Who Invest More in Advanced Abatement Technology: Theory and Evidence

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Abstract

We study firm investment in abatement technology under a linear-demand and heterogeneous firm framework. In contrast to results in existing studies, our findings indicate that firms' investments in advanced abatement technology exhibit an inverted-U-shape with respect to firms' productivity. In response to tightened environmental regulations, more-productive firms raise their respective investments in abatement technology, whereas less-productive firms do the opposite; Pollution emission intensity of a firm decreases with productivity level. The key theoretical predictions are confirmed by empirical tests using Chinese data.

Keywords: Pollution; heterogenous firms; abatement technology; emission intensity; China

JEL Code: Q50

1 Introduction

People have become increasingly more concerned about the environment. To understand the pattern and impacts of pollution, researchers have largely undertaken studies at the country and industry levels. However, as firms are pollution generators, related issues must be examined at the firm level. Traditional studies of environmental economics work with models that assume representative firm. This is at odds with reality as in reality firms are different in many aspects and have different environmental behaviors. Recent empirical studies have found that larger firms or more-productive firms have lower emission intensity (Shadbegian and Gray, 2003; Forslid et al., 2011), and larger firms spend more in environmental protection (Biehl and Klassen, 2008).

The lack of theoretical studies at the firm level is due to the unavailability of a general framework that characterizes firm heterogeneity. The Melitz (2003) model in international trade can be used to analyze heterogenous firms' environmental behaviors. Empirical studies at the firm-level are also scarce because of the difficulty in obtaining firm-level environmental data. The present paper makes a contribution to the literature by exploring issues along these two directions.

Recent theoretical studies have focused on heterogeneous firms' environmental behavior. Those studies generally concluded that the pollution emission intensity of a firm decreases with respect to its productivity. Some studies also showed that a firm's investment in abatement technology increases with respect to its productivity. The present paper confirms the decreasing emission intensity result, but shows that firms' investments in abatement technology exhibit an inverted-U-shape with respect to productivity: when productivity is low, an increase in productivity *raises* a firm's investment level, but when productivity is high, a further increase in productivity *reduces* a firm's investment level.

The inverted-U-shaped investment prediction is based on a mix of the Melitz and Ottaviano (2008) model of heterogeneous firms and the Copeland and Taylor (2003) model of pollution. When a firm is not very productive, an increase in productivity induces it to increase its production, which will generate more pollution. It is optimal for the firm to make a larger investment in abatement technology. When a firm is very productive, a further increase in productivity also induces more production, but at a lower rate of increase, as it is more concerned of the price drop. With linear demand, although a more-productive firm always produces more output in equilibrium, it may use less inputs and thus generates less pollution, which implies lower investment in abatement technology. To test our prediction, we introduce the productivity square term as a regressor in the standard regression model. Our empirical analysis using Chinese firm-level data supports the inverted-U-shaped investment pattern.

Our paper makes a number of significant contributions to the growing literature on heterogenous firms and environment. First, all existing theoretical studies use the Melitz (2003) model from the trade literature to analyze the differential effects of trade on heterogeneous firms' environmental performance. For example, Bojona and Missio (2010) showed that more-productive firms are exporters, and they also have lower emission intensity than less-productive firms. Cui (2011) obtained similar results in the presence of the possibility of investment in clean technology.[1] Although our model is built on Melitz and Ottaviano (2008) model, which is also a trade model, our emphasis is on the relationship between firm productivity and emission intensity on the one hand, and that between firm productivity and investment in abatement technology on the other hand, abstract from the effect of trade.

Second, few studies have explicitly analyzed investment in abatement technology using the Copeland and Taylor (2003) cum Melitz (2003) model. Cui (2011) reinterpreted technological adoption in the Bustos (2011) model as adoption of different environmental technology, with clean technology associated with larger fixed cost and smaller marginal cost than dirty technology. Cui (2011) showed that high-productivity firms adopt the clean technology. Forslid et al. (2011) found that under some parameter restrictions, firm investment in abatement technology is positively related to firm productivity. On the contrary, we show that investment in abatement technology

[1] Yokoo (2009) also introduced firm heterogeneity to an environment model, but examined a very different issue: how environmental regulation affects a country's competitiveness, i.e., the Porter hypothesis. The result is very simple: tightening regulation drives out less-productive firms, thereby increasing the average productivity.

exhibits an inverted-U-shape with respect to firm productivity. Thus, we must appeal to data to resolve the difference. Forslid et al. (2011) found empirical support to their prediction using Swedish firm-level data. Similarly we also find empirical support to our prediction using Chinese data. Both works may be correct as these two papers used data from different countries. However, the Swedish data in Forslid et al. (2011) may in fact exhibit an inverted-U-shape had the productivity square term been introduced in their regression model as was done in our model.[2]

Third, all existing papers predicted that more-productive firms have lower emission intensity. This negative relationship between pollution emission and firm productivity is confirmed by a number of empirical studies: Cui (2011) used detailed facility-level data of the US manufacturing industry in year 2002 and 2005, Forslid et al. (2011) used Swedish firm-level data, and Shadbegian and Gray (2003) used US paper mills industry data in 1985.[3] Our study also confirms this relationship using Chinese data.[4]

Fourth, we examine the effects of environmental policy on firms' environmental behavior and obtain results that differ from those in existing studies. Yokoo (2009) showed that, without investment in abatement technology, tightening environmental regulation results in resource reallocation from less-productive firms to more-productive firms. Forslid et al. (2011) predicted that the incentive to invest in abatement technology will fall for all firms in response to tightening environmental regulations. The logic is that as pollution tax goes up, firms will pollute less. Thus, the incentive to invest in abatement technology will also fall due to economies of scale. On the contrary, we find that although the scale effect prevails among less-productive firms, more-productive firms will increase their investment in abatement technology in response to a rise in pollution tax. The reason behind this result is closely linked to the inverted-U-shaped investment curve. As very productive firms do not have a large investment in abatement technology, the marginal cost of raising investment level to reduce pollution is very effective for them.[5]

The inverted-U shape has been mentioned in many studies of environmental economics. However, they often refer to phenomena different from the present study. Most earlier studies in this area are about the relationship between a country's pollution and its economic development. One interesting exception is the recent paper by Perino and Requate (2012) who examined the inverted-U shape at the firm level. However, their focus and results are very different from those of the present paper. First, Perino and Requate (2012) showed that under the social optimum,

[2] Other empirical observations are subject to similar reinterpretation. Statistics Canada (2006) reported that larger businesses in Canada spend more (in per employee terms) in environmental protection, and Biehl and Klassen (2008) showed that within the same industry, larger firms spend more on pollution abating activities.

