ESSAYS ON ENVIRONMENTAL POLICIES AND INDUSTRIAL ORGANIZATION

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ESSAYS ON ENVIRONMENTAL POLICIES AND INDUSTRIAL ORGANIZATION

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This dissertation consists of three essays that focus on theoretical analysis of the effect of information, environmental consciousness, and environmental policies on green technological change and market outcomes.

In the first essay of the dissertation, "Investment in Cleaner Technology and Signaling Distortions in a Market with Green Consumers", I consider a market where consumers have higher willingness to pay for the product produced by cleaner technology but they differ in terms of their consciousness. However, consumers are unaware of the actual environmental performance of the firm and thus, the single seller signals its actual technology through its price. The paper focuses on the effect of increasing regulation on the nature of signaling behavior of the firm and the incentive to invest in clean technology in the presence of high market power. I find that while a clean firm charges higher price when regulation is weak, this may not hold when regulation is sufficiently stringent. With weak regulation, a monopolist has no incentive to invest in the development of a potentially less damaging technology even though consumers are willing to pay more for the clean product; but this incentive is positive if regulation is strong enough. With weak regulation, the incentive of the firm to directly disclose its environmental performance (say, through eco-labeling) rather than signal it through price is increasing in the level of regulation, but the opposite holds when regulation is sufficiently stringent.

The second essay of my dissertation titled "Competitive Investment in Clean Technology and Uninformed Green Consumers" focuses on investment in clean technology in a market with strategic competition between firms and when some consumers are environmentally conscious (willing to pay more for the product produced by the cleaner technology) but uninformed about

the actual production process of the firms. Though investment is publicly observed, the outcome of the investment is uncertain and remains a private knowledge to the firm. Firms signal their private information about the realized technological outcome of investment through product prices. The incentive to invest is generally higher compared to the full information benchmark, so that requiring mandatory disclosure or public dissemination of information may discourage investment in clean technology. I study the effect of changes in consumer consciousness and environmental regulation on the incentive to invest in clean technology. Competition has a positive effect (relative to monopoly) on the incentive to invest, and this incentive is generally increasing in the level of regulation as well as consciousness. However, high consciousness and/or regulation may lead to multiple equilibrium with zero and high investment outcomes where the latter is Pareto dominant.

In the third chapter, "Environmental Regulation and Industry Dynamics", I examine how increasing stringency of environmental regulation affects investment in technological change and how that, in turn, affects intertemporal changes in size distribution, entry, and exit of firms. In a dynamic deterministic perfectly competitive industry subject to exogenous environmental regulation, ex ante identical firms decide whether to invest in improvement of the compliance technology. The market equilibrating process generates differences in investment, inter-firm heterogeneity and shake-out. Firms that exit earlier invest less, are smaller, and have higher cost of compliance. The main contribution of this analysis is to provide conditions under which more stringent regulation generates an equilibrium path that is characterized by higher shake-out of firms and higher investment in compliance technology. Apart from relating regulation and industry dynamics, it provides some justification for the ambiguous empirical effect of environmental regulation on market structure.

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CHAPTER 1

# INTRODUCTION

The growing environmental consciousness among consumers and increasing stringency of environmental policies by public authorities in the past decades have encouraged private firms to invest in the adoption and development of cleaner technology that causes lesser or no environmental damage. In other words, environmental consciousness of consumers and environmental regulations act as effective market based approaches to protect the environmental quality per se. This dissertation is an attempt to critically analyze the efficacy of environmental consciousness and regulation on promoting green technological change.

Consumers are environmentally conscious in the sense that they are willing to pay more for goods produced in an environment-friendly manner. While consumer consciousness should encourage firms to invest in cleaner technology, environmental groups often claim that the effectiveness of consciousness in inducing such investment is limited because consumers lack information about the actual production process of individual firms. Thus a firm with cleaner technology has an incentive to distinguish itself from a firm with dirtier processes which, in turn, distorts its market power and profit. There are mechanisms such as eco-labeling or credible third party certification that may allow firms to voluntarily disclose such information, but these are not available in many markets, and in any case, the information revealed is at best partial. This argument then goes on to suggest the need for mandatory disclosure laws and public provision of information about firms' actual technology (or environmental performance to conscious consumers). In the next two chapters, I critically examine this argument by studying the effect of consciousness and information on the incentives of firms to invest in cleaner technology when a firm reveals its actual environmental performance through the price of the produce. Existing literature has largely focused on the normative question of optimal policy to reduce the negative externalities created by the production process of firms when the public authorities lack the information about firms' technology and consequential environmental damage; in contrast, I investigate the incentive of firms to invest in cleaner technology under the information asymmetry between consumers and private firms.

Environmental regulation such as emission taxes, pollution permit requirements, liability laws etc. that impose additional cost on the firms for their negative environmental externalities in turn affect the kind of prices needed to be adopted to convey the right information to consumers. Further, when consumers do not learn about technology change, the incentive to shift to cleaner technology is not just based on reducing the burden of regulation on production cost but also on the indirect effect of change in cost differentials between cleaner and dirtier firms, on their market power and profits (signaling distortion). It is important to understand the link between regulation and consciousness in promoting green technological change when a firm decides whether to directly disclose its environmental performance or signal through price.

In the second chapter, I analyze the pricing and investment behavior of a monopolist 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.

The third chapter focuses on a market where consumers or at least some of them are environmentally conscious but not fully informed about the actual production technology or environmental performance of firms that engage in strategic price competition and signal their environmental performance to uninformed consumers through prices. I study the effect of environmental consciousness of consumers and environmental regulation on the incentive to invest in cleaner technology. I find that compared to full information incomplete information generates higher strategic incentive to invest in cleaner technology particularly when consciousness and/or regulation is not too high which appears to fit the current reality in many industries. Thus, requiring mandatory disclosure of technology or environmental performance may discourage such investment. Even though consumers are uninformed, competition has a positive effect (relative to monopoly) on the incentive to invest which implies that anti-competitive policies should be discouraged. The fact that (in contrast to full information) under incomplete information higher environmental consciousness and/or regulation may reduce the incentive to invest in clean technology has important implication for public policy design as well as for environmental activists' campaign to increase green consciousness.

In addition to consumer consciousness, significant increase in the stringency of environmental regulation on the manufacturing industries, in recent decades, has induced firms to undertake investment in learning, technology adoption and other activities in order to reduce their future costs of compliance. This, in turn, affects the dynamic structure (entry-exit decision of firms) of the industry. In the last chapter of my dissertation, I digress from the problem of asymmetric information and mainly focus on the relationship between environmental regulation and industry dynamics.

More specifically, I examine how the increasing stringency of exogenously given environmental regulation affects size distribution, capital formation in firms, inter-firm heterogeneity, entry-exit and shake-out (early exit) of firms in a deterministic competitive industry with endogenous entry and exit where firms invest in reduction of their future compliance cost. The level of regulation is exogenously fixed and constant over time. The compliance cost of a firm at each point of time depends on its current output, its accumulated past investment and the level of regulation. I outline sufficient conditions under which industries with more stringent regulation are associated with higher investment in compliance cost reduction and higher shake-out of firms over time;

the opposite may be true under certain circumstances. The analysis indicates that the effect of a change in regulation on market structure may be lagged over time. The results explain the empirical regularities observed by industry dynamics literature and also provide justification for the contradictory empirical evidence on the effect of environmental regulation on shake-out of firms.

CHAPTER 2

# INVESTMENT IN CLEANER TECHNOLOGY AND SIGNALING DISTORTIONS IN A MARKET WITH GREEN CONSUMERS

## 2.1. 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.

[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.

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 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

[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.

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 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,

[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.

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.

### 2.2. 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 $\beta_C$ units of emission per unit of output if it is *clean*, and a firm emits $\beta_D$ per unit of output if it is *dirty* where

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

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:

$$V(e, \rho) = 1 + \rho(A - \frac{e}{\beta_D}) \tag{2.1}$$

where $A > 1$, and $\rho$ 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

[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.

given by $\rho(A - \frac{e}{\beta_D})$ depends on the level of environmental consciousness of the consumer ($\rho$) and the actual emission of the firm ($e = \beta_C, \beta_D$). Observe that for any $\rho$,

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

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

$$\begin{aligned} Q &= 1 + \frac{1-p}{\overline{\rho}(A - \frac{\beta_C}{\beta_D})} \text{ where } p \in \left[1, 1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D})\right] \text{ if the firm is of clean type,} \\ &= 1 + \frac{1-p}{\overline{\rho}(A-1)} \text{ where } p \in [1, 1 + \overline{\rho}(A-1)] \text{ if the firm is of dirty type.} \end{aligned} \tag{2.2}$$

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 2.1 in Appendix A).

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.

### 2.2.1. Low emission price

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 2.1:** 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

[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.

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 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 2.1, 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., $t \leq t^R$.

### 2.2.2. High emission price

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 2.2:** 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 2.2 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.

### 2.2.3. 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 2.3:** (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 $\left(\text{i.e., } t \leq t^U\right)$ or high $\left(\text{i.e., } t \geq t^D\right)$, then there is *no signaling distortion*, and the market outcome is as under full information.

**Proof.** See Appendix A. ■

Let $\Delta_P$ 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 $\Delta_P$ 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 $\Delta_P$ 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 2.4:** 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 $\Delta_P$) 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 $\Delta_P$) in the separating equilibrium decreases with an increase in emission price (i.e., increase in regulation).

**Proof.** See Appendix A. ■

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 2.3 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.

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 2.5:** (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 $\left(\text{i.e., } t \leq t^U\right)$ or high $\left(\text{i.e., } t \geq t^D\right)$, then there is *no signaling distortion*, and the market outcome is as under full information.

**Proof.** See Appendix A. ■

Let $\Delta_P$ 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 $\Delta_P$ 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 $\Delta_P$ 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 2.6:** 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 $\Delta_P$) 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 $\Delta_P$) in the separating equilibrium decreases with an increase in emission price (i.e., increase in regulation).

**Proof.** See Appendix A. ■

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.

### 2.3. 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 $\beta_D$ 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 2.2, 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 (2.1) and (2.2) 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

[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.

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 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 2.7:** $(i)$ 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 A. ■

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 $\Delta_I$ 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 $\pi_C^L$ is the profit earned by the clean type and $\pi_D^{FI}$ is the (full information) profit earned by the dirty type in the separating equilibrium. Further, $\Delta_I$ 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 $\pi_C^{FI}$ 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 2.2, 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 2.5 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 2.1** 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 $(\Delta_\pi)$ 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 $(\Delta_I)$ 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 $[2, 24.18]$, $\Delta_\pi^{FI}$ is a non-monotone function of emission price (see Figure 8) whereas $\Delta_\pi$ 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.

### 2.4. 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.

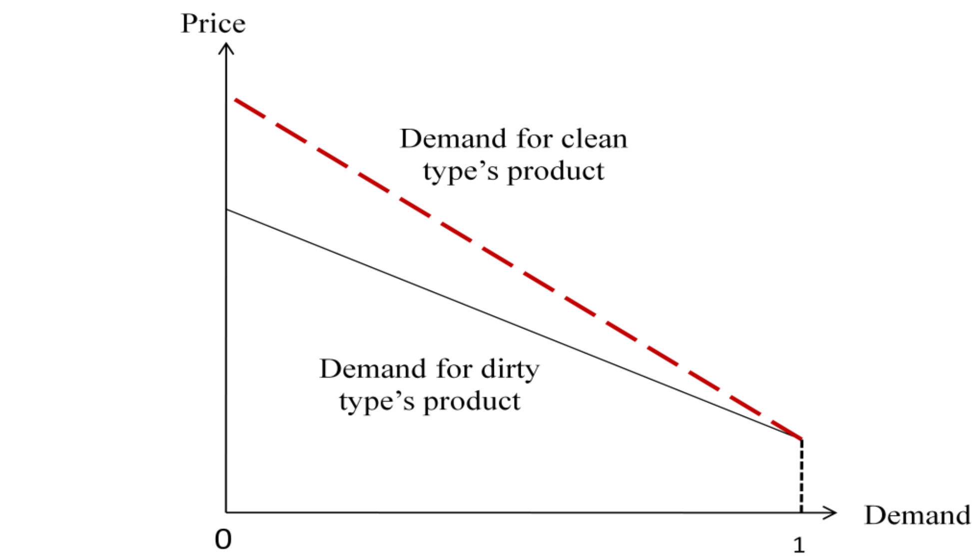


Figure 1: Demand for the clean and the dirty type

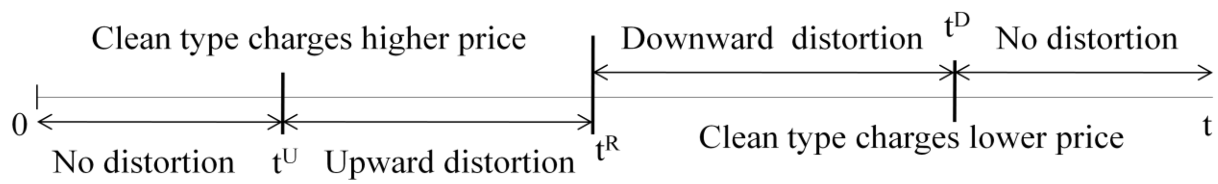


Figure 2: Signaling distortion

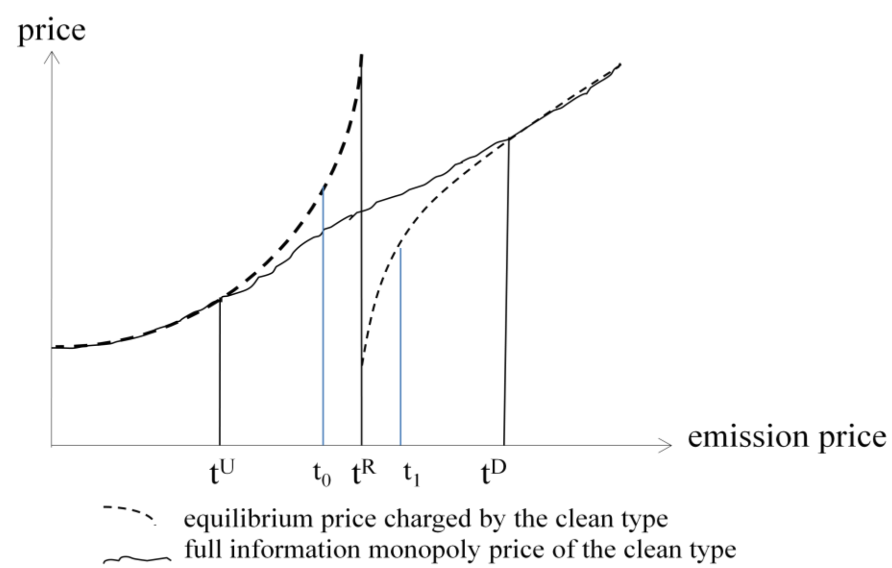


Figure 3: Measure of signaling distortion

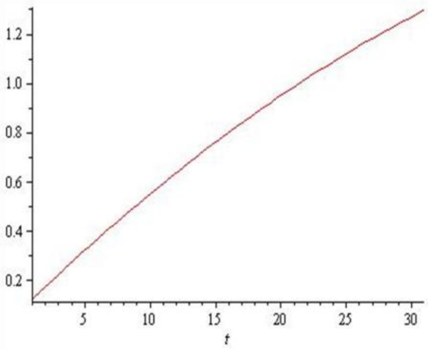


Figure 4: Incentive to invest (full information)

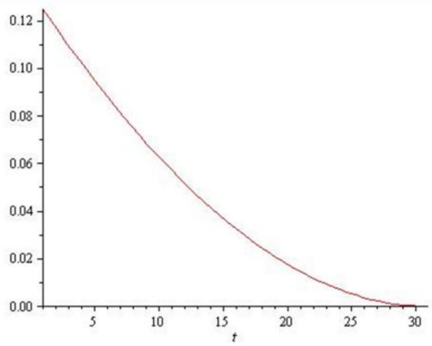


Figure 5: Profit distortion due to signaling

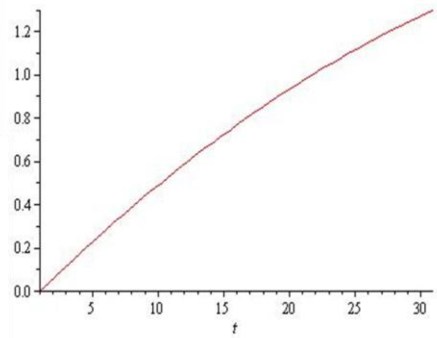


Figure 6: Incentive to invest (incomplete information)

