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Essays on Environmental Policy and Markets

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ESSAYS ON ENVIRONMENTAL POLICY AND MARKETS

A Dissertation Presented

by

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Resource Economics

ESSAYS ON ENVIRONMENTAL POLICY AND MARKETS

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DEDICATION

To my family

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Writing this dissertation was one more challenge in my life. Like every other challenges that I have come across there were always people that offered the support I needed to get through. My parents, my professors and my friends all deserve my sincere gratitude for their love, prayers, support, and patience over the years.

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ABSTRACT

ENVIRONMENTAL POLICY AND MARKETS

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This dissertation consists of two theoretical papers on market-based environmental policy. The first paper exploits the correlation between the environmental performance of firms and their economic performance to show that financial markets can be used to help enforce environmental policy and to design more efficient regulations. The results indicate that when markets punish firms for not complying with environmental standards, environmental regulators can exploit this by setting stricter standards. In fact, it is possible for the regulator to use market-driven enforcement to reduce a firm's emissions and monitoring of the firm simultaneously. The second paper provides a theoretical analysis of the nature of an optimal emissions tax when firms' emissions are not perfectly observable. The purpose is to examine how the optimal tax is affected by enforcement costs and the market structure. We obtain the result that market imperfections and enforcement costs push the optimal tax lower than the marginal damage when the number of firms in the market is exogenous. However, when the number of firms is determined endogenously enforcement costs generate two countervailing effects on the optimal tax. The overall effect of enforcement costs on the optimal tax depends on the strength of direct relative to indirect effects when there is free entry and exit.

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CHAPTER 1

EXPLOITING FINANCIAL MARKETS TO IMPROVE ENVIRONMENTAL QUALITY

1.1 Introduction

Analytical and empirical studies have identified a correlation between the environmental performance of firms and their economic performance. Good environmental performance in these studies refers to consistent compliance or over-compliance with environmental standards and/or the adoption of effective voluntary programs. Measures of economic performance vary from profit to stock market measures. Positive or negative effects of environmental performance on economic performance suggest that markets can be exploited to help enforce environmental policies and to design more efficient regulations. In this paper we examine environmental standard setting with both regulatory and market-driven enforcement. A unique feature of the model is that we consider a conventional emissions standard for a firm combined with a stricter standard with which the regulator certifies that the firm is over-compliant. We demonstrate how regulators may be able to exploit market penalties and rewards for environmental performance to pursue more stringent environmental regulations.

Empirical studies that attempt to link financial performance to environmental performance have focused in large part on correlation and regression analysis (for example, Mamingi et al., 2006; Al-Tuwaijri et al, 2004). There also has been emphasis on event studies, which emphasizes the impact on a firm's financial measure before and after incidents of violations or recognition for good environmental performance (for example, Hamilton, 1995;

Klassen & McLaughlin, 1996; Laplante et al, 1994; Bosch et al, 1998).[1] There is evidence that announcements or disclosure of violations result in negative security price movements across all industries (Shane, Spicer & Barry, 1983; Konar and Cohen, 1997, 2001; Gupta and Goldar, 2005; Dasgupta et al, 2001; 2006). The difference in the intensity of movements in firm value reflects investors' anticipation of the subsequent effects on the costs of abatement (Ditz, 2002; Laplante & Lanoie, 1994; Patten and Nance, 1998). Moreover, there is evidence that firms exposed to large negative effects of violations subsequently reduce their emissions more than their industry peers (Konar and Cohen, 1997).

Violations often result in lawsuits, whose settlement and/or subsequent investments in abatement invoke a negative reaction from investors (Muoghalu, 1990; Badrinath & Bolster, 1996). Violations, as well as lawsuits often lead to penalties, and like lawsuits, regulatory penalties have been shown to cause a fall in a firm's value (Hughes, 2000). Even challenging the lawsuits or contesting regulatory penalties further erodes the value of a firm (Bosch et al, 1998).

On the other hand, good environmental performance positively correlates with firm value (Al-Tuwaijri et al, 2004; Russo et al, 1997; Gupta and Goldar, 2005; Khanna and Anton, 2002; Salama, 2005; Klassen and McLaughlin, 1996; Hamilton, 1995; Feldman et al, 1996), as does good environmental record keeping; for example, extensive disclosures of the environmental impact of a firm's activities (Blacconiere et al, 1994). A good record of

[1] An event-study assesses the impact of new information on stock prices by measuring the changes in the average of the stock prices when such information (event) is made public (McWilliams et al, 1999). It uses the 'efficient capital market' model, which assumes that security prices are likely to reflect all the available information about the future profit of a given firm. Event-studies aim to isolate any abnormal stock returns associated with the release of a specific piece of information.

environmental performance reduces financial risks to firms (Halkos and Sepetis, 2007) and attracts investors seeking “greener’ investments (Barnea et al, 2005).[2]

A firm’s environmental performance also has implications for its performance in product markets. It has been shown that the demand for goods is negatively affected by noncompliance (Stafford, 2007). High polluting industries, especially those with greater consumer contact, often tend to have higher participation rates in voluntary programs (Arora and Cason, 1996).

The ability of firms to exploit gains in emissions abatement for economic and financial advantage offers environmental regulators a unique opportunity to enhance and complement existing regulations to increase their effectiveness. Firms with the potential to achieve higher abatement levels can be targeted with regulatory and market-oriented incentives. A program with this characteristic is the National Environmental Performance Track (NEPT), which is an exclusive club of over-compliant firms aimed at promoting their abatement achievements with the assistance of the Environmental Protection Agency (EPA). Over-compliance data for this program is being used by financial advisory and investment firms. Another approach to promote ‘green’ investments has been the introduction of stock market indices that focus on

[2] Other efforts to establish a market value for environmental performance have focused on measuring a firm’s performance and exposure through a set of performance indicators and checklists (Repetto & Austin, 2000). However, such checklists provide no informative link between a firm’s environmental performance and its market value. A related approach uses these performance indicators to produce a ratings system, and firms are ranked according to some index or category. For example, financial advisory and investment firms such as Trucost, Innovest, Calvert, KLD, etc help companies and investors measure the environmental impacts of business activities in quantitative and financial terms using performance ratings.

the use of abatement technologies. For example, WilderHill Energy Index tracks the clean energy sector.[3]

In this paper, we focus on the implications of the link between environmental and financial performance. The positive relationship between financial and environmental performance identified in empirical work suggests that firms that over-comply with environmental standards are rewarded in financial markets while noncompliant firms are punished by these markets. We demonstrate how market-driven enforcement complements and contributes to the objectives of conventional environmental regulation. The role of monitoring and enforcement on compliance with conventional standards is well documented (for example see Shimshack & Ward, 2008; Stranlund et al, 2009). But there is no work that addresses whether market-driven enforcement can be exploited in the design of environmental regulations. We show that the regulator can combine conventional regulatory enforcement, financial market forces, and certification for over-compliance to achieve better environmental performance.

Our results show that market enforcement can be exploited to set stricter emissions standards. In particular certifying the achievement of over-compliance can lead to improved environmental quality. Furthermore, market enforcement allows the regulator to reduce monitoring effort while simultaneously setting a stricter single emissions standard. Setting two emissions standards - over-compliance and regular standards - is a more efficient policy option than a single emissions standard, and it results in better environmental quality. However, setting two emissions standards may require an increase in monitoring effort.

[3] See http://www.wildershares.com/

1.2 The Analytical Framework: Emissions Standards and Compliance

Throughout the analysis we focus on environmental standard setting and enforcement for a single risk neutral firm. Suppose the market value of the firm, given a level of emissions *e*, is $w(e)$, which is strictly concave. Let e^n denote the firm's emissions level when it does not control its emissions; that is, e^n is the solution to $w^{/}(e) = 0$ - the level of emissions which maximizes the firm's per share value. Note that $w^{/}(e) > 0$ for $e < e^n$. The firm's emissions produce environmental damage $d(e)$, which is strictly increasing and strictly convex.

