Regulation, Free-Riding Incentives, and Investment in R&D with Spillovers[*]

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Abstract

In this paper, we analyze a duopoly market with investment in abatement technology under environmental regulation. We use a three-stage game where firms invest in a green technology with spillover effects in the first stage, the regulator sets the emission fee in the second stage, and production of the polluting good occurs in the third stage. We analyze two different regulatory regimes: (1) each firm faces the same emission fee (uniform fee), and (2) each firm faces an emission fee dependent on the investment in green technology (type-dependent fee). Firms can differ through their costs of investing in the abatement technology (asymmetric efficiency). We obtain that social welfare is unambiguously higher under the type-dependent regime than otherwise. In addition, we find that the asymmetry in efficiency of investment affects firms' profits, identifying that efficient (inefficient) firms favor type-dependent (uniform) policy regimes.

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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 emission fees.[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 emission fee 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 amount of pollution. 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 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.

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

[2] Katsoulacos and Xepapadeas (1996, who consider an emission fee and simultaneous R&D subsidy), Montero (2002a, emissions standards, fee, tradeable permits, and auctioned permits), Poyago-Theotoky (2007, emission fee) and Strandholm and Espinola-Arredondo (2016, emission fee) 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. The following papers do not consider an R&D spillover: Biglaiser and Horowitz (1995, emission fee, technology standard, and R&D subsidy), Denicolo (1999, emission fees and permits), Conrad (2000, emission fee), and Montero (2002b, emission fees, performance standards, tradeable permits, and auctioned permits). 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; 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).

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 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 use our previous welfare ranking across policy regimes to identify a preference alignment between regulator and firms. This occurs when a firm is efficient at investing in R&D and 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),[5] 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 (2002b) 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;[6] and (3) in the third stage, every firm i competes

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[5]Amir (2000) discusses both approaches showing that they are equivalent when the spillover is not very large.

[6]We consider a complete information game where the regulator can perfectly infer firms' costs. This can be rationalized if there is repeated interaction with polluting firms, such as companies in the U.S. chemical industry which have faced recurrent regulation since the Clean Air Act in 1970. Alternatively, our setting also describes markets with polluting firms that were once publicly owned and managed, but have recently been privatized.

à la Cournot choosing its output level q_i[7]. For generality, firms can be symmetric in their R&D abilities, if $\gamma_i = \gamma_j$, or asymmetric, if $\gamma_i \neq \gamma_j$, where the latter can occur when one of the two firms has a previous history of innovation in the market, or in similar industries, while its rival lacks such experience. 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 $ED = \frac{1}{2}d(e_i^2 + e_j^2)$, where $d > 1$.[8] This function follows Munoz-Garcia and Akhundjanov (2016), and allows the environmental damages from each firm to mainly affect the area surrounding the firm, such as the discharge of hot water by power plants back to the river after using it as a coolant. Other types of pollution with relatively localized effects include noise pollution (near airports and highways, currently regulated by local authorities), light pollution (mostly regulated by city ordinances), and radioactive waste (which usually affects a relatively small area; as the Yucca Mountain nuclear waste repository). Appendix 1 shows that, in a context where pollution damage is linear or quadratic (i.e., pollution affects all jurisdictions), the emission fees under uniform and type-dependent regulation coincide. In such a setting, firms' investment in R&D also coincide across both regulatory regimes, and thus both regimes do not entail different welfare outcomes or profits in equilibrium.

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 $0 < \beta \leq 1$ firm i benefits from every unit of investment in R&D by firm j (either fully, if $\beta = 1$, or partially, if $0 < \beta < 1$).

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.*

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[7]This time structure can be rationalized by how time consuming R&D projects can become, as they often take months or years to be completed. Once the results of the projects are completed, our model considers that the regulator sets emission fees, and immediately after firms compete in quantities.

[8]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.

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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 $t_i(z_i, z_j)$. 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.[9]

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

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[9]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.

