Investment in Cleaner Technology and Signaling Distortions in a Market with Green Consumers.

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Abstract

I analyze the pricing and investment behavior of a firm that signals the environmental attribute of its production technology through its price to uninformed environmentally conscious consumers. I then analyze the effect of change in environmental regulation on the signaling outcome and the firm's *ex ante* incentive to invest in cleaner technology. When regulation is weak, a firm signals cleaner technology through higher price and in this case, the firm earns lower profit when it has cleaner technology and has no incentive to invest in cleaner technology. The price charged by the clean firm declines sharply beyond a critical level of regulation. When regulation is sufficiently stringent, the firm with cleaner technology charges lower price but earns higher signaling profit, and *ex ante* the firm has positive incentive to invest in cleaner technology. With weak regulation, the incentive of the firm to directly disclose its environmental performance rather than signal it through price (signaling distortion of profit) is increasing in the level of regulation, but the opposite holds when regulation is sufficiently stringent.

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1 Introduction

The willingness of environmentally conscious or "green" consumers to pay more for goods produced with lower environmental damage[1], and the market incentives it generates for firms, have received considerable attention in recent years. One can view this as an important social mechanism that disciplines the negative environmental externalities created by rent seeking firms and is therefore complementary to environmental regulation by public authorities. The efficacy of consumer consciousness is, however, constrained by the fact that consumers often do not have sufficient information about the environmental attributes of the production technology of firms. Some information is provided through ecolabeling[2] and other certification intermediaries as well as the fact that firms are in compliance with government regulations; it is, however, fair to say that such information often pertains to only certain specific kinds of environmental damage and remains significantly limited relative to the environmental concerns of consumers. Even if regulatory authorities succeed in gathering better information about the actual environmental performance of firms and make it publicly accessible,[3] such information may not always percolate down to individual consumers. This gap between consumer concern and the availability of information is likely to increase in the future with increase in environmental consciousness.

In situations where direct credible communication of environmental performance to consumers is too costly, product prices and other market variables play an important role in signaling the environmental performance of firms. Signaling often requires firms to distort their actions in order to convince consumers that such actions could only be taken by a firm that has a certain type of technology. Thus, the market outcome and the profit of the firms in a signaling outcome can differ significantly from the full information economy. The signaling incentives of firms and in particular, the extent of signaling distortions, are influenced by environmental regulations that modify the private production cost associated with different types of technology through pollution taxes, emission permits, liability of actual damage etc. Like consumer consciousness (and perhaps related to it), the stringency of environmental regulation has been increasing over time. It is important to understand how changes in the level of environmental regulation affects the incentive to signal and the signaling outcome in the market. Further, with

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

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

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

uninformed green consumers, the *ex ante* incentive of a firm to invest in cleaner technology ultimately depends on the difference in profitability of clean and dirty technology as generated in the signaling outcome which, in turn, is influenced by environmental regulation. This effect of environmental regulation on investment in cleaner technology that works through signaling outcomes deserves clear understanding. This paper attempts to address these issues systematically in a simple framework.

In particular, I consider a monopoly where environmentally conscious consumers are uninformed about the environmental damage caused by the production process of the firm.[4] A firm signals the environmental attribute of its production technology which is either *clean* or *dirty* to uninformed green consumers through its price.[5] I treat regulation as exogenous and abstract from information problems between the regulator and the firm.[6] I use this framework to understand how changes in regulation may influence the incentive of a firm with market power to invest in the development of less damaging environmental production process.

In a monopoly market that is not subject to any environmental regulation, Mahenc (2007, 2008) shows that better environmental quality is signaled by higher price, if the marginal production cost is relatively higher for the clean type. In this paper, I show that this continues to hold when the industry is subject to environmental regulation, but regulation is "weak". However, under significantly higher level of environmental regulation, the firm may use a *lower* price to signal its clean technology. This part of the analysis is closely related to quality-signaling games considered in the industrial organization literature (see, for instance, Bagwell and Riordan, 1991). However, unlike much of the quality-signaling literature, in my framework, 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".[7]

An important contribution of this paper is that it brings out the effect of environmental regulation on its price used to signal various levels of environmental performance that, in turn, influences market power, profitability, and consumer surplus. The fact that consumers are uninformed about the actual environmental performance of the firm though they are willing to pay more for the product produced by a clean technology, creates an incentive for the firm to act differently from the way it would have behaved under full information. In particular, when the firm is of clean type it may need to charge a price different from its full information

[4] Even if public regulation takes the form of emission permit or tax, information about the actual trades or tax payments by the firm may not be available to consumers.

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

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

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

monopoly price in order to convince consumers that it is not of dirty type; it could do so by charging a price that would never be optimal had the firm been of a dirty type (with a different effective marginal cost of production) even if consumers were fooled into believing that the firm was clean. This deviation from the full information monopoly price by the firm when it is of the clean type is the *price distortion due to signaling* which in turn generates *profit distortion due to signaling*. The extent and nature of price distortion depends, among other things, on the difference in effective marginal cost of production of clean and dirty types and the latter, in turn, depends on the extent of regulation. This allows me to examine the effect of change in regulation on price distortion and also profit distortion due to signaling.

I find that there is no price or profit distortion due to signaling when the level of environmental regulation is either very low or very high. However, in an intermediate range of regulation there is signaling distortion. Further, within this range, there is a critical level of regulation such that the clean type charges higher price compared to its full information price if the level of regulation is below the critical level. Below the critical level, increase in regulation increases the extent of price distortion due to signaling which, loosely speaking, increases the *loss* of both consumer and producer surplus. However, as regulation increases beyond the critical level, there is a downward jump in the clean firm's signaling price to a level below its full information monopoly price which reduces market power and increases consumer welfare. Price distortion and profit distortion decline as regulation is increased beyond the critical level. My analysis sheds light on a possible beneficial effect of increasing regulation that can act through reduction in both price and profit distortion and market power under incomplete information and result in increase of consumer welfare. Note that this effect is entirely independent of any beneficial effect that regulation has through changes in the environmental externality caused by the firm.

The profit distortion due to signaling reflects the incentive of the firm to move, if possible, to a world of full information through direct and credible disclosure to consumers. The effect of increase in regulation on the extent of profit distortion therefore establishes an interesting relationship between environmental regulation and the incentive for direct disclosure of environmental performance through an eco-label (or other third party certification) as well as its incentive to lobby for imposition of mandatory disclosure regulation. When regulation is weak, firms have greater incentive for direct disclosure when environmental taxes or other regulations become more stringent; but once the level of regulation goes beyond a critical level, further increase in regulation will only reduce this incentive (and firms will be more likely to stay with the signaling outcome).

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

To the best of my knowledge, the existing literature contains no analysis of the relationship between environmental regulation, signaling of environmental attribute of technology to green consumers through price, and their relation to the incentive of a firm to invest in cleaner technology. I show that even though green consumers are willing to pay more for the product of a *clean* firm and even when the cost of investment is arbitrarily small, a monopolist has no incentive to invest in cleaner technology if regulation is not strong enough. However, if regulation exceeds a critical level, higher regulation increases the effectiveness of consumer consciousness and creates incentive to invest in the development of potentially cleaner technology. This provides theoretical support for the principal claim of the celebrated Porter Hypothesis i.e., "stringent regulation can actually produce greater innovation" (Porter (1991); Porter and van der Linde (1995)). Further, I discuss how the incentive of a firm to invest in cleaner technology changes with the level of environmental regulation and provide a numerical example to illustrate the effect of regulation on this incentive.

