POLLUTION ABATEMENT R&D INVESTMENT UNDER DIFFERENT MARKET STRUCTURES AND REGULATORY REGIMES

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Abstract

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In this dissertation, I explore how the incentives for firms to invest in green technology are affected by changes in market structure and regulation. In the first chapter, I use an entry-deterrence model in which the incumbent decides whether or not to invest in green technology where an entrant can benefit from a technology spillover. I identify cases where entry is blockaded, the incumbent will under-invest in the technology to deter entry, and when the incumbent will accommodate entry.

In the second chapter, I analyze a duopoly market with investment in green technology under two types of environmental regulation: a uniform fee where both firms face the same fee, and a type-dependent fee that is based on the firm's emissions. Firms can differ in their cost of investing in the technology. I find that social welfare is unambiguously higher under the type-dependent regime.

In the third chapter, I use a two-stage game of a duopoly decided to adopt a green technology under emission fees, quotas, and a tradeable permit scheme. I find that firm and regulator incentives are misaligned as firms achieve higher profits under a quota, but social welfare is higher under a fee.

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CHAPTER ONE

How Environmental Regulation Can Induce Under-Investment in Green Technology

1 Introduction

A focus on cleaner technologies, such as sustainable developments, demand for renewable or sustainable energy, and climate change, are three major influences on the investment in research and development (R&D) within firms.[1] This behavior has been fueled as environmental regulation becomes more spread over countries and more demanding over time.[2] Therefore, firms' investment in R&D can be understood as a tool that firms use to ameliorate the cost imposed by environmental policy. The literature has shown that environmental regulation can potentially affect the market structure in which firms operate; see Dean and Brown (1995), Millimet et al. (2009), and Espínola-Arredondo and Muñoz-García (2013). However, the effect of firm's investment in R&D with spillovers on entry-deterring practices has been overlooked.

Worldwide, investment and innovation in green technologies was $281 billion in 2014 according to the National Science Foundation's Science and Engineering Indicators 2016 report.[3] Therefore, it is important to understand the following questions: how does investment in R&D affect the entry decision in a polluting industry?, does the presence of spillover effects in R&D emphasize or ameliorate the entry patterns?, when would an incumbent firm

[1] A survey developed by Battelle/R&D Magazine and presented in its *2014 R&D Magazine Global Funding Forecast* found that these are three of the top four factors influencing managers to invest in R&D: *http://www.rdmag.com/articles/2013/12/2014-r-d-magazine-global-funding-forecast*

[2] An overview of policies can be accessed at the Center for Climate and Energy Solutions' website: *http://www.c2es.org/international/key-country-policies/policies-key-countries*.

[3] This report can be found at the National Science Foundation's website: *https://www.nsf.gov/statistics/2016/nsb20161/#/report/chapter-6/highlights/investment-and-innovation-in-clean-energy-technologies-highlights*.

engage in entry deterrence practices?, and, under which contexts is entry socially optimal? In answering these questions, we can shed some light on the effects of environmental policy on investment in R&D and its consequences on competition. We develop a three stage game that considers an environmental policy and the investment in R&D with a spillover by the incumbent firm. The structure of the game is as follows: (1) in the first stage, the incumbent chooses a level of investment in the abatement technology; (2) in the second stage, (i) the entrant decides whether or not to enter, and (ii) given the market structure, the regulator sets an emissions fee based on the investment in abatement technology by the incumbent and; (3) in the third stage, firms compete *à la* Cournot if entry occurs, otherwise the incumbent acts as a monopolist. The incumbent employs the abatement technology in the third stage, and it is not able to prevent any potential entrant from taking advantage of a portion of the benefits from the technology (spillover effect). The tax on emissions is paid in the third stage.

As mentioned before, one way firms seek to reduce the burden of an emission fee is to invest in pollution reducing technology. Abatement R&D could include development of a production process that pollutes less, end-of-the-pipe abatement, or a number of other strategies. The incumbent firm patents a share of the innovation, but a proportion of the knowledge is not patentable, thus being available to potential entrants. The natural gas extraction industry represents the problem at hand. According to the US Bureau of Labor Statistics (BLS), this industry was concentrated in the 2000's, and it is regulated by the US Environmental Protection Agency (EPA).[4] In addition, there has been considerable investment in environmental R&D within the industry, one example of this is Conoco Phillips.[5] A portion of the R&D focuses on cleaning and preventing groundwater from being contam-

[4]An overview of regulations can be found at *https://www.epa.gov/regulatory-information-sector/oil-and-gas-extraction-sector-naics-211*.

[5]Specifically, starting at page 19 of their 2015 Sustainability Report, found here: *http://www.conocophillips.com/ sustainable-development/environment/water/managing-local-water-risks/Pages/default.aspx*.

inated with harmful substances. This knowledge about abating pollution can spill over to a potential entrant. Hence, it is important to study how investment into environmental technologies with spillover could be affected by the environmental policy and the threat of entry.

Our model builds on the entry-deterrence literature started in the 1970's (Spence (1977) and Selten (1978)) by considering environmental regulation and R&D. Dean and Brown (1995) show empirically that environmental policy can be a significant barrier to entry. We theoretically analyze the strategic effects of regulation and investment in R&D on entry. Espínola-Arredondo and Muñoz-García (2013) and Espínola-Arredondo et al. (2014) examine the effects of emission fees when there is a threat of entry under the cases of complete and incomplete information. However, they did not consider the effect of regulation on the investment of abatement technology with spillover.

A number of papers investigate the role of research and development structure (cooperative/non-cooperative) in an oligopolistic industry (D'Aspremont and Jacquemin (1988), Damania (1995), Miyagiwa and Ohno (2002), Poyago-Theotoky (2007), Stepanova and Tesoriere (2011), and Tesoriere (2015)), but are silent about its effect on entry deterrence. In addition, these papers focus on R&D with spillover effects that lower the production costs of the firms. In contrast, we consider R&D focused on lowering harmful emissions from production. This helps us identify the strategic effects of the emission fee on firms' investment in R&D. Schoonbeek and de Vries (2009) develop an entry deterrence model showing that there are cases in which both the regulator and incumbent monopolist prefer a high enough emissions tax to deter entry but they do not consider investment in abatement technology. Our contribution to the literature is two-fold: (1) we analyze environmental R&D with spillover effects in the context of entry-deterrence, and (2) examine how the investment in environmental R&D affects entry deterrence practices.

Finally, Poyago-Theotoky (2007) primarily focuses on how the organization structure of R&D affects social welfare. Firms invest in environmental R&D simultaneously and the degree of cooperation between them vary. In contrast, our paper focuses on the relationships between the spillover, entry, and social welfare where only one firm invests in R&D. Specifically, our model analyzes how a monopolist's R&D decision responds to entry when there is a spillover of the benefits of abatement technology to a potential entrant.

Our results indicate that when there is entry, an increase in the spillover produces an increase in social welfare. Second, if the severity of damage from pollution is low, the incumbent's incentive to invest in R&D technology is low. As a consequence, entry of another firm into the market decreases an already low investment level, which results in social welfare from entry being lower than if there was no entry. The trade-off faced by the regulator is between decreasing expected emissions from more investment in R&D and increasing consumer surplus from entry. In addition, we identify a case in which the incumbent would prefer to deter entry over accommodating entry. This situation arises when entry costs are sufficiently high, the incumbent under-invests in R&D which increases the emission fee that the entrant faces, thus, making entry unprofitable. Moreover, if the abatement technology presents a minor spillover effect, social welfare under entry deterrence may be larger than that under entry. The regulator could promote entry-deterrence by changing the entry costs through increasing the administrative and licensing costs to potential entrants. When the entry costs are increased, the entry-deterring level of investment increases, which ultimately decreases the environmental damage from production, thus increasing social welfare. Firm and regulator incentives align under entry when the spillover is high and entry cost is low, and are aligned under no entry when the entry cost is too high. However, we also observe cases of misalignment in which the regulator prefers entry while the incumbent prefers to deter entry. This case occurs when the spillover is very high and the cost of R&D is moderate, inducing the incumbent to reduce its investment in R&D in order to make entry less attractive. Finally, our results suggest that the regulator should support investment in R&D with spillover effects and lower costs of R&D as this promotes competition and generates higher levels of social welfare. These can be accomplished with policies like subsidies or grants that target projects with potential of high spillover effects, or tax credits that reward the firm for the R&D with high spillover effects.[6]

The next section of the paper presents the model and entry decision. Section 3 discusses the comparative static results, and compares equilibrium levels between entry and no entry. Section 4 concludes the paper.

2 Model

Consider a monopolist that faces an emissions tax and the threat of entry. In the first stage of the game, the polluting monopolist (incumbent) makes a decision on the amount to invest in R&D to develop abatement technology. The cost of investing in abatement is $\frac{1}{2}\gamma z^2$, where $\gamma > 0$ represents how costly it is to invest in R&D, and z is the total amount of abated pollution from production.

The overall amount of emissions produced by the incumbent is $\epsilon_i = q_i - z$, where ϵ denotes emissions, q is the output level, and the subscript i indicates the incumbent. As a result of the spillover, the entrant produces total emissions of $\epsilon_e = q_e - \beta z$, where the subscript e indicates the entrant, and the technology spillover is β, where $0 \leq \beta \leq 1$. As previously discussed, the spillover in this context can be understood as either the proportion of the incumbent's innovation that cannot be patented and thus can be freely used by the entrant.

[6] One example is the Small Business Innovation Research (SBIR) program through the US Environmental Protection Agency. Through the EPA, SBIR funds feasible high-quality projects with a goal of producing a cleaner production process. More information can be found at: *https://www.epa.gov/sbir/about-sbir-program*.

The entrant must incur a fixed cost to enter, $F > 0$. Firms face a linear demand $P(Q) = a - Q$, where P is price, $a > 0$, and $Q = q_i + q_e$ is the aggregate output level. Both firms have the same marginal cost of production c, where $a > c > 0$. The regulator sets an emission fee, t, that maximizes social welfare as defined by the sum of the producer and consumer surplus, tax revenue, and the environmental damage. The net environmental damage from the production of the good is $\frac{1}{2}d(Q - (1 + \beta)z)^2$, where $d > 1$ measures the severity of the environmental damage from net emissions. The lower bound on d ensures that the environmental damage from pollution is harmful enough to warrant a positive emission fee in the case of entry. This specification allows us to provide comparisons with Poyago-Theotoky (2007), who uses the same environmental damage function.[7]

We next describe the game structure in our model. The timing of the game represents the relationship between investment in R&D, the regulatory process, and the implementation of the technology.[8] In the first stage of the game, the incumbent firm makes a decision on the amount of abatement R&D (z) to invest in. In the second stage, the entrant decides whether to join the market, and the regulator takes the market structure as given and maximizes social welfare by choosing the per unit emissions tax (t) levied on polluting firms. In the third and final stage, the entrant decides whether to enter the market and production occurs, creating pollution in the process, which is abated by the investment made in the first stage. If entry ensues, firms compete *à la* Cournot. If there is no entry, then the incumbent acts as a monopolist in the third stage. As a benchmark for comparison, we first solve the game for the case where there is no threat of entry, and afterwords we analyze the case of entry. In both cases, the game is solved by backward induction.

[7]Comparison to the equilibrium in the paper is provided at the end of the appendix.

[8]Investment in R&D is a process that takes significant time from the initial investment to implementation of the technology, whereas the regulatory (or legislative) process can update itself (to meet emission goals) based on the expected emissions from the new technology. In addition, if the regulator acts in the third stage instead of the second, the equilibrium should not be affected since the regulator is taking the market structure as given.

2.1 Case 1: No Entry

We begin the analysis by examining the case where there is no threat of entry. Comparing these equilibrium results with those when entry threats are present will help identify how much investment in R&D is affected by entry. The structure and solving of the model begins with the third and final stage.

2.1.1 *Third Stage: Production*

First, let us briefly discuss the condition where there is no entry. Specifically, entry does not ensue when the entrant's profits are negative. If entry is not profitable, the incumbent maximizes monopoly profits, π_i^{ne},

$$\max_{q_i} \pi_i^{ne} = (a - q_i)q_i - cq_i - t(q_i - z),$$

which occurs at $q_i(t) = \dfrac{a-c-t}{2}$, yielding $\pi_i^{ne}(t) = \dfrac{(a-c-t)^2}{4}$. In order to guarantee a positive output level, $t < a - c$. Hence, the incumbent has incentive to reduce the emission fee through investing in abatement technology.

2.1.2 *Second Stage: Regulation*

In the second stage, the regulator maximizes social welfare (SW) by choosing the emission fee t, anticipating that only one firm operates in the market since there is no threat of entry (potential entrant's profits are negative). The regulator's problem is

$$\max_t SW = \int_0^{q_i(t)} (a - c - x)\, dx - \tfrac{1}{2} d \left[q_i(t) - z\right]^2 - \tfrac{1}{2}\gamma z^2,$$

where the first term is the sum of consumer and producer surplus from production,[9] the second term is the environmental damage from emissions, and the third term is the incumbent's cost of investing in abatement technology. Differentiating with respect to t and rearranging gives the regulator's tax as a function of the level of R&D investment undertaken by the incumbent firm in the first stage,

$$t(z) = \frac{(d-1)(a-c) - 2dz}{d+1}. \tag{1}$$

The optimal tax rate is decreasing in the level of investment in R&D. As the incumbent invests more in abatement, the reduction in emissions is met with a decrease in the tax rate. The incumbent uses this information to decide how much to invest in abatement R&D in the first stage.

2.1.3 First Stage: Abatement

In the first stage, the incumbent anticipates the actions in the second and third stages and solves

$$\max_z \Pi_i^{ne} = \delta\pi_i^{ne} - \tfrac{1}{2}\gamma z^2,$$

where Π_i^{ne} is the incumbent's discounted profit, which is composed of the incumbent's profit in the third stage, π_i^{ne}, the discount factor $\delta \in [0,1]$, and the cost of investing in R&D in the first stage, $\frac{1}{2}\gamma z^2$. Differentiating with respect to z and rearranging, we find, and present in the following proposition, the optimal investment in R&D, emission fee, and quantity produced in the absence of entry threats.[10]

Proposition 1. *The equilibrium investment in abatement, tax, and quantity produced under*

[9] Tax revenue is included in the first term.
[10] All proofs are relegated to the appendix.

no entry are (denoted by the 'ne' superscript):

$$z^{ne} = \frac{(a-c)(d(d+2)-1)\delta}{\gamma(d+1)^2 + 2d(d+2)\delta}, \tag{2}$$

$$t^{ne} = \frac{(a-c)\left(\gamma\left(d^2-1\right) - 2d\delta\right)}{\gamma(d+1)^2 + 2d(d+2)\delta}, \tag{3}$$

$$q^{ne} = \frac{(a-c)(\gamma(d+1) + d(d+3)\delta)}{\gamma(d+1)^2 + 2d(d+2)\delta}, \tag{4}$$

where $z^{ne} > 0$ and $q^{ne} > 0$ for all parameter values. In addition, $t^{ne} > 0$ if $\gamma > \dfrac{2d\delta}{d^2-1}$.

Therefore, in order for the emission fee to be positive, the cost of investment in R&D must be sufficiently high. If the investment cost is too low, the optimal response from the regulator is to impose an emission subsidy to correct for the market failure from a monopolist's under-production.[11]

2.2 Case 2: Entry

Similar to the case of no entry, we solve the game starting in the third stage with the production decision.

2.2.1 Third Stage: Cournot Competition

If entry occurs, both firms choose output simultaneously to maximize their profits. The incumbent's and the entrant's maximization problems are, respectively,

$$\max_{q_i} \pi_i^{ent} = (a - q_i - q_e)q_i - cq_i - t(q_i - z), \text{ and}$$

$$\max_{q_e} \pi_e^{ent} = (a - q_e - q_i)q_e - cq_e - t(q_e - \beta z) - F.$$

[11] This phenomenon was also noted by Poyago-Theotoky (2010).

Taking first-order conditions and solving for the the output level, we obtain the symmetric solution of a standard Cournot model, $q_i = q_e = q = \dfrac{a-c-t}{3}$. Like the case of no entry, an increase in the emissions tax, t, decreases the profit-maximizing quantity. The entrant will join that market if it obtains positive profits from entering.

2.2.2 Second Stage: Regulation

In the case of entry, the regulator seeks to maximize social welfare by choosing the emissions tax rate t anticipating entry into the market since potential entrant profits are positive,

$$\max_t SW = \int_0^{Q(t)} (a-c-x)\,dx - \frac{1}{2}d\left[Q(t)-(1+\beta)z\right]^2 - \left[\frac{1}{2}\gamma z^2 + F\right].$$

Differentiating and solving for t yields the optimal tax as a function of the investment in R&D, $t(z) = \frac{(a-c)(2d-1)-3(\beta+1)dz}{2(d+1)}$. The optimal tax rate is decreasing in the investment in abatement and the spillover parameter β. Specifically, when the spillover or abatement investment increases, net emissions decrease, which lowers the environmental damage from production, thus lowering the emission fee. The incumbent uses this information in the first stage to choose the amount of abatement to invest in.

2.2.3 First Stage: Abatement

In the first stage, the incumbent chooses the investment in R&D that solves,

$$\max_z \Pi_i^{ent} = \delta\pi_i^{ent} - \frac{1}{2}\gamma z^2,$$

where Π_i^{ent} is the incumbent's discounted profit in the first stage, which contains the incumbent's profits in the third stage when entry ensues, π_i^{ent}, and the cost of investing in R&D. The next proposition summarizes the equilibrium results under entry.

Proposition 2. *The equilibrium investment in abatement, tax, and quantity produced under entry are (denoted by the 'ent' superscript):*

$$z^{ent} = \frac{(a-c)(d(\beta+2d+2)-1)\delta}{d(\beta+1)((5-\beta)d+6)+2\gamma(d+1)^2\delta}, \tag{5}$$

$$t^{ent} = \frac{(a-c)\left(2\gamma\left(2d^2+d-1\right)-d(\beta+1)(2(\beta-2)d+3)\delta\right)}{4\gamma(d+1)^2+2d(\beta+1)((5-\beta)d+6)\delta}, \tag{6}$$

$$q^{ent} = \frac{(a-c)(d(\beta+1)(2d+5)\delta+2\gamma(d+1))}{4\gamma(d+1)^2+2d(\beta+1)((5-\beta)d+6)\delta}, \tag{7}$$

where $z^{ent} > 0$ and $q^{ent} > 0$ for all parameter values. In addition, there are 3 cases where $t^{ent} > 0$:

1. *If $1 < d < \frac{3}{2}$ and $0 < \beta < \frac{4d-3}{2d}$,*
2. *if $1 < d < \frac{3}{2}$, $\frac{4d-3}{2d} < \beta < 1$, and $\gamma > \frac{(\beta+1)d\delta(2(\beta-2)d+3)}{2(2d^2+d-1)}$,*
3. *or if $d > \frac{3}{2}$,*

otherwise, $t^{ent} < 0$.

The conditions on a positive emission fee are similar to that in the case of no entry but are complicated by the addition of the spillover. In the first case, the environmental damage and spillover are relatively low, which induces a positive fee since a low spillover does not effectively reduce total emissions. In the second case, the environmental damage is still relatively low, but the spillover and the cost of investing in R&D are higher than in case 1. Here, the high cost of investing offsets the benefits from the spillover, resulting in low investment in R&D and, thus, requiring a positive emission fee. Finally, if the environmental damage is sufficiently high (independent of the cost of investment in R&D and spillover), an emission fee needs to be in place to correct the effects of the negative externality. We next analyze the comparative statics of the equilibrium values.

2.3 Comparative Statics

We now investigate how the equilibrium levels of quantity (q), tax (t), and investment in R&D (z) are affected by a change in the spillover (β, which is only relevant in the case of entry), severity of the environmental damage (d), and investment cost (γ). The following corollary summarizes our findings which hold for the case of entry and no entry.

Corollary 1. *Regardless of the entrant's decision, an increase in the environmental damage increases the investment in R&D and the emissions fee, but decreases the output level. In addition, an increase in the cost of investment or decrease in the discount factor decreases the investment in R&D and output, but increases the emissions fee.*

As the environmental damage increases, the investment and tax rate increase, while the quantity produced decreases. These three results go hand-in-hand. Since the severity of damage is high, there is a greater marginal damage to society for each unit of production and the incumbent expects a high emissions tax. Hence, the incumbent firm increases its investment in abatement, which lowers the expected emissions per unit in production. Even though there is an increase in R&D, the environmental damage from production increases, which increases the emission fee. In addition, the increase in tax rate produces a higher marginal cost, so firms scale back their production.

When the cost of investment in R&D (γ) increases, the incumbent faces a higher marginal cost of abatement. Therefore, it reacts by investing in a lower amount of abatement, which entails an increase in emissions, ultimately causing more environmental damage. In response to the increase in emissions, the social planner increases the tax rate, thus, increasing the marginal cost for each unit produced and, therefore, decreasing the firms' production. A similar line of reasoning can be used for a change in the discount factor. If the discount factor decreases, then the incumbent cares less about future profits and, hence, this investment in R&D only increases the incumbent's costs. Corollary 2 summarizes the effects of a change in the spillover.

Corollary 2. *Under entry, an increase in the spillover decreases the emission fee and increases the output level. In addition, the investment in R&D increases in the spillover if* $\gamma > \phi$*, where* $\phi \equiv \frac{\delta(d(2(\beta+1)-d(\beta(\beta+4)+4(\beta-2)d-15))-6)}{2(d+1)^2}$*, and decreases in the spillover if* $\gamma < \phi$*.*

An increase in the spillover decreases the emission fee as more total emissions are abated. As a result of the lower fee, the marginal costs of production decrease and, hence, output will increase. The spillover's effect on investment depends heavily on the cost of investment. An increase in the spillover decreases the investment in R&D if the cost of investment is not too high, i.e. $\gamma < \phi$. When R&D costs are low, the incumbent is investing in a large amount of R&D and an increase in benefits from R&D are small, to match the low marginal cost. However, when cost of R&D is relatively high, $\gamma > \phi$, the investment in R&D is low and an increase in the spillover has a larger effect in lowering the emission fee (through lower overall emissions) than the loss in profits from the increase in the entrant's free riding.

2.4 Equilibrium Comparison

Next, we compare the no entry equilibrium (equations (2), (3), (4)) with the entry equilibrium (equations (5), (6), and (7)). We start with the investment in R&D.

Corollary 3. *The incumbent invests more in R&D when there is no threat of entry into the market.*

When there is entry, even without a spillover (i.e. $\beta = 0$), any investment in abatement lowers the emission fee faced by both firms (observed in section 2.2.2). With a lower tax, the entrant can benefit from a lower effective marginal cost and, thus, produce more, which ultimately lowers the incumbent's profits. This leads to the incumbent reducing its investment in R&D when there is threat of entry.

Corollary 4. *The incumbent produces more when there is no threat of entry. In addition, the aggregate quantity under no entry is greater than that under entry if $\beta < \theta$, where $\theta \equiv \frac{-2d^2-3d+1}{2d} + \frac{1}{2}\sqrt{\frac{4d^4+12d^3+13d^2-10d+1}{d^2}}$ or if $\theta < \beta < \frac{d^2+3d-2}{d^2+3d}$ and $\gamma < \frac{d(1+\beta)((1-\beta)d(d+3)-2)\delta}{(d+1)(1-\beta+d(\beta(\beta+2d+3)-2))}$. Otherwise, aggregate quantity under entry exceeds that under no entry.*

When there is entry, the incumbent decreases its production and investment in R&D compared to the case of no entry. The amount in which the incumbent decreases production is dependent on the spillover. From corollary 2, we know the tax is decreasing in the spillover and that the quantity produced is increasing in the spillover. In addition, we find that when the spillover is low enough and entry occurs, the incumbent's production is less than half of the output under no entry.

The comparison of the emission fee is not as straight forward. For most allowable parameter values, the emission fee is greater under entry than under no entry. With a spillover of $\beta < 1$, the total amount of abatement per unit of output is lower in the case of entry than if there is no entry. Since the entrant's emissions are not abated at the same level as the incumbent, there are more emissions per unit produced in the industry as a whole. Therefore, more expected environmental damage per unit in the case of entry applies upward pressure on the tax rate. When the spillover is high, the difference in abatement per unit produced between entry and no entry is small, but aggregate output is greater under entry (corollary 4), leading to a higher emission fee under entry. The emission fee can be higher under no entry if the spillover, cost of investment and environmental damage are all sufficiently high.[12]

2.5 Entry deterrence

The monopolist has incentive to under-invest in R&D if it leads to a situation of entry deterrence and, thus, the profits from such an under-investment are greater than those from accommodating entry.[13] Hence, we first need to identify the value of z that makes the entrant obtain zero profits, $\hat{z}$, thus keeping it out of the market. As a consequence, the incumbent is willing to deter entry if $\hat{z}$ yields a higher profit than accommodating profit, Π_i^{ent}.