[3] There are a few firm-level empirical studies in trade literature that compare exporters and non-exporters with regard to their environmental performance. According to these studies, exporters' emission intensity is generally lower than that of non-exporters (e.g., Holladay, 2010).

[4] Some other studies relate firm attributes to firm environmental performance. Zhang et al. (2008) used data collected from 89 Chinese firms from a county to show that firms with larger scale are more active in improving their environmental management performance, which is measured based on 12 indicators obtained from surveys. Earnhart and Lizal (2010) used US data based on firms from chemical manufacturing industry and found that better managed firms (measured by return on sales) have higher levels of environmental management.

[5] There is another strand of literature that is concerned about the opposite direction: the effect of regulation on productivity (Gray, 1987). For example, Gray and Shadbegian (2003) found that tightened environmental regulations result in higher abatement cost and, subsequently, lower productivity at the plant level.

the share of firms adopting new abatement technology exhibits an inverted-U shape with respect to the marginal damage of pollution. In contrast, we show that under individual firms' optimal choice, the relationship between a firm's investment in advanced abatement technology and the firm's productivity exhibits inverted-U shape. Second, they showed that the relationship between policy stringency and the rate of technology adoption is inverted U-shaped. In contrast, we show that in response to a stringent policy, the more productive firms increases their investment level while the less efficient firms reduce their investment level. Third, in their model, all firms have the same productivity level, but with different costs of adopting the new technology (in the extension, they allowed firms to have different abatement cost curves). In contrast, our model builds on the recent firm heterogeneity literature and assume that firms have different productivity in production but face the same abatement technology.

The rest of the paper is organized as follows. We present the model in Section 2. Sections 3 and 4 contain all the theoretical analyses and equilibrium results. Empirical analyses are conducted in Section 5. Section 6 concludes the paper.

2 Model

Our model introduces pollution and abatement technology (Copeland and Taylor, 2003) to a heterogeneous-firms framework a la Melitz and Ottaviano (2008). Specifically, we consider an economy with N identical consumers and two industries: a homogeneous goods industry and a differentiated goods industry. We will treat homogenous goods as the numeraire, with prices equal to one and perfect competition. Our focus is on the differentiated goods industry, which is characterized by monopolistic competition.

2.1 Preference and demand

As in Melitz and Ottaviano (2008), we assume that each consumer has the following quasi-linear form

$$U = Q_0 + \alpha \int_{i\in\Omega} q_i di - \frac{1}{2}\beta \left(\int_{i\in\Omega} q_i di \right)^2 - \frac{1}{2}\gamma \int_{i\in\Omega} q_i^2 di \tag{1}$$

where α, β, and γ are positive parameters; Q_0 is the consumption of the numeraire; Ω is the set of all varieties from the differentiated goods industry; and q_i is the consumption of variety i. A consumer maximizes her utility subject to a budget constraint. As a result, market demand for variety i from all N consumers is $p_i = \alpha - \frac{\beta}{N} \int_{j\in\Omega} q_j dj - \frac{\gamma}{N} q_i$. β measures substitutability among varieties.

Given the monopolistic competition in the differentiated goods industry, the seller of variety i regards himself as a monopolist, and competition from all other varieties is totally captured in the vertical intercept of the demand function. Let M be the measure of Ω (i.e., the total number of varieties) and $P = \int_{i\in\Omega} p_i di$ be the aggregate price of all varieties. Then, the demand function for variety i is

$$p_i = A - bq_i \tag{2}$$

where

$$A = \frac{\alpha\gamma + \beta P}{\beta M + \gamma} \quad \text{and} \quad b = \frac{\gamma}{N}. \tag{3}$$

The demand slope b is exogenous, but the demand intercept A is endogenous, depending on both the degree of product substitution (captured by β) and the degree of market competition (captured by P and M).

2.2 Production and costs

Production of both the homogeneous good and differentiated goods needs to employ a composite of inputs which may include labor, capital, and others. The technology for the homogeneous goods is simple. By choosing units properly, we assume that producing one unit of homogeneous goods requires one unit of inputs. Hence, input price is also equal to unity. We turn to production of the differentiated goods next.

We will consider a short-run version of Melitz-Ottaviano model. Short run indicates a fixed measure of incumbent firms and no free entry to the differentiated goods industry. All firms draw their respective productivity parameter φ randomly from a uniform distribution on $[0, 1]$. After observing its productivity level, each firm decides whether to stay in or leave the market. Each firm that chooses to stay produces a distinct variety.

Production of each variety needs a bundle of inputs. Production generates pollution. However, a standard pollution abatement technology is available to all firms at no cost. By devoting inputs to abatement, a firm can reduce its pollution level. If a firm with productivity level φ employs x units of inputs and allocates a fraction, $\theta \in [0, 1]$, to pollution abatement, the amount of inputs available for production is $(1 - \theta)x$. As in Copeland and Taylor (2003), the output of the variety that the firm produces is assumed to be

$$q = \sqrt{\varphi(1 - \theta)x}. \tag{4}$$

As a result, a firm's actual productivity is endogenously determined where φ is its exogenously given productivity. Moreover, pollution generated from the firm's production is $z = R(\theta)\, x$, where $R(\theta)$ is the standard abatement function that satisfies $R(0) = 1, R(1) = 0$ and $R'(\theta) < 0$. We follow Copeland and Taylor (2003) to assume $R(\theta) = (1 - \theta)^{\frac{1}{v}}$, where $0 < v < 1$. v captures the effectiveness of the standard abatement technology: a larger v indicates lower efficiency as $\frac{\partial R}{\partial v} > 0$.

Aside from using a fraction of its inputs to reduce pollution, the firm can also invest in advanced abatement technology to enhance the efficiency of pollution reduction. Let $f(k)$ denote the advanced abatement technology with investment level k, in terms of units of input bundles.

Then, the firm's total pollution level will be

$$z = f(k)R(\theta)\,x \tag{5}$$

where $f(k) > 0$, $f^{'}(k) < 0$, and $f^{''}(k) > 0$. The convexity of $f(\cdot)$ indicates that as investment increases, its marginal effectiveness goes down. For tractability, we assume $f(k) = \left(\frac{1}{1+k}\right)^{\frac{1}{v}}$.