For simplicity the payoff and damage functions are assumed to be quadratic functions. Thus, their marginals have the following linear forms:

$$\begin{aligned} w^{/}(e) &= w - w^{//}e \\ d^{/}(e) &= d + d^{//}e \end{aligned} \tag{1}$$

where $w, d, w^{//}$, and $d^{//}$ are all positive constants. We assume throughout that $w > d$, so that it will never be optimal to completely eliminate the firm's emissions. In this section the firm faces a single emissions standard *s* which forbids emissions above that level. The firm is compliant if $e \le s$, but it is noncompliant if $e > s$. To counteract the firm's incentive to not comply with the standard the government monitors and enforces the emissions standard. Monitoring may involve onsite inspections and evaluating self- reporting by the firm of its abatement activities.

Enforcement here means that a violation of the standard is punished with a fixed fine. The government monitors the firm with a probability $\pi \in (0,1]$. There are no errors in monitoring, That is, there are no type 1 or type 2 errors. The firm pays a government-mandated fine, ϕ_p, when it is caught cheating. A fixed government-mandated penalty for violation is suitable for our model for a couple of reasons. First, it avoids uncertainty for the firm when it makes compliance decisions so that the firm has perfect information about the benefits and costs of compliance and noncompliance. Secondly, penalties (and/or the guidelines on how they can be imposed) are usually set out in advance in the form of legislation or order. Changes to such legislation within a reasonable time may be difficult. Also, applying penalties indiscriminately may expose the regulator to costly litigation.

In addition, the stock market punishes the firm for noncompliance through divestment by investors.[4] This leads to a loss, ϕ_m, in the market value of its assets. We refer to this as market enforcement of the standard. The market relies on government monitoring for signals about the firm's compliance status. Thus the market penalty is applied only when the government discovers that the firm has violated the standard. Furthermore, we assume that the effects of the government-mandated penalty and market punishment are separable.

The government incurs monitoring costs of, $\mu\pi$, where μ is constant marginal monitoring costs. There are no costs of penalizing the firm if it is caught in violation.[5]

Because the government and market penalties are fixed values that do not depend on the firm's choice of emissions, the firm's compliance decision is binary. The firm either complies with the standard by choosing $e = s$ or it violates the standard by not reducing its emissions, that is, by choosing $e = e^n$. We make the common assumption that the firm will comply with the standard if it is indifferent between compliance and noncompliance. Therefore, the firm is compliant if and only if its payoff from complying with the standard is

---

[4] This could also be a loss in value because some consumers leave the firm.

[5] Cohen (1986) in a study of the prevention of oil pollution in US coastal waters estimated that the marginal cost of preventing one gallon of oil to be $5.50. Of this amount, only $3.98 is the cost to the industry associated with additional prevention effort. The remaining $1.52 is the enforcement cost associated with the US Coast guard having to operate more frequent patrols.

not less than its expected payoff when it violates the standard; that is, $w(s) \geq w(e^n) - \pi(\phi_p + \phi_m)$. Alternatively, the firm complies if and only if

$$w(e^n) - w(s) \leq \pi(\phi_p + \phi_m). \tag{2}$$

The interpretation of equation (2) is that the firm complies if and only if the gain from noncompliance, $w(e^n) - w(s)$, is not greater than the expected penalty for noncompliance, $\pi(\phi_p + \phi_m)$.

Throughout we assume that it is efficient from society's point of view that the firm reduce its emissions below e^n. Given the all-or-nothing nature of the firm's compliance decision, this implies that the government chooses π and s so that the firm is compliant. Moreover, to economize on monitoring costs the government chooses π and s so that (2) holds with equality. This implicitly defines the amount of monitoring necessary to motivate the firm to comply with some standard *s*, given the penalties ϕ_m and ϕ_p; that is,

$$\pi(s) = \frac{w(e^n) - w(s)}{\phi_p + \phi_m}. \tag{3}$$

Obviously we have to have $\pi(s) \in [0,1]$. $\pi(s) \geq 0$ is guaranteed by $w(e^n) > w(s)$. Moreover, if $[w(e^n) - w(s)]/[\phi_p + \phi_m] > 1$, then the firm violates the standard even if $\pi = 1$. This outcome would violate our assumption that it will be efficient to reduce the firm's emissions. This implies that if $[w(e^n) - w(s)]/[\phi_p + \phi_m] > 1$ for some *s*, the government needs to reduce the standard so that $[w(e^n) - w(s)]/[\phi_p + \phi_m] \leq 1$.

Using (3) note that

$$\pi'(s) = -\frac{w'(s)}{\phi_p + \phi_m} < 0, \tag{4}$$

which indicates that the monitoring necessary to achieve compliance is monotonically decreasing in the emissions standard. This is intuitive because a stricter standard increases the firm's motivation to cheat, which increases the monitoring required to ensure compliance with the standard.

To determine the optimal emissions standard for the firm the regulator maximizes the difference between the firm's payoff and damages and monitoring costs, subject to $e = s$ and (3). Thus, the regulator's problem can be expressed as

$$\max_s \; w(s) - d(s) - \mu\pi(s)\,. \tag{5}$$

Using (4) the first order condition for an interior choice of s can be written as

$$d^{/}(s) - w^{/}(s) - \frac{w^{/}(s)\mu}{\phi_p + \phi_m} = 0\,. \tag{6}$$

Denote the solution to (6) as $\bar{s}_r$. Using the linear forms of $d^{/}$ and $w^{/}$ from (1) and (6) we can solve for $\bar{s}_r$ explicitly:

$$\bar{s}_r = \frac{Aw - d}{Aw^{//} + d^{//}}\,, \text{ where } A = 1 + \frac{\mu}{\phi_p + \phi_m}\,. \tag{7}$$

From here on we refer to $\bar{s}_r$ as the regular standard. The first-best emissions standard — the standard that equates $w^{/}(s)$ and $d^{/}(s)$ — can be determined from (7) by setting marginal monitoring costs μ equal to zero. The first best- standard is s_1 in Figure 1. For $\mu > 0$, it is straightforward to show that $\bar{s}_r$ is increasing in μ. This reflects the well-known fact that it is optimal to set a less strict standard when the marginal cost of enforcing compliance with the standard is greater.

It is also straightforward to show that $\bar{s}_r$ is decreasing in the regulatory and market penalties for noncompliance. Hence, when markets punish firms for not complying with environmental standards, environmental regulators can exploit this by setting stricter standards. Our regular standard $\bar{s}_r$ and the optimal standard in the absence of market penalties, s_2, are graphed in Figure 1 with the use of equation (6).

The final task of this section is to determine if market enforcement of environmental standards allows a regulator to reduce its enforcement effort. There are two countervailing effects at work in the answer to this question. First, holding a standard constant, an additional market penalty for noncompliance allows the regulator to reduce the amount of monitoring it must expend to keep the firm compliant. However, a market penalty implies that the optimal emissions standard should be stricter, which will tend to increase the monitoring requirement. To determine which effect dominates, using (3), monitoring at standards $\bar{s}_r$, s_r and s_2 are $\pi(s_r) = \frac{w(e^n) - w(s_r)}{\phi_p + \phi_m}$ and $\pi(s_2) = \frac{w(e^n) - w(s_2)}{\phi_p}$ respectively. Substitute the quadratic forms of the linear equations for d' and w' from (1) into $\pi(s_r)$ and $\pi(s_2)$ to obtain

$$\pi(\bar{s}_r) - \pi(s_2) = \frac{(wd'' + w''d)^2 \phi_m [(w''\mu)^2 - (d'' + w'')^2 \phi_p (\phi_m + \phi_p)]}{2w'' \left\{ d''\phi_p + w''(\phi_p + \mu)^2 [d''(\phi_p + \phi_m) + w''(\phi_p + \phi_m + \mu)]^2 \right\}}.$$

Note that $\pi(s_r) = \pi(s_2)$ in the absence of market enforcement; that is, when $\phi_m = 0$. However, when $\phi_m > 0$, $sign[\pi(\bar{s}_r) - \pi(s_2)] = sign[(w''\mu)^2 - (d'' + w'')^2 \phi_p (\phi_m + \phi_p)]$. This relationship suggests that it may be possible to use market-driven enforcement to reduce a firm's emissions and monitoring of the firm simultaneously. The latter is more likely when marginal monitoring costs are relatively small and/or regulatory and market penalties are relatively large.

