Investment in Green Technology and Entry Deterrence*

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Abstract

This paper analyzes an entry-deterrence model in which the incumbent decides whether to invest in research and development (R&D) that promotes clean technology. We consider the case in which the entrant could benefit from a technology spillover, and analyze the conditions that facilitate the incumbent's entry-deterrence behavior. We show that higher levels of the spillover make entry more attractive compared to a standard entry game. In addition, regulator and incumbent prefer entry when the spillover from clean technology is sufficiently high and the cost of investing in R&D is relatively low. However, preferences are misaligned when the spillover and cost of R&D are low.

Keywords: Entry-deterrence; Emission fee; Research and development; Spillover.

JEL Classification: H23; L12; O32; Q58.

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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] As a consequence, firms' investment in R&D can be understood as a tool that firms use to ameliorate the cost of environmental policy. The literature has shown that environmental regulation can potentially affect the market structure in which firms operate.[3] 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.[4] 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 facilitate or deter entry?, When would an incumbent firm 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, the entrant decides whether or not to enter, and given the market structure, the regulator sets an emissions fee based on the investment in abatement technology by the incumbent; and (3)

[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] See Dean and Brown (1995), Millimet et al. (2009), and Espínola-Arredondo and Muñoz-García (2013).

[4] National Science Foundation's Science and Engineering Indicators 2016 report, which can be found at: *https://www.nsf.gov/statistics/2016/nsb20161/#/report/chapter-6/highlights/investment-and-innovation-in-clean-energy-technologies-highlights*.

in the third stage, firms compete à la Cournot if entry occurs, otherwise the incumbent acts as a monopolist.

As mentioned before, one way firms seek to reduce the burden of an emission fee is to invest in pollution-reducing technology, such as end-of-the-pipe abatement. The incumbent firm patents a share of the innovation, but a proportion of the knowledge is not patentable, thus being available to potential entrants (spillover). 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).[5] In addition, there has been considerable investment in environmental R&D within the industry, one example of this is Conoco Phillips.[6] A portion of the R&D focuses on cleaning and preventing groundwater from being contaminated with harmful substances. Hence, the knowledge about abating pollution can spill over to a potential entrant.

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 complete and incomplete information. We contribute to this literature by considering the effect of regulation on R&D with spillovers and its effect on entry-deterrence.

A number of papers investigate the role of research and development structure (cooperative/non-cooperative) in an oligopolistic industry, but are silent about its effect on entry deterrence.[7] In addition, they focus on R&D with spillover effects that lower production costs. In contrast, we consider R&D that reduces harmful emissions from production, identifying the strategic effects of

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

[6] 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*.

[7] See D'Aspremont and Jacquemin (1988), Damania (1995), Miyagiwa and Ohno (2002), Poyago-Theotoky (2007), Stepanova and Tesoriere (2011), and Tesoriere (2015)).

the emission fee on firms' investment. 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 co-operation between them vary. In contrast, our paper focuses on the relationships between the spillover, entry deterrence, 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 entry occurs, 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. In this case, the regulator could promote entry-deterrence by changing the entry costs through increasing the administrative and licensing costs to potential entrants. When entry costs are increased, the entry-deterring level of investment in R&D 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 by lowering its cost, 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 those firms that have invested in R&D with high spillover effects.[8]

The next section of the paper presents the model and equilibrium comparisons. Section 3 examines the incumbent's entry-deterrence behavior, and section 4 discusses social welfare. Section 5 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. [9] 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. Cost convexity indicates decreasing returns to investing in abatement.

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.[10] As a result of the

[8] 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*.

[9] Our model investigates how the threat of entry affects an incumbent's decision to invest in abatement technology. Allowing the entrant to also acquire the technology reduces the free riding effect and has a smaller impact on the incumbent's investment.

[10] This form of the abatement technology models the separate nature of end-of-the-pipe abatement and production, similar to Poyago-Theotoky (2007).

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 the proportion of the incumbent's innovation that cannot be patented and thus can be freely used by the entrant.

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 environmental damage, $\frac{1}{2}d(Q - (1+\beta)z)^2$, 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 both market structures. This specification allows us to provide comparisons with Poyago-Theotoky (2007), who uses the same environmental damage function.[11]

We next describe the time structure of our model. 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 to join the market, and the regulator maximizes social welfare by choosing the per unit emissions tax (t) levied on polluting firms. In the third and final stage, 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.[12] As a benchmark for comparison, in each stage 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.