2.3 Environmental regulations

A government can regulate pollution in many ways. It can impose a pollution tax, a pollution quota, a tax on using pollution-generating inputs, or a quantitative restriction on energy use. In this paper, we consider pollution tax, τ, imposed on each unit of pollution generated by a firm.

3 Equilibrium analysis

3.1 Optimal profits

Facing demand (2), production (4) and (5), and environmental regulation τ, a firm with productivity φ chooses its total inputs x, the fraction of inputs for abatement θ, and investment in advanced technology k to maximize its profit. To this end, optimization is conducted by first deriving the optimal profit for any given k, denoted by $\pi(\varphi; k)$, and then deriving the optimal investment level.

Using (4) and (5) to eliminate θ, the production function can be written as

$$q = \sqrt{\varphi(1+k)z^{\nu}x^{1-\nu}}. \tag{6}$$

For a given x, choosing the fraction θ is equivalent to choosing the pollution level z. Thus, we can view output as a result of using both inputs and pollution in the production process. This production function yields the following cost minimization problem:

$$\min_{\{x,\ z\}} \{\tau z + x\} \qquad \text{s.t.} \quad \varphi(1+k)z^{\nu}x^{1-\nu} = q^2.$$

The first-order conditions are given by

$$\begin{aligned} \tau &= \lambda\varphi(1+k)\nu z^{\nu-1}x^{1-\nu} \\ 1 &= \lambda\varphi(1+k)(1-\nu)z^{\nu}x^{-\nu}, \end{aligned}$$

where λ is the Lagrangian multiplier. From these two equations we obtain

$$\frac{z}{x} = \frac{\nu}{1-\nu}\frac{1}{\tau}. \tag{7}$$

The equation above is the pollution-to-input ratio, which is independent of the productivity level. With higher pollution tax, every firm allocates a larger fraction of inputs to pollution abatement to reduce pollution. This ratio increases with v, meaning that pollution-to-input ratio is higher with a less effective abatement technology. Using this result in $\varphi(1+k)z^{\nu}x^{1-\nu} = q^2$, we can solve for the optimal z and x as below

$$x = \left(\frac{1-\nu}{\nu}\tau\right)^{\nu} \frac{q^2}{\varphi(1+k)}, \qquad z = \left(\frac{1-\nu}{\nu}\tau\right)^{\nu-1} \frac{q^2}{\varphi(1+k)}.$$

Hence, the minimum cost function for a given k is

$$C\left(q;\varphi,k\right) = \frac{\rho}{\varphi(1+k)}q^2,$$

where

$$\rho = \frac{\tau^{\nu}}{\nu^{\nu}\left(1-\nu\right)^{1-\nu}},$$

which increases with the pollution tax rate.

The firm chooses q to maximize its profit (excluding investment cost):

$$\max_{q>0}[(A-bq)q - C\left(q;\varphi,k\right)].$$

The first-order condition yields the optimal output

$$q(\varphi;k) = \frac{A\varphi(1+k)}{2[b\varphi(1+k)+\rho]}, \tag{8}$$

and the optimal price and profit, respectively,

$$p(\varphi;k) = \frac{bA\varphi(1+k)+2\rho A}{2[b\varphi(1+k)+\rho]}, \qquad \pi(\varphi;k) = \frac{A^2\varphi(1+k)}{4[b\varphi(1+k)+\rho]}. \tag{9}$$

3.2 Optimal investment in advanced abatement technology

Based on the previous analysis, we obtain the following optimization problem for k:

$$\max_{k}[\pi(\varphi;k) - k].$$

From (9), $\pi(\varphi;k)$ is strictly concave in k. The optimal investment level can be obtained from the first-order condition, which gives

$$k(\varphi) = \begin{cases} \frac{A\sqrt{\rho\varphi}-2\rho}{2b\varphi} - 1 > 0 & \text{for all } \ \varphi \in (\varphi^*, \varphi^{**}) \\ 0 & \text{otherwise,} \end{cases} \tag{10}$$

where φ^* and φ^{**} are given as

$$\varphi^* \equiv \frac{\rho}{16b^2}\left(A - \sqrt{A^2-16b}\right)^2 \ \text{ and } \ \varphi^{**} \equiv \frac{\rho}{16b^2}\left(A + \sqrt{A^2-16b}\right)^2. \tag{11}$$

To examine how firms with different productivity levels choose their respective investments, we take the partial derivative of k with respect to productivity φ, for $\varphi \in (\varphi^*, \varphi^{**})$, which gives

$$\frac{\partial k}{\partial \varphi} = \frac{4\rho - A\sqrt{\rho\varphi}}{4b\varphi^2} \begin{cases} > 0 & \text{for all } \ \varphi < 16\rho/A^2 \\ < 0 & \text{for all } \ \varphi > 16\rho/A^2. \end{cases} \tag{12}$$

The analysis leads to the following proposition:

Proposition 1. *(i) Only firms with intermediate levels of productivity, $\varphi \in (\varphi^*, \varphi^{**})$, make positive investments in advanced abatement technology.*

(ii). For those firms that make positive investments, the investment level increases with productivity level when $\varphi < \frac{16\rho}{A^2}$ but decreases with productivity level when $\varphi > \frac{16\rho}{A^2}$.

Depending on the relative value of ρ and A, there are four representative cases, which are all depicted in Figure 1. We can understand the inverted-U-shaped investment pattern mainly through two channels: demand and regulation. Figure 1-1 represents the case in which $\varphi^{**} < 1$, that is, $\rho < \frac{16b^2}{\left(A+\sqrt{A^2-16b}\right)^2}$. This condition is more likely to hold for weak market demand (small A) and weak environmental regulation (small ρ). Two observations are called from the above. First, firms with very low or very high productivity do not make any investment in advanced abatement technology. Second, the positive investment levels shows an inverted-U-shaped curve with respect to the increase in productivity. Every firm faces the tradeoff between allocating resources to production to increase output and allocating resources to abatement to reduce payment of pollution tax. However, the tradeoff works differently for different firms. Generally, a scale effect is observed, whereby it is optimal to invest more in abatement technology when pollution is high. Least-productive firms do not use plenty of inputs in their production anyway and so do not generate much pollution. Thus, investing in advanced abatement technology is not worthwhile. For medium-productive firms, those with higher productivity produce more, hire more inputs, and generate more pollution. Investing more in advanced abatement technology is worthwhile. However, among high-productive firms, those with even higher productivity, although producing more, hire less inputs and generate relatively less pollution. Naturally, they have lower levels of investment in advanced abatement technology. For extremely-productive firms, they no longer hire plenty of inputs any more, and consequently, they do not generate much pollution, which suggests that they have zero investment in advanced abatement technology.

