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Competitive investment in clean technology and uninformed green consumers

Aditi Sengupta *

0341 Haley Center, Department of Economics, Auburn University, Auburn, AL 36849, United States

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ABSTRACT

In a market where consumers and the regulatory authorities 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 firms' 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 an expected liability on firms in this setting. Compared to full information, incomplete information generates higher strategic incentive to invest in cleaner technology particularly when consciousness and/or expected liability are not too high. Requiring mandatory disclosure of technology or environmental performance may discourage such investment. Even though consumers and the regulator are uninformed, competition has a positive effect (relative to monopoly) on the incentive to invest.

Introduction

Environmental consciousness among consumers (i.e., their willingness to pay for the product produced with lower environmental damage) 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 the effect of green consciousness on profit maximizing firms' technology choice may be limited. This is particularly relevant in markets where there are no reliable voluntary disclosure mechanisms (such as eco-labeling or credible third party certification[1]) that enable at least partial disclosure of the actual technology or environmental performance of firms. This would appear to suggest the need for mandatory disclosure of

* Fax: +1 334 844 4615.
E-mail address: azs0074@auburn.edu

[1] Karl and Orwatt (2000), Dosi and Moretto (2001), Sedjo and Swallow (2002), Mason (2006), and Grolleau and Ibanez (2008) show that some information about environmental performance of a technology can be revealed by eco-label or third party certification.

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information[2] about technology or production process used by firms 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 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 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 and regulator 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 this paper, I consider environmental regulation in the form of a liability structure[3] which ensures that a firm has to pay penalty for the environmental damage caused by its own production technology once the damage becomes observable. Even though the regulator and the consumers cannot anticipate whether a firm's production technology will create environmental damage in the future, the firm may be well aware of its own risk of environmental damage. Thus, the expected penalty or liability payment faced by the firm enters its expected marginal cost of production. This, in turn, implies that liability rule creates an additional incentive for firms to invest in cleaner technology. Alternatively, the anticipated liability payment can be also interpreted as a threat of future environmental regulation like emission tax or permit after policy makers become aware of the actual environmental damage caused by the firms. The stringency of this anticipated liability is assumed to be exogenously determined by the regulatory authorities.[4] An important contribution of this paper is that it offers an analysis of the interaction between anticipated liability and consumer consciousness when consumers and regulatory authorities are uninformed, and the circumstances under which they are complementary in inducing the technological change.[5]

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 with a technology that poses lower environmental risk. The production technology of a firm can be of two potential types *dirty* and *clean*. 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. Thus, a non-investing firm and an unsuccessful investing firm face an anticipated liability payment whereas an investing firm that has successfully adopted the clean technology does not incur any expected cost of regulation. 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.[6]

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.[7] The underlying competitive signaling game in this paper draws on the specific model of Janssen and Roy (2010), but introduces a particular 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.[8] In particular, Moraga-Gonzalez and Padron-Fumero (2002) analyze the effect of different environmental policies on the aggregate emissions and welfare when two

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[2] Following are few examples of mandatory disclosure such as Toxic Release Inventory (USA), Environmental Reporting Decree (the Netherlands), Green Accounts (Denmark), and Pollutant Release and Transfer Register (UK).

[3] US's the Comprehensive Environmental Response, Compensation and Liability Act of 1980, Superfund Amendments of 1986, and EU's Environmental Liability Directive are few examples of liability rule.

[4] Sergerson and Miceli (1998) note that the threat of environmental regulation may depend on many external factors such as political support.

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

[6] Hwang et al. (2006) find that consumers use price as a signal of the quality of genetically modified food (corn, bread, and egg).

[7] Unlike much of this literature, in this model, the effective marginal cost of production depends on the level of exogenously given expected environmental liability, and for significantly higher level of liability, the clean type has lower effective marginal cost of production compared to the dirty type. Thus, lower price may signal better "quality".

[8] See among others Cremer and Thisse (1999), Arora and Gangopadhyay (2003), Bansal and Gangopadhyay (2003) Anton et al. (2004), Conrad (2005), Deltas et al. (2013), and García-Gallego and Georgantzís (2008).

strategically competing firms decide whether to adapt cleaner technology in the presence of environmentally conscious consumers. 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 of environmental performance by a monopolist when the latter is not observed and the possibility of reputation overcoming the moral hazard problem. Sengupta (2012) 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).[9]

Several papers have analyzed the effects of anticipated liability on firms' incentive to become cleaner. Anton and Khanna (2002) show that the threat of environmental liabilities plays statistically significant role in inducing corporate environmentalism among firms. Moreover, Anton et al. (2004) provide empirical evidence that the presence of liability threats and also consumer consciousness drive firms towards environmental self-regulation. Sergerson and Miceli (1998) find that the threat of regulation encourages firms to participate in voluntary agreements with a regulator to reduce pollution. These papers do not take into account the effect of an expected environmental liability firms' incentive to invest in cleaner technology when environmentally conscious consumers and the regulator are unaware of the actual environmental damage.

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, an 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 (2012), I show that in the presence of competition, firms have strategic incentive to invest even when anticipated liability is low. Firms invest not only to reduce the burden of liability 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 pro-competitive policies can promote green technological change. Further, I examine and compare the investment equilibria under full and incomplete information.

When environmental consciousness and/or anticipated liability are low and the rival does not invest, a firm has higher strategic incentive to invest in order to soften price competition under incomplete information compared to full information; however, this *incentive* to invest decreases with an increase in the level of consciousness and/or expected regulation. Interestingly, in this case the non-investing firm enjoys a positive externality because of the incomplete information about the realized technology of its rival which also diminishes with higher level of environmental consciousness and/or regulation. In fact, if consciousness and/or anticipated liability are moderately high, then there is sufficient incentive to invest if the rival firm invests, but insufficient incentive to do so if the rival does not invest.

The remainder of the paper is organized as follows. The next section describes the model. In "Benchmark: incentive to invest under mandatory disclosure law" section, I examine the strategic incentive of a firm to invest in cleaner technology under full information. "Signaling environmental quality through price" section 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 "Incentive to invest in cleaner technology" section, I study the strategic incentive to invest in cleaner technology under incomplete information and compare the investment behavior of firms with that of under full information. Finally, I illustrate the possible investment equilibria under full and incomplete information in "Investment equilibria" section. The last section concludes.

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 causes zero damage if it is *clean*.[10] The risk of environmental damage caused by a dirty type is given by $\beta \in (0, 1]$. I assume that a dirty type causes a damage of one unit per unit of output. Thus, β can be also interpreted as the expected damage per unit of output. Each firm produces at constant unit cost. 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., $0 < m_D < m_C$.[11] Firms face an exogenously given anticipated liability payment for per unit of observable environmental damage denoted by t[12]. Under existing strict liability rule a firm will have to pay penalty if the firm's production process causes significant observable environmental damage in the future. The anticipated liability may also represent the threat of future regulation which is internalized by the dirty firms in their expected marginal cost structures.

[9] In the product quality literature, Shieh (1993) analyzes whether a monopolist has an incentive to invest in cost reducing technology when consumers are not aware of the firm's investment decision and the quality of the product. In somewhat different context, Daughety and Reinganum (1995) show that a monopolists decision to invest in cost reducing research and development increases safety of the product when the marginal cost of risk per unit of output sold is significantly high.

[10] This is a simplifying assumption; a positive rate of damage for the clean type (which is less than the per unit damage of the dirty type) would not alter the main qualitative results.

[11] The case where cleaner technology is more cost effective ($m_C < m_D$) is discussed in the Appendix.

[12] 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 expected liability is socially optimal as there is no emission or damage function explicitly modelled.

Let $\gamma_D = m_D + t\beta$ be the effective marginal cost of a dirty type. As the clean firm does not emit, its effective marginal cost of supplying the product is simply its marginal production cost m_C.