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

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

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.

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

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

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*

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

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.

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Corollary 1. *Consider that $\gamma_i < \gamma_j$. A symmetric marginal 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 $\left|\frac{\partial(z_i^K + z_j^K)}{\partial \gamma_i}\right| > \left|\frac{\partial(z_i^K + z_j^K)}{\partial \gamma_j}\right|$ 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, $t^U - t^{TD}$.[10] 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

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[10]All figures consider exogenous parameters $a = 10, c = 2, d = 3, \beta = 1/3, \gamma_i = 1/3$, 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.

both policies. As the spillover decreases (lower β) the uniform fee becomes more stringent than the type-dependent fee[11].
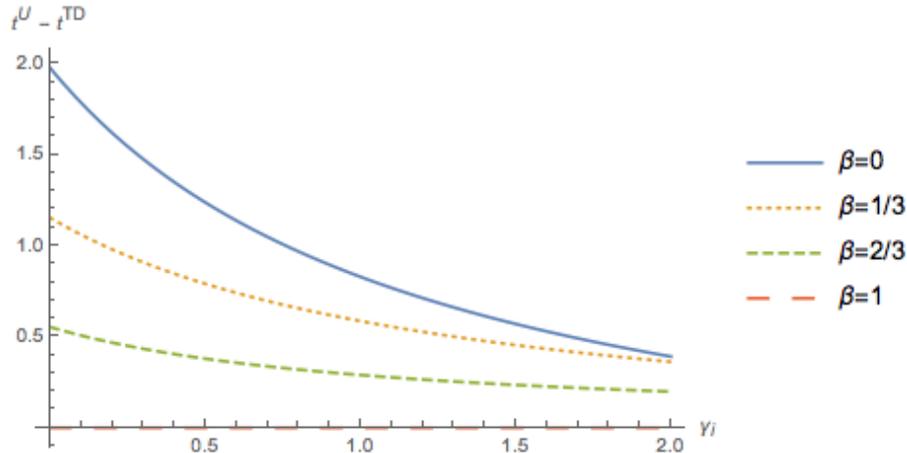

Figure 1: Difference between the uniform and type-dependent fees as a function of firm i's efficiency.

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.
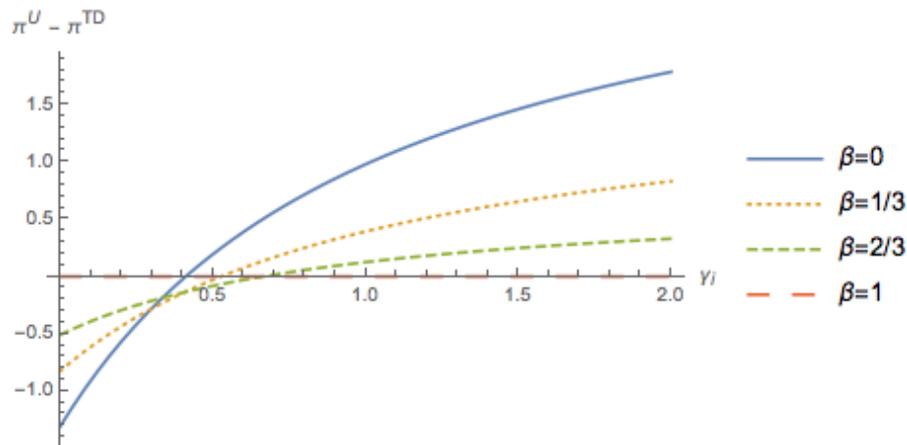

Figure 2: The difference in profits between the uniform and type-dependent fees as a function of firm i's efficiency.

