Regulation, Innovation, and Firm Selection: The Porter Hypothesis Revisited

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Abstract

The Porter Hypothesis (PH) posits that well-designed environmental regulations can stimulate innovation, which may lead to efficiency gains or even profit increase for the regulated firms. Extant theoretical works examining the PH neglect two important aspects in their models and analyses: firm heterogeneity and general equilibrium. In this study, we revisit the PH by incorporating these two features in our model and analysis. We show that the PH holds for high-capability firms, but not for low-capability firms. Although heterogeneous responses exist in innovation investment, the average industry productivity increases.

Keywords: pollution; heterogeneous firms; environmental regulations; Porter Hypothesis

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1 Introduction

In a controversial article, Porter and van der Linde (1995) challenge the conventional view that stringent environmental regulations reduce firm competitiveness because of the additional costs to meet the regulations. They argue that "properly designed environmental standards can trigger innovation that may partially or more than fully offset the cost of complying with them" (Porter and van der Linde 1995, p. 98). This argument is well known as the Porter Hypothesis (PH).

Porter and van der Linde (1995) use a large number of cases to support their argument. Since the publication of their paper, the PH has been extensively scrutinized both theoretically and empirically. Researchers often divide the PH into two versions: the "weak version" claims that properly designed environmental regulations may spur firm innovations whereas the "strong version" extends that properly designed regulations can increase firm performance, such as competitiveness and profits (Ambec et al., 2013). Results from existing empirical studies are mixed partly because they are derived from data of different countries, industries, and time periods. The "weak version" has acquired more supportive evidence than the "strong version". Nevertheless, findings from other recent studies provide additional supportive results to the "strong version" (Ambec et al., 2013).[1]

In theoretical analysis, the PH has received significant attention because conventional wisdom based on standard economic models often suggests the opposite: tightening environmental regulations will lower revenue (e.g., in the case of pollution tax) and/or increase production cost (e.g., in the case of emission standard), thus reducing firms' innovation incentive because the marginal benefit from innovation decreases (Palmer et al., 1995). Models generating results in support of the PH deviate from standard models. Many existing theoretical studies find evidence supporting the PH, mostly the "weak version", by introducing different types of frictions (or "failure") to standard models. In this study, we do not rely on *ad hoc* frictions to analyze the PH. Instead, we introduce firm heterogeneity to the standard monopolistic competition model with general equilibrium analysis and reexamine the PH, both the "weak version" and "strong version", within this framework. Our framework is more applicable to the real world than those in the existing theoretical studies on the PH, and it allows empirical researchers to conduct their analysis on the basis of measurable variables and verifiable conditions.

Specifically, we introduce pollution and innovation investment to the model of Melitz and Ottaviano (2008), which features heterogeneous firms in a monopolistically competitive industry. To emphasize the distinguishing features of this studies compared with those in the literature, we first examine the partial equilibrium outcomes of the model, which is equivalent to the

[1] Jaffe et al. (1995) provide an earlier survey of this literature. Using the US data on paper mills' technological choice, Gray and Shadbegian (1998) find that stricter regulations tend to divert investment from productivity to abatement, thus hindering productivity growth. Based on OECD survey data, Lanoie et al. (2011) provide evidence of the causal link suggested by the PH. A recent paper by Greenstone et al. (2012) uses a comprehensive data and sophisticated method to estimate the effects of environmental regulations on the competitiveness of US manufacturing. The effects are generally negative, that is, strict environmental regulations result in decreased total factor productivity. The opposite finding is obtained for carbon monoxide regulations.

monopoly model in Section 2. We show that a stringent environmental regulation, or an increase in compliance cost, leads to different responses of firms in their innovation investments. Firms with high capability of innovation increase their investments, whereas firms with low capability of innovation reduce their investments. Firms with the lowest capability of innovation even stop operation and exit the market. The PH holds for some firms but not for others within the same industry. These heterogeneous responses are due to two opposite forces in operation when the compliance cost increases. On one hand, provided that the production scale is fixed, firms are incentivized to increase their innovation investments for improving operating efficiency as the marginal benefits of investment (to offset the increased compliance cost) grow. On the other hand, every firm downsizes its production scale, thus reducing the incentive to invest because the benefit of investment is shared across all units of production. Under reasonable conditions, the negative scale effect is dominated by the positive cost-offsetting effect for high-capability firms, but the opposite outcome holds for low-capability firms.

When firms adjust their innovation investments and production scale, the competition environment changes. The changed competition environment further induces individual firms to adjust their investments and production. This latter effect is the general equilibrium effect of tightening environmental regulations. In the partial equilibrium case, the least capable firms exit the market, relaxing the competition for the surviving firms and providing additional incentives for the surviving firms to invest in innovation. If the general equilibrium effect is sufficiently strong, the resulting equilibrium profits for the most capable firms can *increase* despite the rising compliance cost. This effect lends support to the "strong version" of the PH. The regulations may even raise the total industry investments in innovations, and thus, the whole industry becomes more productive.

Brannlund and Lundgren (2009) and Ambec et al. (2013) provide comprehensive literature reviews of the PH. We only discuss some of the existing theoretical studies to highlight the connections and contributions of the present paper.

One set of studies are related to market failure. For example, Morh (2001) considers the situation in which new technology is available but nobody adopts it because, on one hand, there is a learning cost in adopting the new technology, and on the other hand, there is a positive externality of using the new technology on other firms in the industry. Under such situation, the new technology may not be introduced, resulting in a suboptimal outcome. If the regulation authority introduces an environmental policy that forces all firms to adopt the new technology, the outcome can be a win-win situation. Andre and Gonzalez (2009) and Greaker (2006) also examine coordination failure under other situations: Andre and Gonzales (2009) focus on product quality, while Greaker (2006) look into technology spillover. A common point made in these studies is that although market fails to solve the coordination problem, environmental regulations can. In the same vein, Xepapadeas and de Zeeuw (1999) analyze firms' capital investment decision when faced with pollution tax. They assume that firms can change their composition of capital by installing modern machines and disposing old ones. Although modern machines are both more productive and less pollution-intensive, installing such machines requires additional cost. In this setup, Xepapadeas and de Zeeuw (1999) find that increase in production costs, resulted from stringent environmental policy, triggers a modernization of the capital stock and thus increases average productivity. However, firms profit decreases, not supporting the "strong version" of the PH.[2] Hart (2004) constructs an environmental new-growth model, which combines two types of research (environmentally oriented and ordinary research) with production vintages, to show that an environmental tax not only gives incentives to reduce pollution (through more environmentally oriented research) and shifts profits from old vintages to new, but also possibly increase growth rate.

Another set of studies focus on organizational failure. By developing a principal-agent model with renegotiation, Ambec and Barla (2002) formalize the idea that stringent environmental regulations may help firms to overcome organization inertia and thus increase productivity. In their model, a manager (the agent) obtains private information about the outcome of an investment in research and development (R&D). A successful R&D program implies both a more productive and less pollution intensive production technology. To favor revelation by the agent, informational rent must be offered to the agent. The information rent is a cost for the principal (the owner of the firm) that reduces incentive to invest in R&D. Ambec and Barla (2002) show that environmental regulations reduce informational rent and thus increases R&D.

The present paper is different from the above-discussed theoretical literature in two ways. First, all existing models assume either a single firm or many *identical* firms. Under such assumptions, all firms respond to a change in environmental regulations in a uniform manner. By contrast, we explicitly assume that firms within the same industry are heterogenous. Actually, firms differ in many aspects. Although most studies following the recent literature of international trade assume firm heterogeneity in production productivity (Melitz, 2003), the present paper assumes that firms possess *different innovation capabilities*. In the technology literature, researchers have defined the characteristics of innovation capability and emphasized the importance of innovation capability in affecting firm performance (Adler and Shenbar, 1990; Christensen, 1995; Guan and Ma, 2003; Acemoglu et al., 2013). Our result that firms with different innovation capabilities respond to environmental regulations distinctly can help to understand the contradictory empirical evidence found in different studies: By pooling all observations in a regression analysis, the estimated results only deliver the average effects across firms.[3]

Second, another aspect that is overlooked by previous studies is the general equilibrium effect of environmental policies. Firms' innovation incentives depend crucially on the competitive environment in which the firms operate. Firms' innovations in return change the competition. Thus, environmental regulations that apply universally to all firms in an industry ultimately

[2] Feichtinger et al. (2005) show that the positive result of Xepapadeas and de Zeeuw (1999) is sensitive to the functional forms of their model and that the opposite can possibly occur when those functional forms are changed, that is, an emission tax may actually increase the capital's average age.

[3] Cao et al. (2016) find that faced with the same environmental regulation, Chinese firms with different productivity make different investments in advanced abatement technologies. This evidence supports the prediction of their theory.

alters the competitive environment of the industry. By considering this general equilibrium effect, the present study shows that the PH tends to be supported.

The rest of the paper is organized as follows. In Section 2, we analyze the monopoly model. In Section 3, we examine the monopolistic competition model to emphasize the general equilibrium effect. In Section 4, we check the main results under a general consumer preference. In Section 5, we explore the case of a different type of environmental regulation (i.e., emission standard) as opposed to pollution tax in all other sections. In Section 6, we conclude the paper.