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

2 Signaling environmental quality through price

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

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

Note that here the type of the firm i.e., whether its production technology is clean or dirty is given, and it is known to the firm but not to consumers. The firm produces output 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.,

$$0 < m_D < m_C.$$

Emission in the industry is regulated with the firm being required to purchase emission permit from a competitive emission permit market at an exogenously given price t. Here emission is a proxy for any kind of environmental damage, and the emission price (t) 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 required to pay a penalty or damage compensation by a court of law in the future, and the emission price would then capture the future expected liability payments.[8] 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. The valuation (maximum willingness to pay) of a consumer for a unit of the product depends on the firm's actual emission e per unit of output and is given by:

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

where $A > 1$, and ρ is a consumer specific environmental consciousness index that is distributed *uniformly* on an interval $[0, \overline{\rho}]$. The valuation for the product consists of two parts; the intrinsic valuation of the product is exactly equal to 1 for all consumers whereas the second component given by $\rho(A - \frac{e}{\beta_D})$ depends on the level of environmental consciousness of the consumer (ρ) and the actual emission of the firm ($e = \beta_C, \beta_D$). Observe that for any ρ,

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

i.e., a consumer with any level of environmental consciousness values a product produced by a firm of clean type more than that of the dirty type and are willing to pay a price premium of $\rho(1 - \frac{\beta_C}{\beta_D})$ for the product produced by a clean type. Note that this price premium depends on the the level of environmental consciousness specific for the consumer and it varies from 0 to $\overline{\rho}(1 - \frac{\beta_C}{\beta_D})$. Further, I assume that $V(\beta_C, \rho) > X_C$ and $V(\beta_D, \rho) > X_D$. The heterogeneity among consumers generates downward sloping true demand for a product

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

[8] 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.

The demand for the dirty firm's product is more elastic than that of the clean one because of the price premium (see Figure 1). I assume the following

$$\frac{\beta_C}{\beta_D} < \frac{(1+\overline{\rho}(A-1)-m_C)}{(1+\overline{\rho}(A-1)-m_D)} \qquad \text{(Assumption 1)}$$

to ensure that the marginal cost of a firm is always less than the choke price. Consumers are not aware of the actual environmental performance of a firm (or the trades in the emission permit market). *Ex ante,* consumers believe that the firm is of clean (C) type with probability $\mu \in (0,1)$ and of dirty (D) type with probability $(1-\mu)$.

The *full information equilibrium* monopoly price for a firm of clean type (which produces at effective marginal cost of X_C) is given by

$$P_C^{FI} = \frac{1}{2}\left[1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})+X_C\right],$$

whereas, if it is of dirty type (with effective marginal cost of X_D) then the full information equilibrium monopoly price is

$$P_D^{FI} = \frac{1}{2}\left[1+\overline{\rho}(A-1)+X_D\right].$$

The following assumption ensures that the full information monopoly price at no regulation ($t=0$) is greater than the lowest price 1

$$\overline{\rho}\,(A-1)+m_D > 1; \qquad \text{(Assumption 2)}$$

this also guarantees the existence of separating equilibrium (see Lemma 1 in Appendix).

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

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.,

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

At any emission price $t < t^R$, the effective marginal cost of a clean type is strictly higher than that of a dirty type whereas the relative cost structure gets reversed at any emission price $t > t^R$.

In the rest of the paper, I will refer any emission price $t < t^R$ and $t > t^R$ as low and high emission price respectively; these will also correspond to weak and strong regulation respectively.

2.1 Low emission price: Clean type has higher effective cost of production

For any emission price $t \leq t^R$, the effective marginal cost of a clean type is higher than that of a dirty type $(X_C \geq X_D)$, and I find that in the unique separating equilibrium[9] high price signals environment friendly production process.

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

In a separating equilibrium, where the type of the firm is always revealed, if the firm is of a dirty type it will always charge its full information monopoly price. Note that for any emission price $t \leq t^R$, the full information monopoly price of a dirty type is lower than that of the clean type; the difference in prices depends on the difference between the effective marginal costs of the clean type and the dirty type which in turn varies with the level of emission price. If dirty type imitates the higher price charged by the clean type, it will fool consumers into believing that the product is actually being sold by a clean type and therefore, will face a higher market demand. However, as the full information monopoly price of the clean type is higher, despite the fact that the demand curve for the clean product is higher, the actual quantity sold at that price may be lower than what the dirty type sells at its full information monopoly price (with consumer knowing that its a dirty firm). This trade-off between imitating a higher price and selling lower quantity determines the incentive of the dirty type to imitate. The higher the clean firm's price is relative to the dirty type's full information monopoly price the less is the quantity sold by imitating the clean type's high price. If the difference is large enough there is an incentive to imitate. More importantly, as the dirty type has a lower marginal cost of production, it is more interested (than the cleaner type) in selling high quantity at lower price rather than lower quantity at higher price. Further, lower the difference in marginal cost between the two types, the smaller the relative incentive of the dirty type to charge higher price.

Under significantly lower emission price, the large difference in the effective marginal costs implies significant difference in the full information monopoly prices of the clean and the dirty

[9] In the separating equilibrium, a clean type must charge a price such that after observing the price consumers believe that it is a clean type with probability one; in other words, consumers should be convinced that a dirty type will not charge such a price as it is not profitable for the dirty type to do so.

type. If the dirty type imitates the clean type's action i.e., charges full information monopoly price of the clean type then the dirty type (with relatively lower effective marginal cost) sells lower quantity and earns lower profit compared to what it would have earned if it charges its own full information monopoly price. In that case, the dirty type does not have any incentive to imitate the clean type. Therefore, in the separating equilibrium a firm of clean type charges its own full information monopoly price when the emission price is below a critical level.

An increase in the level of emission price reduces the gap between the effective marginal costs of both types which implies that the difference between full information monopoly prices of the clean type and the dirty type becomes smaller; this, in turn, increases the incentive of the dirty type to imitate the clean type. In other words, if the dirty type imitates the clean type's higher price-lower quantity combination then it earns higher profit compared to the profit it earns when it charges its own full information monopoly price. Therefore, in order to convince the consumers and deter the dirty type from imitating its higher price-lower quantity combination, the clean type charges a higher price than its own full information monopoly price; this deviation by the clean type from its own full information monopoly price is referred as *upward signaling distortion*.

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

As mentioned in the Section 1, in the absence of any environmental regulation, Mahenc (2007, 2008) shows that higher price always signals better environmental quality of a monopolist. In my framework, a monopolist behaves in the same manner as long as the emission price is below the critical level i.e., $t \leq t^R$.

2.2 High emission price: Clean type has lower effective cost of production

Recall that at any emission price $t \geq t^R = \frac{m_C - m_D}{\beta_D - \beta_C}$ which is referred as high emission price, the effective marginal cost of a clean type is relatively lower than that of the dirty firm $(X_C \leq X_D)$; this contradicts the standard assumption (i.e., a clean type has higher marginal cost). In this case, the difference between the effective marginal cost of the clean type and the dirty type increases and thus, the incentive of the dirty type to imitate the clean type decreases with increase in the emission price.