Corollary 5. *The level of R&D that deters entry solves* $\Pi_e(\hat{z}) = 0$*, which occurs at*

$$\hat{z} = \frac{\omega\alpha - (d+1)^2\sqrt{\frac{\beta^2((4d^2+1)\omega^2-4d(5d+6)F)+4\beta d(\omega^2-2(2d+3)F)+4d^2F}{(d+1)^2}}}{(\beta+1)d(6\beta+(5\beta-1)d)},$$

where $\omega = a - c$ *and* $\alpha = (\beta(2d(d+1)-1)+d)$*. When the incumbent invests an amount* $\hat{z}$ *in R&D its profits become* $\Pi_i^{ED}(\hat{z}) = \frac{(a-c-\hat{z})(a-c+d(d+2)\hat{z})}{(d+1)^2} - \frac{1}{2}\gamma\hat{z}^2$*, where 'ED' denotes entry deterrence. In addition, the incumbent invests in* $\hat{z}$ *if* $\Pi_i^{ED}(\hat{z}) > \Pi_i^{ent}(z^{ent})$*.*

Figure 1 shows a situation where the incumbent would prefer to deter entry by under-investing in R&D where the entrant's profit π_e^{ent}, is zero at investment level $\hat{z}$.[14] If the

[12] Numerically, this situation can occur when $a = 10$, $c = 1$, $\beta = 1$, $\gamma = 6$, $\delta = 1$, and $d > 12$.

[13] The complexity of the profit functions makes the analytic solutions intractable and unable to solve analytically. However, we can numerically find a general situation where the incumbent would prefer to engage in entry deterrence than accommodate entry.

[14] Parameter values for figure 1 are $a = 10, c = 1, d = 2.5, \beta = .25, \delta = 1, \gamma = 1.5$, and $F = 3$.

incumbent's no entry profits, π_i^{ne}, at $\hat{z}$ (point A) is higher than their profit under entry, π_i^{ent}, at equilibrium investment z^{ent} (point B), then the incumbent will prefer to deter entry. This situation is sustained if the entry cost is relatively high. However, if the fixed entry cost is extremely high, the incumbent does not need to lower its investment to $\hat{z}$ in order to deter entry as the entrants profit will lie below zero at z^{ent} and entry is blockaded. We next investigate the levels of fixed costs that facilitate these different situations.

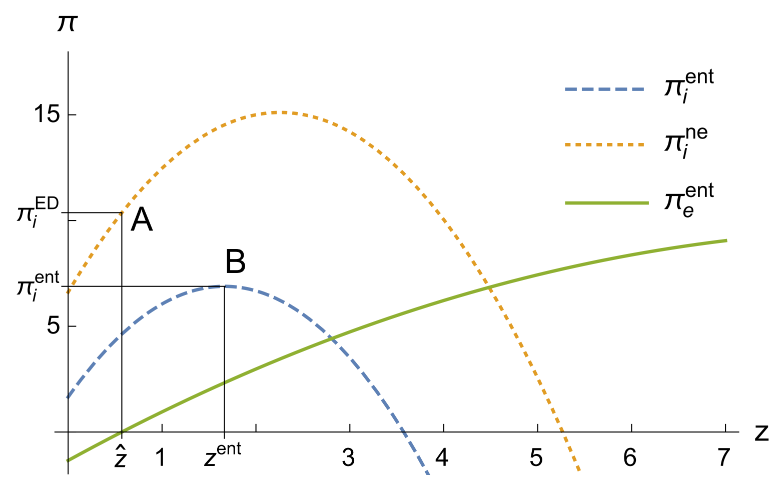

Figure 1: A case where the monopolist would prefer to deter entry by under-investing in abatement technology.

In order for entry deterrence behavior to be preferred to accommodating entry, the fixed cost of entry needs to be sufficiently high. Any investment in R&D benefits the entrant through a lower emission fee, thus, as the investment increases, the fixed cost that allows for profitable entry also increases. Hence, we can find two values of fixed entry costs that define three regions: (1) a high level, $\bar{F}$, where entry is blockaded if fixed costs are above $\bar{F}$; (2) a lower level, $\underline{F}$, where entry will be accommodated if the costs are below this level; and (3) if the $\underline{F} < F < \bar{F}$, entry deterrence behavior is supported.

To find $\bar{F}$, we plug the equilibrium conditions from entry (from proposition 2) into the entrant's profit function and solve for F. The upper bound on fixed costs were entry is deterred is $\bar{F}$ If the fixed costs is above $\bar{F}$, then the fixed cost to entry is too high and entry is blockaded. The value of $\underline{F}$ is found in a similar manner, but the entrant's profit is evaluated at $\hat{z}$.[15] These values are presented in the following proposition.

Proposition 3 *The level of fixed entry cost that blocks entry is*

$$\bar{F} = \frac{(a-c)^2\left(-(\beta+1)d\Gamma + 4\gamma^2(d+1)^2 + 4\gamma(d+1)\eta\right)}{4\left((\beta+1)d((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2},$$

where $\Gamma = -6\beta + 4(\beta(2\beta-5)-1)d^3 + 4\left(\beta^3 - 6\beta - 5\right)d^2 + (\beta-5)(2\beta+5)d$, *and* $\eta = \beta + d\left(-\beta^2 + \beta + 4\beta d^2 + 2(\beta+1)^2 d + 5\right)$. *In addition, the level of fixed cost that deters entry,* $\underline{F}$*, solves* $\Pi_e^{ent}(\hat{z}, q^{ent}(\hat{z}), t^{ent}(\hat{z})) = 0$.

Figure 2 shows the regions where entry is accommodated, deterred, and blockaded. As shown in the figure, $\bar{F}$ is upward sloping as the spillover increases. Intuitively, as the benefits from investment in R&D increase through a higher spillover, a higher fixed cost is required so that entry is not profitable. In addition, β has little effect on $\underline{F}$ as the profits from deterring entry and accommodating entry are being affected in the same way by the spillover until a very high level of β. At this point, the entrant is receiving a large (almost complete) benefit of the R&D through low emissions and a lower tax rate, greatly incentivizing the incumbent to lower investment and deter entry. Next, we can investigate how $\underline{F}$ and $\bar{F}$ change if there is an increase in the environmental damage or cost of investment.

Figure 3 shows how $\underline{F}$ and $\bar{F}$ change when the environmental damage d increases from 2.5 to 5 (the new levels of fixed cost limits are denoted by $\underline{F}'$ and $\bar{F}'$). As we can see in the figure, an increase in environmental damage rotates $\bar{F}$ counter-clockwise. In this case, the fixed cost that blockades entry is lower at low levels of the spillover and higher at high levels of the spillover. A similar, but more extreme shift happens to $\underline{F}$. At very low levels of the

[15] This level of fixed cost, $\underline{F}$, cannot be solved for analytically and we represent it graphically using the same parameter values as in figure 1.

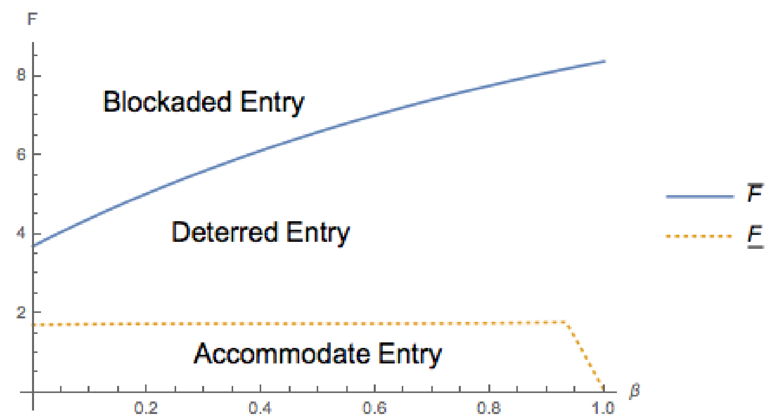

Figure 2: The regions of fixed cost that accommodate, deter, and blockade entry given levels of the spillover, β.

spillover, the fixed cost that accommodates entry increases. A higher environmental damage reduces the set of parameter values under which the incumbent under-invests in R&D in order to deter entry since the burden from the emission fee becomes more important. The higher level of environmental damage increases the investment in R&D (corollary 1) and makes any under-investment further away from the monopoly equilibrium, and thus less profitable.

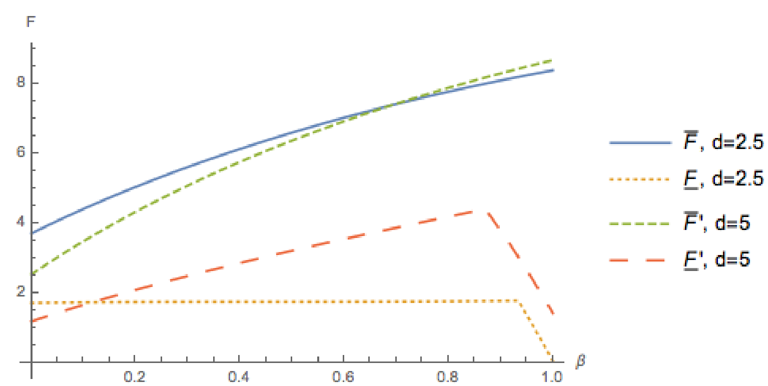

Figure 3: The regions of fixed cost that accommodate, deter, and blockade entry plotted with two different levels of d.

Figure 4 shows how $\underline{F}$ and $\bar{F}$ change when the cost of investment γ increases from 1.5 to 3 (the new levels of fixed cost limits are denoted by $\underline{F}'$ and $\bar{F}'$). This increase in investment decreases both $\underline{F}$ and $\bar{F}$ for all levels of the spillover (except for $\underline{F}$ at a level of the spillover close to one). An increase in the cost of investment decreases the investment in R&D and decreases the benefits to the entrant. Thus, the regions in which entry is blockaded expands while the region in which entry is accommodated shrinks.

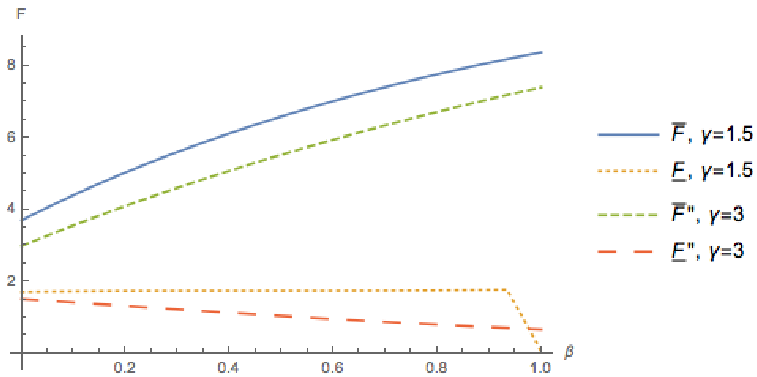

Figure 4: The regions of fixed cost that accommodate, deter, and blockade entry plotted with two different levels of γ.

2.6 Social Welfare Comparison

Most critical to policy makers is the comparison between the social welfare under entry and no entry. Intuitively, we expect to identify cases where entry into the market is socially optimal and cases where entry lowers social welfare. The complexity of the equilibrium social welfare functions does not make comparisons intuitive or tractable. Therefore, we analyze the social welfare numerically and graphically (figure 5) with parameter values consistent with the rest of the analysis.

Result 1. *If the spillover is low or fixed entry cost is high, then $SW^{ne} > SW^{ent}$. However, if the spillover is high and the fixed entry cost is low, then $SW^{ent} > SW^{ne}$.*

The first result is a case in which there are low technology spillovers. In this context, social welfare under no entry is higher than that under entry for $\beta < \beta^* = 0.65$. Under entry and low spillovers, the environmental damage increases since the entrant's pollution is not abated at the same rate as the incumbent's pollution. The increase in environmental damage outweighs the benefits to the consumers from increased competition. When the spillover is significant, i.e. $\beta > \beta^*$, the entrant's pollution is closer to that of the incumbent's and the increase in environmental damage per unit is smaller than at a lower spillover. This facilitates a situation where entry is desired as the increase in consumer surplus from increased competition outweighs the increase in environmental damage. Since the fixed cost enters linearly into the social welfare function when there is entry, a higher F shifts the social welfare under entry downward, increasing the parameter values of β for which no entry is socially preferred. Figure 5 shows the comparison of the social welfare functions when there is entry and when there is no entry over the range of the spillover.[16] Our results suggest that the regulator should support investment in R&D that produces a significant spillover since this investment would promote competition and generate a higher level of social welfare.

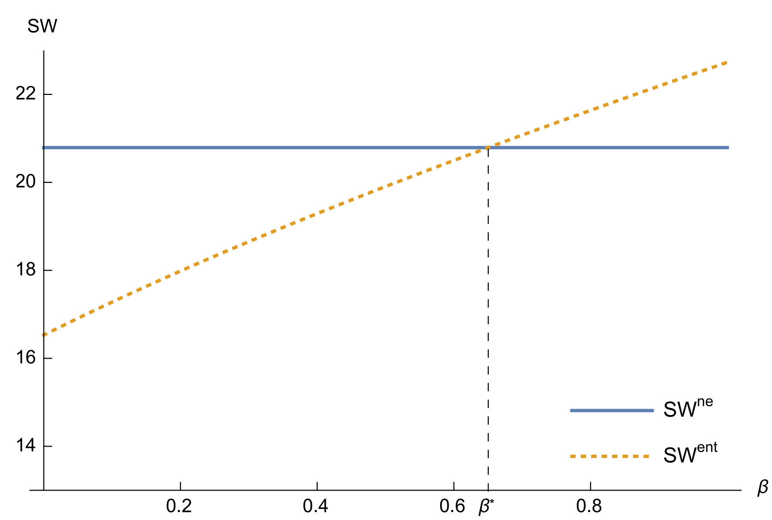

Figure 5: Comparison of social welfare under the the cases of entry and no entry.

The two variables that most influence the highest level of the spillover that supports no

[16]The parameter values in figure 5 are the same as those in figure 1.

entry as socially optimal, β^*, are the cost of investment, γ, and the fixed entry cost, F. As the cost of investment increases, β^* decreases, which increases the range of the spillover where entry is socially preferred. As mentioned before, when the investment cost increases the incumbent firm chooses a lower level of investment. The low level of investment means that little of the environmental damage is being abated regardless of entry, and, hence, the benefits from more competition must outweigh the damage. As the fixed costs to entry increase, social welfare under entry linearly shifts downward, making no entry preferred for a larger range of the spillover.

Finally, we investigate when the regulator's and incumbent's incentives are aligned. To do this, we take the difference of social welfare under entry and no entry, set it equal to zero, and solve for F, calling this value of fixed cost $\tilde{F}$. Using the same parameter values as those in figure 2, we can find $\tilde{F}$ as a function of β and plot it over that same figure. Shown in figure 6, the area below $\tilde{F}$ (regions II and III), is where social welfare is highest under entry, and above $\tilde{F}$ is where no entry is socially optimal.[17]

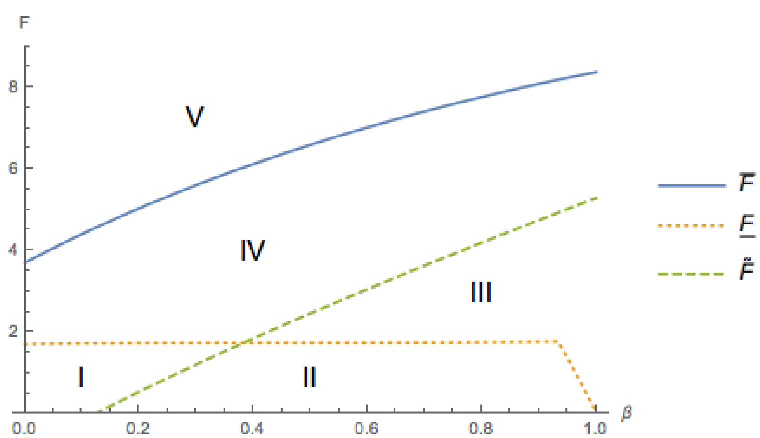

Figure 6: Pairs of (F, β) where social welfare under entry and no entry coincide overlayed on Figure 2.

Firm and regulator incentives are aligned in regions II and V. In region II, the incumbent accommodates entry, while in region V, entry is blockaded as the fixed cost is sufficiently high.

[17]In this example, there is no region where entry deterrence is socially optimal.

In these two cases, the regulator does not need to engage in policy to achieve the socially optimal outcome since for pairs of β and F below $\tilde{F}$ indication that entry is socially preferred which coincides with the firm's incentive to accommodate entry. The same argument applies for region V where no entry is socially preferred. In the remaining regions, I, III, and IV, firm and regulator incentives are misaligned, leading to different policy recommendations.

In region I, the incumbent will accommodate entry, but the spillover is too low for entry to be socially optimal. It is recommended that the regulator either promote investment with high spillover effects or significantly increase the barriers to entry. In region IV, the incumbent deters entry while the regulator prefers no entry (blockaded entry). When the incumbent deters entry, it lowers its investment, which leads to lower social welfare. Here, the regulator would want to encourage the incumbent to invest more by making sure there is no threat of entry. If the spillover is relatively high, the regulator could lower the cost of entry through entrepreneurship grants to encourage entry into the market, thus bringing the (F, β) pair closer to region II. Finally, if (F, β) lies in region III, the incumbent prefers to deter entry while the regulator would want entry to occur. To align incentives, the regulator would want to lower entry costs.[18]

2.7 Policy Considerations

In this section, we will discuss policy considerations first in the context of two cases: (1) entry and no entry, and (2), when entry deterrence behavior is preferred by the incumbent.

The first policy consideration arises in the situation where it is socially optimal that there is no entry into the market, even though the threat of entry exists (since potential entrant profits are positive). Since the emission fee is set to maximize social welfare depending on the number of firms in the market, it would not be optimal to use this as a tool to deter

[18] In this figure, there are no pairs of β and F where entry deterrence is socially preferred.

entry. Instead, the regulator could increase the fixed cost of entry F when entry is not socially optimal through an increase in licensing fees or other administrative costs. If the costs are raised sufficiently, so that there is no longer a threat of entry, the regulator has successfully facilitated a situation that maximizes social welfare.

The second set of policy considerations is when the incumbent prefers to deter entry, and depends on whether or not the social welfare under entry deterrence is socially preferred to either entry or no entry. If the incumbent under-invests, i.e. $\hat{z}$, SW^{ED} can be greater than SW^{ent} if the spillover is low. If social welfare is highest under entry and the incumbent has incentive to deter entry, the regulator can support competition through policies that promote investment in R&D, especially R&D with high spillovers. To achieve this, the regulator can directly lower the cost of R&D through subsidies and grants, or it can specifically reward investment in R&D that has high spillovers with tax credits that help the incumbent remain competitive in the market. From the discussion on entry deterrence, the regulator needs to keep in mind the following: (1) whether the negative effects of pollution are severe, (2) the effect of the emission fee on competition or investment in R&D, and (3) the cost of R&D since affordable technology is critical to avoid entry-deterrence practices.

3 Conclusion

We analyze how an entry-deterrence model is affected by the inclusion of investment in R&D with the possibility of spillover to a potential entrant. From a social welfare point of view, we show that if the spillover is low or if a low environmental damage is accompanied by a high spillover, having only one firm in the market is socially preferred to entry deterrence behavior by the incumbent. A second firm entering into the market is most beneficial for society when the spillover is high. If the spillover is low, entry deterrence may be preferred to entry, and the regulator should consider increasing barriers to entry, as that will increase the level of abatement R&D needed to deter entry, thus alleviating the negative social welfare implications of decreasing investment.

There is a trade-off when we consider entry into the market, since it benefits consumers, but it also increases the environmental damage from increased production. Whether or not entry is beneficial to society depends heavily on the spillover and entry costs. If the fixed cost to enter is sufficiently low enough, it is profitable for a second firm to enter the market even if it is not socially optimal. When the spillover is small, the regulator has two options to maximize welfare: (1) create a larger barrier to entry for a potential entrant by requiring large licensing fees; or (2) incentivize entry by promoting R&D with a high spillover. Because a high spillover decreases the benefits of R&D to the incumbent, the regulator could provide a subsidy to the incumbent to counteract the disincentive.

The next step is to further integrate the entry model with that of P-T, where there are multiple incumbents facing the threat of entry. The combination of these two frameworks would reinforce downward pressures on the already low investment in abatement technology in each framework. This could decrease the investment even closer to zero, or it could potentially yield a level of investment that lies between the two frameworks. Another extension to the model could incorporate entry of another firm that produces a good that is either a (imperfect) substitute or complement to the incumbent's good. In this situation, it may not be privately optimal for the incumbent to decrease its investment when there is entry since it is not directly negatively impacting the goods market competition like that of an identical good.

4 Appendix

4.1 Proof of Proposition 1

In the third stage, the incumbent acts as a monopolist and solves

$$\max_{q_i} \pi_i^{ne} = (a - q_i)q_i - cq_i - t(q_i - z),$$

with first-order condition

$$\frac{\partial \pi_i^{ne}}{\partial q_i} = a - c - t - 2q_i = 0.$$

Solving for q_i gives $q_i(t) = \dfrac{a-c-t}{2}$. Hence, $q_i(t) > 0$ if $t > a - c$. The regulator's problem in in the second stage is

$$\max_{t} SW = \int_0^{q_i(t)} (a - c - x)\, dx - \tfrac{1}{2} d\, [q_i(t) - z]^2 - \tfrac{1}{2}\gamma z^2,$$

where the first-order condition is

$$\frac{\partial SW}{\partial t} = \frac{1}{4}(a(d-1) - d(c + t + 2z) + c - t) = 0.$$

Solving for t yields $t = \frac{(d-1)(a-c)-2dz}{d+1}$, which guarantees $q_i(t) > 0$ since $t < a - c$ for all parameter values. In the first stage, the monopolist maximization problem is

$$\max_{z} \Pi_i^{ne} = \delta((a - q_i)q_i - cq_i - t(q_i - z)) - \tfrac{1}{2}\gamma z^2,$$

with first-order condition

$$\frac{\partial \Pi_i^{ne}}{\partial z} = \frac{d(d+2)\delta(a - c - 2z) + \delta(c - a) + \gamma\left(-(d+1)^2\right) z}{(d+1)^2} = 0.$$

Solving for z gives us the no entry equilibrium level of investment $z^{ne} = \frac{(a-c)(d(d+2)-1)\delta}{\gamma(d+1)^2+2d(d+2)\delta}$. Plugging this into the results from the second and third stages gives us the remainder of proposition 1:

$$t^{ne} = \frac{(a-c)\left(\gamma\left(d^2-1\right)-2d\delta\right)}{\gamma(d+1)^2+2d(d+2)\delta}, \tag{8}$$

$$q^{ne} = \frac{(a-c)(\gamma(d+1)+d(d+3)\delta)}{\gamma(d+1)^2+2d(d+2)\delta}. \tag{9}$$

z^{ne} and q^{ne} are positive since $a > c$, $\beta \in [0,1]$, and $d > 1$. However, the sign of t^{ne} depends on the sign of $\gamma(d^2-1)-2d\delta$, which gives the condition that $t^{ne} > 0$ if $\gamma > \frac{2d\delta}{d^2-1}$. Finally, we need to guarantee that $t^{ne} < a-c$, which is the condition that supports $q^{ne} > 0$. Therefore, we need that

$$\frac{\gamma\left(d^2-1\right)-2d\delta}{\gamma(d+1)^2+2d(d+2)\delta} < 1$$

$$\gamma[(d^2-1)-(d+1)^2] < 2d\delta(d+2)+2d\delta$$

$$-\gamma[2d+1] < 2d\delta(d+3),$$

which holds for all parameter values.

4.2 Proof of Proposition 2

In the third stage, the incumbent and entrant solve,

$$\max_{q_i} \pi_i^{ent} = (a-q_i-q_e)q_i - cq_i - t(q_i - z), \text{ and}$$

$$\max_{q_e} \pi_e^{ent} = (a-q_e-q_i)q_e - cq_e - t(q_e - \beta z) - F.$$

Taking first-order conditions and solving for the the output level, we obtain the symmetric solution of a standard Cournot model, $q_i = q_e = q = \dfrac{a-c-t}{3}$. In the second stage, the regulator's problem is

$$\max_t SW = \int_0^{Q(t)} (a-c-x)\,dx - \frac{1}{2}d\left[Q(t)-(1+\beta)z\right]^2 - \left[\frac{1}{2}\gamma z^2 + F\right].$$

with first-order condition

$$\frac{\partial SW}{\partial t} = \frac{1}{9}(-2)(-2ad+a+d(2c+2t+3(\beta+1)z)-c+2t) = 0.$$

Solving for t gives $t(z) = \frac{(a-c)(2d-1)-3(\beta+1)dz}{2(d+1)}$. In the first stage, the incumbent solves

$$\max_z \Pi_i^{ent} = \delta((a-q_i-q_e)q_i - cq_i - t(q_i-z)) - \frac{1}{2}\gamma z^2,$$

with first-order condition

$$\frac{\partial \Pi_i^{ent}}{\partial z} = \frac{\delta(a-c)(d(\beta+2d+2)-1)+(\beta+1)d\delta z((\beta-5)d-6)-2\gamma(d+1)^2 z}{2(d+1)^2} = 0.$$

Solving for z gives the equilibrium level of investment under entry gives $z^{ent} = \frac{(a-c)(d(\beta+2d+2)-1)\delta}{d(\beta+1)((5-\beta)d+6)+2\gamma(d+1)^2\delta}$. Plugging this into the results from the second and third stages gives us the equilibrium values of the emission fee and quantity:

$$t^{ent} = \frac{(a-c)\left(2\gamma\left(2d^2+d-1\right)-d(\beta+1)(2(\beta-2)d+3)\delta\right)}{4\gamma(d+1)^2+2d(\beta+1)((5-\beta)d+6)\delta}, \tag{10}$$

$$q^{ent} = \frac{(a-c)(d(\beta+1)(2d+5)\delta+2\gamma(d+1))}{4\gamma(d+1)^2+2d(\beta+1)((5-\beta)d+6)\delta}. \tag{11}$$

z^{ent} and q^{ent} are positive since $a > c$, $\beta \in [0,1]$, and $d > 1$. However, t^{ent} depends on the sign of the numerator, determined by $2\gamma\left(2d^2+d-1\right) - d\delta(\beta+1)(2d(\beta-2)+3)$. The numerator, and thus t^{ent}, is positive if one of the following conditions hold:

1. If $1 < d < \frac{3}{2}$ and $0 < \beta < \frac{4d-3}{2d}$,

   The numerator is positive if $d\delta(\beta+1)(2d(\beta-2)+3) < 0$. Simplifying yields $2d(\beta - 2) + 3 < 0 \rightarrow \beta - 2 < \frac{-3}{2d} \rightarrow \beta < \frac{4d-3}{2d}$. This condition, $\frac{4d-3}{2d} < 1$, and binding on $beta$, if $d < \frac{3}{2}$.