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 and 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 $V > m_C$ and $V > \gamma_D$. Observe that the proportion of conscious consumers (α) and the premium (Δ) are two dimensions of the extent of environmental consciousness of consumers. I assume that all consumers are aware of the unit production cost of the clean type (m_C) as well as of the dirty type (m_D) and the anticipated liability rate (t).

Firms are initially endowed with a dirty production technology which means that each firm creates β units of expected damage per unit of output and incurs an effective marginal cost of γ_D. In the first stage, firms simultaneously decide whether or not to invest in the development of clean technology.[13] 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 $\mu \in (0,1)$[14] 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 does not emit and incurs an effective marginal cost of m_C. In the next stage, firms choose prices simultaneously to signal the environmental performance to consumers. The solution concept used in the signaling game is that of Perfect Bayesian Equilibrium which is supported by the out-of-equilibrium beliefs[15] that satisfy Cho–Sobel (1990) D1 Criterion.[16] 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 anticipated liability at which the effective marginal cost of a clean type (m_C) is exactly equal to that of the dirty type (γ_D) i.e., $t^R = (m_C - m_D)/\beta$. In the main text of the paper, I focus on the case where the anticipated liability is not too high $(t \le t^R)$ i.e., where the effective marginal cost of a clean type is higher than that of a dirty type. If $t \ge t^R$ the relative cost structure gets reversed; this case is discussed in the Appendix. The ex ante expected profits of an investing firm are $\pi_{I,I}$ and $\pi_{I,NI}$ if the rival invests and does not invest respectively whereas the ex ante expected profits of a non-investing firm given that the rival invests and does not invest are denoted by $\pi_{NI,I}$ and $\pi_{NI,NI}$ respectively.

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 and the expected profit when it does not invest. The strategic incentive to invest differs between situations where the rival firm does not invest and the rival invests. In particular, the *unilateral incentive* (*UI*) to invest in cleaner technology is defined as the difference between ex ante expected profit of an investing firm when the rival does not invest and the expected profit of a firm when both firms do not invest $(UI = \pi_{I,NI} - \pi_{NI,NI})$, whereas the *reciprocal incentive* (*RI*) to invest is the ex ante expected profit of an investing firm when both firms invest minus the ex ante expected profit of a non-investing firm when the rival invests $(RI = \pi_{I,I} - \pi_{NI,I})$. If $UI \ge 0$ then a firm has incentive to invest in cleaner technology even if the rival does not invest; moreover if $RI \ge 0$ then a firm has reciprocal incentive to invest. In the rest of the paper, I will refer unilateral and reciprocal incentives of a firm under full and incomplete information with subscripts *FI* and *II* respectively.

Benchmark: incentive to invest under mandatory disclosure law

Under mandatory disclosure law, firms are required to report their true environmental attributes to the regulatory authorities. Alternatively, the regulatory authorities can also on their own acquire information about actual environmental performance of firms and disseminate the information among public. As a result, consumers as well as the rival firms become completely aware of the actual environmental performance of a firm. It may appear that since consumers are

[13] The equilibrium investment behavior of a firm depends on the cost of investment which I currently abstract from; I will discuss all possible investment equilibria in "Investment equilibria" section.

[14] It can be alternatively interpreted as the probability that the newly developed technology eliminates accidents that can damage the environment or prevents currently unknown externalities on the environment in the future.

[15] Consumers form beliefs about the quality of the product after observing the prices charged by the firms on the equilibrium path. Firms compute their expected profits on the basis of these consumer beliefs. However, in order for the firms to decide that the price they charge on the equilibrium path is actually optimal they need to figure out the profit they would earn if they charged a different price (an "out of equilibrium" price). In the latter event (a zero probability event in the conjectured equilibrium), the buyers' optimal buying behavior would depend on what they would believe about the quality of the product if they were to observe such an out of equilibrium price. Criteria such as the Intuitive Criteria and the D1 refinement impose strong restrictions on these out of equilibrium beliefs and therefore refine the set of Perfect Bayesian Equilibrium. In this paper, I have used D1 refinement criterion which happens to be one of the stronger "reasonableness" restriction on specification of out of equilibrium beliefs.

[16] 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 (2010) modify and adapt D1 criterion in their model with multiple senders (firms). An out-of-equilibrium belief satisfies D1 criterion if consumers believe that the off equilibrium 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.

willing to pay a price premium for the product produced by relatively cleaner technology, firms should always have significant incentive to become cleaner when consumers are indeed aware of the actual environmental performance of the firm. In this section, I examine the incentive of firms to invest when investment as well as the technological outcome of the investment are publicly observed.

First, I describe the full information equilibrium of the pricing game after investment decisions are made and the realized technology of the investment is made public. Observe that the dirty type generates strictly higher surplus than the clean type $(V-\gamma_D > V+\Delta-m_C)$ at any anticipated liability $t<\bar{t}=t^R-\Delta/\beta$, whereas the opposite holds true when the anticipated liability is higher i.e., $t>\bar{t}$. At $t=\bar{t}$, the surplus generated by the clean type is exactly equal to that of the dirty type. When no firm invests then both remain dirty for sure; as a result they involve in aggressive price competition and charge a price equal to the dirty type's effective marginal cost earning zero profit. When at least one firm invests then at any anticipated liability $t \le \bar{t}$ the clean type charges its own effective marginal cost. The dirty type charges its effective marginal cost if the rival is of dirty type too. However, if the rival is of clean type then for $t \le t^R-\Delta/\alpha\beta$ the dirty type charges a price at which an environmentally conscious consumer is indifferent between buying from the clean and the dirty type; whereas for $t^R-\Delta/\alpha\beta \le t \le \bar{t}$ it charges clean type's effective marginal cost and sells only to the consumers who are not environmentally conscious.[17] At any anticipated liability $t \ge \bar{t}$, the clean type charges a price at which a consumer is indifferent between buying from the clean and the dirty type if the rival is of dirty type[18] (whereas it charges its own effective marginal cost if the rival is of clean type too), and the dirty type charges its effective marginal cost.[19]

The following proposition illustrates a firm's strategic incentive to invest under full information.

Proposition 1. *Under full information at any level of anticipated liability $t \le \bar{t}$, no firm has any strictly positive incentive to invest. However, when the liability is significantly higher $(t>\bar{t})$ a firm has strictly positive unilateral and reciprocal incentive to invest.*

Proof. See Appendix.

Under full information, if both firms happen to be of the same type then they equally share the market. If they are of different types then the dirty type takes over the entire market under lower anticipated liability $(t \le \bar{t})$ otherwise (i.e., $t \ge \bar{t}$) the clean type caters to the entire market. Thus, no firm has any incentive to become clean under lower level of anticipated liability $(t<\bar{t})$. However when the liability is relatively strong $(t>\bar{t})$ both unilateral and reciprocal incentives of a firm are strictly positive. At $t=\bar{t}$, a firm has zero strategic incentive to invest which implies that essentially a firm is indifferent between investing and not investing in the cleaner technology irrespective of what its rival does.

Signaling environmental quality through price

Consider the incomplete information framework outlined in “Model” section. In this section, I analyze the pricing game following any profile of investment decision made in the first stage. There are three possible scenarios: (1) neither firm invests, (2) only one firm invests, and (3) both firms invest.

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

A more interesting case arises under the second situation viz. when only one firm invests. Here the pricing game is a one sided incomplete information game; the firm that invests is clean with probability μ and remains dirty with probability $(1-\mu)$, while a firm that does not invest stays dirty for sure. If the investing firm is clean it tries to convince the consumers that it is of clean type by choosing a sufficiently 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 wants to fool 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. The clean type has more incentive to charge higher price because of its relatively higher effective marginal cost.