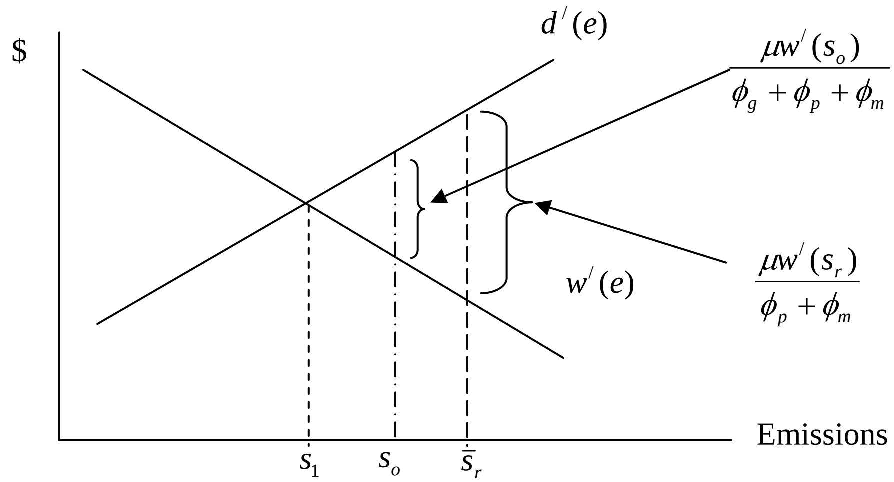

Figure 1: An Optimal Emissions Standard with Market-Driven Enforcement

1.3 Market-Driven Enforcement Allows the Setting of an Over-compliance Standard

We have established that the regulator can exploit market punishment of environmental violations to set stricter emissions standards. In this section, we show how it might be possible for a regulator to set an even stricter standard by which it certifies that a firm is over-compliant. Over-compliance refers to environmental performance beyond the requirements of a regular emissions standard. Over-compliance is optional for the firm, but the firm may find it worthwhile if financial markets reward this choice.

It is worth noting that several other reasons for firms' over-compliance, especially with voluntary programs, have been advanced in a different context in the literature. These reasons include pressure to appeal to "green" consumers (Stafford, 2007; Videras & Alberini, 2000; Arora & Cason,1996), to pre-empt regulation, to seek relief from the regulatory authority, and to gain an advantage over competitors (Videras & Alberini, 2000). However, it can be successfully argued that all these reasons for firm's over-compliance also boosts the firm's valuation and hence its share price. So the results of this paper may have applications in these other settings as well.

Suppose the firm now faces two standards, a regular standard s_r and an over-compliance standard s_o, with $0 < s_o < s_r$. Note that the regular standard here does not have an overbar as in the last section. We remove it when denoting the regular standard when there is also an over-compliance standard. Suppose that if the firm reduces its emissions to the over-compliance standard and is audited by the regulator that the regulator makes the firm's over-compliance public through some sort of certification. Upon learning of this certification investors incorporate this information into their decisions. Financial advisory firms commonly employ such information in their business risk analysis. Suppose further that the financial markets reward the firm with an increase in the market value of ϕ_g when it is revealed that the firm has reached the over-compliance standard. Note that the firm's expected payoff from reaching the over-compliance standard is $w(s_o) + \pi\phi_g$.

An example of a program that promotes over-compliance is the EPA's National Environmental Performance Track (NEPT), which is an exclusive club of over-compliant firms. Since this program motivates the forthcoming analysis, it is worth describing NEPT. We then proceed to lay out what we believe would be an effective approach for the program.

In its basic form, NEPT simply groups facilities that have demonstrated consistent compliance with existing regulations, voluntarily implemented programs (for example Environmental Management Systems (EMS)) to increase abatement, and can make verifiable commitments to improve on that performance. Facilities make independent choices for abatement objectives and self report achievements within a certain time period. The program is promoted through the use of administrative and market-oriented incentives. For example, members are afforded administrative incentives such as low priority for inspection targeting purposes and discretion in assessing penalties for violations. Market-oriented incentives include the use of the NEPT logo for marketing purposes, awards for best performers and the use of over-compliance data by financial advisory and investment firms such as Innovest, Trucost, Calvert and KLD in their evaluation of the business risks associated with the environmental costs of pollution related activities.[6] Membership in the program therefore indicates low risk of a violation compared to non-members.

A potential weakness of the program is that over-compliance is relative; it is not a unique predetermined target to be achieved by a firm. In the case of a specific pollutant it is just a measure of how far the firm's emissions are below the emissions standard. Because over-compliance is not a unique target to be achieved there is little incentive for a firm to increase its emissions standard/over-compliance gap. In other words, a firm may simply strive for minimum over-compliance performance to enjoy the administrative and market-oriented benefits.

Suppose instead that over-compliance is achieved by attaining a certain over-compliance standard below the regular standard. Just like in the case of the regular standard, this over-compliance standard is monitored and enforced. A firm that achieves this over-compliance standard receives a certification for its achievement from the regulator. We wish to determine whether the regulator can set an over-compliance standard that the firm will find optimal to achieve. Suppose the regulator has set a regular standard that the firm would comply with. This requires that the regulator monitors the firm so that the detection probability is

[6] National Environmental Performance Track (NEPT), http://www.epa.gov/perftrac/benefits/investing.htm.
U.S. Environmental Protection Agency. 2000. "Green Dividends? The Relationship Between Firms' Environmental Performance and Financial Performance", Washington D.C.

$\pi(s_r)$ defined by (3). Given $\pi(s_r)$, the firm will comply with an over-compliance standard if and only if

$$w(s_o) + \pi(s_r)\phi_g - w(s_r) \leq 0 \quad (8)$$

Since $w(s)$ is increasing in *s*, there exist $s_o < s_r$ such that (8) holds as long as $\phi_g > 0$. This is an important result that suggests that if a firm will comply with a regular standard, there is a stricter over-compliance standard that it will be motivated to achieve without the need for additional enforcement pressure. Simply setting the standard and certifying that the firm has met it improves environmental performance without additional public resources.

1.4 Optimal Over-Compliance

Of course, the regular standard, the over-compliance standard, and monitoring to support compliance with both should all be chosen optimally. That is the task of this section. To begin, note from (8) that given s_r and $\pi(s_r)$, the strictest over-compliance standard the firm will comply with is determined by

$$w(s_o) + \pi(s_r)\phi_g - w(s_r) = 0\,. \quad (9)$$

Under the assumption that the regulator would like to guarantee that the firm will reduce its emissions to the over-compliance standard, we impose (8) on the design of the optimal policy. Note that choosing s_r gives us s_o through equation (9) and $\pi(s_r)$ through equation (3). Thus, all the elements of the optimal policy follow from choosing the optimal regular standard s_r.

Proceeding accordingly, (8) implicitly defines the over-compliance standard as a function of the regular standard, $s_o(s_r)$. Then the optimal policy is found by first choosing s_r to maximize

$$w(s_o(s_r)) - d(s_o(s_r)) - \mu\pi(s_r). \tag{10}$$

The first-order condition is

$$[w'(s_o) - d'(s_o)]s_o'(s_r) - \mu\pi'(s_r) = 0. \tag{11}$$

The optimal values of s_o, s_r, and π are the simultaneous solutions to (10), (8), and (3).