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

First, note that Proposition 2 contrasts sharply existing results in the literature that suggest that higher price always signal better environmental performance. In the separating equilibrium, if a firm is of dirty type it cannot do better than charging its own full information monopoly price at any emission price $t \geq t^R$. Consider an emission price which is moderately high i.e., though the effective marginal cost of the clean type is lower than that of the dirty type, the gap between the full information monopoly price of the dirty type and the clean type is small enough to create an incentive for the dirty type to imitate the clean type's action. In this case, since the effective marginal cost of a dirty type is more than that of a clean type ($X_D \geq X_C$), a clean firm cannot reveal its type by charging a higher price relative to the price charged by the dirty type. Rather, in the separating equilibrium, a clean type prefers to sell a higher quantity and charges a price lower than its own full information monopoly price; this deviation by the clean type is known as *downward signaling distortion*. On the other hand, increase in the emission price beyond a critical level increases the gap between the effective marginal costs of both types which in turn reduces the incentive of the dirty to type to imitate clean type's price. In this case, if the firm is of clean type it charges its full information monopoly price which is lower than that of the full information monopoly price of the dirty type (as the effective marginal cost is higher for the clean type compared to the dirty type).

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

2.3 Signaling distortion and welfare effects

From the above discussion one can conclude that a monopolist signals its environmental performance to consumers through price, and the choice of signaling equilibrium price depends on the level of emission price. The fact that consumers are uninformed about the actual environmental performance of the firm though they are willing to pay more for the product produced by a clean technology creates an incentive for the firm to act differently from the way it would have behaved under full information. In particular, if a firm is of clean type it chooses a price in the fully revealing equilibrium such that if the firm were of a dirty type it would not have charged the same price; thus, the firm can convince the consumers of its actual environmental performance by choosing the optimal price. However, for a certain range of emission price the incentive of the dirty type to imitate the clean type's action is quite high and the clean type charges a price which is not equal to its own full information monopoly price. This deviation from the full information monopoly price by the firm when it is of the clean type is known as signaling distortion. The extent and nature of signaling distortion depends, among other things, on the difference in effective marginal cost of production and the latter, in turn, depends on the extent of regulation.

Recall that for any emission price $t \leq t^R$ the effective marginal cost of the clean type is higher than that of the dirty type and is lower otherwise. The following proposition and Figure 2 summarize the effect of increase in the level of emission price on the signaling behavior of a monopolist.

Proposition 3 *(i) There exists a critical level of emission price t^U such that at any emission price $t \in [t^U, t^R]$, the clean type charges a higher price compared to its own full information monopoly price to signal its environmental performance (i.e., there is* upward signaling distortion*).*
(ii) There exists a critical emission price t^D such that at any $t \in [t^R, t^D]$, a clean firm charges a price which is lower than its own full information monopoly price to signal its environmental performance (i.e., there is downward signaling distortion*).*
(iii) If the emission price is significantly low $\left(i.e., t \leq t^U\right)$ or high $\left(i.e., t \geq t^D\right)$, then there is no signaling distortion*, and the market outcome is as under full information.*

Proof. See Appendix. ■

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

To show the monotonicity of the measure of price distortion due to signaling I assume that

$$A - 1 > \frac{1}{\left(1 - \frac{\beta_C}{\beta_D}\right)^2}, \qquad \text{(Assumption 3)}$$

and this assumption will be maintained in the rest of this section. Note that $\frac{\beta_C}{\beta_D}$ is the ratio of environmental damage (emission) per unit of output caused by the clean type and the dirty type firm. Assumption 3 implies that the demand is sufficiently large compared to the relative environmental damage caused by the clean type and the dirty type.

Proposition 4 *When the emission price is low* $\left(t^U \leq t \leq t^R \text{ i.e., weak regulation}\right)$*, the extent of upward signaling distortion* (*the absolute value of* Δ_P) *in the separating equilibrium increases with an increase in emission price* (*i.e., increase in regulation*)*. On the other hand, when the emission price is high* $\left(t^R \leq t \leq t^D \text{ i.e., strong regulation}\right)$*, the extent of downward signaling distortion* (*the absolute value of* Δ_P) *in the separating equilibrium decreases with an increase in emission price* (*i.e., increase in regulation*)*.*

Proof. See Appendix. ■

In Figure 3, the upward sloping curve of broken-line denotes the full information monopoly price of the clean type whereas the curve with solid-line depicts the equilibrium price charged by the clean type in the signaling equilibrium. The two curves converge for any emission price $t \leq t^U$ and $t \geq t^D$ which implies that there is no signaling distortion. However, at any emission price $t^U \leq t \leq t^R$ the curve of broken line is below the solid line curve which represents upward signaling distortion whereas downward signaling distortion by the clean type is depicted over a higher range of emission price viz., $t^R \leq t \leq t^D$. It is evident from the Figure 3 that the extent of upward price distortion due to signaling i.e., the distance between two curves increases as emission price increases whereas the measure of downward price distortion due to signaling decreases as the two curve comes closer to each other with increase in regulation. Observe that exactly at emission price $t = t^R$ there is a discontinuity or downward jump in the signaling equilibrium price of the clean type. This implies that in the signaling equilibrium the clean type charges a price either less than or more than its full information monopoly price.

Let Δ_π be the measure of profit distortion due to signaling i.e., the difference between signaling distortion profit and the full information profit of the clean type. Note that full information profit of the clean type is always atleast as large as the profit earned by the clean type firm in the separating equilibrium i.e., $\Delta_\pi \leq 0$; further, for any $t \in \left[t^U, t^R\right]$ the absolute value of Δ_π increases with increase in the level of emission price; whereas, for any $t \in [t^R, t^D]$, and the absolute value of Δ_π decreases with regulation.

Proposition 5 *When the emission price is low* $\left(t^U \leq t \leq t^R \text{ i.e., weak regulation}\right)$*, the extent of upward signaling distortion of profit* (*the absolute value of* Δ_π) *in the separating equilibrium increases with an increase in emission price* (*i.e., increase in regulation*)*. On the other hand, when the emission price is high* $\left(t^R \leq t \leq t^D \text{ i.e., strong regulation}\right)$*, the extent of downward signaling distortion of profit* (*the absolute value of* Δ_π) *in the separating equilibrium decreases with an increase in emission price* (*i.e., increase in regulation*)*.*

Proof. See Appendix. ■

Observe that loss in profit due to signaling through price creates an incentive for the clean type to directly and credibly disclose its environmental performance through an eco-label or other third party certification. The extent of profit distortion due to signaling can be interpreted as the maximum amount that a clean type firm is willing to spend to acquire such an eco-label. Proposition 5 illustrates that under weak regulation the incentive to acquire an eco-label increases with regulation, on the other hand, when the level of regulation is significantly strong it decreases with an increase in the emission price. The presence of profit distortion due to signaling also increases the incentive of a clean type to lobby for mandatory disclosure of the environmental performance of a firm. It is evident from Proposition 5 that when the emission price is low i.e., $t^U \leq t \leq t^R$ the clean type's incentive to lobby for compulsory disclosure increases whereas it decreases with increase in emission price when the regulation is stringent i.e., $t^R \leq t \leq t^D$.

