Chapter 6: Regulation when firms invest in abatement[1]

6.1 Introduction

This chapter extends the baseline model of environmental regulation by allowing firms to invest in abatement technologies that reduce emissions. While previous chapters focused on output decisions under regulatory constraints, we now introduce a richer strategic environment in which firms choose both their abatement levels and output quantities. This addition captures real-world scenarios where firms respond to environmental policy not only by adjusting production but also by adopting cleaner technologies.

We begin by modeling a three-stage game: firms first invest in abatement, then the regulator sets a per-unit emission fee, and finally firms choose output levels. The analysis explores how abatement decisions affect equilibrium output, emissions, and the regulator's optimal policy. We show that firms' incentives to invest in abatement depend on pollution severity, production costs, and the cost of abatement itself.

Next, we allow for spillovers in abatement, where one firm's investment benefits its rivals by reducing their emissions. This introduces strategic externalities that influence both investment and regulatory outcomes. We compare non-cooperative and cooperative abatement decisions, showing how coordination among firms—such as through environmental research joint ventures (ERJVs)—can internalize spillovers and lead to higher investment levels.

Finally, we examine sequential abatement decisions, where early adopters influence the behavior of followers. Case studies from manufacturing and refining industries illustrate how firms strategically time their investments in response to regulatory pressure and technological diffusion.

6.1.1 Guiding questions

1. What motivates firms to invest in abatement technologies under regulation?
2. How do spillovers in abatement affect strategic and cooperative behavior?
3. What are the welfare implications of environmental research joint ventures (ERJVs)?
4. How does the timing of abatement decisions influence equilibrium outcomes?
5. What role does regulatory commitment play in shaping investment strategies?
6. How do different regulatory designs affect incentives for green innovation?

6.2 Modeling assumptions

Consider a similar setting as in chapter 2, namely, a duopoly where firms face an inverse demand function $p(Q) = 1 - Q$, and operating with symmetric marginal cost c, where

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$1 > c \geq 0$. While in chapter 2 the EA sets an emission fee t and firms respond with their output decisions, we now add a previous stage, where firms invest in abatement technologies that reduce emissions. Examples of abatement include installing smokestack scrubbers on factories, wastewater treatment systems, and advanced filtration systems for industrial emissions, among others.
The time structure of the game is, then, as follows:

1. In the first stage, every firm i independently and simultaneously invests in abatement, $z_i \geq 0$, which helps firm i reduce its emissions, from $e_i = q_i$ to

$$e_i = q_i - z_i - \beta z_j \tag{6.1}$$

   where $j \neq i$, and $\beta \in [0, 1]$ denote spillovers. The strength of the spillover can give rise to different cases:

   (a) When $\beta = 0$, spillovers in abatement are absent and firm i's emissions become $e_i = q_i - z_i$. Intuitively, firm i's emissions are only reduced by its own investment in abatement.

   (b) When $\beta \in (0, 1)$ firm i benefits from a share, β, of its rival's abatement effort (i.e., unpatentable innovations, previous employees bringing know-how to firm i, etc.).

   (c) When $\beta = 1$ every firm fully benefits from every unit of its rival's abatement effort, i.e., $e_i = q_i - z_i - z_j$.

   The total cost of investing $z_i \geq 0$ in abatement is

$$C(z_i) = \frac{\gamma (z_i)^2}{2}, \tag{6.2}$$

   being increasing and convex in abatement.[2] Parameter $\gamma > 0$ denotes firm i's investment efficiency, with a lower γ indicating a higher efficiency. When $\gamma \to 0$, abatement is, essentially, free for the firm; while when $\gamma \to +\infty$, abatement is prohibitively costly, preventing any investment, $z_i = 0$. As a consequence, we can say that the results in this model embody those in chapter 2 when $\gamma \to +\infty$ as a special case, where firms cannot invest in abatement; otherwise, firms invest positive amounts in abatement and the results of this model differ from those in chapter 2.

2. In the second stage, the regulator observes the investment decisions $z = (z_1, z_2)$, and sets a per-unit emission fee $t \geq 0$, implying that every firm i pays $te_i = t(q_i - z_i - \beta z_j)$ in emission fees.

3. In the third stage, every firm i observes the investment decisions and the emission fee, and responds simultaneously and independently choosing its output level q_i (i.e., firms compete à la Cournot).

[2] The marginal cost of abatement is γz_i, which is unambiguously positive; and increasing in z_i. Therefore, the total cost of abatement is increasing in z_i and convex in z_i.

Stages 2 and 3 coincide with the sequential-move games in previous chapters, while stage 1 is new. In other words, we are allowing firms to choose their abatement decisions *before* the regulator sets the per-unit emission fee in stage 2. Section 6.6 studies how our results are affected when, instead, firms choose their abatement *after* the regulator sets emission fee t. For comparison purposes, the regulator considers the same welfare function as in previous chapters,

$$W = CS + PS + T - Env, \tag{6.3}$$

although total tax collection is now $T = tE = t(Q - Z)$, since aggregate emissions must take into account the effect of aggregate abatement, that is, $E = Q - Z$, where $Z = z_1 + z_2$ denotes aggregate abatement. Similarly, environmental damage is

$$Env = dE^2 = \frac{d}{2}(Q - Z)^2, \tag{6.4}$$

where $d \geq \frac{1}{2}$ denotes pollution severity. The welfare function, then, coincides with that in previous chapters when abatement is prohibitively expensive, $\gamma \to +\infty$, no firm invests in abatement and, hence, $Z = 0$. Otherwise, abatement is positive, and net emissions are lower, giving rise to two effects on welfare. On one hand, for a given output level, a larger abatement decreases environmental damages (direct positive effect). On the other hand, a larger abatement decreases the stringency of emission fees, since the EA needs to curb less emissions as we show below, allowing firms to increase their output, which increases consumer and producer surplus (indirect positive effect).

We proceed by solving the game through backward induction, initially identifying equilibrium behavior in the absence of spillovers ($\beta = 0$), and subsequently considering the presence of spillover effects ($\beta > 0$). This analysis assumes that firms do not coordinate their investment-abatement decisions. Later, section 6.4 explores how equilibrium results would change if firms coordinated their abatement efforts.

6.3 Non-cooperative abatement

6.3.1 No spillovers

Third stage. In the final stage, each firm i selects its output q_i to maximize

$$\max_{q_i \geq 0} \quad (1 - q_i - q_j)q_i - cq_i - t(q_i - z_i) \tag{6.5}$$

The cost of abatement, $C(z_i) = \frac{\gamma(z_i)^2}{2}$, is incurred in the first stage, when firms invest in abatement, explaining why we did not include it in the above objective function. (Nonetheless, if we did, it would not affect our subsequent first-order conditions with respect to q_i, since cost $C(z_i) = \frac{\gamma(z_i)^2}{2}$ is not a function of q_i.)

Differentiating with respect to q_i yields the same best response function as in chapter 2, $q_i(q_j) = \frac{1-c-t}{2} - \frac{1}{2}q_j$. In a symmetric equilibrium, $q_i = q_j = q$, every firm's output function becomes $q = \frac{1-c-t}{3}$, aggregate output is $Q(t) = \frac{2(1-c-t)}{3}$, and equilibrium profit becomes

$$\begin{aligned}
\pi_i &= (1 - q - q)q - (c + t)q + tz_i \\
&= \frac{(1 - c - t)^2}{9} + tz_i,
\end{aligned}$$

which can be more compactly rewritten as $\pi_i = q^2 + tz_i$.