2. if $1 < d < \frac{3}{2}$, $\frac{4d-3}{2d} < \beta < 1$, and $\gamma > \frac{(\beta+1)d\delta(2(\beta-2)d+3)}{2(2d^2+d-1)}$,

   If $d < \frac{3}{2}$ and $\frac{4d-3}{2d} \leq \beta \leq 1$, then the entire numerator needs to be positive, which happens when γ is high.

3. or if $d > \frac{3}{2}$,

   from case (1), we are looking for $2d(\beta-2)+3 < 0$. Rearranging gives $\frac{3}{2} < d(2-\beta)$, which always holds if $d > \frac{3}{2}$.

otherwise, $t^{ent} < 0$. We also need to guarantee that $t^{ent} < (a-c)$, so that $q^{ent} > 0$. Therefore, we need that

$$\frac{(2\gamma\left(2d^2+d-1\right) - d(\beta+1)(2(\beta-2)d+3)\delta)}{4\gamma(d+1)^2 + 2d(\beta+1)((5-\beta)d+6)\delta} < 1,$$

$$2\gamma\left(2d^2+d-1\right) - d(\beta+1)(2(\beta-2)d+3)\delta < 4\gamma(d+1)^2 + 2d(\beta+1)((5-\beta)d+6)\delta,$$

$$\begin{aligned} 2\gamma[(2d^2+d-1) - 2(d+1)^2] &< d\delta[2(\beta+1)((5-\beta)d+6) \\ &\quad + (\beta+1)(2d(\beta-2)+3)], \\ -6\gamma(d+1) &< 3d\delta(2d+5)(1+\beta), \end{aligned}$$

which holds for all parameter values.

4.3 Proof of Corollary 1.

Let us now examine the effect of a change in the environmental damage or abatement costs on the equilibrium results, first in the case of no entry and, second, when there is entry.

The case of no entry:

$$\frac{\partial z^{ne}}{\partial d} = \frac{4(d+1)\delta(a-c)(\gamma+\delta)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} > 0,$$
$$\frac{\partial z^{ne}}{\partial \gamma} = -\frac{(d+1)^2(d(d+2)-1)\delta(a-c)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} < 0,$$
$$\frac{\partial z^{ne}}{\partial \delta} = \frac{\gamma(d+1)^2(d(d+2)-1)(a-c)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} > 0,$$
$$\frac{\partial t^{ne}}{\partial d} = \frac{2(a-c)(\gamma+\delta)\left(2\delta d^2+\gamma(d+1)^2\right)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} > 0,$$
$$\frac{\partial t^{ne}}{\partial \gamma} = \frac{2d\left(d^3+3d^2+d-1\right)\delta(a-c)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} > 0,$$
$$\frac{\partial t^{ne}}{\partial \delta} = -\frac{2\gamma d\left(d^3+3d^2+d-1\right)(a-c)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} < 0,$$
$$\frac{\partial q^{ne}}{\partial d} = -\frac{(a-c)(\gamma+\delta)\left(2\delta d^2+\gamma(d+1)^2\right)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} < 0,$$
$$\frac{\partial q^{ne}}{\partial \gamma} = -\frac{d(d+1)(d(d+2)-1)\delta(a-c)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} < 0,$$
$$\frac{\partial q^{ne}}{\partial \delta} = \frac{\gamma d\left(d^3+3d^2+d-1\right)(a-c)}{\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2} > 0,$$

since $a > c$, $d > 1$, and $\gamma > 0$. The case of entry:

$$\begin{aligned}
\frac{\partial z^{ent}}{\partial d} &= \frac{\delta(a-c)\left((\beta+1)\delta\left((\beta-2)(\beta-1)d^2-2(\beta-5)d+6\right)+\zeta\right)}{\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} > 0,\\
\frac{\partial z^{ent}}{\partial \gamma} &= -\frac{2(d+1)^2\delta(a-c)(d(\beta+2d+2)-1)}{\left((\beta+1)d\delta(6-(\beta-5)d)+2\gamma(d+1)^2\right)^2} < 0,\\
\frac{\partial z^{ent}}{\partial \delta} &= \frac{2\gamma(d+1)^2(a-c)(d(\beta+2d+2)-1)}{\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} > 0,\\
\frac{\partial t^{ent}}{\partial d} &= \frac{3(a-c)\left(-(\beta+1)^2(5\beta-13)d^2\delta^2-2(\beta+1)\gamma\delta\eta+4\gamma^2(d+1)^2\right)}{2\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} > 0,\\
\frac{\partial t^{ent}}{\partial \gamma} &= \frac{3(\beta+1)d(d+1)\delta(a-c)(d(\beta+2d+2)-1)}{\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} > 0,\\
\frac{\partial t^{ent}}{\partial \delta} &= -\frac{3(\beta+1)\gamma d(d+1)(a-c)(d(\beta+2d+2)-1)}{\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} < 0,\\
\frac{\partial q^{ent}}{\partial d} &= \frac{(a-c)\left((\beta+1)^2(5\beta-13)d^2\delta^2+2(\beta+1)\gamma\delta\eta-4\gamma^2(d+1)^2\right)}{2\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} < 0,\\
\frac{\partial q^{ent}}{\partial \gamma} &= -\frac{(\beta+1)d(d+1)\delta(a-c)(d(\beta+2d+2)-1)}{\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} < 0,\\
\frac{\partial q^{ent}}{\partial \delta} &= \frac{(\beta+1)\gamma d(d+1)(a-c)(d(\beta+2d+2)-1)}{\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} > 0,
\end{aligned}$$

where $\zeta = 2\gamma(\beta + d(6-(\beta-2)d)+4)$ and $\eta = (\beta d(d+2) - 6d(d+1) - 1)$. The comparative statics above hold since $a > c$, $d > 1$, and $\gamma > 0$.

4.4 Proof of Corollary 2.

Let us now consider an increase in the spillover in the case of entry:

$$\begin{aligned}
\frac{\partial t^{ent}}{\partial \beta} &= -\frac{3d\delta(a-c)\left((\beta+1)^2d^2(2d+5)\delta+2\gamma(d+1)(d(2\beta+2d+3)-1)\right)}{2\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} < 0,\\
\frac{\partial q^{ent}}{\partial \beta} &= \frac{\delta(a-c)\left((\beta+1)^2(2d+5)\delta d^3+2\gamma(d+1)d(d(2\beta+2d+3)-1)\right)}{2\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} > 0,\\
\frac{\partial z^{ent}}{\partial \beta} &= \frac{d\delta(a-c)\left(\delta(d(d(\beta(\beta+4)+4(\beta-2)d-15)-2(\beta+1))+6)+2\gamma(d+1)^2\right)}{\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2} \lesseqgtr 0.
\end{aligned}$$

The sign of $\dfrac{\partial z^{ent}}{\partial \beta}$ is determined by the sign of $(\delta(d(d(\beta(\beta+4)+4(\beta-2)d-15)\ -2(\beta+1))+6)+2\gamma(d+1)^2)$. If $\gamma > \phi$, where $\phi \equiv \frac{\delta(d(2(\beta+1)-d(\beta(\beta+4)+4(\beta-2)d-15))-6)}{2(d+1)^2}$, then $\dfrac{\partial z^{ent}}{\partial \beta} > 0$. If $\gamma < \phi$, then $\dfrac{\partial z^{ent}}{\partial \beta} < 0$.

4.5 Proof of Corollary 3.

First, we can show that $z^{ent} < z^{ne}$ for all parameter values:

$$z^{ent} < z^{ne},$$
$$\frac{(a-c)(d(\beta+2d+2)-1)\delta}{d(\beta+1)((5-\beta)d+6)+2\gamma(d+1)^2\delta} < \frac{(a-c)(d(d+2)-1)\delta}{\gamma(d+1)^2+2d(d+2)\delta},$$

which simplifies to,

$$\frac{d\delta\left(\beta+d\left(4\beta+\beta\left[d(d(4-\beta)+12-2\beta)-\beta\right]+d(d+4)+1\right)-6\beta-2\right)}{(d+1)^2((\beta-2)d+1)} < \gamma$$

which holds for all parameter values since the numerator of the left-hand side is positive and the denominator is negative given that $\beta \in [0,1]$.

4.6 Proof of Corollary 4.

Let us next examine if the output level under no entry exceeds that under entry.

$$
\begin{gathered}
q^{ne} > q^{ent}, \\
\frac{(a-c)(\gamma(1+d)+d^2p^2)}{2d^2p^2+\gamma(1+d)^2} > \frac{(a-c)\left((\beta+1)^2d^2p^2+2\gamma(1+d)\right)}{4(\beta+1)^2d^2p^2+4\gamma(1+d)^2}, \\
\frac{\gamma(d+1)+d(d+3)\delta}{\gamma(d+1)^2+2d(d+2)\delta} - \frac{(\beta+1)d(2d+5)\delta+2\gamma(d+1)}{4\gamma(d+1)^2-2(\beta+1)d\delta((\beta-5)d-6)} > 0,
\end{gathered}
$$

which we can simplify to

$$
\gamma d\delta(d+1)\left(7\beta+2d^2(1-\beta)+d(3-\beta)(2\beta+5)+11\right) \\
+2(\beta+1)d^2\delta^2(8+3d(d+4)-\beta d(d+3))+ > 0
$$

which holds for all allowable parameter values since $3d(d+4) > \beta d(d+3)$. Total quantity produced when there is entry is

$$
Q = \frac{(a-c)((\beta+1)d(2d+5)\delta+2\gamma(d+1))}{2\gamma(d+1)^2-(\beta+1)d\delta((\beta-5)d-6)}.
$$

The comparison of total quantity when entry ensues to no entry, $Q = 2q^{ent} < q^{ne}$, is

$$
\begin{gathered}
\frac{(a-c)\left((\beta+1)^2d^2p^2+2\gamma(1+d)\right)}{2(\beta+1)^2d^2p^2+4\gamma(1+d)^2} < \frac{(a-c)(\gamma(1+d)+d^2p^2)}{2d^2p^2+\gamma(1+d)^2}, \\
d\delta\{\gamma(d+1)[1-\beta+d(\beta(\beta+2d+3)-2)]+d\delta(1+\beta)((1-\beta)d(d+3)-2)\} < 0, \\
\gamma < \frac{d\delta(1+\beta)((1-\beta)d(d+3)-2)}{(d+1)(1-\beta+d(\beta(\beta+2d+3)-2))}.
\end{gathered}
$$

In order for the right-hand side to be positive, we need that $\theta < \beta < \frac{d^2+3d-2}{d^2+3d}$, where $\theta \equiv \frac{-2d^2-3d+1}{2d} + \frac{1}{2}\sqrt{\frac{4d^4+12d^3+13d^2-10d+1}{d^2}}$.

If $\beta < \theta$, then the inequality condition on γ switches signs (since we multiply through by a negative), and the condition always holds:

$$\gamma > 0 > \frac{d\delta(1+\beta)((1-\beta)d(d+3)-2)}{(d+1)(1-\beta+d(\beta(\beta+2d+3)-2))},$$

and, therefore, $2q^{ent} < q^{ne}$.

4.7 Proof of Corollary 5.

To find the level of investment that deters entry $\hat{z}$, we plug the functions from the second and third stages ($t(z)$, and ($q(t)$)) into the entrant's profit function and solve for the value that makes the entrant's profit zero. Any investment less than this will result in negative profits for the entrant. Specifically, the entrant's profit becomes

$$\pi_e^{ent} = (a - q_e(t(z)) - q_i(t(z)))q_e(t(z)) - cq_e(t(z)) - t(z)(q_e(t(z)) - \beta z) - F = 0,$$

where from proposition 2 we have

$$t(z) = \frac{(a-c)(2d-1) - 3(\beta+1)dz}{2(d+1)}, \text{ and}$$
$$q(t) = \frac{1}{3}(a-c-t)$$

Plugging in and solving for z gives the entry deterring level of investment

$$\hat{z} = \frac{\omega\alpha \pm (d+1)^2\sqrt{\frac{\beta^2((4d^2+1)\omega^2-4d(5d+6)F)+4\beta d(\omega^2-2(2d+3)F)+4d^2F}{(d+1)^2}}}{(\beta+1)d(6\beta+(5\beta-1)d)}.$$

where $\omega = a - c$ and $\alpha = (\beta(2d(d+1) - 1) + d)$. This suggests that there are two levels of investment that deter entry, low and high. However, the parameters needed for the high level of investment to deter entry lead to a case where there is an emission subsidy.

The incumbent's profit when there is entry is

$$\Pi_i^{ent} = \frac{(a-c)^2(2\gamma + 4d(\beta + d) + 1)}{4(\beta+1)d((5-\beta)d + 6) + 8\gamma(d+1)^2},$$

and under entry deterrence, the incumbent's profit is

$$\Pi_i^{ED}(\hat{z}) = \frac{2(d(d+2) - 1)\hat{z}(a-c) + 2(a-c)^2 - \hat{z}^2(\gamma + (\gamma+2)d(d+2))}{2(d+1)^2}.$$

In order to compare when entry-deterrence is profitable, we must compare the profits numerically.

4.8 Proof of Proposition 3.

The entrant's profit function in equilibrium is

$$\Pi_e^{ent} = \frac{(a-c)^2\left(-(\beta+1)d\Gamma + 4\gamma^2(d+1)^2 + 4\gamma(d+1)\eta\right)}{4\left((\beta+1)d((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2} - F,$$

where $\Gamma = -6\beta + 4(\beta(2\beta-5)-1)d^3 + 4\left(\beta^3 - 6\beta - 5\right)d^2 + (\beta-5)(2\beta+5)d$, and $\eta = \beta + d\left(-\beta^2 + \beta + 4\beta d^2 + 2(\beta+1)^2 d + 5\right)$. Setting $\Pi_e^{ent} = 0$ and solving for F is the level of fixed cost that blocks entry:

$$\bar{F} = \frac{(a-c)^2\left(-(\beta+1)d\theta + 4\gamma^2(d+1)^2 + 4\gamma(d+1)\phi\right)}{4\left((\beta+1)d((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2}.$$

4.9 Numerical proof of Lemma 1.

The social welfare in the case of entry (SW^{ent}) is:

$$SW^{ent} = \frac{\omega^2\left(-\delta^2\left((\beta+1)^2 d\left(d\left(4(\beta-4)d^2-2\beta+(\beta-5)(\beta+9)d-29\right)+1\right)\mu\right)\right.}{2\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2}$$
$$+\frac{\omega^2\left(4(\beta+1)\gamma d(2d+5)\delta(d+1)^2+4\gamma^2(d+1)^3\right)}{2\left((\beta+1)d\delta((\beta-5)d-6)-2\gamma(d+1)^2\right)^2}-F,$$

where $\mu = \gamma(d(\beta+2d+2)-1)^2$. When there is no entry, the social welfare (SW^{ne}) is:

$$SW^{ne} = \frac{\omega^2\left(\gamma^2(d+1)^3+\gamma\delta\left(2d(d+1)^2(d+3)-(d(d+2)-1)^2\delta\right)+\chi\delta^2\right)}{2\left(\gamma(d+1)^2+2d(d+2)\delta\right)^2},$$

where $\chi = d(d(d(3d+13)+13)-1)$. From here, we compare the social welfare in each case using the numerical example developed in the paper: $a = 10, c = 1, d = 2.5, \delta = 1, \gamma = 1.5$, and $F = 3$. $SW^{ne} = 22.5967$, and

$$SW^{ent}(\beta) = \frac{\beta(\beta(\beta(-17.2\beta-233.44)+1093.65)+3950.46)+2599.81}{(\beta(1.\beta-6.4)-11.32)^2},$$

Solving $SW^{ne} - SW^{ent} = 0$ for β yields $\beta = 0.65$.

4.10 Comparison with Poyago-Theotoky (2007).

We next compare the equilibrium investment from our model to that developed by Poyago-Theotoky (2007, hereafter P-T).[19] Our model facilitates this comparison if we set $\delta = 1$, so that there is no discounting of profits, and $d > 3/2$, an assumption made to support a positive emission fee in P-T. Since P-T assumes that two firms are already operating in the market and both are investing in abatement technology, there will be different incentives

[19]Since we used the same environmental damage function, cost of investing in R&D, model structure, and notation, the comparison is straightforward.

for the firms to invest in R&D. Specifically, we compare the equilibrium abatement, tax, and quantity produced under entry from our model to the case in which firms choose the investment in R&D non-cooperatively in P-T.

We explore the comparison between individual firm investment in R&D in P-T (referred to as the non-cooperative investment) to the incumbent's level of investment in our model. We observe that the level of investment is lower in the non-cooperative case than in the case of entry in our paper for all parameter values. In the non-cooperative case, each firm is investing in R&D and benefiting from their competitors R&D through the spillover. This means that each firm is factoring in the spillover of R&D from their competitor into the marginal benefits of investment and free-riding off of their competitor's investment, thus lowering their own investment. However, total investment in R&D is higher in the P-T model since both firms are investing in R&D. This results in a higher emission fee when only one firm invests in the entry case, and higher firm production in the P-T case.

The equilibrium investment, fee, and quantity in P-T are

$$
\begin{aligned}
z^{P-T} &= \frac{(a-c)(d(\beta+2d+2)-1)}{(\beta+1)d(\beta(d+3)+7d+9)+2\gamma(d+1)^2}, \\
t^{P-T} &= \frac{(a-c)\left(2\gamma\left(2d^2+d-1\right)+(\beta+1)^2(2d-3)d\right)}{2(\beta+1)d(3(\beta+3)+(\beta+7)d)+4\gamma(d+1)^2}, \\
q^{P-T} &= \frac{(a-c)((\beta+1)d(3\beta+4d+7)+2\gamma(d+1))}{2(\beta+1)d(3(\beta+3)+(\beta+7)d)+4\gamma(d+1)^2}.
\end{aligned}
$$

The comparison of the investment is

$$
\begin{aligned}
z^{ent} &> z^{P-T} \\
\frac{(a-c)(d(\beta+2d+2)-1)}{d(\beta+1)((5-\beta)d+6)+2\gamma(d+1)^2} &> \frac{(a-c)(d(\beta+2d+2)-1)}{(\beta+1)d(\beta(d+3)+7d+9)+2\gamma(d+1)^2}, \\
(\beta+1)d(\beta(d+3)+7d+9)+2\gamma(d+1)^2 &> d(\beta+1)((5-\beta)d+6)+2\gamma(d+1)^2, \\
(\beta+1)d(\beta(d+3)+7d+9) &> d(\beta+1)((5-\beta)d+6), \\
\beta(d+3)+7d+9 &> (5-\beta)d+6, \\
2\beta d+3\beta+2d+3 &> 0,
\end{aligned}
$$

which holds for all parameter values. The comparison of total investment is

$$
\begin{aligned}
z^{ent} &< 2z^{P-T} \\
\frac{(a-c)(d(\beta+2d+2)-1)}{d(\beta+1)((5-\beta)d+6)+2\gamma(d+1)^2} &> \frac{2(a-c)(d(\beta+2d+2)-1)}{(\beta+1)d(\beta(d+3)+7d+9)+2\gamma(d+1)^2}, \\
(\beta+1)d(\beta(d+3)+7d+9)+2\gamma(d+1)^2 &> 2[d(\beta+1)((5-\beta)d+6)+2\gamma(d+1)^2], \\
2(1+d)^2\gamma+d(1+\beta)[2(6+d(5-\beta))-3(3+\beta)-d(7+\beta)] &> 0, \\
2(1+d)^2\gamma+d(1+\beta)[1-\beta+d(1-\beta)] &> 0,
\end{aligned}
$$

which holds for all parameter values.

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CHAPTER TWO

Free-Riding Incentives, and Investment in R&D with Spillovers

1 Introduction

Firms' investment in clean (or environmentally friendly) research and development (R&D) has increased over time, from less than $30 billion in 2005 to $159 billion in 2012 worldwide.[1] Given its large scale, several authors analyzed firms' free-riding incentives in their R&D decisions, as well as how these incentives are affected by environmental regulation.[2] These papers show that, in the absence of spillovers, every firm under-invests relative to the social optimum since its investment reduces environmental damages which induces a laxer environmental policy thus benefiting all firms. In the presence of spillovers, this free-riding incentive is emphasized, since firms also benefit from the investment in R&D of their rivals.

The aforementioned literature assumes that all firms are subject to uniform environmental policies. However, when firms are asymmetric, they may invest different amounts in clean R&D, generating a distinct quantity of pollution per unit of output. This asymmetry calls for a type-dependent environmental policy that takes into account the different marginal environmental damage each firm generates (first-best policy),[3] whereas a uniform

[1] National Science Foundation's Science and Engineering Indicators (2014), Chapter 6 (https://www.nsf.gov/statistics/seind14/index.cfm/chapter-6).

[2] Biglaiser and Horowitz (1995), Denicolo (1999), Conrad (2000), and Montero (2002a), which assume no spillover effects, and Katsoulacos and Xepapadeas (1996), Montero (2002b), Poyago-Theotoky (2007) and Strandholm and Espinola-Arredondo (2016) which allow for spillovers, whereby a firm's investment in R&D not only reduces its own emissions but also helps its rivals decrease a proportion of their own. Grilleches (1992), Cameron (1998), and Weiser (2005) report an average private rate of return to R&D around 20-30%, and an estimated spillover of 40-60%. While Comin (2004) identified omitted variable bias in some of these estimates, thus reducing their size, most of the literature still finds significant spillovers from R&D.

[3] For instance, nuclear and coal-fired power plants are subject to different regulations, as they use distinct inputs to produce electricity. Carbon-fired power plants face federal carbon limits on electricity generation. In contrast, nuclear plant operations are subject to the Clean Water Act, which regulates thermal discharges;

regulation, that sets the same emission fee to all firms, represents a second best policy in this context. Our model considers these two regulatory regimes and focuses on settings where the regulator can accurately observe each firm's pollution before choosing emission fees (point pollution) or, alternatively, contexts in which R&D is observable thus helping the regulator infer the reduction in pollution.[4] We show that a type-dependent policy can ameliorate the above free-riding problem, thus providing firms with more incentives to invest in clean R&D, ultimately helping regulators more rapidly achieve the emission targets set in international environmental agreements. Intuitively, under no spillovers, every firm's investment is completely appropriated by itself, since it faces a laxer environmental policy, which is different from its rival's. When spillover effects are present, firms face free-riding incentives, although smaller than under a uniform regulation.

Our model considers a three-stage game where, in the first stage, two firms invest in green technology (where we allow for spillover effects); in the second stage, the regulator sets the emission fee (we separately analyze uniform and type-dependent policy regimes); and in the third stage, firms compete à la Cournot in the product market. In addition, we examine the case where firms jointly maximize profits by choosing their levels of investment in R&D in the first stage, commonly known as an environmental research cartel (ERC). In this setting, every firm internalizes both positive externalities that its investment produces on other firms: the reduction in emission fees and the spillovers. Therefore, the ERC does not exhibit free-riding incentives. Comparing investment levels in the ERC against the above non-cooperative game, we evaluate firms' free-riding incentives in both regimes.

We demonstrate that emission fees are more stringent under uniform than type-dependent

cooling water intake location, design, construction, and capacity; storm water discharges; dredging, filling, and wetlands impacts; see EPA (2008). In addition, under the Clean Air Act, the EPA has the authority to list hazardous air pollutants and develop and enforce emission limits for each of them. Last, the EPA has also the authority to issue generally applicable environmental radiation standards.

[4]Several papers have looked at the effects of such fine-tuned environmental policy, but do not consider investment in clean R&D, see Tietenberg (1974), Henderson (1977), Hochman et al. (1977), Hochman and Ofek (1979), and Munoz-Garcia and Akhundjanov (2016).

policies, as the regulator considers the aggregate marginal environmental damage thus ignoring firms' asymmetry in R&D investment during the first stage. However, the difference in emission fees across policy regimes diminishes as spillovers increase. Intuitively, when spillovers are small, firms exhibit different marginal environmental damages, yielding distinct emission fees in each regime. However, when spillover effects are large, all firms benefit from each other's investment, and thus marginal environmental damages coincide. In this context, the use of either policy regime yields the same emission fees, investment in R&D, and welfare. Therefore, when regulating industries with small spillovers, the use of type-dependent policies becomes more relevant since they promote further investment in R&D and larger welfare. However, when spillovers are significant both policy regimes yield similar outcomes, such as in clustered industries, where several authors find large spillovers; see Jaffe, et al. (1993), Audretsch and Feldman (1996), Almedia and Kogut (1997), Jaffe and Trajtenberg (2002), and Liu et al. (2010). When firms are located far from other competitors in the same industry, however, spillover effects are generally small, and our results would indicate that it is precisely in this type of industry where the choice of policy regime matters the most.