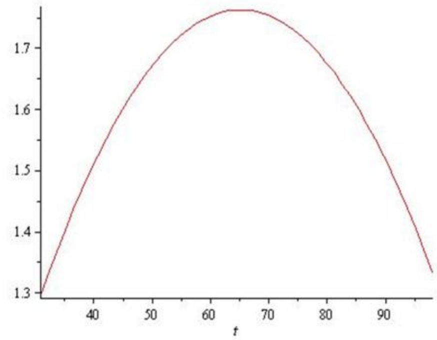


Figure 7: Incentive to invest (t > 30.88)

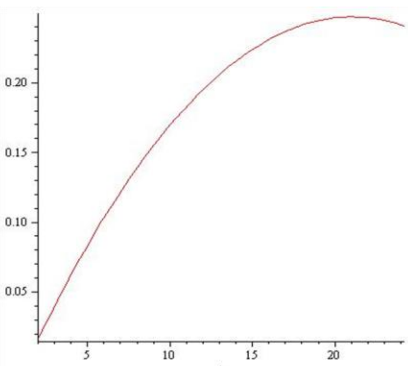


Figure 8: Incentive to invest (full information)

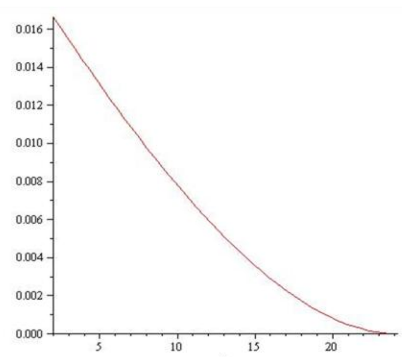


Figure 9: Profit distortion due to signaling

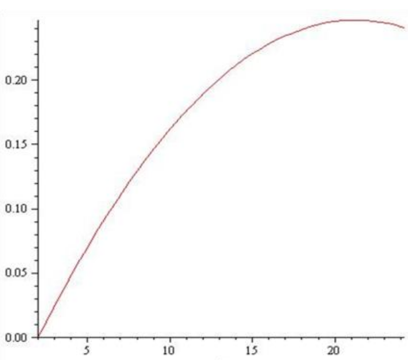


Figure 10: Incentive to invest (incomplete information)

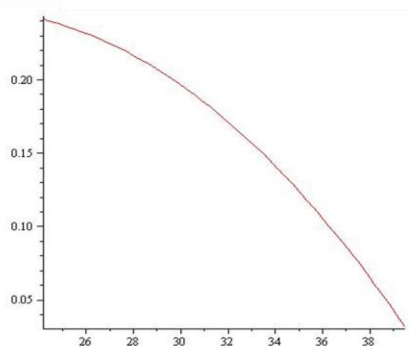


Figure 11: Incentive to invest (t > 24.18)

CHAPTER 3

# COMPETITIVE INVESTMENT IN CLEAN TECHNOLOGY AND UNINFORMED GREEN CONSUMERS

## 3.1. Introduction

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

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

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

In addition to consumer consciousness, economic instruments of environmental regulation such as taxes, pollution permit requirements, liability laws etc. that impose costs on firms for their environmental externality also create incentives for investment in cleaner technology. Such regulations often affect the profitability of different types of technology, and the incentive of dirty firms to pretend to be clean by imitating the actions of clean firms in the market place. All of these, in turn, affect the signaling outcomes in the market resulting from any profile of investment decisions by firms. The second contribution of this paper is that it offers an analysis of the interaction between environmental regulation and consumer consciousness when consumers are uninformed, and the circumstances under which they are complementary in inducing technological change.[11]

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

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

at lower emission intensity. Consumers are uninformed about the actual emission caused or technology used by firms. Firms are also subject to public environmental regulation in the form of an emission permit requirement or emission tax. Regulation is assumed to be exogenous. Further, even though the public authority has information about the actual emissions (from actual permit trading or tax payments) of individual firms, such information is not directly available to consumers. Firms are initially endowed with a dirty technology and may invest in the development of a cleaner production technology where the outcome of investment i.e., whether the realized production process is clean or dirty, is intrinsically uncertain; the latter may reflect uncertainty about the success of the project or the environmental impact of the new technology. Investment is observed publicly but not the realized technology. In the next stage, firms with private information about their realized technology set prices competitively. In particular, firms may signal the environmental attribute of their production technology to uninformed consumers through prices.

The signaling and market competition stage of the model in this paper is closely related to models of signaling product quality in the presence of price competition in an oligopoly (Daughety and Reinganum (2007) , (2008) ; Janssen and Roy (2010)).[12] The underlying competitive signaling game in this paper draws on the specific model of Janssen and Roy (2010), but introduces a specific type of heterogeneity among consumers. Note that the focus of this paper is on the incentive to invest in technological change generated when firms signal private information about technology rather than the possibility of signaling. Further, unlike the quality signaling literature that often assumes symmetry between firms, analyzing the incentive to invest requires evaluation of market outcomes in asymmetric situations where one firm invests and the other does not.

There is a large theoretical literature on the effect of consumer consciousness on production technology and environmental performance of firms when there is no information problem

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

between consumers and firms.[13] 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 (2010) contains an analysis of a monopoly version of this paper; it is shown that even though green consumers are willing to pay more for the product of a clean firm, under incomplete information a firm does not have any incentive to invest in cleaner technology unless regulation is excessively high (so that the clean technology is cheaper to use).

To the best of my knowledge, this paper is the first comprehensive analysis of the strategic incentive to invest in clean technology in the presence of competition and incomplete information.[14] I find that when both firms invest, incomplete information allows firms to gain market power and thus softens price competition; in fact, unlike markets with complete information, when consumers are uninformed, increase in environmental consciousness among consumers may increase the market power and profitability of not only the clean type but also the dirty type. In contrast to the monopoly case in Sengupta (2010), I show that in the presence of competition, firms have strategic incentive to invest even when regulation is weak. Firms invest not only to reduce the burden of regulation but also to change the information structure in the market (as consumers observe investment) that, in turn, alters the intensity of competition and allows the firms to gain market power. This connection between investment in technology and competitive market power is an important contribution yielded by this analysis which implies that in order to promote green technological change anti-competitive policies should be discouraged.

When environmental consciousness and/or regulation is low, if the rival does not invest then a firm has higher strategic incentive to invest in order to soften price competition under incomplete

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

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

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

The remainder of the paper is organized as follows. Section 2 describes the model. In Section 3, I examine the strategic incentive of a firm to invest in cleaner technology under full information. Section 4 illustrates how competing firms signal their environmental performance through prices when consumers and rival firm are not aware of the actual technology of the firm. In section 5, I study the strategic incentive to invest in cleaner technology under incomplete information and compare the investment behavior of firms with that of under full information. Section 6 concludes.

### 3.2. Model

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

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

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

$$0 < m_D < m_C.^{15}$$

Emission in the industry is regulated with each firm being required to purchase emission permit from a competitive emission permit market at an exogenously given price $t$. Here emission is a proxy for any kind of environmental damage, and the emission price represents any expected cost that a firm may have to incur for the environmental damage caused by the production process. For example, under liability rule, if a firm's production process causes significant environmental damage over time then in the long run, it might be subjected to legal liability, and the emission price would then capture the future expected payments under liability.[16] Let

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

be the effective marginal cost of a clean and dirty type respectively.

There is a unit mass of risk-neutral consumers in the market. Consumers have unit demand i.e., each consumer buys at most one unit of the good. A fraction, say $\alpha \in [0, 1]$ of consumers are environmentally conscious whereas $(1 - \alpha)$ proportion of the consumers are not environmentally conscious. Consumers that are not environmentally conscious have equal valuation (maximum willingness to pay) $V$ for a unit of the product of the clean type as well as of the dirty type. However, the environmentally conscious consumers are willing to pay a premium, $\Delta > 0$, for a unit of the clean type's product; in other words, all environmentally conscious consumers have identical valuation $V$ for a unit of the dirty product and $(V + \Delta)$ for a unit of a clean product. I assume that $V > X_C$ and $V > X_D$. Observe that the proportion of conscious consumers $\alpha$ and the premium $\Delta$ are two dimensions of the extent of environmental consciousness of consumers.

Firms are initially endowed with a dirty production technology i.e., each produces $\beta_D$ units of emission per unit of output and incurs an effective marginal cost of $X_D$. In the first stage,

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

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

firms simultaneously decide whether or not to invest in the development of clean technology. The cost of investment is denoted by $f > 0$. The actions chosen by each firm at this stage i.e., whether or not it has invested is observed by both firms and consumers. If it does not invest, a firm remains dirty with probability one, and this is known to all. If it invests then the realized production technology is clean with probability $\mu \in (0, 1)$ and dirty with probability $1 - \mu$, but the realized production technology is pure private information - unknown to the rival firm as well as to consumers. The realizations of production technology after investment are independent across firms. If a firm attains a clean technology as a result of investment then the firm emits $\beta_C < \beta_D$ per unit of output and incurs an effective marginal cost of $X_C$. In the next stage, firms choose prices simultaneously to signal the environmental performance to consumers. Finally, consumers observe the prices charged by the firms, update their beliefs, decide whether to buy, and from which firm to buy.

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

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

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

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

### 3.3. Benchmark: incentive to invest under full information

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

**Lemma 3.1:** When no firm invests then both remain dirty for sure, involve in aggressive price competition, and charge a price equal to the dirty type's effective marginal cost i.e., $p_D^{FI} = X_D$ in the full information equilibrium.

When at least one firm invests then

(i) at any emission price $t \leq \bar{t}$, $p_C^{FI} = X_C$ and $p_D^{FI} = X_C - \Delta$ if the rival is of clean type (whereas $p_D^{FI} = X_D$ if the rival is of dirty type).

(ii) at any emission price $t \geq \bar{t}$, $p_C^{FI} = X_D + \Delta$ if the rival is of dirty type (whereas $p_C^{FI} = X_C$ if the rival is of clean type too) and $p_D^{FI} = X_D$.

In the full information equilibrium, if the firms are of different types then the type that generates higher surplus enjoys market power and captures entire market whereas if the firms are of same type then they involve in aggressive price competition, lose all market power, and share the market equally. Consider the case where at least one firm invests. Recall that at any emission price $t \leq \bar{t}$ the dirty type generates higher surplus; in the event when the rival is of clean type the dirty type sells to all consumers and charges a price

$$p_D^{FI} = X_C - \Delta$$

such that a consumer is indifferent between buying from the clean type and the dirty, and the clean type charges its effective marginal cost $X_C$ . However, at any emission price $t \geq \bar{t}$ the clean type generates higher surplus than the dirty type (i.e., $V + \Delta - X_C \geq V - X_D$); in the full information equilibrium the dirty type charges its effective marginal cost $X_D$ whereas the clean type charges a price $p_C^{FI}$ at which a consumer is indifferent between buying from the clean type at $p_C^{FI}$ and the dirty type at $X_D$ i.e.,

$$p_C^{FI} = X_D + \Delta.$$

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

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

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

if both firms invest,

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

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

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

and

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

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

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

if both firms invest,

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

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

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

whereas the reciprocal incentive of a firm to invest is

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

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

**Proposition 3.1:** When consumers are fully aware of the actual environmental performance of firms, under weak regulation $\left(t \leq \bar{t}\right)$ no firm invests even if the fixed cost of investment is zero whereas when the regulation is strong $\left(t \geq \bar{t}\right)$ at least one firm invests if the unilateral incentive to invest $(UI_{FI})$ is greater than the fixed cost of investment $(f)$ and both firms invest if the reciprocal incentive $(RI_{FI})$ is higher than the fixed cost $(f)$.

### 3.4. Signaling environmental quality through price

Consider the incomplete information multi-stage investment game described in Section 2. In the first stage firms decide whether to invest or not. Though rival firm and the consumers observe the investment decision but the realized technology of the investing firm remains private knowledge. In the next stage, firms with private information about their actual technology decide on prices to reveal their environmental performance to consumers. In this section, I study this second stage subgame.

There are three different situations: (1) both firms do not invest $(NI, NI)$, (2) one invests and other does not $(I, NI)$, and (3) both firms invest $(I, I)$. In the first case, since both firms decide not to invest both remain dirty for sure, and the second stage pricing game degenerates to a standard full information symmetric Bertrand price competition game.

**Lemma 3.2:** When both firms do not invest then for any emission price, both firms charge a common price equal to the effective marginal cost of production of the dirty type $(X_D)$, and both earn zero profit.

A more interesting case arises under the second situation i.e., when only one firm invests; here I have a one sided incomplete information game. The firm that invests (firm $I$) becomes clean $(C)$ with probability $\mu$ and dirty $(D)$ with probability $(1-\mu)$, while a firm that does not invest (firm $NI$) remains dirty $(D)$ with probability one. The solution concept used in the signaling games is that of Perfect Bayesian Equilibrium which is supported by the out-of-equilibrium beliefs that satisfy Cho-Sobel (1990) D1 Criterion.

**Lemma 3.3:** When only one firm invests, at any emission price $t \leq \bar{t}$, there exists a unique separating D1 equilibrium in the second stage pricing game. A clean type charges a price equal to its effective marginal cost $X_C$ earning zero expected profit while a firm that does not invest as well as a firm that invests but remains dirty choose randomized price (mixed strategy) with identical support $[\underline{p}_D, \overline{p}_D]$

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

earning strictly positive expected profit.

The above lemma implies that when only one firm invests there does not exist any separating equilibrium in pure strategies under weak regulation (i.e., $t \leq \bar{t}$). Recall that for any emission price $t \leq \bar{t}$ the dirty type generates higher surplus than the clean type. Thus, the non-investing firm $NI$ that remains dirty for sure enjoys market power and steals the business in the state when the rival (investing) firm is of clean type, but also has an incentive to undercut the rival in case it is of dirty type. In 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.

In the perfect Bayesian separating equilibrium, firm $I$ of type $C$ charges a deterministic price $p_C$, and firm $NI$ as well as firm $I$ of type $D$ randomize price over an identical support $[\underline{p}_D, \overline{p}_D]$ but with different probability distributions, $F_{NI}(p)$ and $F_I(p)$ respectively (that I describe below). At $\overline{p}_D$ i.e., the upper bound of the support, a consumer is indifferent between buying from a clean type at $p_C$ and from a dirty type at price $\overline{p}_D$. Note that since firm $I$ of type $C$ cannot charge a lower price than its rival firm $NI$, 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 $X_C$. The existence of this separating equilibrium is guaranteed since the upper bound of the price support of the dirty type ( $\overline{p}_D = X_C - \Delta$) is greater than its effective marginal cost i.e., $\Delta \leq X_C - X_D$. Since at price $\overline{p}_D$ firm $I$ of type $D$ undercuts firm $NI$ with probability one, at price $\overline{p}_D$ firm $NI$ sells only in the state where the rival firm $I$ is of type $C$, and the equilibrium expected profit of firm $NI$ is given by:

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

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

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

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

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

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

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

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

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

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

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

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

The one sided incomplete information Bayesian equilibrium described above can be supported by the following out-of-equilibrium beliefs of consumers: if a firm charges any off equilibrium price $p > X_C$ or $p < X_C$ then consumers believe that the firm is of clean or dirty type respectively with probability one. Given these out-of-equilibrium beliefs, no firm has an incentive to unilaterally deviate to any out-of-equilibrium price. It can be argued that these out-of-equilibrium beliefs satisfy the D1 refinement; the set of quantities for which it is profitable for a clean type to deviate to any price $p > X_C$ is larger than that of the dirty type, and since a clean type will never deviate to any price $p < X_C$.D1 refinement is trivially satisfied in this case.