Lemma 1. *If only one firm invests, at any level of anticipated liability $t \le \bar{t}$ there exists a unique separating D1 equilibrium in the pricing game. A clean type charges a price equal to its effective marginal cost m_C earning zero expected profit while a firm that*

[17] If there was no environmentally conscious consumers $(\alpha=0)$ then the dirty type would have charged m_C for any anticipated liability $t \le \bar{t}$. However for $\alpha>0$, the dirty type has to charge a lower price $(m_C-\Delta)$ to attract all consumers and thus earns a profit of $(m_C-\Delta-\gamma_D)$. As t increases dirty type's profit decreases. The dirty type earns higher profit than $(m_C-\Delta-\gamma_D)$ if it sells at m_C to only environmentally not conscious consumers i.e., $(1-\alpha)(m_C-\gamma_D) > (m_C-\Delta-\gamma_D)$, at any $t>t^R-\Delta/\alpha\beta$.

[18] The price at which a consumer is indifferent between buying from the clean type and the dirty type is equal to the effective marginal cost of the clean type (i.e., $\gamma_D+\Delta=m_C$) when $t=\bar{t}$.

[19] 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., $\gamma_D+\Delta \le V$ which implies that $t \le (V-\Delta-m_D)/\beta$) the clean type captures the entire market in the state where the rival is of dirty type; otherwise, only α 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.

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* $\overline{p}_D = m_C - \Delta$ *and* $\underline{p}_D = \mu \overline{p}_D + (1-\mu)\gamma_D$ *and thus earn strictly positive expected profit.*

Proof. See Appendix.

The above lemma implies that when only one firm invests there does not exist any separating equilibrium in pure strategies under lower anticipated liability. Recall that for any anticipated liability $t \le \overline{t}$ 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 that remains dirty for sure enjoys market power and steals all 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. 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 (viz. $p > m_C$ or $p < m_C$) 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 $p > m_C$ is larger than that of the dirty type, and since a clean type will never deviate to any price below its own effective marginal cost D1 refinement is trivially satisfied in this case.

However, under relatively *higher* anticipated liability ($\overline{t} \le t \le t^R$) the condition for existence ($\Delta \le m_C - \gamma_D$) of the separating equilibrium described in Lemma 1 does not hold.

Lemma 2. *For any level of anticipated liability* $\overline{t} \le t \le t^R$, *if only one firm invests then in the unique D1 separating equilibrium the dirty type charges a price equal to its effective marginal cost* γ_D, *and all consumers buy from the dirty type with probability one whereas the clean type charges a higher price* $p_C = \gamma_D + \Delta$ *and sells zero.*

Interestingly even though the clean type yields higher surplus than the dirty type (as $\Delta \ge m_C - \gamma_D$) 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 otherwise it equally shares the market with the rival. Note that 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 both types 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 $p < \gamma_D + \Delta$ or $p > \gamma_D + \Delta$ 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 $p < \gamma_D + \Delta$ 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 $p > \gamma_D + \Delta$ then the clean type finds it strictly profitable to deviate as well; thus, the out-of-equilibrium beliefs satisfy the D1 Criterion.

Under the one-sided incomplete information pricing game ex ante expected profits of investing and non-investing firms are

$$\pi_{I,NI} = \begin{cases} (1-\mu)[m_C - \gamma_D - \Delta] & \text{if } t \le \overline{t} \\ 0 & \text{if } \overline{t} \le t \le t^R \end{cases} \tag{1}$$

and

$$\pi_{NI,I} = \begin{cases} \mu[m_C - \gamma_D - \Delta] & \text{if } t \le \overline{t} \\ 0 & \text{if } \overline{t} \le t \le t^R \end{cases} \tag{2}$$

respectively.

If both firms invest then the market competition of this analysis is almost similar to the signaling game considered by Janssen and Roy (2010); however note that unlike their model I consider a heterogeneous set of consumers i.e., a fraction of consumers that are environmentally conscious pay a price premium for the product produced by clean technology. Following the construction of the Perfect Bayesian equilibrium in their paper, one can illustrate the pricing equilibrium when both firms invest.

Lemma 3. *At any level of anticipated liability* $t \le t^R$ *if both firms invest then in the unique separating D1 equilibrium, 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*

$$p_C = \begin{cases} m_C & \text{if } t \le t^R - \dfrac{2\Delta}{\beta} \\ \gamma_D + 2\Delta & \text{if } t^R - \dfrac{2\Delta}{\beta} \le t < \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ V & \text{if } t = \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ \dfrac{2\Delta}{(2-\alpha)} + \gamma_D & \text{if } \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} < t \le \dfrac{V + \Delta - m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \\ V + \Delta & \text{if } t > \dfrac{V + \Delta - m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \end{cases} \tag{3}$$

$$\overline{P}_D = p_C - \Delta \quad \text{and} \quad \underline{P}_D = \mu[p_C - \Delta] + (1-\mu)\gamma_D. \tag{4}$$

Proof. See Appendix.

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) randomizes over a price interval. Lack of information about the actual environmental attributes of firms does not only allow 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 dirty type does not have a strong incentive to imitate the clean type when environmentally conscious consumers are not willing to pay a significant price premium for the product produced by the clean type or when the anticipated liability is not stringent enough to bridge the gap between effective marginal costs of the clean and dirty type. Therefore, under anticipated liability $t \le t^R - 2\Delta/\beta$ the clean type can afford to prevent the dirty type from imitating by charging a price as low as its own effective marginal cost. However, as the incentive to imitate increases with increase in the level of anticipated liability and environmental consciousness of consumers the clean type charges a higher price which in turn helps to increase the market power and profitability of both types. If $t = (V - m_D)/\beta - 2\Delta/\beta$ then the clean type raises its price to common valuation of the product i.e., the full information monopoly price of the dirty type and thus, loses some of the consumers that are not environmentally conscious. When $(V - m_D)/\beta - 2\Delta/\beta < t \le (V + \Delta - m_D)/\beta - 2\Delta/\beta(2-\alpha)$, if the clean type happens to sell then it will capture only the environmentally conscious segment of the market since the anticipated liability is high enough to make the clean type charge a higher price than the common valuation of the product. As anticipated liability increases $(t > (V + \Delta - m_D)/\beta - 2\Delta/\beta(2-\alpha))$, the clean type may lose some of the environmentally conscious consumers who are indifferent between buying products of the clean type at the maximum possible price (full information monopoly price of the clean type) and product of the dirty type at a lower price.

The 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 $p \ne p_C$ 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.[20] 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 discussion, 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.

[20] For a formal proof see Janssen and Roy (2010).

The equilibrium expected profits[21] of the clean type and dirty type are

$$\pi_C = \begin{cases} 0 & \text{if } t \le t^R - \dfrac{2\Delta}{\beta} \\ \dfrac{\mu}{2}(2\Delta + \gamma_D - m_C) & \text{if } t^R - \dfrac{2\Delta}{\beta} \le t < \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ \dfrac{\mu(V - \gamma_D - \Delta)}{(V - \gamma_D)}(V - m_C) & \text{if } t = \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ \dfrac{\alpha\mu}{2}\left(\dfrac{2\Delta}{(2-\alpha)} + \gamma_D - m_C\right) & \text{if } \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} < t \le \dfrac{V + \Delta - m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \\ \dfrac{\mu(V - \gamma_D)}{(V + \Delta - \gamma_D)}(V + \Delta - m_C) & \text{if } t > \dfrac{V + \Delta - m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \end{cases} \tag{5}$$

and

$$\pi_D = \begin{cases} \mu(m_C - \Delta - \gamma_D) & \text{if } t \le t^R - \dfrac{2\Delta}{\beta} \\ \mu\Delta & \text{if } t^R - \dfrac{2\Delta}{\beta} \le t < \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ \mu(V - \Delta - \gamma_D) & \text{if } t = \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ \dfrac{\mu\alpha\Delta}{(2-\alpha)} & \text{if } \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} < t \le \dfrac{V + \Delta - m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \\ \mu(V - \gamma_D) & \text{if } t > \dfrac{V + \Delta - m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \end{cases} \tag{6}$$