Our findings also suggest that profits are larger when firms operate under a type-dependent than a uniform regime when a firm is significantly more efficient in investing in R&D than its rival, as the former can appropriate a large portion of its investment. An increase in environmental damage expands the region of parameters for which the type-dependent policy yields larger profits than the uniform regime. This means that the most efficient firm has further incentives to lobby for a type-dependent policy since its investment in R&D entails a more significant reduction in its own emission fee which its rival cannot benefit from. We also find that the profit difference across regimes diminishes as spillovers increase since, as described above, firms face the same emission fees. In this setting, firms are not critically affected by the policy regime that regulators use to curb externalities. In contrast, when spillovers are small, the profit difference is substantial, leading efficient (inefficient) firms to favor type-dependent (uniform, respectively) policies. For instance, Exxon-Mobil has openly claimed on its website that, in the context of climate policies, "We believe that effective policies will be those that ensure a uniform [...] cost of greenhouse gas emissions across the economy." According to our findings, this type of statements suggests that Exxon-Mobil would be less efficient in clean R&D than its industry rivals, and thus prefers a uniform policy. However, this needs to be empirically analyzed.

Finally, we compare welfare across policy regimes, showing that the type-dependent policy yields a larger welfare than the uniform policy. We find a preference alignment between regulator and firms when a firm is efficient at investing in R&D, where both welfare and profits are larger in the type-dependent than uniform regime. Intuitively, not only profits are larger in this regime, but also investment, yielding a smaller environmental damage. In this context both regulator and firm would favor a similar policy regime. In contrast, when a firm is relatively inefficient, its profits are larger under a uniform policy, whereas investment in R&D and environmental damage are larger in the type-dependent regime, ultimately entailing a preference misalignment between firm and regulator. When we consider an increase in the spillover effects, both the welfare gain and profit gain from a type-dependent regime are positive, but shrink, thus reducing the incentives to lobby for this type of policy.

The model we develop is similar to those in d'Aspremont and Jacquemin (1988), Kamien et al. (1992), and Poyago-Theotoky (2007), where the last paper focuses on the degree of cooperation between two firms investing in green technology. Damania (1996) investigates a colluding oligopolist's decision to invest in green technology that lowers both emissions and production costs in a repeated game under a uniform emission fee. Montero (2002a) evaluates the incentives for symmetric firms in an oligopoly to undergo investment in abatement under different uniform policies. In contrast, we focus on the effects of two different types of regulation when firms are differentiated by their efficiency in developing green technology, and the regulator can fine-tune policy based on the firm's efficiency. Organization of R&D joint ventures (or cartels) within an industry has been studied in several papers, but the effects of fine-tuned policy instruments have not been implemented in these studies, see d'Aspremont and Jacquemin (1988), Kamien et al. (1992), Stepanova and Tesoriera (2011), and Tesoriere (2015).

The next section presents our model. Section 3 analyzes equilibrium results in each stage of the game, while section 4 compares emission fees, investment in R&D and welfare across policy regimes, and section 5 discusses our results.

2 Model

Consider a duopoly market similar to Poyago-Theotoky (2007) where: (1) in the first stage, every firm i independently and simultaneously chooses its investment in R&D, z_i, at cost $\frac{1}{2}\gamma_i z_i^2$ where $\gamma_i > 0$ represents the efficiency of investing in z_i; (2) in the second stage, the regulator selects an emission fee t by maximizing social welfare; and (3) in the third stage, every firm i competes à la Cournot choosing its output level q_i. Firms face linear demand $p(Q) = a - Q$ where p is price, $a > 0$, and $Q \equiv q_i + q_j$ is the aggregate output level. Both firms have the same marginal cost of production c, where $a > c > 0$.

Our model allows for two forms of emission fees: uniform, where both firms are subject to the same fee t; and type dependent, whereby each firm is subject to a distinct fee t_i, which might affect firms' incentives to invest in R&D. In order to sustain type-dependent fees, we consider that environmental damage is $ED = \frac{1}{2}d(e_i^2 + e_j^2)$.[5] Furthermore, firms can be asymmetric in their investment efficiency, i.e., $\gamma_i \neq \gamma_j$ where $\gamma_i, \gamma_j > 0$, thus allowing for

[5] If, instead, environmental damage is given by $ED = \frac{1}{2}d(e_i + e_j)^2$, the regulator equates the tax rate to the marginal environmental damage of emissions from the industry as a whole, thus obtaining the same fee under both policy regimes.

different technologies.

3 Equilibrium Analysis

3.1 Third Stage

Solving by backward induction, we first analyze optimal output under both policy regimes in the third stage of the game. Therefore, every firm solves:

$$\max_{q_i} \pi_i = (a - q_i - q_j)q_i - cq_i - t(q_i - z_i - \beta z_j),$$

where $t = t_i$ when the fee is type-dependent, and $\beta \in [0, 1]$ represents the knowledge spillover from firm j to i. Hence, when $\beta = 0$ spillover effects are absent, whereas when $\beta = 1$ firm i benefits from every unit of investment in R&D by firm j.

Lemma 1. *In the third stage, every firm i chooses output according to $q(t_i, t_j) = \frac{a-c-2t_i+t_j}{3}$ under a type-dependent fee, and $q(t) = \frac{a-c-t}{3}$ under a uniform fee.*

Hence, when the emission fee is uniform, a reduction in t benefits both firms. However, when the fee is type-dependent, a reduction on firm i's tax is completely appropriated by this firm (which increases its output level) but harms its rival, decreasing its production.

3.2 Second Stage

The following lemma examines optimal fees under uniform regulation in the second stage of the game. In this case, the regulator solves:

$$\max_t SW = CS + PS + T - ED \tag{1}$$

where CS and PS represent consumer and producer surplus, respectively, and T denotes total tax revenue. A similar problem applies when regulation is type-dependent, and thus the regulator can set a pair of fees (t_i, t_j).

Lemma 2. *In the second stage, under a uniform regulation, the regulator sets an emission fee of*

$$t(z_i, z_j) = \frac{2(a-c)(d-1) - 3d(1+\beta)(z_i + z_j)}{2(d+2)},$$

and in the case of type-dependent regulation, a fee of

$$t_i(z_i, z_j) = \frac{(a-c)(d-1) - z_i[1 + 2d + \beta(d-1)] - z_j[d - 1 + \beta(2d+1)]}{d+2}$$

for every firm i.

While an increase in either firm's investment in R&D produces a symmetric reduction in the uniform emission fee $t(z_i, z_j)$, such effect is asymmetric when firms face type-dependent regulation, $t_i(z_i, z_j)$. In particular, when knowledge spillovers are absent, $\beta = 0$, firm i's investment in R&D decreases its emission fee $t_i(z_i, z_j)$ since each unit of pollution is now less damaging. Similarly, an increase in its rival's investment in R&D, z_j, also decreases firm i's emission fee t_i. However, this reduction occurs because a larger z_j decreases fee t_j and increases firm j's output, which in turn reduces firm i's output level in the subsequent Cournot game; as described in Lemma 1. Anticipating such a reduction in production, the regulator sets a lower fee t_i.[6]

When spillovers are present, $\beta > 0$, similar effects arise, but an increase in firm j's investment now facilitates firm i's pollution abatement, producing a larger decrease in the optimal emission fee t_i than when spillover effects are absent. In this context, an increase in the rival's investment produces a larger reduction in firm i's emission fee t_i than an increase in its own investment would. As expected, this result implies that firms have more incentives to free-ride off each other's investment in R&D as the spillover effect increases. In addition, a marginal increase in environmental damage d produces the same increase in both type of emission fees; where such increase is ameliorated when the spillover increases as firms benefit from a larger share of the abatement technology.

3.3 First Stage

We next analyze optimal investment in R&D in the first stage of the game under uniform regulation, and afterwards under type-dependent policy. In the case of uniform fees, every firm i solves

$$\max_{z_i} \pi_i = [a - q_i(t(z_i, z_j)) - q_j(t(z_i, z_j))]q_i(t(z_i, z_j)) \\ - cq_i(t(z_i, z_j)) - t[q_i(t(z_i, z_j)) - z_i - \beta z_j] - \frac{1}{2}\gamma_i z_i^2. \qquad (2)$$

which includes total revenue, production cost, tax payments which depend on net emissions, $q_i(t(z_i, z_j)) - z_i - \beta z_j$, and the cost of investing in R&D.

[6] In particular, an increase in z_i decreases fee $t_i(z_i, z_j)$ by $-2 + \frac{3}{2+d}$, whereas an increase in z_j reduces $t_i(z_i, z_j)$ by $-1 + \frac{3}{2+d}$. Therefore, firm i's own investment in R&D produces a larger reduction in fee t_i than an increase in its rival's investment does.

Proposition 1. *In the first stage, every firm i chooses an R&D investment level of*

$$z_i^U = \frac{2(a-c)(d(\beta+d+2)-2)(3(\beta^2-1)d-C_j)}{A[3d(\beta^2-1)(6(\beta+3)+(\beta+7)d)+BC_i+C_j(AB-C_i(d+2))]} \quad (3)$$

where U denotes uniform fee, $A \equiv (\beta+1)d$, $B \equiv (\beta-5)d-12$, and $C_i \equiv 2\gamma_i(d+2)$. In addition, z_i^U decreases in γ_i but increases in γ_j.

Hence, firm i invests less in R&D as the cost of investing increases (larger γ_i), but invests more as the cost of its rival increases. This is because z_i and z_j are strategic substitutes, implying that an increase in γ_j shifts firm j's best response function downwards, thus reducing z_j, which ultimately increases z_i since best response functions are negatively sloped. In addition, when firm i is the more efficient firm, $\gamma_i < \gamma_j$, the aggregate investment in R&D, $z_i^U + z_j^U$, increases in firm i's efficiency (lower γ_i) but decreases on the competitor's efficiency level.

Let us now examine the optimal investment in R&D under type-dependent regulation. In this context, every firm i solves a similar maximization problem as that in (2) but the tax payment term considers t_i instead of t.

Proposition 2. *In the first stage, every firm i chooses an R&D investment level of*

$$z_i^{TD} = \frac{(a-c)(d(d+3)-2\beta)(E-\frac{C_j}{2})}{(\beta+1)[Ed((\beta+3)(d+3)-2(\beta-1))-DC_i]-DC_j(\beta+1)-(2+d)^3\gamma_i\gamma_j} \quad (4)$$

where $D \equiv (1-\beta+d(d+3))$, $E \equiv (\beta^2-1)(d+1)$, and TD denotes type-dependent fee. *In addition, z_i^{TD} decreases in γ_i but increases in γ_j.*

We next analyze aggregate investment in R&D, and how it is affected by the asymmetry in investment efficiency.

Corollary 1. *Consider that* $\gamma_i < \gamma_j$*. A symmetric improvement in efficiency produces* $\left|\frac{\partial z_i^K}{\partial \gamma_i}\right| > \left|\frac{\partial z_j^K}{\partial \gamma_j}\right|$ *in individual investments, and* $\left|\frac{\partial\left(z_i^K+z_j^K\right)}{\partial \gamma_i}\right| > \left|\frac{\partial\left(z_i^K+z_j^K\right)}{\partial \gamma_j}\right|$ *in aggregate investment for every policy regime* $K = \{TD, U\}$*, where* $\frac{\partial(z_i+z_j)}{\partial \gamma_i} < 0$ *for every firm* i*.*

Hence, if firm i is the most efficient ($\gamma_i < \gamma_j$), a symmetric improvement in efficiency produces a larger increase in investment in R&D from firm i than from j. In addition, an increase in any firm's efficiency in R&D produces a larger increase in its own investment than the decrease in its rival's investment, thus generating an overall increase in total investment in R&D. Finally, aggregate investment increases more substantially when firm i becomes even more efficient than when the inefficient firm j does. Therefore, regulators should expect aggregate investment to be larger in settings where firms are very asymmetric in their efficiencies than in contexts with relatively symmetric firms.

4 Comparison

We next compare equilibrium investment levels under uniform and type-dependent regulation.

Corollary 2. *Every firm* i*'s best response function in the investment stage under a type-dependent fee lies above the best response function under a uniform fee for all* z_j *and all parameter values. In addition, equilibrium investment in R&D satisfies* $z_i^{TD} > z_i^U$ *for all parameter values.*

Intuitively, when firm i invests an additional unit in R&D under type-dependent regulation, it reduces its future emission fee more significantly than when facing uniform regulation. As a consequence, firms have more incentives to invest in R&D. This result can be rationalized on the basis of free-riding incentives. Under uniform policies, an increase in firm i's investment produces a significant decrease in the emission fee, as the regulator considers the aggregate effect of less pollution, which firm j benefits. However, under type-dependent fees, the same increase in firm i's investment only generates a small decrease in firm j's emission fee as the regulator now considers individual emissions. Overall, firms free-ride on each other less under the type-dependent regime, ultimately leading them to increase their investment in R&D.

Emission Fees. Figure 1 depicts the difference between the emission fee under the uniform regime and the type-dependent regime, $t^U - t^{TD}$.[7] When the spillover is less than one, all curves lie in the positive quadrant, which means that the uniform fee is higher than the type-dependent fee. When $\beta = 1$, the fees coincide. Since a perfect spillover of technology means that any R&D undertaken by one firm is fully and freely utilized by all other firms, the environmental damage per unit of output coincides across regimes, leading the regulator to set the same emission fee under both policies. As the spillover decreases (lower β) the uniform fee becomes more stringent than the type-dependent fee[8].

Profits. We next investigate firm profits under the two policy regimes. The numerical examples help us further understand the conditions under which profits are higher in one regime than the other. Figures 2 and 3 show the profit difference across regimes, $\pi_i^U - \pi_i^{TD}$, for every firm i, as a function of its own efficiency, γ_i, when the efficiency of its rival is held constant at $\gamma_j = 2/3$. Specifically, figure 2 evaluates the profit difference at different values of the spillover, β, while figure 3 evaluates it at different values of environmental damage, d. When curves are in the positive quadrant, firm i's profits are greater under the uniform than the type-dependent regime.

[7] All figures consider $a = 10, c = 2, d = 3, \beta = 1/3, \gamma_i = 1/3$, and $\gamma_j = 2/3$. Other parameter values yield similar results in all figures except figures 6 and 8, which we discuss after presenting them. Figures with alternative parameter values can be provided by the authors upon request.

[8] If the fee differential across regimes $t^U - t^{TD}$ of figure 2 is evaluated at different environmental damages $d = \{1, 2, 3, 4\}$, such differential remains unaffected by d. As described in Section 2, a marginal increase in

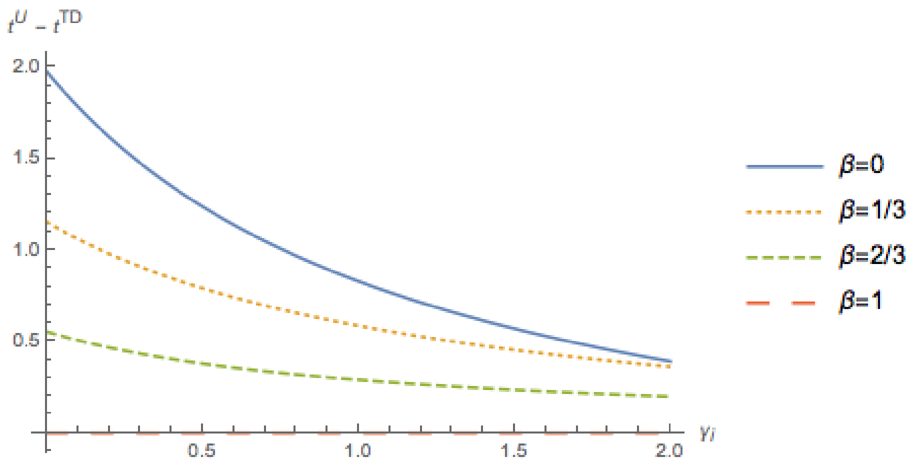

Figure 1: Difference between the uniform and type-dependent fees as a function of firm i's efficiency.

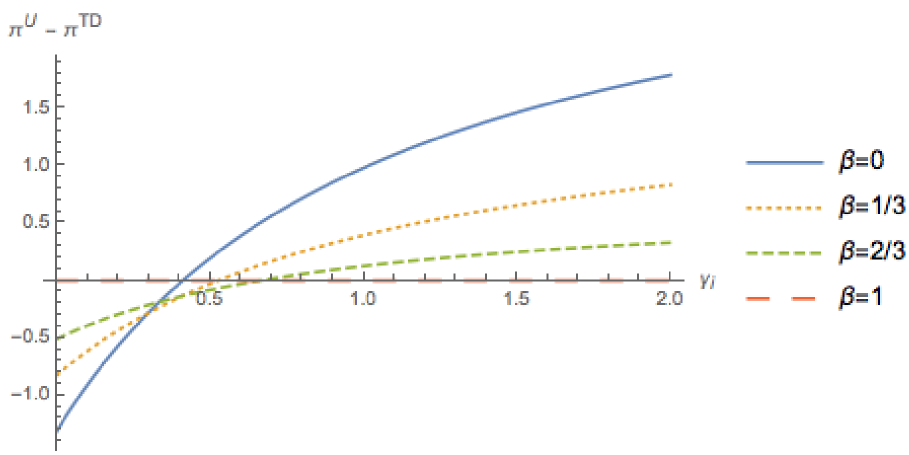

Figure 2: The difference in profits between the uniform and type-dependent fees as a function of firm i's efficiency.

Specifically, when $\beta = 1$, the profits under each regime coincide, which is a result of the fees being equal in this special case. As shown above, when spillovers are not total ($\beta < 1$), the emission fee that firm i faces under a uniform regime is more stringent than under a type-dependent regime, regardless of its relative efficiency γ_i. Moreover, the fee differential across regimes, $t^U - t^{TD}$, is particularly large when firm i is relatively efficient, but diminishes as the firm becomes more inefficient. When firm i is relatively efficient, its fee under the

d produces a symmetric increase in t^U and t^{TD}.

uniform regime is much larger than in the type-dependent regime, while the opposite ranking applies to its rival, conferring firm i a significant advantage in the type-dependent regime; as depicted in the left-hand side of figure 2. In contrast, when firm i is relatively inefficient, the ranking of fees for firm i and j is reversed, leaving firm j with a strong competitive advantage in the type-dependent regime. In this case, firm i would obtain higher profits under the uniform than the type-dependent regime (see right-hand side of figure 2).[9] When there is no spillover, profits are larger under the uniform fee for the largest set of γ_i's (the cutoff is $\gamma_i = 0.41$). The profit differential and range of γ_i that allows for higher profits under the uniform fee shrinks as the spillover increases. Indeed, since the fee differential across regimes, $t^U - t^{TD}$, decreases in the spillover, the profit differential also shrinks.

Figure 3 shows the same profit as figure 2, but now evaluated at different environmental damages $d = \{1, 2, 3, 4\}$. Here, we can see that when $d = 1$, profits are higher under the uniform regime for a larger range of γ_i. For larger levels of environmental damage, however, the range of γ_i that supports a higher profit under the uniform fee shrinks. Alternatively, when pollution is more damaging, profits under the type-dependent regime are larger for a wider set of parameter values.

Finally, firm i's investment differential, $z_i^{TD} - z_i^U$, is the largest when it is relatively efficient, but decreases (and approaches zero) as the firm becomes very inefficient; see figure 4. The opposite argument applies to firm j, which invests much more in R&D under the type-dependent regime than in the uniform regime when its rival is relatively inefficient.

Social Welfare. We next analyze social welfare under both policy regimes. Figure 5 shows that social welfare under a type-dependent fee is higher than under a uniform fee for all $\beta < 1$. This implies, that if the cost of monitoring emission fees for each firm is not

[9]Note that when firm i is slightly more efficient than firm j (i.e., γ_i approaches $\gamma_j = 2/3$ from below), firm i prefers a uniform policy regime. This is due to the fact that the fee differential across regimes $t^U - t^{TD}$ is convex in γ_i. Intuitively, as firm i becomes more inefficient, the relative loss from being subject to a uniform regime than a type-dependent regime decreases at a decreasing rate.

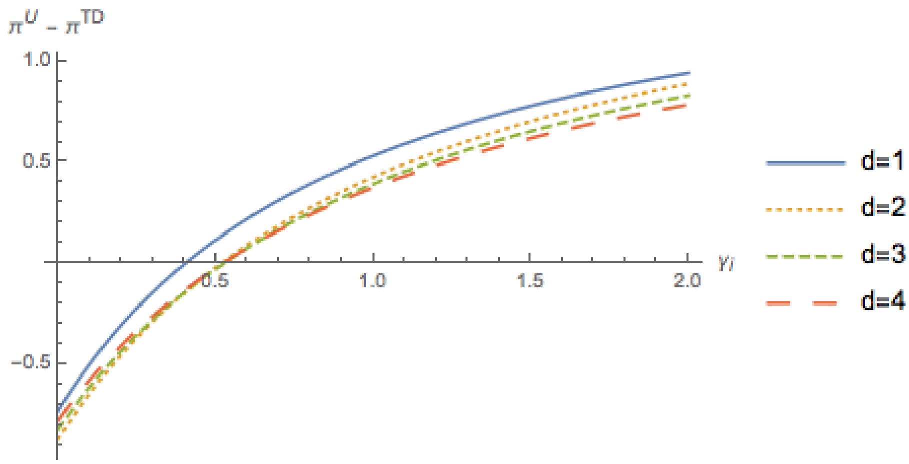

Figure 3: The difference in profits between the uniform and type-dependent fees as a function of firm i's efficiency.

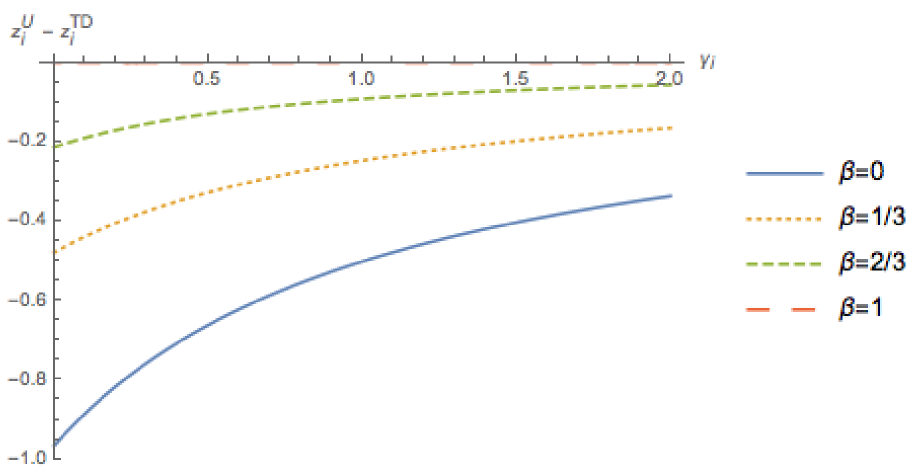

Figure 4: The difference in investment between the uniform and type-dependent fees as a function of firm i's efficiency.

significantly higher than measuring the overall emissions from the industry, the regulator should favor the use of a type-dependent policy. In addition, when the spillover effect is total, $\beta = 1$, the social welfare under each policy regime coincide. Therefore, at high levels of spillover, the cost difference of monitoring pollution becomes more relevant in deciding what type of regulation is socially preferred. If we compare the social welfare under both policy regimes given different levels of environmental damage, as in figure 6, we see that the social welfare difference shrinks as d increases. That is, more harmful pollution decreases the difference between social welfare under a type-dependent fee and a uniform fee.[10]

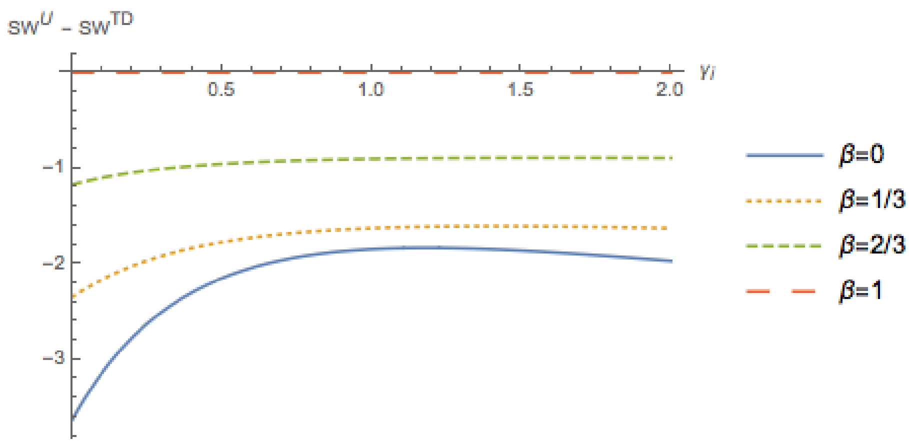

Figure 5: Social welfare difference between the two regulation types for different spillovers.