Second stage. Anticipating output q and profit π_i, the regulator sets the emission fee t that maximizes welfare:

$$\begin{aligned} \max_{t \geq 0} \; W &= CS + PS + T - Env \\ &= \frac{Q(t)^2}{2} + \left(Q(t)^2 + tZ - \frac{\gamma}{2}Z^2\right) + t(Q(t) - Z) - \frac{d}{2}(Q(t) - Z)^2 \end{aligned} \tag{6.6}$$

where $Q(t) = \frac{2(1-c-t)}{3}$ denotes the equilibrium aggregate output and $Z = z_i + z_j$ represents aggregate abatement. Differentiating with respect to t, yields

$$-\frac{4(1-c-t)}{9} - \left(\frac{8(1-c-t)}{9} + t\right) + \frac{2(1-c-2t)}{3} + \frac{2d[2(1-c-t) - 3Z]}{9} = 0$$

and, solving for t, yields the equilibrium fee

$$t(Z) = \frac{(2d-1)(1-c) - 3dZ}{2(1+d)} \tag{6.7}$$

This fee becomes more stringent with higher pollution severity (higher d) since $\frac{\partial t(Z)}{\partial d} = \frac{3(1-c-Z)}{2(1+d)^2} > 0$ if aggregate abatement is not excessive, $Z < 1 - c$; but less stringent when output is more costly to produce (higher c) because $\frac{\partial t(Z)}{\partial c} = -\frac{2d-1}{2(1+d)} < 0$.
Importantly, this fee decreases with aggregate abatement Z, implying that when either firm i or j increases its abatement (z_i or z_j), the regulator anticipates fewer net emissions and reduces the severity of the emission fee:

$$\frac{\partial t}{\partial z_i} = \frac{\partial t}{\partial z_j} = -\frac{3d}{2(1+d)} < 0 \tag{6.8}$$

This effect is symmetric across firms, allowing firm i to free ride on its rival's investment z_j. Interestingly, this also happens in the absence of spillover effects because every firm's invesment in abatement reduces total emissions, thus lowering the stringency of the emission fee. In section 5.3 we evaluate how these free-riding incentives are ameliorated when firms coordinate their R&D decisions.

First stage. Anticipating profit $\pi_i = q^2 + t(Z)z_i$, and evaluating it at fee $t(Z)$, each firm i chooses its abatement z_i to maximize:

$$\begin{aligned} \max_{z_i \geq 0} \; \pi_i &= q^2 + t(Z)z_i - \gamma\frac{(z_i)^2}{2} \\ &= \frac{(1-c+dZ)^2}{4(1+d)^2} + \frac{(2d-1)(1-c) - 3dZ}{2(1+d)}z_i - \gamma\frac{(z_i)^2}{2} \end{aligned} \tag{6.9}$$

where $Z = z_i + z_j$. Differentiating with respect to z_i, yields a best response function of

$$z_i(z_j) = \frac{(1-c)[2d(1+d) - 1]}{2\gamma(1+d)^2 + d(6+5d)} - \frac{d(3+2d)}{2\gamma(1+d)^2 + d(6+5d)}z_j \tag{6.10}$$

where the first term represents the vertical intercept, which is positive for all admissible parameters since $d > 1/2$ by definition;[3] and the second term denotes the slope, which is unambiguously negative. More formally, the best response function for investments in abatement is negatively slope or, in other words, firms regard each other's abatement levels as *strategic substitutes*. Figure 6.1 illustrates best response function $z_i(z_j)$ evaluated at $c = \frac{1}{2}$, $d = 1$, and $\gamma = 2$.

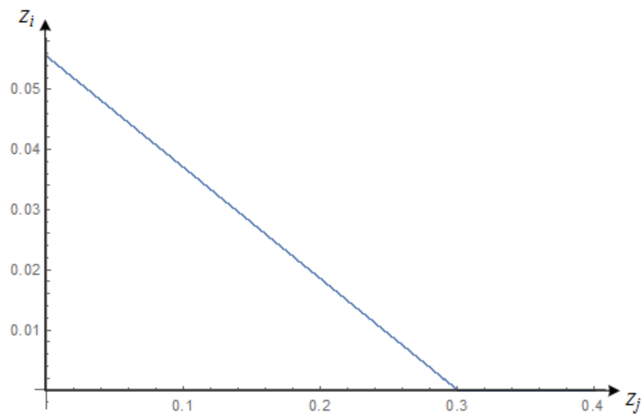


Figure 6.1. Best response function $z_i(z_j)$.

Intuitively, this happens because an increase in firm j's abatement induces a reduction in net emissions that the EA responds by setting a less stringent emission fee. As a consequence, firm i has less incentives to invest in abatement when its rival invests more in abatement, entailing that firm i can free ride off its rivals' abatement, via less stringent fees.
The vertical intercept shifts upwards when pollution is more severe. To confirm this comparative statics, let $z_i^{Vert.}$ and z_i^{Slope} denote the first and second term, respectively, in the above best response function, $z_i(z_j)$, representing the vertical intercept and the slope. Differentiating with respect to pollution severity, d, we obtain

$$\frac{\partial z_i^{Vert.}}{\partial d} = \frac{2(1-c)[3+4\gamma+d(5+d+2\gamma(3+d)]}{[2\gamma(1+d)^2+d(6+5d)]^2} \tag{6.11}$$

which is unambiguously positive, and

$$\frac{\partial z_i^{Slope}}{\partial d} = \frac{3d^2-2\gamma(1+d)(3+d)}{[2\gamma(1+d)^2+d(6+5d)]^2} \tag{6.12}$$

which is negative if and only if

$$\gamma > \overline{\gamma} \equiv \frac{3d^2}{2(1+d)(3+d)}.$$

Figure 6.2 depicts this cutoff, showing that it originates at a vertical intercept of $\gamma = \frac{1}{14}$ when $d = \frac{1}{2}$; then increases in d since $\frac{\partial \overline{\gamma}}{\partial d} = \frac{3d(3+2d)}{(1+d)^2(3+d)^2} > 0$; and reaches a maximum height

[3] Term $[2d(1+d)-1]$ is positive if $2d(1+d) > 1$. Since $d \geq \frac{1}{2}$ by assumption, $2d > 1$ and $(1+d) > \frac{3}{2}$, entailing that the product $2d(1+d)$ must be larger than 1.

of $\gamma = \frac{3}{2}$ when $d \to +\infty$. Hence, when abatement is relatively costly, $\gamma > \frac{3}{2}$, condition $\gamma > \overline{\gamma}$ holds for all values of d.

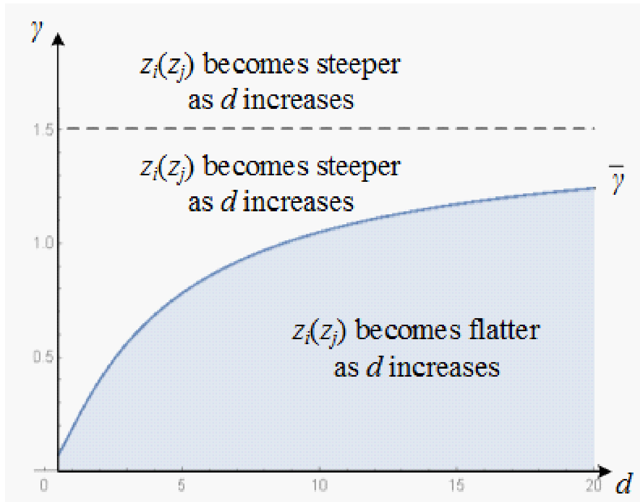


Figure 6.2. Cutoff $\overline{\gamma}$ as a function of d

Therefore, when pollution becomes more severe (higher d), firms anticipate the EA setting a more stringent fee, providing them with stronger incentives to invest in abatement (i.e., the best response function shifts upwards as d increases). However, the best response function becomes steeper when abatement is relatively costly, indicating that free-riding incentives are stronger. This is due, again, to firms anticipating more stringent emission fees, thus providing them with more incentives to avoid abatement, and free-riding its rival, particularly when this investment is costly.