respectively. Thus, the ex ante expected profit of an investing firm is

$$\pi_{I,I} = \mu\pi_C + (1-\mu)\pi_D$$

$$= \begin{cases} (1-\mu)\mu[m_C - \gamma_D - \Delta] & \text{if } t \le t^R - \dfrac{2\Delta}{\beta} \\ \mu\Delta - \dfrac{\mu^2}{2}(m_C - \gamma_D) & \text{if } t^R - \dfrac{2\Delta}{\beta} \le t < \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ \mu\left[\dfrac{\mu(V - \gamma_D - \Delta)}{(V - \gamma_D)}(V - m_C) + (1-\mu)(V - \gamma_D - \Delta)\right] & \text{if } t = \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ \mu\left[\dfrac{\mu\alpha}{2}\left(\gamma_D + \dfrac{2\Delta}{(2-\alpha)} - m_C\right) + (1-\mu)\dfrac{\alpha\Delta}{(2-\alpha)}\right] & \text{if } \dfrac{V - m_D}{\beta} - \dfrac{2\Delta}{\beta} < t \le \dfrac{V + \Delta - m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \\ \mu\left[\dfrac{\mu(V - \gamma_D)}{(V + \Delta - \gamma_D)}(V + \Delta - m_C) + (1-\mu)(V - \gamma_D)\right] & \text{if } t > \dfrac{V + \Delta - m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \end{cases} \tag{7}$$

Next, I examine the effect of environmental consciousness on the market power (defined by a firm's ability to charge a price higher than its own marginal cost and measured by the mark up i.e., the difference between price and marginal cost) and expected profit of an investing firm. Rise in the level of environmental consciousness among consumers is measured by the increase in the premium that consumers are willing to pay (Δ) for the cleaner product as well as by the increase in the proportion of conscious consumers (α).

Proposition 2. *Under incomplete information, at any level of anticipated liability $t^R - 2\Delta/\beta \le t$, an increase in the environmental consciousness among consumers increases the market power and expected profit of an investing firm.*

The proof of this proposition directly follows from (3) and (7). Recall that beyond a moderate level of anticipated liability ($t = t^R - 2\Delta/\beta$) increase in the environmental consciousness among consumers increases the dirty type's incentive to imitate the clean type. To prevent the dirty type, the clean type charges higher price. In other words, an investing firm's ability to charge a higher price (i.e., market power) increases. This, in turn, increases the positive profit earned by the dirty type and the *ex ante* expected profit of an investing firm.

[21] The expected profit of any type is equal to the product of the probability that the type sells in the market and the difference between the equilibrium price charged by the type and its effective marginal cost.

Incentive to invest in cleaner technology

In this section, I investigate whether firms have any strategic incentive to invest in cleaner technology under incomplete information (ignoring any cost of investment) and how environmental consciousness and the anticipated liability affect this incentive. Further, I examine whether the strategic incentive to invest increase or decrease if the outcome of the investment (the realized technology) can be publicly observed. In other words, I compare firms' incentive to invest in cleaner technology under incomplete information and full information.

Incentive to invest under incomplete information

Recall that the unilateral incentive to invest in cleaner technology is defined as the difference between ex ante expected profit of an investing firm when the rival does not invest and the expected profit of a firm when neither firm invests. Strictly positive unilateral incentive implies that a firm has an incentive to invest in cleaner technology even when the rival does not invest. The following proposition illustrates the unilateral incentive of a firm under incomplete information.

Proposition 3. *Under incomplete information a firm has positive unilateral incentive to invest in cleaner technology iff* $t \le \bar{t}$.

Given that the rival does not invest, if a firm decides not to invest and thus remains dirty for sure then both earn zero profit because of aggressive price competition. However recall that at any anticipated liability $t \le \bar{t}$ if the firm invests but still remains dirty then it has a strictly positive ex ante expected profit because of the stochastic monopoly power enjoyed by the non-investing firm (whereas the clean type of the investing firm earns zero profit as it is always undercut by the non-investing rival). Thus, the unilateral incentive of a firm is given by

$$UI_{II} = \pi_{I,NI} = (1-\mu)(m_C - \gamma_D - \Delta) > 0 \quad \text{if } t \le \bar{t} \tag{8}$$

(from (1)); this implies that a firm does have a strictly positive unilateral incentive to invest in clean technology. Observe that the gain from investment which is a measure of unilateral incentive to invest depends on the profit earned by the dirty type.

From (1) and (2), note that a non-investing rival gains more compared to an investing firm if the probability of a successful investment is high (viz. $\mu \ge \frac{1}{2}$); it is a major strategic externality. This, in turn, implies that increase in μ, the probability of a successful investment (viz. probability of being clean), has a disincentive effect on investment under lower anticipated liability ($t \le \bar{t}$). The strategic externality enjoyed by the non-investing firm increases with an increase in μ. In this range of anticipated liability increase in consciousness premium (Δ) and anticipated liability (t) reduce the ex ante expected profit of a firm and also the gain from investment when the rival firm does not invest. Beyond a critical level of anticipated liability ($t \ge \bar{t}$), in particular, when the 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 in equilibrium.

Further, observe that unlike the *monopolist*[22] a firm has a positive unilateral incentive to invest even when the liability is low. 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 future liability payment 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.

Next consider the case when the rival invests.

Proposition 4. *Under incomplete information for any level of anticipated liability* $t^R - 2\Delta/\beta \le t \le t^R$, *the firm has a positive reciprocal incentive to invest in cleaner technology*.

Proof. See Appendix.

The intuition for the above proposition is as follows. Recall that under incomplete information when both firms invest, the equilibrium price distribution of the dirty type is positively related to the deterministic (equilibrium) price of the clean type. This implies that an increase in the market power of the clean type induces higher market power to the dirty type. This, in turn, increases the profitability of an investing firm. Thus, one can conclude that a firm has strictly positive reciprocal incentive to invest as long as the clean type enjoys market power i.e., when $t^R - 2\Delta/\beta \le t \le t^R$.

[22] In Sengupta (2012), I find that a single seller does not have any incentive to invest in cleaner technology under weak regulation $(t \le t^R)$ as the dirty type always earns higher expected profit than the clean type.

Effect of anticipated liability and environmental consciousness

In this subsection, I explore how the unilateral and reciprocal incentives to invest change with respect to environmental consciousness (premium (Δ) as well as the proportion of environmentally conscious consumers (α)) and the level of anticipated liability. First, consider the case where the rival firm does not invest.

Proposition 5. *Increase in environmental consciousness, in particular premium (Δ) paid by the conscious consumers for the clean type shrinks the range of anticipated liability $(t \le \bar{t})$ over which a firm has positive unilateral incentive to invest $(\partial \bar{t}/\partial \Delta < 0)$ and also decreases the gain from investment by the firm $(\partial UI_{II}/\partial \Delta < 0)$.*

The rise in environmental consciousness among consumers (viz. the premium (Δ) paid by the conscious consumers for the product of the clean type) decreases the price $(\overline{p}_D = m_C - \Delta)$ at which a consumer is indifferent between buying from the clean type and the dirty type, and increase in the level of threat increases the effective marginal cost of the dirty type more than that of the clean type. Therefore, increase in consciousness and liability reduce the profit of the non-investing firm as well as the profit of the dirty type of the investing firm. This, in turn, reduces the gain from unilateral incentive to invest (which is given by $(1-\mu)[m_C - \gamma_D - \Delta]$) in this case.

Further, one can analyze the effect of environmental consciousness of consumers and anticipated liability on a firm's reciprocal incentive to invest in cleaner technology under incomplete information from (18)–(21) (in Appendix).

Proposition 6. *Increase in the premium paid by the environmentally conscious consumers for a unit of the clean product (Δ) expands the range of anticipated liability along which a firm has positive reciprocal incentive to invest (i.e., $\partial \bar{t}/\partial \Delta < 0$). The gain from investment goes up with increase in the premium $(\partial RI_{II}/\partial \Delta \ge 0)$.*

Moreover, the reciprocal incentive of a firm to invest in cleaner technology is non-decreasing in the proportion of environmentally conscious consumers $(\partial RI_{II}/\partial \alpha \ge 0)$.