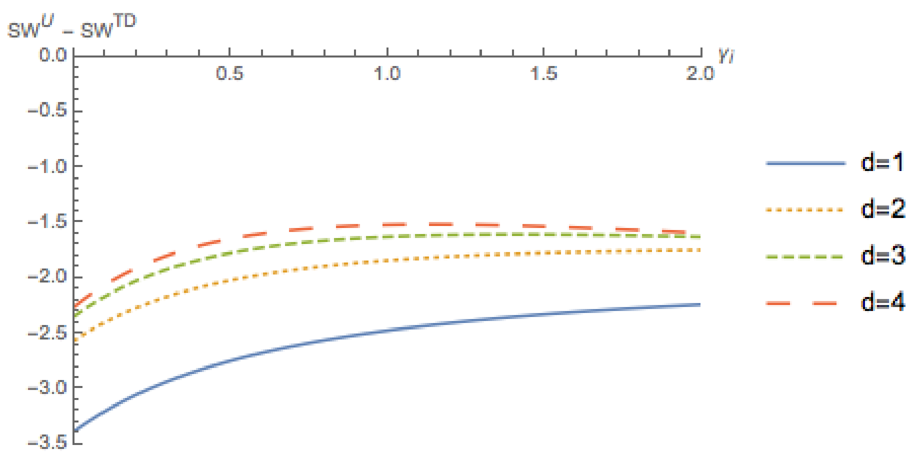

Figure 6: Social welfare difference between the two regulation types for different environmental damages.

Environmental Research Cartel (ERC). In order to evaluate the free-riding effect of investment in R&D, we need to evaluate the investment decision if the firms were to

[10]When spillovers are extremely small and firm j's efficiency is low (a high γ_j) compared to firm i, the type-dependent policy regime is still preferred to a uniform policy but the environmental damage has a smaller effect on this difference. Furthermore, it may be the case that at higher levels of environmental damage the type-dependent regime is favored even more than at low levels of environmental damage compared to a uniform policy.

collude in the first stage. This will give us the joint profit maximizing amount of investment in R&D. This case, known as an environmental research cartel (ERC) in Poyago-Theotoky (2007), uses the second and third stage decisions from lemmas 1 and 2, but firms maximize joint profits by solving:

$$\max_{z_i, z_j} \pi_i + \pi_j.$$

The objective function of this joint maximization problem is the same under both policy regimes. This means that, under each regime, when firms are engaged in an ERC, each firm faces the same emission fee.[11]

Proposition 3. *The equilibrium level of investment in R&D for every firm i when firms engage in an environmental research cartel is*

$$z_i^{ERC} = \frac{(\beta+1)\gamma_j\left[d(d+3)-2\right](a-c)}{\gamma_j\left[2(\beta+1)^2 d(d+3)+\gamma_i(d+2)^2\right]+2(\beta+1)^2\gamma_i d(d+3)}.$$

Figure 7 compares the ERC level of investment to that of the independent investment under the two regulatory regimes (z_i^U from Proposition 1, z_i^{TD} from Proposition 2).[12] This figure shows that, under a uniform policy regime, the more efficient firm i invests more when joining an ERC with its rival than when independently choosing its investment level. Similarly, under a TD regime firm i invests more when joining an ERC, but only if spillover effects are significant. When there is no spillover, i.e. $\beta = 0$, firm i's rival receives no benefit from firm i's investment. In this case, firm i will invest more under the type-dependent regime since it is increasing in competitiveness in the market by facing a lower emission fee than its rival. As the spillover increases, firm j benefits from a larger share of firm i's investment

[11]The ERC equates the marginal costs of investment in green technology between the two firms. Under the type-dependent regime, this results in each firm facing the same emission fee, which coincides with the uniform fee.

[12]Figure 7 considers the same parameter values as figure 1, where $\gamma_i = 1/3 < 2/3 = \gamma_j$.

in R&D, the positive externalities that firm i generates becomes larger, emphasizing firm j's free-riding incentives and decreasing the difference between investment under the type-dependent regime and the ERC. When independently choosing R&D firm i ignores this external effect, whereas in the ERC the firm internalizes such positive effects, ultimately increasing its investment.

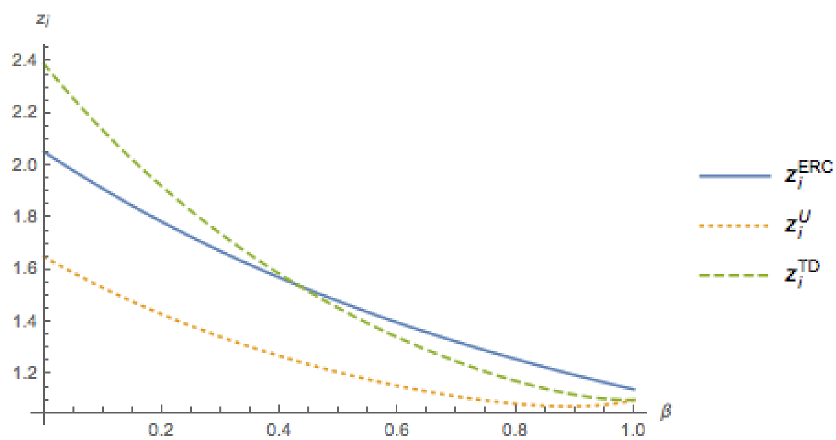

Figure 7: Investment in R&D as a function of the spillover under the two regimes and the ERC.

We observe a similar trend when we compare aggregate investment in R&D between the ERC and the two policy regimes, as shown in figure 8. The level of investment when firms are in an ERC is higher than under the uniform regime and at relatively high levels of the spillover under the type-dependent regime. At low levels of the spillover, the total investment is higher under the type-dependent fee than the ERC. From a policy perspective, allowing an ERC would increase total investment over a uniform emission fee but most likely decrease the total investment from a type-dependent fee. [13]

[13] At high levels of efficiency for both firms (low γ_i and γ_j) the aggregate ERC could fall below the aggregate investment under uniform policy if the spillover is low enough and the environmental damage is high. This suggests that when both firms are efficient at investing in R&D and the incentives to invest are high (through a large emission fee from large environmental damage), firms will over-invest in abatement technology.

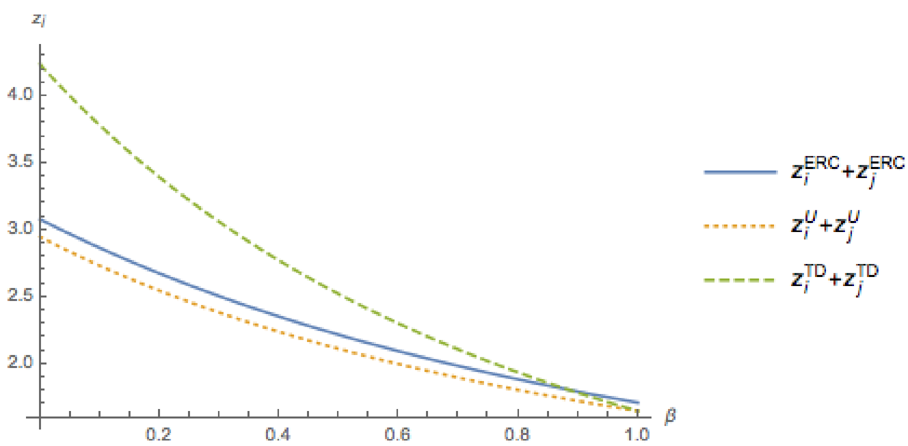

Figure 8: The total level of investment in R&D as a function of the spillover under the two regimes and the ERC.

5 Discussion

When is type-dependent regulation critical. Our results show that when spillovers are small, such as when firms are located far apart or operate in different industries, regulators should pay close attention to the difference in each firm's pollution when designing environmental policy. Doing so induces firms to increase their investment in R&D, reducing pollution, and thus helping regulators more easily reach their environmental targets. In contrast, when spillover effects are significant, such as in industry clusters, the use of either policy regime does not entail substantial differences in investment levels. Since the uniform regime is easier to implement, our findings imply that the regulator can rely on this policy tool to achieve similar welfare levels.

Efficiency and type-dependent policies. We find that firms exhibiting efficiency in R&D investment would gain from a change in policy regime. In particular, a move from uniform to type-dependent fees increases the efficient firm's profits, appropriating a larger proportion of their investment, while it reduces the profits of inefficient firms who would favor uniform policies. Hence, regulators should expect efficient firms aggressively lobbying for fine-tuned regulation that takes into account each firm's characteristics, whereas inefficient firms would favor uniform standards across the industry.

Preference alignment. When firms are efficient at investing in R&D, they would favor type-dependent policies, as described above. Similarly, regulators would like to introduce this policy as it yields a large reduction in pollution, and thus an increase in welfare, relative to uniform fees. Therefore, both regulator and firm would favor a similar policy regime, thus facilitating the introduction of more fine-tuned policies. However, when firms are inefficient, they prefer a uniform policy, while regulators still find welfare gains from introducing type-dependent fees. In this case, the preferences of firms and regulator become misaligned over policy.

Future Research The first avenue of future research would be along the lines of incomplete information. There are two places where this analysis would be valuable. The first is when firms have incomplete information about the investment cost of their rival. The second would be when the regulator has incomplete information about the firms' investment costs. Another extension would be if firms have asymmetric marginal costs. Since each firm can invest in R&D to reduce its emission fee under a type-dependent regime, a firm that is less efficient at production could invest more in abatement to reduce its tax burden to become more competitive.

6 Appendix

6.1 Proof of Lemma 1

The first-order condition for firm i under the type-dependent fee is

$$a - c - 2q_i - q_j - t_i = 0.$$

Solving for q_i gives the reaction function $q_i\left(q_j\right) = \frac{1}{2}(a - c - q_j - t_i)$. Simultaneously solving the reaction functions for the two firms yields the output function $q(t_i, t_j) = \frac{a - c - 2t_i + t_j}{3}$.

6.2 Proof of Lemma 2

In the second stage, the regulator maximizes social welfare by choosing the uniform emission fee by solving the following problem:

$$\max_t SW = 2(a-c)q(t) - \frac{1}{2}(2q(t))^2 - \frac{1}{2}d(q_i(t) - z_i - \beta z_j)^2 - \frac{1}{2}d(q_j(t) - \beta z_i - z_j)^2 - \frac{1}{2}\gamma_i z_i^2 - \frac{1}{2}\gamma_j z_j^2.$$

The first-order condition is

$$\frac{1}{9}(2a(d-1) - d(2c + 2t + 3(\beta + 1)(z_i + z_j)) + 2(c - 2t)) = 0.$$

Solving for t in this first-order condition, gives us the optimal uniform emission fee

$$t(z_i, z_j) = \frac{2(a-c)(d-1) - 3d(1+\beta)(z_i + z_j)}{2(d+2)}.$$

If the regulator is setting a type-dependent fee, the maximization problem is

$$\max_{t_i,t_j} SW = (a-c)(q_i(t_i,t_j)+q_j(t_i,t_j)) - \frac{1}{2}(q_i(t_i,t_j)+q_j(t_i,t_j))^2$$
$$- \frac{1}{2}d(q_i(t_i,t_j)-z_i-\beta z_j)^2 - \frac{1}{2}d(q_j(t_i,t_j)-\beta z_i - z_j)^2 - \frac{1}{2}\gamma_i z_i^2 - \frac{1}{2}\gamma_j z_j^2.$$

The first-order conditions are

$$\frac{\partial SW}{\partial t_i} = \frac{1}{9}(a(d-1)-d(c+5t_i-4t_j-3\beta z_i+6z_i+6\beta z_j-3z_j)+c-t_i-t_j) = 0,$$
$$\frac{\partial SW}{\partial t_j} = \frac{1}{9}(a(d-1)-d(c-4t_i+5t_j+6\beta z_i-3z_i-3\beta z_j+6z_j)+c-t_i-t_j) = 0.$$

Solving for (t_i, t_j) in the first-order conditions, we obtain the type-dependent fee

$$t_i(z_i,z_j) = \frac{(a-c)(d-1)-z_i[1+2d+\beta(d-1)]-z_j[d-1+\beta(2d+1)]}{d+2},$$

for every firm i.

6.3 Proof of Proposition 1

In the first stage, under uniform regulation, every firm i has the first-order condition,

$$\frac{\partial \pi_i}{\partial z_i} = \frac{2(a-c)[d(\beta+d+2)-2]-C_i(d+2)z_i+A[z_iB-2(\beta+1)(d+3)z_j]}{2(d+2)^2} = 0.$$

where $A \equiv (\beta+1)d$, $B \equiv (\beta-5)d-12$,$C_i \equiv 2\gamma_i(d+2)$. Each firm i's reaction function is,

$$z_i(z_j) = \frac{2[(-a(d(\beta+d+2)-2)+c(d(\beta+d+2)-2)+(\beta+1)^2 d(d+3)z_j]}{(\beta+1)d[(\beta-5)d-12]-2\gamma_i(d+2)^2}.$$

Solving the two reaction functions yields the symmetric equilibrium

$$z_i^U = \frac{2(a-c)(d(\beta+d+2)-2)(3d(\beta^2-1)-C_j)}{A[3d(\beta^2-1)(6(\beta+3)+(\beta+7)d)+BC_i+C_j(AB-C_i(d+2))]}.$$

The comparative static on firm i's investment level given a decrease in its efficiency (increase in γ_i) is negative:

$$\frac{\partial z_i^U}{\partial \gamma_i} = -\frac{2(a-c)(d(\beta+d+2)-2)\left(3\left(\beta^2-1\right)d-C_j\right)\left(2A(d+2)B-4\gamma_j(d+2)^3\right)}{A^2[3d(\beta^2-1)(6(\beta+3)+(\beta+7)d)+BC_i+C_j(AB-C_i(d+2))]^2} < 0,$$

and the comparative static on firm i's investment level given a decrease in its rival's efficiency (increase in γ_j) is positive:

$$\frac{\partial z_i^U}{\partial \gamma_j} = \frac{8(\beta+1)^2 d(d+2)(d+3)(a-c)(d(\beta+d+2)-2)\left(2\gamma_i(d+2)-3\left(\beta^2-1\right)d\right)}{A^2[3d(\beta^2-1)(6(\beta+3)+(\beta+7)d)+BC_i+C_j(AB-C_i(d+2))]^2} > 0.$$

6.4 Proof of Proposition 2

Under the type-dependent fee, each firm i solves the following:

$$\max_{z_i} \pi_i = (a-q_i-q_j)q_i - cq_i - t_i(q_i - z_i - \beta z_j) - \frac{1}{2}\gamma_i z_i^2,$$

where $t_i(z_i, z_j)$, $q_i(t_i(z_i, z_j), t_j(z_i, z_j))$, and $q_j(t_i(z_i, z_j), t_j(z_i, z_j))$. The first-order condition is

$$\frac{\partial \pi_i}{\partial z_i} = \frac{(a-c)(d(d+3)-2\beta) - z_i\gamma_i(d+2)^2 - (\beta+1)(2z_iD + (\beta+1)d(d+3)z_j)}{(d+2)^2} = 0,$$

where $D \equiv (1-\beta+d(d+3))$. The reaction function for each firm i is

$$z_i(z_j) = \frac{(a-c)(d(d+3)-2\beta) - (\beta+1)^2 d(d+3)z_j}{2(\beta+1)D + \gamma_i(d+2)^2}.$$

Solving the reaction functions gives the investment level for every firm i,

$$z_i^{TD} = \frac{(a-c)(d(d+3)-2\beta)(E-\frac{C_j}{2})}{(\beta+1)[Ed((\beta+3)(d+3)-2(\beta-1))-DC_i]-DC_j(\beta+1)-(2+d)^3\gamma_i\gamma_j},$$

where $E \equiv (\beta^2-1)(d+1)$.

The comparative static on firm i's investment level given a decrease in efficiency (increase in γ_i) is negative:

$$\frac{\partial z_i^{TD}}{\partial \gamma_i} = -\frac{(a-c)(d(d+3)-2\beta)\left(\frac{1}{2}C_j - E\right)(2(\beta+1)(d+2)D+\gamma_j(d+2)^3)}{[(\beta+1)[Ed((\beta+3)(d+3)-2(\beta-1))-DC_i]-DC_j(\beta+1)-(2+d)^3\gamma_i\gamma_j]^2} < 0.$$

A decrease in firm j's efficiency (increase in γ_j) increases firm i's investment:

$$\frac{\partial z_i^{TD}}{\partial \gamma_j} = \frac{(\beta+1)^2 d(d+2)(d+3)(a-c)(d(d+3)-2\beta)\left(\frac{1}{2}C_i - E\right)}{[(\beta+1)[Ed((\beta+3)(d+3)-2(\beta-1))-DC_i]-DC_j(\beta+1)-(2+d)^3\gamma_i\gamma_j]^2} > 0.$$

since $\frac{1}{2}C_i > E$.

6.5 Proof of Corollary 1

To prove the first two parts of Corollary 1, we need to show that if $\gamma_i < \gamma_j$ then $\frac{\partial(z_i+z_j)}{\partial \gamma_i} < 0$, $\frac{\partial(z_i+z_j)}{\partial \gamma_j} < 0$, and $\frac{\partial z_i^U + z_j^U}{\partial \gamma_i} < \frac{\partial z_i^U + z_j^U}{\partial \gamma_j}$ in each of the regulatory schemes. In the uniform fee case,

$$\frac{\partial z_i^U + z_j^U}{\partial \gamma_i} = -\frac{4(d+2)^2(a-c)(d(\beta+d+2)-2)\left(3\left(\beta^2-1\right)d-2\gamma_j(d+2)\right)^2}{\left(A\left(3\left(\beta^2-1\right)d(6(\beta+3)+(\beta+7)d)+C_iB\right)+C_j\left(AB-2\gamma_i(d+2)^2\right)\right)^2} < 0,$$

$$\frac{\partial z_i^U + z_j^U}{\partial \gamma_j} = -\frac{4(d+2)^2(a-c)(d(\beta+d+2)-2)\left(3\left(\beta^2-1\right)d-2\gamma_i(d+2)\right)^2}{\left(A\left(3\left(\beta^2-1\right)d(6(\beta+3)+(\beta+7)d)+C_iB\right)+C_j\left(AB-2\gamma_i(d+2)^2\right)\right)^2} < 0,$$

and since $\gamma_i < \gamma_j$:

$$\frac{\partial z_i^U + z_j^U}{\partial \gamma_i} < \frac{\partial z_i^U + z_j^U}{\partial \gamma_j}.$$

In the case of type-dependent fees, we find the same set of results:

$$\frac{\partial z_i^{TD} + z_j^{TD}}{\partial \gamma_i} = -\frac{(d+2)^2(a-c)(d(d+3)-2\beta)\left(\left(\beta^2-1\right)(d+1)-\gamma_j(d+2)\right)^2}{[(\beta+1)[Ed(L-2(\beta-1))-DC_i]-DC_j(\beta+1)-(2+d)^3\gamma_i\gamma_j]^2} < 0,$$
$$\frac{\partial z_i^{TD} + z_j^{TD}}{\partial \gamma_j} = -\frac{(d+2)^2(a-c)(d(d+3)-2\beta)\left(\left(\beta^2-1\right)(d+1)-\gamma_i(d+2)\right)^2}{[(\beta+1)[Ed(L-2(\beta-1))-DC_i]-DC_j(\beta+1)-(2+d)^3\gamma_i\gamma_j]^2} < 0,$$

where $L = (\beta+3)(d+3)$, and since $\gamma_i < \gamma_j$:

$$\frac{\partial z_i^{TD} + z_j^{TD}}{\partial \gamma_i} < \frac{\partial z_i^{TD} + z_j^{TD}}{\partial \gamma_j}.$$

To prove the last part of Corollary 1, we need to show that $\left|\frac{\partial z_i}{\partial \gamma_i}\right| > \left|\frac{\partial z_j}{\partial \gamma_j}\right|$ under each regime. This is equivalent to showing that $\frac{\partial z_i}{\partial \gamma_i} - \frac{\partial z_j}{\partial \gamma_j} < 0$ since both comparative statics are negative, as shown in propositions 1 and 2:

$$\frac{\partial z_i^U}{\partial \gamma_i} - \frac{\partial z_j^U}{\partial \gamma_j} = \frac{16(d+2)^2(a-c)(\gamma_i-\gamma_j)(d(\beta+d+2)-2)G}{\left(A\left(3\left(\beta^2-1\right)d(6(\beta+3)+(\beta+7)d)+C_iB\right)+C_j\left(AB-2\gamma_i(d+2)^2\right)\right)^2} < 0,$$

where $G \equiv (4(\gamma_i+\gamma_j)+d(-3(\beta-2)\beta+4(\gamma_i+\gamma_j)+d(-2(\beta-1)\beta+\gamma_i+\gamma_j+4)+9)) > 0$ and $\gamma_i - \gamma_j < 0$; and

$$\frac{\partial z_i^{TD}}{\partial \gamma_i} - \frac{\partial z_j^{TD}}{\partial \gamma_j} = \frac{(d+2)^2(a-c)(\gamma_i-\gamma_j)(d(d+3)-2\beta)H}{[(\beta+1)[Ed(L-2(\beta-1))-DC_i]-DC_j(\beta+1)-(2+d)^3\gamma_i\gamma_j]^2} < 0,$$

where $H \equiv \left(4\left(\gamma_i+\gamma_j+1-\beta^2\right)+d^2(\gamma_i+\gamma_j+3-\beta(\beta-2))+d(4\gamma_i+4\gamma_j+9-3(\beta-2)\beta)\right) > 0$.

6.6 Proof of Corollary 2

It is sufficient to show that if both the vertical and horizontal intercepts of the response function for firm i under the type-dependent fee are greater than under the uniform fee, then reaction function under the type-dependent fee lies above that of the uniform fee for all values and that $z_i^{TD} > z_i^U$ for all parameter values.

The vertical intercept for $z_i^{TD}(z_j)$ is

$$z_i^{TD}(0) = \frac{(a-c)[d(d+3)-2\beta]}{2(\beta+1)[d(d+3)+1-\beta]+\gamma_i(d+2)^2}$$

and the vertical intercept for $z_i^U(z_j)$ is

$$z_i^U(0) = \frac{2(a-c)[2-d(\beta+d+2)]}{(\beta+1)d[(\beta-5)d-12]-2\gamma_i(d+2)^2}.$$

We next want to show that $z_i^{TD}(0) - z_i^U(0) > 0$, that is,

$$\frac{(a-c)[d(d+3)-2\beta]}{2(\beta+1)[d(d+3)+1-\beta]+\gamma_i(d+2)^2} - \frac{2(a-c)[2-d(\beta+d+2)]}{(\beta+1)d[(\beta-5)d-12]-2\gamma_i(d+2)^2} > 0.$$

Solving for γ_i yields

$$\gamma_i > -\frac{(\beta+1)(d(-2\beta+d(d+5)+6)+4)}{2(d+2)^2},$$

which always holds given that $\gamma_i > 0$ and $\beta < 1$, which implies that the right hand side is negative. Next, we show that the horizontal intercept of the reaction function under the type-dependent fee is greater than that under the uniform fee. The horizontal intercept under the type-dependent fee is

$$\frac{(a-c)[d(d+3)-2\beta]}{(\beta+1)^2 d(d+3)},$$

while under the uniform fee the intercept is

$$\frac{(a-c)[d(\beta+d+2)-2]}{(\beta+1)^2 d(d+3)}.$$

We need to show that

$$\frac{(a-c)[d(d+3)-2\beta]}{(\beta+1)^2 d(d+3)} - \frac{(a-c)[d(\beta+d+2)-2]}{(\beta+1)^2 d(d+3)} > 0.$$

Which simplifies to

$$\frac{(1-\beta)(d+2)(a-c)}{(\beta+1)^2 d(d+3)} > 0,$$

which always holds since $\beta < 1$.