In a symmetric equilibrium, where $z_i = z_j$ in the above best response function, $z_i(z_j)$, we find that equilibrium abatement becomes

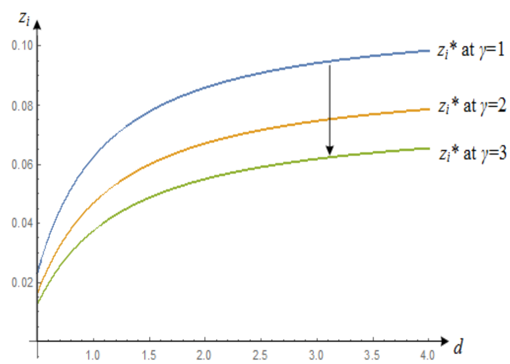
$$z_i^* = \frac{(1-c)[2d(1+d)-1]}{2\gamma(1+d)^2 + d(9+7d)} \tag{6.13}$$

which is unambiguously positive since $d > \frac{1}{2}$ by definition. The comparative statics of this abatement satisfy

$$\begin{aligned} \frac{\partial z_i^*}{\partial d} &= \frac{(1-c)[9+8\gamma+2d(7+6\gamma+2d(1+\gamma))]}{[2\gamma(1+d)^2+d(9+7d)]^2} > 0 \\ \frac{\partial z_i^*}{\partial \gamma} &= -\frac{2(1-c)(1+d)^2[2d(1+d)-1]}{[2\gamma(1+d)^2+d(9+7d)]^2} < 0 \\ \frac{\partial z_i^*}{\partial c} &= -\frac{2d(1+d)-1}{2\gamma(1+d)^2+d(9+7d)} < 0 \end{aligned} \tag{6.14}$$

implying that firms invest more in abatement when pollution is more severe (higher d), as they anticipate the EA setting more stringent emission fees; but invest less when abatement becomes more expensive (higher γ) or when their production costs increase (higher c). The latter occurs because the EA expects less output and emissions when c increases, requiring a less stringent emission fee, which ultimately reduces firms' need to invest in abatement to lower their tax burden.

Figure 6.3a depicts equilibrium abatement, z_i^*, as a function of pollution severity, d. As in previous figures, we consider $c = \frac{1}{2}$. The figure illustrates that abatement increases in d, but shifts downwards as investments become more expensive (higher γ). A similar argument applies to figure 6.3b, where equilibrium abatement z_i^* shifts downwards as production costs increase (higher c), where we fix γ at $\gamma = 1$.



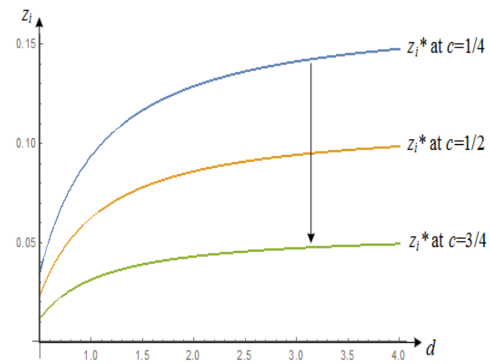


Figure 6.3a. Equilibrium abatement decreases in γ.

Figure 6.3b. Equilibrium abatement decreases in c.

Therefore, aggregate output is $Z^* = z_i^* + z_j^* = \frac{2(1-c)[2d(1+d)-1]}{2\gamma(1+d)^2+d(9+7d)}$. Inserting this result into emission fee $t(Z)$, we find that this fee in equilibrium becomes

$$t(Z^*) = \frac{(1-c)[d(2\gamma - 3 + 2d(1+2\gamma)) - 2\gamma]}{4\gamma(1+d)^2 + 2d(9+7d)} \tag{6.15}$$

which is positive for all

$$\gamma > \gamma_t \equiv \frac{(3-2d)d}{2(2d^2+d-1)}.$$

Figure 6.4 depicts cutoff γ_t as a function of pollution severity, d, on the horizontal axis. Cutoff γ_t originates at a vertical asymptote at $d = \frac{1}{2}$, then decreases in d, crosses the horizontal axis at $d = \frac{3}{2}$, and converges to $\gamma = -\frac{1}{2}$ when $d \to +\infty$. Therefore, when pollution is relatively severe $d > \frac{3}{2}$, cutoff γ_t is negative, implying that condition $\gamma > \gamma_t$ unambiguously holds, and the emission fee is positive. Otherwise, cutoff γ_t can be positive, and we need abatement costs to be sufficiently expensive, $\gamma > \gamma_t$, for emission fees to remain positive. To understand this result, consider the opposite scenario: if abatement costs are low, $\gamma \leq \gamma_t$, firms would easily invest in abatement, lowering net emissions. Since, in addition, pollution is not severe in this context, $d \leq \frac{3}{2}$, it would become socially optimal to provide a per-unit subsidy, rather than an emission fee, to increase aggregate output.

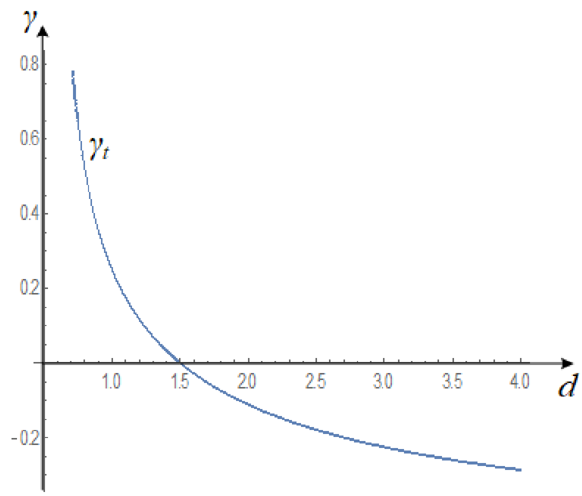
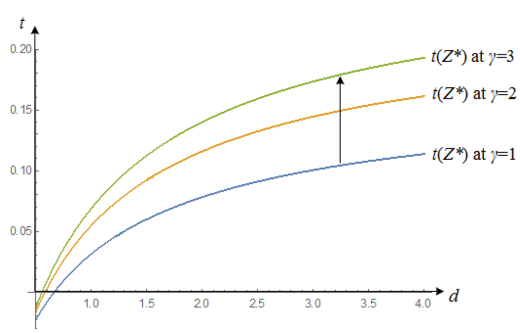


Figure 6.4. Cutoff γ_t.

Figure 6.5a depicts fee $t(Z^*)$, evaluated at our ongoing parameter $c = \frac{1}{2}$ and allowing for three values of γ. As shown above, the fee can be negative if pollution is not severe (low d, in the left-hand side of the figure), but this result becomes less likely to arise as abatement becomes more costly (higher γ). Graphically, the portion of the curve $t(Z)$ lying inside the negative quadrant becomes smaller as γ increases. An increase in this cost implies that firms invest less in abatement, as shown above. Anticipating more emissions per unit of output, the EA sets a more stringent fee, shifting $t(Z^*)$ upwards in figure 6.5a.
Similarly, we can use fee $t(Z^*)$ to find the equilibrium output, $q(t)$, yielding

$$q(t(Z^*)) = \frac{2(1-c)[d(7+4d) + 2\gamma(1+d)]}{4\gamma(1+d)^2 + 2d(9+7d)} \tag{6.16}$$

that is positive for all admissible parameters. Figure 6.5b depicts this output considering, for consistency, the same parameter values as in figure 6.5a. When pollution is more severe (higher d) or when abatement is more costly (higher γ), the EA sets a more stringent emission fee, inducing firms to lower their output levels.



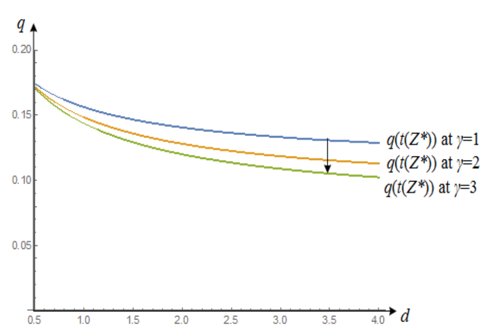


Figure 6.5a. Emission fee increases in d and γ.

Figure 6.5b. Equilibrium output decreases in d and γ.