Figure 1-2 represents the case in which $\varphi^{**} > 1$ and $\frac{16\rho}{A^2} < 1$, which together imply $\rho \in \left(\frac{16b^2}{\left(A+\sqrt{A^2-16b}\right)^2}, \frac{A^2}{16}\right)$. Compared with the previous case, market demand is stronger in this case, and environmental regulation is tougher. With stronger demand, all firms produce more than in the previous case. Even the most efficient firms ($\varphi = 1$) also hire a large quantity of inputs. As a large amount of inputs generates much pollution, the optimal decision for the most efficient firms is to render positive investment in advanced abatement technology. With tougher environmental regulation, firms are more concerned about pollution tax, and thus, investment in abatement technology. Nevertheless, the inverted-U-shape in investments still appears.

Figure 1-3 represents the case in which $\varphi^* < 1$ and $\frac{16\rho}{A^2} > 1$, which together imply $\rho \in \left(\frac{A^2}{16}, \frac{16b^2}{\left(A-\sqrt{A^2-16b}\right)^2}\right)$. In this case, demand is weaker, and environmental regulation is tougher compared with the case in Figure 1-2. Although firms do not produce as much as that in Figure

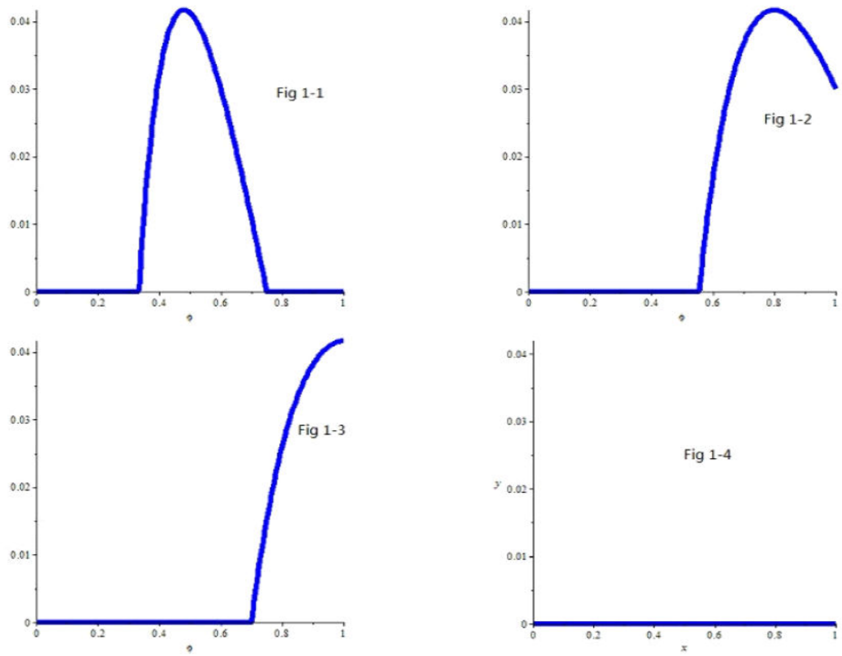

Figure 1: Optimal Investments

1-2, they need to be concerned more about pollution tax. As such, even the more efficient firms do not reduce their investment in advanced abatement technology. The inverted-U-shape does not appear. Compared with Figure 1-2, Figure 1-3 shows more firms with zero investment in abatement technology.

Figure 1-4 represents the case in which $\varphi^* > 1$, that is, $\rho > \frac{16b^2}{\left(A-\sqrt{A^2-16b}\right)^2}$. As the right-hand side is an increasing function of A, this condition is more likely to hold with smaller A. This is the case of weakest demand among all four cases. When demand is very weak, every firm produces a small amount, and consequently, does not generate much pollution. This is also the case with the toughest regulation, which induces all firms to allocate more inputs to pollution abatement, resulting in low level of pollution (see (7)). Thus, investing in abatement technology is not worthwhile.

Proposition 1 establishes the inverted-U-shape result, which contradicts existing results in studies such as Forslid et al. (2011), who predicted that the level of abatement investment is an increasing function of productivity. Two possible reasons may explain the difference: different approaches to modelling pollution and different demand structure. First, pollution generated by firms can be modeled through two approaches. One approach assumes that a firm's pollution emission is proportional to the amount of input it uses, called the input-pollution approach. The other approach assumes that a firm's pollution emission is proportional to the output the firm produces, hence called the output-pollution approach. Most existing studies on environment and heterogeneous firms, including Forslid et al. (2011), use the output-pollution approach. By contrast, like Copeland and Taylor (2003), we use the input-pollution approach. In the representative firm model, as that in Copeland and Taylor (2003), these two approaches are mathematically equivalent and do not produce qualitatively and economically different results. They could be different, mathematically and economically, in the heterogeneous firm model, however. The key question is whether our inverted-U-shape result can only be obtained under the input-pollution approach. This is a legitimate question as in the input-pollution approach, more-efficient firms may need less inputs, which may result in lower pollution and hence lower investment in advanced abatement technology. In checking whether Proposition 1 may still hold should the output-pollution approach be used, the effect of the following modification to our model must be examined: $z = R(\theta)\varphi x$, in which φx represents output rather than input as this term includes the productivity level. Repeating the analysis before, we can obtain the optimal output as $q = \sqrt{\varphi^{1-v}(1+k)x^{1-v}z^v}$. After the transformation $\Phi = \varphi^{1-v}$, where Φ is viewed as firms' productivity parameter, we have $q = \sqrt{\Phi(1+k)x^{1-v}z^v}$, which is the same as (6) in functional form. Thus, all the analyses are on track. Hence, we will still have the inverted-U-shaped investment in abatement technology with the turning point at $\Phi = \frac{16\rho}{A^2}$ or $\varphi = \left(\frac{16\rho}{A^2}\right)^{\frac{1}{1-v}}$. Our new result differs from the existing studies not because of the different approaches to the modeling of pollution generation.

We now turn to the second possible reason, which is about demand structure. Forslid et al. (2011) used the Melitz (2003) model, which has CES preference and constant markup. In such a model, a more-productive firm always employs more inputs, which implies larger investment in advanced abatement technology. In contrast, we adopt the Melitz and Ottaviano (2008) framework of linear demand. With linear demand, although a more-productive firm always produces more output in equilibrium, it may use less inputs and thus generates less pollution, which implies lower investment in abatement technology. This difference explains the different results between our paper and prior ones.