6.7 Proof of Proposition 3.

Under a uniform policy regime, the ERC will maximize joint profits:

$$\begin{aligned}\max_{z_i, z_j} \pi_i + \pi_j = (a - q_i - q_j)q_i - cq_i - t(q_i - z_i - \beta z_j) - \frac{1}{2}\gamma_i z_i^2 \\ + (a - q_i - q_j)q_j - cq_j - t(q_j - z_j - \beta z_i) - \frac{1}{2}\gamma_j z_j^2,\end{aligned}$$

where $q_i(t(z_i, z_j))$ and $q_j(t(z_i, z_j))$. The first-order conditions are

$$\begin{aligned}\frac{\partial \pi_i + \pi_j}{\partial z_i} &= \frac{(\beta+1)\left[a(d(d+3)-2) - d(d+3)(c+2(\beta+1)(z_i+z_j)) + 2c\right] - \gamma_i (d+2)^2 z_i}{(d+2)^2} = 0 \\ \frac{\partial \pi_i + \pi_j}{\partial z_j} &= \frac{(\beta+1)\left[a(d(d+3)-2) - d(d+3)(c+2(\beta+1)(z_i+z_j)) + 2c\right] - \gamma_j (d+2)^2 z_j}{(d+2)^2} = 0.\end{aligned}$$

The first-order conditions under each policy regime are identical, thus each policy induces the same level of investment. The equilibrium investment in green technology for each firm is

$$
\begin{aligned}
z_i^{ERC} &= \frac{(\beta+1)\gamma_j \left[d(d+3)-2\right](a-c)}{\gamma_j \left[2(\beta+1)^2 d(d+3)+\gamma_i (d+2)^2\right]+2(\beta+1)^2\gamma_i d(d+3)} \\
z_j^{ERC} &= \frac{(\beta+1)\gamma_i \left[d(d+3)-2\right](a-c)}{\gamma_j \left[2(\beta+1)^2 d(d+3)+\gamma_i (d+2)^2\right]+2(\beta+1)^2\gamma_i d(d+3)}.
\end{aligned}
$$

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CHAPTER THREE

Promotion of Green Technology Under Different Environmental Policies

1 Introduction

Around seven million premature deaths (one in eight total deaths worldwide) are attributed to air pollution[1]. One way to mitigate this damage is through more environmentally friendly ("green") production processes. Green technology can reduce emissions from production through the use of green energy, electric vehicles, carbon capture storage and usage, and other abatement technologies that reduce pollution from production of a good. Adoption of these technologies in an entire industry follows an "S"-shaped curve. When the technology is in its infancy, adoption is slow. As more firms adopt the technology, the rate of adoption speeds up until it is almost universally adopted and the growth of adoption slows again (See Kemp and Volpi, 2008, for a more extensive discussion). If green technology is available in an industry, it may be in society's best interest for the regulator to promote the use of this technology through policy. This paper takes an extensive look at the social welfare implications under different environmental policies that aim to promote green technology adoption in order to provide policy makers with the best approach to this problem.

Policies that encourage adoption of green technology can be of the form of an emissions fee, a reduction in the existing emissions fee if the technology is adopted (type-dependent fee), tradeable permit (cap-and-trade), or a quota. Of this sample of policies, I evaluate which policy leaves society in the best situation possible based on social welfare, and how firm incentives align with each policy regime. I also evaluate these policies under adoption

[1] According to the World Health Organization: *http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/*

costs asymmetries and when adoption increases marginal cost of production.

Much of the literature focuses on how policies impact a firm's incentive to innovate and the effects on social cost largely ignoring consumer surplus (Wenders 1975, Magat 1979, Downing and White 1984, Milliman and Prince 1989, Carraro and Soubeyran 1996, Jung et al. 1996, Montero 2002, and Requate and Unold 2003). The consensus in the literature is that market based policies outperform command-and-control policies in minimizing social costs. Looking solely at social costs, i.e. environmental damage and adoption costs, ignores the any changes in the firms' cost structure that could affect equilibrium quantity and price. The literature largely assumes a case where all, or many, of the firms operating in the market adopt the technology. This paper examines a setting in which firms in a competing duopoly choose to adopt or not to adopt the technology, including an equilibrium where only one firm will adopt the technology.

Amacher and Malik (2002) study technology adoption in the context of an emission fee on how the decision changes based on whether the regulator commits to a tax either before or after the adoption decision. The focus in Amacher and Malik is on social costs (adoption costs plus damages), not social welfare as a whole. Requate (1998) looks at the social welfare under implications of innovation under taxes and tradeable permits under Bertrand competition and N firms finding that permits create a more efficient market than taxes. In contrast, I study a duopoly's decision to adopt technology under these policies (and more) identifying what situations facilitate adoption, and the effect on social welfare.

To evaluate the incentives behind adoption of green technology, I use a two-stage game. In the first stage, compete over quantity and decide whether to invest in the green technology. In the second stage, firms compete again over quantity and, if they chose to invest in the green technology, they abate a portion of their pollution. After evaluating the adoption decision, I add a stage zero where the regulator maximizes social welfare by choosing the optimal amount of emission fee or quota.

I find that social welfare is highest under an emission fee, than under a quota or tradeable permit scheme, which provide the same level of social welfare. Under an emission fee, the tax revenue generated from the fee increases social welfare even when the fee and quota produce the same quantity after the investment. If, under a tradeable permit scheme, permits are distributed freely and traded at a price equal to the fee, social welfare under this scheme coincides with that under a quota. Firm profits, however, do not follow the same ordering, and profits under a quota exceed those obtained under a fee. Since a quota is not increasing the costs to the firm for production, at the same output level, profits will be higher under a quota. A type-dependent fee increases firm profits compared to the uniform fee since the adopting firm pays a decreased fee on their emissions, but is not greater than profits under a quota. This leads to a misalignment of preferences between firms and the regulator, such that a regulator prefers a fee to maximize social welfare and firms prefer a quota. A type-dependent fee can help increase profits compared to the uniform fee, but not enough for a firm to prefer it than a quota.

Section 2 of the paper presents the model, starting with the emission fee and symmetric firms in section 2.1. Then, different settings are introduced in this structure. First, firms have different costs of adoption, and, second, the acquisition of the green technology affects the marginal production cost. Section 2.2 presents the type-dependent fee where adoption of the technology decreases the fee. In section 2.3, I compare the limits on the cost of adoption under the fee. The tradeable permit scheme is describes in section 2.4. Then, in section 2.5 I present the model under an emissions quota in the baseline case and then when adoption costs are asymmetric and investment increases the marginal cost of production. In section 3, I compare the social welfare and profit implications of each policy, and section 4 concludes the paper.

2 Model

To evaluate the social welfare implications of the various policies, I use a two-stage model with two firms competing over quantity. In the first period, each firm chooses its output level that generates environmental damage through emissions, and they have to decide whether or not to adopt a green technology. In the second stage, the firms again compete over quantity, but will have less emissions if they chose to adopt the green technology. This game structure models the adoption decision of two firms who are actively competing in the market and face environmental regulation. First, I solve the case where there is a per-unit tax on emissions. Once this case is established, I evaluate quotas and tradeable permits.

2.1 Emission Fee

In each stage, the two firms independently maximize their profit by choosing quantity q_{kn}, where $k = \{i, j\}$ indicates the firm and $n = \{1, 2\}$ is the period. Firms face the same linear inverse demand $P = a - Q_n$ in each period where P is the price, $a > 0$, and $Q_n = q_{in} + q_{jn}$ is total production in period n respectively. Each firm produces the good at constant marginal cost c, where $a > c > 0$, and emits $e_{kn} = \gamma q_{kn}$ from production in each period where $\gamma > 0$ represents emissions per unit produced. If the technology is adopted, the firms emissions are reduced to $e_{k2} = (\gamma - \alpha)q_{k2}$ in the second period, where $\alpha > 0$ and $\gamma - \alpha > 0$. The environmental damage function is dE_n^2, where $d > 0$ is a measure of environmental damage and $E_n = e_{in} + e_{jn}$ is the total amount of emissions from production. In the baseline case, each firm pays the same emissions fee t in each period.[2] I assume that $t < \frac{a-c}{\gamma}$ so that firms will produce positive quantities when they do not invest in the technology.

[2] In this game, it is not necessary for the environmental policy to be set optimally since I am analyzing firms' reaction to policy. Once the adoption game is solved, I add a stage zero where the regulator sets the optimal policy.

If the firm decides to invest in the green technology, it pays a one time fee of $Z_k > 0$ in the first stage, where Z_i and Z_j can differ depending on the firm's ability to incorporate the technology into their production process. In the first case, I assume that $Z_i = Z_j = Z$, but relax this assumption in later extensions. This paper assumes an industry where a green technology is already developed and firms focus only on the implementation of it into their production process. Examples of abatement technology include smoke stack scrubbers that remove pollutants from entering the air, underground liners to prevent leakage of pollution into the soil and entering groundwater, and treating waste water before disposal.

The game is solved using backward induction, first, solving for profits in the second stage by choosing quantity, taking their investment in the first stage as given. In the first stage, each firm chooses quantity to maximize profit and whether or not to purchase the green technology in order to maximize second stage profits. In the second stage, each firm maximizes profit by choosing q_{k2}. Firms face two potential profit functions depending on the adoption of technology in the first period. Second period profit for firm i, if it does not invest in the green technology, when there is an emissions fee is

$$\Pi_{i2}^{NI} = (a - (q_{i2} + q_{j2}))q_{i2} - cq_{i2} - t\gamma q_{i2}.$$

The first-order condition for firm i is[3]

$$\frac{\partial \Pi_{i2}^{NI}}{\partial q_{in}} = a - q_{jn} - 2q_{in} - (c + t\gamma) = 0,$$

and the best-response function is $q_{i2} = \dfrac{a - c - t\gamma}{2} - \dfrac{1}{2}q_{j2}$, which the firm uses regardless of the investment decision of the other firm.

[3]Firm j faces a symmetric first-order condition if it does not invest in the first stage.

If firm i chooses to invest in the green technology, its profits in the second stage are

$$\Pi_{i2}^{INV} = (a - (q_{i2} + q_{j2}))q_{i2} - cq_{i2} - t(\gamma - \alpha)q_{i2}.$$

In this case, firm i's first-order condition is

$$\frac{\partial \Pi_{i2}^{INV}}{\partial q_{i2}} = a - q_{j2} - 2q_{i2} - (c + t(\gamma - \alpha)) = 0,$$

with best-response function $q_{i2} = \dfrac{a - c - t(\gamma - \alpha)}{2} - \dfrac{1}{2}q_{j2}$.

The two response functions define 4 sets of equilibrium quantities and profits: (1) neither firm invests, (2) both firms invest, and (3 and 4) one firm invests and the other does not invest.[4] The corresponding quantities and profits in each case are presented in table 1.

	Quantity	Profit
Neither firm invests	$q_{i2} = \frac{1}{3}(a - c - \gamma t)$	$\Pi_{i2}^{NI,NI} = \frac{1}{9}(a - c - t\gamma)^2$
Both firms invest	$q_{i2} = \frac{1}{3}(a - c - t(\gamma - \alpha))$	$\Pi_{i2}^{I,I} = \frac{1}{9}(a - c - t(\gamma - \alpha))^2$
Only firm i invests	$q_{i2} = \frac{1}{3}(a - c - t(\gamma - 2\alpha))$	$\Pi_{i2}^{I,NI} = \frac{1}{9}(a - c - t(\gamma - 2\alpha))^2$
Only firm j invests	$q_{i2} = \frac{1}{3}(a - c - t(\gamma + \alpha))$	$\Pi_{i2}^{NI,I} = \frac{1}{9}(a - c - t(\gamma + \alpha))^2$

Table 1. Equilibrium quantity and profit in the baseline emission fee.

In the first stage, each firm makes two decisions: (1) how much to produce, and (2) whether or not to invest in the green technology. The quantity decision is made independent of the investment decision since the investment decision does not affect the marginal conditions in the first stage. First period profits from production of the good is identical to second period profits if neither firm invests, i.e. $q_{k1} = \frac{1}{3}(a - c - \gamma t)$ and $\Pi_{k1}^{NI} = \frac{1}{9}(a - c - t\gamma)^2$

[4]Under symmetry, cases 3 and 4 are identical, but when there is asymmetry these cases can differ.

when it does not adopt the green technology and $\Pi_{k1}^{INV} = \frac{1}{9}(a - c - t\gamma)^2 - Z$ when it does adopt.

		Firm j	
		Invest	No Invest
Firm i	Invest	$\Pi_{i2}^{I,I} - Z,\ \Pi_{j2}^{I,I} - Z$	$\Pi_{i2}^{I,NI} - Z,\ \Pi_{j2}^{NI,I}$
	No Invest	$\Pi_{i2}^{NI,I},\ \Pi_{j2}^{I,NI} - Z$	$\Pi_{i2}^{NI,NI},\ \Pi_{j2}^{NI,NI}$

Table 2. Normal form representation of the game.

Since each firm's profit from production in the first stage is unaffected by their decision to invest, the firm's decision to invest is based on the following two-by-two game with second period profits and investment presented in table 2.

The following proposition presents the Nash equilibrium for the emission fee.[5]

Proposition 1. *There are three sets of Nash equilibria:*

1. *{Invest, Invest} if* $Z < \frac{1}{9}(4t\alpha(a - c - t\gamma)$.
2. *{No Invest, No Invest} if* $Z > \frac{1}{9}(4t\alpha(a - c - t(\gamma - \alpha))$.
3. *{Invest, No Invest} and {No Invest, Invest} if* $\frac{1}{9}(4t\alpha(a - c - t\gamma) < Z < \frac{1}{9}(4t\alpha(a - c - t(\gamma - \alpha))$. *A mixed strategy exists if the probability of firm j (firm i) choosing 'invest' is* $\sigma_t = \frac{4t\alpha(a-c-t(\gamma-\alpha))-9Z}{4t^2\alpha^2}$*, then firm i (firm j, respectively) will be indifferent between 'invest' and 'not invest'. Further, firm i (firm j) will invest if firm j's (firm i's) probability of investing is less than* σ_t.

This process is used with the different policy options and cost asymmetries which we can then compare based on the social welfare implications of the equilibrium of the game.

[5]Profit functions for the different policies and cost asymmetries are provided in the appendix.

When the cost of investment is too high, neither firm will invest in the green technology. However, if the cost of investment is low, then both firms will choose to invest in the technology. If the cost of investment relatively high, then the equilibrium is for only one firm to invest, and there can exist a mixed strategy where the firms would be indifferent between investing and not investing in the technology if the probability of the other firm investing is σ_t.

Figure 1 shows the upper limit on the cost of investment in which a firm will invest in the technology dependent on the emission fee and other firm's decision to invest, denoted as $Z(t)$, showing the three regions of adoption cost and emission fee that supports each of the three possible equilibria.[6] If there is no emission fee, there is no incentive to adopt the green technology as there is no other benefit to the green technology outside of reducing the emission fee. When the tax is low, the reduction in pollution does not result in a significant decrease in the firm's marginal costs, and hence, the cost of the green technology must be low. As the tax increases, the firm is willing to pay more for the green technology. When the tax becomes more stringent, profits become smaller and the investment cost must also decrease. At $t = 8$, the tax is high enough that firms will not make positive profits if they both choose to invest, although if the tax is higher, we are in the case where the equilibrium is for one firm to invest in the green technology, as seen in the upper limit on Z when the other firm does not invest.

Next, I explore some asymmetries that could arise in this game under an emissions fee, particularly in the cost of adoption, the marginal cost of production if adoption occurs, and emission fee decreasing as a result of adoption.

[6]Parameter values for figure all figures unless otherwise noted are: $a = 10$, $c = 2$, $d = 2$, $\gamma = 1$, $\alpha = 0.5$, $t = 7$, and $\bar{E} = 1.5$.

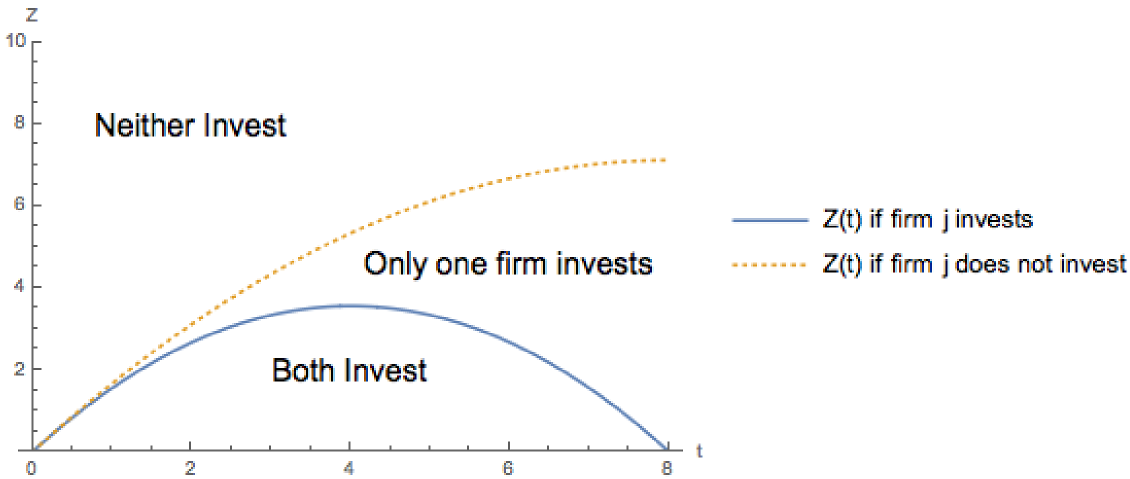

Figure 1: Upper limit on the Z that supports firm i's investment in green technology.

2.1.1 Asymmetric cost of adoption

The first asymmetry I explore is when firms can have different costs of adoption, $Z_i \neq Z_j$. Without loss of generality, assume that firm i has a lower cost of technology adoption than firm j, so that $Z_i < Z_j$. The equilibrium is best explained using best-response function,

$$\text{firm } i \text{ will} \begin{cases} \textit{invest} \text{ if} & \text{firm } j \textit{ invests and } Z_i < \frac{1}{9}(4t\alpha(a-c-t\gamma)) \\ \textit{invest} \text{ if} & \text{firm } j \text{ does } \textit{not invest and } Z_i < \frac{1}{9}(4t\alpha(a-c-t(\gamma-\alpha))) \\ \textit{no invest} & \text{otherwise} \end{cases}$$

Firm j has a symmetric best response function. The following corollary summarizes the Nash equilibria.

Corollary 1. *In this case, there are four sets of Nash equilibria:*

1. $\{$*Invest, Invest*$\}$ *if* $Z_j < \frac{1}{9}(4t\alpha(a-c-t\gamma)$.

2. $\{$*No Invest, No Invest*$\}$ *if* $Z_i > \frac{1}{9}(4t\alpha(a-c-t(\gamma-\alpha))$.

3. $\{$*Invest, No Invest*$\}$ *and* $\{$*No Invest, Invest*$\}$ *if* $\frac{1}{9}(4t\alpha(a-c-t\gamma) < Z_i < Z_j < \frac{1}{9}(4t\alpha(a-$

$c - t(\gamma - \alpha))$. A mixed strategy exists if the probability of firm j (firm i) choosing 'invest' is $\sigma_{tj} = \frac{4t\alpha(a-c-t(\gamma-\alpha))-9Z_j}{4t^2\alpha^2}$, then firm i (firm j, respectively) will be indifferent between 'invest' and 'not invest', and firm i (firm j) will invest if firm j's (firm i's) probability of investing is less than σ_{tj}.

4. *{Invest, No Invest} if $Z_i < \frac{1}{9}(4t\alpha(a - c - t(\gamma - \alpha)) < Z_j$.*

The first three cases of this corollary are similar to the proposition 1, where both firms will invest if the adoption cost is low, neither will invest if the cost is too high, and a third case where the Nash equilibria is for only one firm to invest. In the third case, even though firm i has a lower adoption cost, a Nash equilibrium where only the high cost firm adopts exists. In this case, firm i's best response to firm j's adoption is to not adopt the technology (and firm j's best response to firm i adopting is to not adopt). This case only happens when the cost of adoption to both firms is relatively high and their is not a big discrepancy between the adoption costs.

A fourth case exists where the Nash equilibria is for only the low cost firm to invest in the green technology and the high cost firm to not invest in the technology if one firm's cost is relatively low and the other's cost is high. In this case, the low cost firm gains a competitive advantage since it can lower its emissions and pay a lower fee on each unit of production compared to its rival. In the mixed strategy, the upper limit on probability of firm j investing that supports firm i investing, σ_{tj}, now depends on the firm j's adoption cost, Z_j. Since firm j faces a higher adoption cost, $\sigma_{ti} > \sigma_{tj}$, and the low cost firm is more likely to adopt.

2.1.2 Investment increases marginal cost of production

The second asymmetry to explore is where adoption of the green technology increases the marginal cost of production from c to c'.[7] In addition to the fixed costs of adopting a green technology, the production process becomes more intensive and the marginal cost of producing each unit increases. This can happen if the technology requires maintenance or if the the adopted technology needs labor in order to abate the emissions. In this setting, profits in the first stage are unaffected, but second stage profits if the firm invests are $\Pi_{i2}^{INV} = (a-(q_{i2}+q_{j2}))q_{i2} - c'q_{i2} - t(\gamma-\alpha)q_{i2}$. In this setting, there are three sets of equilibria, which are presented in the following proposition.

Proposition 2. *There are three cases of Nash Equilibria:*

1. *{Invest, Invest} if* $Z < \frac{4}{9}(a-c-t\gamma)(t\alpha+c-c')$ *and* $c'-c < t\alpha$.
2. *{Not Invest, Not Invest} if* $Z > \frac{4}{9}(t\alpha+c-c')(a-c'-t(\gamma-\alpha))$.
3. *{Invest, No Invest} and {No Invest, Invest} if* $\frac{4}{9}(t\alpha+c-c')(a-c-t\gamma) < Z < \frac{4}{9}(t\alpha+c-c')(a-c'-t(\gamma-\alpha))$ *and a mixed strategy where firms will be indifferent between 'invest' and 'not invest' if the opposite firm's probability of investing is* $\sigma_{c(-k)} = \frac{4(t\alpha+c-c')(a-c'-t(\gamma-\alpha))-9Z}{4(t\alpha+c-c')^2}$ *and choose to invest if the probability of the other firm choosing invest is less than* $\sigma_{c(-k)}$

The intuition for each of the equilibria is similar to that of proposition 1, with the addition of the conditions on the increase in marginal cost. If the cost of adoption is not too high and increase in marginal cost is bigger than the decrease in the emission fee, both firms will invest in the technology. If the cost of adoption is too high, then neither firm will invest in the technology. This can happen if the increase in marginal cost is too high, i.e.

[7] The cost of adoption is symmetric, i.e. $Z_i = Z_j = Z$. It is not mathematically necessary that $c' > c$. If adoption of the technology lowers the marginal cost of production, the equilibrium conditions are still valid.

$(c' - c) > \frac{(a-c)\alpha}{\gamma}$, or if the emission fee is too high, i.e. $t > \frac{a-c'}{\gamma-\alpha}$, which makes the adoption cost cut-off negative. There is also a case where the technology is too costly for both firms to adopt, but there is still incentive for one firm to adopt where a mixed strategy can exist.

2.2 Type-dependent fee

Next, we investigate the case where a firm faces a lower emission fee if they adopt a the green technology. Specifically, the fee will decrease from t to t'. This case represents the situation where the regulator can adjust its policy if a firm adopts and uses a green technology (e.g. CO_2 scrubbers) and "rewards" the firm by imposing a lower fee on its emissions. This setting does not affect the first stage, but does affect profits in the second stage if the firm adopts such that $\Pi_{i2}^{INV} = (a - (q_{i2} + q_{j2}))q_{i2} - cq_{i2} - t'(\gamma - \alpha)q_{i2}$. Similar to the previous case, firm k's reaction function is

$$\text{firm } i \text{ will} \begin{cases} \textit{invest} \text{ if} \quad \text{firm } j \, \textit{invests and} \, Z < \frac{4}{9}(a - c - t\gamma)(t\gamma - t'(\gamma - \alpha)) \\ \textit{invest} \text{ if firm } j \text{ does } \textit{not invest and} \, Z < \frac{4}{9}(a - c - t'(\gamma - \alpha))(t\gamma - t'(\gamma - \alpha)) \\ \textit{no invest} \quad \text{otherwise} \end{cases}$$

We can now identify three cases of Nash equilibria presented in the next proposition.

Proposition 3. *There are three cases of Nash equilibria:*

1. *{Invest, Invest} if* $Z < \frac{4}{9}(a - c - t\gamma)(t\gamma - t'(\gamma - \alpha))$.

2. *{No Invest, No Invest} if* $Z > \frac{4}{9}(a - c - t'(\gamma - \alpha))(t\gamma - t'(\gamma - \alpha))$.

3. *{Invest, No Invest} and {No Invest, Invest} if* $\frac{4}{9}(a - c - t\gamma)(t\gamma - t'(\gamma - \alpha)) < Z < \frac{4}{9}(a - c - t'(\gamma - \alpha))(t\gamma - t'(\gamma - \alpha))$. *A mixed strategy exists if the probability of firm j (firm i) choosing to invest is* $\sigma_{t'} = \frac{4(a-c-t'(\gamma-\alpha))(t\gamma-t'(\gamma-\alpha))-9Z}{4(t\gamma-t'(\gamma-\alpha))^2}$, *then firm i (firm j, respectively) will be indifferent between investing and not investing, and firm i (firm j)*

will invest if firm j's (firm i's) probability of investing is less than $\sigma_{t'}$. If the probability of the other firm adopting is greater than $\sigma_{t'}$, then it will not adopt the technology.

This proposition follows the same basic intuition of the previous case, except that the limits on the investment are now affected by the emission fee in each case of adoption. Since adoption decreases both the emissions and emission fee, firms see a larger benefit to adoption than under the uniform fee. This means that firms are more willing to adopt a more expensive technology, as seen in the next section.

2.3 Comparison of investment limits

At this point, it is worth comparing the different limits on the investment cost that supports an equilibrium where both firms invest between the three cases presented thus far: baseline (symmetric), investment increases marginal cost, and type-dependent regulation. This comparison is presented in figure 2.[8] This figure shows that when the type-dependent fee lowers the emission fee ($t > 3$), the upper limit on investment cost is higher that either the baseline or marginal cost increase case. We can also see that when the investment increases the marginal cost the limit on the investment cost is most restrictive. Figure 3 shows the lower limit of investment cost that supports the equilibrium where neither firm adopts the technology. A similar ranking occurs as with the limit on cost that supports both firms adopting (figure 2).