Toward characterizing the optimal policy to induce over-compliance, first use (8) to obtain $s_o'(s_r) = -\frac{w'(s_r) - \pi'(s_r)\phi_g}{w'(s_o)}$. From (4), $\pi'(s_r) = -w'(s_r)/(\phi_p + \phi_m)$. Substituting this into $s_o'(s_r)$ yields

$$s_o'(s_r) = \frac{w'(s_r)}{w'(s_o)}\left[\frac{\phi_g + \phi_p + \phi_m}{\phi_p + \phi_m}\right] > 0. \tag{12}$$

The sign of (12) simply indicates that the over-compliance standard is lower as the regular standard is lower. Substitute (12) and $\pi'(s_r) = -w'(s_r)/(\phi_p + \phi_m)$ into the first order condition (11) and rearrange the result to obtain

$$w'(s_o)\left[1 + \frac{\mu}{\phi_g + \phi_p + \phi_m}\right] - d'(s_o) = 0. \tag{13}$$

Using the linear forms of $w'(s_o)$ and $d'(s_o)$ from (1), solving (13) yields the optimal over-compliance emissions standard

$$s_o = \frac{Bw - d}{Bw'' + d''}, \text{ where } B = 1 + \frac{\mu}{\phi_g + \phi_p + \phi_m}. \tag{14}$$

Compare (14) to (7) and note that the optimal over-compliance standard has the same basic structure as $\bar{s}_r$, the regular standard when the regulator does not also set an over-compliance standard. Since the firm complies with s_o when the regulator sets it as the over-compliance standard, but it complies with $\bar{s}_r$ when the regulator does not set the over-compliance standard, comparing the two tells us whether the firm chooses lower emissions when faced with s_o. Note that s_o differs from $\bar{s}_r$ only by the inclusion of ϕ_g. It is straightforward to show that s_o is strictly decreasing in ϕ_g. Since $s_o = \bar{s}_r$ for $\phi_g = 0$, $s_o < \bar{s}_r$ for $\phi_g > 0$. This is graphed in Figure 2. Thus, the optimal environmental performance of the firms is improved when a regulator can exploit financial market rewards by setting and certifying compliance with an over-compliance standard.

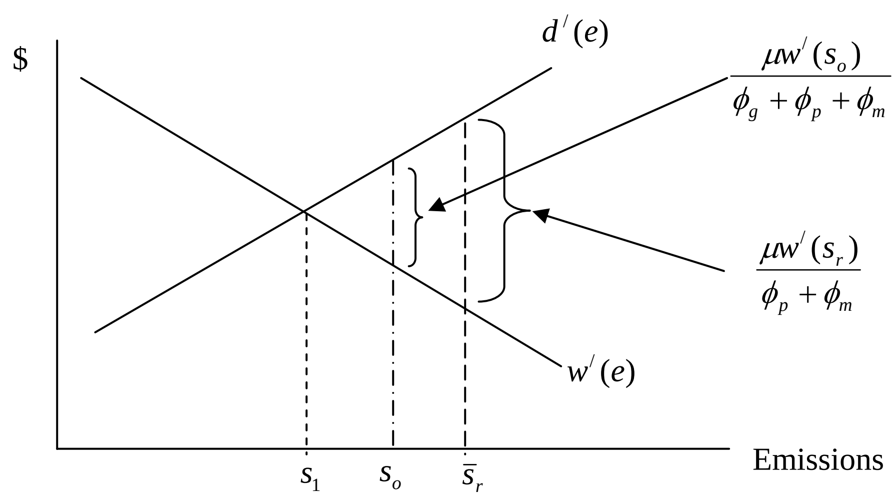

Figure 2: An Optimal Over-Compliance Standard

1.5 Effects of Setting Two Emissions Standards on Monitoring Probability and the Regular Standard

We have argued that setting two standards is good policy. In the case of only the regular standard, it is possible to reduce monitoring if market penalties are large relative to the marginal monitoring costs. However, an over-compliance standard is a stricter standard, which may require increased monitoring. In this section we determine whether setting two emissions standards; an over-compliance standard and a regular standard may result in lower or higher overall standard. The conclusion here will be a guide to understanding whether the monitoring probability will increase or decrease under the two-standards scenario.

First, recall that we have derived an optimal over-compliance emissions standard in (8) for a regulator setting two standards. To obtain a regular emissions standard in this context, which is now a function of the over-compliance standard, we consider the quadratic forms of the linear equations set out in (1) for emissions. The quadratic equations for payoffs from the various compliance choices – noncompliance, compliance and over-compliance – can be written as: $w(e^n) = w + we - \frac{w^{//}}{2} e^2$, $w(s_r) = w + ws_r - \frac{w^{//}}{2} s_r^2$, $w(s_o) = w + ws_o - \frac{w^{//}}{2} s_o^2$. The maximum level of emissions possible for the firm can be expressed as $e = w / w^{//}$, where $w / w^{//}$ is the solution to $w^{/}(e) = 0$. Substitute $e = w / w^{//}$ and the quadratic forms for $w(s_r)$, $w(s_o)$ into equation (8) to obtain

$$\frac{w^{//}}{2}\left(\frac{\phi_p + \phi_m + \phi_g}{\phi_p + \phi_m}\right)s_r^2 - w\left(\frac{\phi_p + \phi_m + \phi_g}{\phi_p + \phi_m}\right)s_r + ws_o - \frac{w^{//}}{2} s_o^2 + \frac{w^2 \phi_g}{2w^{//}(\phi_p + \phi_m)} = 0 . \qquad (15)$$

The equality in (15) assumes that the government chooses s_o, s_r and monitoring probability to minimize monitoring costs.

Furthermore, equation (14) can be re-written as

$$s_o = \frac{w(\phi_p + \phi_m + \phi_g + \mu) - (\phi_p + \phi_m + \phi_g)d}{w^{//}(\phi_p + \phi_m + \phi_g + \mu) + (\phi_p + \phi_m + \phi_g)d^{//}} .$$

Substituting s_o into equation (15) and solving for s_r yields

$$s_r = \frac{w}{w^{//}} - \frac{(\phi_p + \phi_m)^{\frac{1}{2}} (\phi_p + \phi_m + \phi_g)^{\frac{1}{2}} (d^{//} w + dw^{//})}{w^{//}[(\phi_p + \phi_m + \phi_g)(d^{//} + w^{//}) + w^{//}\mu]} . \qquad (16)$$

We can now compare the regular standard obtained from setting a single emissions standard, $\bar{s}_r$ (represented by equation 7) and the minimum emissions standard that results from setting two emissions standards (s_r from equation (16)). $\bar{s}_r$ is the single emissions standard that obtains under government and market punishment while s_r is the minimum regular standard resulting from two emissions standards under combined government enforcement and market rewards. The difference between $\bar{s}_r$ and s_r can be expressed as:

$$[s_r - \bar{s}_r] = \frac{w}{w^{//}} - \frac{(\phi_p + \phi_m)^{\frac{1}{2}}(\phi_p + \phi_m + \phi_g)^{\frac{1}{2}}(d^{//}w + dw^{//})}{w^{//}[(\phi_p + \phi_m + \phi_g)(d^{//} + w^{//}) + w^{//}\mu]} - \frac{w(\phi_p + \phi_m + \mu) - (\phi_p + \phi_m)d}{w^{//}(\phi_p + \phi_m + \mu) + (\phi_p + \phi_m)d^{//}} .$$

The sign of $[s_r - \bar{s}_r]$ can be expressed as:

$$Sign[s_r - \bar{s}_r] = Sign[(d^{//} + w^{//})(\phi_m + \phi_p)^{\frac{1}{2}}(\phi_g + \phi_m + \phi_p)^{\frac{1}{2}} - w^{//}\mu] . \qquad (17)$$

Equation (17) suggests that $s_r < \bar{s}_r$ only if marginal monitoring costs are large relative to penalties or penalties are relatively small compared to monitoring costs. In these cases, then using the feature in (4) that the monitoring probability is monotonically decreasing in the emissions standard, we can conclude that setting two standards may result in a higher probability of monitoring than under a single regular emissions standard. $s_r < s_r$ implies s_r is a stricter emissions standard than s_r. As discussed earlier, a stricter emissions standard is more difficult to achieve. There is a greater incentive to cheat at a stricter standard and therefore increased enforcement is required to deter cheating. This result means that in setting two standards the regulator may need to monitor more, but better environmental quality and a more efficient outcome are achieved.