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

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 is more stringent under the uniform than the type-dependent regime, while the opposite ranking applies to its rival, providing firm i with 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).[12] 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.
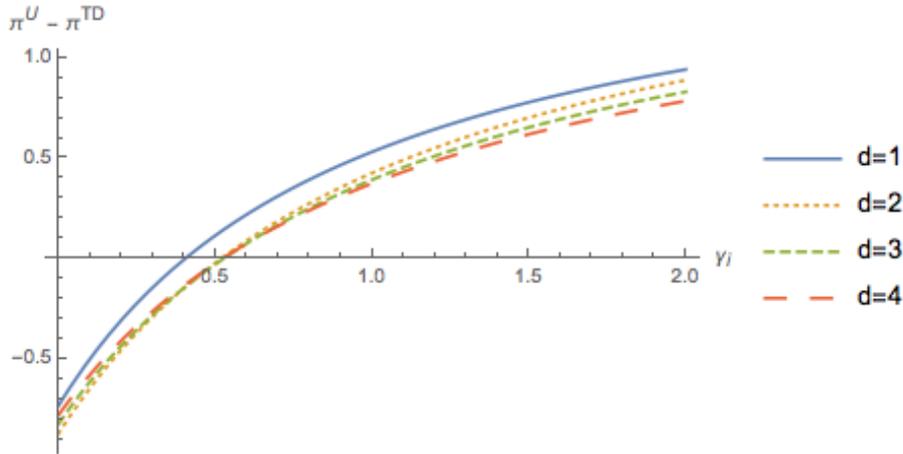

Figure 3: The difference in profits between the uniform and type-dependent fees as a function of firm i's efficiency.

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

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[12]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.

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.
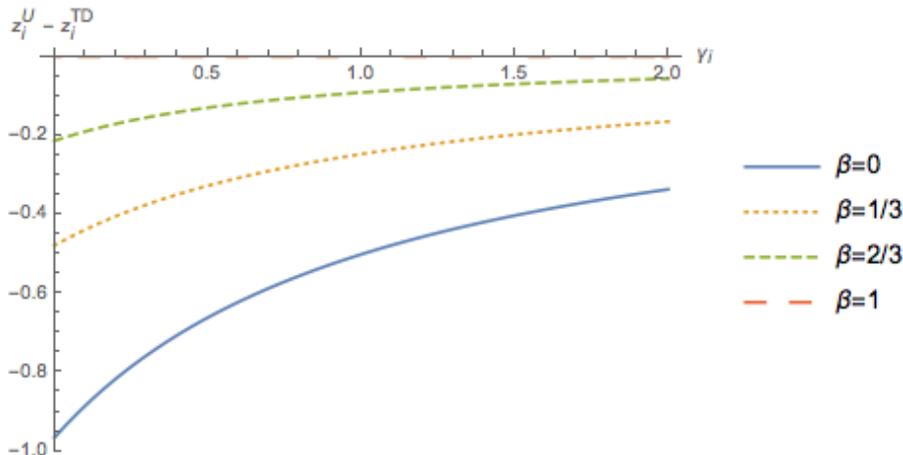

Figure 4: The difference in investment between the uniform and type-dependent fees as a function of firm i's efficiency.

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 welfare ranking could, however, be reversed if the cost of monitoring emission fees for each firm is significantly higher than measuring the overall emissions from the industry. 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.[13]

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 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.