Since the cutoff on the level of investment that facilitates both firms investing is lower when the green technology increases marginal cost and the type-dependent fee increases the level of investment limit, one option is for the regulator to implement a type-dependent fee if the cost of investment increases marginal cost. The type-dependent fee has the effect of

[8]This figure has the same parameter values as figure 1 with additional parameters $c' = 3$ and $t' = 3$. In the case of the type-dependent fee, the post-adoption fee t' is only lower than the pre-adoption fee t when $t > 3$.

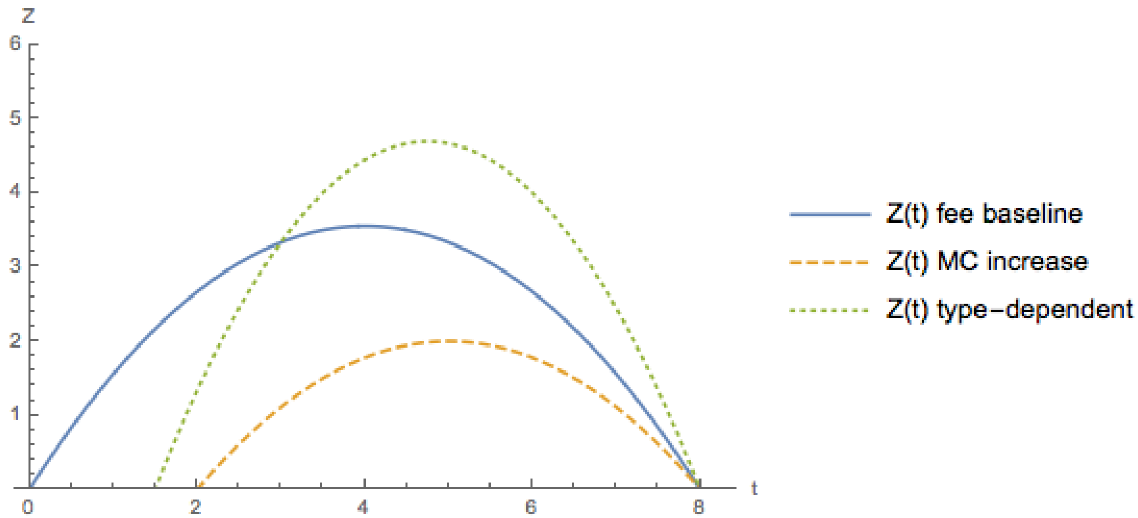

Figure 2: Comparison of the limit of Z that supports both firms investing between the different settings.

reducing the marginal cost so that the regulator compensates the firm for any increase in marginal cost from adopting the technology through a lower fee. This could be set so that the fee reduction perfectly corrects for the increase in marginal cost or over-corrects for the increase and rewards the firm for the investment by having a lower overall marginal cost for the adoption.

2.4 Tradeable Permit Scheme

If the policy is a tradeable permit scheme (cap-and-trade), then the regulator sets an emissions cap quota for all firms in the economy and distributes permits (either through appropriation or auction), and firms can buy and sell permits as needed. If the market for permits is perfectly competitive, then the price on permits acts the same as an emission fee since all firms are price takers in the permit market. The price of the permit acts as an emission fee, and we have the same equilibrium as in proposition 1, where t is the permit price. The analysis for a tradeable permit scheme will follow that of the emission fee for any

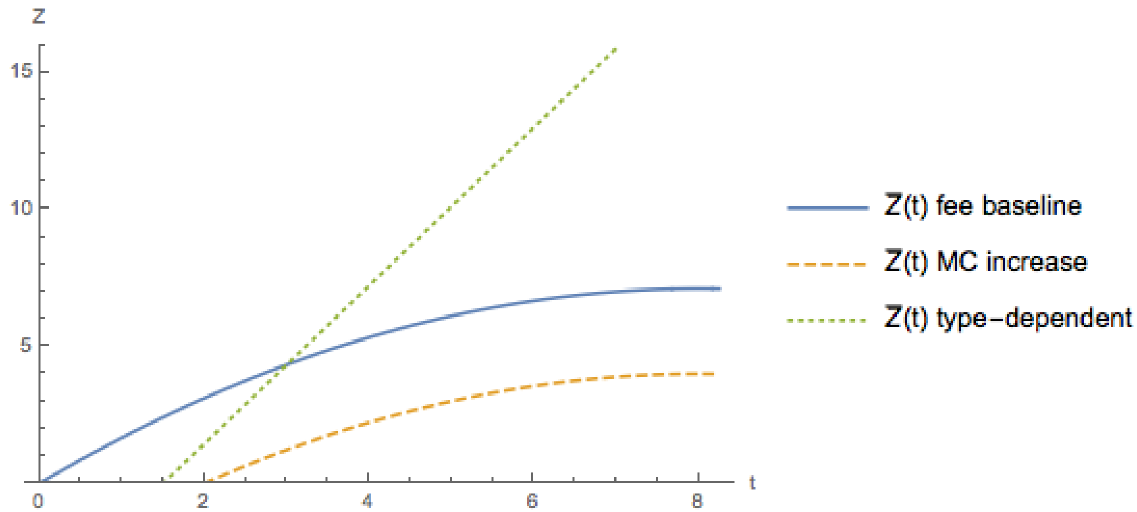

Figure 3: Comparison of the lower limit of Z that supports neither firms investing between the different settings.

of the extensions.

2.5 Quota

Next we investigate the equilibria when there is an emissions quota. In this case, we put an upper bound on individual firm emissions at a level of $\bar{E}$. If the quota is not binding, then the firms will act as though there is no regulation and there will be no incentive to adopt the technology. Therefore, the emission quota is set so that it is binding. Solving $\bar{E} = q_k e_k$, I find that each firm k will choose $q_k = \frac{\bar{E}}{\gamma}$ if the firm does not invest in the abatement technology and $q_k = \frac{\bar{E}}{\gamma-\alpha}$ if it does invest in the abatement technology. From here, I plug the the quantities into the profit functions and can solve for the Nash equilibrium, which is summarized in the following proposition.

Proposition 4. *There are three sets of Nash Equilibria:*

1. *{Invest, Invest} if* $Z < \frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{(\gamma-\alpha)^2\gamma^2}$ *and* $\bar{E} < \frac{\gamma(a-c)(\gamma-\alpha)}{3\gamma-\alpha}$.

2. $\{$*No Invest, No Invest*$\}$ *if* $Z > \frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-2\alpha))}{(\gamma-\alpha)^2\gamma^2}$.

3. $\{$*Invest, No Invest*$\}$ *and* $\{$*No Invest, Invest*$\}$ *and a mixed strategy if* $\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{(\gamma-\alpha)^2\gamma^2} < Z < \frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-2\alpha))}{(\gamma-\alpha)^2\gamma^2}$. *A mixed strategy exists if the probability of firm* k *choosing 'invest' is* $\sigma_Q = \frac{\bar{E}\alpha\gamma(a-c)(\gamma-\alpha)-\alpha\bar{E}^2(3\gamma-2\alpha)+\gamma^2 Z(\gamma-\alpha)^2}{\alpha^2\bar{E}^2}$, *then firm* k *will be indifferent between 'invest' and 'not invest'. If the probability of firm* k *investing is greater than* σ_Q, *then the other firm will not invest.*

A lower quota means that a firm must pollute less and thus produce less. Investing in the abatement technology reduces the per unit emissions and increases the amount of production that can happen. If the quota is set too high, firms will not have incentive to reduce pollution by adopting the technology. If the quota and cost of investment are low enough, the firm will have higher profits if it invests in the green technology.

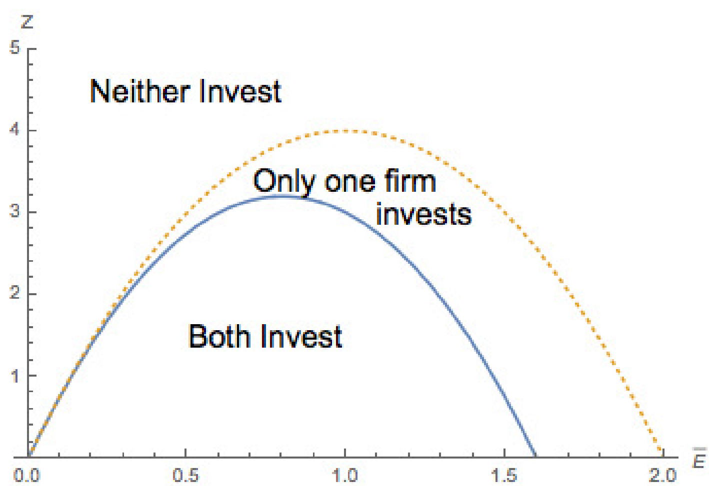

Figure 4: Upper limit of Z that supports firm i's investment in green technology.

Similar to figure 1, we can graph the regions of Z and $\bar{E}$ that support the three cases outlined in proposition 3, shown in figure 4.The intuition in the case of the quota follows that of the fee. If the cost of adoption is too high, neither firm will invest in the green technology. If the quota is stringent, the adoption cost will have to be low in order for the firms to invest since the increase in market profits are small (not including the investment cost). If the quota is higher and leads to output close to the unregulated equilibrium and a decrease in the market price. Thus, the change in market profits is small and there is little incentive to invest in the technology.

2.5.1 Asymmetric cost of adoption

The following corollary summarizes the equilibria that can occur if the firms have asymmetric costs of adopting the green technology, where firm j has the higher adoption cost. The equilibrium quantities and profits are the same as under the baseline quota, only that $Z_i < Z_j$.

Corollary 2. *There are four cases of Nash Equilibria:*

1. *{Invest, Invest} if* $Z_i < Z_j < \frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{(\gamma-\alpha)^2\gamma^2}$ *and* $\bar{E} < \frac{\gamma(a-c)(\gamma-\alpha)}{3\gamma-\alpha}$.
2. *{No Invest, No Invest} if* $Z_j > Z_i > \frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-2\alpha))}{(\gamma-\alpha)^2\gamma^2}$.
3. *{Invest, No Invest} and {No Invest, Invest} if* $\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{(\gamma-\alpha)^2\gamma^2} < Z_i < Z_j < \frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-2\alpha))}{(\gamma-\alpha)^2\gamma^2}$. *A mixed strategy exists if the probability of firm k choosing 'invest' is* $\sigma_{Qk} = \frac{\bar{E}\alpha\gamma(a-c)(\gamma-\alpha)-\bar{E}^2(3\gamma-2\alpha)-\gamma^2(\gamma-\alpha)^2 Z_k}{\bar{E}^2\alpha^2}$*, then the other firm will be indifferent between 'invest' and 'not invest'. The firm will not invest if the probability of the other firm adopting is greater than* σ_{Qk}.
4. *{Invest, No Invest} if* $Z_i < \frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{(\gamma-\alpha)^2\gamma^2} < Z_j$ *and* $\bar{E} < \frac{\gamma(a-c)(\gamma-\alpha)}{3\gamma-\alpha}$.

Similar to under the fee when adoption costs are asymmetric, the lower cost adopter is more willing to adopt the technology although both firms will adopt if the technology is cheap enough. It is also possible that the high cost firm can adopt and the low cost firm will not adopt if the technology cost for both firms is relatively high as each of their best-responses is to do the opposite of the other firm.

2.5.2 Investment increases marginal cost of production

The case when investment in the green technology increases the marginal cost of production from c to c' under a quota is presented in the following proposition. In this setting, equilibrium quantities are the same under a quota since the quota is binding, but the profit if the firm invests in the technology is $\Pi_{i2}^{INV} = (a-(q_{i2}+q_{j2}))q_{i2} - c'q_{i2} - t(\gamma-\alpha)q_{i2}$, which is identical to the same setting under the emission fee.

Proposition 5. *There are three cases of Nash Equilibria:*

1. *{Invest, Invest} if* $Z < \frac{\bar{E}(\alpha\bar{E}(\alpha-3\gamma)-\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma))}{\gamma^2(\alpha-\gamma)^2}$, $\bar{E} < \frac{\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma)}{\alpha(\alpha-3\gamma)}$, *and* $c'-c < \frac{(a-c)\alpha}{\gamma}$.
2. *{No Invest, No Invest} if* $Z > \frac{\bar{E}(\alpha\bar{E}(2\alpha-3\gamma)-\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma))}{\gamma^2(\alpha-\gamma)^2}$
3. *{Invest, No Invest} and {No Invest, Invest} if* $\frac{\bar{E}(\alpha\bar{E}(\alpha-3\gamma)-\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma))}{\gamma^2(\alpha-\gamma)^2} < Z < \frac{\bar{E}(\alpha\bar{E}(2\alpha-3\gamma)-\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma))}{\gamma^2(\alpha-\gamma)^2}$, $\bar{E} < \frac{\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma)}{\alpha(\alpha-3\gamma)}$, *and* $c'-c < \frac{(a-c)\alpha}{\gamma}$. *A mixed strategy exists if the probability of firm k choosing 'invest' is* $\sigma_{Qc} = \frac{4(c'-c-t\alpha)(-a+c'+t(\gamma-\alpha))-9Z}{4(c-c'+t\alpha)^2}$, *then firm k will be indifferent between 'invest' and 'not invest'. If the probability of the other firm investing is greater than* σ_{Qc}, *then the firm will not invest.*

The intuition for this set of equilibria align with that in the case of an emission fee where adoption of the technology increases marginal costs, and has the same limits on the increase in costs that causes the firms to not invest in the technology. If the costs of adoption are low, both firms will invest. If the cost of adoption is too high, then neither firm will invest in the technology. This can happen if the increase in marginal cost is too high, i.e. $(c' - c) > \frac{(a-c)\alpha}{\gamma}$, or if the emission fee is too high, i.e. $t > \frac{a-c'}{\gamma-\alpha}$, which makes the adoption cost cut-off negative. There is also a region of costs between these two equilibria where the equilibrium is for one firm to adopt and a mixed strategy can exist.

3 Social Welfare

The next step is to evaluate stage zero of the game, where the regulator maximizes social welfare at the Nash Equilibria when both firms invest in the green technology under each of the policy regimes. Social welfare is calculated as the sum of consumer and producer surplus net environmental damage and green technology investment,

$$SW = \int_0^{Q_2} (a - c - x)\, dx - d(e_{i2} + e_{j2})^2 - 2Z.$$

The regulator maximize social welfare by choosing either the optimal emission fee or quota (which act through $q_{k2}(t)$ or $q_{k2}(\bar{E})$. In the case of the fee, the first-order condition is

$$\frac{\partial SW}{\partial t} = \frac{1}{9}\left(2a\alpha - 8d(\alpha-\gamma)^3(a - c + t(\alpha-\gamma)) - 2a\gamma - 2\alpha c + 2c\gamma - \alpha^2 t + 2\alpha\gamma t - \gamma^2 t\right) = 0.$$

Solving for t yields the optimal fee,

$$t^* = \frac{2(a-c)\,(4d(\gamma-\alpha)^2 - 1)}{(\gamma-\alpha)\,(8d(\gamma-\alpha)^2 + 1)}.$$

For the optimal emission fee to be positive, we need that $d > \frac{1}{4(\gamma-\alpha)^2}$.[9] Social welfare at the optimal fee is,

$$SW(t^*) = \frac{(a-c)^2}{2\left(8d(\gamma-\alpha)^2+1\right)} - 2Z.$$

Using the same social welfare function, we can use the quantity conditions from the quota to find the optimal level of emissions. In the case of the quota, the first-order condition is

$$\frac{\partial SW}{\partial \bar{E}} = \frac{a-c}{\gamma-\alpha} - 8d\bar{E} - \frac{\bar{E}}{(\alpha-\gamma)^2} = 0.$$

Solving for $\bar{E}$ yields the optimal quota,

$$\bar{E}^* = \frac{(a-c)(\gamma-\alpha)}{8d(\alpha-\gamma)^2+1}.$$

Plugging this back into the social welfare function yields,

$$SW(\bar{E}^*) = \frac{(a-c)^2}{2\left(8d(\alpha-\gamma)^2+1\right)} - 2Z,$$

which is the same social welfare as that under the optimal fee. This result is different than those found in the literature comparing the welfare effects of fees and quotas. Summarizing, welfare outcomes are the same in the situation where two competing firms are adopting a technology under fees and quotas.

Next, we can evaluate firm profits under the optimal policies, shown with social welfare in figure 5.[10] We can see that firms have lower profits when facing a fee since they face an increased cost to production than that under a quota. A similar phenomenon was found in

[9] If d is smaller than this cutoff, the fee turns into a subsidy as the lower production from the duopoly (compared to perfect competition) reduces social welfare more than the environmental damage from emissions.

[10] Figure 5 uses the same parameter values as figure 1. Under Cournot competition, equilibrium output is $q_{kn} = \frac{a-c}{3} = 8/3$. The quota is set at $\bar{E}^* = \frac{4}{1+2d}$. Therefore, the quota is binding if $d > .25$. In order for the emission to be positive, we need that $d > 1$ in this case.

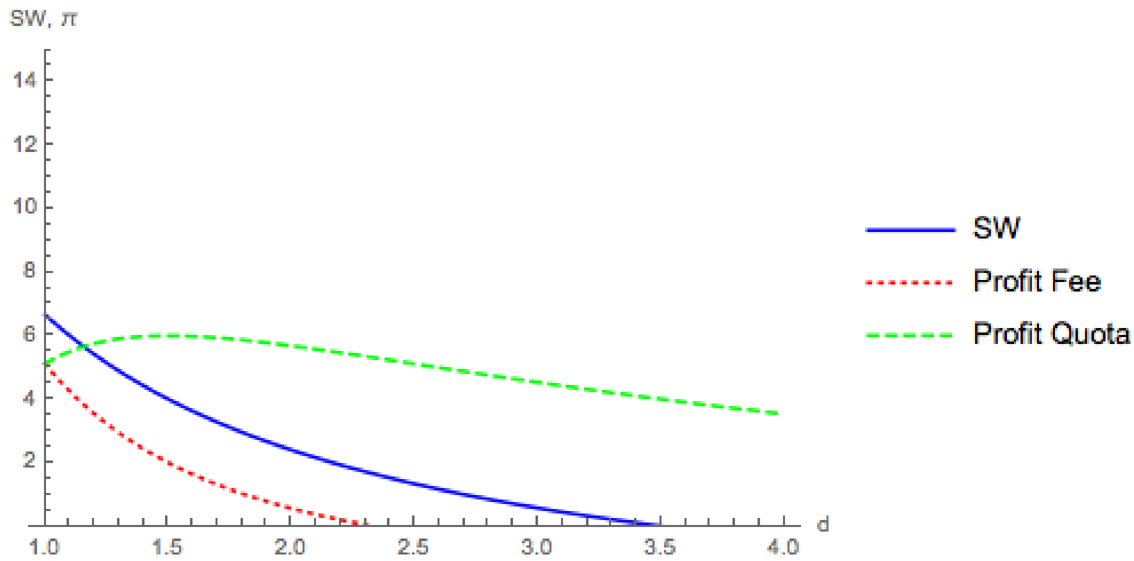

Figure 5: Social welfare and firm i's profits under a fee and quota.

Wenders (1975), who showed that firms have little incentive to provide pollution abatement under an emission fee. In this case, if firms are adopting a green technology and face the certainty of environmental policy, regulators should expect greater opposition to a fee than a quota.

4 Conclusion

The literature has established that market-based policies, such as fees, outperform command-and-control policies when evaluated on the basis of social costs (adoption cost and environmental damage). This analysis includes changes in consumer surplus that happen when production is altered. This analysis, with full inclusion of social welfare, finds that market based approaches have the same welfare implications as command-and-control approaches. However, firm incentives are not indifferent to policy regimes. Regulators should expect firms to lobby for market based approaches over quotas when facing the certainty of environmental policy.

A common condition leading to a Nash Equilibrium where both firms adopt is that the technology is affordable. If the emissions fee or quota is too stringent, firms have no incentive to act in the market and will exit. Further, firms have higher profits under a quota than a fee and may more willing to invest in a more expensive technology. Given a situation where the firms would adopt the technology under the quota but not the fee, the regulator needs to compare social welfare under the fee when firms do not adopt and that under quota with adoption. The problem becomes more dynamic at this point where it could be that the green technology is in its infancy and its price is expected to decrease over time. Then, the regulator may consider a subsidy or rebate on adoption to encourage the firms to adopt early if commitment to the fee is desired.

This analysis could be furthered by exploring what happens when firms have initial emissions that are asymmetric. Each firm has further incentives to invest as the more efficient firm could increase its cost advantage by investing in the technology, and the less efficient firms could become more competitive if it invests in the technology. Another possible extension is of asymmetric information where firms are unaware of the emissions or costs of their competitor. Finally, allowing for the potential of consumer willingness to pay to increase when the firm invests in green technology would increase the benefits from adoption further than simply lowering emissions.

5 Appendix

5.1 Outline of proof of Proposition 1

The best-response function for firm i if it does not invest is $q_{i2} = \dfrac{a-c-t\gamma}{2} - \dfrac{1}{2}q_{j2}$, which the firm uses regardless of the investment decision of the other firm. If firm i chooses to invest in the green technology, its best-response function is $q_{i2} = \dfrac{a-c-t(\gamma-\alpha)}{2} - \dfrac{1}{2}q_{j2}$. Firm j has symmetric best-response functions.

In the case that neither firm adopts, the equilibrium is solved by the following system (the same system is used for first period equilibrium),

$$q_{i2} = \frac{a-c-t\gamma}{2} - \frac{1}{2}q_{j2},$$
$$q_{j2} = \frac{a-c-t\gamma}{2} - \frac{1}{2}q_{i2}.$$

Solving this system gives equilibrium $q_{i2} = q_{j2} = \frac{1}{3}(a-c-\gamma t)$. Plugging these quantities into the profit function $\Pi_{i2}^{NI} = (a-(q_{i2}+q_{j2}))q_{i2} - cq_{i2} - t\gamma q_{i2}$ gives profit $\Pi_{i2}^{NI,NI} = \frac{1}{9}(a-c-t\gamma)^2$.

If both firms invest, equilibrium quantities are found by solving the system,

$$q_{i2} = \frac{a-c-t(\gamma-\alpha)}{2} - \frac{1}{2}q_{j2},$$
$$q_{j2} = \frac{a-c-t(\gamma-\alpha)}{2} - \frac{1}{2}q_{i2}.$$

Solving for quantities gives the equilibrium when both firms invest, $q_{i2} = q_{j2} = \frac{1}{3}(a - c - t(\gamma-\alpha))$. Plugging this into the profit function for firm i when both firms invest, $\Pi_{i2}^{INV} = (a-(q_{i2}+q_{j2}))q_{i2} - cq_{i2} - t(\gamma-\alpha)q_{i2}$, yields $\Pi_{i2}^{I,I} = \frac{1}{9}(a-c-t(\gamma-\alpha))^2$.

If firm i invests and firm j does not invest, the following system is used

$$q_{i2} = \frac{a-c-t(\gamma-\alpha)}{2} - \frac{1}{2}q_{j2},$$
$$q_{j2} = \frac{a-c-t\gamma}{2} - \frac{1}{2}q_{i2}.$$

The equilibrium quantities are $q_{i2} = \frac{1}{3}(a-c-t(\gamma-2\alpha))$ and $q_{j2} = \frac{1}{3}(a-c-t(\gamma+\alpha))$. Plugging these quantities into their respective firm's profit function yields $\Pi_{i2}^{I,NI} = \frac{1}{9}(a-c-t(\gamma-2\alpha))^2$ and $\Pi_{j2}^{NI,I} = \frac{1}{9}(a-c-t(\gamma+\alpha))^2$. These are summarized in the following table.

	Quantity	Profit
Neither firm invests	$q_{i2} = \frac{1}{3}(a-c-\gamma t)$	$\Pi_{i2}^{NI,NI} = \frac{1}{9}(a-c-t\gamma)^2$
Both firms invest	$q_{i2} = \frac{1}{3}(a-c-t(\gamma-\alpha))$	$\Pi_{i2}^{I,I} = \frac{1}{9}(a-c-t(\gamma-\alpha))^2$
Only firm i invests	$q_{i2} = \frac{1}{3}(a-c-t(\gamma-2\alpha))$	$\Pi_{i2}^{I,NI} = \frac{1}{9}(a-c-t(\gamma-2\alpha))^2$
Only firm j invests	$q_{i2} = \frac{1}{3}(a-c-t(\gamma+\alpha))$	$\Pi_{i2}^{NI,I} = \frac{1}{9}(a-c-t(\gamma+\alpha))^2$

Table 3. Equilibrium quantity and profit under the baseline emission fee.

Using these profits to populate the following 2x2 simultaneous move game, we can solve for the cases that give each equilibria.

		Firm j: Invest	Firm j: No Invest
Firm i	Invest	$\Pi_{i2}^{I,I} - Z,\ \Pi_{j2}^{I,I} - Z$	$\Pi_{i2}^{I,NI} - Z,\ \Pi_{j2}^{NI,I}$
	No Invest	$\Pi_{i2}^{NI,I},\ \Pi_{j2}^{I,NI} - Z$	$\Pi_{i2}^{NI,NI},\ \Pi_{j2}^{NI,NI}$

Table 4. Normal form representation of the game under the baseline emission fee.