1.6 Conclusions and Further Research

In this paper we have demonstrated how regulators may be able to exploit market penalties and rewards for environmental performance to pursue more stringent environmental regulations. Better environmental performance can be achieved using a combination of conventional regulatory enforcement, financial market forces, and certification for over-compliance.

Since markets punish firms for non-compliance with environmental standards and reward good performance, regulators can exploit this by setting stricter standards. In particular certifying the achievement of over-compliance can lead to improved environmental performance. Market enforcement allows the regulator to reduce monitoring effort while simultaneously setting a stricter single emissions standard. Setting two emissions standards - over-compliance and regular standards - is a more efficient policy option than a single emissions standard, and it results in better environmental quality. However, setting two emissions standards may require an increase in monitoring.

A possible area of further research in the work presented here relates to the implicit assumption that the firm's emissions are deterministic. An important question is what if the firm's emissions are random or consist of a random component? This randomness may affect the probabilities of monitoring for the regulator and therefore may necessitate enforcement strategies different from those adopted here.

CHAPTER 2

THE EFFECTS OF MARKET STRUCTURE AND ENFORCEMENT COSTS ON AN EMISSIONS TAX

2.1 Introduction

The well established theoretical prescription that efficiency of pollution control policy requires an emissions tax equal to marginal damage (Pigouvian tax) be imposed on polluters is based on competitive market assumptions. This equality between an emissions tax and marginal damage does not hold in a non-competitive setup and when the firm's emissions are not perfectly observable. A good deal of analysis on emissions taxes often assume that emissions are perfectly observable, monitored and that the tax is enforced at no cost to the regulatory authority. However, emissions are typically unobservable, prompting the regulator to enforce a tax on emissions to prevent or at least minimize cheating. Costly enforcement ultimately distorts the optimal emissions tax away from marginal damage. The purpose of the paper is to provide a theoretical analysis of the nature of an optimal emissions tax when firms' emissions are not perfectly observable under both perfect competition and Cournot competition, with and without free market entry. The focus on these two market structures is important; the Cournot model provides a very simple link between perfect competition and monopoly models. This crucial link lies in the firms' ability to charge a price premium.

Several authors have explored the concept of the effects of market structure on the Pigouvian tax on polluting firms. A pollution tax on a monopoly has two effects; it induces a welfare gain from reduced pollution but there is a welfare loss due to reduced output (Oates and Strassmann, 1984). Hence, the use of a Pigouvian tax involves a tradeoff between reduced emissions and reduced output. These two welfare effects imply that a tax on emissions could, in fact, induce a net welfare loss.

When the firm responds to the tax by reducing output, particularly in an imperfectly competitive market, the result is an optimal tax that falls short of marginal social damage. The amount by which the optimal tax falls short of marginal damage depends on the price elasticity of demand. But even when the market is imperfectly competitive and the firm responds to the imposition of a tax by increasing abatement, the result is an optimal tax equal to marginal social damage (Barnett, 1980; Lee, 1975). These results hold for a fixed number of firms in the industry.

However, the size of the market affects the nature of an optimal emissions tax. The number of entrants in free-entry equilibrium can either be excessive, insufficient, or optimal. In the absence of the emissions tax the equilibrium number of firms is predicted to be greater than the optimal number of firms (Mankiw and Whinston, 1986). An emissions tax pushes the equilibrium number of firms closer to the optimal number of firms, which has the effect of increasing welfare. If this welfare effect is strong enough, the optimal emissions tax may exceed marginal damage (Katsoulacos and Xepapadeas, 1995).

The three welfare effects of the emissions tax cited above assume that emissions are perfectly observable and the tax is costlessly enforced. Emissions taxes are usually based on self-reported emissions by polluting firms. Often, there is an incentive for firms to under-report their emissions and pay less taxes. A common attempt to prevent this problem is to enforce the tax by establishing a mechanism to verify that firms are indeed reporting their true level of emissions and hence are paying the right amount of tax. This monitoring activity is costly to the regulator, for example it takes manpower to set up and run audits. How this costly monitoring affects the optimal tax is the subject matter of this piece of work.

The results indicate that when the number of firms in the industry is determined exogenously, enforcing an emissions tax results in an optimal tax rate smaller than the social marginal damage when there are no market imperfections. Enforcement pushes the optimal tax lower than marginal damage because enforcing the tax adds to the social cost of pollution control. The optimal tax reduces further when there are market imperfections. The implication is that an optimal tax rate imposed on a fixed number of firms with some market power would have to be adjusted downward to account for product market distortions and enforcement costs.

Enforcement costs have direct and indirect effects, with a countervailing influence on the optimal tax when entry is endogenous. The direct effect of enforcement costs derives from a higher marginal enforcement cost of inducing lower emissions, which pushes the optimal tax lower. The indirect effect of enforcement costs results from the role of the tax as a deterrent to entry. This indirect effect is positive and hence pushes the optimal tax up. The optimal tax is greater than marginal damage if the indirect effect outweighs the direct effect of enforcement costs. Alternatively, the optimal tax would be smaller than marginal damage if the indirect effect falls short of the direct effect of enforcement costs.

2.2 The Basic Model: Emissions Tax, Enforcement and Individual Choices of Output and Abatement

In this section we model the behavior of oligopolistic firms that compete in Cournot fashion. Consider n identical Cournot firms. Each firm faces a tax t on their reported emissions, r_i. Firms always have the incentive to under-report their emissions and therefore pay lower taxes; thus, the emissions tax must be enforced. A firm under-reports its emissions when self-reported emissions are smaller than actual emissions, that is, $r_i < e_i$ where e_i is *i's* emissions of some uniformly mixed pollutant. The regulator establishes a mechanism to verify that firms are indeed reporting their true level of emissions and hence are paying the right amount of tax. Each firm faces a constant expected marginal penalty, denoted μ, for violations. Requiring the expected marginal penalty for violations to be constant is a special assumption intended to simplify the analysis here. This assumption is also associated with our use of results found in Stranlund et al (2009).

In monitoring and enforcing an emission standard the regulator incurs $k(\mu)$ in enforcement costs, which are a function of the constant expected marginal penalty a firm faces for any cheating. We assume that monitoring the firm's emissions is without error; only firms that cheat and are audited will be caught and punished. The enforcement costs, $k(\mu)$, are strictly increasing and strictly convex in the expected marginal penalty. That is, $k^{/}(\mu) > 0$ and $k^{//}(\mu) > 0$. The total expected penalties, expressed as $\mu(e_i - r_i)$, imposed on the firm are proportional to the size of violation. The emissions from firms cause some environmental damage, $d(\sum_{i=1}^{n} e_i) = d(E)$, where $E = \sum_{i=1}^{n} e_i$ represents aggregate emissions. The damage function is strictly increasing and strictly convex in E.

Let $p = p(Q)$ be the price a firm receives per unit of output, where Q represents the industry's output. The price is a linear function of aggregate industry output only. A linear demand function assumption allows us to make straightforward statements throughout the paper, eliminating ambiguities in the results. Let $q_{-i} = \sum_{j \neq i} q_j$ denote output for the rest of the industry except *i*. Also let $c(q_i, e_i)$ represents firm $i's$ cost of output and abatement. The cost function is strictly increasing and strictly convex in output for a fixed level of emissions. Similarly, the cost function is strictly decreasing and strictly convex in emissions for some fixed output level. Furthermore, we make the common assumption that output and emissions are complements, that is, $c_{qe}(q_i, e_i) < 0$ and the Hessian matrix of the cost function is positive definite. The firm also incurs fixed costs of entry F. Fixed costs are important when we examine the industry's equilibrium and/or optimum number of firms as well as the social welfare implications of firm $i's$ choices.