6.3.2 Allowing for spillovers in abatement

When a firm's green investments generate spillover effects, they reduce not only the firm's own emissions but also those of its rivals. In a context with two firms, 1 and 2, with investments z_1 and z_2, firm 1's emissions are

$$e_1 = q_1 - z_1 - \beta z_2 \tag{6.17}$$

where $\beta \in [0, 1]$ represents spillover effects. When $\beta = 0$, firm 1's emissions are $e_1 = q_1 - z_1$, just being affected by its own investment in abatement, as in previous sections.
When $\beta > 0$, however, firm 2's investment, z_2, benefits firm 1, by reducing its net emissions. This spillover can be due to innovations being non-patentable, allowing firm 1 to copy part of firm 2's innovation for free, or because workers' know-how is transferable when they switch firms. It can also be due to measurement errors. For instance, if firms are closely located, the measurement of firm 1's emissions is reduced by the investments in abatement of firm 2. When $\beta = 1$, spillovers are total, indicating that firm 1 fully benefits from every dollar invested by firm 2 in abatement, i.e., $e_1 = q_1 - z_1 - z_2$. In other words, firm 1's emissions are equally affected by its own investment and by its rival's investment.
A similar argument applies to firm 2's emissions in this context, $e_2 = q_2 - z_2 - \beta z_1$, which are lowered by firm 1's investment in abatement, z_1. More generally, in a setting with $n \geq 2$ firms, firm i's emissions are given by $e_i = q_i - z_i - \beta Z_{-i}$, where $Z_{-i} \equiv \sum_{j \neq i} z_j$ denotes the aggregate abatement from firm i's rivals.

Symmetric vs. Asymmetric Spillovers. The reader should notice that this model considers that spillover effects are symmetric, meaning that firm i equally benefits from an increase in any of its rivals' investment in abatement, i.e., an increase in z_j produces the same effect on e_i as an increase in z_k, for any two firms k and j where $k \neq j \neq i$. More involved models could allow, instead, for spillover effects to be asymmetric across firms, that is,

$$e_1 = q_1 - z_1 - \beta_1 z_2 \quad \text{and} \quad e_2 = q_2 - z_2 - \beta_2 z_2, \tag{6.18}$$

where parameters β_1 and β_2 can differ, the former measuring how firm 1 benefits from firm 2's abatement and the latter representing how firm 2 benefits from firm 1's abatement.

Third stage. In this setting, every firm i solves a similar maximization problem in the third stage,

$$\max_{q_i \geq 0} \; (1 - q_i - q_j)q_i - cq_i - t(q_i - z_i - \beta z_j) \tag{6.19}$$

This formulation mirrors the profit function in equation (6.5), with the exception of the last term, which now incorporates spillover effects in R&D through the term βz_j. Consequently, net emissions are reduced not only by a firm's own abatement efforts but also by its rival's investment. Despite this modification, the equilibrium output remains $q = \frac{1-c-t}{3}$, indicating that Cournot competition is unaffected by the presence of spillovers. Technically, spillovers do not directly influence output decisions; however, they exert an indirect effect by reducing the stringency of the emission fee, as we demonstrate below.

Second stage. Anticipating the equilibrium output q and profits π_i, the regulator sets the emission fee t as in the previous section. The resulting equilibrium fee is

$$t(Z) = \frac{(2d-1)(1-c) - 3d(1+\beta)Z}{2(1+d)} \tag{6.20}$$

This expression coincides with the fee derived in equation (6.7) when spillover effects are absent ($\beta = 0$). When spillover effects intensify (β increases), the fee decreases. Intuitively, a given level of investment in abatement reduces emissions for both firms more effectively, thereby requiring less stringent regulatory intervention. This is confirmed by examining the sensitivity of the fee to marginal increases in abatement:

$$\frac{\partial t(Z)}{\partial z_i} = \frac{\partial t(Z)}{\partial z_j} = -\frac{3d(1+\beta)}{3(1+d)} < 0, \tag{6.21}$$

which is increasing in spillover effects, β, reinforcing the notion that stronger spillovers reduce the need for high emission fees. Evaluating $q = \frac{1-c-t}{3}$ at the equilibrium emission fee found in (6.20), we obtain an output level $q = \frac{1-c+d(1+\beta)Z}{2(1+d)}$.

First stage. In the first stage, each firm chooses its abatement level z_i to maximize

$$\max_{z_i \geq 0} \ \Pi_i = \frac{[1-c+d(1+\beta)Z]^2}{4(1+d)^2} + \frac{(2d-1)(1-c)-3d(1+\beta)Z}{2(1+d)}(z_i+\beta z_j) - \frac{\gamma\,(z_i)^2}{2} \tag{6.22}$$

Differentiating with respect to z_i, yields the best response function

$$z_i(z_j) = \frac{[d(2+\beta+2d)-1](1-c)}{d(1+\beta)\,[6+(5-\beta)d]+2\gamma(1+d)^2} - \frac{d(3+2d)(1+\beta)^2}{d(1+\beta)\,[6+(5-\beta)d]+2\gamma(1+d)^2}z_j, \tag{6.23}$$

This expression coincides with the best response in equation (6.10) when spillover effects are absent, $\beta = 0$. When spillovers are present, $\beta > 0$, abatement levels remain strategic substitutes (i.e., the best response function is still negatively sloped). This slope, however, increases with β, indicating that spillovers amplify each firm's incentive to free ride on its rival's investment. Firm j's R&D investment, z_j, then generates two externalities for firm i:

(i) a reduction in the emission fee t (tax-saving effect, TSE), and

(ii) a decrease in per-unit emissions due to spillovers (emission reduction effect, ERE).

While the TSE occurs regardless of spillovers, the ERE is present only when spillovers are present, $\beta > 0$.
In a symmetric equilibrium, $z_i = z_j = z$, abatement becomes

$$z^{NC} = \frac{[d(2+\beta+2d)-1](1-c)}{d(1+\beta)\,[9+7d+\beta(3+d)]+2\gamma(1+d)^2}. \tag{6.24}$$

Figure 6.6 depicts this equilibrium abatement, as a function of β in the horizontal axis and evaluated, for illustration purposes, at $c = 1/2$ and $\gamma = 1/4$. Stronger spillover effects (higher

β) expand the external effect in ERE, inducing every firm to invest less in abatement.

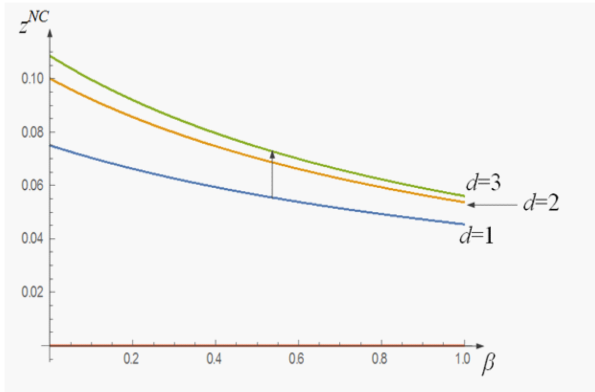


Figure 6.6. Abatement as a function of β

For completeness, figure 6.6 considers three different pollution severities, $d = 1$, $d = 2$, and $d = 3$. Because higher pollution severity leads to more stringent emission fees, firms have stronger incentives to invest in abatement, thereby explaining the upward shift in the equilibrium abatement z^{NC} in the figure. Conversely, an increase in the production cost c results in a less stringent emission fee, lowering firms' incentives to invest in abatement, implying a downward shift in z^{NC}.

6.4 Cooperative abatement decisions

Still allowing for spillovers, let us now identify the investment in abatement that firms choose when coordinating their investment decisions. As described above, every firm's individual investment gives rise to two positive externalities, which firms' joint decision can help internalize. This setting is is commonly known as "environmental research cartel" (ERC), since it it analogous to a cartel where firms coordinate their R&D decisions in industries without environmental regulation. If, in addition, firms share information from their innovations completely, $\beta = 1$, thus avoiding duplicities in their R&D, the ERC would become a so-called environmental research joint venture (ERJV).