3.3 Pollution emission and resource allocation

We now explore other outcomes of the model. Our first question is how firms differ in allocating the fraction of their inputs to pollution abatement. From (5), we obtain

$$\theta = 1 - \left(\frac{z}{x}\right)^{\nu}(1+k). \tag{13}$$

From (7), the ratio $\frac{z}{x}$ is constant across all firms and independent of k. Thus, $\frac{\partial\theta}{\partial\varphi} = -\frac{\partial k}{\partial\varphi}$, and with Proposition 1, we immediately establish the following property:

Proposition 2. *(i) All firms with* $\varphi < \varphi^*$ or $\varphi > \varphi^{**}$ *have the same fraction of inputs devoted to pollution abatement.*

(ii). For those firms with $\varphi \in (\varphi^*, \varphi^{**})$, the fraction of inputs devoted to pollution abatement decreases with productivity level if $\varphi < \frac{16\rho}{A^2}$ but increases with productivity level if $\varphi > \frac{16\rho}{A^2}$.

As indicated by (13), substitution occurs between θ and k, which is easy to understand. If a firm decides to allocate a larger fraction of its inputs to pollution abatement, pollution emission will be reduced. As such, a larger investment to improve the abatement technology is not desirable. Similarly, if a firm has made a large investment on abatement technology, it will need to worry less about the total emission generated from its production, thereby leaving more inputs for production is optimal. Following the property of k as presented in Proposition 1, this substitution makes it easy to understand the opposite changes in θ and k with respect to a change in productivity. For less-productive firms, that is, $\varphi < \frac{16\rho}{A^2}$, those with higher productivity invest more in advanced abatement technology, which in turn allows theme to allocate a smaller fraction of inputs to abatement and leave more to production, without generating too much pollution. By contrast, for more-productive firms, that is, $\varphi > \frac{16\rho}{A^2}$, those with higher productivity invest less on advanced abatement technology, which in turn will require them to allocate a larger fraction of inputs to pollution abatement.

Our second question is about a firm's emission intensity, which is defined as the total emission divided by total output. This is a common measure of environmental performance. Let e denote the emission intensity, then $e = \frac{z}{q}$. We can prove the following proposition (see Appendix):

Proposition 3. *A more-productive firm has a lower emission intensity: $\frac{\partial e}{\partial \varphi} < 0$.*

In the proof of Proposition 3, we also show that $\frac{\partial q}{\partial \varphi} > 0$, that is, more-productive firms produce more output. Among the firms making positive investment in abatement technologies, we can also prove (i) $\frac{\partial z}{\partial \varphi} > 0$ for low-productivity firms, and (ii) under some conditions, $\frac{\partial z}{\partial \varphi} < 0$ for the high-productivity firms. Thus, the monotonicity of $q(\varphi)$ contributes to the decrease in emission intensity, but it is not the only reason. The firm's emission level may actually drops as its productivity increases, and even if the emission level goes up, the rate of increase is lower than that of the increase in output.

3.4 General equilibrium

The above analyses are partial equilibrium analyses as they are carried out for any given A. We now derive the equilibrium A, which, together with the previous analyses, will constitute the general equilibrium.

Using the optimal $k(\varphi)$ in (9), we obtain the following individual prices:

$$p(\varphi) = \begin{cases} \frac{A}{2} + \frac{\sqrt{\rho}}{\sqrt{\varphi}} & \text{if } \varphi \in (\varphi^*, \varphi^{**}) \\ \frac{A(b\varphi + 2\rho)}{2(b\varphi + \rho)} & \text{otherwise.} \end{cases}$$

We next calculate the aggregate price based on these individual prices. No firm exits the market as there is no fixed cost of production; thus, $M = 1$. As the individual prices take two forms, depending on the range of productivity level, we need to analyze the aggregate price in various cases respectively.

First, suppose that $\varphi^* \leq 1$ but $\varphi^{**} \geq 1$. Then, the aggregate price is

$$P = \int_0^{\varphi^*} \frac{A(b\varphi + 2\rho)}{2(b\varphi + \rho)} d\varphi + \int_{\varphi^*}^1 \left(\frac{A}{2} + \frac{\sqrt{\rho}}{\sqrt{\varphi}} \right) d\varphi = \frac{A}{2} \left(1 + \frac{\rho}{b} \ln \frac{b\varphi^* + \rho}{\rho} \right) + 2\sqrt{\rho}(1 - \sqrt{\varphi^*}).$$

The above condition, together with the expression of A given in (3) and that of φ^* given in (11), determines the equilibrium A. We can prove the existence of equilibrium A such that $\varphi^* \leq 1$ but $\varphi^{**} \geq 1$. For this equilibrium to exist, γ must be sufficiently small.[6]

Second, suppose that $\varphi^{**} < 1$. Then, the aggregate price is

$$\begin{aligned} P &= \int_{[0,\varphi^*] \cup [\varphi^{**},1]} \frac{A(b\varphi + 2\rho)}{2(b\varphi + \rho)} d\varphi + \int_{\varphi^*}^{\varphi^{**}} \left(\frac{A}{2} + \frac{\sqrt{\rho}}{\sqrt{\varphi}} \right) d\varphi \\ &= \frac{A}{2} \left[1 + \frac{\rho}{b} \ln \frac{(b\varphi^* + \rho)(b + \rho)}{(b\varphi^{**} + \rho)\rho} \right] + 2\sqrt{\rho}(\sqrt{\varphi^{**}} - \sqrt{\varphi^*}). \end{aligned}$$

The above condition, together with the expression of A given in (3) and those of φ^* and φ^{**} given in (11), determines the equilibrium A. We can prove the existence of equilibrium A, under which $\varphi^{**} < 1$. For this equilibrium to exist, $\alpha > \frac{2}{\beta}\left(\beta^2 + \gamma^2\right)$ and ρ must be sufficiently small.[7]

Third, suppose that $\varphi^* > 1$. Then, the aggregate price is

$$P = \int_0^1 \frac{A(b\varphi + 2\rho)}{2(b\varphi + \rho)} d\varphi = \frac{A}{2} \left(1 + \frac{\rho}{b} \ln \frac{b + \rho}{\rho} \right).$$

The above condition, together with the expression of A given in (3), determines the equilibrium A, which is $A = 2\alpha\gamma / \left[\beta \left(1 - \frac{\rho}{b} \ln \frac{b+\rho}{\rho} \right) + 2\gamma \right]$.