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.

Proposition 7. *The reciprocal incentive of a firm to invest in clean technology increases with the level of anticipated liability $(\partial RI_{II}/\partial t \ge 0)$.*[23]

Note that at a higher level of liability (more precisely at any expected liability $(V+\Delta-m_D)/\beta - 2\Delta/\beta(2-\alpha) \le t \le t^R$) when the clean type charges a fixed price (insensitive to anticipated liability) even though a firm has a positive reciprocal incentive to invest in clean technology the gain from investment goes down with increase in the level of liability. The intuition is as follows. In this range of anticipated liability the gain from investment is equal to the ex ante expected profit of an investing firm when the rival invests, and this expected profit goes down with increase in anticipated liability. I also find that there is a complementarity between anticipated liability (t) and price premium (Δ) paid by the environmentally conscious consumers in promoting green technological change. In other words, increase in both anticipated liability and price premium increases the reciprocal incentive to invest except when the liability is $(V+\Delta-m_D)/\beta - 2\Delta/\beta(2-\alpha) \le t \le t^R$.

Incomplete information vs. full information

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. The comparison can be made from Propositions 1, 3, and 4; it is depicted in Fig. 1. The next proposition narrows down the important features of the comparison.

Proposition 8. *The unilateral incentive to invest in clean technology is higher under incomplete information compared to that of the full information particularly when anticipated liability is below a critical level $(t \le \bar{t})$.*

If the level of anticipated liability exceeds a certain level $(t^R - 2\Delta/\beta)$, a firm has higher reciprocal incentive to invest in cleaner technology under incomplete information compared to that of the full information.

This implies that mandatory disclosure law or public dissemination of information about actual environmental performance of firms is not necessary to encourage 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

[23] This does not hold true for any expected liability $(V+\Delta-m_D)/\beta - 2\Delta/\beta(2-\alpha) \le t \le t^R$ when the clean type charges $p_C = V+\Delta$.

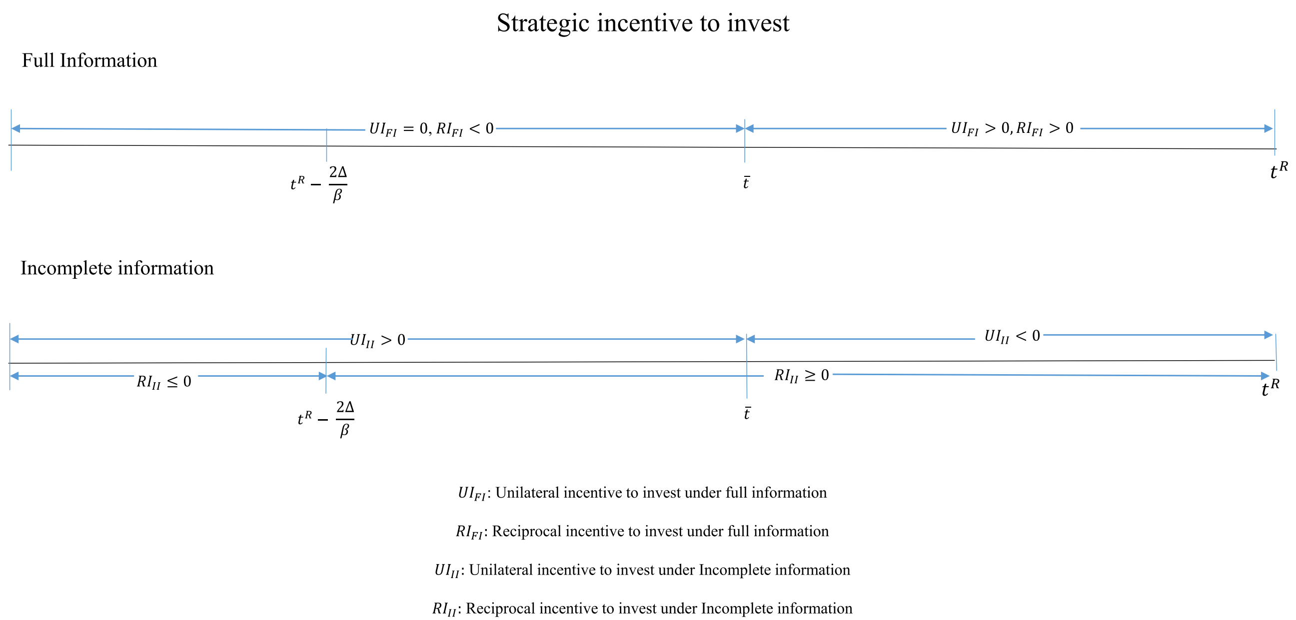

Fig. 1. Strategic incentive to invest.

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.

Investment equilibria

So far I have analyzed whether a firm has strategic incentive to invest in cleaner technology under incomplete information without talking about the investment outcome. Obviously, the actual investment behavior of a firm depends on the cost of investment. Consider the investment game described in "Model" section. Suppose investment requires a fixed cost say, $f>0$.[24] In equilibrium, at least one firm invests if the unilateral incentive to invest is at least as high as the fixed cost ($UI_{II} \geq f$), and both firms invest when the reciprocal incentive to invest exceeds the fixed cost of investment ($RI_{II} \geq f$). I find the investment equilibria under full information as well as under incomplete information by comparing the respective unilateral and reciprocal incentives of a firm. The interesting characteristics of the investment equilibria are summarized in the following proposition.

Proposition 9. (*i*) *For any anticipated liability $t<\bar{t}$, no firm invests in the full information equilibrium even when there is no cost of investment ($f=0$) whereas at least one firm invests under incomplete information if $f \leq UI_{II}$.* (*ii*) *Relative to full information, incomplete information reduces the critical level of fixed cost of investment below which both firms invest in equilibrium.*[25]

The proof of the proposition directly follows from comparing the reciprocal and unilateral incentives to invest under incomplete as well as full information (see Propositions 1, 3, and 4). From the above Proposition one can conclude that lack of information about a firm's environmental performance does not discourage strategically interacting firms to invest in cleaner technology. Since the unilateral as well as reciprocal incentive to invest increase with increase in environmental consciousness (see Propositions 5 and 6), the environmental consciousness parameters, namely green premium (Δ) and proportion of environmentally conscious consumers (α), have similar positive effects on the equilibria where at least one or both firms invest.[26]

Conclusion

This paper focuses on firms' strategic incentive to invest in clean technology in a market where firms compete in prices, face an exogenously given level of anticipated liability, and some consumers are environmentally conscious (i.e., they are 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 anticipated liability are 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 anticipated liability may reduce the incentive to invest.

Appendix A. Appendix

Proof of Proposition 1. The ex ante expected profit of a firm $\mu\pi_C+(1-\mu)\pi_D$ where π_C is the clean type's expected profit and π_D is the dirty type's expected profit. The ex ante expected profit of an investing firm under full information when the

[24] An alternative interpretation of this fixed cost can be given by the maximum amount of third-party certification fee that a firm is willing to pay to reveal its own environmental performance instead of signaling through price.

[25] For a detailed description of relevant bounds of the fixed cost please see the technical version of Proposition 25 (ii) in Appendix.