In this context, solving the game again by backward induction, we find that equilibrium behavior in stages 2-3 is unaffected. It changes in the first stage, however, since firms now choose z_i and z_j to maximize their joint profits as follows

$$\max_{z_i, z_j \geq 0} \Pi_i + \Pi_j \tag{6.25}$$

where profit Π_i was defined in expression (6.22). Differentiating with respect to z_i and z_j, yields an equilibrium investment

$$z^{ERC} = \frac{[(1+d)(2d-1)](1-c)}{4d(3+2d)(1+\beta)^2 + 2\gamma(1+d)^2} \tag{6.26}$$

which is positive since $d > 1/2$ by assumption. Figure 6.7 illustrates z^{ERC} using, for comparison purposes, the same parameter values as in figure 6.6. Visually comparing z^{NC} and

z^{ERC} in figures 6.6 and 6.7, suggests that $z^{ERC} > z^{NC}$ under most, but not all, parameter conditions. The next section formally ranks these investment levels.

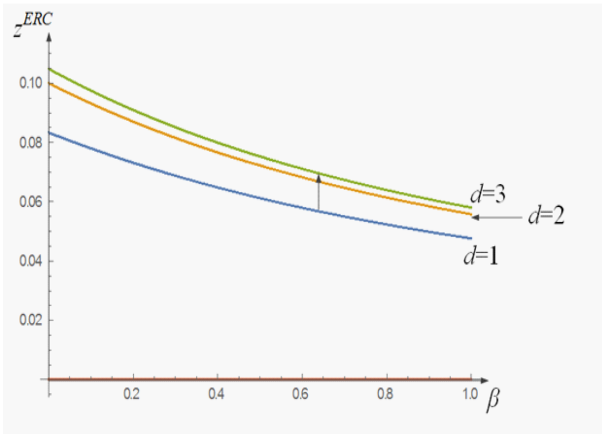


Figure 6.7. z^{ERC} as a function of β.

6.4.2 Investment comparison

Figure 6.8 depicts the difference $z^{ERC} - z^{NC}$, as a function of β on the horizontal axis, and evaluated at the same same parameter values as in figure 6.6.

No spillovers. When spillovers are absent, $\beta = 0$, only the TSE is present, illustrated in the vertical intercepts of the figure. In this context, $z^{ERC} > z^{NC}$ holds when environmental damages are small (i.e., $d = 1$). When they increase to $d = 2$, both investment levels coincide, $z^{ERC} = z^{NC}$; and when these damages further increase to $d = 3$, the investment ranking changes to $z^{ERC} < z^{NC}$. Intuitively, when damages are small, fees are less stringent, and aggregate output is high, lying in the *inelastic* portion of the demand curve. In this case, every firm j's investment, z_j, induces less stringent emission fees, which helps firm i increase its output, lowering the equilibrium price, but by a less-than-proportional amount, ultimately increasing firm i's profit (positive externality).

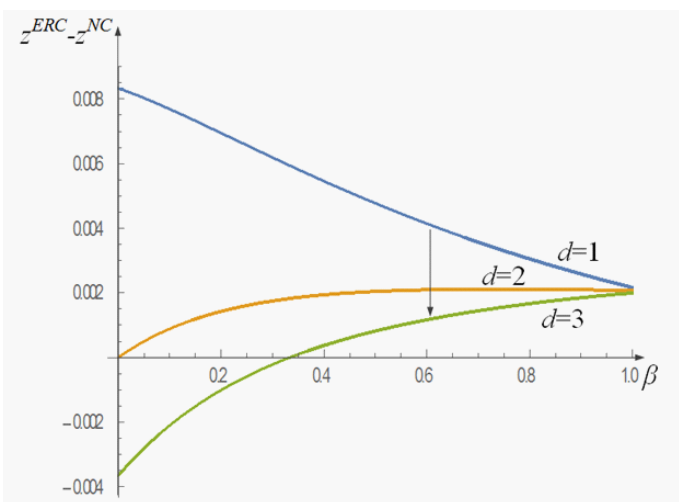


Figure 6.8. $z^{ERC} - z^{NC}$ as a function of β.

In contrast, when environmental damages become more severe, emission fees are more stringent, and aggregate output lies in the *elastic* portion of the demand curve. In this setting, every firm's investment, while still lowering emission fees and output, it yields a more-than-proportional decrease in prices, ultimately decreasing its rival's profits (negative externality). This explains why the ERC helps internalize a positive externality when d is relatively low, increasing investment relative to the NC scenario; but it internalizes a negative externality when d is high, decreasing investments in abatement relative to the NC scenario.

Spillovers. When spillover effects are present, $\beta > 0$, the ERC seeks to internalize both the TSE, which can be positive or negative as shown above; and that stemming from ERE, which is unambiguously positive. When β is sufficiently high (strong spillovers), the positive externality in ERE dominates that in TSE, regardless of whether the latter is positive or negative (i.e., for all values of d). Graphically, all curves depicting the difference $z^{ERC} - z^{NC}$ lie on the positive quadrant of figure 6.8 when β is sufficiently high, i.e., $\beta > 1/3$, implying that $z^{ERC} > z^{NC}$.
Finally, when firms fully share the results of their innovation in an ERJV, $\beta = 1$, the difference $z^{ERC} - z^{NC}$ is unambiguously positive, and unaffected by changes in pollution severity (i.e., different values of d yield the same height, at the right-hand side of the figure).

6.4.2 Alternative cooperative rules

Ouchida and Goto (2016) examine how government policy affects the formation and effectiveness of Environmental Research Cartels (ERCs), drawing parallels with Kamien et al. (1992). They consider four institutional regimes:

(i) environmental R&D competition, which is analogous to the NC setting in Poyago-Theotoky (2007) allowing for a generic spillover effect $\beta \in [0, 1]$.

(ii) environmental R&D cartelization, which is equivalent to the ERC considered in section 6.4, still assuming a generic spillover β.

(iii) environmental ERJV competition, where each firm independently chooses its R&D investment, as in model (i), but setting $\beta = 1$ thus avoiding duplicities in firms' innovations.

(iv) environmental RJV cartelization, which coincides with the ERC in model (ii) but assuming that $\beta = 1$.

The government's policy space is defined by two binary choices: whether to permit full spillovers (i.e., allow $\beta = 1$) and whether to allow investment coordination among firms. These choices determine which of the four regimes can emerge in equilibrium. As summarized in Table 6.1:

a) If both ERJVs and coordination are prohibited, only model (i) arises.

b) If ERJVs are allowed ($\beta = 1$) but coordination is prohibited, models (i) and (iii) may emerge, depending on firms' profitability.

c) If coordination is allowed but ERJVs are prohibited ($\beta \neq 1$), models (i) and (ii) are feasible.

d) If both ERJVs and coordination are permitted, all four regimes can potentially arise, with equilibrium selection driven by firms' strategic preferences.

		ERJVs are...	
		Banned	Allowed
		$\beta \neq 1$	$\beta = 1$
Coordinated	Banned	Model (i)	Model (ii)
abatement is...	Allowed	Model (iii)	Model (iv)

Table 6.1. Alternative cooperative rules.

Ouchida and Goto (2016) demonstrate that firms have strong incentives to form ERJV cartels, particularly when duplication in R&D is costly and spillovers are substantial. However, they also show that ERJV cartelization is not universally welfare-superior. The welfare ranking depends critically on the severity of pollution and the cost of innovation.

When pollution is relatively mild (i.e., low d), and R&D costs are moderate, independent competition (model (i)) tends to be socially optimal. In this case, allowing coordination or full spillovers may lead to excessive investment or duplication, reducing overall welfare. Accordingly, the optimal policy would prohibit both coordination and ERJVs.

Conversely, when pollution is severe or R&D costs are high (i.e., large γ), ERJV cartelization (model (iv)) becomes both privately and socially preferred. Coordinated investment under full spillovers allows firms to internalize the positive externalities associated with abatement, leading to higher aggregate investment and improved environmental outcomes.