4 Effects of environmental policies

In this subsection, we examine firms' investment in advanced abatement technology in response to changes in environmental policies. The type of environmental policy we focus on is the pollution tax. ρ is an increasing function of τ. From (10), we observe that τ affects k through ρ only, and $sign\left(\frac{\partial k}{\partial \tau}\right) = sign\left(\frac{\partial k}{\partial \rho}\right)$ because $\frac{\partial \rho}{\partial \tau} > 0$. Furthermore,

$$\frac{\partial k}{\partial \rho} = \frac{\frac{A}{4}\sqrt{\frac{\varphi}{\rho}} - 1 + \frac{\sqrt{\rho\varphi}}{2\sqrt{r}} \cdot \frac{\partial A}{\partial \rho}}{b\varphi} \tag{14}$$

for those firms that make positive investment in advanced abatement technology. As we cannot obtain the closed form solution for the equilibrium A (except in the case of $\varphi^* > 1$, which is less

[6] The proof is quite lengthy. It is available upon request from the authors.
[7] The proof is quite lengthy. It is available upon request from the authors.

interesting), let us first examine the equilibrium effects of changing pollution tax by treating A as constant. We will return later to discuss the possible change when the general equilibrium effect is taken into consideration. Assuming $\frac{\partial A}{\partial \rho} = 0$ for the moment, we immediately know that $\frac{\partial k}{\partial \rho} > 0$ if and only if $\varphi > \frac{16\rho}{A^2}$, which is just the turning point of the productivity level for the inverted-U-shaped investment curve. Hence, we establish the following result.

Proposition 4. *Suppose that $\frac{16\rho}{A^2} < 1$ in equilibrium. Then, an increase in pollution tax results in contrasting responses from the firms: more-productive firms ($\varphi > \frac{16\rho}{A^2}$) raise their investment in advanced abetment technology, whereas less-productive ones ($\varphi < \frac{16\rho}{A^2}$) reduce their investments.*

The proposition applies to the range of firms that make positive investment before the tax increase. For firms at the margins between investing or not investing before the tax increase, we can obtain $\frac{\partial \varphi^{**}}{\partial \rho} > 0$ and $\frac{\partial \varphi^{*}}{\partial \rho} > 0$. That is, low-productivity marginal firms (i.e., those just above the critical level φ^*) switch from making positive investment to making zero investment when pollution tax increases. By contrast, high-productivity marginal firms (i.e., those just above the critical level φ^{**}) switch from making zero investment to making positive investment in response to pollution tax increases. The intuition is as follows. In response to an increase in pollution tax, a firm can do two things. On the one hand, the firm can reallocate more input from production to pollution reduction. On the other hand, it can increase investment in abatement technology to reduce the existing level of pollution. The proposition shows that less-efficient firms prefer using the former method to reduce pollution, and as a result, they correspondingly reduce their abatement-technology investment level to save cost, whereas more-efficient firms find the latter approach more profitable. The key reason is that reallocating one unit of input from production to pollution reduction hurts the more-efficient firms' profits more compared with the less-efficient firms' profits due to their difference in production efficiency.

Forslid et al. (2011) predicted that the incentive to invest in abatement technology will fall for all firms as pollution cost increases. As pollution tax goes up, firms will pollute less, which reduces their incentive to invest in abatement technology (the scale effect). Our prediction is different with regard to high-productivity firms. In Forslid et al. (2011), high-productive firms always generate more pollution than low-productivity firms and will thus invest more in abatement technology. By contrast, in our setting, high-productivity firms do not always have larger investment. This difference indicates that the marginal effect of further investment is lower in their model than in our model, thus, high-productivity firms find it optimal to increase their investment in our model but to reduce their investment in the model proposed by Forslid et al. (2011).

We now turn to the general equilibrium effect by including the indirect effect through A. From (9), every firm raises its optimal price in response to the tax increase (holding A constant, $\frac{\partial p}{\partial \tau} > 0$). This move tends to raise A. Thus, $\frac{\partial A}{\partial \tau} > 0$ or $\frac{\partial A}{\partial \rho} > 0$. From (14), this indirect effect raises the value of $\frac{\partial k}{\partial \rho}$. As long as $\frac{\partial A}{\partial \rho}$ is not too large, we can still have $\frac{\partial k}{\partial \rho} < 0$ for φ sufficiently close to φ^*, i.e., very low productivity. Then, the qualitative aspect of Proposition 4 is still valid (with a different cut-off productivity level). Even if $\frac{\partial k}{\partial \rho} > 0$ for all φ, our finding is still and even more in contradiction to that of Forslid et al. (2011).

5 Empirical test

We now bring the key theoretical predictions to the data. We will not test all our theoretical results partly due to data availability and partly due to the theoretical focus of this paper.

5.1 Data

Our empirical analysis uses data drawn from the Energy Saving and Abatement Survey (ESAS), which covers 800 manufacturing firms in China for the period between 2005 and 2009. The survey was conducted jointly by Chinese Academy of Social Sciences (CASS) and Center for China in the World Economy (CCWE) of Tsinghua University. It contains information about each firm's energy usage, pollutive input usage, input prices, expenditure on abatement technologies, and others.

In testing Proposition 1, data on abatement technology expenditure are of particular use. In the data, expenditure consists of investment in process optimization, expenses for the retrofitting of old equipment and purchasing of new equipment, and labor costs associated with these activities. Expenditure is a very good measure of investment in abatement technology upgrading.

We need more information about each firm's production and financial data in order to measure firm productivity. However, such information is not available in the ESAS dataset. Thus, we turn to the Annual Surveys of Manufacturing Firms in China (ASMF) conducted by the National Bureau of Statistics of China. This survey includes all firms with annual sales over RMB 5 million yuan. It contains detailed accounting information of all the surveyed firms, which allows us to estimate firm productivity. For our empirical analysis, we need to merge the ESAS data with the ASMF data for the period of 2005 to 2009. The merged dataset consists of a balanced panel of 800 firms. Some summary statistics are reported in Table 1. On average, each firm spends RMB 6.6 million on abatement technology per year. This amount is significant given the total fixed assets of an average firm, which is RMB 123 million yuan.