[26] If firms make the investment decision cooperatively in the first stage then for a lower liability ($t \leq t^R-2\Delta/\beta$) only one firm invests in the equilibrium, and for any liability $t^R-\Delta/\beta \leq t \leq t^R$ both firms find it optimal to invest (see (1), (2) and (7)).

rival invests and the rival does not invest are respectively

$$\pi_{I,I}=\begin{cases}\mu(1-\mu)(m_C-\Delta-\gamma_D) & \text{if } t\le t^R-\dfrac{\Delta}{\alpha\beta}\\ \mu(1-\mu)(1-\alpha)(m_C-\gamma_D) & \text{if } t^R-\dfrac{\Delta}{\alpha\beta}\le t\le \bar{t}\\ \mu(1-\mu)(\gamma_D+\Delta-m_C) & \text{if } \bar{t}\le t\le \dfrac{V-\Delta-m_D}{\beta}\\ \mu(1-\mu)\alpha(\gamma_D+\Delta-m_C) & \text{if } \dfrac{V-\Delta-m_D}{\beta}\le t\end{cases} \tag{9}$$

$$\pi_{I,NI}=\begin{cases}0 & \text{if } t\le\bar{t}\\ \mu(\gamma_D+\Delta-m_C) & \text{if } \bar{t}\le t\le\frac{V-\Delta-m_D}{\beta}\\ \mu\alpha(\gamma_D+\Delta-m_C) & \text{if } \dfrac{V-\Delta-m_D}{\beta}\le t\end{cases} \tag{10}$$

The first expression of (9) is the profit of an investing firm when it remains dirty (with probability $(1-\mu)$) whereas the rival has become clean (with probabilityμ) and the dirty type charges a price $(m_C-\Delta)$ which is higher than the effective marginal cost of the dirty type. Recall from above discussion that this is the only circumstance an investing firm earns non-zero profit when $t\le t^R-\Delta/\alpha\beta$. Similarly, the second expression of (9) is the only non-zero profit earned by the investing firm at any anticipated liability $t^R-\frac{\Delta}{\alpha\beta}\le t\le\bar{t}$ when it remains dirty (with probability $(1-\mu)$) whereas the rival has become clean (with probability μ), the dirty type charges m_C, and only environmentally not conscious i.e., $(1-\alpha)$ proportion of the consumers buy from the dirty type. I can explain rest of the profit expressions in the similar fashion. Whereas the ex ante expected profit of a non-investing firm under full information when the rival invests is

$$\pi_{NI,I}=\begin{cases}\mu(m_C-\Delta-\gamma_D) & \text{if } t\le t^R-\frac{\Delta}{\alpha\beta}\\ \mu(1-\alpha)(m_C-\gamma_D) & \text{if } t^R-\frac{\Delta}{\alpha\beta}\le t\le\bar{t}\\ 0 & \text{if } \bar{t}\le t\end{cases} \tag{11}$$

and when the rival does not invest $(\pi_{NI,NI})$ is zero. Thus, the unilateral and reciprocal incentive of a firm to invest in cleaner technology under full information are

$$UI_{FI}=\begin{cases}0 & \text{if } t\le\bar{t}\\ f_1(t)\equiv\mu(\gamma_D+\Delta-m_C) & \text{if } \bar{t}\le t\le\dfrac{V-\Delta-m_D}{\beta}\\ f_3(t)\equiv\mu\alpha(\gamma_D+\Delta-m_C) & \text{if } \dfrac{V-\Delta-m_D}{\beta}\le t\end{cases} \tag{12}$$

and

$$RI_{FI}=\begin{cases}-\mu^2(m_C-\Delta-\gamma_D)<0 & \text{if } t\le t^R-\dfrac{\Delta}{\alpha\beta}\\ -\mu^2(1-\alpha)(m_C-\gamma_D)<0 & \text{if } t^R-\dfrac{\Delta}{\alpha\beta}\le t\le\bar{t}\\ f_2(t)\equiv\mu(1-\mu)(\gamma_D+\Delta-m_C) & \text{if } \bar{t}\le t\le\dfrac{V-\Delta-m_D}{\beta}\\ f_4(t)\equiv\mu(1-\mu)\alpha(\gamma_D+\Delta-m_C) & \text{if } \dfrac{V-\Delta-m_D}{\beta}\le t\end{cases} \tag{13}$$

respectively. □

Proof of Lemma 1. 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 the upper bound of the support $(\overline{p}_D)$, 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 (m_C). The existence of this separating equilibrium is guaranteed since the upper bound of the price support of the dirty type $(\overline{p}_D=m_C-\Delta)$ is greater than its effective marginal cost $(\Delta\le m_C-\gamma_D)$. 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 $\pi_{NI,I}=\mu[\overline{p}_D-\gamma_D]$ for any price $p\in[\underline{p}_D,\overline{p}_D]$, and the dirty type of investing firm earns the same expected profit. Therefore, the lower bound of the mixed strategy price support is $\underline{p}_D = \mu\overline{p}_D + (1-\mu)\gamma_D$. The non-investing firm assigns probability mass μ to the upper bound $\overline{p}_D$ of its price support as it knows that the rival investing firm becomes clean with probabilityμ. 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 $\pi_{NI,I}$ viz. $[\mu + (1-\mu)(1-F_I(p))](p-\gamma_D) = (\overline{p}_D - \gamma_D)\mu$. This yields the probability distribution function of the dirty type of the investing firm

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

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 $\pi_{NI,I}$ viz. $(p-\gamma_D)(1-F_{NI}(p)) = (\overline{p}_D - \gamma_D)\mu$; this yields the probability distribution function of the non-investing firm $F_{NI}(p) = 1 - \mu((\overline{p}_D - \gamma_D)/(p-\gamma_D))$ where $F_{NI}(\overline{p}_D) = 1-\mu$ and $F_{NI}(\underline{p}_D) = 0$. □

Proof of Lemma 3. 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 $p_C \in [m_C, V+\Delta]$ which is always higher than the price charged by the dirty type. At the upper bound of the support $(\overline{P}_D)$, 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

$$\pi_D = [\mu + (1-\mu)(1-F_D(p))](p-\gamma_D). \tag{14}$$

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

$$(\overline{P}_D - \gamma_D)\mu = (p_C - \Delta - \gamma_D)\mu \tag{15}$$

which is identical to the equilibrium expected profit of the dirty type π_D. The lower bound of the support $\left(\underline{P}_D\right)$ 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 π_D. This implies $\underline{P}_D - \gamma_D = \pi_D = (p_C - \Delta - \gamma_D)\mu$. Therefore, the lower bound of the support is

$$\underline{P}_D = \mu[p_C - \Delta] + (1-\mu)\gamma_D. \tag{16}$$

Note that the equilibrium price distribution and the expected profit π_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 $[\mu + (1-\mu)(1-F_D(p))](p-\gamma_D)$; this is equal to π_D for every price $p \in \left[\underline{P}_D, \overline{P}_D\right]$ i.e., $[\mu + (1-\mu)(1-F_D(p))](p-\gamma_D) = (p_C - \Delta - \gamma_D)\mu$ (from (14) and (15)) which implies that

$$F_D(p) = 1 - \frac{\mu}{(1-\mu)}\left(\frac{p_C - \Delta - \gamma_D}{p-\gamma_D} - 1\right) \quad \text{where } F_D(p)$$

is continuous on $\left[\underline{P}_D, \overline{P}_D\right]$, $F_D\left(\underline{P}_D\right) = 0$, and $F_D(\overline{P}_D) = 1$. 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 as long as $p_C < V$. The incentive compatibility constraint of the dirty type and the clean type are $\mu/2(p_C - \gamma_D) \le (p_C - \Delta - \gamma_D)\mu$ and $\mu/2(p_C - m_C) \ge (p_C - \Delta - m_C)\mu$ respectively which imply $2\Delta + \gamma_D \le p_C \le 2\Delta + m_C$. To be more precise, $\max\{2\Delta + \gamma_D, m_C\} \le p_C < \min\{2\Delta + m_C, V\}$. The strategies and the out-of-equilibrium beliefs described above constitute a perfect Bayesian equilibriumwhich satisfies the incentive compatibility constraints of the clean and the dirty type iff $2\Delta + \gamma_D \le V$ i.e., $t \le (V - 2\Delta - m_D)/\beta$. If $t \le t^R - 2\Delta/\beta$ then the clean type charges its effective marginal cost m_C such that the firm loses its market power whereas if $t^R - 2\Delta/\beta \le t < (V - 2\Delta - m_D)/\beta$ then clean type charges $\gamma_D + 2\Delta$. At $t = (V - 2\Delta - m_D)/\beta$ the consumers ($(1-\alpha)$ fraction of all consumers) that are not environmentally conscious may not buy from the clean type since $p_C = V$. In other words, 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 $\pi_C = ((\alpha + \lambda(1-\alpha))\mu/2)(V - m_C)$ and that of the dirty type is $\pi_D = \mu(V - \Delta - \gamma_D)$ whereλ 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 $((\alpha + \lambda(1-\alpha))\mu/2)(V - \gamma_D) \le \mu(V - \Delta - \gamma_D)$ which implies $\lambda \le (2-\alpha)(V-\gamma_D) - 2\Delta/(1-\alpha)(V-\gamma_D)$. Similarly the clean type has no incentive to imitate the dirty type iff $\lambda \ge (2-\alpha)(V - m_C) - 2\Delta/(1-\alpha)(V - m_C)$. 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