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[13]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.
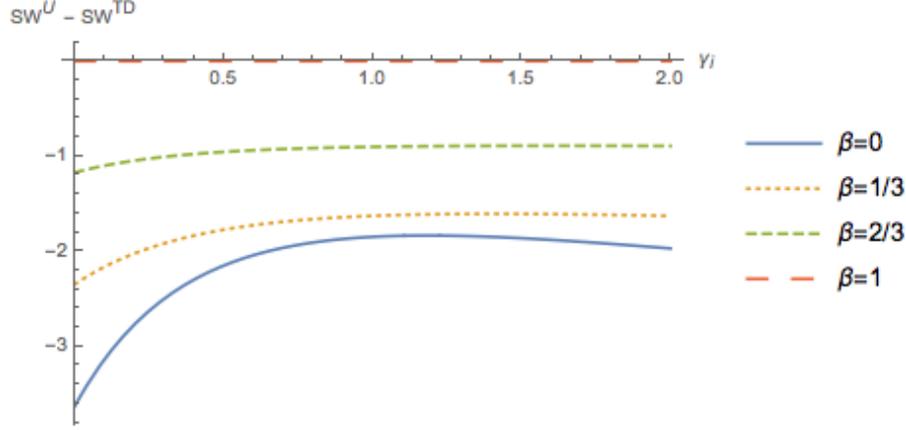
Figure 5: Social welfare difference between the two regulation types for different spillovers.
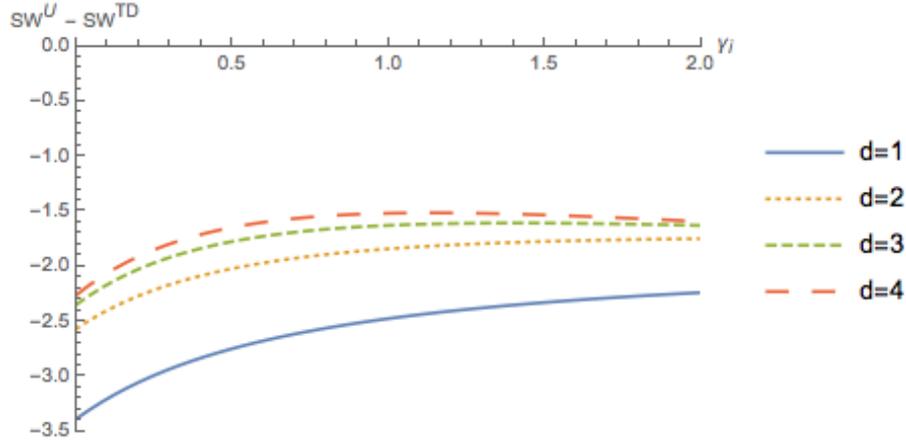

Figure 6: Social welfare difference between the two regulation types for different environmental damages.

This means that, under each regime, when firms are engaged in an ERC, each firm faces the same emission fee.[14]

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

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

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).[15] This figure shows that, under a uniform policy regime, the more efficient firm i invests more when joining an ERC

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[14]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.

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

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. Intuitively, as firm j benefits from a larger share of firm i's investment in R&D, the positive externalities that firm i generates becomes larger, emphasizing firm j's free-riding incentives. 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.
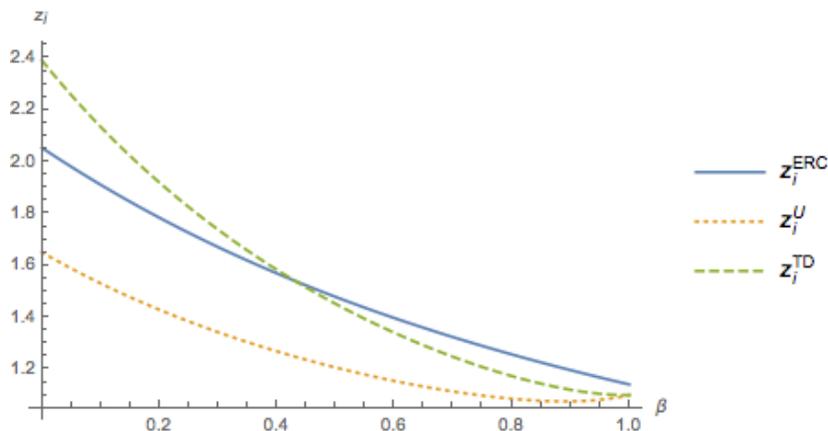

Figure 7: Investment in R&D as a function of the spillover under the two regimes and the ERC.