5.2 Regression analysis

Based on Proposition 1, we construct the following regression model:

$$log(AI_{ijmt}) = \gamma_1 TFP_{it} + \gamma_2 TFP_{it}^2 + \beta^T X_{ijmt} + \epsilon_{ijmt} \tag{15}$$

where AI_{ijmt} is abatement expenditure of firm i from industry j and province m in year t; TFP_{it} is firm i's productivity in year t; X_{ijmt} is a vector of control variables including capital-labor ratio,

Table 1: **Summary Statistics**

	Mean	Std. Dev.	Observations
Abatement Investment	6637.4	52791.2	4000
Total Fixed Assets	123120.5	990911.6	4000
Employment	560.3	3298.6	4000
Value Added	90753.6	565512.4	4000

Note: Abatement investment, capital expenditure, and value added are in thousand RMB.

number of workers, year dummy, industry dummy, ownership dummy, and province dummy; and ϵ_{ijmt} is a random term. The introduction of the productivity square term, TFP_{it}^2, allows us to capture the possibility of the inverted-U-shape of investment in abatement technology.

Before running the above regression, we need to first estimate each firm's productivity level. Following the literature, we estimate firms' total factor productivity (TFP). TFP can be estimated in three ways. We first use the simple ordinary least square (OLS) regression approach. Specifically, we assume that production takes a Cobb-Douglas form with respect to labor and capital, and then regress the value-added of a firm on the number of workers (L) and capital stock (K) it has. The predicted Solow residual is used as the estimate of each firm's (the natural log of) TFP. However, this OLS estimation of TFP may suffer from the simultaneity bias problem. Specifically, input choices could be endogenously determined by productivity shocks that are unobservable, which may lead to an upward bias in the estimation coefficients of more variable inputs, such as capital (Van Biesebroeck, 2007). For this reason, to obtain robust results, we also use two alternative estimation approaches, namely, panel fixed-effect estimation and semi-parametric estimation. In semi-parametric estimation, proposed by Levinsohn and Petrin (2003), the Levinsohn and Petrin (LP) method uses the variation in intermediate input to proxy unobservable productivity shocks, thus reducing the simultaneity problem.

We run regression (15) using three TFP estimates, respectively. The regression results are reported in Table 2. The first two columns report the results using Solow residual as the TFP measurement; columns (3) and (4) present findings using the TFP obtained from the panel fixed effect estimation; and the last two columns present outcomes employing the TFP estimates based on the LP approach. The qualitative results from all six regressions are the same: the coefficient of TFP_{it} is positive, whereas the coefficient of TFP_{it}^2 is negative, all statistically significant at the 1% level.

The positive sign of the TFP_{it} coefficient, γ_1, and the negative sign of the TFP_{it}^2 coefficient, γ_2, are necessary but not sufficient conditions to prove the inverted-U-shape of the abatement technology expenditure. They only confirm the concave property of the expenditure as a function of productivity level. If the domain of TFP is the entire real line, R, i.e., in $(0, \infty)$, then they are also sufficient conditions. However, if the domain of TFP is only a subset of R, which is the case in the present paper, they are not sufficient. Following Lind and Mehlum (2010), we proceed to test additional restrictions. A simple sufficient test for inverted-U-shape can be carried out by

Table 2: **Productivity and Investment in Abatement Technology**

	(1) OLS	(2) OLS	(3) FE	(4) FE	(5) LP	(6) LP
TFP	0.470***	0.529***	0.855***	0.752***	2.94×10^{-4}***	2.35×10^{-4}***
	(0.014)	(0.009)	(0.085)	(0.067)	(5.05×10^{-6})	(4.65×10^{-6})
TFP^2	-0.015***	-0.017***	-0.093***	-0.066***	-2.69×10^{-9}***	-2.28×10^{-9}***
	(7.70×10^{-4})	(4.7×10^{-4})	(0.020)	(0.016)	(7.24×10^{-11})	(6.34×10^{-11})
log(K/L)	0.399***		0.465***		0.256***	
	(0.016)		(0.018)		(0.013)	
log(L)		0.989***		0.949***		0 .612***
		(0.011)		(0.016)		(0.014)
Industry	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Observations	4000	4000	4000	4000	4000	4000
R^2	0.5133	0.8165	0.3696	0.6140	0.6726	0.7563

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

evaluating the slope of the estimated quadratic curve at the two end points of the data range, denoted by φ_l and φ_h, respectively. This requires

$$\gamma_1 + 2 \cdot \varphi_l \cdot \gamma_2 > 0 \qquad \text{and} \qquad \gamma_1 + 2 \cdot \varphi_h \cdot \gamma_2 < 0. \tag{16}$$

We test the above conditions using ordinary F-test. For each of the regressions (from different TFP measures), we calculate the slopes at the two endpoints of the TFP measure and find that they have the correct sign, i.e., positive at φ_l and negative at φ_h. The corresponding F-test also yields very significant results. The results are presented in Table 3. Thus, an inverted-U-shaped relationship exists between abatement technology investment and productivity level.

To determine if the inverted-U-shape is driven by some outliers, we also redo the test by excluding observations with the 1% and 5% of the highest TFP firms, respectively. The inverted-U-shape is persistent.

As pointed out in the empirical literature on environment and productivity, the causality may run the opposite direction. That is, investment in abatement technology may in fact affect a firm's TFP.[8] This potential endogeneity problem is less serious in our case as we are not claiming a monotonic relationship between TFP and investment in abatement technology. Given the difficulty in identifying an instrumental variable for TFP, as an alternative, we address this issue by using one year lagged TFP and lagged TFP squared as the instrument for TFP and TFP squared. The OLS results, reported in Table 4, show that the inverted-U-shape result is robust based on TFP estimates from OLS and LP methods. With the fixed-effect TFP estimator, the parameters of TFP and TFP squared are not statistically significant.

[8] For example, Earnhart and Lizal (2011) found evidence from Czech that good environmental performance appears to improve profitability by lowering costs. See also Gray (1987).