2 Monopoly Model

In this section, we consider and analyze a monopoly model. Specifically, we assume that in an economy, a continuum of industries exists, and these industries are symmetric and independent. The inverse demand curve in each industry is assumed to be linear, given as $p = A - bq$, where A is a demand shifter that is exogenously given.

Each industry consists of one firm. Each firm needs to invest on an innovation to obtain the technology to produce its product. We assume that each firm obtains its innovation capability (i.e., innovative capacity in Acemoglu et al., 2013), denoted as $\theta \geq 0$, randomly from a distribution $G(\theta)$. Upon realizing its draw of θ, every firm makes a decision whether to stay in or exit its industry. If a firm stays, it first chooses the level of innovation investment k, which gives the firm the following production function (technology):

$$x = \frac{q^2}{k},$$

where q is the unit of output, and x is the unit of intermediate inputs required to produce q. The cost of investment for a firm with its drawn capability θ, called a type-θ firm, is θk. Thus, a firm's innovation capability is higher if its θ is lower. Following Copeland and Taylor (2003), we assume that production of the intermediate inputs generates pollution, but production of the final goods does not. The firm chooses and allocates labor optimally between intermediate inputs and abatement activities. Consequently, we can assume that producing the inputs requires both labor (l) and emission (z) in the Cobb-Douglas form described as follows:[4]

$$x = z^{\eta} \cdot l^{1-\eta}, \quad \eta \in (0, 1). \tag{1}$$

[4] Suppose that producing intermediate inputs generates pollution as a by-product. Pollution can be reduced if a firm puts resources into abatement activities. Assume that by allocating a fraction, Δ, of labor l into abatement activities, the amount of intermediate inputs (x) and emission (z) is given by $x = (1 - \Delta)l$, and $z = \varphi(\Delta)l$, where $0 \leqslant \Delta \leqslant 1$, $\varphi(0) = 1$, $\varphi(1) = 0$ and $d\varphi/d\Delta < 0$. As in Copeland and Taylor (2003), assume $\varphi(\Delta) = (1 - \Delta)^{\frac{1}{\eta}}$, where $\eta \in (0, 1)$. We can use the above three equations to eliminate Δ, and get $x = z^{\eta} l^{1-\eta}$. Thus, although pollution is a by-product of intermediate input production, we can equivalently view it as an input of the final good production.

We suppose that each unit of pollution emission is charged with a pollution tax τ and that the wage rate is given as w. Wage rate w is exogenously given, and so without loss of generality, we normalize $w = 1$. Then, the implied minimum cost of unit input is given by

$$c = \eta^{-\eta} \cdot (1-\eta)^{-(1-\eta)} \cdot \tau^{\eta}.$$

Thus, changes in c is equivalent to changes in τ, and for succinctness, we refer to c as *compliance cost*. In what follows, we use *tightening of regulation* to signify that the regulation authority raises the compliance cost c.

As c is the unit cost of input, the total production cost for a firm with investment k and output q is given by

$$cx = \frac{cq^2}{k}. \tag{2}$$

A type-θ firm's profit is given by

$$\pi(\theta) = (A - bq)q - \frac{cq^2}{k} - \theta k.$$

We can view a firm's profit optimization as a two-stage decision. In the first stage, the firm chooses the level of investment k. In the second stage, it decides on how much to produce, that is, the level of q.

We solve the problem backwards. Conditional on k, the firm's second-stage problem is to maximize the operating profit: $Max_{q\geq 0}\left[(A-bq)q - \frac{cq^2}{k}\right]$. From the first-order condition, we obtain the optimal quantity produced and the optimal operating profit, denoted as $\Pi(k)$:

$$\widetilde{q}(k) = \frac{Ak}{2(bk+c)} \quad \text{and} \quad \Pi(k) = \frac{A^2 k}{4(bk+c)}.$$

Moving backward, the first-stage problem is: $Max_{k\geq 0}\left[\Pi(k) - \theta k\right]$. From the first-order condition, we obtain the optimal level of investment

$$k^*(\theta) = \frac{1}{b}\left(\frac{A\sqrt{c}}{2\sqrt{\theta}} - c\right). \tag{3}$$

As a result, the optimal quantity produced and price are

$$q^*(\theta) = \frac{A - 2\sqrt{\theta c}}{2b} \text{ and } p^*(\theta) = \frac{A + 2\sqrt{\theta c}}{2}.$$

The corresponding profit is given by

$$\pi^*(\theta) = \Pi(k^*(\theta)) - \theta k^*(\theta) = \frac{1}{4b}(A - 2\sqrt{\theta c})^2 \tag{4}$$

Clearly, $\frac{\partial k^*(\theta)}{\partial \theta} < 0$. That is, high capability firms invest more in innovation because their investments are more effective (i.e., marginal returns to investment is higher).

A firm obtains non-negative profit, or can survive, if and only if $k(\theta) \geq 0$. On the basis of (3), we find that after drawing their respective θ, firms with innovation capability $\theta \leq \theta^*$ stay in their respective industries, whereas firms with $\theta > \theta^*$ exit their industries, where

$$\theta^* \equiv \frac{A^2}{4c}.$$

An increase in the compliance cost results in a smaller cutoff θ^*, that is, fewer firms can survive. This result is the *selection effect.*

We now evaluate the PH. In particular, we examine how a firm's innovation investments responds to an increase in compliance cost c. To answer this question, we derive partial derivative of k with respect to c and obtain

$$\frac{\partial k^*}{\partial c} = \frac{1}{2b\sqrt{c}}\left(\frac{A}{2\sqrt{\theta}} - 2\sqrt{c}\right). \tag{5}$$

Thus,

$$\frac{\partial k^*}{\partial c} > 0 \quad \text{if and only if} \quad \theta < \hat{\theta} \equiv \frac{A^2}{16c}.$$

The above analysis leads to the following proposition.

Proposition 1: *In the monopoly model, in response to an increase in compliance cost,*

(i) marginal firms (i.e., least capable firms) exit their industries; and

(ii) for surviving firms, those with high innovation capability, $\theta < \hat{\theta}$*, increase their innovation investments, whereas those with low innovation capability,* $\theta \in (\hat{\theta},\, \theta^*)$*, reduce their innovation investments.*

This proposition indicates that the "weak version" of the PH holds for high-capability firms, but fails for low-capability firms. The question is why firms with varying levels of innovation capability react to the same policy change in the opposite directions. Two opposing forces arise from an increase in the compliance cost. On one hand, holding production scale constant, operating cost increases with rising compliance cost; and thus, a firm acquires stronger incentives to undertake more R&D to offset the increased compliance cost. That is, the marginal benefit of innovation increases. On the other hand, when the compliance cost rises, a firm's production scale shrinks, which reduces R&D incentives because the marginal benefit of innovation decreases. The proposition implies that for high-capability firms, the positive effect (i.e., cost-offsetting effect) dominates, whereas for low-capability firms, the negative effect (i.e., scale effect) dominates. The following analysis demonstrates such difference.

We reconsider a firm's decision as the following two stages, which are equivalent to the maximization analyzed earlier to obtain (3). In the first stage, the firm chooses k to minimize its total cost (including variable cost and investment cost) for any given quantity produced: $Min_{k\geq 0}\left(\frac{cq^2}{k}+\theta k\right)$. This decision yields the investment function: $k=k(q,c)=\sqrt{\frac{c}{\theta}}q$. From which we obtain

$$\frac{\partial k}{\partial c}=\frac{q}{2\sqrt{\theta c}}>0 \quad \text{and} \quad \frac{\partial k}{\partial q}=\sqrt{\frac{c}{\theta}}>0.$$

The first property shows that holding q constant, when c increases, the firm has an incentive to increase k. This consequence is the cost-offsetting effect. The second property indicates that when q is higher, the firm has an incentive to increase k. This outcome is the scale effect. The functional form $k(q,c)$ is independent of the preference (demand) structure. That is, these two effects are general.