However, when only one firm invests under relatively higher emission price $t$ such that $\bar{t} \leq t \leq t^R$, then the separating equilibrium described in Lemma 3.4 does not exist. In particular, the condition for existence (*i.e.*, $\Delta \leq X_C - X_D$) of such a separating equilibrium does not hold.

**Lemma 3.4:** For any emission price $\bar{t} \leq t \leq t^R$, if only one firm invests then in the unique D1 separating equilibrium the dirty type charges a price equal to its effective marginal cost $X_D$, and all consumers buy from the dirty type with probability one whereas the clean type charges a price

$$p_C = X_D + \Delta$$

and sells zero.

Interestingly even though the clean type yields higher surplus than the dirty type (as $\Delta \geq X_C - X_D$) the clean type can never sell. In the separating equilibrium the non-investing dirty type sells with probability one in the state where the rival investing firm is of clean type; if the clean type can sell with a strictly positive probability then the dirty type of the investing firm will have an incentive to imitate the clean type. Thus, in this pure strategy unique separating equilibrium the clean type as well as the dirty type earn zero profit. The above unique separating equilibrium can be supported by the following out-of-equilibrium beliefs of consumers: if a firm charges any price $p < X_D + \Delta$ or $p > X_D + \Delta$ then consumers believe that the firm is of dirty or clean type respectively with probability one. Note that for any level of quantity if it is profitable for a clean type to deviate to any price $p < X_D + \Delta$ then the dirty type also finds it profitable to deviate, whereas for any level of quantity if it is profitable for the dirty type to deviate to a price $p > X_D + \Delta$ then the clean type finds it strictly profitable to deviate as well; thus, the out-of-equilibrium beliefs satisfy the D1 Criterion.

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

Table 3.1 : Different regions of emission price

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

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

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

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

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

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

**Lemma 3.5:** For $t \leq t^R$ (weak regulation), if both firms invest then in any symmetric separating perfect Bayesian equilibrium that is supported by the out-of-equilibrium beliefs that satisfy D1 criterion[17], a clean type charges a deterministic price $p_C$ which is higher than any price charged by a dirty type; dirty type follows a mixed pricing strategy with support $\left[\underline{P}_D, \overline{P}_D\right]$ and a continuous distribution function $F_D(p)$, where

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

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

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

In Region B a clean type charges a deterministic price $p_C$ which is higher than dirty type's full information price $V$ but lower than its own full information monopoly price $V + \Delta$ i.e., $p_C = \max\{X_C, \frac{2\Delta}{(2-\alpha)} + X_D\}$, and all environmentally conscious consumers (i.e., $\alpha$ fraction of the consumers) buy with probability one

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

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

Note that there does not exist any separating equilibrium in pure strategies. In the separating equilibrium, the dirty type (with lower effective marginal cost) should earn sufficient positive rent otherwise it will imitate clean type's equilibrium price. In the state where the rival is of clean type (higher effective marginal cost), a dirty type can earn a strictly positive rent by charging a lower price and does not have any incentive to imitate the clean type's higher price. However, in a state where the rival is of dirty type, it has an incentive to undercut the dirty rival (with the same effective marginal cost). Therefore, the dirty type (with lower effective marginal cost) involves in price dispersion i.e., plays mixed strategy.

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

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

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

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

$$\pi_D^* = \left[\mu + (1-\mu)(1 - F_D(p))\right](p - X_D). \tag{3.3}$$

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

$$\left(\overline{P}_D - X_D\right)\mu = (p_C - \Delta - X_D)\,\mu \tag{3.4}$$

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

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

Therefore, the lower bound of the support is

$$\underline{P}_D = \mu\left[p_C - \Delta\right] + (1-\mu)\,X_D. \tag{3.5}$$

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

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

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

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

(from (3.3) and (3.4)) which implies that

$$F_D(p) = 1 - \frac{\mu}{(1-\mu)}\left(\frac{p_C - \Delta - X_D}{p - X_D} - 1\right) \tag{3.6}$$

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

The symmetric Bayesian equilibrium can be supported by the following out-of-equilibrium beliefs of consumers: if the price $p$ charged by a firm is such that $p \neq p_C$ and $p \notin \left[\underline{P}_D, \overline{P}_D\right]$, then consumers believe that the firm is of dirty type with probability one. Given these out-of-equilibrium beliefs, no firm has an incentive to unilaterally deviate to any out-of-equilibrium price. It can be argued that these out-of-equilibrium beliefs satisfy the D1 refinement.[18] 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.

Consider Region A. In the perfect Bayesian separating equilibrium, a clean type can sell only in the state where its rival is clean too, and they equally divide the market among themselves as consumers are indifferent between firms; in this case, all consumers buy from the clean type with probability one. The strategies and the out-of-equilibrium beliefs described above constitute a perfect Bayesian equilibrium which satisfies the incentive compatibility constraints of the clean and the dirty type iff

$$\frac{V - X_D}{V + \Delta - X_D} \geq \frac{1}{2}. \tag{3.7}$$

where

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

are the incentive compatibility constraints of the dirty and clean type respectively. Note that (3.7) is always satisfied under $t < \max\{\frac{V-m_C}{\beta_C}, \frac{V-2\Delta-m_D}{\beta_D}\}$. In this unique separating equilibrium, the price $p_C$ charged by the clean type is lower than its full information monopoly price $V + \Delta$; in particular, when $t \leq t^R - \frac{2\Delta}{(\beta_D - \beta_C)}$ then the clean type charges its effective marginal cost $X_C$ such that the firm loses its market power whereas if $t^R - \frac{2\Delta}{(\beta_D - \beta_C)} \leq t \leq t^R$ then clean type charges $X_D + 2\Delta$. Further, the expected profit of a clean type is

$$\begin{aligned}
\pi_C^* &= \frac{\mu}{2}(p_C - X_C) \\
&= 0, \text{ if } t \leq t^R - \frac{2\Delta}{(\beta_D - \beta_C)} && (3.8) \\
&= \mu[\Delta - \frac{X_C - X_D}{2}], \text{ if } t^R - \frac{2\Delta}{(\beta_D - \beta_C)} \leq t \leq t^R, && (3.9)
\end{aligned}$$

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

and the expected profit of a dirty type is

$$\begin{aligned}\pi_D^* &= \mu(p_C - \Delta - X_D) \\ &= \mu\left[X_C - X_D - \Delta\right], \text{ if } t \leq t^R - \frac{2\Delta}{(\beta_D - \beta_C)} \quad (3.10) \\ &= \mu\Delta, \text{ if } t^R - \frac{2\Delta}{(\beta_D - \beta_C)} \leq t \leq t^R \quad (3.11)\end{aligned}$$

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

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

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

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

which implies that

$$p_C \geq \frac{2\Delta}{(2-\alpha)} + X_D. \quad (3.12)$$

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

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

and this incentive compatibility constraint of the clean type yields

$$p_C \leq \frac{2\Delta}{(2-\alpha)} + X_C \quad (3.13)$$

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

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

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

$$\frac{V - X_D}{V + \Delta - X_D} \geq \frac{(2-\alpha)}{2} \quad (3.14)$$

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

$$\begin{aligned}
\pi_C^* &= \frac{\alpha\mu}{2}\left(p_C - X_C\right) \\
&= 0 \text{ when } t \leq t^R - \frac{2\Delta}{(2-\alpha)\left(\beta_D - \beta_C\right)} && (3.15) \\
&= \frac{\alpha\mu}{2}\left(\frac{2\Delta}{(2-\alpha)} + X_D - X_C\right) \text{ when } t^R - \frac{2\Delta}{(2-\alpha)\left(\beta_D - \beta_C\right)} \leq t \leq t^R && (3.16)
\end{aligned}$$

and of the dirty type

$$\begin{aligned}
\pi_D^* &= \mu\left(p_C - \Delta - X_D\right) \\
&= \mu\left(X_C - \Delta - X_D\right) \text{ when } t \leq t^R - \frac{2\Delta}{(2-\alpha)\left(\beta_D - \beta_C\right)} && (3.17) \\
&= \mu\frac{\alpha}{2-\alpha}\Delta \text{ when } t^R - \frac{2\Delta}{(2-\alpha)\left(\beta_D - \beta_C\right)} \leq t \leq t^R && (3.18)
\end{aligned}$$

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

On the other hand, if $\frac{V-X_D}{V+\Delta-X_D} \leq \frac{(2-\alpha)}{2}$ (i.e.,.$t \geq \frac{V - \frac{(2-\alpha)\Delta}{\alpha} - m_D}{\beta_D}$) then the clean type charges its full information monopoly price i.e., $p_C = V + \Delta$ and all environmentally conscious consumers may not buy with probability one. The incentive compatibility constraint of the dirty type is

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

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

$$\eta^* = \frac{2\left(V - X_D\right)}{\alpha\left(V + \Delta - X_D\right)}, \tag{3.19}$$

the equilibrium profit of the clean type and dirty type are

$$\pi_C^* = \frac{\mu\left(V - X_D\right)\left(V + \Delta - X_C\right)}{\left(V + \Delta - X_D\right)} \tag{3.20}$$

and

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

respectively.

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

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

and that of the dirty type is

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

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

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

which implies

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

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

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

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

$$\max\{0, \frac{(2-\alpha)(V - X_C) - 2\Delta}{(1-\alpha)(V - X_C)}\} \leq \lambda \leq \min\{\frac{(2-\alpha)(V - X_D) - 2\Delta}{(1-\alpha)(V - X_D)}, 1\} \tag{3.21}$$

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

$$(2-\alpha)(V - X_D) > 2\Delta \tag{3.22}$$

and (3.21) boils down to

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

The D1 equilibrium value of $\lambda$ is

$$\lambda^* = \frac{(2-\alpha)(V-X_D)-2\Delta}{(1-\alpha)(V-X_D)} \tag{3.23}$$

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

$$\pi_C^* = \frac{\mu(V-X_D-\Delta)}{(V-X_D)}(V-X_C) \tag{3.24}$$

and

$$\pi_D^* = \mu(V-\Delta-X_D). \tag{3.25}$$

From the above discussion, one can identify that there are two major sources of signaling distortion. One stems from the fact that in the equilibrium all environmentally conscious consumers though they are willing to pay more for the product produced by the cleaner technology buy from the dirty type except when both firms are of clean type. However, 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.

Note that lack of information about the actual environmental attributes of firms allows not only the clean type but also the dirty type to enjoy stochastic market power even when there are consumers who are willing to pay more for the products of the cleaner type. Rise in the level of environmental consciousness among consumers increases the premium that consumers are willing to pay ($\Delta$) for the cleaner product or the proportion of conscious consumers ($\alpha$); this in turn yields higher rent for the clean as well as for the dirty type.

**Proposition 3.2:** Consider the moderate range of regulation $\frac{V-\frac{2\Delta}{(2-\alpha)}-m_D}{\beta_D} < t < \frac{V-2\Delta-m_D}{\beta_D}$. In this range, increase in the environmental consciousness among consumers increases the market power and profit of both clean and dirty.

At a significantly lower level of regulation $\left(t \leq t^R - \frac{2\Delta}{(\beta_D-\beta_C)}\right)$ the difference in the effective marginal cost is large which implies that the incentive of a dirty type to imitate the clean type is relatively low; thus, the clean type can charge the lowest possible price i.e., its effective marginal cost in the separating equilibrium without getting imitated by the dirty type. Recall that in the separating equilibrium the price distribution of the dirty type depends on the deterministic price charged by the clean type; in particular, for a given price of the clean type the price distribution shifts downward as the premium increases.[19] Therefore, in this range of emission price the price distribution and thus the strictly positive profit of the dirty type go down as the premium paid by the conscious consumers goes up. However, the dirty type earns sufficient rent such that the incentive compatibility constraint is not binding i.e., the dirty type does not have an incentive to imitate the clean type's price. Beyond a critical level of emission price, the incentive of the dirty type to imitate becomes significantly strong such that the clean type's price goes up with the premium which in turn increases the positive profit earned by the dirty type (see (3.11) and (3.18)). In other words, under a moderately high emission price $t \in \left(\frac{V-\frac{2\Delta}{(2-\alpha)}-m_D}{\beta_D}, \frac{V-2\Delta-m_D}{\beta_D}\right)$ the dirty type enjoys higher stochastic market power with the increase in the premium paid by the conscious consumers for the cleaner product. Similar argument can be made for the increase in the proportion of the environmentally conscious consumers i.e., $\alpha$. In the situation where only the fraction of the conscious consumers buy from the clean type (in the state where the rival is of clean type too) increase in the number of conscious consumers positively affects the clean type's profit (see (3.16)). As a result it becomes more lucrative for the dirty type to imitate the clean type's price and thus in the separating equilibrium the dirty type will earn higher profit too (see (3.18)).

### 3.5. Incentive to invest under incomplete information

Firms initially endowed with dirty production technology decide whether or not to incur a fixed cost $f$ in the adoption of cleaner technology. Though the rival firm and the consumers observe the firm's decision to invest but the outcome of the investment i.e., whether the firm could successfully adopt clean technology remains a private knowledge to the firm. In this section,

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

I investigate whether firms have any strategic incentive to invest in cleaner technology under incomplete information and how environmental consciousness and the level of environmental regulation affect this incentive. Further, I examine whether the strategic incentive to invest increase or decrease if all consumers became informed; in other words, I compare firms' incentive to invest in cleaner technology under incomplete information and full information.

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

Prior to realization of environmental quality of production technology, the expected profit of each firm is always zero if both firms do not invest in cleaner technology. When only one firm invests, at any emission price $t \leq \bar{t}$ the clean type of the investing firm earns zero profit as it is always undercut by the non-investing rival; in other words, the non-investing rival which is of dirty type for sure enjoys stochastic monopoly power. The investing firm can earn strictly positive rent only in the state where it is of dirty type. However, for any emission price $t \geq \bar{t}$, both clean and dirty type earn zero profit (Lemma 3.4) . When one firm invests, the ex ante (prior to realization of their types) equilibrium profit of a firm that invests and that does not invest are given by $\pi_I^*$ and $\pi_{NI}^*$ respectively.

**Proposition 3.3:** At any emission price $t \leq \bar{t}$

$$\pi_I^* = (1-\mu)[X_C - X_D - \Delta], \; \pi_{NI}^* = \mu[X_C - X_D - \Delta]. \tag{3.26}$$

whereas for any emission price $\bar{t} \leq t \leq t^R$ the investing as well as the non-investing firm earn zero profit.

The above proposition says that at a lower level of regulation $\left(t \leq \bar{t}\right)$ even if the fixed cost of investment is zero, a non-investing rival gains more compared to an investing firm i.e., $\pi_{NI}^* >$

$\pi_I^* > 0$ if the probability of a successful investment is high i.e., $\mu \geq \frac{1}{2}$; it is a major strategic externality. This, in turn, implies that increase in the probability of a successful investment (viz. probability of being clean) $\mu$ has a disincentive effect on investment. The strategic externality enjoyed by the non-investing firm increases with increase in $\mu$. Further, note that the rise in environmental consciousness among consumers (viz. the premium ($\Delta$) paid by the conscious consumers for the product of the clean type) decreases the price ($\overline{p}_D = X_C - \Delta$) at which a consumer is indifferent between buying from the clean type and the dirty type, and increase in the level of regulation increases the effective marginal cost of the dirty type more than that of the clean type. Therefore, increase in consciousness and regulation reduce the profit of the non-investing firm as well as the profit of the dirty type of the investing firm.

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

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

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

From Table 1 in the last section, recall the different regions corresponding to different range of environmental regulation.