This paper is silent about the normative question of optimal environmental regulation since environmental damage is not explicitly modeled. However, it is possible to study how change in the level of exogenously given level of regulation affects market power of the clean type and consumer surplus.

Table 1

Emission Price	$t \leq t^U$	$t^U \leq t \leq t^R$	$t^R \leq t \leq t^D$	$t \geq t^D$
Consumer Surplus	Decreases	Decreases	Decreases	Decreases
Market Power	Decreases	Increases	Decreases	Decreases
Producer Surplus	Decreases	Increases	Decreases	Decreases

Table 1 summarizes the effect of increase in the emission price on consumer surplus, producer surplus, and market power of the clean type. Consumer surplus decreases as signaling equilibrium price increases with increase in the level of regulation (except in the neighborhood of the emission price $t = t^R$). Market power and producer surplus increase with regulation only when the clean type charges a price above its full information price and decrease otherwise.

Observe that if the level of environmental regulation shifts from an emission price $t = t^R - \epsilon$ to $t = t^R + \epsilon$ where $\epsilon > 0$ and infinitesimally small, then the signaling equilibrium price of a clean type falls, market power and producer surplus decrease, and consumer surplus increases. In Figure 3, if the emission price increases from t_0 to t_1 then signaling equilibrium price of the clean type falls down from p_0 to p_1; as a result, the consumer surplus increases, and market power as well as producer surplus decrease. This is perhaps the most striking result as it contradicts the standard belief that more stringent regulation worsens consumer welfare and helps rent seeking firm to gain more market power. In particular, an increase in the emission price affects the signaling behavior of a monopolist where the consumers are not aware of the actual environmental performance of the firm and this, in turn, may increase the well being of consumers.

3 Effect of environmental regulation on the incentive to invest

Suppose that a firm is initially endowed with a dirty production technology i.e., it produces β_D units of emission per unit of output and incurs a post-regulation marginal cost of $X_D = m_D + t\beta_D$, where m_D is the unit cost of production, and t is the exogenously given emission price. Before going in to production, the firm decides whether or not to undertake a project to develop cleaner technology. If it decides to undertake the project, it has to incur (an exogenously fixed amount) $f > 0$ as cost of investment. If undertaken, the project is successful with probability $\mu \in (0, 1)$ in which case it leads to development and adoption of a *clean* production technology; however, the project is unsuccessful and the technology remains *dirty* with probability $(1 - \mu)$. If a firm does not invest then it incurs zero investment cost and remains *dirty* for sure. If investment leads to clean technology, the firm emits $\beta_C < \beta_D$ per unit of output incurring a post-regulation marginal cost of $X_C = m_C + t\beta_C$, where m_C is the unit cost of production. I assume that if the realized outcome is a clean production technology then the firm always uses that technology.[10] As described in section 2, there is a unit mass of risk neutral consumers with unit demand; the valuation of a consumer for per unit of the product, true demand for the product are given by (1) and (2) respectively.

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

If the effective marginal cost of the dirty type is lower than the clean type i.e., $X_D < X_C$ then in the signaling equilibrium the dirty type (which charges its own full information monopoly price) earns higher profit than the profit earned by the dirty type if it imitates the higher price and lower quantity of the clean type; otherwise, the dirty type will always imitate the clean type. The market profit of the dirty type if it imitates the clean type is always larger relative to that of the clean type as the effective marginal cost of the dirty is lower than the clean type. Therefore, in this case, a firm has no incentive to invest in development of clean technology since

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

the dirty type always earn higher profit than the clean type; this continues to hold even if the cost of investment is zero. However, if the cost structure is reversed i.e., $X_D > X_C$, then the clean type earns higher profit in the separating equilibrium. Therefore, under strong regulation when the effective marginal cost of the clean type is higher than the dirty type, a firm endowed with dirty technology has an incentive to invest in clean technology. Observe that for any $t > t^R$ (which implies $X_D > X_C$) as emission price increases, the difference between profits earned by a clean type and a dirty type decreases.

Proposition 6 *(i) If the emission price $t \leq t^R = \frac{m_C - m_D}{\beta_D - \beta_C}$ i.e., regulation is weak, a firm does not invest in cleaner technology (no matter how small the cost of investment f).*
(ii) At any emission price $t > t^R = \frac{m_C - m_D}{\beta_D - \beta_C}$ i.e., if regulation is strong, and in addition, the cost of investment f is not too large, then the firm invests in development of clean production technology.

Proof. See Appendix. ■

The fact that at significantly higher level of regulation $\left(t > t^R\right)$ the monopolist does have an incentive to invest in cleaner technology confirms the fundamental claim of famous Porter Hypothesis that "stringent regulation" induces "innovation".

The incentive to invest in cleaner technology is measured by the difference in the expected profit earned by the firm if it invests in cleaner technology and the profit earned by the firm if it does not invest and thus remains dirty. Let Δ_I denote the measure of the incentive to invest in cleaner technology under incomplete information. For any emission price $t \in \left[t^R, t^D\right]$,

$$\begin{aligned}\Delta_I &= \mu\pi_C^L + (1-\mu)\,\pi_D^{FI} - \pi_D^{FI} \\ &= \mu\left(\pi_C^L - \pi_D^{FI}\right)\end{aligned}$$

where π_C^L is the profit earned by the clean type and π_D^{FI} is the (full information) profit earned by the dirty type in the separating equilibrium. Further, Δ_I can be decomposed as follows

$$\begin{aligned}\Delta_I &= \mu\left(\pi_C^L - \pi_C^{FI}\right) + \mu(\pi_C^{FI} - \pi_D^{FI}) \\ &= \mu\left(\Delta_\pi + \Delta_\pi^{FI}\right)\end{aligned}$$

where π_C^{FI} is the profit earned by the clean type under full information, $\Delta_\pi = \pi_C^L - \pi_C^{FI}$ is the profit distortion due to signaling discussed at the end of Section 2, and $\Delta_\pi^{FI} = \pi_C^{FI} - \pi_D^{FI}$ is the measure of incentive to invest in cleaner technology under full information; profit distortion due to signaling is negative at any emission price i.e., $\Delta_\pi < 0$, but when the regulation is strong $\left(t \in \left[t^R, t^D\right]\right)$ the incentive to invest in cleaner technology under full information is positive i.e., $\Delta_\pi^{FI} > 0$. The following expression represents the effect of regulation on the incentive to invest in cleaner technology:

$$\frac{\partial \Delta_I}{\partial t} = \mu \left(\frac{\partial \left(-\Delta_\pi\right)}{\partial t} + \frac{\partial \Delta_\pi^{FI}}{\partial t} \right).$$