In the second stage, taking the $k(q,c)$ schedule as given, the firm maximizes its profit by choosing the optimal quantity to produce: $Max_{q\geq 0}\left[(A-bq)q-\frac{c(\tau)q^2}{k(q,c)}-\theta k(q,c)\right]$. This choice determines the optimal quantity produced: $q=q(c)$. Substituting back into the k function, we obtain the optimal investment: $k(c)=k(q(c),c)$. Taking full derivative to derive

$$\begin{aligned}\frac{dk(c)}{dc} &= \frac{\partial k}{\partial c}+\frac{\partial k}{\partial q}\frac{dq}{dc}=\frac{\partial k}{\partial c}-\frac{\partial k}{\partial q}\frac{q}{c}\epsilon_{qc}\\ &= \frac{q}{2\sqrt{\theta c}}-\sqrt{\frac{c}{\theta}}\frac{q}{c}\epsilon_{qc}=\frac{q}{\sqrt{\theta c}}\left(\frac{1}{2}-\epsilon_{qc}\right)=\frac{q}{\sqrt{\theta c}}\left(\frac{1}{2}-\epsilon_{pc}\epsilon_{qp}\right),\end{aligned}$$

where

$$\epsilon_{qc}=-\frac{dq}{dc}\frac{c}{q}, \quad \epsilon_{pc}=\frac{dp}{dc}\frac{c}{p}, \quad \text{and} \quad \epsilon_{qp}=-\frac{dq}{dp}\frac{p}{q}.$$

As a result,

$$sign\left[\frac{dk(c)}{dc}\right]=sign\left(\frac{1}{2}-\epsilon_{pc}\epsilon_{qp}\right).$$

In equilibrium, the low-θ firms always produce more (i.e., q is higher). Under a linear demand, the high-capability firms are producing at the inelastic range of the demand curve, implying a lower ϵ_{qp} for them. When cost increases, the markup of high-capability firms are higher, allowing for a lower pass-through (lower ϵ_{pc}). These two features together explain a positive sign of $\frac{dk(c)}{dc}$ for high-capability firms (i.e., $\frac{1}{2}-\epsilon_{pc}\epsilon_{qp}>0$), and a reversed sign for low-capability firms because both ϵ_{pc} and ϵ_{qp} are large for them.

3 Monopolistic-competition model: General equilibrium effects

The preceding analysis shows how individual firms in their respective monopolist industries adjust their innovation investments *directly* in response to regulation changes. Regulations may also alter the competitive environment in the market where firms operate, which in turn further affects firms' innovation incentives. This consequence can be viewed as the indirect effect of regulation. In the previous section, we deliberately omitted the indirect effect to emphasize the direct effect. We did that by assuming that firms are monopolists, each in a different (independent) industry. To capture the indirect effect, we now assume that all firms are in the same industry characterized by monopolistic competition. In particular, all firms produce differentiated but substitutable goods. To keep the model similar to the previous one as much as possible, we adopt the consumer preference of Melitz and Ottaviano (2008), which results in linear demand for each product variety (firm). Specifically, we assume that L identical consumers exist and each (representative) consumer has the following quasi-linear preference on the industry's products:

$$U = q_0^c + \alpha \int_{i \in \Omega} q_i^c di - \frac{1}{2}\beta \left(\int_{i \in \Omega} q_i^c di \right)^2 - \frac{1}{2}\gamma \int_{i \in \Omega} (q_i^c)^2 \, di,$$

where α, β, and γ are positive parameters, q_0^c is the consumption of the numeraire good, Ω is the set of all varieties from the industry, and q_i^c is the consumption of variety i produced by firm i. A consumer maximizes her utility subject to a budget constraint. We assume that consumers have positive demands for the numeraire good. Then, market demand for variety i from all L consumers is $p_i = \alpha - \frac{\beta}{L} \int_{j \in \Omega} q_j dj - \frac{\gamma}{L} q_i$. Parameter β measures substitutability among varieties.

Let M be the measure of Ω and $P = \int_{i \in \Omega} p_i di$ be the aggregate price of all varieties. Then, the demand function for variety i can be written as

$$p_i = A - bq_i, \quad \text{where } b = \frac{\gamma}{L} \ \text{ and } \ A = \frac{\alpha\gamma + \beta P}{\beta M + \gamma}. \tag{6}$$

We are not stressing the roles of γ and L, and thus, without loss of generality, we suppose $\gamma = L$ to obtain $b = 1$, which saves notation.

Competition from all varieties is completely captured in the vertical intercept (A) of the demand function. For example, holding other things constant, if M (the measure of active firms) increases, then A decreases. The reason is that a larger number of firms in the market reflects stronger competition, which effectively reduces the size of residual demand for each firm. If on average the industry's aggregate price (P) drops, competition becomes tougher, and the residual demand for each firm shrinks correspondingly.[5] When compliance cost changes, individual firms responds to the change directly, which results in changes in M (selection effect)

[5] We can view the model/analysis in Section 2 as a partial equilibrium of the present model. In particular, in the current model, if each firm treats its demand shifter A fixed when adjusting its innovation investment and production decision, the situation is exactly the same as in the monopoly model.

and P. Consequently, A changes, which further induces changes in individual firms' innovation incentives. This outcome is the *general equilibrium effect*, which is absent in the previous model.

To simplify the ensuing analysis and to follow the literature, we parameterize the model by assuming that the innovation-capability parameter θ follows a Pareto distribution with cumulative distribution function $G(\theta) = \theta^{\sigma}$, for $\theta \in [0, 1]$, where $\sigma > 0$. Before entering into the market, firms have no information about their cost parameter θ, but they know the distribution. Entry is costly, and each firm must pay a fixed and irreversible cost F. After paying the entry cost, each firm draws its θ randomly from $G(\theta)$. Upon knowing its own type, each firm decides whether to stay or exit the market. If it stays, it decides its innovation investment and production.

Given A, each firm's decision is similar that analyzed in the previous section, only firms with $\theta < \theta^* = \frac{A^2}{4c}$ can survive in the market. Let N denote the number of firms that pay the fixed entry cost. This N is endogenously determined in equilibrium. Then, we obtain the number of surviving firms as

$$M = NG(\theta^*). \tag{7}$$

Aggregate price is obtained by integrating individual prices of all surviving firms, which is

$$P = N\int_0^{\theta^*} p(\theta)dG(\theta) = N\int_0^{\theta^*}\left(\frac{A}{2} + \sqrt{\theta c}\right)dG(\theta) = \frac{(4\sigma+1)\,A^{2\sigma+1}N}{2(2\sigma+1)\,(4c)^{\sigma}}. \tag{8}$$

Substituting (7) and (8) into (6), we obtain

$$(4c)^{\sigma} = \frac{\beta N}{2(2\sigma+1)\gamma}\left(\frac{A^{2\sigma+1}}{\alpha - A}\right), \tag{9}$$

which defines the equilibrium relationship between A and N.

Prior to entry, the expected profit of a firm is $\int_0^{\theta^*} \pi^*(\theta)dG(\theta) - F$, where $\pi^*(\theta)$ is given in (4). Free entry yields the condition of zero expected profit. Using (2) and (4), the free-entry condition becomes

$$\int_0^{\theta^*} \pi^*(\theta)dG(\theta) = \int_0^{\theta^*} \frac{1}{4}(A - 2\sqrt{\theta c})^2 dG(\theta) = F.$$

N does not enter into the free-entry condition directly. Thus, this condition alone suffices to pin down equilibrium A. After some manipulations, we obtain

$$A = \zeta F^{\frac{1}{2(\sigma+1)}} c^{\frac{\sigma}{2(\sigma+1)}}, \qquad \text{where } \zeta = 2[(2\sigma+1)(\sigma+1)]^{\frac{1}{2(\sigma+1)}}. \tag{10}$$

ζ is a constant. (9) and (10) yield the equilibrium number of entrants

$$N = \frac{2^{2\sigma+1}(2\sigma+1)\gamma}{\beta}\left(\frac{\alpha - A}{A^{2\sigma+1}}\right)c^{\sigma} = \frac{2^{2\sigma+1}(2\sigma+1)\gamma}{\beta\zeta F^{\frac{2\sigma+1}{2(\sigma+1)}}}\left(\alpha c^{\frac{\sigma}{2(\sigma+1)}} - \zeta F^{\frac{1}{2(\sigma+1)}} c^{\frac{\sigma}{\sigma+1}}\right). \tag{11}$$

Substituting the equilibrium A from (10) in $\theta^* = \frac{A^2}{4c}$, we obtain the equilibrium exit threshold

$$\theta_e^* = \frac{1}{4}\zeta^2 F^{\frac{1}{\sigma+1}} c^{-\frac{1}{\sigma+1}}.$$

Clearly, $\frac{\partial \theta_e^*}{\partial c} < 0$. A more stringent regulation raises the cost for every firm and makes the least capable firms, which have very low profits before the change of regulation, unprofitable. These firms drop out from the market. The equilibrium number of firms is given by

$$M = NG(\theta_e^*) = N\left(\theta_e^*\right)^{\sigma} = \frac{2^{2\sigma-1}(2\sigma+1)\gamma}{\beta}\zeta F^{\frac{1-2\sigma}{2(\sigma+1)}}\left(\alpha c^{-\frac{\sigma}{2(\sigma+1)}} - \zeta F^{\frac{1}{2(\sigma+1)}}\right),$$

and so $\frac{dM}{dc} < 0$. Furthermore, from (10), we have $\frac{\partial A}{\partial c} > 0$. Hence, an increase in compliance cost causes an upward shift of the demand intercept for each surviving firm. We note that

$$P = \frac{(4\sigma+1)\,A^{2\sigma+1}N}{2(2\sigma+1)\,(4c)^{\sigma}} = \frac{(4\sigma+1)\,\gamma\zeta^{2\sigma}}{\beta}\left(\alpha - \zeta F^{\frac{1}{2(\sigma+1)}} c^{\frac{\sigma}{2(\sigma+1)}}\right),$$

and thus $\frac{\partial P}{\partial c} < 0$. P decreases as c increases because the surviving firms are more productive on average. As $A = \frac{\alpha\gamma+\beta P}{\beta M+\gamma}$, the property of $\frac{\partial A}{\partial c} > 0$ must be because the effect of the decrease in M (i.e., selection effect) dominates that of the decrease in P.