$$\max\left\{0, \frac{(2-\alpha)(V-m_C)-2\Delta}{(1-\alpha)(V-m_C)}\right\} \le \lambda \le \min\left\{\frac{(2-\alpha)(V-\gamma_D)-2\Delta}{(1-\alpha)(V-\gamma_D)}, 1\right\} \tag{17}$$

The necessary and sufficient condition for the above restriction on λ to be satisfied is $(2-\alpha)(V-\gamma_D) > 2\Delta$. Thus (17) boils down to $(2-\alpha)(V-m_C)-2\Delta/(1-\alpha)(V-m_C) \le \lambda \le (2-\alpha)(V-\gamma_D)-2\Delta/(1-\alpha)(V-\gamma_D)$. The D1 equilibrium value of λ is $(2-\alpha)(V-\gamma_D)-2\Delta/(1-\alpha)(V-\gamma_D)$ and the equilibrium profit of the clean type and the dirty type are $\pi_C = \mu(V-\gamma_D-\Delta)/(V-\gamma_D)(V-m_C)$ and $\pi_D = \mu(V-\Delta-\gamma_D)$. If $t > (V-2\Delta-m_D)/\beta$ (in other words, when $p_C > V$) then 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 $\pi_C = \alpha\mu/2(p_C-m_C)$. The dirty type does not have any incentive to imitate the clean type as long as $\alpha\mu/2(p_C-\gamma_D) \le \mu(p_C-\Delta-\gamma_D)$ which implies that $p_C \ge 2\Delta/(2-\alpha)+\gamma_D$. Similarly, the clean type does not have any incentive to imitate the dirty type iff $\alpha\mu/2(p_C-m_C) \ge \mu(p_C-\Delta-m_C)$ and this incentive compatibility constraint of the clean type yields $p_C \le 2\Delta/(2-\alpha)+m_C$. The strategies along with the out of equilibrium beliefs constitute a perfect Bayesian equilibrium if and only if the price of the clean type $p_C \in (V, V+\Delta)$ satisfies the incentive compatibility constraints viz. $2\Delta(2-\alpha)+\gamma_D \le p_C \le 2\Delta/(2-\alpha)+m_C < V+\Delta$. If $(V-2\Delta-m_D)/\beta < t \le (V+\Delta-m_D)/\ \beta-2\Delta/\beta(2-\alpha)$ then the clean type charges a price $p_C = 2\Delta/(2-\alpha)+\gamma_D$ which is lower than its own full information price $(V+\Delta)$, all environmentally conscious consumers (α fraction of the consumers) buy with probability one. Finally, if $t \ge (V+\Delta-m_D)/\beta-2\Delta/\beta(2-\alpha)$ then the clean type charges its own full information monopoly price and even all environmentally conscious consumers may not buy. The incentive compatibility constraint of the dirty type is $\alpha\mu\eta/2(V+\Delta-\gamma_D) \le \mu(V-\gamma_D)$ where η is the fraction of environmentally conscious consumers that buy from the clean type. This implies that the equilibrium value ofη is $2(V-\gamma_D)/\alpha(V+\Delta-\gamma_D)$. □

Proof of Proposition 4. Depending on the relative values of the parameters, I have four different cases. Case 1: Suppose $\Delta < V-m_C < 2\Delta(2-\alpha) < 2\Delta$ i.e., $t^R-2\Delta/\beta \le \bar{t} \le (V-m_D)/\beta-2\Delta/\beta \le (V+\Delta-m_D)/\beta-2\Delta/\beta(2-\alpha) \le t^R$. The reciprocal incentive to invest in cleaner technology under incomplete information is given by

$$RI_{II} = \begin{cases} -\mu^2(m_C-\gamma_D-\Delta) < 0 & \text{if } t \le t^R - \dfrac{2\Delta}{\beta} \\ f_5(t) \equiv 2\mu\Delta - \left(\mu + \dfrac{\mu^2}{2}\right)(m_C-\gamma_D) & \text{if } t^R - \dfrac{2\Delta}{\beta} \le t \le \bar{t} \\ f_6(t) \equiv \mu\Delta - \dfrac{\mu^2}{2}(m_C-\gamma_D) & \text{if } \bar{t} \le t < \dfrac{V-m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ f_5(t) \equiv \mu\left[\dfrac{\mu(V-\gamma_D-\Delta)}{(V-\gamma_D)}(V-m_C) + (1-\mu)(V-\gamma_D-\Delta\right] & \text{if } t = \dfrac{V-m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ f_8(t) \equiv \mu\left[\dfrac{\mu\alpha}{2}\left(\gamma_D + \dfrac{2\Delta}{(2-\alpha)} - m_C\right) + (1-\mu)\dfrac{\alpha\Delta}{(2-\alpha)}\right] & \text{if } \dfrac{V-m_D}{\beta} - \dfrac{2\Delta}{\beta} < t \le \dfrac{V+\Delta-m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \\ f_9(t) \equiv \mu\left[\dfrac{\mu(V-\gamma_D)}{(V+\Delta-\gamma_D)}(V+\Delta-m_C) + (1-\mu)(V-\gamma_D)\right] & \text{if } \dfrac{V+\Delta-m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \le t \le t^R \end{cases} \tag{18}$$

Case 2: Suppose $V-m_C < \Delta < 2\Delta/(2-\alpha) < 2\Delta$. This implies that $t^R-2\Delta/\beta \le (V-m_D)/\beta-2\Delta/\beta \le \bar{t} \le (V+\Delta-m_D)/\beta-2\Delta/\beta(2-\alpha) \le t^R$.

$$RI_{II} = \begin{cases} -\mu^2(m_C-\gamma_D-\Delta) < 0 & \text{if } t \le t^R - \dfrac{2\Delta}{\beta} \\ f_5(t) \equiv 2\mu\Delta - \left(\mu + \dfrac{\mu^2}{2}\right)(m_C-\gamma_D) & \text{if } t^R - \dfrac{2\Delta}{\beta} \le t < \dfrac{V-m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ f_5(t) \equiv \mu\left[(V-m_C) - \dfrac{\mu(m_C-\gamma_D)}{(V-\gamma_D)}(V-\gamma_D-\Delta)\right] & \text{if } t = \dfrac{V-m_D}{\beta} - \dfrac{2\Delta}{\beta} \\ f_7(t) \equiv \mu\left[\left(1 + \dfrac{\mu\alpha}{2}\right)(\gamma_D-m_C) + \dfrac{2\Delta}{(2-\alpha)}\right] & \text{if } \dfrac{V-m_D}{\beta} - \dfrac{2\Delta}{\beta} < t \le \bar{t} \\ f_8(t) \equiv \mu\left[\dfrac{\mu\alpha}{2}\left(\gamma_D + \dfrac{2\Delta}{(2-\alpha)} - m_C\right) + (1-\mu)\dfrac{\alpha\Delta}{(2-\alpha)}\right] & \text{if } \bar{t} \le t \le \dfrac{V+\Delta-m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \\ f_9(t) \equiv \mu\left[\dfrac{\mu(V-\gamma_D)}{(V+\Delta-\gamma_D)}(V+\Delta-m_C] + (1-\mu)(V-\gamma_D)\right] & \text{if } \dfrac{V+\Delta-m_D}{\beta} - \dfrac{2\Delta}{\beta(2-\alpha)} \le t \le t^R \end{cases} \tag{19}$$