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[11] Comparison to the equilibrium in the paper is provided in the Appendix, section 6.7.

[12] 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. **Third Stage: Production**

If entry does not occur, the incumbent solves,

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

which occurs at $q_i(t) = \dfrac{a-c-t}{2}$, yielding $\pi_i^{ne}(t) = \dfrac{(a-c-t)^2}{4} + tz$. In order to guarantee a positive output level when there is no R&D, $t < a - c$. Hence, the incumbent has incentive to reduce the emission fee through investing in abatement technology.

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

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

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

which yields the standard Cournot output, $q_i = q_e = q = \dfrac{a-c-t}{3}$, and profits, $\pi_i^{ent} = \frac{2(a-c-t)^2}{9} + tz$ and $\pi_e^{ent} = \frac{2(a-c-t)^2}{9} + t\beta z - F$. Like the case of no entry, an increase in the emissions tax, t, decreases the profit-maximizing quantity. Finally, in both cases (no entry and entry), profits decrease in the emission fee if the investment in R&D, z, is sufficiently low.

2.2. **Second Stage: Regulation**

Given no entry, the regulator maximizes social welfare (SW) by choosing the emission fee t as follows,

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

where the first term is the sum of consumer and producer surplus from production,[13] 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 optimal emission fee as a function of R&D investment undertaken by the incumbent in the first

[13] Tax revenue is included in the first term.

stage,

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

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.

Similarly, in the case of entry, the regulator solves,

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

Differentiating and solving for t yields the optimal tax,

$$t^{ent}(z) = \frac{(a-c)(2d-1) - 3(\beta+1)dz}{2(d+1)}. \tag{2}$$

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.

2.3. **First Stage: Abatement**

In the first stage, the incumbent anticipates the actions in the second and third stages and, in the case of no entry, 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, $\frac{1}{2}\gamma z^2$. The following proposition finds the optimal investment in R&D, emission fee, and quantity produced.[14]

[14] All proofs are relegated to the appendix.

Proposition 1. *The equilibrium investment in abatement, tax, quantity produced, and profits under no entry are,*

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

$$t^{ne} = \frac{(a-c)\left[\gamma\left(d^2-1\right) - 2d\delta\right]}{\gamma(d+1)^2 + 2d(d+2)\delta}, \tag{4}$$

$$q^{ne} = \frac{(a-c)[\gamma(d+1) + d(d+3)\delta]}{\gamma(d+1)^2 + 2d(d+2)\delta}, \tag{5}$$

where $z^{ne} > 0$ *and* $q^{ne} > 0$ *for all parameter values. In addition,* $\Pi_i^{ne} = \frac{\delta(a-c)^2\left(2\gamma+\delta(d+1)^2\right)}{2\gamma(d+1)^2+4d\delta(d+2)}$, *and* $t^{ne} > 0$ *if* $\gamma > \frac{2d\delta}{d^2-1}$.

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 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.[15]

In the case of entry, 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, individual and quantity, and profits produced under entry are,*

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

$$t^{ent} = \frac{(a-c)\left[2\gamma\left(2d^2+d-1\right) - d(\beta+1)(2(\beta-2)d+3)\delta\right]}{4\gamma(d+1)^2 + 2d(\beta+1)((5-\beta)d+6)\delta}, \tag{7}$$

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

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

where $z^{ent} > 0$ and $q^{ent} > 0$ for all parameter values. Aggregate quantity produced is $Q^{ent} = 2q^{ent}$, and profits are

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

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

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

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 $\gamma > \frac{(\beta+1)d\delta(2(\beta-2)d+3)}{2(2d^2+d-1)}$; or

(3) if $d > \frac{3}{2}$; otherwise, $t^{ent} \leq 0$.

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. Similar to the case when there is no entry, the regulator sets a fee if the reduction in social welfare from pollution outweighs the gains in consumer surplus from increasing output. 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 from the entrant. The regulator therefore sets an emission fee to reduce pollution through lower output. 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, thus reducing the incentives for the incumbent to invest and 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 the equilibrium investment in R&D and emission fee under no entry and entry.