**Proposition 3.4:** In Region A

$$\pi^* = (1-\mu)\mu\left[X_C - X_D - \Delta\right], \text{ if } t \leq t^R - \frac{2\Delta}{(\beta_D - \beta_C)} \quad (3.27)$$

$$= \mu\left[\Delta - \mu(\frac{X_C - X_D}{2})\right], \text{ if } t^R - \frac{2\Delta}{(\beta_D - \beta_C)} \leq t \leq t^R. \quad (3.28)$$

In Region B

$$\pi^* = (1-\mu)\,\mu\,(X_C - \Delta - X_D) \text{ if } t \le t^R - \frac{2\Delta}{(2-\alpha)(\beta_D-\beta_C)} \tag{3.29}$$

$$= \frac{\alpha\mu}{2}\left[\frac{2\Delta}{(2-\alpha)} + \mu\,(X_D - X_C)\right] \text{ if } t^R - \frac{2\Delta}{(2-\alpha)(\beta_D-\beta_C)} \le t \le t^R. \tag{3.30}$$

In Region C

$$\pi^* = \mu\,(V - X_D)\left[\frac{\mu\,(V+\Delta-X_C)}{(V+\Delta-X_D)} + (1-\mu)\right]. \tag{3.31}$$

In Region D

$$\pi^* = \mu\,(V - X_D - \Delta)\left[\frac{\mu\,(V-X_C)}{(V-X_D)} + (1-\mu)\right]. \tag{3.32}$$

First consider the case where rival does not invest in cleaner technology. Let $UI_{II}$ be the *unilateral incentive to invest* under incomplete information; it is the difference between the *ex ante* expected profit of a firm if it invests given that the rival does not and the expected profit earned by the firm if it does not invest (thus remains dirty with probability one). Table 3.2 and Proposition 3.5 illustrate the unilateral incentive of a firm when rival does not invest under incomplete information and how this incentive changes with respect to environmental consciousness (in this case premium that a conscious consumer pays for a unit product of the clean type i.e., $\Delta$) and the level of regulation.

Table 3.2 : Unilateral Incentive to invest

| $t$ | $UI_{II}$ | $\frac{\partial UI_{II}}{\partial t}$ | $\frac{\partial UI_{II}}{\partial \Delta}$ |
|---|---|---|---|
| $t \le \bar{t}$ | $(1-\mu)(X_C - X_D - \Delta)$ | $< 0$ | $< 0$ |
| $\bar{t} \le t \le t^R$ | 0 | - | - |

Recall that unilateral incentive to invest is the maximum fixed cost that a firm would pay in order to invest in cleaner technology when the rival does not invest; in other words, at least one firm invests in the equilibrium if the unilateral incentive to invest is at least as high as the fixed cost of investment.

**Proposition 3.5:** Consider the situation where the rival does not invest.
At any emission price $t \leq \bar{t}$ at least one firm invests if the unilateral incentive to invest $(UI_{II})$ in cleaner technology is higher than the fixed cost of investment $(f)$ whereas if $\bar{t} \leq t \leq t^R$ then no firm invests in the equilibrium even if the fixed cost of investment is zero.

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

At a lower emission price $(t \leq \bar{t})$ if a firm decides not to invest and thus remains dirty for sure then it earns zero profit because of the aggressive price competition with the non-investing rival. However, if the firm invests then it has a strictly positive ex ante expected profit because of the stochastic monopoly power enjoyed by the non-investing firm; this in turn implies that a firm does have a unilateral incentive to invest in clean technology. In other words, the gain from investment which is a measure of unilateral incentive to invest depends on the profit earned by the dirty type. From Proposition 3.3, we know that in this range of emission price increase in environmental consciousness $(\Delta)$ and regulation $(t)$ reduce the *ex ante* expected profit of a firm and also the gain from investment when the rival firm does not invest. Moreover, beyond a critical level of emission price $\left(t > \bar{t}\right)$, it is not possible to earn strictly positive rent for any firm which implies that no firm invests in the Nash equilibrium of the first stage investment game even at zero cost of investment.

Next consider the case when rival invests. In this case, both firms invest in the equilibrium if the reciprocal incentive to invest $(RI_{II})$ in cleaner technology under incomplete information is more than the fixed cost of investment $f$. The following four tables depict the reciprocal incentive to invest $(RI_{II})$ i.e., the maximum fixed cost of investment for which both firms find it profitable to invest to adopt cleaner technology in the equilibrium, and the effect of environmental consciousness (premium $(\Delta)$ as well as the proportion of environmentally conscious consumers $(\alpha)$) and the level of regulation on this reciprocal incentive.

Table 3.3: Reciprocal incentive to invest in Region A

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

Table 3.4: Reciprocal incentive to invest in Region B

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

Table 3.5: Reciprocal incentive to invest in Region C

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

Table 3.6: Reciprocal incentive to invest in Region D

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

Note that the reciprocal incentive to invest in cleaner technology under incomplete information is negative when the clean type charges its effective marginal cost to reveal its actual environmental performance (see Lemma 3.5); otherwise, a firm has a positive incentive to invest when the rival invests.

**Proposition 3.6:** When consumers and rival firm are not aware of the actual environmental performance of a firm then both firms invest in the equilibrium if the reciprocal incentive to invest $(RI_{II})$ is higher than the fixed cost of investment $(f)$.

Observe that unlike the monopolist[20] at least one firm invests in cleaner technology even when regulation is weak (provided the fixed cost of investment is small enough). In other words, in the presence of competition, firms may have strategic incentive to invest in the cleaner technology. The intuition is as follows. Firms invest not only to reduce the burden of regulation but also to change the information structure in the market (as consumers observe investment decision) that, in turn, changes the intensity of competition and allows them to gain market power. If no firm invests then each firm earns zero profit due to Bertrand price competition whereas, when at least one firm invests each earn strictly positive profit; though investing firm may earn lower profit.

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

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

**Proposition 3.7:** When the rival firm invests, increase in the premium paid by the environmentally conscious consumers for a unit of the clean product ($\Delta$) expands the range of emission price along which both firms always invest. The gain from investment goes up with increase in the premium except in Region D when $t \in \left[\bar{t}, t^R\right]$.

Moreover, as more consumers become environmentally consciousness (i.e., $\alpha$ increases) the reciprocal incentive of a firm to invest in cleaner technology goes up.

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

**Proposition 3.8:** The reciprocal incentive of a firm to invest (in particular the gain from investment) in clean technology increases with the level of environmental regulation $\left(\frac{\partial RI_{II}}{\partial t} > 0\right)$ except in Region C and Region D under a significantly higher level of regulation (i.e., $\bar{t} \leq t \leq t^R$).

Note that at a higher level of regulation when the clean type charges a fixed price (insensitive to emission price) even though a firm has a unilateral incentive to invest in clean technology the gain from investment goes down with increase in the level of regulation. The intuition is as follows. In this range of regulation the gain from investment is equal to the ex ante expected profit of any firm when both firms invest, and this expected profit (see (3.31) and (3.32)) goes down with increase in regulation. Moreover, regulation enhances the efficacy of environmental consciousness (*i.e.*, $\frac{\partial RI_{II}}{\partial \alpha}$ is increasing in $t$) in Region B. For significant range of parameters (in

Region C and Region D) there is a complementarity between regulation and price premium $\Delta$ paid by the environmentally conscious consumers in promoting green technological change.

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

**Proposition 3.9:** The unilateral incentive to invest in clean technology is higher in case of incomplete information compared to the full information when emission price is below a critical level $\left(\text{i.e., } t \leq \bar{t}\right)$.

**Proposition 3.10:** Under weak environmental regulation $\left(t \leq t^R\right)$, a firm has higher reciprocal incentive to invest in cleaner technology under incomplete information compared to full information.

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

### 3.6. Conclusion

This paper focuses on firms' strategic incentive to invest in clean technology in a market where firms compete in prices and some consumers are environmentally conscious (willing to pay more for the cleaner product) but uninformed about the actual production process of the firms. Though investment is publicly observed, the outcome of investment is uncertain and observed only by the firm. Firms may signal their private information about the realized technological outcome of investment through product prices. I find that lack of information of conscious consumers about the actual technology used by firms and their environmental performance often leads to higher incentive to invest in cleaner technology when firms compete strongly in the market. In fact, incomplete information generates higher investment compared to full information particularly when consciousness and/or regulation is not too high which appears to fit the current reality in many industries. Therefore, mandatory disclosure law or public dissemination of information may indeed reduce investment in cleaner technology. However, incomplete information also generates higher market power and may imply that a dirty firm serves the market even though it does not generate higher surplus. Under incomplete information, competition generates higher incentive to invest relative to monopoly power. Further, in contrast to full information, under incomplete information, higher consciousness and/or regulation may reduce the incentive to invest. Note that the analysis has important significance for public policy design as well as for environmental activists' campaign to increase green consciousness. I also find multiple equilibrium at higher level of consciousness and/or regulation under incomplete information with high investment being better (i.e., yields higher pay-off) for firms; thus, there is a scope for industry level effort to resolve this coordination problem.

CHAPTER 4

# ENVIRONMENTAL REGULATION AND INDUSTRY DYNAMICS

## 4.1. Introduction

In recent decades there is a significant increase in the stringency of environmental regulations imposed on manufacturing industries. These regulations impact the choice of technology, production scale, investment behavior, as well as entry and exit decisions of firms. One significant consequence of regulation is that firms undertake investment in learning, technology adoption, and other activities in order to reduce their future costs of compliance. It is important to understand how increasing stringency of regulation affects the incentives of firms to invest in compliance cost reduction and how such investments, in turn, affect the entry and exit decisions of firms and more generally, the *dynamic* structure of the industry. This paper is an attempt to address this question in a simple dynamic competitive framework where an industry with free entry and exit faces an exogenous level of environmental regulation. In particular, I study the relationship between the level of environmental regulation and the dynamic equilibrium path of an industry.

The existing literature on environmental regulation and investment has predominantly focused on the so-called Porter Hypothesis (Porter 1991; Porter and van der Linde 1995). According to the hypothesis, more stringent environmental regulation encourages firms to innovate and develop more cost effective methods of achieving regulatory compliance. In the process, firms may also discover new technologies that reduce emissions and production costs. A small body of recent (theoretical and empirical) literature finds limited support for this in their attempt to study the effect of environmental regulation on technological change;[21] however, this literature does not consider the linkage to endogenous changes in market structure. In addition, a

[21] For a survey of the effect of environmental policy on technological change, see Jaffe et al. (2003).

growing empirical literature studies the effect of more stringent environmental regulation on the structure of industries (without considering the effect on technological change). Most of these studies indicate that increase in environmental regulation leads to higher exit, entry barriers, and market concentration; but some studies do find evidence to the contrary.[22]

The theoretical literature on the links between environmental regulation and endogenous changes in market structure mostly assumes a *static* framework that abstracts from issues of technological change. Assuming a linear demand function and a cost function that is additively separable in outputs and emissions, Katsoulacos and Xepapadeas (1996) find that the equilibrium number of firms in the market is decreasing in emission tax. Shaffer (1995) and Lee (1999) extend this analysis to more general demand and production cost functions, while assuming that emissions are proportional to output and find that the effect of an increase in the emission tax on firm's output is ambiguous, but the impact on the equilibrium number of firms in the market is always negative. More recently, Lahiri and Ono (2007) show that if the inverse demand function is concave, output per firm is unambiguously higher with an increase in the emission tax, implying a decline in the equilibrium number of firms in the market. However, the converse may be true if the inverse demand function is convex. Requate (1997) finds that a more stringent absolute *emission standard* always reduces the equilibrium number of firms. Farzin (2003) shows that if environmental quality is complementary to the consumption of the industry product then there may exist a positive relationship between the stringency of the standard and the equilibrium number of firms. In models of symmetric monopolistic competition, Lange and Requate (1999) and Requate (2005) find an inverse relationship between emission tax and the number of firms under reasonable parametric restrictions.

Somewhat closer to the spirit of our analysis, is the small body of static models that attempts to link environmental regulation to market structure by explicitly taking into account *how regulation modifies the optimal scale of firms*. In a model where symmetric firms have upward sloping marginal and U-shaped average cost curves, Conrad and Wang (1993) show that an

[22] For a recent survey of the existing literature on the effects of environmental regulation on market structure, see Millimet, Roy and Sengupta (2008).

increase in emission tax reduces the optimal scale of firms, increases the effective marginal cost, and reduces total output; the net effect of an increase in regulation on the equilibrium number of firms is therefore ambiguous. The equilibrium number of firms declines with an increase in the emission tax if the demand function for the final product is sufficiently elastic. Kohn (1997) argues that if there are sufficient economies of scale in the abatement technology, the optimal scale and output of polluting firms may increase with emission tax and in such situations, the imposition of a (Pigouvian) emission tax is more likely to reduce the number of firms (even if the demand curve for the final product is sufficiently inelastic).

To the best of our knowledge, there is no significant body of work in the existing theoretical literature that systematically links changes in environmental regulation to *dynamic* changes in industry structure that arise *via* their effect on endogenous changes in investment in better abatement and compliance technology. This paper is an attempt to fill this important gap in the literature by explicitly introducing environmental regulation in a model of industry dynamics and technological change.

Over the last few decades, the general literature on theoretical and empirical models of industry dynamics has expanded very sharply.[23] In these models, the scope for technological change through investment in capital formation or learning is a part of the description of the technological environment of the industry; the latter is fixed exogenously and the focus is on characterizing the nature of the dynamic industry path (including technological change). In this paper, the degree of environmental regulation determines the scope for firms to reduce their compliance costs through investment in technological change. Our focus is on how different levels of exogenous regulation lead to differences in the dynamic path of the industry, particularly in the time path of market structure. This differentiates the object of our study from the mainstream literature on industry dynamics.

I introduce environmental regulation in a specific model of technological change and industry dynamics due to Petrakis and Roy (1999) that generated among other things, increasing size

[23] Seminal papers include Jovanovic (1982), Pakes and Ericson (1998), Hopenhayn (1992*a*, 1992*b*, 1993) and Jovanovic and MacDonald (1994).

dispersion and endogenous shake-out (early exit) of firms over time in a dynamic competitive industry. In their paper, investment reduces firm-specific future production cost in a deterministic fashion. As in much of the industry dynamics literature, their focus is on characterizing the qualitative properties of the equilibrium path for a given technological environment.[24] In our paper, investment reduces compliance cost and the latter depends on environmental regulation; our focus is the *comparative dynamics of regulation on the equilibrium path of the industry.*

As in Petrakis and Roy (1999), investment in compliance cost reduction generates inter firm heterogeneity and shake-out of firms over the industry equilibrium path, exiting firms have smaller accumulated investment (higher compliance cost). Further, the equilibrium path is socially optimal and shake-out of firms on the time path does not reflect any anti-competitive behavior. The main contribution of the analysis in our paper is the comparison of time paths of entry, exit and investment in the dynamic equilibrium of a more regulated industry to that of a less regulated industry.

It is important to clarify at this stage that I do *not* focus on the normative question of optimal level of regulation and do *not* study the effects of unanticipated changes in regulation along a particular time path; rather I compare the equilibrium paths corresponding to different exogenous regulation levels.

I identify the economic conditions under which more stringent regulation leads to an equilibrium with higher shake-out of firms over time. Often, the latter is associated with higher dispersion in firm size. However, more regulation may also be associated with lower shake-out of firms. More stringent environmental regulation always increases the (minimum) cost of producing any vector of output for the industry and therefore, the equilibrium prices so that the time path of industry output is lower. Whether or not this leads to more shake-out depends on the effect on the (optimal) scale of individual firms. Here, there is a direct and an indirect effect. The direct effect arises from the manner in which change in regulation shifts the intertemporal production cost function (inclusive of compliance cost) for any fixed investment path and, in

[24]See also, Petrakis, Rasmusen and Roy (1997) for a model of cost reduction through learning by doing in a similar framework.

particular, how it shifts the optimal scale of firms. This is essentially a dynamic version of the effect captured in existing static models. The indirect effect arises from the fact that higher regulation alters optimal investment of firms in compliance cost reduction that, in turn, shifts the cost function and the optimal scale of firms. In our model, investment is complementary to regulation and output i.e., investment reduces the marginal cost of output and higher regulation increases the marginal effectiveness of investment in cost reduction. Therefore, the indirect effect always expands the optimal scale of firms as long as firms invest more with higher regulation. If the direct effect works in the same direction as the indirect effect, higher regulation is likely to lead to an equilibrium path with more shake-out of firms. Even if the direct effect does not expand the optimal scale of firms, if the indirect effect generated by cost reducing investment is sufficiently strong and, in particular, the marginal cost of firms fall sharply with investment, larger shake-out of firms can result.

Our analysis indicates that a higher level of regulation may be associated with more initial entry in the market (when increase in regulation makes the initial marginal cost curves significantly steeper). Nonetheless, sufficient shake-out of firms may change the comparison of market structures after some time. In particular, the somewhat mixed empirical evidence on exit of firms in the immediate years following regulation is not surprising and it is, therefore, important to look at delayed effects on turnover to capture the dynamic impact.