We now turn to the effect of an increase in compliance cost c on firms' innovation investments. For any given A, the optimal k is given as in (3). With A being endogenously determined, the effect can be decomposed to two parts as

$$\frac{dk}{dc} = \frac{\partial k}{\partial c} + \frac{\partial k}{\partial A}\frac{\partial A}{\partial c}.$$

The first part is the partial equilibrium effect (or the direct effect mentioned earlier), which takes A as given and unchanged. This effect has been analyzed in the previous section and more specifically in (5). The second part is the general equilibrium effect. An increase in c causes a change in the competitive environment, A, which in turn affects k. This effect is positive because $\frac{\partial k}{\partial A} > 0$ and $\frac{\partial A}{\partial c} > 0$. Thus, *in general equilibrium, surviving firms have stronger innovation incentives than in the case of partial equilibrium.*

By substituting (10) back into (3), we obtain the equilibrium expression of k as

$$k^* = \left(\frac{\zeta}{2\sqrt{\theta}} F^{\frac{1}{2(\sigma+1)}} c^{\frac{2\sigma+1}{2(\sigma+1)}} - c\right). \tag{12}$$

Direct differentiation gives

$$\frac{dk^*}{dc} = \left(\frac{2\sigma+1}{2\sigma+2}\right)\left[\frac{\zeta}{2\sqrt{\theta}}\right] F^{\frac{1}{2(\sigma+1)}} c^{-\frac{1}{2(\sigma+1)}} - 1, \tag{13}$$

from which, we obtain

$$\frac{dk^*}{dc} > 0 \text{ if and only if } \theta < \hat{\theta}_e \equiv \left(\frac{2\sigma+1}{2\sigma+2}\right)^2 \theta_e^*.$$

Thus, heterogeneous responses remain present. In response to more stringent regulations, high-capability firms increase their innovation investments, whereas low-capability firms reduce their innovation investments.

An interesting question is why the innovation investments of low-capability firms continue to decrease although the general equilibrium effect raises all firms' investment incentives. We notice that

$$\frac{\partial A}{\partial c} = \frac{\sigma}{2(\sigma+1)}\zeta F^{\frac{1}{2(\sigma+1)}} c^{-\frac{\sigma+2}{2(\sigma+1)}} \quad \text{and} \quad \frac{\partial k}{\partial A} = \frac{\sqrt{c}}{2b\sqrt{\theta}}.$$

As c increases, A increases, which in turn raises k for all firms. However, $\frac{\partial k}{\partial A}$ is smaller for larger θ. That is, the general equilibrium effect for low-capability firms is excessively small that it is dominated by the partial equilibrium effect, which is negative for them.

In addition,

$$\frac{\hat{\theta}_e}{\theta_e^*} = \left(\frac{2\sigma+1}{2\sigma+2}\right)^2 > \frac{1}{4} = \frac{\hat{\theta}}{\theta^*}.$$

Thus, under Pareto distribution, the above relationship implies that conditional on survival, a larger fraction of firms increase their innovation investment, as predicted by the PH, in the general equilibrium analysis than that in partial equilibrium.

3.1 The "strong version" of Porter Hypothesis

Porter and van der Linde (1995) posit the possibility that after an increase in compliance cost, even the profitability of firms may increase in certain cases. We have already shown that after an increase in compliance cost, The residual demand for all the surviving firms increases along with the innovation investments of high-capability firms. The question is whether these positive effects are sufficiently strong to offset the negative effect from the cost increase. We evaluate this "strong version" of PH in this subsection.

By substituting (10) and (12) into (4), we obtain the equilibrium profit $\pi^*(\theta, c) = \frac{1}{4}\zeta^2 F^{\frac{1}{\sigma+1}} c^{\frac{\sigma}{\sigma+1}} - 2\zeta\sqrt{\theta} F^{\frac{1}{2(\sigma+1)}} c^{\frac{2\sigma+1}{2(\sigma+1)}}$. Taking derivative with respect to c, we obtain

$$\frac{\partial \pi^*}{\partial c} = \left[\frac{\zeta}{4}\frac{\sigma}{2\sigma+1} F^{\frac{1}{2(\sigma+1)}} c^{\frac{-1}{2(\sigma+1)}} - \sqrt{\theta}\right] \frac{(2\sigma+1)F^{\frac{1}{2(\sigma+1)}}\zeta c^{\frac{-1}{2(\sigma+1)}}}{\sigma+1},$$

which is positive if and only if

$$\theta < \theta_s \equiv \frac{1}{16}\left(\frac{\sigma}{2\sigma+1}\right)^2 \zeta^2 F^{\frac{1}{\sigma+1}} c^{\frac{-1}{\sigma+1}} = \frac{1}{4}\left(\frac{2\sigma}{2\sigma+1}\right)^2 \theta_e^* < \hat{\theta}_e.$$

Hence, we have $\theta_s < \hat{\theta}_e < \theta_e^*$. We state the above result in the following proposition.

Proposition 2. *As a result of tightening regulation,*

(i) marginal firms (i.e., lowest-capability firms) ($\theta > \theta_e^*$) exit the market;

(ii) low-capability firms ($\hat{\theta}_e < \theta < \theta_e^*$) reduce their innovation investment and their profits fall;

(iii) high-capability firms ($\theta_s < \theta < \hat{\theta}_e$) increase their innovation investment but their profits fall; and

(iv) highest-capability firms ($\theta < \theta_s$) increase their innovation investment and their profits increase.

The sorting pattern described above is shown graphically in Figure 1. The intuition behind the proposition is as follow. First, although the negative cost shock hurts all firms, the damage to the more capable firms is relatively less because their demand elasticity is smaller. Second, the more capable firms increase their innovation investment to offset (partly) the negative effect of the cost increase. Third, the exit of some firms from the industry benefits all firms staying in the industry (selection effect). These features have implications on both productivity and profits of different firms at various degrees. When these effects are very strong, we have case (iv), and when they are less strong, we have cases (ii) and (iii). The least capable firms do not have these two benefits, and thus exit the market.

In the monopoly model, although the "weak version" of the PH holds for the high-capability firms, the “strong version” never holds as all firms’ profits drop after pollution tax increases. By contrast, the result of Proposition 2(iv) supports the "strong version" of the PH. These two models together indicate that the efficiency gain from increased investments *per se* is not sufficiently strong to raise profits, but the efficiency gain together with the selection effect raises profits.

3.2 Entry and composition of firms

In the preceding analysis, we focus on individual firms ex post decisions of innovation investment and output. In this subsection, we examine ex ante entry and ex post composition of each type of firms in equilibrium.

Taking derivative of the number of entrants N from (11) with respect to c, we obtain

$$\frac{dN}{dc} > 0, \text{ if and only if } \zeta F^{\frac{1}{2(\sigma+1)}} c^{\frac{\sigma}{2(\sigma+1)}} < \frac{\alpha}{2}.$$

The condition $\zeta F^{\frac{1}{2(\sigma+1)}} c^{\frac{\sigma}{2(\sigma+1)}} < \frac{\alpha}{2}$ implies low initial compliance cost. The intuition is as follows. Firms make their ex ante entry decisions on the basis of the expected profits. On one hand, an increased c exerts a direct and negative effect on every firm’s probability. On the

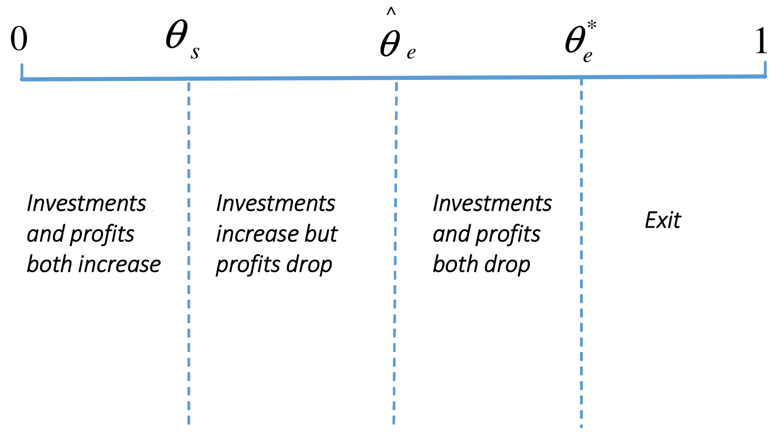

Figure 1: Sorting Pattern

other hand, increasing c exerts an indirect and positive effect on every surviving firm because of the increased demand intercept A in general equilibrium. When c is small, the latter effect dominates, which encourages entry. On the contrary, when c is already large, the former effect dominates; and thus, entry is discouraged.

Under the condition of low c, as the compliance cost increases, more entrants ex ante exist (N increases) along with more exiters ex post (M decreases). These two results, together with the fact that only the high-capability firms can survive, imply the effects of compliance cost on the composition of firms, as depicted in Figure 2. We state this result in Proposition 3.