2.4. **Equilibrium Comparison**

Next, we compare the no entry equilibrium (equations (3), (4), (5)) with the entry equilibrium (equations (6), (7), and (8)). We start by examining the investment in R&D.

Corollary 1. *The incumbent invests more in R&D when there is no threat of entry into the market than otherwise.*

When there is entry, even without a spillover (i.e. $\beta = 0$), any investment in abatement lowers the emission fee faced by both firms. 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 2. *The incumbent's production increases when there is no threat of entry. In addition, the aggregate quantity under no entry is greater than that under entry if* $\beta < \theta$ *and for all values of* γ*, 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* $\gamma < \frac{d\delta(1+\beta)((1-\beta)d(d+3)-2)}{(d+1)(1-\beta+d(\beta(\beta+2d+3)-2))}$*. Otherwise, aggregate quantity under entry exceeds that under no entry.*

In the case of 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 depends on the spillover. This result describes how the free riding effect from the spillover affects the incumbent's output level. In Appendix 6.8, we show that 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 2), leading to a higher emission fee under entry.

The following section discusses how the incumbent can lower its investment in R&D to deter entry.

3. Entry deterrence

The monopolist has incentive to under-invest in R&D if it leads to a situation of entry deterrence, inducing its competitor to stay out of the market, and the profits from such an under-investment are greater than those from accommodating entry. Hence, we first need to identify the value of investment in R&D that makes the entrant obtain zero profits, i.e. $\hat{z}$, 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 the accommodating profit, Π_i^{ent}.

Corollary 3. *The level of R&D that deters entry solves $\pi_e^{ent}(\hat{z}) = 0$, 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 represents the case 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 $\hat{z}$.[16] The incumbent has incentives to deter entry if its entry deterrence profit, $\Pi_i^{ED}(\hat{z})$ (see point A), are higher than those from accommodating entry, $\Pi_i^{ent}(z^{ent})$ (see 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

[16] Parameter values for figure 1 are $a = 10, c = 1, d = 2.5, \beta = .25, \delta = 1, \gamma = 1.5$, and $F = 3$. The results are robust to a large range of parameter values.

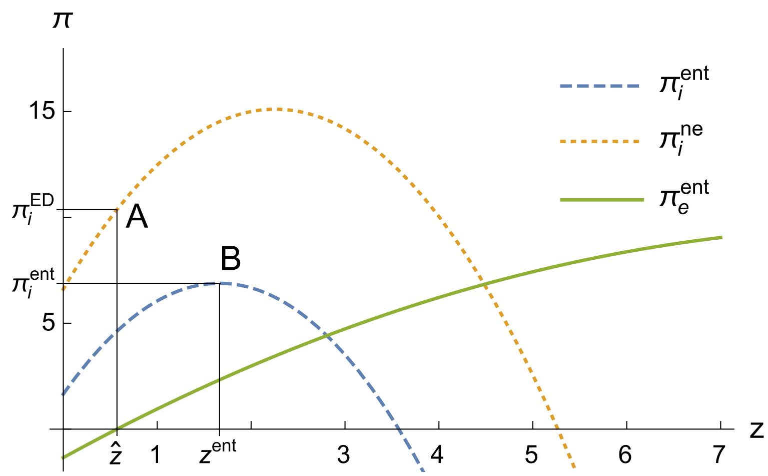

FIGURE 1. The monopolist prefers to deter entry by under-investing in R&D.

as entry is blockaded. We next investigate the levels of fixed costs that facilitate these different situations.

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 identify two values of fixed entry costs that represent 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.[17]

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* $\eta = \beta + d\left(-\beta^2 + \beta + 4\beta d^2 + 2(\beta+1)^2 d + 5\right)$.

Figure 2 (which uses the same parameter values as figure 1) shows the regions where entry is accommodated, deterred, and blockaded. As shown in the figure, $\bar{F}$ is upward sloping as the

[17] The complexity of the profit functions makes the analytic solutions intractable and unable to solve for $\underline{F}$ analytically.

spillover increases. Intuitively, as the benefits from investment in R&D increase through a higher spillover, a higher fixed cost is required to make entry unprofitable. 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, thus requiring the incumbent to lower investment, and face a higher emission fee, if it seeks to deter entry.