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. [16]

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

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[16]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.
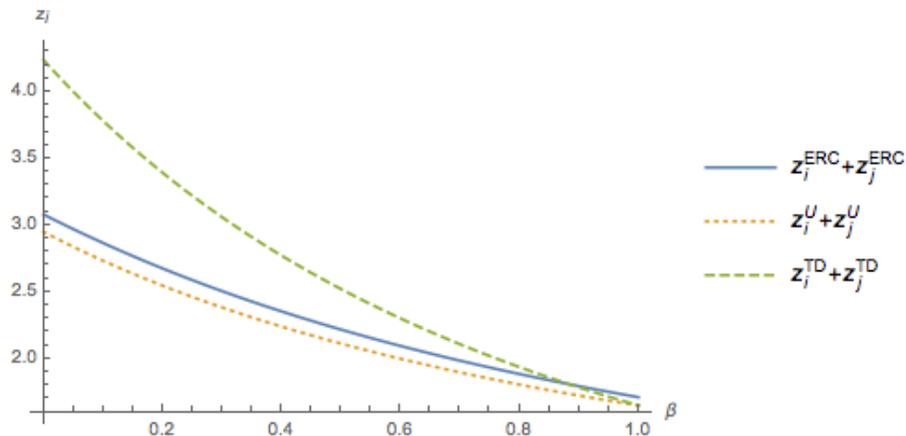
Figure 8: The total level of investment in R&D as a function of the spillover under the two regimes and the ERC.

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.

Further Research. Our model can be extended along different dimensions. First, we consider that R&D investment is deterministic, but a different setting could assume that firm i's investment z_i is succesful with a positive probability, affecting the difference in emission fees across policy regimes. Second, we consider that every firm benefits from its own R&D investment, and a share of its rival's (spillover effect). However, abatement patents could follow an R&D tournament structure, as in Lazear and Rosen (1981) and Nalebluff and Stiglitz (1983). In this setting, every firm would only benefit from either its own R&D investment (if it wins the tournament) or from a share of its rival's (if it loses), rather than from both. In these two extensions, R&D expenditure can differ from R&D outcomes, implying that taxing outcomes can induce firms to invest suboptimal amounts in R&D. In this context, it would be interesting to analyze whether this inefficiency is, as in our model, larger when the regulator uses a uniform rather than type-dependent policies.

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6 Appendix

6.1 Appendix 1 - Fees under alternative damage functions

This appendix investigates the optimal tax rates under uniform and type-dependent regulation under linear and quadratic environmental damage functions. The results from the third stage are unaffected in each policy regime.

Linear damage. Under a linear environmental damage function $ED = \frac{1}{2}d(e_i + e_j)$ and uniform fee, the regulator solves:

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

The first-order condition is

$$\frac{1}{9}\left(-2(a-c) + 3d - 4t\right) = 0,$$

which yields $t = \frac{1}{4}(3d - 2(a-c))$. Under linear environmental damage, the marginal environmental damage of each unit is the same regardless of the amount of R&D. Hence, the optimal fee does not depend on the amount of R&D.

Under the type-dependent regime, the regulator solves:

$$\max_{t_i, t_j} SW = (a-c)(q_i(t_i, t_j) + q_j(t_i, t_j)) - \frac{1}{2}(q_i(t_i, t_j) + q_j(t_i, t_j))^2$$

$$- \frac{1}{2}d(q_i(t_i, t_j) - z_i - \beta z_j + q_j(t_i, t_j) - \beta z_i - z_j) - \frac{1}{2}\gamma_i z_i^2 - \frac{1}{2}\gamma_j z_j^2,$$

with first-order conditions

$$\frac{\partial SW}{\partial t_i} = \frac{1}{18}\left(-2(a-c) + 3d - 2(t_i + t_j)\right) = 0,$$

$$\frac{\partial SW}{\partial t_j} = \frac{1}{18}\left(-2(a-c) + 3d - 2(t_i + t_j)\right) = 0.$$

Since the first-order conditions are symmetric, we obtain that $t_i = t_j$, which yields $t_i = t_j = \frac{1}{4}(3d - 2(a-c))$, which coincides with the fee under the uniform regime.