Proposition 3. *If initial compliance cost is low, specifically,* $\zeta F^{\frac{1}{2(\sigma+1)}} c^{\frac{\sigma}{2(\sigma+1)}} < \frac{\alpha}{2}$, *then, an increase in the compliance cost induces more entry to the industry and a larger number of high-capability firms remain in the industry, whereas a larger number of low-capability firms exit.*

If, however, the initial compliance cost is high ($\zeta F^{\frac{1}{2(\sigma+1)}} c^{\frac{\sigma}{2(\sigma+1)}} > \frac{\alpha}{2}$), we have $\frac{dN}{dc} < 0$ (and $\frac{dM}{dc} < 0$). As a result, when the compliance cost increases, the number of entrants decreases along with the number of surviving firms at every capability level.

3.3 Industry level productivity

In this subsection, we analyze another aspect of industry at the aggregate level, namely, the total and average level of industry innovation investments, or productivity.

Productivity is determined by innovation investment. We have shown that changes in compliance cost results in heterogenous responses from firms in their equilibrium innovation investments. Thus, we need further investigation to obtain industry-level innovation investments. First, the aggregate innovation investments of the industry can be obtained as

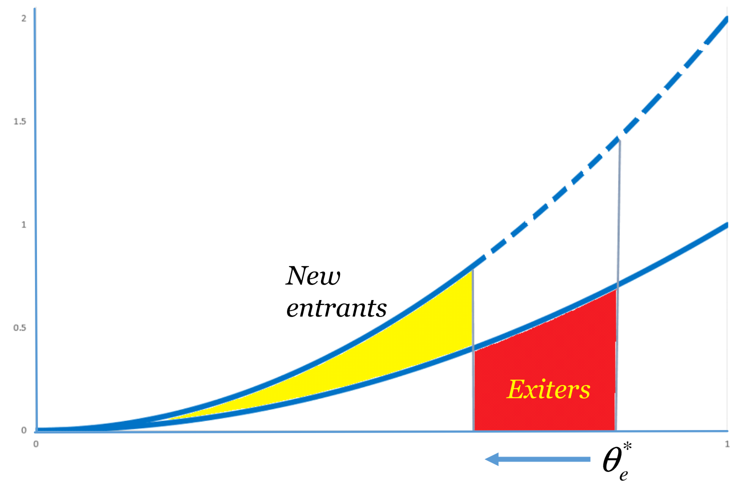

Figure 2: Changes in firm composition when initial environmental cost is low.

$$K(c) = N \int_0^{\theta_e^*(c)} k^*(\theta, c) dG(\theta) = \frac{2\sigma+1}{2\sigma-1} \frac{2\gamma\varsigma^{2\sigma-1}}{\beta F^{\frac{1}{2(\sigma+1)}}} \left[\alpha c^{\frac{\sigma+2}{2(\sigma+1)}} - \zeta F^{\frac{1}{2(\sigma+1)}} c \right].$$

Evidently,

$$\frac{dK}{dc} > 0, \text{ if and only if } \quad c < \left[\frac{(\sigma+2)\,\alpha}{2\,(\sigma+1)\,\varsigma} \right]^{\frac{2(\sigma+1)}{\sigma}} F^{-\frac{1}{\sigma}}.$$

Thus, as c continuously increase from an initially low level, the aggregate innovation investments of the entire industry first increase but then decrease. That is, K has an inverted-U shape with respect to c.

Conditional on surviving, we define and obtain the average investments as

$$\overline{k}(c) = \frac{1}{G\left(\theta_e^*\right)} \int_0^{\theta_e^*(c)} k^*\left(\theta, c\right) dG\left(\theta\right) = \frac{c}{2\sigma - 1}.$$

The above result is obtained under the condition $\sigma > \frac{1}{2}$, without which the integrand becomes not integrable on $[0,\ \theta_e^*(c)]$. Under this condition, $\overline{k}$ is an increasing function of c.

The intuition for the changes of total and average industry-level innovation investments in response to changes in regulation is as follows. When the regulation becomes tightened, three types of changes occur in firms. First, the least-capability firms exit. Second, the low-capability firms reduce their investment level. Third, the high-capability firms increase their investment level. The first two changes reduce the total industry investment, whereas the last change raises total industry investment. When the compliance cost is small, the distribution of firms favors high-capability firms as Proposition 3 indicates. Thus, total industry investments tend to increase. However, when the compliance cost is high, fewer high-capability firms increase their investment; and thus, total industry investments tend to drop. As for the average investment, the number of firms staying in the industry after an increase in compliance cost decreases, and the average capability of the staying firms increases. Hence, average investment always increases although total investment may decrease.

4 A general model

In the preceding sections, we have obtained results supporting the PH based on models with linear demand for individual firms' products. We now show that the PH holds in general models. To do so, we follow Zhelobodko et al. (2012) in considering one class of consumer preferences in which consumers' utility function is additive separable. In particular, we suppose that N varieties of differentiated goods, indexed by $i \in [0, N]$, are available in the market, and a representative consumer's utility is given as

$$U = \int_0^N u(q_i)di, \text{ with } u(0) = 0, \; u'(\cdot) > 0 \text{ and } u''(\cdot) < 0.$$

The individual utility function $u(\cdot)$ is continuous and differentiable. The consumer optimization problem is

$$\max_{\{q_i \geq 0\}_{i=0}^N} \int_0^N u(q_i)di, \quad \text{s.t.} \quad \int_0^N p_i q_i di = w,$$

where w is the consumer's income to be spent on these differentiated goods, and we normalize $w = 1$. From the first-order condition, we obtain the inverse demand function for each variety ($i \in [0, N]$) as

$$p_i = \frac{1}{\lambda} u'(q_i),$$

where λ is the Lagrange multiplier.

As in the preceding sections, each firm draws its innovation capability θ from $G(\theta)$ after paying the fixed entry fee F. After observing their θ, some firms may exit the industry. All remaining firms make their respective investment in innovation and engage in monopolistic competition in the product market. Each firm treats the Lagrange multiplier λ as an exogenous parameter when making its decisions. As firms are symmetric in the product market, we omit subscript i in the analysis below for simplicity. Faced with λ and c, a type-θ firm obtains its operating profit net of investment cost as

$$\pi^* (\theta, \lambda; c) = \max_{\{k \geq 0, q \geq 0\}} \left[\frac{1}{\lambda} u'(q)q - \frac{cq^2}{k} - \theta k \right].$$

From the first-order condition with respect to k, we obtain $\frac{cq^2}{k^2} = \theta$. Thus, $\pi^* (\theta, \lambda; c)$ can be written as

$$\pi^* (\theta, \lambda; c) = \max_{\{q \geq 0\}} \left[\frac{1}{\lambda} u'(q) q - 2\sqrt{\theta c} q \right]. \tag{14}$$

The first-order condition with respect to q gives

$$u''(q)q + u'(q) = 2\lambda\sqrt{\theta c}, \tag{15}$$

which determines the optimal quantity of a type-θ firm. We denote this optimal quantity as $q = q(\theta, \lambda; c)$.

Assume that the second-order condition is satisfied, which means $u'''(q)q + 2u''(q) < 0$. Then, based on the first-order condition (15) and the second-order condition, for any given λ and c, q is an decreasing function of θ: $\frac{\partial q}{\partial \theta} < 0$.

Every firm must pay a fixed cost of production, f.[6] The following equation define the cutoff capability level, $\theta^*(\lambda; c)$,

$$\pi^* (\theta^*, \lambda; c) - f = 0. \tag{16}$$

Applying the envelope theorem to (14) gives $\frac{\partial \pi^*}{\partial \theta} < 0$. Thus, firms with $\theta \leq \theta^*$ stay, and those with $\theta > \theta^*$ exit the market.

Finally, the free-entry condition is given by

$$\int_0^{\theta^*(\lambda;c)} [\pi^* (\theta, \lambda; c) - f] dG(\theta) = F. \tag{17}$$

By applying the envelope theorem to (14) again, we obtain $\frac{\partial \pi^*}{\partial \lambda} < 0$. Using this property, together with $\frac{\partial \pi^*}{\partial \theta} < 0$, in (17), we obtain $\frac{\partial \theta^*(\lambda;c)}{\partial \lambda} < 0$. Thus, the left-hand-side of the free-entry condition is decreasing in λ. The left-hand-side approaches infinity when $\lambda \to 0$, and it reaches zero when λ is sufficiently large because $\theta^*(\lambda; c)$ approaches 0. By the intermediate value theorem, a unique solution of λ exists, denoted as $\lambda^* = \lambda^*(c) > 0$, such that the free-entry condition holds. Accordingly, we obtain the equilibrium cut-off efficiency point $\theta^*(c) = \theta(\lambda^*; c)$ and equilibrium quantity $q_\theta(c) = q(\theta^*, \lambda^*; c)$, as functions of c. $k = \sqrt{\frac{c}{\theta}} q$; thus, we obtain the equilibrium investment $k_\theta(c) = \sqrt{\frac{c}{\theta}} q_\theta$ of the type-θ firm.