6.5 Sequential abatement decisions

6.5.1 Motivation

A natural extension of the baseline model involves examining how equilibrium outcomes are affected when firms invest in pollution abatement sequentially rather than simultaneously. This distinction is particularly relevant in industries where the scale and complexity of environmental investments vary significantly. While small-scale projects—such as installing end-of-pipe scrubbers or minor filtration upgrades—are typically implemented simultaneously across firms, larger and more capital-intensive undertakings often unfold over extended periods. These include the installation of new machinery, comprehensive retrofitting of production facilities, or post-disaster clean-up operations. In such cases, firms may observe their rivals' abatement decisions before committing to their own, introducing a dynamic strategic element into the investment process.

Consider, for instance, Intel's announcement in May 2020 of its commitment to reduce greenhouse gas emissions by 10% by 2030—the first such pledge in the chipset industry. In the following year, AMD responded with its own environmental goals, including a 50% reduction in absolute emissions by 2030. Similar patterns of staggered investment are observed in industries such as steel manufacturing, where large-scale abatement projects are common.

Strandholm et al. (2023) analyze this sequential investment structure, abstracting from spillover effects to isolate the role of timing. Their model retains the three-stage structure:

firms invest in abatement, the regulator sets an emission fee, and firms compete in output à la Cournot. Importantly, they show that the equilibrium output in the third stage remains unchanged from the simultaneous-move setting:

$$q(t) = \frac{1 - c - t}{3} \tag{6.27}$$

where c is the marginal cost of production and t is the per-unit emission fee. Similarly, the regulator's optimal fee in the second stage is unaffected by the timing of investment:

$$t(Z) = \frac{(2d - 1)(1 - c) - 3d(1 + \beta)Z}{2(1 + d)}, \tag{6.28}$$

where d captures the severity of pollution, β denotes the spillover parameter, and Z is aggregate abatement. This coincides with the emission fee found in previous sections of the chapter; see equation (6.20).

6.5.2 Strategic effects of sequentiality

The main divergence arises in the first stage. In the sequential setting, the follower (firm 2) observes the leader's (firm 1's) investment in abatement and responds optimally. The follower's best response function is negatively sloped in the leader's investment, indicating that firms perceive each other's abatement efforts as strategic substitutes. Anticipating this, the leader internalizes the follower's reaction and chooses an investment level $z_1^{Seq} > 0$ that induces a positive response from the follower, $z_2^{Seq} > 0$.
A particularly interesting result from Strandholm et al. (2023) is the emergence of a first-mover advantage under specific conditions. The leader may choose to invest less than the follower, $z_1^{Seq} < z_2^{Seq}$, if its cost of investment, denoted by γ, exceeds a critical threshold:

$$\gamma > \widehat{\gamma} \equiv \max \left\{ 0, \frac{4d - 3}{2} \right\} \tag{6.29}$$

as depicted in figure 6.9. This behavior reflects a form of strategic free-riding, where the leader leverages the follower's investment to reduce its own costs while still benefiting from a less stringent emission fee. The intuition parallels that of sequential public good games, where early contributors reduce their own effort, expecting later contributors to compensate their loss contribution. In the context of environmental R&D, the leader's investment reduces the marginal benefit of abatement for the follower, who then increases its own investment to maintain competitiveness and reduce regulatory costs.

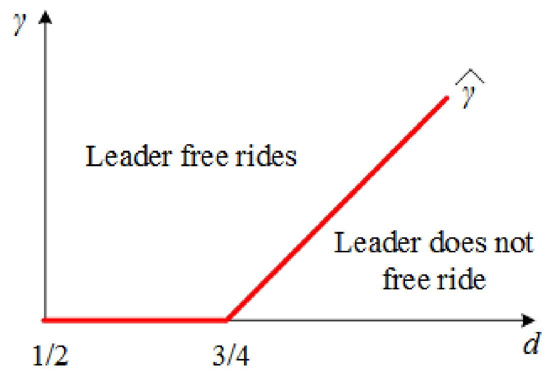


Figure 6.9. Leader's free-riding incentives in abatement.

The severity of pollution plays a critical role in shaping these strategic incentives. As illustrated in figure 6.9, higher values of d lead to more stringent emission fees, t, increasing the marginal benefit of investing in abatement, and reducing the leader's incentive to free-ride. Conversely, when pollution is mild, the regulatory response is weaker, and the leader is more likely to rely on the follower's investment. This dynamic underscores the importance of environmental context in determining the strategic behavior of firms under sequential investment.

6.5.3 Comparing sequential and simultaneous abatement

An important question in the analysis of environmental R&D is how the timing of investment decisions affects the level of abatement undertaken by firms. Strandholm et al. (2023) compare equilibrium investment under sequential and simultaneous settings. Their findings indicate that, for each firm i, the equilibrium investment in the sequential setting exceeds that in the simultaneous setting:

$$z_i^{Seq} > z_i^{NC} \tag{6.30}$$

where z_i^{NC} denotes the non-cooperative investment level derived in Section 6.3; see equation (6.13). This inequality holds unambiguously across a wide range of parameter values, suggesting that the ability to observe and respond to a rival's investment enhances strategic incentives to invest in abatement.

However, the magnitude of this difference, $z_i^{Seq} - z_i^{NC}$, increases as pollution becomes more severe (higher d). Intuitively, firms face a more stringent emission fee both when choosing their investments sequentially and simultaneously, leading them to invest more when competing sequentially than otherwise. In contrast, this difference is reduced when investments in abatement become more expensive (higher γ). In this case, firms invest less in abatement under both time structures, making these investments more similar in both settings. Overall, the first-mover advantage of the leader, as captured by $z_i^{Seq} - z_i^{NC}$, is emphasized when pollution is severe (high d) or when abatement is inexpensive (low γ); leading the follower to respond investing less in abatement than under a simultaneous context.

6.5.4 Dominant strategies under pre-commitment regulation

While the sequential structure introduces strategic interdependence in investment decisions, this complexity is absent in models where the regulator sets the emission fee *prior* to firms' abatement choices. Lambertini et al. (2017) analyze such a setting and find that each firm's optimal abatement level in the second stage is

$$z_i(t) = \frac{t}{\gamma},$$

where γ denotes the firm's cost parameter. Crucially, this decision is independent of the rival's investment, z_j, implying that abatement is a strictly dominant strategy. Each firm maximizes its own payoff by choosing the same investment level regardless of its competitor's actions.

This result underscores a key insight: the strategic effects of sequentiality only arise when firms invest *before* the regulator sets the emission fee. In industries where regulation is fixed and difficult to adjust—such as those governed by long-term policy frameworks or legislative mandates—firms' investment decisions are effectively decoupled from strategic considerations. In contrast, when regulation is responsive to firms' behavior, as in dynamic or adaptive policy environments, the timing of investment becomes a critical determinant of strategic interaction and equilibrium outcomes.

6.6 Different regulatory timing

6.6.1 Motivation

Lambertini et al. (2017) consider a similar setting, in which the sequence of regulatory and firm-level decisions is reversed relative to the baseline model. Specifically, the regulator commits to an emission fee in the first stage, after which firms independently choose their abatement investments in the second stage, followed by Cournot competition in output markets. This configuration—commonly referred to as "regulatory commitment"—is particularly relevant for industries where firms can revise their abatement decisions with relative ease, such as in the case of installing scrubbing technologies, pipe filters, or other modular pollution control mechanisms. In these contexts, regulatory parameters are often fixed over time due to institutional or legislative constraints, while firms retain flexibility in adjusting their investment strategies.

By contrast, the timing structure adopted in Poyago-Theotoky (2007) is more appropriate for industries characterized by large-scale, irreversible investments in environmental technologies. In such settings, firms' abatement decisions are difficult to modify once implemented, whereas regulatory authorities may retain the ability to adjust policy instruments in response to observed market behavior. This distinction underscores the importance of aligning the model's temporal structure with the technological and institutional realities of the industry under consideration. For generality, Lambertini et al. (2017) also allow for $n \geq 2$ firms, thus examining how aggregate investment is affected by the number of firms in the industry, potentially recommending entry under certain conditions to boost abatement.