The Nash equilibrium is *(Invest, Invest)* if the dominant strategy for both firms is to invest. For this, both $\Pi_{k2}^{I,I} - Z > \Pi_{k2}^{NI,I}$ and $\Pi_{k2}^{I,NI} - Z > \Pi_{k2}^{NI,NI}$. More explicitly,

$$\frac{1}{9}(a-c-t(\gamma-\alpha))^2 - Z > \frac{1}{9}(a-c-t(\gamma+\alpha))^2, \text{ and}$$
$$\frac{1}{9}(a-c-t(\gamma-2\alpha))^2 - Z > \frac{1}{9}(a-c-t\gamma)^2$$

Solving for Z in each inequality,

$$\frac{1}{9}(a-c-t(\gamma-\alpha))^2 - \frac{1}{9}(a-c-t(\gamma+\alpha))^2 > Z, \text{ and}$$
$$\frac{1}{9}(a-c-t(\gamma-2\alpha))^2 - \frac{1}{9}(a-c-t\gamma)^2 > Z$$

which simplifies to

$$\frac{1}{9}(4\alpha t(a-c-t\gamma)) > Z, \text{ and}$$
$$\frac{1}{9}(4\alpha t(a-c-t(\gamma-\alpha))) > Z.$$

Since $Z < \frac{1}{9}(4\alpha t(a-c-t\gamma))$ is more restrictive than the second inequality, this is needed for *(Invest, Invest)* to be the Nash equilibrium.

The Nash equilibrium is *(No Invest, No Invest)* if the dominant strategy for both firms is to not invest. For this, both $\Pi_{k2}^{NI,I} > \Pi_{k2}^{I,I} - Z$ and $\Pi_{k2}^{NI,NI} > \Pi_{k2}^{I,NI} - Z$. This is a similar system to above,

$$\frac{1}{9}(a-c-t(\gamma-\alpha))^2 - Z < \frac{1}{9}(a-c-t(\gamma+\alpha))^2, \text{ and}$$
$$\frac{1}{9}(a-c-t(\gamma-2\alpha))^2 - Z < \frac{1}{9}(a-c-t\gamma)^2.$$

This simplifies to

$$\frac{1}{9}(4\alpha t(a-c-t\gamma)) < Z, \text{ and}$$
$$\frac{1}{9}(4\alpha t(a-c-t(\gamma-\alpha))) < Z.$$

For the *(No Invest, No Invest)* equilibrium, we need the more restrictive condition, i.e. $Z > \frac{1}{9}(4\alpha t(a-c-t(\gamma-\alpha)))$.

The final set of equilibria occurs when each firm will invest only if the other firm chooses not to invest, so the Nash equilibria are *(Invest, No Invest), (No Invest, Invest)* and a mixed strategy where firms will randomize over the two actions if the expected profit from investing and not investing are equal. This occurs when $\Pi_{k2}^{NI,I} > \Pi_{k2}^{I,I} - Z$ and $\Pi_{k2}^{I,NI} - Z > \Pi_{k2}^{NI,NI}$, or, more explicitly

$$\frac{1}{9}(a-c-t(\gamma-\alpha))^2 - Z < \frac{1}{9}(a-c-t(\gamma+\alpha))^2, \text{ and}$$
$$\frac{1}{9}(a-c-t(\gamma-2\alpha))^2 - Z > \frac{1}{9}(a-c-t\gamma)^2$$

This simplifies to

$$\frac{1}{9}(4\alpha t(a-c-t\gamma)) < Z, \text{ and}$$
$$\frac{1}{9}(4\alpha t(a-c-t(\gamma-\alpha))) > Z,$$

which is the range that Z needs to be in to support the *(Invest, No Invest), (No Invest, Invest)* equilibrium.

If the probability of firm j adopting is σ_t, and not adopting is $1-\sigma_t$, then firm i is indifferent between adopting and not adopting if

$$\sigma_t(\Pi_{i2}^{I,I} - Z) + (1-\sigma_t)(\Pi_{i2}^{I,NI} - Z) = \sigma_t \Pi_{i2}^{NI,I} + (1-\sigma_t)\Pi_{i2}^{NI,NI},$$

$$\sigma_t(\frac{1}{9}(a-c-t(\gamma-\alpha))^2 - Z) + (1-\sigma_t)(\frac{1}{9}(a-c{-}t(\gamma-2\alpha))^2 - Z) =$$

$$\sigma_t(\frac{1}{9}(a-c{-}t(\gamma+\alpha))^2) + (1-\sigma_t)(\frac{1}{9}(a-c-t\gamma)^2),$$

$$\sigma_t(4\alpha t(a-c-\gamma t) - 9Z) = (1-\sigma_t)(4\alpha t(a-c-t(\gamma-\alpha)) - 9Z)$$

$$\sigma_t(4\alpha t(a-c-\gamma t) - 4\alpha t(a-c-t(\gamma-\alpha))) = 4\alpha t(a-c-t(\gamma-\alpha)) - 9Z$$

$$\sigma_t(4\alpha t(a-c-\gamma t) - 4\alpha t(a-c-t(\gamma-\alpha))) = 4\alpha t(a-c-t(\gamma-\alpha)) - 9Z$$

$$\sigma_t = \frac{4t\alpha(a-c-t(\gamma-\alpha)) - 9Z}{4t^2\alpha^2}$$

A similar strategy is employed for the remaining propositions. The profits for each extension are given below.

5.2 Asymmetric cost of adoption under a fee

When the adoption cost is asymmetric, the marginal conditions are the same as the previous setting and only the cost of adoption is different. Therefore, equilibrium quantities are unchanged from the previous case. The profit functions are:

- If both firms invest, each firm has profit $\Pi_{k2}^{I,I} = \frac{1}{9}(a-c-t(\gamma-\alpha))^2 - Z_k$
- If one firm invests, the investing firm has profit $\Pi_{k2}^{I,NI} = \frac{1}{9}(a-c-t(\gamma-2\alpha))^2 - Z_k$, and the firm that does not invest has profit $\Pi_{k2}^{NI,I} = \frac{1}{9}(a-c-t(\gamma+\alpha))^2$
- If neither firm invests, each firm has profit $\Pi_{k2}^{NI,NI} = \frac{1}{9}(a-c-t\gamma)^2$

The equilibrium conditions are solved for in a nearly identical way to the previous setting, where only Z changes to Z_k.

5.3 Investment increases marginal cost of production under a fee

First period market profits are the same as the previous cases. Second period profit for firm i if it does not invest in the green technology is

$$\Pi_{i2}^{NI} = (a - (q_{i2} + q_{j2}))q_{i2} - cq_{i2} - t\gamma q_{i2}.$$

The first-order condition for firm i is

$$\frac{\partial \Pi_{i2}^{NI}}{\partial q_{in}} = a - q_{jn} - 2q_{in} - (c + t\gamma) = 0,$$

and the best-response function is $q_{i2} = \dfrac{a - c - t\gamma}{2} - \dfrac{1}{2}q_{j2}$, which the firm uses regardless of the investment decision of the other firm. If firm i chooses to invest in the green technology, its profits in the second stage are

$$\Pi_{i2}^{INV} = (a - (q_{i2} + q_{j2}))q_{i2} - c'q_{i2} - t(\gamma - \alpha)q_{i2}.$$

In this case, firm i's first-order condition is

$$\frac{\partial \Pi_{i2}^{INV}}{\partial q_{i2}} = a - q_{j2} - 2q_{i2} - (c' + t(\gamma - \alpha)) = 0,$$

with best-response function $q_{i2} = \dfrac{a - c' - t(\gamma - \alpha)}{2} - \dfrac{1}{2}q_{j2}$.

Using the best-response functions, I can find equilibrium quantities presented in the following table.

	Quantity	Profit
Neither firm invests	$q_{i2} = \frac{1}{3}(a - c - \gamma t))$	$\Pi_{i2}^{NI,NI} = \frac{1}{9}(a - c - t\gamma)^2$
Both firms invest	$q_{i2} = \frac{1}{3}(a - c' - t(\gamma - \alpha t))$	$\Pi_{i2}^{I,I} = \frac{1}{9}(a - c' - t(\gamma - \alpha))^2$
Only firm i invests	$q_{i2} = \frac{1}{3}(a - 2c' + c - t(\gamma - 2\alpha))$	$\Pi_{i2}^{I,NI} = \frac{1}{9}(a - 2c' + c - t(\gamma - 2\alpha))^2$
Only firm j invests	$q_{i2} = \frac{1}{3}(a - 2c - t(\gamma + \alpha) + c')$	$\Pi_{i2}^{NI,I} = \frac{1}{9}(a - 2c - t(\alpha + \gamma) + c')^2$

Table 5. Equilibrium quantity and profit under the emission fee when adoption is accompanied by an increase in marginal cost.

We can use the same process for finding the equilibrium in proposition 1 for proposition 3. The Nash equilibrium is *(Invest, Invest)* if the dominant strategy for both firms is to invest. For this, both $\Pi_{k2}^{I,I} - Z > \Pi_{k2}^{NI,I}$ and $\Pi_{k2}^{I,NI} - Z > \Pi_{k2}^{NI,NI}$. More explicitly,

$$\frac{1}{9}(a - c' - t(\gamma - \alpha))^2 - Z > \frac{1}{9}(a - 2c - t(\alpha + \gamma) + c')^2, \text{ and}$$
$$\frac{1}{9}(a - 2c' + c - t(\gamma - 2\alpha))^2 - Z > \frac{1}{9}(a - c - t\gamma)^2$$

Solving for Z in each inequality,

$$\frac{1}{9}(a - c' - t(\gamma - \alpha))^2 - \frac{1}{9}(a - 2c - t(\alpha + \gamma) + c')^2 > Z, \text{ and}$$
$$\frac{1}{9}(a - 2c' + c - t(\gamma - 2\alpha))^2 - \frac{1}{9}(a - c - t\gamma)^2 > Z.$$

which simplifies to

$$\frac{4}{9}(a - c - t\gamma)(t\alpha + c - c') > Z, \text{ and}$$
$$\frac{4}{9}(a - c' - t(\gamma - \alpha))(t\alpha + c - c') > Z.$$

Since $Z < \frac{4}{9}(a - c - t\gamma)(t\alpha + c - c')$ is more restrictive than the second inequality, this is needed for *(Invest, Invest)* to be the Nash equilibrium. Since $t < \frac{a-c}{\gamma}$, in order for this to be a potential equilibrium, it must also be that $t > \frac{c'-c}{\alpha}$. Or, combining, $\frac{c'-c}{\alpha} < t < \frac{a-c}{\gamma} \rightarrow c' - c < \frac{(a-c)\alpha}{\gamma}$. The remaining equilibria are found by changing the signs on equality.

5.4 Type-dependent fee

First period market profits are the same as the previous cases. Second period profit and response function for firm i if it does not invest in the green technology is the same as in proposition 1. If firm i chooses to invest in the green technology, its profits in the second stage are

$$\Pi_{i2}^{INV} = (a - (q_{i2} + q_{j2}))q_{i2} - cq_{i2} - t'(\gamma - \alpha)q_{i2}.$$

In this case, firm i's first-order condition is

$$\frac{\partial \Pi_{i2}^{INV}}{\partial q_{i2}} = a - q_{j2} - 2q_{i2} - (c + t'(\gamma - \alpha)) = 0,$$

with best-response function $q_{i2} = \dfrac{a - c - t'(\gamma - \alpha)}{2} - \dfrac{1}{2}q_{j2}$.

Using the best-response functions, I can find equilibrium quantities. Equilibrium profits and quantities are presented in the following table.

	Quantity	Profit
Neither firm invests	$q_{i2} = \frac{1}{3}(a - c - \gamma t))$	$\Pi_{i2}^{NI,NI} = \frac{1}{9}(a - c - t\gamma)^2$
Both firms invest	$q_{i2} = \frac{1}{3}(a - c - t'(\gamma - \alpha))$	$\Pi_{i2}^{I,I} = \frac{1}{9}(a - c - t'(\gamma - \alpha))^2$
Only firm i invests	$q_{i2} = \frac{1}{3}(a - c - 2t'(\gamma - \alpha) + t\gamma)$	$\Pi_{i2}^{I,NI} = \frac{1}{9}(a - c - 2t'(\gamma - \alpha) + \gamma t)^2$
Only firm j invests	$q_{i2} = \frac{1}{3}(a - c - 2t\gamma + t'(\gamma - \alpha))$	$\Pi_{i2}^{NI,I} = \frac{1}{9}(a - c - 2\gamma t + t'(\gamma - \alpha))^2$

Table 6. Equilibrium quantity and profit under the type-dependent emission fee.

We can use the same procedure as in proposition 1 to solve for the equilibrium. The Nash equilibrium is *(Invest, Invest)* if the dominant strategy for both firms is to invest. For this, both $\Pi_{k2}^{I,I} - Z > \Pi_{k2}^{NI,I}$ and $\Pi_{k2}^{I,NI} - Z > \Pi_{k2}^{NI,NI}$ (Since the other two equilibria are found by changing signs on these inequalities, they are not shown). More explicitly,

$$\frac{1}{9}(a-c-t'(\gamma-\alpha))^2 - Z > \frac{1}{9}(a-c-2t'(\gamma-\alpha)+\gamma t)^2, \text{ and}$$
$$\frac{1}{9}(a-c-2\gamma t+t'(\gamma-\alpha))^2 - Z > \frac{1}{9}(a-c-t\gamma)^2$$

Solving for Z in each inequality,

$$\frac{1}{9}(a-c-t'(\gamma-\alpha))^2 - \frac{1}{9}(a-c-2t'(\gamma-\alpha)+\gamma t)^2 > Z, \text{ and}$$
$$\frac{1}{9}(a-c-2\gamma t+t'(\gamma-\alpha))^2 - \frac{1}{9}(a-c-t\gamma)^2 > Z.$$

which simplifies to

$$\frac{4}{9}(a-c-t\gamma)(t\gamma-t'(\gamma-\alpha)) > Z, \text{ and}$$
$$\frac{4}{9}(t\gamma-t'(\gamma-\alpha))(a-c-t'(\gamma-\alpha)) > Z.$$

Since $Z < \frac{4}{9}(a-c-t\gamma)(t\gamma-t'(\gamma-\alpha))$ is more restrictive than the second inequality, this is needed for *(Invest, Invest)* to be the Nash equilibrium.

5.5 Quota

In the case of a binding emissions quota, $\bar{E} = q_{kn}e_{kn}$, each firm k will choose $q_{kn} = \frac{\bar{E}}{\gamma}$ if the firm does not invest in the abatement technology (and in the first stage), and $q_{k2} = \frac{\bar{E}}{\gamma-\alpha}$ if it does invest in the abatement technology. Profit functions from before are unchanged except that the firms no longer face a fee, i.e.

$$\Pi_{i2}^{INV} = (a - (q_{i2} + q_{j2}))q_{i2} - cq_{i2},$$
$$\Pi_{i2}^{NI} = (a - (q_{i2} + q_{j2}))q_{i2} - cq_{i2}.$$

Plugging the appropriate equilibrium quantities into the above profit functions yields the equilibrium under each combination of invest and not invest, which are presented in the following table.

	Quantity	Profit
Neither firm invests	$q_{i2} = \frac{\bar{E}}{\gamma}$	$\Pi_{i2}^{NI,NI} = \frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}$
Both firms invest	$q_{i2} = \frac{\bar{E}}{\gamma-\alpha}$	$\Pi_{i2}^{I,I} = \frac{\bar{E}((a-c)(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2}$
Firm i invests, firm j does not	$q_{i2} = \frac{\bar{E}}{\gamma-\alpha}$	$\Pi_{i2}^{I,NI} = \frac{\bar{E}(\gamma(a-c)(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2}$
Firm j invests, firm i does not	$q_{i2} = \frac{\bar{E}}{\gamma}$	$\Pi_{i2}^{NI,I} = \frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma}$

Table 7. Equilibrium quantity and profit under the baseline quota.

We can solve for the limit on Z that supports the different equilibria using the same process as proposition 1. The Nash equilibrium is *(Invest, Invest)* if the dominant strategy for both firms is to invest. For this, both $\Pi_{k2}^{I,I} - Z > \Pi_{k2}^{NI,I}$ and $\Pi_{k2}^{I,NI} - Z > \Pi_{k2}^{NI,NI}$. More explicitly,

$$\frac{\bar{E}((a-c)(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2} - Z > \frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma}, \text{ and}$$
$$\frac{\bar{E}(\gamma(a-c)(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2} - Z > \frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}.$$

Solving for Z in each inequality,

$$\frac{\bar{E}((a-c)(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2}-\frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma}>Z, \text{ and}$$
$$\frac{\bar{E}(\gamma(a-c)(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2}-\frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}>Z.$$

which simplifies to

$$\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{\gamma^2(\alpha-\gamma)^2}>Z, \text{ and}$$
$$\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-2\alpha))}{\gamma^2(\alpha-\gamma)^2}>Z.$$

Since $Z<\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{\gamma^2(\alpha-\gamma)^2}$ is more restrictive than the second inequality, this is needed for *(Invest, Invest)* to be the Nash equilibrium. For this equilibrium to be feasible, we need that the numerator is positive, or $\bar{E}<\frac{\gamma(a-c)(\gamma-\alpha)}{3\gamma-\alpha}$.

The Nash equilibrium is *(No Invest, No Invest)* if the dominant strategy for both firms is to not invest. For this, both $\Pi_{k2}^{NI,I}>\Pi_{k2}^{I,I}-Z$ and $\Pi_{k2}^{NI,NI}>\Pi_{k2}^{I,NI}-Z$. This is a similar system to above,

$$\frac{\bar{E}((a-c)(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2}-Z<\frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma}, \text{ and}$$
$$\frac{\bar{E}(\gamma(a-c)(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2}-Z<\frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}.$$

This simplifies to

$$\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{\gamma^2(\alpha-\gamma)^2}<Z, \text{ and}$$
$$\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-2\alpha))}{\gamma^2(\alpha-\gamma)^2}<Z.$$

For the *(No Invest, No Invest)* equilibrium, we need the more restrictive condition, i.e. $Z > \frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-2\alpha))}{\gamma^2(\alpha-\gamma)^2}$.

The final set of equilibria occurs when each firm will invest only if the other firm chooses not to invest, so the Nash equilibria are *(Invest, No Invest), (No Invest, Invest)* and a mixed strategy where firms will randomize over the two actions if the expected profit from investing and not investing are equal. This occurs when $\Pi_{k2}^{NI,I} > \Pi_{k2}^{I,I} - Z$ and $\Pi_{k2}^{I,NI} - Z > \Pi_{k2}^{NI,NI}$, or, more explicitly

$$\frac{\bar{E}((a-c)(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2} - Z < \frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma}, \text{ and}$$
$$\frac{\bar{E}(\gamma(a-c)(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2} - Z > \frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}.$$

This simplifies to

$$\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-\alpha))}{\gamma^2(\alpha-\gamma)^2} < Z, \text{ and}$$
$$\frac{\bar{E}\alpha(\gamma(a-c)(\gamma-\alpha)-\bar{E}(3\gamma-2\alpha))}{\gamma^2(\alpha-\gamma)^2} > Z.$$

which is the range that Z needs to be in to support the *(Invest, No Invest), (No Invest, Invest)* equilibrium.

If a mixed strategy exists and the probability that firm j adopts the technology is σ_Q and the probability firm j does not invest is $(1-\sigma_Q)$, then firm i is indifferent between invest and no invest if

$$\sigma_Q(\Pi_{i2}^{I,I} - Z) + (1-\sigma_Q)(\Pi_{i2}^{I,NI} - Z) = \sigma_Q \Pi_{i2}^{NI,I} + (1-\sigma_Q)\Pi_{i2}^{NI,NI},$$

$$\sigma_Q(\frac{\bar{E}((a-c)(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2} - Z) + (1-\sigma_Q)(\frac{\bar{E}(\gamma(a-c)(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2} - Z)$$
$$= \sigma_Q \frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma} + (1-\sigma_Q)(\frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}),$$

$$\sigma_Q\left(-\frac{\alpha^2\bar{E}^2}{\gamma^2(\alpha-\gamma)^2}\right) = \frac{\alpha\gamma\bar{E}(a-c)(\alpha-\gamma)+\alpha\bar{E}^2(3\gamma-2\alpha)+\gamma^2 Z(\alpha-\gamma)^2}{\gamma^2(\alpha-\gamma)^2}$$
$$\sigma_Q\alpha^2\bar{E}^2 = \bar{E}\alpha\gamma(a-c)(\gamma-\alpha)-\alpha\bar{E}^2(3\gamma-2\alpha)+\gamma^2 Z(\gamma-\alpha)^2$$
$$\sigma_Q = \frac{\bar{E}\alpha\gamma(a-c)(\gamma-\alpha)-\alpha\bar{E}^2(3\gamma-2\alpha)+\gamma^2 Z(\gamma-\alpha)^2}{\alpha^2\bar{E}^2}$$

5.6 Asymmetric cost of adoption under a quota

The profit functions are the same as above but allowing for $Z_i < Z_j$:

- If both firms invest, each firm has profit $\Pi_{k2}^{I,I} = \frac{\bar{E}((a-c)(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2} - Z_k$
- If one firm invests, the investing firm has profit $\Pi_{k2}^{I,NI} = \frac{\bar{E}(\gamma(a-c)(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2} - Z_k$, and the firm that does not invest has profit $\Pi_{k2}^{NI,I} = \frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma}$
- If neither firm invests, each firm has profit $\Pi_{k2}^{NI,NI} = \frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}$

Solving for the equilibrium in this setting follows directly from the symmetric adoption under a quota.

5.7 Investment increases marginal cost of production under a quota

Since equilibrium quantity under the quota is bounded, a change in the marginal cost of production from adoption will not affect the equilibrium quantities in each case, the only change from the symmetric quota is the profit of the firm when they invest. Equilibrium quantities and profits are presented in the following table.

	Quantity	Profit
Neither firm invests	$q_{i2} = \frac{\bar{E}}{\gamma}$	$\Pi_{i2}^{NI,NI} = \frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}$
Both firms invest	$q_{i2} = \frac{\bar{E}}{\gamma-\alpha}$	$\Pi_{i2}^{I,I} = \frac{\bar{E}((a-c')(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2}$
Firm i invests, firm j does not	$q_{i2} = \frac{\bar{E}}{\gamma-\alpha}$	$\Pi_{i2}^{I,NI} = \frac{\bar{E}(\gamma(a-c')(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2}$
Firm j invests, firm i does not	$q_{i2} = \frac{\bar{E}}{\gamma}$	$\Pi_{i2}^{NI,I} = \frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma}$

Table 8. Equilibrium quantity and profit under the baseline quota when adoption increases the marginal cost of production.

We can solve for the limit on Z that supports the different equilibria using the same process as proposition 1. The Nash equilibrium is *(Invest, Invest)* if the dominant strategy for both firms is to invest. For this, both $\Pi_{k2}^{I,I} - Z > \Pi_{k2}^{NI,I}$ and $\Pi_{k2}^{I,NI} - Z > \Pi_{k2}^{NI,NI}$. More explicitly,

$$\frac{\bar{E}((a-c')(\gamma-\alpha)-2\bar{E})}{(\alpha-\gamma)^2} - Z > \frac{\bar{E}\left(a-c-\bar{E}\left(\frac{1}{\gamma-\alpha}+\frac{1}{\gamma}\right)\right)}{\gamma}, \text{ and}$$
$$\frac{\bar{E}(\gamma(a-c')(\gamma-\alpha)-\bar{E}(2\gamma-\alpha))}{\gamma(\gamma-\alpha)^2} - Z > \frac{\bar{E}(\gamma(a-c)-2\bar{E})}{\gamma^2}.$$

which simplifies to

$$\frac{\bar{E}(\alpha\bar{E}(\alpha-3\gamma)-\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma))}{\gamma^2(\alpha-\gamma)^2} > Z, \text{ and}$$
$$\frac{\bar{E}(\alpha\bar{E}(2\alpha-3\gamma)-\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma))}{\gamma^2(\alpha-\gamma)^2} > Z.$$

Since $Z < \frac{\bar{E}(\alpha\bar{E}(\alpha-3\gamma)-\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma))}{\gamma^2(\alpha-\gamma)^2}$ is more restrictive than the second inequality, this is needed for *(Invest, Invest)* to be the Nash equilibrium. For this to be positive, we need both $\bar{E} < \frac{\gamma(\alpha-\gamma)((a-c)\alpha+(c-c')\gamma)}{\alpha(\alpha-3\gamma)}$, and $c' - c < \frac{(a-c)\alpha}{\gamma}$.

Since $t < \frac{a-c}{\gamma}$, in order for this to be a potential equilibrium, it must also be that $t > \frac{c'-c}{\alpha}$. Or, combining, $\frac{c'-c}{\alpha} < t < \frac{a-c}{\gamma} \rightarrow c' - c < \frac{(a-c)\alpha}{\gamma}$. The remaining equilibria are found by changing the signs on equality.

In the case of a mixed strategy, if the probability of firm k choosing 'invest' is $\sigma_{Qc} = \frac{4(c'-c-t\alpha)(-a+c'+t(\gamma-\alpha))-9Z}{4(c-c'+t\alpha)^2}$, then firm k will be indifferent between 'invest' and 'not invest'. If the probability of the other firm investing is greater than σ_{Qc}, then the firm will not invest.

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