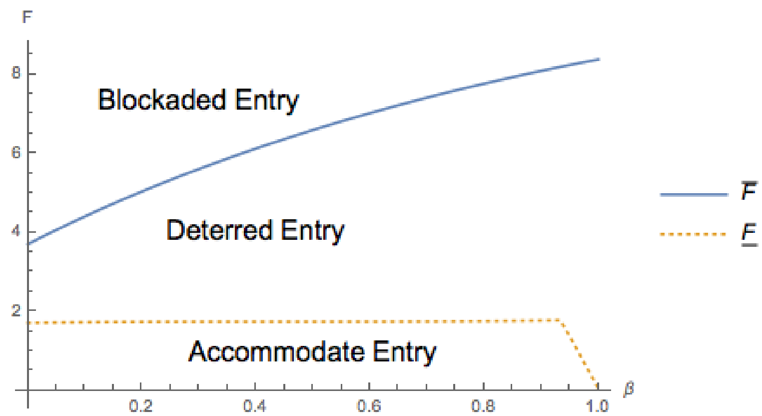

FIGURE 2. Regions of fixed cost that accommodate, deter, and blockade entry.

Figure 3 depicts how an increase in the environmental damage affects $\underline{F}$ and $\bar{F}$ (the new levels of fixed cost limits are denoted by $\underline{F}'$ and $\bar{F}'$). As presented 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. The higher environmental damage incentivizes the incumbent to invest in more R&D at all levels of the spillover. At low levels of the spillover, the entrant does not reap the benefits from increased R&D and faces a higher fee when the environmental damage is high, i.e., $d = 5$. At higher levels of the spillover, the entrant is able to take advantage of the incumbent's increased R&D through lower emissions and a lower fee, hence, lowering its costs and increasing the level of fixed cost that blockades entry. A similar, but more extreme shift happens to $\underline{F}$. Except for at very low levels of the spillover, the fixed cost that accommodates entry increases. At higher levels of environmental damage, the increased emission fee is more harmful to profits than competition. This results in the apparent shrinking' of the area where entry is deterred. The benefits from a decreased fee increasingly outweigh the benefits from deterring entry as the spillover increases. Therefore, decreasing R&D to deter entry is only profitable to the incumbent if it does not have to decrease its investment very far, which requires a higher fixed cost than the case in which environmental damage is low.

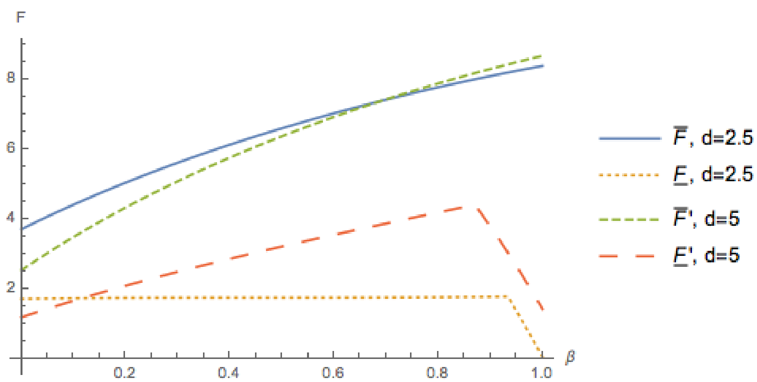

Figure 3. The incumbent's strategic behavior under different levels of d.

Figure 4 shows how cutoffs $\underline{F}$ and $\bar{F}$ change when the cost of investment, γ, increases (the new levels of fixed cost cutoffs 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 spillover close to one). An increase in the cost of investment decreases the investment in R&D , thus decreasing the entrant's benefits due to a higher emission fee. This increase in costs produces a downward shift of the cutoff for which entry is blockaded, expanding the region under which blockaded entry is supported. In addition, a more expensive investment makes entry-deterrence more attractive when the entry cost is low (since, for most values of β, $\underline{F}''$ is lower than $\underline{F}$). With the increase in investment cost, investment decreases in the case of entry and profits decrease, but the level of investment needed to deter entry does not change ($\hat{z}$ does not depend on γ). Hence, the incumbent is more willing to lower its investment in R&D to deter entry than when its costs are lower.