6.6.2 Equilibrium behavior

Firm i's net emissions are, then, given by $e_i = q_i - z_i - \beta Z_{-i}$, where $Z_{-i} \equiv \sum_{j \neq i} z_j$ denotes the aggregate abatement efforts from firm i's rivals. For simplicity, we consider that $d = 2$, so environmental damages are $ED = (e_1 + ... + e_n)^2$.

Third stage. Every firm i chooses its output q_i to solve

$$\max_{q_i \geq 0} \pi_i (q_i) = (1 - q_i - Q_{-i})q_i - cq_i - t (q_i - z_i - \beta Z_{-i}) \tag{6.31}$$

where $Q_{-i} = \sum_{j \neq i} q_j$ denotes the aggregate output from firm i's rivals. Differentiating with respect to q_i, we obtain firm i's best response function $q_i(Q_{-i}) = \frac{1-c-t}{2} - \frac{1}{2}Q_{-i}$. In a symmetric equilibrium, $q_i = q_j = q$, which entails $Q_{-i} = (N-1)q_i$. Therefore, equilibrium output becomes

$$q_i(t) = \frac{1-c-t}{n+1},$$

which is decreasing in the emission fee t that the regulator sets in the first period, the number of firms competing in the industry, n, and the marginal production cost c. In addition, aggregate output is $Q(t) = nq_i(t) = \frac{n(1-c-t)}{n+1}$, which increases in the number of firms in the industry, n, decreases in the emission fee t, and in the marginal production cost c. Furthermore, $Q(t)$ asymptotically approaches $1-c-t$ when the market becomes perfectly competitive.

Substituting output $q_i(t)$ into the firm i's profit function, we find that

$$\begin{aligned} \pi_i(z_i, t) &= [1 - q_i (t) - Q_{-i} (t)] \, q_i (t) - cq_i (t) - t (q_i (t) - z_i - \beta Z_{-i}) - \frac{\gamma}{2} z_i^2 \\ &= \left(\frac{1-c-t}{n+1} \right)^2 + t (z_i + \beta Z_{-i}) - \frac{\gamma}{2} z_i^2. \end{aligned} \tag{6.32}$$

Second stage. Every firm i anticipates the profit that it earns in the third stage, $\pi_i(z_i, t)$, and chooses its abatement effort z_i to solve

$$\max_{z_i \geq 0} \pi_i(z_i, t) = \left(\frac{1-c-t}{n+1} \right)^2 + t (z_i + \beta Z_{-i}) - \frac{\gamma}{2} z_i^2 \tag{6.33}$$

Differentiating with respect to z_i, we obtain

$$t = \gamma z_i,$$

where the left side indicates the benefit from a marginal increase in abatement (lower taxes) and the right side measures the cost of this additional abatement. Notably, this first-order condition is independent of the abatement decisions of rival firms, denoted, Z_{-i}. As a result, each firm's optimal investment in abatement constitutes a *strictly dominant strategy*: firm i selects the same level of abatement regardless of its competitors' investments.

Solving for z_i in $t = \gamma z_i$ yields the equilibrium abatement effort

$$z_i(t) = \frac{t}{\gamma}, \tag{6.34}$$

which is monotonically increasing in the emission fee t. Intuitively, as the regulator imposes more stringent environmental policy (i.e., higher t), firms face stronger incentives to invest in pollution control technologies to mitigate their tax burden. In the absence of regulation—when $t = 0$—firms optimally choose zero investment in green R&D. Moreover, the equilibrium abatement level is decreasing in the cost parameter γ, implying that firms facing higher innovation costs invest less in environmental technologies.
At the aggregate level, total abatement in the industry is

$$Z(t) = nz_i(t) = \frac{nt}{\gamma}, \tag{6.35}$$

where n denotes the number of firms. This expression reveals that aggregate abatement increases with both the stringency of regulation and the degree of market competition. As Lambertini et al. (2017) observe, "if taxation were exogenous, we obtain a clear-cut Arrowian result: increased competition (higher n) leads to an increase in aggregate R&D (innovation)." However, when emission fees are endogenously determined—as in models where the regulator responds to firms' behavior—the comparative statics may reverse. In such cases, the strategic interaction between firms and the regulator introduces feedback effects that complicate the relationship between market structure and innovation intensity.
Therefore, the emission of every firm i becomes $e_i(t) = q_i(t) - z_i(t) - \beta(n-1) z_i(t)$. Inserting $q_i(t) = \frac{1-c-t}{n+1}$ and $z_i(t) = \frac{t}{\gamma}$, we obtain that

$$e_i(t) = \frac{1-c-t}{n+1} - \frac{t(1+\beta(n-1))}{\gamma},$$

and equilibrium profits become

$$\begin{aligned} \pi_i(t) &= \left(\frac{1-c-t}{n+1}\right)^2 + t\left(\frac{t}{\gamma} + \beta(n-1)\frac{t}{\gamma}\right) - \frac{\gamma}{2}\left(\frac{t}{\gamma}\right)^2 \\ &= \left(\frac{1-c-t}{n+1}\right)^2 + \frac{t^2(1+2\beta(n-1))}{2\gamma}. \end{aligned} \tag{6.36}$$

First stage. In this stage, the regulator chooses the emission fee that maximizes the social welfare, as follows,

$$W(t) = \frac{1}{2}[Q(t)]^2 + n\pi_i(t) - n^2[e_i(t)]^2$$

which simplifies to

$$\begin{aligned} W(t) = &\frac{n^2}{2}\left(\frac{1-c-t}{n+1}\right)^2 + n\left(\frac{1-c-t}{n+1}\right)^2 + \frac{Nt^2[1+2\beta(n-1)]}{2\gamma} \\ &- n^2\left[\left(\frac{1-c-t}{n+1}\right)^2 - \frac{2t(1-c-t)[1+\beta(N-1)]}{\gamma(n+1)} + \frac{t^2[1+\beta(n-1)]^2}{\gamma^2}\right] \\ = &\frac{2n^2[1+\beta(n-1)](1-c-t)t}{\gamma(n+1)} - \frac{n(n-2)(1-c-t)^2}{2(n+1)^2} \\ &+ \frac{n\left[\gamma(1+2\beta(n-1)) - 2n(1+\beta(n-1))^2\right]t^2}{2\gamma^2} \end{aligned}$$

Differentiating with respect to t, we obtain the optimal emission fee

$$t(n) = \frac{\gamma\left[2n(n+1)(1+\beta(n-1)) + \gamma(n-2)\right](1-c)}{4\gamma n(n+1)\left[1+\beta(n-1)\right] + \gamma^2(n-2) - A(\gamma)} \tag{6.37}$$

where, for compactness, $A(\gamma) \equiv (n+1)^2\left[\gamma(1+2\beta(n-1)) - 2n(1+\beta(n-1))^2\right]$. Furthermore, we thereafter consider $c = 0$ and $\gamma = 5$, which helps us focus on the role of the number of firms, n, and spillover effects, β, on aggregate investments in abatement. In this illustrative context, the equilibrium abatement effort, $z_i(n) = \frac{t(n)}{\gamma}$, is

$$z_i(n) = \frac{2n(n+1)\left[1+\beta(n-1)\right] + 5(n-2)}{20n(n+1)\left[1+\beta(n-1)\right] + 25(n-2) - A(5)}. \tag{6.38}$$

Roadmap. We next evaluate aggregate abatement $Z(n) = n \times z_i(n)$ in the case of no spillovers, $\beta = 0$, showing that such investment is unambiguously increasing in the number of firms, n. Then, we evaluate $Z(n)$ in the case of positive spillovers, $\beta > 0$, demonstrating that this investment exhibits an inverted U-shape.