Differentiating the equilibrium quantity q_θ with respect to c, we derive

$$\frac{dq_\theta}{dc} = \frac{\partial q}{\partial c} + \frac{\partial q}{\partial \lambda} \frac{d\lambda}{dc}. \tag{18}$$

Evaluating the first-order condition (15) at equilibrium and taking differentiation, we obtain

$$\left[u'''(q_\theta)q_\theta + 2u''(q_\theta)\right] \frac{\partial q}{\partial \lambda} = 2\sqrt{\theta c}, \text{ and } \left[u'''(q_\theta)q_\theta + 2u''(q_\theta)\right] \frac{\partial q}{\partial c} = \lambda^* \sqrt{\frac{\theta}{c}}.$$

[6] We do not need the fixed cost of production in the models of previous sections to determine the threshold θ because of linear demand.

Substituting these expressions into (18), we obtain

$$\frac{dq_\theta}{dc} = \frac{\lambda^*}{u'''(q_\theta)q_\theta + 2u''(q_\theta)}\sqrt{\frac{\theta}{c}} + \frac{2\sqrt{\theta c}}{u'''(q_\theta)q_\theta + 2u''(q_\theta)}\frac{d\lambda^*}{dc}.$$

We introduce a general notation ϵ_x to denote the elasticity of variable x with respect to c, that is,

$$\epsilon_x = \frac{d\ln(x)}{d\ln(c)}.$$

Then,

$$\frac{dq_\theta}{dc} = \frac{\lambda^*\sqrt{\frac{\theta}{c}}}{u'''(q_\theta)q_\theta + 2u''(q_\theta)}\left(1 + 2\epsilon_{\lambda^*}\right).$$

Using the first-order condition (15), we obtain

$$\epsilon_{q_\theta} = \frac{1}{2}\frac{u''(q_\theta)q_\theta + u'(q_\theta)}{u'''(q_\theta)q_\theta + 2u''\left(q_\theta\right)}\frac{1 + 2\epsilon_{\lambda^*}}{q_\theta}.$$

We now calculate ϵ_λ from the free-entry condition. Evaluating the free entry condition at equilibrium, differentiating with respect to c, and noticing that the value of the integrand is zero at θ^*, we can simply write the total derivative as

$$\int_0^{\theta^*}\left(\frac{\partial\pi^*}{\partial c} + \frac{\partial\pi^*}{\partial\lambda}\frac{d\lambda^*}{dc}\right)dG(\theta) = 0.$$

By applying the envelope theorem to (14), we obtain

$$\frac{\partial\pi^*}{\partial c} = -q\left(\theta,\lambda;c\right)\sqrt{\frac{\theta}{c}}, \quad \frac{\partial\pi^*}{\partial\theta} = -q\left(\theta,\lambda;c\right)\sqrt{\frac{c}{\theta}},$$

and

$$\frac{\partial\pi^*}{\partial\lambda} = -\frac{1}{\lambda^2}u'[q\left(\theta,\lambda;c\right)]q\left(\theta,\lambda;c\right).$$

After manipulation, we obtain

$$\int_0^{\theta^*}[R(\theta)\epsilon_{\lambda^*} + q_\theta\sqrt{\theta c}]dG(\theta) = 0, \qquad \text{where } \; R(\theta) = \frac{1}{\lambda^*}u'(q_\theta)q_\theta.$$

$R(\theta)$ is the equilibrium revenue of a type-θ firm. As ϵ_{λ^*} is independent of θ, it can be solved from the above equation as

$$\epsilon_{\lambda^*} = -\frac{\int_0^{\theta^*} V(\theta) dG(\theta)}{2\int_0^{\theta^*} R(\theta) dG(\theta)},$$

where $V(\theta) = 2q_\theta\sqrt{\theta c} = \frac{cq_\theta^2}{k_\theta} + \theta k_\theta$ is the variable cost of production plus investment cost for a type-θ firm.

$\epsilon_{\lambda^*} \in \left(-\frac{1}{2}, 0\right)$ because $0 < V(\theta) < R(\theta)$ for all $\theta < \theta^*$. As a result, from the expression of q_θ, we always obtain $\epsilon_{q_\theta} < 0$. That is, in response to a more stringent environmental regulation, the surviving firms decrease their equilibrium production scale.

On the basis of $k_\theta = \sqrt{\frac{c}{\theta}} q_\theta$, we obtain

$$\epsilon_{k_\theta} = \frac{1}{2} + \epsilon_{q_\theta}.$$

Define

$$MR(q) = \frac{1}{\lambda}[u''(q)q + u'(q)],$$

which is the marginal revenue function. Inserting the expression of ϵ_{q_θ}, we find that $\epsilon_{k_\theta} > 0$ if and only if

$$\frac{MR(q)}{MR'(q)q} > -\frac{1}{2\epsilon_\lambda + 1} \in (-\infty, -1). \tag{19}$$

That is, if inequality (19) holds for a firm, the firm will increase its innovation investment in response to a more stringent environmental regulation. We explore conditions for the above inequality under two cases.

Case 1. The $MR(q)$ curve crosses the horizontal axis once.

Result 1: If $\exists\, q_\phi \in (0, +\infty)$, such that $u''(q_\phi)q_\phi + u'(q_\phi) = 0$, then $\exists\, \varepsilon > 0$, when $\theta^* \in [0, \varepsilon)$, $\epsilon_{k_\theta} > 0$.

To prove this result, we rewrite the first-order condition (15) as $MR(q) = 2\sqrt{\theta c}$. Given the equilibrium λ^*, this condition pins down the equilibrium $q = q_\theta$ for each firm with θ. As the second-order condition implies that $MR(q)$ is a decreasing function of q, we obtain that q_θ is a decreasing function of θ. Then, supposing that $\exists\, q_\phi \in (0, +\infty)$, such that $u''(q_\phi)q_\phi + u'(q_\phi) = 0$, we obtain $MR(q_\phi) = 0$, which implies $\theta = 0$ for the firms with q_ϕ. That is, q_ϕ is the equilibrium quantity of every type-0 firm, that is, $q_0 = q_\phi$. As a result,

$$\frac{MR(q_0)}{MR'(q_0)q_0} = 0 > -1 > -\frac{1}{2\epsilon_\lambda + 1}.$$

By continuity, the inequality (19) holds for certain neighborhood of $\theta = 0$, completing the proof.

One example is the utility function which takes a CARA form (Behrens and Murata, 2007), such as $u(q) = 1 - e^{-mq}$, where $m > 0$. Then, $u'(q) = me^{-mq}$, $u''(q) = -m^2 e^{-mq}$, and so $MR(q) = m(1-q)e^{-mq}$, which crosses the horizontal axis at $q_0 = 1$ and only once.

Case 2. The $MR(q)$ curve does not cross the horizontal axis.

Result 2: Supposing that for any $q \in (0, +\infty)$, then, $u''(q)q+u'(q) > 0$, and $\lim_{q\to+\infty} u''(q)q+u'(q) = 0$. We define $g(x) = MR(\frac{1}{x})$. If $g(x)$ is locally convex at $x = 0$, then $\exists\ \varepsilon > 0$, when $\theta^* \in [0, \varepsilon)$, $\epsilon_{k_\theta} > 0$.

We now prove the above result. $g(0) = \lim_{x\to 0} MR(\frac{1}{x}) = \frac{1}{\lambda} \lim_{q\to+\infty} u''(q)q + u'(q) = 0$. Then

$$\lim_{q\to+\infty} \frac{MR(q)}{MR'(q)\cdot q} = \lim_{x\to 0} \frac{MR(\frac{1}{x})}{MR'(\frac{1}{x})\cdot\frac{1}{x}} = \lim_{x\to 0} \frac{g(x)}{g'(x)\cdot(-x^2)\cdot\frac{1}{x}} = \lim_{x\to 0} -\frac{\frac{g(x)-g(0)}{x-0}}{g'(x)}.$$

As $g(x) > 0$, if $g(x)$ is convex at $x = 0$, then $\frac{g(x)-g(0)}{x-0} < g'(x)$ in the neighborhood of $x = 0$. Consequently, the following result holds in the neighborhood of $x = 0$:

$$\lim_{x\to 0} \frac{\frac{g(x)-g(0)}{x-0}}{g'(x)} \leqslant 1.$$

Thus,

$$\lim_{q\to+\infty} \frac{MR(q)}{MR'(q)\cdot q} = \lim_{x\to 0} -\frac{\frac{g(x)-g(0)}{x-0}}{g'(x)} \geqslant -1 > -\frac{1}{2\epsilon_\lambda + 1}.$$

For example, we let the utility function be of the Stone-Geary form, that is, $u(q) = log(1+q)$. Then, $u'(q) = \frac{1}{1+q}$, $u''(q) = -\frac{1}{(1+q)^2}$, and so $u''(q)q + u'(q) = \frac{1}{(1+q)^2}$, which does not cross the horizontal axis. Moreover, $g\left(x\right) = \frac{1}{\lambda}\left(\frac{x}{1+x}\right)^2$, which is locally convex at $x = 0$ because $g''\left(0\right) = 2 > 0$.