Case 3: Suppose $\Delta < 2\Delta/(2-\alpha) < V - m_C < 2\Delta$ which implies $t^R - 2\Delta/\beta \le \bar{t} \le (V-m_D)/\beta - 2\Delta/\beta \le t^R \le (V+\Delta-m_D)/\beta - 2\Delta/\beta(2-\alpha)$. The reciprocal incentive to invest is given by

$$RI_{II} = \begin{cases} -\mu^2(m_C-\gamma_D-\Delta) < 0 & \text{if } t \le t^R - \frac{2\Delta}{\beta} \\ f_5(t) \equiv 2\mu\Delta - \left(\mu + \frac{\mu^2}{2}\right)(m_C-\gamma_D) & \text{if } t^R - \frac{2\Delta}{\beta} \le t \le \bar{t} \\ f_6(t) \equiv \mu\Delta - \frac{\mu^2}{2}(m_C-\gamma_D) & \text{if } \bar{t} \le t < \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta} \\ f_5(t) \equiv \mu\left[\frac{\mu(V-\gamma_D-\Delta)}{(V-\gamma_D)}(V-m_C) + (1-\mu)(V-\gamma_D-\Delta\right]\Big) & \text{if } t = \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta} \\ f_9(t) \equiv \mu\left[\frac{\mu\alpha}{2}\left(\gamma_D + \frac{2\Delta}{(2-\alpha)} - m_C\right) + (1-\mu)\frac{\alpha\Delta}{(2-\alpha)}\right] & \text{if } \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta} < t \le t^R \end{cases} \tag{20}$$

Case 4: Finally $V - m_C \ge 2\Delta$ i.e., $t^R - 2\Delta/\beta \le \bar{t} \le t^R \le (V-m_D)/\beta - 2\Delta/\beta$. The reciprocal incentive to invest is given by

$$RI_{II} = \begin{cases} -\mu^2(m_C-\gamma_D-\Delta) < 0 & \text{if } t \le t^R - \frac{2\Delta}{\beta} \\ f_5(t) \equiv 2\mu\Delta - \left(\mu + \frac{\mu^2}{2}\right)(m_C-\gamma_D) & \text{if } t^R - \frac{2\Delta}{\beta} \le t \le \bar{t} \\ f_6(t) \equiv \mu\Delta - \frac{\mu^2}{2}(m_C-\gamma_D) & \text{if } \bar{t} \le t \le t^R \end{cases} \tag{21}$$

Technical version of Proposition 9 (ii): Both firms invest in the equilibrium under incomplete information but not under full information

Case 1:

$$\text{if } f \le f_5(t) \quad \text{when } t^R - \frac{2\Delta}{\beta} \le t \le \bar{t}$$
$$\text{if } f_2(t) < f \le f_6(t) \quad \text{when } \bar{t} \le t \le \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta}$$
$$\text{if } f_2(t) < f \le f_8(t) \quad \text{when } \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta} \le t \le \frac{V-m_D}{\beta} - \frac{\Delta}{\beta}$$
$$\text{if } f_4(t) < f \le f_8(t) \quad \text{when } \frac{V-m_D}{\beta} - \frac{\Delta}{\beta} \le t \le \frac{V+\Delta-m_D}{\beta} - \frac{2\Delta}{\beta(2-\alpha)}$$
$$\text{if } f_4(t) < f \le f_9(t) \quad \text{when } \frac{V+\Delta-m_D}{\beta} - \frac{2\Delta}{\beta(2-\alpha)} \le t \le t^R$$

Case 2:

$$\text{if } f \le f_5(t) \quad \text{when } t^R - \frac{2\Delta}{\beta} \le t \le \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta}$$
$$\text{if } f \le f_7(t) \quad \text{when } \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta} \le t \le \bar{t}$$
$$\text{if } f_2(t) < f \le f_8(t) \quad \text{when } \bar{t} \le t \le \frac{V-m_D}{\beta} - \frac{\Delta}{\beta}$$
$$\text{if } f_4(t) < f \le f_8(t) \quad \text{when } \frac{V-m_D}{\beta} - \frac{\Delta}{\beta} \le t \le \frac{V+\Delta-m_D}{\beta} - \frac{2\Delta}{\beta(2-\alpha)}$$
$$\text{if } f_4(t) < f \le f_9(t) \quad \text{when } \frac{V+\Delta-m_D}{\beta} - \frac{2\Delta}{\beta(2-\alpha)} \le t \le t^R$$

Case 3:

$$\text{if } f \le f_5(t) \quad \text{when } t^R - \frac{2\Delta}{\beta} \le t \le \bar{t}$$
$$\text{if } f_2(t) < f \le f_6(t) \quad \text{when } \bar{t} \le t \le \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta}$$
$$\text{if } f_2(t) < f \le f_8(t) \quad \text{when } \frac{V-m_D}{\beta} - \frac{2\Delta}{\beta} \le t \le \frac{V-m_D}{\beta} - \frac{\Delta}{\beta}$$

$$\text{if } f_4(t) < f \le f_8(t) \quad \text{when } \frac{V-m_D}{\beta} - \frac{\Delta}{\beta} \le t \le t^R$$

Case 4:

$$\text{if } f \le f_5(t) \quad \text{when } t^R - \frac{2\Delta}{\beta} \le t \le \bar{t}$$

$$\text{if } f_2(t) < f \le f_6(t) \quad \text{when } \bar{t} \le t \le \frac{V-m_D}{\beta} - \frac{\Delta}{\beta}$$

$$\text{if } f_4(t) < f \le f_6(t) \quad \text{when } \frac{V-m_D}{\beta} - \frac{\Delta}{\beta} \le t \le t^R$$

Cost reversal case: I consider the case when the anticipated liability is high $\left(t \ge t^R\right)$ i.e., the effective marginal cost of the dirty type is higher than that of the clean type $(\gamma_D \ge m_C)$.[27] When consumers are completely aware of the environmental impact of firms then the clean type has competitive advantage over the dirty type; thus, the dirty type cannot sell anything. This implies that under full information a firm has a strategic incentive to invest in cleaner technology when the anticipated liability is high. Under incomplete information, if only one firm invests then there does not exist any separating equilibrium in the second stage pricing game; the non-investing firm as well as the investing firm charge effective marginal cost of the dirty type, and the investing firm captures the entire market. The ex ante expected profit of an investing firm is equal to $(\gamma_D - m_C)$ which implies that a firm has a unilateral incentive to invest. When both firms invest then the dirty type charges its effective marginal cost whereas the clean type randomizes over a price range $p \in [\underline{P}_C, \gamma_D]$ with a continuous distribution function $F_C(p)$ where $\underline{P}_C = m_C + (1-\mu)(\gamma_D - m_C)$ and

$$F_C(p) = 1 - \left(\frac{1-\mu}{\mu}\right)\left(\frac{\gamma_D - m_C}{p - m_C} - 1\right).$$

This symmetric Bayesian equilibrium is supported by the following out-of-equilibrium beliefs of the consumers: if a firm charges any price $p > \gamma_D$ 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. The ex ante expected profit of an investing firm (when the rival invests) is given by $\mu(\gamma_D - m_C)$; this implies that a firm has a strictly positive reciprocal incentive to invest under higher anticipated liability. □

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[27] Note that irrespective of the level of liability the effective marginal cost of the dirty type exceeds that of the clean type if cleaner technology is cheaper i.e., $m_C < m_D$.