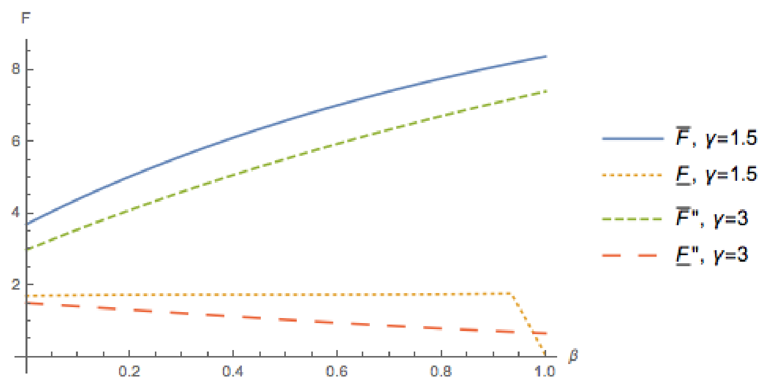

Figure 4. The incumbent's strategic behavior under different levels of γ.

4. 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 tractable or intuitive. Therefore, we analyze the social welfare numerically and graphically with parameter values consistent with the rest of the analysis (see Appendix 6.9).

Let us first investigate when the incentives of the regulator and incumbent align. To do this, we take the difference of social welfare under entry and no entry (blockaded entry), set it equal to zero, and solve for F, obtaining cutoff $\tilde{F}$. 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 (see figure 5). The area below $\tilde{F}$ (regions II and III), represents the case in which social welfare under entry is higher than under no entry, and above $\tilde{F}$ the opposite occurs (no entry is socially preferred). In this numerical example, there is no region where the regulator would support entry deterrence. Entry deterrence reduces abatement and eliminates competition, both effects decrease social welfare.

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. In these two cases, the regulator does not need to engage in policies that alter fixed costs of entry, since equilibrium behavior is socially optimal. Specifically, in region V, no entry is socially preferred since

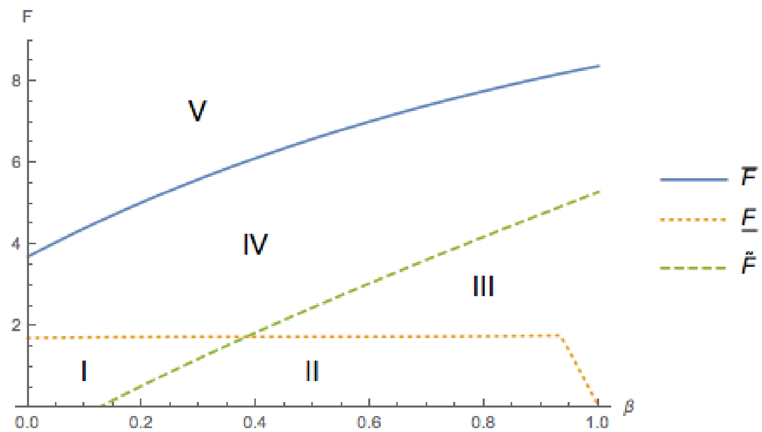

FIGURE 5. Pairs of (F, β) where social welfare under entry and no entry coincide.

social welfare under no entry is higher than under entry. In region II, however, entry is socially preferred given that entry costs are low and the spillover is high enough to make social welfare under entry the highest.

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. In this case, the regulator can induce a socially optimal outcome either by promoting investment with high spillover effects or significantly increasing 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, for instance, by increasing the administrative costs to the entrant. 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]

[18] A robustness check on the regions described in Figure 5 as provided in the Appendix (section 6.8) with different values of d and γ.

From a policy standpoint, if the incumbent decides to deter entry by under-investing in R&D, social welfare under entry deterrence can be greater than under entry 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.

5. Conclusion

We analyze how an entry-deterrence model is affected by the inclusion of investment in R&D with environmental regulation and the possibility of spillover to a potential entrant. Our results show that, if entry costs and spillover effects are intermediate, the incumbent has incentives to deter entry by strategically under-investing in clean R&D to make entry unprofitable. We also identify, that under large parameter conditions, such equilibrium behavior is not socially optimal. In two contexts, the regulator may choose to lower entry and administrative costs to tilt equilibrium behavior towards settings where the incumbent finds it optimal to allow entry by investing a large amount on R&D.

Entry 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, 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 increase 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.