5 Emission standard

The objective of this extension is to show that qualitatively similar results can be obtained for different types of environmental regulations. For this purpose, we focus on emission standard and simplify the analysis by restricting to the monopoly model (one monopolist in one industry), as in Section 2. We suppose that the firm (monopolist) in a particular industry draws its innovation capability θ. Emission intensity is defined as the emission level per unit of final goods output. The government imposes an emission standard ρ, that is, the firm emission intensity must be no higher than ρ.

Unlike in the preceding analysis where we hide the pollution level in the background, now we need to address it explicitly. The firm allocates a fraction, $\Delta \in (0, 1)$, of labor into abatement activities, and the rest for intermediate inputs production. Moreover, if the firm employs l units of labor, the amount of intermediate inputs produced is $x = (1 - \Delta)l$ and the emission level is $z = (1 - \Delta)^{\frac{1}{\eta}} l$, where $\eta \in (0, 1)$. Given the final goods output q, with the intermediate inputs requirement function $x = \frac{q^2}{k}$, we obtain the labor requirement as a function of q:

$$l = \frac{q^2}{(1-\Delta)k},$$

which is also the variable cost function under the normalization $w = 1$. Clearly, the larger the fraction of labor is devoted to abatement, the larger is the amount of labor required to produce a given quantity of the final product.

The emission intensity, e, can be defined and calculated as

$$e \equiv \frac{z}{q} = \frac{z}{x}\frac{x}{q} = (1-\Delta)^{\frac{1}{\eta}-1}\frac{q}{k}. \tag{20}$$

Thus, the firm's maximization problem is[7]

$$Max_{\{\Delta,k,q\}}\left[(A-bq)q - \frac{q^2}{(1-\Delta)k} - \theta k\right], \quad \text{s.t. } (1-\Delta)^{\frac{1}{\eta}-1}\frac{q}{k} \leqslant \rho \ \text{ and } \Delta \geq 0.$$

We first characterize the equilibrium outcomes, and then examine how the firm's innovation investment changes when the emission standard is tightened.

If constraint $e \leq \rho$ is not binding for the firm, then it is always optimal to set $\Delta = 0$. Intuitively, if the firm's emission intensity is already low or the emission standard is not high (large ρ), production resources need not be diverted into abatement activities. Under such a situation, the firm's optimization problem becomes

$$Max_{\{k,q\}}\left[(A-bq)q - \frac{q^2}{k} - \theta k\right].$$

From the first-order condition with respect to k, we obtain $\frac{q}{k} = \sqrt{\theta}$, which implies $e = \sqrt{\theta}$. Thus, if $\theta < \rho^2$, the firm automatically meets the emission standard without putting any resources into abatement activity. The firm's optimal decision is

$$\Delta = 0, \quad q = \frac{A-2\sqrt{\theta}}{2b}, \quad \text{and} \quad k = \frac{A-2\sqrt{\theta}}{2b\sqrt{\theta}}. \tag{21}$$

The firm survives if and only if $k > 0$, or $\theta < \frac{A^2}{4}$.

To summarize this part for all industries, if $\rho > \frac{A}{2}$, then only firms with $\theta \in (0, \frac{A^2}{4})$ survive, the emission standard are not binding for them, and their optimal decisions are given in (21); if $\rho < \frac{A}{2}$, then firms with $\theta \in (0, \rho^2)$ do not find the emission standard binding and thus their optimal decisions are given in (21), but firms with $\theta \in (\rho^2, \frac{A^2}{4})$ find the constraint binding. We

[7] Implicilty, another constraint, $\beta \leq 1$, exists.

need to analyze separately the optimal decisions of firms with $\theta \in (\rho^2, \frac{A^2}{4})$.

To save space, we fully characterize the outcomes under a given emission standard ρ in the following lemma and leave the proof in the Appendix. In the lemma, we only present the results of the surviving firms. Other firms exit their respective industries under various situations. We first define a cut-off point

$$\tilde{\theta} \equiv \frac{(1-\eta)^{1-\eta}}{(2-\eta)^{2-\eta}} A^{2-\eta} \rho^{\eta}.$$

Lemma 1. *(i). If $\rho \geqslant \frac{1}{2}A$, then firms with $\theta \in (0, \frac{A^2}{4})$ have their optimal decisions as given by (21).*

(ii). If $\frac{1-\eta}{2-\eta}A \leq \rho < \frac{1}{2}A$, then firms with $\theta \in (0, \rho^2]$ have their optimal decisions as given by (21); and firms with $\theta \in (\rho^2, \rho(A-\rho))$ have their optimal decisions as $q = \frac{A-\rho-\frac{\theta}{\rho}}{2b}$, $k = \frac{A-\rho-\frac{\theta}{\rho}}{2b\rho}$, and $\Delta = 0$.

(iii). If $0 < \rho < \frac{1-\eta}{2-\eta}A$, then firms with $\theta \in (0, \rho^2]$ have their optimal decisions as given by (21); firms with $\theta \in (\rho^2, \frac{\rho^2}{1-\eta}]$ have their optimal decisions as $q = \frac{A-\rho-\frac{\theta}{\rho}}{2b}$, $k = \frac{A-\rho-\frac{\theta}{\rho}}{2b\rho}$, and $\Delta = 0$; firms with $\theta \in (\frac{\rho^2}{1-\eta}, \tilde{\theta})$ have their solutions as $q = \frac{1}{2b}\left[A - \frac{2-\eta}{1-\eta}\rho^{-\frac{\eta}{2-\eta}}(1-\eta)^{\frac{1}{2-\eta}}\theta^{\frac{1}{2-\eta}}\right]$, $k = \frac{A\rho^{-\frac{\eta}{2-\eta}} - (2-\eta)(1-\eta)^{-\frac{1-\eta}{2-\eta}}\theta^{\frac{1}{2-\eta}}\left(\rho^{-\frac{\eta}{2-\eta}}\right)^2}{2b[(1-\eta)\theta]^{\frac{1-\eta}{2-\eta}}}$, and $\Delta = 1 - [(1-\eta)\theta]^{-\frac{\eta}{2-\eta}}\rho^{\frac{2\eta}{2-\eta}}$.

With the above equilibrium outcomes, we examine how firms' innovation investment changes in response to tightening of emission standard (i.e., reduction of ρ). We state the results in the following proposition and provide a proof in the Appendix.

Proposition 4. *If the government tightens the emission standard, then the least capable firms decrease their innovation investments, firms with medium levels of capability increase their investments, and the most capable firms do not adjust their investment levels.*

The result is similar to that in pollutions tax in the sense that tightening environmental regulations induce the high-capability firms to increase their innovation investments. This result supports the "weak version" of the PH. The only difference is that the highest-capability firms also increase their investment in the case of pollution tax, but keep their investment levels unchanged in the case of emission standard. This is not surprising because in the case of emission standard, the highest-capability firms have very low emission intensity and thus tightening of emission standard does not affect them, whereas a change in pollution tax affects every firm regardless of its innovation capability.[8]

[8] Tightening the emission standard also drives out the least capable firms from the markets in some cases, but not in all cases. This outcome is another difference from the effects of raising pollution tax.

6 Conclusion

The PH stimulates heated debates in both public policy circle and academic research. The empirical evidence is inconclusive, which is not surprising because the empirical studies are based on data of different countries, industries, and time periods. Even Porter and van der Linde (1995) claim that only properly designed environmental regulations may induce more innovations and raise firm performance. The environmental regulations in reality are not likely to be properly designed.

Theoretical investigations of the PH are important because they can help identify reasons and conditions for the PH to hold, which in turn provides guidance for empirical analysis. Critics of the PH is not always doubtful about the validity of the PH in some cases, but challenges the generality of the PH. The existing studies in the theoretical literature of the PH have identified a number of situations, with market or organizational failure, in which the PH holds. The present paper pushes this frontier further by showing that both the "weak version" and "strong version" of the PH can hold in situations without market or organizational failure. It holds in a model of monopolistic competition with heterogenous firms. The two distinguishing features of this model and analysis, namely, firm heterogeneity and general equilibrium, add valuable insights to the PH debate.

The main conclusion from the present study that the PH holds for the more capable firms but fails for the less capable firms within the same industry should be general. We have derived this result from the monopolistic competition model, with linear demand and general demand, with pollution tax and emission standard. It would be important to show that the result holds in more general settings. It would be even more important to bring this prediction to data for empirical verification. Cao et al. (2016) provide evidence consistent with this prediction although they focus on investments in advanced abatement technology, rather than efficiency-improving innovation investments.

7 Appendix

Proof of Lemma 1.

We divide the proof into four steps. The first step has been given in the text which leads to the result of (i).

Step 2. For (ii), we suppose $\rho < \frac{A}{2}$, and consider firms with cost parameter $\theta \geqslant \rho^2$. The earlier analysis shows that if these firms continue to set $\Delta = 0$, the emission constraint is binding. Thus, the question is whether they should continue to set $\Delta = 0$ and adjust other decisions to meet the constraint, or set $\Delta > 0$. We approach this issue by guess-and-verify below.