The profit function for each firm is given by

$$\Pi_i = p(q_i + q_{-i})q_i - c(q_i, e_i) - tr_i - \mu(e_i - r_i)\,. \tag{1}$$

Note that in the short run fixed costs are irrelevant in (1).

We now address the nature of the tax imposed on firms that are caught evading a part of their emissions tax liabilities. To simplify the analysis we assume that the expected marginal penalty for violation is set to induce full compliance. This assumption is supported by recent work by Stranlund et al (2009) that suggests that inducing full compliance with a constant expected marginal penalty will usually be optimal and that this constant expected penalty should be set equal to the emissions tax. Simply, an emissions tax set equal to the expected marginal penalty for violation faced by the firm will induce the firm to report only its true level of emissions, $e_i = r_i$. In other words, $e_i = r_i$ if $t = \mu$.

With the regulator inducing full compliance, the profit function for each firm becomes:

$$\Pi_i = p(q_i + q_{-i})q_i - c(q_i, e_i) - te_i \tag{2}$$

Note that (2) does not imply that enforcing the tax has no effect on the firm's profit function. It only indicates that enforcing the tax eliminates any single firm's incentive to cheat.

2.3 Individual choice of Output and Abatement: Comparative Statics

Firms choose compliance strategies and select q_i and e_i to maximize profit. The first-order conditions for (2) are:

$$\begin{aligned} & p^{/}(q_i + q_{-i})q_i + p(q_i + q_{-i}) - c_q(q_i, e_i) = 0; \\ & -c_e(q_i, e_i) - t = 0. \end{aligned} \tag{3}$$

For symmetric equilibrium, the first-order conditions can be written as

$$\begin{aligned} & p^{/}(nq)q + p(nq) - c_q(q,e) = 0; \\ & -c_e(q,e) - t = 0. \end{aligned} \tag{4}$$

Equation (4) implicitly defines equilibrium output and emissions for each firm as a function of *n* and *t*. These solutions can be expressed as:

$$\begin{aligned} & q = q(n,t); \\ & e = e(n,t). \end{aligned} \tag{5}$$

To examine how the tax and market size affect the profit-maximizing decisions of the individual firm, substitute (5) into equations (4) to obtain

$$\begin{aligned} & p^{/}(nq(n,t))q(n,t) + p(nq(n,t)) - c_q(q(n,t), e(n,t)) \equiv 0; \\ & -c_e(q(n,t), e(n,t)) - t \equiv 0. \end{aligned} \tag{6}$$

Differentiate (6) with respect to *t*:

$$\begin{aligned} & p^{//}nqq_t + (n+1)p^{/}q_t - c_{qq}q_t - c_{qe}e_t = 0; \\ & -c_{eq}q_t - c_{ee}e_t - 1 = 0. \end{aligned}$$

These can be written in matrix form as

$$\begin{bmatrix} p^{//}nq + (n+1)p^{/} - c_{qq} & -c_{qe} \\ -c_{eq} & -c_{ee} \end{bmatrix} \begin{bmatrix} q_t \\ e_t \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \tag{7}$$

The determinant of the Hessian matrix in (7) is $[(n+1)p^{/} - c_{qq}][-c_{ee}] - c_{eq}^2$, which we require to be positive to satisfy the second order condition. Also, note that the linear demand function assumption implies that $p^{//} = 0$. Hence, from here on we drop the terms involving $p^{//}$. Denote the determinant of the Hessian with S. The solutions for q_t and e_t in (7) is given by

$$q_t = \frac{1}{S}\begin{vmatrix} 0 & -c_{qe} \\ 1 & -c_{ee} \end{vmatrix};$$

$$e_t = \frac{1}{S}\begin{vmatrix} (n+1)p^{/} - c_{qq} & 0 \\ -c_{eq} & 1 \end{vmatrix}.$$

These solutions to can be expressed as follows:

$$\begin{aligned} q_t(n,t) &= c_{qe} / S < 0; \\ e_t(n,t) &= (n+1)p^{/} - c_{qq} / S < 0. \end{aligned} \tag{8}$$

To see that $S > 0$, re-write it as $-(n+1)p^{/}c_{ee} + c_{qq}c_{ee} - c_{eq}^2$. Note that $c_{qe} < 0$ and $c_{qq}c_{ee} - c_{eq}^2 > 0$ is the determinant of the Hessian matrix of the cost function which is positive definite. Since $p^{/} < 0$, $c_{ee} > 0$, and $-(n+1)p^{/}c_{ee} > 0$, clearly, $S = [(n+1)p^{/} - c_{qq}][-c_{ee}] - c_{eq}^2 > 0$.

Equations (8) characterize the response of an individual firm to changes in the tax. Firms' profit-maximizing output and emissions are decreasing in the tax. The tax serves as a deterrent to emissions through output decisions.

We now turn to the effect of market size on profit-maximizing output and emissions. To examine the impact of the size of the market on equilibrium output and emissions differentiate (6) with respect to *n*:

$$\begin{aligned} &p^{//}q^2 + p^{/}q + p^{//}nqq_n + (n+1)p^{/}q_n - c_{qq}q_n - c_{qe}e_n = 0; \\ &-c_{eq}q_n - c_{ee}e_n = 0. \end{aligned}$$

These can be re-written, setting $p^{//} = 0$ as

$$\begin{bmatrix} (n+1)p' - c_{qq} & c_{qe} \\ -c_{eq} & -c_{ee} \end{bmatrix} \begin{bmatrix} q' \\ e' \end{bmatrix} = \begin{bmatrix} -p'q \\ 0 \end{bmatrix}.$$

Solve to obtain

$$q_n = \frac{1}{S} \begin{vmatrix} -p'q & -c_{qe} \\ -c_{eq} & 0 \end{vmatrix};$$

$$e_n = \frac{1}{S} \begin{vmatrix} (n+1)p' - c_{qq} & -p'q \\ -c_{eq} & 0 \end{vmatrix}.$$

The solution to q_n and e_n can be expressed as follows:

$$\begin{aligned} q_n(n,t) &= p'qc_{ee} / S < 0; \\ e_n(n,t) &= -p'qc_{eq} / S < 0. \end{aligned} \tag{9}$$

Equations (9) characterize the response of an individual firm to an entrant in the market. A firm's profit-maximizing output and emissions are decreasing in the market size. The market size factor reflects the 'business stealing effect' (Mankiw & Whinston, 1986). That is, output per firm falls as the number of firms in the industry increases. Emissions per firm also fall, due to a fall in production activity.

2.4 Optimal Tax with Exogenous Number of Firms

In this section we examine the nature of an emissions tax that is enforced when market entry is blocked. Recall that the social planner sets $\mu = t$. Thus, enforcement costs (*k*) as a function of the tax can be written as $k(t) = k(\mu)$, where $k(t)$ is strictly increasing and strictly convex in the tax, $k'(t) > 0$ and $k''(t) > 0$. The costs of enforcement we model here are resources spent on monitoring a firm's compliance. The social planner's objective is to maximize the sum of consumer and producer surplus less environmental damage, fixed entry and enforcement costs. That is,

$$\underset{t}{Max}\ W(t) = \int_0^{nq(n,t)} p(z)dz - nc(q(n,t), e(n,t)) - d(ne(n,t)) - nk(t) - nF\ . \tag{10}$$

In (10) fixed entry costs have no effect on the nature of an optimal emissions tax when there is no entry. The optimal tax rate is the solution to (10). To determine this optimal tax rate differentiate (10) with respect to *t*:

$$p(nq)nq_t - n[c_q q_t + c_e e_t] - nd^{/} e_t - nk^{/}(t) = 0\ .$$

The first-order condition implies that we can separate the total social cost of pollution control for a given number of firms into pollution control effects, represented by $(c_e + d^{/})ne_t + nk^{/}(t)$ and market imperfections (represented by $(p - c_q)nq_t$). A market imperfection has a balancing effect on the cost of pollution control. Note that enforcement costs clearly increase the cost of pollution control.