Table 3: **Testing Inverted-U-Shaped Curve**

	$2\gamma_2\varphi_l + \gamma_1$	$2\gamma_2\varphi_h + \gamma_1$
TFP estimated by OLS, control for KL ratio	0.469***	-0.585***
	(1122.32)	(198.88)
TFP estimated by OLS, control for employment	0.528***	-0.606***
	(3807.81)	(566.70)
TFP estimated by FE, control for KL ratio	0.838***	-0.600**
	(104.59)	(6.19)
TFP estimated by FE, control for employment	0.739***	-0.283
	(133.25)	(2.25)
TFP estimated by LP, control for KL ratio	2.94×10^{-4}***	-3.71×10^{-4}***
	(3384.93)	(718.07)
TFP estimated by LP, control for employment	2.35×10^{-4}***	-3.29×10^{-4}***
	(2551.54)	(756.17)

F-statistics in parentheses.All F-statatistics are with degree of freedom of (13,946)

*** p<0.01, ** p<0.05, * p<0.1

Table 4: **Productivity and Investment in Abatement Technology: Lagged TFP**

	(1) OLS	(2) OLS	(3) FE	(4) FE	(5) LP	(6) LP
$lagTFP$	0.434***	0.480***	0.167	0.083	3.47×10^{-4}***	2.80×10^{-4}***
	(0.017)	(0.011)	(1.03)	(0.129)	(7.19×10^{-6})	(6.46×10^{-6})
$lagTFP^2$	-0.014***	-0.015***	0.031	0.038	-4.02×10^{-9}***	-3.52×10^{-9}***
	(0.001)	(0.0006)	(0.020)	(0.045)	(1.26×10^{-10})	(1.09×10^{-10})
log(K/L)	0.390***		0.477***		0.245***	
	(0.013)		(0.020)		(0.015)	
log(L)		0.955***		0.947***		0.618***
		(0.014)		(0.018)		(0.016)
Industry Dummy	YES	YES	YES	YES	YES	YES
Year Dummy	YES	YES	YES	YES	YES	YES
Observations	3200	3200	3200	3200	3200	3200
R^2	0.4870	0.7729	0.3544	0.5933	0.6639	0.7521

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 5: **Productivity and Electricity Intensity**

	(1) OLS	(2) OLS	(3) FE	(4) FE	(5) LP	(6) LP
TFP	-0.0280***	-0.0316***	-0.2456***	-0.2463***	-9.44×10^{-6}***	6.77×10^{-6}***
	(0.0038)	(0.0038)	(0.0177)	(0.0176)	(1.67×10^{-6})	(1.77×10^{-6})
log(K/L)	-0.0124		-0.0188***		-0.0072	
	(0.0079)		(-0.008)		(0.0080)	
log(L)		-0.0675***		-0.0603***		-0.038
		(0.0093)		(0.0176)		(0.033)
Industry Dummy	YES	YES	YES	YES	YES	YES
Year Dummy	YES	YES	YES	YES	YES	YES
Observations	4000	4000	4000	4000	1900	1900
R^2	0.4992	0.5055	0.5157	0.5203	0.4962	0.4985

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

5.3 Emission intensity

We now test Proposition 3, which says that the emission intensity of more-productivity firms is lower than that of less-productivity firms. In general, measuring country-level pollution emission is difficulty and the task is even harder at the firm level. Data are simply not available to us. Alternatively, we use a firm's usage of pollution generating inputs as a proxy for its pollution emission. Although not a perfect measure of pollution emission, it is consistent with our model in which a firm's pollution emission depends on its total input. Note that there are many types of pollution generating inputs and different inputs generate different degrees of pollution. Hence, without a very good conversion matrix, we use a single input, namely electricity, as the proxy because electricity is the most commonly used input in all firms. Although using electricity per se does not generate pollution directly, producing electricity does. As such, the amount of electricity used by a firm represents its share of pollution generated from producing electricity in the economy.

Then, our regressor, namely emission intensity, is the ratio of the electricity usage by a firm to the firm's total value added, which is inflation-adjusted. We regress this emission intensity on three measures of TFP, respectively, controlling for electricity price and other variables as in the main regression. Table 5 shows the results. TFP has a clear negative impact on the emission intensity of the firms, confirming our theoretical prediction.

6 Conclusion

This paper incorporates pollution emissions (Copeland and Taylor, 2003) and endogenous investments in abatement technology into a model with firm heterogeneity in productivity and endogenous markup (Melitz and Ottaviano, 2008). The analysis shows how firms with different productivity levels optimally choose the level of investment in advanced abatement technology. In particular, we find that the incentive to invest in such technology is positively related to the pollution emission that a firm generates and takes an inverted-U-shaped curve against productivity. Nevertheless, more-productive firms always have lower emission intensity than less-productive firms. In response to a rise in pollution tax, less-productive firms reduce their investment, whereas more-productive firms raise their investment.

The present paper demonstrates the theoretical possibility of the inverted-U-shaped investment in abatement technology, which is supported by China data based on a survey. The result may not hold for every industry and in every country. It is therefore important to find necessary and sufficient conditions for the inverted-U-shape result to hold. Examining the welfare effects of strengthening environmental regulation and deriving the optimal pollution tax policy are also worth further investigation. These are left for future research.

More rigorous empirical research should be carried out in future research when richer data are available. For example, we should employ a more accurate data or estimates of individual firms' pollution emission level in order to have a better test of the relationship between emission intensity and productivity.

Appendix

Proof of Proposition 3.

From the production function, we have $z^{\nu}x^{1-\nu} = \frac{q^2}{\varphi(1+k)}$. From (7) and (8) we get

$$e = \frac{z}{q} = \frac{q}{\varphi(1+k)} \left(\frac{\nu}{1-\nu}\right)^{1-\nu} \left(\frac{1}{\tau}\right)^{1-\nu} = \left(\frac{\nu}{1-\nu}\right)^{1-\nu} \left(\frac{1}{\tau}\right)^{1-\nu} \frac{A}{2\left(b\varphi(k+1)+\rho\right)}.$$

We can easily see that $\frac{\partial e}{\partial(\varphi(1+k))} < 0$. From the expression of optimal k, we have

$$\varphi(1+k) = \max\{\varphi, \frac{A}{2}\sqrt{\varphi\rho} - \rho\}.$$

Thus, $\frac{d(\varphi(1+k))}{d\varphi} > 0$ except at the non-differentiable kink point. Thus, $\frac{\partial e}{\partial\varphi} < 0$.

In fact, we can also show $\frac{dq}{d\varphi} > 0$. Substituting the expression of optimal k from (10) into q in (8), we get $q = \frac{1}{2b}\left(\frac{A\sqrt{\rho\varphi}-2\rho}{\sqrt{\rho\varphi}}\right)$ for $\varphi \in (\varphi^*, \varphi^{**})$, and $q = \frac{A\varphi}{2(b\varphi+\rho)}$ for $\varphi \notin (\varphi^*, \varphi^{**})$. Both are increasing functions of φ.

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