Section 2 outlines the basic structure of the model, the definition of industry equilibrium and the basic qualitative properties of the equilibrium path. Section 3 contains the main results of this paper and a set of examples to illustrate some key points. Section 4 concludes.

### 4.2. Preliminaries

#### 4.2.1. Model

Consider a $T(1 < T < \infty)$ *period dynamic* model of a homogenous good industry with a continuum of *ex ante* identical potential entrant firms (each of measure zero) that can enter at any period and after entry, can exit the industry in any period. The model is a direct adaptation of that in Petrakis and Roy (1999) to our specific context. The market demand is stationary over time and given by $D(p)$. I denote the inverse demand function by $P(Q)$ where $P : R_+ \rightarrow R_+$ is continuous and strictly decreasing.

In each period $t$, firm $i's$ production cost depends on its current output $q_t(i) \geq 0$ and it is denoted by $c(q_t(i))$ where $c : R_+ \rightarrow R_+$ is continuously differentiable, $c(0) > 0$, $c^{'} > 0$ and $c^{''} > 0$. In other words, firms have upward sloping marginal cost curves and a firm has to incur a positive cost to be active in the industry even if it produces zero output i.e., firm incurs a strictly positive fixed cost of production in every period that it stays active in the industry.

Let $\alpha \in R_+$ be the exogenous level of regulation imposed on the industry in order to control the pollution generated by these firms. I assume that $\alpha$ remains constant over time.[25] Higher value of $\alpha$ implies higher level of regulation (say higher tax rate); $\alpha = 0$ indicates no regulation.

In each period $t$, firm $i$ invests $x_t(i) \geq 0$ in reduction of its own compliance cost. I assume that there are no externalities across firms arising from an individual firm's investment in cost reduction. The stock of capital of firm $i$ in period $t$ is given by $y_t(i) \in R_+$ which is accumulation of firm-specific learning. If firm $i$ enters in period $\underline{\tau}$, then for $t > \underline{\tau}$,

$$y_t(i) = x_{\underline{\tau}}(i) + x_{\underline{\tau}+1}(i) + ...... + x_{t-1}(i) \quad \text{and} \quad y_{\underline{\tau}}(i) = 0.$$

I do not allow for depreciation of stock of capital.[26] $\gamma(x_t(i))$ is the cost of investment incurred by firm $i$ in period $t$ where $\gamma : R_+ \rightarrow R_+$ is continuously differentiable, strictly increasing convex function; $\gamma(0) = 0$, $\gamma^{'}(x) > 0$ and $\gamma^{''}(x) \geq 0 \; \forall \; x > 0$.

Given output $q$, capital stock $y$ and level of regulation $\alpha$ the cost of compliance of a firm in any time period is $\phi(q, y, \alpha)$, where $\phi : R^3_+ \rightarrow R_+$ is twice continuously differentiable in all the arguments. I impose the following assumptions on $\phi(q, y, \alpha)$:

**Assumption 1** : $\phi(q, y, 0) = 0$ and $\phi(0, y, \alpha) = 0$.

**Assumption 2** : $\phi_q > 0$, $\phi_y \leq 0$ and $\phi_\alpha > 0$.

[25] The assumption is not inconsistent with optimal regulatory setting if the marginal damage is constant over time and with respect to the level of emission. In this case, the optimal level $\alpha$ (say, emission tax), is set equal to marginal damage, which remains constant in every period, and that, does not depend on the level of emission. Note that, in reality the level of environmental regulation does not change too often and thus, in order to study the effect of regulation on entry, exit and related issues it is not unreasonable to assume a fixed level of regulation at least as a first approximation.

[26] However, qualitative nature of the results will not change unless the rate of depreciation is significantly large.

**Assumption 3** : $\gamma^{'}(0) < -\delta\phi_y(q, 0, \alpha)\, \forall q > 0, \alpha > 0$, where $\delta \in (0, 1)$ is the discount factor.[27]

**Assumption 4** : $\phi_{qq} > 0$, $\phi_{q\alpha} > 0$, $\phi_{yq} \leq 0$, $\phi_{y\alpha} \leq 0$ and $\phi_{yy} \geq 0$.

Assumption 1 implies that if there is no regulation then a firm does not incur any compliance cost. Further, the cost of compliance is zero if a firm is inactive. Assumption 2 implies that the cost of compliance increases with output, decreases with the stock of capital and increases as the level of regulation increases. Observe that $-\phi_y$ is the marginal reduction in compliance cost due to increase in the stock of capital. Assumption 3 guarantees that if there is a positive regulation then each firm that stays in the industry for more than one period finds it profitable to make strictly positive investment. Assumption 4 says that the marginal (compliance) cost of output increases with output and the level of regulation; marginal return on investment in cost reduction (weakly) increases with output and (weakly) increases with regulation but (weakly) decreases in the level of investment.

The effective production cost function for a firm at any point of time with accumulated investment $y$ and facing regulation level $\alpha$ is therefore given by $c(q) + \phi(q, y, \alpha)$. Let $p_m(y, \alpha)$ $= \min_{q \geq 0} \left[ \frac{c(q)+\phi(q,y,\alpha)}{q} \right]$ to be the current minimum average cost and $q_m(y, \alpha)$ the corresponding current minimum efficient scale of a firm with accumulated investment $y$ facing exogenous regulation $\alpha$. In remainder of the paper, I refer minimum efficient scale as optimal scale of a firm.

For all $\alpha > 0$, I assume that

$$\lim_{Q \downarrow 0} P(Q) > p_m(0, \alpha).$$

This ensures the existence of a non-trivial competitive equilibrium. Further, note that the dynamic scale economies created by the possibility of compliance cost reduction are bounded because the effective marginal cost of production $\left(c^{'}(q) + \phi_q(q, y, \alpha)\right)$, the supply curve of an individual firm at any point of time, is bounded below by $c^{'}(q)$ and $c^{'}(q) \rightarrow \infty$ as $q \rightarrow \infty$.

Observe that the exogenous level of regulation $\alpha$ can be interpreted in terms of different pollution control instruments. Suppose $e(q, y)$ is the net value of emission or pollution when the

[27] Assumption 2 and Assumption 3 are alternative verisons of $(A3)$ and $(A6)$ of Petrakis and Roy (1999).

firm produces output $q$ and possesses stock of capital $y$. Then

$$\phi(q, y, \alpha) = \alpha e(q, y)$$

where $\alpha$ is the unit tax or subsidy or unit emission charge. In case of *marketable permits* (quantity rationing), one can define $\alpha$ as the exogenously given number of marketable permits. Under *liability rules* a producer suffers financial loss of magnitude

$$\phi(q, y, \alpha) = f(e(q, y) - \alpha)$$

if he violates the socially acceptable benchmark $\alpha$. If there is a *technology standard* $\alpha$ to be met then

$$\phi(q, y, \alpha) = \left[\widehat{C}\left(q, y, \alpha\right) - c(q)\right]$$

where $\widehat{C}\left(q, y, \alpha\right)$ is the cost function under the given technology standard $\alpha$ when a firm produces output $q$ and $y$ is the present stock of capital.

Finally, I assume that once a firm exits the industry it loses all its accumulated capital and cannot re-enter on the dynamic equilibrium path.[28]

#### 4.2.2. Industry equilibrium

In this subsection, I use the analysis in Petrakis and Roy (1999) to define and characterize the properties of industry equilibrium for any given level of environmental regulation $\alpha$. I will use these results in the subsequent sections to study the effect of change in $\alpha$.

For any pair of time periods $\underline{\tau}$ and $\overline{\tau}$, where $1 \leq \underline{\tau} \leq \overline{\tau} \leq T$, let $S\left(\underline{\tau}, \overline{\tau}\right)$ be the set of firms and $n\left(\underline{\tau}, \overline{\tau}\right)$ be the measure (the number of firms) of the set $S\left(\underline{\tau}, \overline{\tau}\right)$ of firms that enter in period $\underline{\tau}$ and exit in period $\overline{\tau}$. Firms active between periods $\underline{\tau}$ and $\overline{\tau}$ must incur at least a fixed cost of production $c\left(0\right)$ in every period $t$. Given price vector $\mathbf{p} = (p_1, ....p_T)$ and the level of regulation $\alpha$, let $\Pi\left(\mathbf{p}, \alpha, \underline{\tau}, \overline{\tau}\right)$ be the maximum discounted sum of profit (net of investment and compliance

[28]While this assumption may appear to be restrictive note that, in equilibrium, (as we show later) no firm enters after period 1. Therefore, once it exits, no firm can re-enter with its capital and make strictly positive intertemporal profit. This also implies that to the extent this capital is industry-specific, there is no resale value of the accumulated capital of the exiting firm.

cost) that a firm can possibly earn if it enters in period $\underline{\tau}$ and exits in period $\overline{\tau}$ :

$$\Pi(\mathbf{p},\alpha,\underline{\tau},\overline{\tau}) = \max_{(q_t,x_t)\geq 0} \sum_{t=\underline{\tau}}^{\overline{\tau}} \delta^{t-\underline{\tau}} \left[p_t q_t - c(q_t) - \phi(q_t,y_t,\alpha) - \gamma(x_t)\right] \tag{4.33}$$

$$\text{where } \; y_t = \sum_{\tau=\underline{\tau}}^{t-1} x_\tau, \qquad t > \underline{\tau}, \quad y_{\underline{\tau}} = 0.$$

Under our assumptions, given price vector $\mathbf{p}$ and regulation level $\alpha$ there exists a solution to the profit maximization problem in the right hand side of (4.33).

**Definition Of Industry Equilibrium** :Given the level of regulation $\alpha$, an industry equilibrium consists of (1) measurable sets $S(\underline{\tau},\overline{\tau})$ of firms that enter in period $\underline{\tau}$ and exit in period $\overline{\tau}$, $1 \leq \underline{\tau} \leq \overline{\tau} \leq T$, (2) output and investment profile $\{(q_t(i), x_t(i)), t = \underline{\tau}, .....\overline{\tau}\}$ $\forall i \in S(\underline{\tau},\overline{\tau})$ and $\{q_t(i), x_t(i)\}$ integrable on $S(\underline{\tau},\overline{\tau})$ and (3) price vector $\mathbf{p} = (p_1, ....p_T)$ such that

$$(a) \;\; D(p_t) = Q_t \;\; \text{where} \;\; Q_t = \int_{S_t} q_t(i)di$$

where $S_t$ is the set of all firms that are active in period $t = 1, 2, ....T$, (b) if $n(\underline{\tau},\overline{\tau}) > 0$, then $\forall i \in S(\underline{\tau},\overline{\tau})$, the output-investment profile $\{(q_t(i), x_t(i)) \, \forall t = \underline{\tau}, .....\overline{\tau}\}$ solves the maximization problem in the right hand side of (4.33) and

$$\begin{aligned}(c) \;\; \Pi(\mathbf{p},\alpha,\underline{\tau},\overline{\tau}) \;\; &= 0 \qquad \text{if} \quad n(\underline{\tau},\overline{\tau}) > 0 \\ &\leq 0 \qquad \text{otherwise.}\end{aligned}$$

Condition (a) implies that the market clears in every period. Condition (b) states that given the equilibrium price vector $\mathbf{p}$ and exogenous regulation level $\alpha$, the output-investment profile for each active firm maximizes the net discounted sum of profits over its lifetime. Condition (c) guarantees that irrespective of the period of entry and exit, all active firms earn exactly zero net intertemporal profit over their lifetime in the industry. Note that no firm can make strictly positive intertemporal profit no matter when it enters or exits the industry. The following proposition is adopted from Proposition 1 of Petrakis and Roy (1999) in the present framework.

**Proposition 4.1 (Petrakis and Roy** (1999)**):** For every $\alpha > 0$, there exists an industry equilibrium and it is (restricted[29]) socially optimal i.e., maximizes discounted sum of consumer

[29] Note that there does not exist any environmental damage or pollution function; thus, the industry equilibrium

and producer surplus in the industry over time.

For firm $i \in S(\underline{\tau}, \overline{\tau})$, $1 \leq \underline{\tau} \leq \overline{\tau} \leq T$, the equilibrium output and investment profile $\{(q_t(i), x_t(i)), t = \underline{\tau}, .....\overline{\tau}\}$ satisfies the following first order conditions

$$p_t - c'(q_t(i)) - \phi_q(q_t(i), y_t(i), \alpha) = 0 \quad \text{if } q_t(i) > 0 \tag{4.34}$$

$$\gamma'(x_t(i)) + \sum_{\tau=t+1}^{\overline{\tau}} \delta^{\tau-t}\phi_y(q_t(i), y_t(i), \alpha) = 0 \quad \text{if } x_t(i) > 0. \tag{4.35}$$

Equation (4.34) implies that firm $i$ equates price to its current effective marginal cost when it produces positive output. The effective marginal cost curve of a firm is its individual supply curve in each period. As a firm's stock of capital accumulates, its supply curve shifts to the right whereas with increase in regulation it shifts to the opposite direction. Condition (4.35) states that the optimal investment for firm $i$ equates the current marginal cost of investment to the future marginal return from investment i.e., the discounted sum of decrease in future compliance costs. It is obvious that $x_{\overline{\tau}} = 0$ i.e., firms do not invest in their last period in the industry.

Observe that if there is no environmental regulation ($\alpha = 0$) then the cost of compliance is zero (from Assumption 1); in that case, firms have no incentive to invest which implies that the industry supply curve, the market price and the market structure remain stationary over time:

$$p_1 = .. = p_T = p_m(0,0),\ q_1 = .. = q_T = q_m(0,0) \text{ and } n_1 = .. = n_T \tag{4.36}$$

Even if there is regulation but the marginal compliance cost is independent of investment (which implies that the industry's supply curve does not shift) then again we have stationary equilibrium[30] though different from the no-regulation case i.e.,

$$p_1 = .. = p_T = p_m(0,\alpha),\ q_1 = .. = q_T = q_m(0,\alpha) \text{ and } n_1 = .. = n_T. \tag{4.37}$$

Here, firms may invest to reduce their fixed cost of compliance so that their average cost as well as profits may change over time (see Example 4 in Appendix). Much of the existing literature on environmental regulation focuses on comparison of the outcomes of these two stationary

is socially optimal in a restricted sense.

[30] This allows for the possibility how investment reduces only the fixed cost of compliance and in which case the profits of the firms may change over time but the outputs, prices and number of firms remain stationary (i.e., no entry-exit).

equilibrium as they do not allow for endogenous changes in compliance cost.

However, if the level of regulation is positive i.e., $\alpha > 0$ and if the effective marginal cost strictly decreases with investment i.e., $\phi_{qy} < 0\ \forall q, y$ then the industry equilibrium path is typically not stationary. In particular, investment changes cost and supply curves of the firms that in turn change the prices over time. Further, it generates the possibility of shake-out (some firms exit earlier than others) and heterogeneity emerges among firms even though they are identical *ex ante*.

**Proposition 4.2 (Petrakis and Roy** (1999)**):** Fix $\alpha > 0$. ($a$) On any industry equilibrium path prices are non-increasing over time; if, further, $\phi_{qy} < 0\ \forall q, y$ then prices are strictly decreasing over a subset of period; in particular $p_1 > p_T$.[31]

($b$) No entry occurs after the initial period.

($c$) Some firms exit before $T$ (shake-out occurs) if

$$\frac{D(p_m\,(y,\alpha))}{q_m\,(y,\alpha)} < \frac{D(p_m\,(0,\alpha))}{q_m\,(0,\alpha)}, \forall y > 0.$$

($d$) Finally, firms that exit earlier on the industry equilibrium path have (weakly and often, strictly) lower accumulated investment, higher compliance cost and smaller size.

To understand part ($a$) of Proposition 2 note that an increase in accumulated investment per firm reduces the effective marginal cost i.e., supply of the firm and consequently the effective marginal cost curve of the industry declines over time. As a result the competitive equilibrium price is decreasing along the time path of an industry. The intuition behind part ($b$) of Proposition 2 is as follows: if a firm enters after period 1 and makes zero intertemporal profit, then by entering and exiting earlier (staying in the industry for the same length of time) it can earn strictly positive discounted sum of profit as it faces a "better" vector of prices (since prices are decreasing over time).