Quadratic damage. When the environmental damage function is quadratic, $ED = \frac{1}{2}d(e_i + e_j)^2$, the regulator solves the following under a uniform fee:

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

The first-order condition is

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

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

Under the type-dependent regime, the regulator solves:

$$\max_{t_i,t_j} SW = (a-c)(q_i(t_i,t_j) + q_j(t_i,t_j)) - \frac{1}{2}(q_i(t_i,t_j) + q_j(t_i,t_j))^2$$

$$- \frac{1}{2}d(q_i(t_i,t_j) - z_i - \beta z_j + q_j(t_i,t_j) - \beta z_i - z_j)^2 - \frac{1}{2}\gamma_i z_i^2 - \frac{1}{2}\gamma_j z_j^2,$$

with first-order conditions

$$\frac{\partial SW}{\partial t_i} = \frac{1}{9}((a-c)(2d-1) - d(t_i + t_j + 3(\beta+1)(z_i + z_j)) - t_i - t_j) = 0,$$

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

Since the first-order conditions are symmetric, we obtain $t_i = t_j$. Solving for the emission fees in this context, we find that $t_i = t_j = \frac{(a-c)(2d-1)-3(\beta+1)d(z_i+z_j)}{2(d+1)}$, which coincides with the fee under the uniform regime.

6.2 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 $q_i(q_j) = \frac{1}{2}(a - c - q_j - t_i)$. Simultaneously solving the reaction functions for the two firms yields the output function $q(t_i,t_j) = \frac{a-c-2t_i+t_j}{3}$. If $2t_i - t_j < a - c$ then $q(t_i,t_j) > 0$. Under a uniform fee, this condition simplifies to $t < a - c$.

6.3 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

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

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where $t(z_i, z_j) > 0$ if $z_i + z_j < \dfrac{2(a-c)(d-1)}{3d(1+\beta)}$.

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

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

where $t_i(z_i, z_j) > 0$ if $z_i < \dfrac{(a-c)(d-1) - z_j[d-1+\beta(2d+1)]}{1+2d+\beta(d-1)}$ for every firm i.

6.4 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,

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

Solving the two reaction functions yields the symmetric equilibrium

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

which is non-negative given the assumptions on our parameters. The comparative static on firm i's investment level given a decrease in its efficiency (increase in γ_i) is negative:

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

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

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

6.5 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

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

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 equilibrium level of investment z_i^{TD} is non-negative given the assumptions of our parameters.

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

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

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

6.6 Proof of Corollary 1

To prove the first part of Corollary 1, we need to show that $\left|\dfrac{\partial z_i}{\partial \gamma_i}\right| > \left|\dfrac{\partial z_j}{\partial \gamma_j}\right|$ under each regime. This is equivalent to showing that $\dfrac{\partial z_i}{\partial \gamma_i} - \dfrac{\partial z_j}{\partial \gamma_j} < 0$ 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

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

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

To prove the last two parts of Corollary 1, we need to show that if $\gamma_i < \gamma_j$ then $\dfrac{\partial(z_i + z_j)}{\partial \gamma_i} < 0$, $\dfrac{\partial(z_i + z_j)}{\partial \gamma_j} < 0$, and $\dfrac{\partial z_i^U + z_j^U}{\partial \gamma_i} < \dfrac{\partial z_i^U + z_j^U}{\partial \gamma_j}$ 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:

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

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

and since $\gamma_i < \gamma_j$:

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

6.7 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 $\beta < 1$.

6.8 Proof of Proposition 3.

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

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

$$+ (a - q_i - q_j)q_j - cq_j - t(q_j - z_j - \beta z_i) - \frac{1}{2}\gamma_j z_j^2,$$

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

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

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

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

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

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

which are both non-negative given the assumptions on our parameters.

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