}\} \leq \lambda \leq \min\{\frac{(2-\alpha)(V-X_D)-2\Delta}{(1-\alpha)(V-X_D)}, 1\} \tag{19}$$

The necessary and sufficient condition for the above restriction on $\lambda$ to be satisfied is the following

$$(2-\alpha)(V-X_D) > 2\Delta \tag{20}$$

and (19) boils down to

$$\frac{(2-\alpha)(V-X_C)-2\Delta}{(1-\alpha)(V-X_C)} \leq \lambda \leq \frac{(2-\alpha)(V-X_D)-2\Delta}{(1-\alpha)(V-X_D)}.$$

The D1 equilibrium value of $\lambda$ is

$$\lambda^* = \frac{(2-\alpha)(V-X_D)-2\Delta}{(1-\alpha)(V-X_D)} \tag{21}$$

and the equilibrium profit of the clean type and the dirty type are

$$\pi_C^* = \frac{\mu(V-X_D-\Delta)}{(V-X_D)}(V-X_C) \tag{22}$$

and

$$\pi_D^* = \mu(V-\Delta-X_D). \tag{23}$$

**Proof of Proposition 4** Consider the investment game when both firms invest; in the unique D1 symmetric separating equilibrium the *ex ante* (prior to realization of the type) expected profit of any firm in the first stage game is given by

$$\pi^* = \mu\pi_C^* + (1-\mu)\pi_D^*.$$

Recall the different regions corresponding to different range of environmental regulation described in Section 4. I calculate the ex ante expected profit of any firm in the first stage game in each region; In Region A

$$\pi^* = (1-\mu)\mu[X_C - X_D - \Delta], \text{ if } t \leq t^R - \frac{2\Delta}{(\beta_D-\beta_C)} \tag{24}$$

$$= \mu\left[\Delta - \mu(\frac{X_C-X_D}{2})\right], \text{ if } t^R - \frac{2\Delta}{(\beta_D-\beta_C)} \leq t \leq t^R. \tag{25}$$

In Region B

$$\pi^* = (1-\mu)\mu(X_C - \Delta - X_D) \text{ if } t \le t^R - \frac{2\Delta}{(2-\alpha)(\beta_D - \beta_C)} \tag{26}$$

$$= \frac{\alpha\mu}{2}\left[\frac{2\Delta}{(2-\alpha)} + \mu(X_D - X_C)\right] \text{ if } t^R - \frac{2\Delta}{(2-\alpha)(\beta_D-\beta_C)} \le t \le t^R. \tag{27}$$

In Region C

$$\pi^* = \mu(V - X_D)\left[\frac{\mu(V+\Delta-X_C)}{(V+\Delta-X_D)} + (1-\mu)\right]. \tag{28}$$

In Region D

$$\pi^* = \mu(V - X_D - \Delta)\left[\frac{\mu(V-X_C)}{(V-X_D)} + (1-\mu)\right]. \tag{29}$$

The following tables represent the reciprocal incentive to invest in cleaner technology:

In Region A

Table 1

| $t$ | $RI_{II}$ | $\frac{\partial RI_{II}}{\partial\Delta}$ | $\frac{\partial RI_{II}}{\partial t}$ |
|---|---|---|---|
| $t \le t^R - \frac{2\Delta}{\beta_D-\beta_C}$ | $-\mu^2(X_C - X_D - \Delta)$ | $>0$ | $>0$ |
| $t^R - \frac{2\Delta}{\beta_D-\beta_C} \le t \le \bar{t}$ | $\mu\left[2\Delta + \left(1+\frac{\mu}{2}\right)(X_D - X_C)\right]$ | $>0$ | $>0$ |
| $\bar{t} \le t \le t^R$ | $\mu\left[\Delta + \frac{\mu}{2}(X_D - X_C)\right]$ | $>0$ | $>0$ |

In Region B

Table 2

| $t$ | $RI_{II}$ | $\frac{\partial RI_{II}}{\partial\Delta}$ | $\frac{\partial RI_{II}}{\partial\alpha}$ | $\frac{\partial RI_{II}}{\partial t}$ |
|---|---|---|---|---|
| $t \le t^R - \frac{2\Delta}{(2-\alpha)(\beta_D-\beta_C)}$ | $-\mu^2(X_C - X_D - \Delta)$ | $>0$ | $-$ | $>0$ |
| $t^R - \frac{2\Delta}{(2-\alpha)(\beta_D-\beta_C)} \le t \le \bar{t}$ | $\frac{\alpha\mu}{2}\left[\frac{2\Delta}{(2-\alpha)} + \mu(X_D - X_C)\right] - \mu(X_C - X_D - \Delta)$ | $>0$ | $-$ | $>0$ |
| $\bar{t} \le t \le t^R$ | $\frac{\alpha\mu}{2}\left[\frac{2\Delta}{(2-\alpha)} + \mu(X_D - X_C)\right]$ | $>0$ | $>0$ | $>0$ |

In Region C

Table 3

| $t$ | $RI_{II}$ | $\frac{\partial RI_{II}}{\partial\Delta}$ | $\frac{\partial RI_{II}}{\partial\alpha}$ | $\frac{\partial RI_{II}}{\partial t}$ |
|---|---|---|---|---|
| $t \le \bar{t}$ | $\mu(V - X_D)\left[\frac{\mu(V+\Delta-X_C)}{(V+\Delta-X_D)} + (1-\mu)\right] - \mu(X_C - X_D - \Delta)$ | $>0$ | $-$ | $\gtrless 0$ |
| $\bar{t} \le t \le t^R$ | $\mu(V - X_D)\left[\frac{\mu(V+\Delta-X_C)}{(V+\Delta-X_D)} + (1-\mu)\right]$ | $>0$ | $-$ | $<0$ |

In Region D

Table 4

| $t$ | $RI_{II}$ | $\frac{\partial RI_{II}}{\partial\Delta}$ | $\frac{\partial RI_{II}}{\partial\alpha}$ | $\frac{\partial RI_{II}}{\partial t}$ |
|---|---|---|---|---|
| $t \le \bar{t}$ | $\mu(V - X_D - \Delta)\left[\frac{\mu(V-X_C)}{(V-X_D)} + (1-\mu)\right] - \mu(X_C - X_D - \Delta)$ | $>0$ | $-$ | $>0$ |
| $\bar{t} \le t \le t^R$ | $\mu(V - X_D - \Delta)\left[\frac{\mu(V-X_C)}{(V-X_D)} + (1-\mu)\right]$ | $<0$ | $-$ | $<0$ |