As further research, we could consider the case when the regulator pre-commits to regulation; changing the structure of the game so that the regulator acts in the first stage and chooses the emission fee, R&D is chosen in the second stage, and the final stage is unchanged. Preliminary results show that in the case of regulator pre-commitment, the incumbent may invest more in R&D when there is entry into the market than if there is not entry (contrary to the results from this model). When the regulator pre-commits to a fee, the entrant no longer benefits from the incumbent's R&D through a lower emission fee, thus decreasing the free-riding benefits it would have if the regulator were to set the fee after the R&D decision. It would also be interesting to study the case where there are multiple incumbents facing the threat of entry. The new setting could reinforce downward pressures on the already low investment in abatement technology in each framework. 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 deter entry since incumbent and entrant do not produce an identical good.

6. Appendix

6.1. 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:

$$t^{ne} = \frac{(a-c)\left(\gamma\left(d^2-1\right) - 2d\delta\right)}{\gamma(d+1)^2 + 2d(d+2)\delta}, \tag{9}$$

$$q^{ne} = \frac{(a-c)(\gamma(d+1) + d(d+3)\delta)}{\gamma(d+1)^2 + 2d(d+2)\delta}. \tag{10}$$

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

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

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

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

which holds for all parameter values.

6.2. 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

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

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

$$t^{ent} = \frac{(a-c)\left(2\gamma\left(2d^2+d-1\right)-d(\beta+1)(2(\beta-2)d+3)\delta\right)}{4\gamma(d+1)^2+2d(\beta+1)((5-\beta)d+6)\delta}, \tag{11}$$

$$q^{ent} = \frac{(a-c)(d(\beta+1)(2d+5)\delta+2\gamma(d+1))}{4\gamma(d+1)^2+2d(\beta+1)((5-\beta)d+6)\delta}. \tag{12}$$

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

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

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

$$2\gamma[(2d^2+d-1)-2(d+1)^2] < d\delta[2(\beta+1)((5-\beta)d+6)+(\beta+1)(2d(\beta-2)+3)],$$

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

which holds for all parameter values.

6.3. **Proof of Corollary 1.**

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 $\beta \in [0, 1]$.

6.4. **Proof of Corollary 2.**

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

$$q^{ne} > q^{ent},$$

$$\frac{(a-c)(\gamma(1+d)+d^2)}{2d^2+\gamma(1+d)^2} > \frac{(a-c)\left((\beta+1)^2d^2+2\gamma(1+d)\right)}{4(\beta+1)^2d^2+4\gamma(1+d)^2},$$

$$\frac{\gamma(d+1)+d(d+3)\delta}{\gamma(d+1)^2+2d(d+2)\delta} - \frac{(\beta+1)d(2d+5)\delta+2\gamma(d+1)}{4\gamma(d+1)^2-2(\beta+1)d\delta((\beta-5)d-6)} > 0,$$

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

$$\frac{(a-c)\left((\beta+1)^2 d^2 + 2\gamma(1+d)\right)}{2(\beta+1)^2 d^2 + 4\gamma(1+d)^2} < \frac{(a-c)(\gamma(1+d)+d^2)}{2d^2+\gamma(1+d)^2},$$

$$d\delta\{\gamma(d+1)[1-\beta+d(\beta(\beta+2d+3)-2)] + d\delta(1+\beta)((1-\beta)d(d+3)-2)\} < 0,$$

$$\gamma < \frac{d\delta(1+\beta)((1-\beta)d(d+3)-2)}{(d+1)(1-\beta+d(\beta(\beta+2d+3)-2))}.$$

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

6.5. **Proof of Corollary 3.**

To find the level of investment that deters entry, $\hat{z}$, we evaluate the entrant's profit as a function of the incumbent's investment z, where $t(z)$ and $q(t)$ are the equations from states 2 and 3 of the no entry equilibrium, respectively, that are used to obtain proposition 2. Therefore, the entrant's zero-profit condition 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,

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

$$q(t) = \frac{1}{3}(a-c-t)$$

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

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

where $\omega = a - c$ and $\alpha = (\beta(2d(d+1) - 1) + d)$.[19]

Under entry deterrence, using $\hat{z}$ and the emission fee and quantity used for proposition 1 ($t^{ne}(\hat{z})$ and $q = (a - c - t^{ne}(\hat{z}))/2$ from stages 2 and 3 of the no entry equilibrium, respectively), the incumbent's profit is

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

We compare this to the incumbent's profit when it accommodates entry, which comes from the equilibrium values in proposition 2 (z^{ent}, t^{ent}, and q^{ent}), is

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

If $\Pi_i^{ED}(\hat{z}) > \Pi_i^{ent}$, then it is more profitable for the incumbent to deter entry than to accommodate entry.