The optimal tax can be characterized from the first-order condition of (10), by substituting $c_e = -t$ from equation (4) and solving for *t*. That is,

$$p(nq)q_t - c_q q_t + te_t - d^{/} e_t - k^{/}(t) = 0\ .$$

implies

$$t^* = d^{/} - (p - c_q)\frac{q_t}{e_t} + \frac{k^{/}(t)}{e_t}\ . \tag{11}$$

t^* is the optimal tax for a given number of identical firms, $d^{/}$ is the marginal damage from emissions, $(p - c_q) > 0$ is the price premium for the oligopoly and $k^{/}(t)$ represents marginal enforcement costs. The price premium is weighted by the substitution between output and emissions induced by a higher tax.

In a perfectly competitive market where $p = c_q$ and there are no enforcement costs associated with the tax the result in (11) is the Pigouvian tax. The optimal tax equals marginal damage in a perfectly competitive market with a fixed number of industry participants if there are no enforcement costs.

In an oligopolistic market where $p > c_q$ imperfect competition tends to make the optimal tax less than marginal damage; this is the Oates and Strassmann (1984) result. This implies that an optimal tax rate imposed on firms with some market power would have to be adjusted downward to account for such market distortions.

Equation (11) shows that in addition to an adjustment factor to account for an inefficiency associated with less than competitive output of an imperfectly competitive industry, we have another adjustment factor to account for the costs of enforcing the tax. This additional adjustment is represented by $k^{/}(t)/e_t$. This is the per-firm marginal enforcement cost of inducing lower emissions with a higher tax. A higher tax is required to reduce emissions ($e_t < 0$). But a higher tax is associated with higher enforcement costs ($k^{/}(t) > 0$). In general, we have shown that firms will typically respond to the tax by choosing lower emissions. Hence, the regulator chooses a higher tax to reduce emissions. However, a higher tax increases the incentive to cheat. Cheating can only be deterred by increased enforcement and this is costly.

Overall, for a given number of firms enforcing an emissions tax results in an optimal tax rate smaller than the social marginal damage when there are no market imperfections. The cost of enforcement constitutes the main contrast between the result here and the rest of the literature on the impact of market structure on an emissions tax. The Oates and Strassmann result indicates that market imperfections result in the optimal tax that is smaller than marginal damage. In (11), enforcement costs further push the optimal tax lower than marginal damage in an imperfectly competitive industry. This is because enforcing the tax simply adds to the social cost of pollution control.

2.5 Market Entry and the Optimal Tax

We now examine the nature of an optimal emissions tax with endogenous entry. Unlike in the case of an optimal tax with a fixed number of firms, the equilibrium number of firms in this case is endogenously determined. In choosing the tax the regulator accounts for the effect on the tax of firms' entry decisions. Specifically, in a three-stage game, the regulator chooses a tax t and an enforcement strategy. The identical Cournot firms observe the tax and the regulator's enforcement strategy and then decide whether or not to enter the market. Firms that enter the market choose their compliance strategies, output and abatement by maximizing profit. A firm enters the market if and only if its profit covers the fixed cost of entry. The solution to the game is found by backward induction.

The equilibrium number of firms for a given tax rate and fixed entry costs implied by the zero-profit condition is defined by

$$\Pi(n,t) - F = 0 . \tag{12}$$

This implicitly defines the equilibrium number of firms as a function of the tax and fixed costs, $n(F,t)$. The optimal tax given endogenous entry is the solution to

$$\underset{t}{Max} W(n(F,t),t) = \int_0^{nq} p(z)dz - nc(q,e) - d(ne) - nk(t) - nF \ , \tag{13}$$

where $n = n(F,t)$, $q = q(n(F,t),t)$, and $e = (n(F,t),t)$. The first order condition for (13) is:

$$\begin{aligned} &p\left[n_t q + n(q_n n_t + q_t)\right] - n_t c(.) - nc_q\left[(q_n n_t + q_t)\right] - nc_e\left[(e_n n_t + e_t)\right]; \\ &-d^{/}\left[n_t e + n(e_n n_t + e_t)\right] - (n_t k + nk^{/}) - n_t F = 0. \end{aligned} \tag{14}$$

Equation (14) determines the optimal tax when the number of firms is endogenous, and can be re-written as

$$n_t[pq - c - F] + nn_t[p - c_q]q_n + n[p - c_q]q_t - nc_e(e_n n_t + e_t) - d^{/}E_t - n_t k - nk^{/} = 0 .$$

To determine the effect of endogenous number of firms and enforcement costs on the optimal tax we first need to determine the signs of $n_t(F,t)$ and $E_t(n,t)$. $n_t(F,t)$ represents the effect of the tax on entry while $E_t(n,t)$ represents the effect of the tax on aggregate emissions. To determine the sign of $n_t(F,t)$, substitute the equilibrium number of firms, $n(F,t)$, into (12) to obtain

$$\Pi(n(F,t),t) - F \equiv 0 \tag{15}$$

Differentiate (15) with respect to *t* and solve for $n_t(F,t)$ as follows:

$$\prod_n (n(F,t),t) n_t(F,t) + \prod_t (n(F,t),t) = 0 ;$$

$$n_t(F,t) = -\prod_t (n(F,t),t) / \prod_n (n(F,t),t) . \tag{16}$$

Hence, the sign of $n_t(F,t)$ depends on the sign of $\prod_t (n(F,t),t)$ and $\prod_n (n(F,t),t)$. $\prod_t (n(F,t),t)$ is the effect of the tax on the firm's profit while $\prod_n (n(F,t),t)$ is the effect of entry on the firm's profit. Thus, the effect of the tax on the equilibrium number of firms depends on how entry and the tax affect individual firms' profit. First, we discuss the effect of entry on the firm's profit.

To determine of the effect of entry on the profit level for an individual firm, substitute the equilibrium output and emissions levels in (5) into (2). That is,

$$\prod(n,t) = p(nq(n,t)q(n,t) - c(q(n,t), e(n,t)) - te(n,t) = 0 . \tag{17}$$

Differentiate (17) with respect to n to obtain $\prod_n = p^/(q+nq_n)q + pq_n - [c_e + t]e_n - c_q q_n$. From (4) $c_e = -t$; thus, $[c_e + t]e_n = 0$. Also, using (4) we can express $(p - c_q)q_n$ as $-p^/qq_n$. $\prod_n$ can then be re-written as $p^/(q+nq_n)q - p^/qq_n$. This can further be reduced to:

$$\prod_n = p^/q[q+(n-1)q_n]. \tag{18}$$

Recall that $p^/ < 0$ and therefore $p^/q < 0$. Hence, $\prod_n < 0$ if $q+(n-1)q_n > 0$. To see that $q+(n-1)q_n > 0$, substitute $q_n = (p^/qc_{ee})/S$ from equation (9), where $S = [(n+1)p^/ - c_{qq}][-c_{ee}] - c_{eq}^2$. Substituting q_n into $q+(n-1)q_n$ yields $q+(n-1)p^/qc_{ee}/S$ $= [Sq + (n+1)p^/qc_{ee}]/S$. Sq alone can be expressed as $-(n+1)p^/qc_{ee} + q[c_{qq}c_{ee} - c_{eq}^2]$. The whole expression $[Sq + (n+1)p^/qc_{ee}]/S$ becomes $[-(n+1)p^/qc_{ee} + q[c_{qq}c_{ee} - c_{eq}^2] + (n-1)p^/qc]/S = [-2p^/qc_{ee} + q[c_{qq}c_{ee} - c_{eq}^2]]/S$. This is positive because of the convexity of the cost function discussed earlier. Thus, $\prod_n = p^/q[q+(n-1)q_n] < 0$. $\prod_n < 0$ says that profits are decreasing in the Nash equilibrium number of firms. Note that this is in line with the business stealing effect discussed earlier. That is, for a given price, each additional firm in the market results in smaller output per firm. A decrease in the firm's output lowers its profit level.