Proposition 5 illustrates that for any emission price $t \in \left[t^R, t^D\right]$ the absolute value of profit distortion due to signaling decreases with an increase in emission price i.e., $\frac{\partial(-\Delta_\pi)}{\partial t} < 0$. The effect of the increase in the level of regulation on the measure of incentive to invest in cleaner technology under full information is given by

$$\frac{\partial \Delta_\pi^{FI}}{\partial t} = \beta_D q_D^{FI} - \beta_C q_C^{FI}$$

which implies that

$$\frac{\partial \Delta_\pi^{FI}}{\partial t} \gtreqless 0 \text{ iff } \frac{\beta_D}{\beta_C} \gtreqless \frac{q_C^{FI}}{q_D^{FI}}.$$

Note that $\frac{\beta_D}{\beta_C}$ reflects the relative emission by the dirty type and the clean type. The emission per unit of output by the dirty type is greater than that of the clean type i.e.,$\frac{\beta_D}{\beta_C} > 1$; further, dirty type emits significantly more than the clean type then this ratio $\frac{\beta_D}{\beta_C}$ is large whereas it is close to one if the difference in emission per unit of output is not significant. For any emission price $t \in \left[t^R, t^D\right]$, the equilibrium output produced by a clean type is greater than that of the dirty type under full information i.e., $q_C^{FI} > q_D^{FI}$ and therefore, the ratio $\frac{q_C^{FI}}{q_D^{FI}}$ is also greater than one. Observe that if the elasticities of the demand curves for the dirty type and the clean type are similar and (or) the difference in the effective marginal costs is small, then the ratio of equilibrium quantities produced by the clean type and the dirty type in the full information equilibrium $\left(\frac{q_C^{FI}}{q_D^{FI}}\right)$ is likely to be smaller than the relative emission by the dirty type and the clean type $\left(\frac{\beta_D}{\beta_C}\right)$ such that the incentive to invest goes up with increase in the emission price i.e., $\frac{\partial \Delta_\pi^{FI}}{\partial t} > 0$. On the other hand, if the demand elasticities are significantly different and (or) the cost difference is large then the ratio of full information quantities $\left(\frac{q_C^{FI}}{q_D^{FI}}\right)$ is more likely to be greater than the relative emission intensity of the dirty and the clean type $\left(\frac{\beta_D}{\beta_C}\right)$ and thus, the measure of the incentive to invest in cleaner technology of a firm under full information decreases with regulation i.e., $\frac{\partial \Delta_\pi^{FI}}{\partial t} < 0$. Therefore, for any emission price $t \in \left[t^R, t^D\right]$, the effect of increase in emission price on the incentive to invest in cleaner technology under incomplete information remains ambiguous as it depends on the net effect of increase in emission price on profit distortion due to signaling and on the incentive to invest under full information. Note that, for any emission price $t > t^D$, change in the incentive of a firm to invest in cleaner technology with increase in regulation is identical to that of the full information case as the clean type charges its own full information monopoly price.

I provide the following numerical example to illustrate the above discussion of the effect of increase in emission price on the incentive to invest

Example 1 Let assign values to the parameters as follows: $A = 20$, $\beta_C = 0.1, \beta_D = 0.2, m_C = 0.5, m_D = 0.4$, and $\rho = 1$ which imply that $t^R = 1, t^D = 30.88$.

In Figure 4, I plot emission price t on the horizontal; axis and the measure of incentive to invest in cleaner technology under full information $\left(\Delta_\pi^{FI}\right)$ on the vertical axis; for $t \in [1, 30.88]$, the incentive to invest in cleaner technology under full information $\left(\Delta_\pi^{FI}\right)$ increases with increase in emission price. Figure 5, reflects the inverse relation between profit distortion due to signaling (Δ_π) and emission price. However, the effect on emission price on incentive to invest under full information dominates the opposing effect of emission price on profit distortion, and thus the net effect on the incentive to invest in cleaner technology under incomplete information (Δ_I) increases with increase in emission price (see Figure 6). Finally, Figure 7 depicts that for $t > 30.88$, the incentive to invest $\left(\text{which is } \Delta_\pi^{FI}\right)$ is a non-monotone function of emission price i.e., increases, reaches a maximum, and then decreases with increase in emission price.

Next, I consider another set of parameter values: $A = 30$, $\beta_C = 0.7, \beta_D = 0.75, m_C = 0.5, m_D = 0.4$, and $\rho = 1$ which imply that $t^R = 2, t^D = 24.18$.

In this case for any emission price $[2, 24.18]$, Δ_π^{FI} is a non-monotone function of emission price (see Figure 8) whereas Δ_π is a decreasing function (see Figure 9) which in turn leads to a non-monotone relation between the incentive to invest under incomplete information and emission price illustrated in Figure 10. On the other hand, Figure 11 shows that for $t > 24.18$, the incentive to invest goes down with regulation.

4 Conclusion.

I analyze the pricing and investment behavior of a firm that signals the environmental attribute of its production technology through its price to uninformed environmentally conscious consumers. I then analyze the effect of change in environmental regulation on the signaling outcome and the firm's *ex ante* incentive to invest in cleaner technology. When regulation is weak, a firm signals cleaner technology through higher price and in this case, the firm earns lower profit when it has cleaner technology and has no incentive to invest in cleaner technology. The price charged by the clean firm declines sharply beyond a critical level of regulation. When regulation is sufficiently stringent, the firm with cleaner technology charges lower price but earns higher signaling profit, and *ex ante* the firm has positive incentive to invest in cleaner technology. With weak regulation, the incentive of the firm to directly disclose its environmental performance rather than signal it through price is increasing in the level of regulation, but the opposite holds when regulation is sufficiently stringent.

Appendix

Proof of Propositions 1 and 2

Propositions 1 and 2 follow from the following characterization of the equilibrium.

Lemma 1 For any $t \leq t^R$, the unique separating equilibrium prices are

$$P_D^* = P_D^{FI} \text{ and } P_C^* = \max\{P_C^{FI}, P^U\}$$

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

$$P^U = \frac{1}{2}\left[1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})+X_D\right]+\frac{1}{2}\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2},$$

For any $t \geq t^R$ there exists a separating equilibrium

$$P_D^* = P_D^{FI} \text{ and } P_C^* = \min\{P_C^{FI}, P^L\} \tag{3}$$

where

$$P^L = \frac{1}{2}\left[1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})+X_D\right]-\frac{1}{2}\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2}.$$

Proof: A clean type has no incentive to mimic the dirty type if it charges a price P_C in the equilibrium such that $\pi(C,1,P_C) > \pi\left(C,0,P_D^{FI}\right)$[11] i.e., the clean type does not earn higher profit when it imitates a dirty type, and this is possible when clean type charges a price P_C such that $\underline{P} \leq P_C \leq \overline{P}$ (incentive compatibility constraint of a clean type) where

$$\begin{aligned}
\underline{P} &= P_C^{FI} - \sqrt{\left[P_C^{FI}-X_C\right]^2 - \frac{(A-\frac{\beta_C}{\beta_D})}{(A-1)}\left(P_D^{FI}-X_C\right)\left(P_D^{FI}-X_D\right)} \text{ and} \\
\overline{P} &= P_C^{FI} + \sqrt{\left[P_C^{FI}-X_C\right]^2 - \frac{(A-\frac{\beta_C}{\beta_D})}{(A-1)}\left(P_D^{FI}-X_C\right)\left(P_D^{FI}-X_D\right)}.
\end{aligned} \tag{4}$$