The analytic comparison between the incumbent's profit under entry deterrence and entry is intractable. Hence, we next provide a numerical comparison using the parameter values for figure 1: $a = 10, c = 1, d = 2.5, \beta = .25, \delta = 1, \gamma = 1.5$, and $F = 3$. If the incumbent accommodates entry, the incumbent's profit evaluated at $z^{ent} = 1.66$, $t^{ent} = 2.91$, and $q^{ent} = 2.03$ (from proposition 2) is $\Pi_i^{ent} = 6.89$. If the incumbent engages in entry deterrence, the incumbent will lower its investment to $\hat{z} = 0.57$ (from corollary 3), where the accompanying emission fee is set at $t^{ED} = 3.04$, and output is $q^{ED} = 2.98$ (the emission fee and quantity used for proposition 1, evaluated at $\hat{z}$, as previously explained). The incumbent's profit when it deters entry is $\Pi_i^{ED} = 10.37$.

6.6. **Proof of Proposition 3.**

The entrant's profit function in equilibrium is

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

[19] Solving for $\hat{z}$ leads to a quadratic, suggesting that there are two levels of investment that deter entry: a low and high level. We focus on the low level of investment, however the case of over-investing in R&D can occur if the spillover is high and the cost of investment is low, which is likely to result in an emissions subsidy.

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 $\eta = \beta + d\left(-\beta^2 + \beta + 4\beta d^2 + 2(\beta+1)^2 d + 5\right)$. We obtain the level of fixed cost that blocks entry by setting $\Pi_e^{ent} = 0$ and solving for F which is:

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

The value $\underline{F}$ is the limit of the region where $\Pi_i^{ent} > \Pi_I^{ne}(\hat{z})$, where $\hat{z}$ is a function of F. Solving $\Pi_i^{ent} = \Pi_I^{ne}(\hat{z})$ for F defines $\underline{F}$. An analytic solution to this cannot be found, so we turn our attention to the numerical analysis or $\underline{F}$ found in figures 2, 3, and 4.

6.7. **Comparative Statics with respect to the spillover**

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

$$\frac{\partial t^{ent}}{\partial \beta} = -\frac{3d\delta(a-c)\left((\beta+1)^2 d^2(2d+5)\delta + 2\gamma(d+1)(d(2\beta+2d+3)-1)\right)}{2\left((\beta+1)d\delta((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2} < 0,$$

$$\frac{\partial q^{ent}}{\partial \beta} = \frac{\delta(a-c)\left((\beta+1)^2(2d+5)\delta d^3 + 2\gamma(d+1)d(d(2\beta+2d+3)-1)\right)}{2\left((\beta+1)d\delta((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2} > 0,$$

$$\frac{\partial z^{ent}}{\partial \beta} = \frac{d\delta(a-c)\left(\delta(d(d(\beta(\beta+4)+4(\beta-2)d-15) - 2(\beta+1)) + 6) + 2\gamma(d+1)^2\right)}{\left((\beta+1)d\delta((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2} \lesseqgtr 0.$$

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 $\dfrac{\partial z^{ent}}{\partial \beta} < 0$.

6.8. **Social Welfare**

Social welfare under the cases of no entry and entry are

$$SW^{ne} = (a-c)^2 \frac{\left((\gamma-1)\gamma + (\gamma+3)d^4 + \left(\gamma^2+6\gamma+13\right)d^3 + \left(3\gamma^2+12\gamma+13\right)d^2 + \left(3\gamma^2+10\gamma-1\right)d\right)}{2\left(\gamma + (\gamma+2)d^2 + 2(\gamma+2)d\right)^2},$$

$$SW^{ent} = (a-c)^2\left[\frac{(\beta+1)^2 d\left(d\left(2\beta + 4d^2(4-\beta) + (5-\beta)(\beta+9)d + 29\right) - 1\right) - \gamma}{2\left((\beta+1)d((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2}\right.$$
$$\left. - \frac{\gamma d\left(22\beta + d\left(-\beta^2 + 44\beta + 8\beta d(d+4) + 4d(d+7) + 48\right) + 24\right) - 4\gamma^2(d+1)^3}{2\left((\beta+1)d((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2}\right] - F.$$