Part ($c$) of Proposition 2 provides a sufficient condition for shake-out i.e., for some firms to exit earlier. Recall that $p_m\,(y,\alpha)$ is the minimum average cost and $q_m(y,\alpha)$ is the corresponding

[31] For the formal proof of the last part see Appendix.

minimum efficient scale of a typical firm with accumulated investment $y$ under the exogenous level of regulation $\alpha$. The typical profit profile for a firm is that it earns negative profit in initial periods producing below its minimum efficient scale (faces price no larger than its minimum average cost) while in later periods, a mature firm faces prices strictly greater than the minimum average cost and produces more than its minimum efficient scale. Therefore, if the minimum efficient scale expands sufficiently rapidly with investment relative to the expansion of total quantity sold resulting from fall in prices over time, there must be some shake-out of firms. Note that on the equilibrium path, firms that exit earlier as well as those that exit later earn zero intertemporal profit and no firm can do better by altering its exit decision.

Part ($d$) of Proposition 2 implies that a firm that finds it profitable to stay in the industry has higher accumulated investment than the firm that exits in the same period; this allows the staying firm to be profitable at lower future prices. Prices are non-increasing on the dynamic equilibrium path. Even though firms are ex ante identical, some firms may follow a strategy of investing small or not at all and exiting the industry early (as prices fall) while others can follow the strategy of making big investment to sufficiently reduce the future cost of compliance that would allow them to be profitable at low future prices. The equilibrium price path could be one that would make firms indifferent between both strategies - i.e., both would yield zero net intertemporal profit. Under certain circumstances, the equilibrium path is necessarily one where identical firms follow a diversity of such strategies - some being small and exiting early; others investing, being large and staying for a long horizon. If all firms invested big and stayed on in the industry, then the reduction in the effective marginal cost curve of firms and the resultant expansion of the market supply curve could lead to too much of decline in market price, and this in turn, would reduce the incentive to invest too sharply. Therefore, in order to sustain a reasonable amount of investment, market equilibrium may require that some firms invest less and exit earlier than others. The output produced by a firm who stays in the industry is higher than that of the exiting firm.

*An important implication of this result for environmental regulation, is that regulation can endogenously create heterogeneity in compliance cost and size dispersion of firms by creating* *differences in investment and planned survival of firms. Exiting firms are smaller and have higher compliance costs than firms that stay on.*

Note that the above mentioned properties are the characteristics of an industry equilibrium path which is socially optimal. One can intuitively justify that on the time path with a given level of regulation, shake-out of firms in an industry is desirable from the social planner's perspective. Initially the social planner may want a large number of firms in the industry to bring down the total industry cost if the marginal cost curve is steep. But over time as firms invest to reduce future compliance cost, the effective marginal cost of an individual firm may become flatter, its efficient scale may expand so that from the social planner's perspective it is no longer necessary to keep large number of firms in the industry and incur the fixed cost.

I present a numerical example to illustrate all the above mentioned properties of an industry equilibrium path.

**Example 4.1:** Let

$$D(p) = 100 - p, \quad c(q) = 10 + e^{q}, \quad \gamma(x) = 0.5x^2$$

$$\phi(q, y, \alpha) = \alpha e(q, y) = \alpha \exp^{q - \lambda y}$$

where $\exp^{q-\lambda y}$ can be interpreted as the emission function, $\lambda > 0$ as the efficiency of investment in emission reduction and $\alpha$ as the unit emission tax rate. Set $\delta = 0.5$, $T = 3$.I describe the equilibrium paths under three different circumstances:

$(i)$ no regulation i.e., $\alpha = 0$,

$(ii)$ there is a positive regulation $\alpha = 0.03$ but the cost of compliance does not depend on investment i.e., $\lambda = 0$,

$(iii)$ positive environmental regulation $\alpha = 0.03$ and the compliance cost depends on investment; in particular, $\lambda = 1$.

Table 4.1 represents case $(i)$ and case $(ii)$ that illustrate our claim in (4.36) and (4.37) :

Table 4.1: Static equilibrium

| Case | $t$ | $\alpha$ | $q_t$ | $x_t$ | $p_t$ | $\pi_t$ | $D(p_t)$ | $n_t = \frac{D(p_t)}{q_t}$ | $\frac{n_t - n_{t-1}}{n_{t-1}}$ |
|---|---|---|---|---|---|---|---|---|---|
| $(i)$ | – | 0 | 2.1568 | 0 | 8.6440 | 0 | 91.3560 | 42.3558 | – |
| $(ii)$ | – | 0.03 | 2.1410 | 0 | 8.7637 | 0 | 91.2362 | 42.6125 | – |

Both cases yield two different static equilibrium with no investment and no shake-out of firms in the industry.

Table 4.2 depicts case $(iii)$ :

Table 4.2: Dynamic equilibrium

| $t$ | $p_t$ | $D(p_t)$ | $n_t = \frac{D(p_t)}{q_t}$ | $\frac{n_t - n_{t-1}}{n_{t-1}}$ |
|---|---|---|---|---|
| 1 | 8.7637 | 91.2362 | 42.6125 | – |
| 2 | 8.7569 | 91.2430 | 42.5474 | $-0.0015$ |
| 3 | 8.7432 | 91.2567 | 42.5366 | $-0.0002$ |

Note that on the industry's equilibrium dynamic path, price is strictly declining over time and firms exit after every period; the last column represents the rate of shake-out of firms over time.

In period 1, all firms produce at the minimum efficient scale (identical across firms in period 1); firms that exit at the end of period 1 earn zero profit whereas other firms earn strictly negative profit as they invest in cost reduction. In period 2, there are two different types of firms; those that exit at the end of period 2 and those that exit at the end of period 3; the former have invested higher amount in period 1 compared to the latter and therefore, have lower effective marginal cost and higher output (though they all face the same market price). A typical firm that enters in period 1 and exits at the end of period 2 has the following profile of output and investment on the industry equilibrium path :

Table 4.3: Firm that exits at the end of period 2

| $t$ | $q_t$ | $x_t$ | $\pi_t$ |
|---|---|---|---|
| 1 | 2.1410 | 0.1141 | $-0.0065$ |
| 2 | 2.1434 | 0 | 0.0130 |

For a typical firm that enters the industry in period 1 and leaves at the end of period 3 I get the following output and investment profile for three periods:

Table 4.4: Firm that exits at the end of period 3

| $t$ | $q_t$ | $x_t$ | $\pi_t$ |
|---|---|---|---|
| 1 | 2.1410 | 0.1588 | $-0.0126$ |
| 2 | 2.1445 | 0.0990 | 0.0180 |
| 3 | 2.1454 | 0 | 0.0142 |

Observe that a typical firm that exits at the end of period 3 invests more in period 1 and produces more in period 2 than a firm that exits at the end of period 2 on the industry equilibrium path (this depicts the part ($d$) of Proposition 4.2).

### 4.3. Comparative dynamics in two period model

In this section, I study the effect of more stringent environmental regulation on the industry equilibrium path with particular focus on the conditions under which increase in regulation leads to a time path with higher shake-out of firms.

For the sake of tractability, I consider a two period model ($T = 2$). I also make the following additional assumption:

**Additional assumption :** $\frac{D(p_m(x,\alpha))}{q_m(x,\alpha)} < \frac{D(p_m(0,\alpha))}{q_m(0,\alpha)}$ $\forall x > 0, \alpha > 0.$

Using part ($c$) of Result 2 in the previous section, I can see that this guarantees that for every $\alpha > 0$, the industry equilibrium is one where some firms exit at the end of period 1.

Given $(p_1, p_2, \alpha)$ a firm maximizes the discounted sum of profit over *two* periods:

$$\max_{q_1,q_2,x} p_1q_1 - c(q_1) - \phi(q_1, 0, \alpha) + \gamma(x) + \delta\left[p_2q_2 - c(q_2) - \phi(q_2, x, \alpha)\right]. \tag{4.38}$$

The equilibrium output and investment $\{q_1^*, q_2^*, x^*\}$ profile of each firm in period 1 and 2 satisfies the following first order conditions:

$$p_1 - c^{'}(q_1) - \phi_q(q_1, 0, \alpha) = 0 \tag{4.39}$$

$$p_2 - c^{'}(q_2) - \phi_q(q_2, x, \alpha) = 0 \tag{4.40}$$

$$\gamma^{'} + \delta\phi_x(q_2, x, \alpha) = 0.^{32} \tag{4.41}$$

Firms that do not invest ($x = 0$) immediately exit at the end of period 1 and thus earn zero profit i.e.,

$$p_1q_1 - c(q_1) - \phi(q_1, 0, \alpha) = 0. \tag{4.42}$$

A firm that survives till the last period earns negative profit in period 1 but strictly positive profit in period 2; in an equilibrium with shake-out discounted value of this strictly positive profit is equal to the cost of investment incurred by the firm in period 1 i.e.,

$$\gamma(x) - \delta\left[p_2q_2 - c(q_2) - \phi(q_2, x, \alpha)\right] = 0.^{33} \tag{4.43}$$

In an industry equilibrium with shake-out (some firms exit at the end of period 1) each firm produces at the minimum efficient scale in period 1 i.e.,

$$p_1^* = p_m(0, \alpha) \quad \text{and} \quad q_1^* = q_m(0, \alpha)$$

(from (4.39) and (4.42)). Further to compensate for the negative profit earned in period 1 each firm produces more than the minimum efficient scale in period 2 i.e., $q_2^* \geq q_m(x, \alpha)$, price in period 2 is at least as high as the minimum average cost i.e., $p_2^* \geq p_m(x, \alpha)$ and thus each active

[32] The interpretations of the first order conditions are similar to the $T$ period case.

[33] (4.42) and (4.43) can be considered as additional equilibrium conditions to solve for the equilibrium time paths of output and investment when there is shake-out. In lemma 1 (see Appendix) we show that the equilibrium price $p_2^*$ and output $q_2^*$ produced by each firm in period 2 can be obtained by solving (4.43).

firm earns positive profit in period 2. I can conclude that

$$p_m(x,\alpha) \leq p_2^* \leq p_1^* = p_m(0,\alpha)$$

(from part $(a)$ of Proposition 4.2) and

$$q_2^* \geq q_m(x,\alpha) \geq q_m(0,\alpha) = q_1^*$$

(from part $(d)$ of Proposition 4.2).

I begin with an example that shows that higher environmental regulation does not necessarily generate higher shake-out of firms compared to a path with lower regulation.

**Example 4.2:** Let

$$D(p) = p^{-1.5}, \qquad c(q) = 1 + q^2, \qquad \gamma(x) = 0.5x^2$$

$$\phi(q,y,\alpha) = \alpha e(q,y), \;\; e(q,y) = q^{1.5}(1-y)^5$$

where $e(q,y)$ is the emission function and $\alpha$ is an emission tax. I explicitly solve for the two-period industry equilibrium corresponding to four different levels of regulation: $\alpha = 0.03$, $\alpha = 0.05$, $\alpha = 0.07$ and $\alpha = 0.10$. The results are reported in the following table :

**Table 4.5**

| $t$ | $\alpha$ | $q$ | $x_1$ | $p$ | $D(p)$ | $n = \frac{D(p)}{q}$ | $\frac{n_t - n_{t-1}}{n_{t-1}}$ |
|---|---|---|---|---|---|---|---|
| 1 | 0.03 | 0.9925 | 0.0585 | 2.0299 | 0.3457 | 0.3483 | |
| 2 | 0.03 | 0.9961 | 0 | 2.0256 | 0.3468 | 0.3481 | $-0.0004$ |
| 1 | 0.05 | 0.9876 | 0.0865 | 2.0498 | 0.3407 | 0.3449 | |
| 2 | 0.05 | 0.9958 | 0 | 2.0392 | 0.3433 | 0.3448 | $-0.0005$ |
| 1 | 0.07 | 0.9828 | 0.1094 | 2.0696 | 0.3358 | 0.3417 | |
| 2 | 0.07 | 0.9962 | 0 | 2.0519 | 0.3404 | 0.3416 | $-0.0001$ |
| 1 | 0.10 | 0.9827 | 0.1358 | 2.0588 | 0.3313 | 0.3371 | |
| 2 | 0.10 | 0.9827 | 0 | 2.0588 | 0.3313 | 0.3371 | 0 |

The last column indicates the intensity of shake-out of firms. Observe that compared to $\alpha = 0.03$, the industry equilibrium path with $\alpha = 0.05$ is characterized by **higher** shake-out. However, when I compare between $\alpha = 0.05$ and $\alpha = 0.07$ the industry equilibrium exhibits **lower** shake-out of firms on the path more stringent regulation. In fact, if the level of regulation is as high as $\alpha = 0.10$, there is no shake-out of firms at all. Also, observe that higher regulation ($\alpha$) is associated with higher investment by firms that survive till period 2.

The above example illustrates the fact that more stringent regulation does not necessarily lead to higher shake-out in the industry and in particular, it is important to understand the various economic effects that play a role here. In order to do so, I will derive a set of sufficient conditions under which on the path with more stringent environmental regulation, the industry equilibrium exhibits higher shake-out of firms.

First, observe that in an equilibrium with exit in the two period model, the price in period 1 is exactly equal to the minimum average cost of a new entrant i.e., $p_m(0, \alpha)$ and every firm produces at its minimum efficient scale $q_m(0, \alpha)$ earning exactly zero current profit (gross of investment). Therefore, the number of active firms in the market in period 1 is

$$n_1 = \frac{D(p_m(0, \alpha))}{q_m(0, \alpha)}.$$

**Lemma 4.2:** An increase in the stringency of environmental regulation (higher $\alpha$), increases the number of active firms in the industry in period 1, iff $\frac{D(p_m(0,\alpha))}{q_m(0,\alpha)}$ is strictly increasing in $\alpha$.

Notice that this change in the equilibrium number of firms in period 1 when industry is on a higher regulation path is identical to the effect of increase in the level of regulation under a static framework (Conrad and Wang (1993)).

Next, I compare the equilibrium number of firms in period 2 on time paths corresponding to two different exogenous levels of environmental regulation. There are three different effects of higher regulation on the number of firms:

**Effect 1 :** For any given profile of investment, higher level of regulation increases the cost structure of the industry that in turn increases the equilibrium price and decreases total industry output sold. This creates a downward pressure on the number of active firms in period 2.

**Effect 2 :** For any given profile of investment, higher level of regulation shifts both the average cost and the effective marginal cost upward which directly alter the optimal scale of a firm. This may affect the number of firms in either direction depending on the direction and extent of changes in optimal scale.[34]

**Effect 3 :** Increase in regulation may increase cost reducing investment and if this occurs, there is an expansion in the optimal scale of individual firm which tends to reduce the number of firms.

The first two are direct effects and the last one is the indirect effect of more stringent regulation on the number of firms. The net effect of higher regulation is such that on the industry equilibrium path corresponding to higher level of regulation, the price in period 2 is always higher (see (4.5) in Appendix), the total industry output sold in period 2 is lower and therefore, the number of active firms in period 2 solely depends how the optimal scale of an individual firm changes (Effect 2 and Effect 3).

In this model I assume that $\phi_{xq} \leq 0$ i.e., investment is more effective in reducing compliance cost at higher levels of output which implies that investment reduces the marginal cost of output. Further, note that the assumption $\phi_{x\alpha} \leq 0$ guarantees that the effectiveness of investment in compliance cost reduction (weakly) increases with regulation i.e., investment is more effective in reducing the future stream of compliance cost at a higher level of regulation. The degree of complementarity between regulation and investment determines the extent to which higher regulation creates incentive for more investment. The extent to which this investment reduces

[34]For any given level of investment, higher level of regulation shifts both the average and the marginal cost curves upwards. If the average cost curve shifts to the left while moving up (this is likely if marginal cost increases more sharply than fixed cost) the optimal scale decreases. If the decrease in the optimal scale is more than the decrease in the total industry output, then number of firms tends to increase with higher level of regulation. On the other hand, if average cost shifts to the right while moving up with regulation, the optimal scale expands, then the number of firms declines for sure. Therefore, increase or decrease in the number of firms can depend on the nature and extent of change in the optimal scale of individual firms.

the effective marginal cost determines the expansion in the scale of individual firms.