We suppose that the constraint is binding but $\Delta > 0$ for a firm with $\theta \geqslant \rho^2$. Substituting $e = \sqrt{\theta}$ into the objective function to eliminate Δ, the maximization problem becomes

$Max_{\{k,q\}}\left[(A-bq)q-\rho^{-\frac{\eta}{1-\eta}}q^{\frac{2-\eta}{1-\eta}}k^{-\frac{1}{1-\eta}}-\theta k\right]$. The optimal solutions are

$$q(\theta)=\frac{1}{2b}\left[A-\frac{2-\eta}{1-\eta}\rho^{-\frac{\eta}{2-\eta}}(1-\eta)^{\frac{1}{2-\eta}}\theta^{\frac{1}{2-\eta}}\right], \tag{(A1)}$$

and

$$k(\theta)=\frac{A\rho^{-\frac{\eta}{2-\eta}}-(2-\eta)(1-\eta)^{-\frac{1-\eta}{2-\eta}}\theta^{\frac{1}{2-\eta}}\left(\rho^{-\frac{\eta}{2-\eta}}\right)^2}{2b\left[(1-\eta)\theta\right]^{\frac{1-\eta}{2-\eta}}}. \tag{(A2)}$$

The above results are based on the assumption that $\Delta>0$. We now check whether this is the case. Using the above results in $e=\sqrt{\theta}$, we obtain $1-\Delta=\left[(1-\eta)\theta\right]^{-\frac{\eta}{2-\eta}}\rho^{\frac{2\eta}{2-\eta}}$. We find that $1-\Delta\in(0,1)$ if and only if $\theta>\frac{\rho^2}{1-\eta}$, that is, the assumption that $\Delta\in(0,1)$ is only valid for firms with $\theta>\frac{\rho^2}{1-\eta}$. For firms with $\theta\in(\rho^2,\frac{\rho^2}{1-\eta})$, we must have $\Delta=0$.

Step 3. We consider firms with $\theta\in(\rho^2,\frac{\rho^2}{1-\eta})$. With $\Delta=0$ and $e=\sqrt{\theta}$, the optimization problem becomes $Max_{\{q,k\}}\left[(A-bq)q-\frac{q^2}{k}-\theta k\right]$, s.t. $\frac{q}{k}=\rho$. The solutions are

$$q(\theta)=\frac{1}{2b}\left[A-\left(\rho+\frac{\theta}{\rho}\right)\right]\quad\text{and}\quad k(\theta)=\frac{1}{2b}\left(\frac{A}{\rho}-\frac{\theta}{\rho^2}-1\right).$$

If $k>0$ for any $\theta\in(\rho^2,\frac{\rho^2}{1-\eta})$, then we must have $k(\theta)>0$ for $\theta=\frac{\rho^2}{1-\eta}$ (because k is decreasing in θ), that is, $k\left(\frac{\rho^2}{1-\eta}\right)>0$, or equivalently $\rho<\frac{1-\eta}{2-\eta}A$. On the contrary, if $\rho>\frac{1-\eta}{2-\eta}A$, then only firms with $\rho^2<\theta<\rho(A-\rho)$ have positive $k(\theta)$ and can survive, whereas firms with $\theta\in\left(\rho(A-\rho),\frac{\rho^2}{1-\eta}\right)$ exit the market. They exit the market because they cannot set $\Delta>0$, as we have already proved in Step 2. Furthermore, because firms with $\theta\in\left(\rho(A-\rho),\frac{\rho^2}{1-\eta}\right)$ can not survive, firms with $\theta>\frac{\rho^2}{1-\eta}$ can not survive either (because a firm with a lower θ has a larger choice set). We find that if $\rho<\frac{A}{2}$, then $\rho(A-\rho)>\rho^2$, which implies that $(\rho^2,\rho(A-\rho))$ is non-empty.

Step 4. The remaining situation to consider is what happens to firms with $\theta>\frac{\rho^2}{1-\eta}$ when $\rho<\frac{1-\eta}{2-\eta}A$. From step 2, we know that when $\theta>\frac{\rho^2}{1-\eta}$,the solution is given by (A1) and (A2), with $\Delta>0$. Again, for firms to survive, we must have $k>0$, which implies $\theta<\tilde{\theta}$. This condition holds when $\rho<\frac{1-\eta}{2-\eta}A$.

Proof of Proposition 3.

(i). If $\rho\geqslant\frac{1}{2}A$, then tightening emission standard exerts no effect on the investment decision of any surviving firm.

(ii). If $\frac{1}{2}A>\rho>\frac{1-\eta}{2-\eta}A$, then the regulation exerts no effect on investment of firms with $\theta\in(0,\rho^2]$. However, for firms with $\theta\in(\rho^2,\rho(A-\rho))$, $\frac{\partial k}{\partial\rho}=\frac{1}{2b\rho^2}(2\theta-A\rho)$. Apparently, $\frac{\partial k}{\partial\rho}\gtreqless 0$ if and only if $\theta\gtreqless\frac{A\rho}{2}$. Under the current parameter range, $\frac{A\rho}{2}\in(\rho^2,\rho(A-\rho))$.

Therefore, $\frac{\partial k}{\partial \rho} < 0$ for $\theta \in (\rho^2, \frac{A\rho}{2})$, and $\frac{\partial k}{\partial \rho} > 0$ for $\theta \in (\frac{A\rho}{2}, \rho(A-\rho))$, which implies that, facing a tightening of regulation, firms with low capability decrease their investments, those with medium-level capability increase their investments, whereas the most capable firms do not adjust their decisions.

(iii). If $\rho \leqslant \frac{1-\eta}{2-\eta}A$, as before, then the regulation exerts no effect on the investments of firms with $\theta \in (0, \rho^2]$. For firms with $\theta \in (\rho^2, \frac{\rho^2}{1-\eta})$, $\frac{\partial k}{\partial \rho} = \frac{1}{2b\rho^2}(2\theta - A\rho)$. As a result, $\frac{\partial k}{\partial \rho} \gtreqless 0$ for $\theta \gtreqless \frac{A\rho}{2}$. For firms with $\theta \in [\frac{\rho^2}{1-\eta}, \tilde{\theta})$,

$$\frac{\partial k}{\partial \rho} = \frac{\eta}{2b\rho^{\frac{2}{2-\eta}}}\left[\frac{2\theta^{\frac{1}{2-\eta}}}{(1-\eta)^{\frac{1-\eta}{2-\eta}}\rho^{\frac{\eta}{2-\eta}}} - \frac{1}{2-\eta}A\right].$$

Hence, $\frac{\partial k}{\partial \rho} \gtreqless 0$ for $\theta \gtreqless \frac{1}{2^{2-\eta}}\theta^*$. We find that

$$\frac{A\rho}{2} \leqslant \frac{\rho^2}{1-\eta} \Longleftrightarrow \rho \geqslant \frac{1-\eta}{2}A,$$

$$\frac{1}{2^{2-\eta}}\tilde{\theta} = \frac{(1-\eta)^{1-\eta}}{2^{2-\eta}(2-\eta)^{2-\eta}}A^{2-\eta}\rho^{\eta} \geqslant \frac{\rho^2}{1-\eta} \Longleftrightarrow \rho \leqslant \frac{1-\eta}{2(2-\eta)}A.$$

Depending on the location of the two critical points ($\frac{A\rho}{2}$ and $\frac{1}{2^{2-\eta}}\tilde{\theta}$), three scenarios should be considered to sign $\frac{\partial k}{\partial \rho}$.

Scenario 1: $\rho \leqslant \frac{1-\eta}{2(2-\eta)}A$. Then, $\frac{\partial k}{\partial \rho} = 0$ for $\theta \in [0, \rho^2]$, $\frac{\partial k}{\partial \rho} < 0$ for $\theta \in (\rho^2, \frac{\rho^2}{1-\eta}) \cup [\frac{\rho^2}{1-\eta}, \frac{1}{2^{2-\eta}}\theta^*)$, and $\frac{\partial k}{\partial \rho} > 0$ for $\theta \in (\frac{1}{2^{2-\eta}}\theta^*, \theta^*)$.

Scenario 2: $\frac{1-\eta}{2(2-\eta)}A < \rho < \frac{1-\eta}{2}A$. Then, $\frac{\partial k}{\partial \rho} = 0$ for $\theta \in [0, \rho^2]$, $\frac{\partial k}{\partial \rho} < 0$ for $\theta \in (\rho^2, \frac{\rho^2}{1-\eta})$ and $\frac{\partial k}{\partial \rho} > 0$ for $\theta \in (\frac{\rho^2}{1-\eta}, \tilde{\theta})$.

Scenario 3: $\frac{1}{2}A > \rho \geqslant \frac{1-\eta}{2}A$. Then, $\frac{\partial k}{\partial \rho} = 0$ for $\theta \in [0, \rho^2]$, $\frac{\partial k}{\partial \rho} < 0$ for $\theta \in (\rho^2, \frac{A\rho}{2})$, and $\frac{\partial k}{\partial \rho} > 0$ for $\theta \in (\frac{A\rho}{2}, \tilde{\theta})$.

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