Observe that the incentive compatibility constraint for clean type is always satisfied at $P_C = P_C^{FI}$ when $X_D < X_C$. Similarly, a dirty type has no incentive to imitate the clean

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

type i.e., $\pi\left(D,0,P_D^{FI}\right) > \pi\left(D,1,P_C\right)$ if the clean type charges a price P_C such that either

$$\begin{aligned} P_C &\geq P^U = \frac{1}{2}\left[1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})+X_D\right] \\ &+\frac{1}{2}\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2} \\ or\ P_C &\leq P^L = \frac{1}{2}\left[1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})+X_D\right] \\ &-\frac{1}{2}\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2} \end{aligned} \tag{5}$$

(incentive compatibility constraint of a dirty type). Note that

$$\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2>0$$

since

$$\overline{\rho}\sqrt{(A-\frac{\beta_C}{\beta_D})\,(A-1)}+m_D>1$$

which is guaranteed by the Assumption 2 (see in the . For any emission price $t < t^R$ ($\implies X_D < X_C$), $P^U < \overline{P}$ and $P^L < \underline{P}$; this implies that if a clean type charges a price P_C such that $\underline{P} \leq P_C < P^U$ then a dirty type has an incentive to imitate the clean type. On the other hand, if a clean type charges a price below P^L then incentive compatibility constraint of a clean type implies that the clean type finds it profitable to imitate the dirty type as $P^L < \underline{P}$. Therefore, a clean firm cannot reveal its type by charging a lower price than P^U. In particular, if $P_C^{FI} \geq P^U$ then in the separating equilibrium a clean type charges P_C^{FI}; whereas, if $P_C^{FI} < P^U$ i.e.,

$$0 < X_C - X_D < \sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2} \tag{6}$$

then it charges P^U (which is also the minimum upward signaling distortion price) in order to deter the dirty type from imitating its higher price-lower quantity combination.
For any emission price $t > t^R$ ($\implies X_D > X_C$), $P^U > \overline{P}$ and $P^L > \underline{P}$; this implies that if a clean type charges a price above P^U in order to deter dirty firm from imitating its action, it always has an incentive to imitate the dirty type's higher price-lower quantity combination. On the other hand, if a clean type charges a price P_C such that $P^L < P_C \leq \overline{P}$ then a dirty

type has an incentive to imitate the clean type's action Therefore, a clean cannot reveal its type by charging a higher price than P^L. In particular, $P_C^* = \min\{P_C^{FI}, P^L\}$ where P^L is the minimum (downward) signaling distortion price, and $P_C^* = P^L$ if

$$0 < X_D - X_C < \sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2} \quad (7)$$

Proof of Proposition 3.

From Lemma 1, we know that for any $t \le t^R$ in the unique separating equilibrium the clean type charges a price $P_C^* = \max\{P_C^{FI}, P^U\}$. Now observe that $P_C^{FI} \ge P^U$ when $t \le t^U$ and $t^U \le 0$ if $\overline{\rho} \ge \rho^* = \sqrt{\frac{\left(1-\frac{\beta_C}{\beta_D}\right)(1-m_D)^2 + (A-1)(m_C - m_D)^2}{\left(1-\frac{\beta_C}{\beta_D}\right)(A-1)\left(A-\frac{\beta_C}{\beta_D}\right)}}$. Therefore, if $\overline{\rho} \ge \rho^*$ then $P_C^* = P^U$ whereas if $\overline{\rho} < \rho^*$ then for any $t \le t^U$ $P_C^* = P_C^{FI}$ and for any $t \in [t^U, t^R]$ $P_C^* = P^U$. We also know that for any $t \ge t^R$ the clean type charges a price $P_C^* = \min\{P_C^{FI}, P^L\}$ in the unique separating equilibrium. $P_C^{FI} \gtreqless P^L \implies t \lesseqgtr t^D$. Q.E.D.

Proof of Proposition 4

By definition $\Delta = P_C^* - P_C^{FI}$. From Proposition 3, we know that for any $t \in [t^U, t^R]$ $P_C^* = P^U$ and

$$\begin{aligned} \Delta &= P^U - P_C^{FI} \\ &= \frac{1}{2}(X_D - X_C) + \frac{1}{2}\sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2} \\ &> 0 \text{ from } (6). \end{aligned}$$

Observe that

$$\frac{\partial \Delta}{\partial t} = \frac{1}{2}(\beta_D - \beta_C) + \frac{1}{2}\frac{\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(1 + \overline{\rho}(A-1) - X_D\right)\beta_D - \left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)\beta_D}{\sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2}}$$

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

$$
\begin{aligned}
&= \frac{1}{2}\beta_D \left[(1-\frac{\beta_C}{\beta_D}) + \frac{\left(1-\frac{\beta_C}{\beta_D}\right)(1-X_D)}{(A-1)\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2}} \right] \\
&= \frac{\beta_D(1-\frac{\beta_C}{\beta_D})}{2(A-1)W}\left[1-X_D+(A-1)W\right] \qquad (8)
\end{aligned}
$$

for any $t \in [t^U, t^R]$ where

$$
W = \sqrt{\frac{\left(1-\frac{\beta_C}{\beta_D}\right)}{(A-1)}\left[\left(A-\frac{\beta_C}{\beta_D}\right)(A-1)\,\overline{\rho}^2 - (1-X_D)^2\right]}
$$

$\frac{\partial \Delta}{\partial t} > 0$ if either $X_D \le 1$ or $X_D \ge 1$ and

$$
X_D - 1 < (A-1)W. \qquad (9)
$$

Squaring both sides of (12) we get

$$
\begin{aligned}
(X_D-1)^2 &< (A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)\left[\left(A-\frac{\beta_C}{\beta_D}\right)(A-1)\,\overline{\rho}^2 - (1-X_D)^2\right] \\
(X_D-1)^2 &< \frac{(A-1)^3\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right)\overline{\rho}^2}{[1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)]}
\end{aligned}
$$

and since $X_D \le 1 + \overline{\rho}(A-1)$, this always holds if

$$
\begin{aligned}
\overline{\rho}^2(A-1)^2 &< \frac{(A-1)^3\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right)\overline{\rho}^2}{[1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)]} \\
(A-1) &> \frac{1}{\left(1-\frac{\beta_C}{\beta_D}\right)^2} \qquad (10)
\end{aligned}
$$

However, for any $t \in [t^R, t^D]$ $P_C^* = P^L$,

$$
\begin{aligned}
\Delta &= P^L - P_C^{FI} \\
&= \frac{1}{2}(X_D - X_C) - \frac{1}{2}\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2} \\
&< 0 \text{ from } (7)
\end{aligned}
$$

and

$$\begin{aligned}
\frac{\partial(-\Delta)}{\partial t} &= -\frac{1}{2}(\beta_D-\beta_C)+\frac{1}{2}\frac{\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(1+\overline{\rho}(A-1)-X_D\right)\beta_D-\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)\beta_D}{\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2}} \\
&= \frac{1}{2}\beta_D[-(1-\frac{\beta_C}{\beta_D})+\frac{\left(A-\frac{\beta_C}{\beta_D}\right)\left(1+\overline{\rho}(A-1)-X_D\right)-(A-1)\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)}{2\,(A-1)\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2}} \\
&= \frac{1}{2}\beta_D\left[-(1-\frac{\beta_C}{\beta_D})+\frac{\left(1-\frac{\beta_C}{\beta_D}\right)(1-X_D)}{(A-1)\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D})-X_D\right)^2-4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI}-X_D\right)^2}}\right] \\
&= \frac{\beta_D(1-\frac{\beta_C}{\beta_D})}{2(A-1)W}\left[1-X_D-(A-1)\,W\right] \qquad (11)
\end{aligned}$$