When the direct effect expands the optimal scale of firms, the cumulative effect of higher level of regulation expands the production scale of individual firms; as higher regulation always leads to higher prices (lower industry output), the industry is more likely to exhibit greater shakeout of firms over time. Even if the direct effect does not expand the scale of firms, if the indirect effect (Effect 3) generated by cost reducing investment is sufficiently strong and, in particular, the marginal cost of firms fall sharply with investment (relative to demand elasticity which determines the contraction of industry output), larger shake-out of firms results.

For the indirect effect (Effect 3) to operate, however, firms need to invest more with increase in regulation. While the higher compliance cost associated with more stringent regulation creates more scope for cost reduction through investment, there is also a disincentive effect on investment that arises because higher regulation is associated with smaller industry output (higher price) so that the quantity a firm produces in the future is also likely to be smaller. Indeed, if regulation is prohibitive, industry shuts down and there is no investment. Of course, at the other extreme, if there is no regulation then once again, firms have no incentive to invest.

Let us define the following elasticities :

$$\widetilde{\phi}_{q,q} = \frac{q}{\phi_q}\phi_{qq}, \;\; \widetilde{\phi}_{x,x} = -\frac{x}{\phi_x}\phi_{xx}, \;\; \widetilde{\phi}_{x,q} = \frac{q}{\phi_x}\phi_{xq},$$

$$\widetilde{\phi}_{\alpha,q} = \frac{q}{\phi_\alpha}\phi_{\alpha q}, \;\; \widetilde{\phi}_{\alpha,x} = -\frac{x}{\phi_\alpha}\phi_{\alpha x}, \;\; \varepsilon_{\gamma'} = \frac{\gamma''}{\gamma'}x \;\text{ and }\; \varepsilon_{c'} = \frac{c''}{c'}q.$$

**Proposition 4.3:** A marginal increase in the stringency of environmental regulation increases the investment of all firms (that do not exit in period 1) if at least one of the following conditions holds (at the current level of regulation):

$$(1) \;\; \widetilde{\phi}_{\alpha,q} \le 1$$

$$(2) \;\; \widetilde{\phi}_{\alpha,x}\left(\varepsilon_{c'}\frac{c'}{\phi_q} + \widetilde{\phi}_{q,q}\right) > \widetilde{\phi}_{q,x}\left(\widetilde{\phi}_{\alpha,q} - 1\right).$$

**Proof.** See Appendix C. ∎

If the first condition of Proposition 4.3 is satisfied then the optimal scale of each firm in period 2 is higher on the path with more stringent regulation (see (4.6) in Appendix C) and consequently the first order condition (4.41) implies that each active firm invests more compared to those on the lower regulation path. The second condition depicts a situation when the disincentive effect on investment of higher regulation (discussed above) is dominated.

The next proposition underlines a set of sufficient conditions for lower number of firms in period 2 on the path with higher level of regulation.

**Proposition 4.4:** On the industry equilibrium path with more stringent regulation (marginally higher $\alpha$), the number of firms in period 2 is lower than the number of firms on a path with lower level of regulation (lower $\alpha$) if at least one of the following conditions holds (at the current level of $\alpha$):

$$(1)\ \ \widetilde{\phi}_{\alpha,q} \leq 1$$

$$(2)\ \ \left(\delta\widetilde{\phi}_{x,x} - \varepsilon_{\gamma'}\frac{\gamma'}{\phi_x}\right)\left(\widetilde{\phi}_{\alpha,q} - 1\right) \leq \delta\widetilde{\phi}_{\alpha,x}\widetilde{\phi}_{x,q}$$

**Proof.** See Appendix C. ■

Under both conditions, on the path with higher level of regulation the optimal scale of each active firm in period 2 is higher. Recall the three effects of higher regulation on number of firms described earlier. Condition (1) of Proposition 4.4 implies that higher regulation shifts the effective marginal cost less than the average cost and thus both Effect 2 and Effect 3 work in the same direction i.e., bring down the number of firms. Condition (2) of Proposition 4.4 says though $\widetilde{\phi}_{\alpha,q} > 1$ (i.e., the higher regulation shifts the effective marginal cost more than the average cost) but effective marginal cost is more sensitive to investment than average cost; the indirect effect (Effect 3) of higher level of regulation is sufficiently strong enough to negate the direct effect (Effect 2).

If neither of these conditions is satisfied then higher regulation may not increase the optimal scale. In that case, the number of active firms is less if optimal scale of each firm is decreasing at a lower rate than the fall in total industry output sold in the market. An additional sufficient condition for this is provided in footnote 37 in the Appendix C.

Observe that

1. lemma 4.2 provides a necessary and sufficient condition under which on a higher regulation path the equilibrium number of active firms in period 1 is higher i.e., $\frac{dn_1}{d\alpha} > 0$ and

2. Proposition 4.4 gives a set of sufficient conditions under which on a higher regulation path the equilibrium number of active firms in period 2 is lower i.e., $\frac{dn_2}{d\alpha} < 0$.

Thus, lemma 4.2 and Proposition 4.4 imply a set of sufficient conditions under which on the equilibrium path with more stringent regulation the rate of shake-out is higher compared to that of a lower regulation path.

I consider the following example to explain the set of conditions given by each proposition in this section.

**Example 4.3:** Let

$$D(p) = p^{-a},\ D^{'} = -ap^{-a-1}, a > 0 \tag{4.44}$$

where price elasticity of demand is given by

$$\eta_p = -\frac{D^{'}(p)}{D(p)}p = a,$$

$$c(q) = B + q^b, c^{'} = bq^{b-1} > 0 \text{ and } c^{''} = b(b-1)q^{b-2} > 0 \tag{4.45}$$

where $c(0) = B > 0$ and elasticity of the production cost is

$$\widetilde{c}_{q,q} = \frac{q}{c^{'}}c^{"} = b > 1,$$

$$\gamma(x) = 0.5Gx^2,\ \gamma^{'} = Gx > 0,^{35}\ \gamma^{''} = G > 0 \tag{4.46}$$

$$\text{and}\ \ \phi(q, x, \alpha) = \alpha q^h (A - x)^k \tag{4.47}$$

where $h$ is the elasticity of marginal compliance cost of regulation with respect to output $\left(\widetilde{\phi}_{\alpha,q}\right)$ and $k$ is the elasticity of marginal compliance cost of investment with respect to regulation $\left(\widetilde{\phi}_{x,\alpha}\right)$. The details of this parametric example are worked out in the Appendix. For the

[35] This ensures that optimal investment will never reach the upper bound as marginal benefit from investing the maximum amount possible is strictly less than the marginal cost of investment i.e., $\phi_x|_{x=A} = 0 < Gx$.

compliance cost function to satisfy Assumption 1-4 I need

$$h > 1 \text{ and } k \geq 1. \tag{4.48}$$

Observe that $\frac{D(p_m(0,\alpha))}{q_m(0,\alpha)}$ is strictly increasing in $\alpha$ (the necessary and sufficient condition in Lemma 2 holds) if:

$$ah \leq 1 \text{ and } ah\left(\frac{b-1}{h-1}\right) \leq 1 \tag{4.49}$$

Condition 2 of Proposition 4.3 is satisfied i.e., on the path with higher regulation each active firm invests more if

$$k + h - 1 \geq (k-1)(h-1)^2. \tag{4.50}$$

Further, the following always holds:

$$(h-1)\left(k^2-1\right) < k^2 h.$$

so that condition 2 of Proposition 4.4 is satisfied i.e., on the equilibrium path with higher regulation, the number of firms in period 2 is lower. Therefore, the industry equilibrium path with more stringent environmental regulation generates higher shakeout as long as (4.48) and (4.49) hold.

Observe that in the above example, on the equilibrium path with more stringent environmental regulation the number of firms in period 1 may be higher whereas the number of firms in period 2 is always lower. Therefore, the effect of more stringent regulation on the market structure is time dependent i.e., though on the industry equilibrium path with higher regulation there may be higher number of firms in the initial periods but greater number of firms exit over time which implies greater rate of shake-out of firms. In particular, the mixed empirical evidence on exit of firms in the immediate years following regulation is not surprising and it is, therefore, important to look at delayed effects on turnover to capture the dynamic impact.

### 4.4. Conclusion

This paper establishes a relationship between environmental regulation and industry dynamics via investment in compliance technology. The level of regulation is exogenously fixed and constant over time. The compliance cost of a firm at each point of time depends on its current output, its accumulated past investment in firm-specific compliance cost reduction and the level of regulation. I examine the effect of increasing stringency of environmental regulation on the dynamic structure of a *deterministic* perfectly competitive industry with endogenous entry and exit. Exiting firms are smaller and have higher compliance cost. I identify sufficient conditions under which more stringent regulation leads to more investment in the reduction of future cost of compliance by active firms and higher shake-out of firms on an industry equilibrium path; the effects may be the opposite under certain circumstances. Note that higher shake-out of firms on the path with more stringent regulation does not imply an anti-competitive role of environmental regulation rather it is outcome of a socially optimal equilibrium. The analysis indicates that the effect of a change in regulation on market structure may be lagged over time; further, it explains the empirical regularities of industry dynamics and the mixed evidence of the effect of increasing stringency of environmental regulation on industry dynamics i.e., size-distribution, investment behavior, heterogeneity, and entry-exit of firms.

APPENDIX A

# APPENDIX TO CHAPTER 2

Proof of Propositions 2.1 and 2.2

Propositions 2.1 and 2.2 follow from the following characterization of the equilibrium.

**Lemma 2.1** For any $t \le t^R$, 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 $t \ge t^R$ there exists a separating equilibrium

$$P_D^* = P_D^{FI} \text{ and } P_C^* = \min\{P_C^{FI}, P^L\} \tag{4.51}$$

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 $\pi(C,1,P_C) > \pi\left(C,0,P_D^{FI}\right)$[36] 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 $\underline{P} \le P_C \le \overline{P}$ (incentive compatibility constraint of a clean type) where

$$\begin{aligned}\underline{P} &= P_C^{FI} - \sqrt{\left[P_C^{FI}-X_C\right]^2 - \frac{(A-\frac{\beta_C}{\beta_D})}{(A-1)}\left(P_D^{FI}-X_C\right)\left(P_D^{FI}-X_D\right)} \text{ and} \\ \overline{P} &= P_C^{FI} + \sqrt{\left[P_C^{FI}-X_C\right]^2 - \frac{(A-\frac{\beta_C}{\beta_D})}{(A-1)}\left(P_D^{FI}-X_C\right)\left(P_D^{FI}-X_D\right)}. \end{aligned} \tag{4.52}$$

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

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

$$\begin{aligned}
P_C &\geq P^U = \frac{1}{2}\left[1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) + X_D\right] \\
&+\frac{1}{2}\sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2} \\
\textit{or } P_C &\leq P^L = \frac{1}{2}\left[1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) + X_D\right] \\
&-\frac{1}{2}\sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2} \qquad (4.53)
\end{aligned}$$

(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.,

$$0 < X_C - X_D < \sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2} \qquad (4.54)$$

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

$$0 < X_D - X_C < \sqrt{\left(1 + \overline{\rho}(A - \frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A - \frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2} \tag{4.55}$$

Proof of Proposition 2.3.

From Lemma 2.1, we know that for any $t \leq t^R$ in the unique separating equilibrium the clean type charges a price $P_C^* = \max\{P_C^{FI}, P^U\}$. Now observe that $P_C^{FI} \geq P^U$ when $t \leq t^U$ and $t^U \leq 0$ if $\overline{\rho} \geq \rho^* = \sqrt{\frac{\left(1-\frac{\beta_C}{\beta_D}\right)(1-m_D)^2+(A-1)(m_C-m_D)^2}{\left(1-\frac{\beta_C}{\beta_D}\right)(A-1)\left(A-\frac{\beta_C}{\beta_D}\right)}}$. Therefore, if $\overline{\rho} \geq \rho^*$ then $P_C^* = P^U$ whereas if $\overline{\rho} < \rho^*$ then for any $t \leq t^U$ $P_C^* = P_C^{FI}$ and for any $t \in [t^U, t^R]$ $P_C^* = P^U$. We also know that for any $t \geq t^R$ 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 2.4

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

$$\begin{aligned}
\Delta &= P^U - P_C^{FI} \\
&= \frac{1}{2}\left(X_D - X_C\right) + \frac{1}{2}\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2} \\
&> 0 \text{ from } (4.54)\,.
\end{aligned}$$

Observe that

$$\begin{aligned}
\frac{\partial \Delta}{\partial t} &= \frac{1}{2}\left(\beta_D - \beta_C\right) + \frac{1}{2}\frac{\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(1+\overline{\rho}(A-1) - X_D\right)\beta_D - \left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)\beta_D}{\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2}} \\
&= \frac{1}{2}\beta_D[(1-\frac{\beta_C}{\beta_D}) + \frac{\left(A-\frac{\beta_C}{\beta_D}\right)\left(1+\overline{\rho}(A-1) - X_D\right) - (A-1)\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)}{2\left(A-1\right)\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2}} \\
&= \frac{1}{2}\beta_D\left[(1-\frac{\beta_C}{\beta_D}) + \frac{\left(1-\frac{\beta_C}{\beta_D}\right)\left(1-X_D\right)}{\left(A-1\right)\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2}}\right] \\
&= \frac{\beta_D(1-\frac{\beta_C}{\beta_D})}{2(A-1)W}\left[1 - X_D + \left(A-1\right)W\right] \qquad (4.56)
\end{aligned}$$

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

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

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

$$X_D - 1 < (A-1)W. \qquad (4.57)$$

Squaring both sides of (4.60) we get

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

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

$$\begin{aligned} \overline{\rho}^2(A-1)^2 &< \frac{(A-1)^3\left(1-\frac{\beta_C}{\beta_D}\right)\left(A-\frac{\beta_C}{\beta_D}\right)\overline{\rho}^2}{\left[1+(A-1)^2\left(1-\frac{\beta_C}{\beta_D}\right)\right]} \\ (A-1) &> \frac{1}{\left(1-\frac{\beta_C}{\beta_D}\right)^2} \end{aligned} \tag{4.58}$$

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

$$\begin{aligned} \Delta &= P^L - P_C^{FI} \\ &= \frac{1}{2}\left(X_D - X_C\right) - \frac{1}{2}\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2} \\ &< 0 \text{ from } (4.55) \end{aligned}$$

and

$$\begin{aligned} \frac{\partial(-\Delta)}{\partial t} &= -\frac{1}{2}\left(\beta_D - \beta_C\right) + \frac{1}{2}\frac{\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(1+\overline{\rho}(A-1) - X_D\right)\beta_D - \left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)\beta_D}{\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2}} \\ &= \frac{1}{2}\beta_D[-(1-\frac{\beta_C}{\beta_D}) + \frac{\left(A-\frac{\beta_C}{\beta_D}\right)\left(1+\overline{\rho}(A-1) - X_D\right) - (A-1)\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)}{2\left(A-1\right)\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2}} \\ &= \frac{1}{2}\beta_D\left[-(1-\frac{\beta_C}{\beta_D}) + \frac{\left(1-\frac{\beta_C}{\beta_D}\right)\left(1-X_D\right)}{(A-1)\sqrt{\left(1+\overline{\rho}(A-\frac{\beta_C}{\beta_D}) - X_D\right)^2 - 4\frac{A-\frac{\beta_C}{\beta_D}}{A-1}\left(P_D^{FI} - X_D\right)^2}}\right] \\ &= \frac{\beta_D(1-\frac{\beta_C}{\beta_D})}{2(A-1)W}\left[1 - X_D - (A-1)\,W\right] \end{aligned} \tag{4.59}$$

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

$$1 - X_D < (A-1)\,W. \tag{4.60}$$

Squaring both sides of (4.60) we get

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

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

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

<u>Proof of Proposition 2.5</u>

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 $t \in \left[t^R, t^D\right]$

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

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

Proof of Proposition 2.6

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 $f \leq \mu\pi\left(C,1,P_C^*\right) + (1-\mu)\,\pi\left(D,0,P_D^*\right) - \pi\left(D,0,P_D^*\right) = \mu\left[\pi\left(C,1,P_C^*\right) - \pi\left(D,0,P_D^*\right)\right].$

APPENDIX B

## APPENDIX TO CHAPTER 3

Under higher level of emission price i.e., for any emission price $t \geq t^R = \frac{m_C - m_D}{\beta_D - \beta_C}$, the effective marginal cost of a clean type is lower than that of a dirty type $(X_C \leq X_D)$. In this case, I find the following unique symmetric Bayesian equilibrium:

**Lemma 3.6:** For any emission price $t \geq t^R$, there exists a unique symmetric separating D1 equilibrium where the dirty type charges a deterministic price $p_D = X_D$, and the clean type follows the mixed strategy with support $[\underline{P}_C, X_D)$ and a continuous distribution function $F_C(p)$, where $\underline{P}_C = \mu X_C + (1-\mu) X_D$ and $F_C(p) = 1 - \frac{1-\mu}{\mu}\left(\frac{X_D - X_C}{p - X_C} - 1\right)$. Thus, under strong regulation, lower price signals better environmental performance (clean type).