Solving $SW^{ne} - SW^{ent}(F) = 0$ for F, we can obtain $\tilde{F}$:

$$\tilde{F} = (a-c)^2 \Bigg[\frac{\gamma + (\beta+1)^2 d \left(d\left(-2\beta + 4(\beta-4)d^2 + (\beta-5)(\beta+9)d - 29\right) + 1\right)}{2\left((\beta+1)d((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2}$$

$$\frac{\gamma d \left(22\beta + d\left(-\beta^2 + 44\beta + 8\beta d(d+4) + 4d(d+7) + 48\right) + 24\right) - 4\gamma^2(d+1)^3}{2\left((\beta+1)d((\beta-5)d-6) - 2\gamma(d+1)^2\right)^2}$$

$$+ \frac{\left(\gamma^2(d+1)^3 + \gamma(d(d(d(d+6)+12)+10)-1) + d(d(d(3d+13)+13)-1)\right)}{2(\gamma + (\gamma+2)d(d+2))^2} \Bigg].$$

Using parameter values from figure 2 ($a = 10$, $c = 1$, $d = 2.5$, $\delta = 1$, and $\gamma = 1.5$), we can simplify $\tilde{F}$ as a function of β that can be plotted in figure 5:

$$\tilde{F} = \frac{\beta(\beta(\beta(15.401 - 36.6407\beta) + 814.382) + 1213.04) - 160.77}{(\beta(\beta-6.4) - 13.28)^2}.$$

Figures 6 and 7 look at how the regions where firm and regulator incentives align but with values of d and γ considered in figures 3 and 4, respectively. The different parameters do alter each region some, but the general results stay the same.

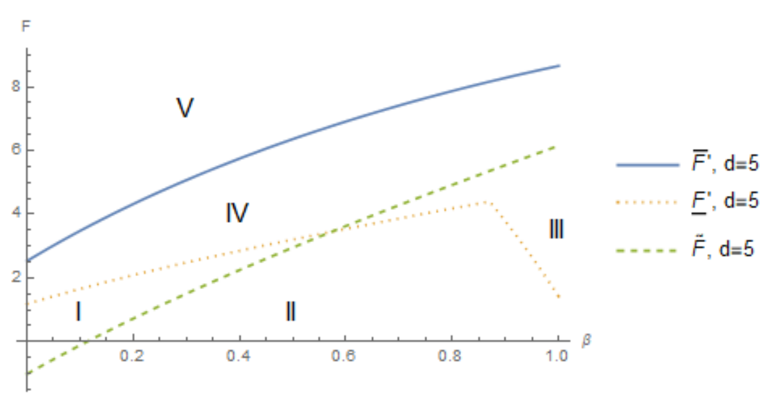

FIGURE 6. Pairs of (F, β) where social welfare under entry and no entry coincide where d has increased from 2.5 to 5.

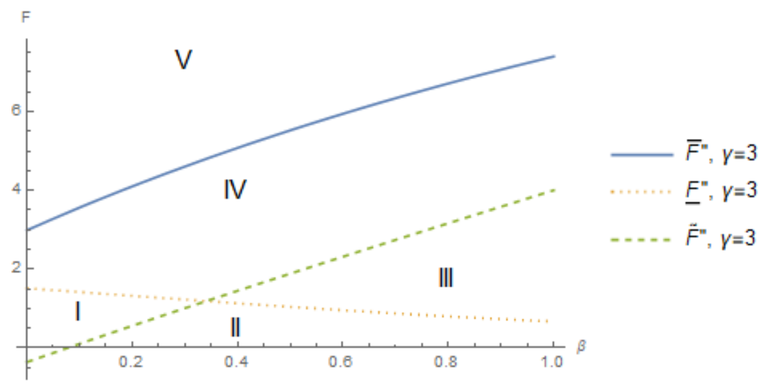

FIGURE 7. Pairs of (F, β) where social welfare under entry and no entry coincide where γ has increased from 1.5 to 3.

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