$\frac{\partial(-\Delta)}{\partial t} < 0$ if either $X_D \geq 1$ or $X_D \leq 1$ and

$$1-X_D < (A-1)\,W. \qquad (12)$$

Squaring both sides of (12) we get

$$\begin{aligned}
(1-X_D)^2 &< (A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)\left[\left(A-\frac{\beta_C}{\beta_D}\right)(A-1)\,\overline{\rho}^2-(1-X_D)^2\right] \\
(1-X_D)^2 &< \frac{(A-1)^3\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right)\overline{\rho}^2}{[1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)]}
\end{aligned}$$

and since $X_D > m_D$, this always holds if

$$(1-m_D)^2 < \frac{(A-1)^3\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right)\overline{\rho}^2}{[1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)]}$$

Using Assumption 2,

$$\frac{(A-1)^3\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right)\overline{\rho}^2}{[1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)]} > \frac{(A-1)\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right)}{[1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)]}(1-m_D)^2$$

so that all we need is

$$\begin{aligned}
\frac{(A-1)\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right)}{\left[1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)\right]} &> 1 \\
(A-1)\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right) &> 1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right) \\
(A-1)\left(1-\frac{\beta_C}{\beta_D}\right)^2 &> 1 \implies A-1 > \frac{1}{\left(1-\frac{\beta_C}{\beta_D}\right)^2}
\end{aligned}$$

Proof of Proposition 5

For any emission price $t \in \left[t^U, t^R\right]$

$$\begin{aligned}
\Delta_\pi &= \pi^U - \pi_C^{FI} \\
&= (P^U - X_C)\left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - P^U}{\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right) - (P_C^{FI} - X_C)\left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - P_C^{FI}}{\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right) < 0
\end{aligned}$$

$$\begin{aligned}
\frac{\partial\left(-\Delta_\pi^U\right)}{\partial t} &= -\beta_C\left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - P_C^{FI}}{\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right) + \beta_C\left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - P^U}{\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right) - \left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - 2P^U + X_C}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right) \\
&= -\beta_C\left(\frac{P^U - P_C^{FI}}{\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right) - \left(\frac{X_C - X_D - W}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right)\beta_D\left[1+\frac{(1-X_D)}{W}\frac{\left(1-\frac{\beta_C}{\beta_D}\right)}{(A-1)}\right] \\
&= \left(\frac{W - X_C + X_D}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right)\left[\beta_D\left[1+\frac{(1-X_D)}{W}\frac{\left(1-\frac{\beta_C}{\beta_D}\right)}{(A-1)}\right] - \beta_C\right] \\
&= \left(\frac{W - X_C + X_D}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right)\frac{\beta_D\left(1-\frac{\beta_C}{\beta_D}\right)}{W(A-1)}\left[W(A-1) + (1-X_D)\right] \\
&> 0 \text{ (from Assumption 3).}
\end{aligned}$$

For any emission price $t \in \left[t^R, t^D\right]$

$$\begin{aligned}
\Delta_\pi &= \pi^L - \pi_C^{FI} \\
&= (P^L - X_C)\left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - P^L}{\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right) - (P_C^{FI} - X_C)\left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - P_C^{FI}}{\overline{\rho}(A-\frac{\beta_C}{\beta_D})}\right) < 0
\end{aligned}$$

$$
\begin{aligned}
\frac{\partial\left(-\Delta_{\pi}^{L}\right)}{\partial t} &= \frac{\partial \pi^{C}}{\partial t} - \frac{\partial \pi^{L}}{\partial t} \\
&= -\beta_C \left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - P_C^{FI}}{\overline{\rho}(A-\frac{\beta_C}{\beta_D})} \right) - \left(\frac{W + X_C - X_D}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})} \right) \left(\frac{\beta_D \{ W(A-1) - (1-X_D)\left(1-\frac{\beta_C}{\beta_D}\right) \}}{W\left(A-1\right)} \right) \cdots \\
&= -\left(\frac{W + X_C - X_D}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})} \right) \left(\frac{\beta_D \{ W(A-1) - (1-X_D)\left(1-\frac{\beta_C}{\beta_D}\right) \}}{W\left(A-1\right)} \right) + \beta_C \left(\frac{1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) + W - X \cdots}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})} \cdots \right. \\
&= \left(\frac{W + X_C - X_D}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})} \right) \left[\beta_C - \frac{\beta_D \{ W(A-1) - (1-X_D)\left(1-\frac{\beta_C}{\beta_D}\right) \}}{W\left(A-1\right)} \right] \\
&= \left(\frac{W + X_C - X_D}{2\overline{\rho}(A-\frac{\beta_C}{\beta_D})} \right) \frac{\beta_D \left(\frac{\beta_C}{\beta_D} - 1 \right)}{W(A-1)} \left[W(A-1) - (1-X_D) \right] \\
&< 0 \text{ (from Assumption 3)}
\end{aligned}
$$

Proof of Proposition 6

For $t \leq t^R$ since $\pi\left(D,0,P_D^*\right) > \pi\left(C,1,P_C^*\right)$, a firm does not have any incentive to invest in cleaner technology. However, for any $t \geq t^R$ $\pi\left(C,1,P_C^*\right) > \pi\left(D,0,P_D^*\right)$ which implies a firm will invest in cleaner technology as long as $f \leq \mu\pi\left(C,1,P_C^*\right) + (1-\mu)\,\pi\left(D,0,P_D^*\right) - \pi\left(D,0,P_D^*\right) = \mu\left[\pi\left(C,1,P_C^*\right) - \pi\left(D,0,P_D^*\right)\right].$