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

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

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

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

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

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

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

which is equal to $\pi_C^*$. From this we can derive that

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

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

The symmetric Bayesian equilibrium described above can be supported by the following out-of-equilibrium beliefs of consumers: if a firm charges any price $p > X_D$ then consumers believe that the firm is dirty type with probability one, whereas if a firm charges a price $p < \underline{P}_C$ then consumers believe that it is clean type with probability one. Given these out-of-equilibrium beliefs, no firm has an incentive to unilaterally deviate to any out-of-equilibrium price. It can be argued that these out-of-equilibrium beliefs satisfy the D1 refinement. Consider any out-of-equilibrium price; observe that for any level of quantity, if it is profitable for a clean type to deviate to the out-of-equilibrium price then the dirty type also finds it strictly profitable to deviate to such a price.

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

For any emission price $t \geq t^R$ the ex ante expected profit of any firm

$$\begin{aligned} \pi^* &= 0 \text{ when no firm invests} \\ &= \mu (X_D - X_C) \text{ when one firm invests} \\ &= \mu (1-\mu)(X_D - X_C) \text{ when both firms invest} \end{aligned}$$

which implies that the unilateral incentive to invest is

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

and the reciprocal incentive to invest is

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

which implies that both firms will never invest in the equilibrium.

**Proposition 3.11:** When consumers and rival firm are not aware of the actual environmental performance of a firm, one firm invests in the equilibrium if the unilateral incentive to invest ($UI_{II}$) in cleaner technology is higher than the fixed cost of investment ($f$).

Note that if unit production cost of a cleaner technology is lower than that of the dirty type i.e.,

$$0 < m_C < m_D$$

then for any level of emission price ($t \geq 0$) the effective marginal cost of the clean type is always less than that of the dirty type $(X_C < X_D)$. In this case, one firm invests in the equilibrium as long as the unilateral incentive to invest is greater than the fixed cost of investment (see Proposition 3.11).

APPENDIX C

## APPENDIX TO CHAPTER 4

**Example 4.4:** Let

$$D(p) = 100 + p^{-1}, \qquad c(q) = 1 + q^2, \qquad \gamma(x) = 0.5x^2$$

$$\phi(y, \alpha) = \alpha F (1 - y)^3$$

where $\alpha F$ is the initial fixed cost of complying with regulation $\alpha$ and this can reduced by investment. I consider two alternative levels of regulation: $\alpha = 0.05$ and 0.10. I set $F = 10$, $\delta = 0.5$. The following are the equilibrium price, output per firm, investment by each firm and number of firms in the industry for $\alpha = 0.05$ and 0.10 respectively :

**Table 4.6**

| $\alpha$ | $p_1 = p_2$ | $q_1 = q_2$ | $x$ | $n_1 = n_2$ |
|---|---|---|---|---|
| 0.05 | 2.3830 | 1.1915 | 0.3333 | 84.2776 |
| 0.10 | 2.6755 | 2.6755 | 0.4514 | 72.7513 |

Therefore, if the environmental regulation is such that it does not affect the effective marginal cost of production then on the dynamic equilibrium path the price, output produced by each firm and number of firms do not change.

Since from the first part of Proposition 4.2 $(a)$ I already know that prices are non-increasing over time therefore it is sufficient to show that if $\phi_{qy} < 0$ then $p_1 \neq p_2$. Suppose this is not true i.e., $p_1 = p_2$. If some firms exit at the end of period 1 then equilibrium price in period 1 is exactly equal to the minimum average cost of a firm with zero accumulated investment i.e., $p_1 = p_m(0, \alpha) = p_2$ and the firms produce at the minimum scale in period 1 i.e., $q_1 = q_m(0, \alpha)$. Then because of Assumption 3 i.e., $\gamma'(0) < -\delta\phi_y(q, 0, \alpha)\, \forall q > 0, \alpha > 0$, with $\varepsilon > 0$ investment a firm can make strictly positive intertemporal profit if it continues to produce the same output in period 2 i.e., $q_2 = q_1 = q_m(0,\alpha)$. Q.E.D.

**Lemma** 4.1 Define $f(p_2) = \max_{q_2,x}\left[\delta\{p_2 q_2 - c(q_2) - \phi(q_2,x,\alpha)\} - \gamma(x)\right]$. There exists a unique $p_2$, say $\widehat{p_2}$, such that $f(\widehat{p_2}) = 0$. Further, $q_2(\widehat{p_2}) = q_2^*$ and $x\left(\widehat{p_2}\right) = x^*$ where $q_2^*$ and $x^*$ are the output produced and investment incurred by each firm in period 2 on the industry equilibrium path..

**Proof.** Observe that, $f(p_2)$ is continuous in $p_2$ by the theorem of the maximum. Now, $x = 0$ cannot be a solution to this maximization problem as I have assumed $\gamma^{'}(0) + \delta\phi_y(q,0,\alpha) < 0 \forall q, \alpha$ (Assumption 3). Therefore, for any $x > 0$, at $p_2 = p_m(0,\alpha)$ $f(p_m(0,\alpha)) > 0$ and at $p_2 = 0$ $f(0) < 0$.Thus one can conclude that $f(p_2)$ is strictly increasing in $p_2$ and from intermediate theorem one can say that there exists a unique $p_2 = \widehat{p_2}$ such that $f(\widehat{p_2}) = 0$.From equilibrium condition given by (4.43) it is obvious that $p_2^* = \widehat{p_2}$ and thus $q_2^* = q_2(\widehat{p_2})$ and $x^* = x\left(\widehat{p_2}\right)$. ■

**Proof of Proposition** 4.3 : To determine the sign of $\frac{dn_2}{d\alpha}$ I take total differential of $(4.43)$, $(4.40)$, $(4.41)$, and market clearing condition for period 2 i.e., $n_2 q_2 = D(p_2)$ w.r.t. $\alpha$. respectively:

$$\delta\left[p_2 - c^{'} - \phi_q\right]\frac{dq_2}{d\alpha} - \left[\gamma^{'} + \delta\phi_x\right]\frac{dx}{d\alpha} + \delta\left[q_2\frac{dp_2}{d\alpha} - \phi_\alpha\right] = 0 \tag{4.1}$$

$$(c^{''} + \phi_{qq})\frac{dq_2}{d\alpha} + \phi_{qx}\frac{dx}{d\alpha} - \frac{dp_2}{d\alpha} + \phi_{q\alpha} = 0 \tag{4.2}$$

$$\delta\phi_{xq}\frac{dq_2}{d\alpha} + \left(\gamma^{''} + \delta\phi_{xx}\right)\frac{dx}{d\alpha} + \delta\phi_{x\alpha} = 0 \tag{4.3}$$

$$n_2\frac{dq_2}{d\alpha} + q_2\frac{dn_2}{d\alpha} - D^{\prime}\frac{dp_2}{d\alpha} = 0 \tag{4.4}$$

Substituting (4.40) and (4.41) in (4.1) I get

$$\frac{dp_2}{d\alpha} = \frac{\phi_\alpha}{q_2} > 0 \tag{4.5}$$

Further, solving (4.2) and (4.3) I derive the following:

$$\frac{dq_2}{d\alpha} = \frac{\left(\gamma^{''} + \delta\phi_{xx}\right)\overbrace{\left(\frac{\phi_\alpha}{q_2} - \phi_{q\alpha}\right)} + \delta\phi_{x\alpha}\phi_{qx}}{\left[\left(c^{''} + \phi_{qq}\right)\left(\gamma^{''} + \delta\phi_{xx}\right) - \delta\phi_{xq}\phi_{qx}\right]} \tag{4.6}$$

$$\frac{dx}{d\alpha} = \frac{-\delta\phi_{x\alpha}\left(c^{''} + \phi_{qq}\right) - \delta\phi_{xq}\overbrace{\left(\frac{\phi_\alpha}{q_2} - \phi_{q\alpha}\right)}}{\left[\left(c^{''} + \phi_{qq}\right)\left(\gamma^{''} + \delta\phi_{xx}\right) - \delta\phi_{xq}\phi_{qx}\right]} \tag{4.7}$$

From the social planner problem it can be shown that

$$\left[\left(c^{''}+\phi_{qq}\right)\left(\gamma^{''}+\delta\phi_{xx}\right)-\delta\phi_{xq}\phi_{qx}\right]>0. \tag{4.8}$$

Therefore, from (4.7) note that

$$\boxed{\frac{dx}{d\alpha}>0 \ \text{ if } \ \widetilde{\phi}_{\alpha,q}\leq 1} \ \text{ and}$$

$$\boxed{\frac{dx}{d\alpha}>0 \text{ if } \ \widetilde{\phi}_{\alpha,x}\varepsilon_{c'}\frac{c^{'}}{\phi_q}+\widetilde{\phi}_{\alpha,x}\widetilde{\phi}_{q,q}>\widetilde{\phi}_{q,x}(\widetilde{\phi}_{\alpha,q}-1)}.$$

**Proof of Proposition** 4.3 : Substituting (4.5) and (4.6) in (4.4) I get

$$\frac{dn_2}{d\alpha} = \frac{1}{q_2}\left[D'\frac{dp_2}{d\alpha}-n_2\frac{dq_2}{d\alpha}\right] \tag{4.9}$$

$$= \frac{D'\phi_\alpha\left[\left(c^{''}+\phi_{qq}\right)\left(\gamma^{''}+\delta\phi_{xx}\right)-\delta\phi_{xq}\phi_{qx}\right]-\delta D(p_2)\phi_{x\alpha}\phi_{qx}}{q_2^2\left[\left(c^{''}+\phi_{qq}\right)\left(\gamma^{''}+\delta\phi_{xx}\right)-\delta\phi_{xq}\phi_{qx}\right]}$$

$$-\frac{D(p_2)\left(\gamma^{''}+\delta\phi_{xx}\right)\overbrace{\left(\frac{\phi_\alpha}{q_2}-\phi_{q\alpha}\right)}}{q_2^2\left[\left(c^{''}+\phi_{qq}\right)\left(\gamma^{''}+\delta\phi_{xx}\right)-\delta\phi_{xq}\phi_{qx}\right]} \tag{4.10}$$

Observe that, $\frac{dn_2}{d\alpha}<0$ if $\frac{dq_2}{d\alpha}>0$ (from (4.9)) and from (4.6) $\frac{dq_2}{d\alpha}>0$ if either of these holds

$$\boxed{(1)\ \widetilde{\phi}_{\alpha,q}\leq 1}$$

$$\boxed{(2)\ \left(\delta\widetilde{\phi}_{x,x}-\varepsilon_{\gamma'}\frac{\gamma^{'}}{\phi_x}\right)(\widetilde{\phi}_{\alpha,q}-1)\leq\delta\widetilde{\phi}_{\alpha,x}\widetilde{\phi}_{x,q}}.$$

The proof is complete.[37]

**Calculations for the example 4.3** :

$$\phi\left(q,x,\alpha\right)=\alpha q^h(A-x)^k$$

satisfies **Assumption 1** $-$ **4** stated in Section **??** i.e.,

Assumption 1: $\phi\left(q,x,0\right)=0$ and $\phi\left(0,x,\alpha\right)=0$.

Assumption 2: $\phi_q=\alpha h q^{h-1}(A-x)^k>0\Rightarrow h>0$, $\phi_x=-\alpha k q^h(A-x)^{k-1}\leq 0\Rightarrow k\geq 0$

and $\phi_\alpha=q^h(A-x)^k>0$.

[37] From (4.10) and (4.8) $\frac{dn_2}{d\alpha}<0$ if $\varepsilon_p\left[\left(\varepsilon_q\frac{c^{'}}{\phi_q}+\widetilde{\phi}_{q,q}\right)\left(\delta\widetilde{\phi}_{x,x}-\varepsilon_{\gamma'}\frac{\gamma^{'}}{\phi_x}\right)-\delta\widetilde{\phi}_{q,x}\widetilde{\phi}_{x,q}\right]$
$>\frac{p_2}{\phi_q}\left[\left(\delta\widetilde{\phi}_{x,x}-\varepsilon_{\gamma'}\frac{\gamma^{'}}{\phi_x}\right)(\widetilde{\phi}_{\alpha,q}-1)-\delta\widetilde{\phi}_{\alpha,x}\widetilde{\phi}_{x,q}\right]$

Assumption 3: $\gamma^{'}(0) + \delta\phi_x(q, 0, \alpha) = -\delta\alpha k q^h A^{k-1} < 0.$

Assumption 4: $\phi_{qq} = \alpha h(h-1) q^{h-2}(A-x)^k > 0 \Rightarrow h > 1,\ \ \phi_{qx} = -\alpha k h q^{h-1}(A-x)^{k-1} \leq 0,$ $\phi_{q\alpha} = hq^{h-1}(A-x)^k > 0,\ \ \phi_{xx} = \alpha k(k-1) q^h (A-x)^{k-2} \geq 0 \Rightarrow k \geq 1$ and $\phi_{x\alpha} = -kq^h(A-x)^{k-1} \leq 0.$

In order to illustrate lemma 4.2 I calculate the following

$$\begin{aligned}
\frac{dn_1}{d\alpha} &= \frac{d\left(\frac{D(p_m(0,\alpha))}{q_m(0,\alpha)}\right)}{d\alpha} \\
&= \frac{D(p_m(0,\alpha))}{\alpha q_m(0,\alpha)}\left[\frac{D^{'}(p_m(0,\alpha))}{D(p_m(0,\alpha))} p_m(0,\alpha)\frac{\alpha}{p_m(0,\alpha)}\frac{dp_m(0,\alpha)}{d\alpha} - \frac{\alpha}{q_m(0,\alpha)}\frac{dq_m(0,\alpha)}{d\alpha}\right] \\
&= \frac{D(p_m(0,\alpha))}{\alpha q_m(0,\alpha)}\left[-\frac{ah\alpha A^k}{bq^{b-h} + \alpha h A^k} + \frac{\alpha A^k}{b\left(\frac{b-1}{h-1}\right) q^{b-h} + \alpha h A^k}\right] \qquad (4.11)
\end{aligned}$$

Observe that on a higher regulation path the rate of fall of total output sold is captured by the first term in parenthesis where the change in equilibrium price is induced by the introduction of a higher level of regulation whereas the rate of decline of the minimum efficient scale in period 1 is given by the second term.

$$\frac{dn_1}{d\alpha} > 0 \text{ if } \ bq^{b-h}\left[1 - ah\left(\frac{b-1}{h-1}\right)\right] + \alpha h A^k[1 - ah] > 0.$$

One of the conditions on the parameters under which this is possible is

$$ah \leq 1 \text{ and } ah\left(\frac{b-1}{h-1}\right) \leq 1.$$

the first condition of Proposition 4.3 is not satisfied as

$$\widetilde{\phi}_{\alpha,q} = h > 1.$$

Whereas condition 2 of Proposition 4.3 i.e.,

$$\delta\alpha(h-1) k(k-1)(A-x)^{k-2} q^h - G(h-1) \leq \delta\alpha h k^2 (A-x)^{k-2} q^h$$

is always true since

$$(h-1)\left(k^2-1\right) < k^2 h.$$

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