To determine the sign of $\prod_t(n(F,t),t)$, differentiate (17) with respect to t to obtain $\prod_t = p^/nqq_t + pq_t - c_q q_t - c_e e_t - te_t - e = [p^/nq + p - c_q]q_t - [c_e + t]e_t - e$. We have shown in (8) that $q_t < 0$ and that $c_e = -t$ in equation (4). Thus, we can re-write $\prod_t(n(F,t),t)$ as

$$\prod_t (n(F,t),t) = (p^{/} nq + p - c_q) q_t - e \,. \qquad (19)$$

Taxes increase the cost of business, as seen in (2). Therefore, it is expected that an increase in the tax should result in a lower profit for the firm, that is, $\prod_t (n(F,t),t) < 0$. In our model this holds if $p^{/} nq + p - c_q > 0$, such that $\prod_t (n(F,t),t) = (p^{/} nq + p - c_q) q_t - e < 0$, $e > 0$ and $q_t < 0$ as shown in (8). $\prod_t (n(F,t),t) < 0$ simply implies that in addition to its role of restricting emissions the tax also acts as an entry barrier.

Note that the requirement that $\prod_t (n(F,t),t) < 0$ if $p^{/} nq + p - c_q > 0$ may not hold in all market structures, for example, perfect competition. In perfect competition there is no price premium, that is, $p - c_q = 0$ and $p^{/} nq < 0$. This suggests that (19) may in fact be ambiguous or even positive. However, a positive outcome would be counterintuitive to the role of the tax as production cost element.

We have discussed the conditions under which $\prod_n (n(F,t),t) < 0$ and $\prod_t (n(F,t),t) < 0$. It follows that in (16) $n_t (F,t) < 0$. This means that the tax acts as an entry barrier, increasing the tax restricts the equilibrium number of firm.

We now examine the effect of increasing the tax on aggregate emissions to determine the sign of $E_t (n,t)$. Since we have assumed identical firms, aggregate emissions as a function of the tax can be expressed as:

$$E(n(F,t),\ t) = n(F,t) e(n(F,t),\ t) \,. \qquad (20)$$

Differentiate (20) with respect to t to obtain $E_t = n_t e + n(e_n n_t + e_t) = n_t(e + ne_n) + ne_t$. Assuming that the ultimate goal of the tax is to serve as a deterrent to emissions, we expect aggregate emissions to be decreasing in the tax. We have already shown that $n_t < 0$, $e_t < 0$ and $e_n < 0$. Thus, $E_t < 0$ holds if $e + ne_n \geq 0$. Note that $n_t(e + ne_n)$ represents the marginal effect of the tax per-firm emissions. Hence, we expect that if emissions per firm are decreasing in the tax, then aggregate emissions ultimately will be decreasing in the tax as well, that is, $E_t < 0$. If $e + ne_n < 0$ then the effect of the tax on aggregate emissions may be ambiguous, a general result that others have obtained, for example, Requate (2005). Or it is possible that the tax results in higher aggregate emissions, a result counterintuitive to the goal of the tax. Such an outcome can be envisioned for a policy that is focused solely on revenue generation

It is important to note that the tax has direct and indirect effects on aggregate emissions. The direct impact of the tax on aggregate emissions obtains from the role of the tax as a deterrent to individual firm's emissions. The indirect effect of the tax on aggregate emissions, represented by $n_t e$ reflects the role of the tax as an entry barrier. The tax results in a smaller number of firms and this in turn results in lower aggregate emissions.

To obtain the optimal tax from (13) first re-write the first-order condition as

$$n_t[pq - c - F] + nn_t[p - c_q]q_n + n[p - c_q]q_t - nc_e(e_n n_t + e_t) - d' E_t - n_t k - nk' = 0.$$

Using the zero profit condition, $p(nq)q - c(q,e) - te - F = 0$, substituting $-c_e = t$ from (3) and re-arranging the terms we obtain the optimal tax given endogenous entry as

$$t^{**} = d' - \frac{(p - c_q)(q_t + n_t q_n)}{E_t} + \frac{n_t k + nk'(t)}{E_t}. \tag{21}$$

In (21) $d^{/}$ is the marginal damage associated with emissions. The term $(p - c_q)q_t$ represents the adjustment for market imperfections, weighted by the substitution between individual firms' output and aggregate emissions induced by a higher tax. The third welfare effect of the tax under endogenous entry implied by Katsoulacos and Xepapadeas (1995) is represented by $(p - c_q)n_t q_n$. Recall that one welfare effect of the tax is the reduction in emissions, the second is the reduction in output and the third is that the tax limits the number of firms in the industry. Hence, $q_t + n_t q_n$ represents the second and third welfare effects, acting as a balance on one another. In the absence of enforcement costs, if the output effects exceed the size effects of the tax then the results is an optimal emissions tax smaller that marginal social damage. On the other hand, a size effect stronger than the output effect of the tax leads to an optimal tax that exceeds the marginal social damage.

The solution above shows that enforcement costs have direct and indirect effects, with a countervailing influence on the optimal tax when entry is endogenous. The direct effect of enforcement costs on the optimal tax is represented by $nk^{/}(t)/E_t$, the per-firm marginal enforcement costs of inducing lower aggregate emissions through a higher tax. Since $nk^{/}(t)/E_t < 0$ the direct effect of enforcement costs is to push down the optimal tax. On the other hand, the indirect effect of enforcement costs on the optimal tax, through the market size, is represented by $n_t k / E_t$. This is the change in enforcement costs achieved by reducing the market size and aggregate emissions through a higher tax. Since $n_t k / E_t > 0$ the indirect effect of enforcement costs is to push the tax up.

The optimal tax, assuming there are no market imperfections, is greater than marginal damage if the indirect effect outweighs the direct effect of enforcement costs. The optimal tax would be smaller than marginal damage if the indirect effect falls short of the direct effect of enforcement costs.

2.6 Conclusions and Further Research

We have examined the nature of an optimal emissions tax when firms' emissions are not perfectly observable under both perfect competition and Cournot competition with and without free market entry. We have shown that for a given number of firms enforcing an emissions tax results in an optimal tax rate smaller than the social marginal damage when there are no market imperfections. The optimal tax reduces further when there are market imperfections. The policy implication here is that an optimal tax rate imposed on firms with some market power would have to be adjusted downward to account for such market distortions and enforcement costs. Enforcement pushes the optimal tax lower from marginal damage because enforcing the tax simply adds to the social cost of pollution control.

Enforcement costs have direct and indirect effects, with a countervailing influence on the optimal tax when entry is endogenous. In this case, the direct effect of enforcement costs, represented by the per-firm marginal enforcement costs of inducing lower aggregate emissions through a higher tax on the optimal tax is negative and therefore pushes down the optimal tax. On the other hand, the indirect effect of enforcement costs on the optimal tax is positive and hence pushes the tax up. The optimal tax, assuming there are no market imperfections, is greater than marginal damage if the indirect effect outweighs the direct effect of enforcement costs and the optimal tax would be smaller than marginal damage if the indirect effect falls short of the direct effect of enforcement costs.

It is well established that the equilibrium number of firms is greater than the optimal number of firms even in the absence of an emissions tax (Mankiw and Whinston, 1986). A tax has the tendency to reduce this gap between the equilibrium and optimal number of firms (Lee, 1999; Katsoulacos and Xepapadeas, 1995). As a result, it might be possible that a joint determination of the optimal emissions tax and number of firms yield results different from the ones in this paper. I leave this issue for future work.

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