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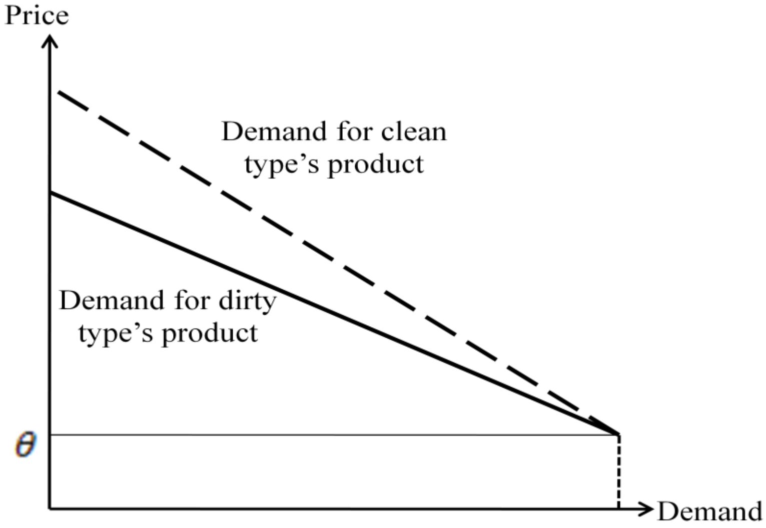
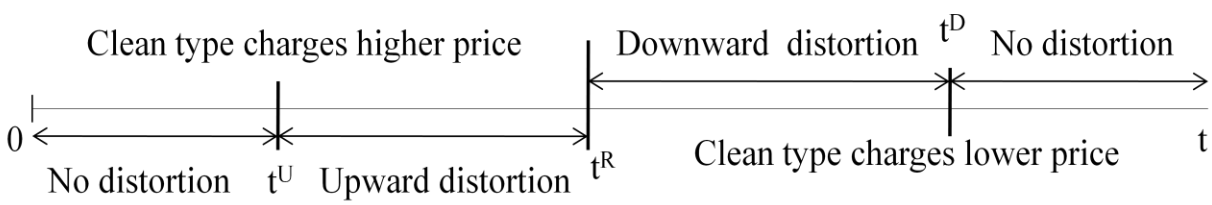


Figure 1



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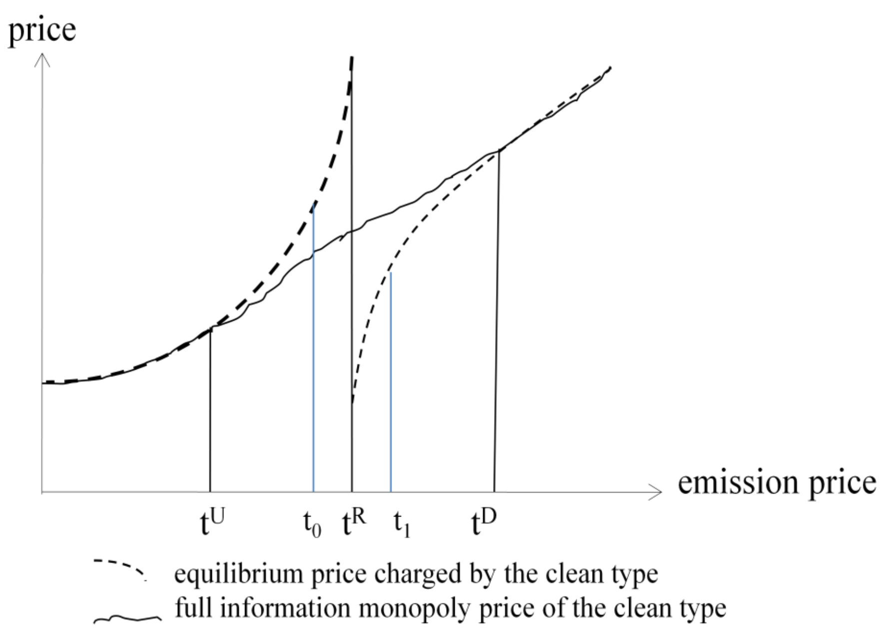

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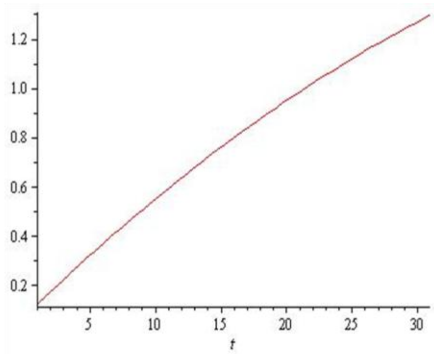

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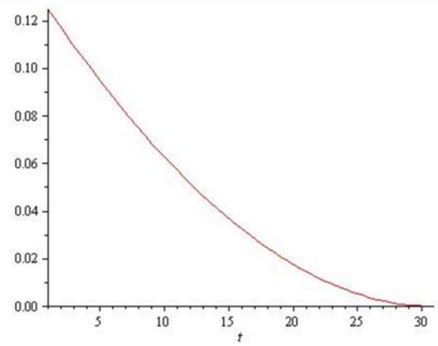

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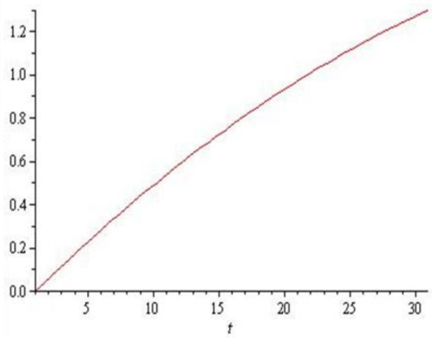

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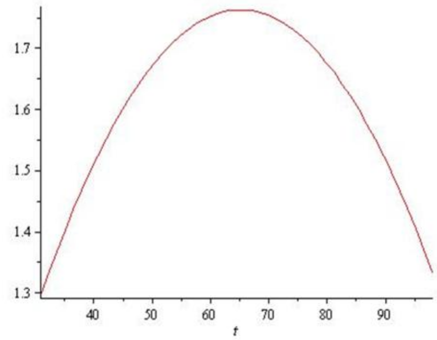

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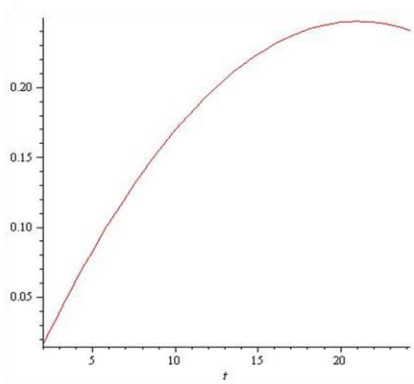

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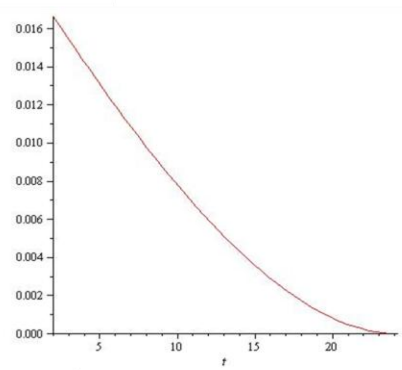

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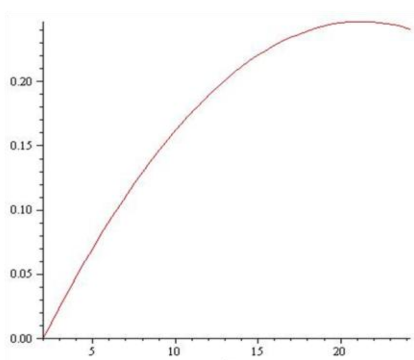

Figure 10

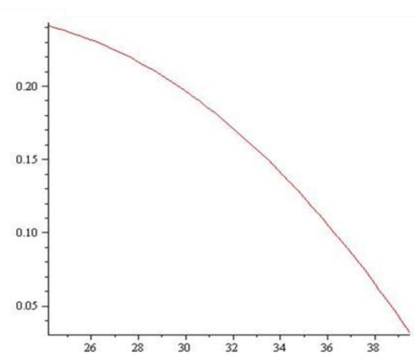

Figure 11