6.6.3 Changes in market concentration - No spillovers

Evaluating aggregate abatement $Z(n) = n \times z_i(n)$ under no spillovers, $\beta = 0$, we find that

$$Z(n) = \frac{n(2n^2 + 7n - 10)}{2n^3 + 19n^2 + 37n - 55}. \tag{6.39}$$

Differentiating the above expression with respect to n yields

$$\frac{\partial Z(n)}{\partial n} = \frac{24n^4 + 188n^3 + 119n^2 - 770n + 550}{\left(2n^3 + 19n^2 + 37n - 55\right)^2}. \tag{6.40}$$

This derivative is strictly positive for all $n \geq 2$, indicating that aggregate abatement increases monotonically with the number of firms in the industry. The intuition behind this result is straightforward: in the absence of spillover effects, each firm does not benefit from the abatement efforts of its competitors. Technically, every firm benefits from TSE, but not from ERE. Consequently, as additional firms enter the market, each firm responds by increasing its own investment to mitigate its individual tax burden. This behavior leads to a cumulative rise in total abatement across the industry.
Figure 6.10 illustrates the relationship between aggregate abatement $Z(n)$ and the number of firms n, evaluated under the assumption of no spillovers (i.e., $\beta = 0$). The figure confirms the positive relationship between market size and total investment in environmental R&D, consistent with the Arrowian prediction that increased competition fosters greater innovation when spillovers are absent.

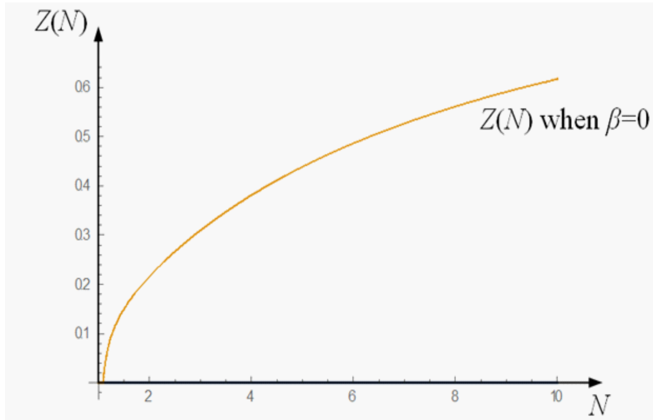


Figure 6.10. Aggregate abatement when $\beta = 0$.

Under no spillovers, a firm's abatement investment does not generate the emission-reduction externality (ERE) discussed earlier. This is due to the timing structure of the game: since the regulator sets the emission fee in the first stage, firms' investments do not influence its stringency. By contrast, in Poyago-Theotoky (2007), the regulator responds to observed abatement levels, so greater investment leads to a less stringent fee in the subsequent stage, creating an incentive to invest strategically.

6.6.4 Changes in market concentration - Spillovers

Evaluating aggregate abatement $Z(n)$ at $\beta = 1/2$, we obtain

$$Z(n) = \frac{2n^4 + 4n^3 + 12n^2 - 20n}{n^5 + 4n^4 + 16n^3 + 24n^2 + 61n - 100}. \quad (6.41)$$

Differentiating with respect to n yields

$$\frac{\partial Z(n)}{\partial n} = \frac{2(-n^8 - 4n^7 - 10n^6 + 40n^5 + 255n^4 + 164n^3 + 6n^2 - 1200n + 1000)}{(n^5 + 4n^4 + 16n^3 + 24n^2 + 61n - 100)^2}. \quad (6.42)$$

The denominator of $\frac{\partial Z(n)}{\partial n}$ is unambiguously positive, but the numerator is only positive if and only if $n < \overline{n} = 3.432$. As a consequence, $\frac{\partial Z(n)}{\partial n}$ is positive for all $n \in [2, \overline{n}]$, but becomes negative otherwise, i.e., when $n > \overline{n} = 3.432$. This result explains the inverted U-shaped relationship between market competition and aggregate abatement: as the number of firms increases, total investment in green innovation initially rises, reaches a peak, and then declines. Figure 6.11 illustrates this non-monotonic pattern, with $Z(n)$ first increasing in n, reaching a maximum, and then decreasing in n.

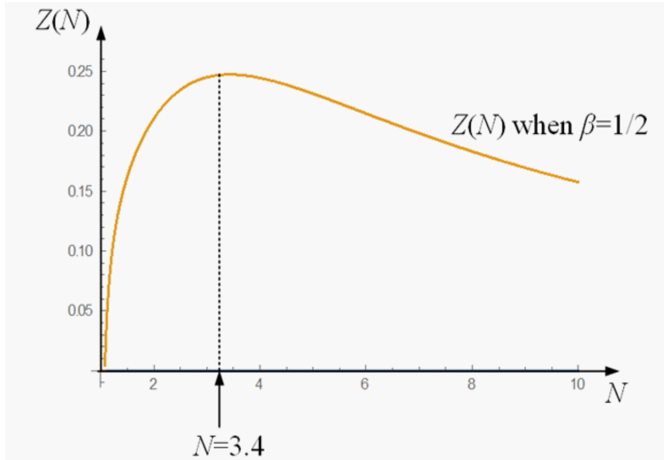


Figure 6.11. Aggregate abatement when $\beta = 1/2$.

When the industry comprises four or fewer firms, increasing the number of competitors tends to stimulate green innovation, as each firm independently invests in abatement. However, as competition intensifies, firms face stronger incentives to free-ride on the abatement efforts of others, leading to a decline in individual investment levels.
Thus, the emission-reduction externality (ERE) identified in Poyago-Theotoky (2007) also arises when $\beta > 0$, suggesting that an Environmental Research Cartel (ERC) could help internalize this externality. Nevertheless, because the tax-saving externality (TSE) is absent under regulatory commitment, the urgency for forming an ERC is reduced compared to settings where firms invest before the regulator sets the emission fee.

6.7 Other extensions

This section briefly reviews several extensions to the baseline model, highlighting how variations in market structure, policy instruments, and institutional design influence environmental R&D outcomes.

6.7.1 Endogenous entry

While much of the literature assumes an exogenous number of firms in polluting industries, $n \geq 2$, Katsoulacos and Xepapadeas (1995) introduce endogenous entry. In their framework, the regulator sets the emission fee in the first stage, firms decide whether to enter in the second stage, and subsequently choose output and abatement levels.
A key finding is that the equilibrium emission fee may exceed the marginal environmental damage—a result not observed under exogenous market structure. This "overinternalization" of externalities can lead to excessive entry and inefficiencies. To address this, the authors propose a two-instrument policy: an entry fee to limit socially excessive entry, and an emission fee set below marginal damages to avoid overinternalization. This combination yields higher welfare than a single emission fee alone.

6.7.2 Subsidies and regulatory design

Ouchida and Goto (2014) extend the Poyago-Theotoky (2007) framework by analyzing the role of subsidies. They show that subsidies can be welfare-improving, particularly when pollution is mild (i.e., low d)). In such cases, the distortion from underproduction in oligopoly may outweigh the environmental externality, making it optimal to subsidize output (i.e., $t < 0$).

When R&D costs are high (large γ), firms invest minimally in abatement, and regulation may paradoxically lead to higher pollution than under laissez-faire. Nonetheless, regulation can still improve welfare. Conversely, when R&D is inexpensive (low γ), firms invest heavily in abatement, resulting in lower emissions relative to the unregulated scenario.

6.7.3 Patenting vs. licensing green technologies

Biglaiser and Horowitz (1995) explore firms' strategic decisions to patent or license green innovations. Their model spans four stages: R&D investment, emission fee determination, technology adoption (patent or license), and output choice. They analyze how firms balance the benefits of exclusive use against the gains from licensing to competitors.

Denicolo (1999) considers a related setting with a single innovating firm, which chooses whether to retain or license its technology. The analysis compares two regulatory regimes: one where emission fees are set before R&D investment, and another where fees respond to observed innovation. These timing differences significantly affect licensing incentives and welfare outcomes.

6.7.4 Product differentiation

Poyago-Theotoky and Teerasuwannajak (2002) investigate how horizontal product differentiation alters regulatory outcomes. They compare two regimes: a pre-commitment emission fee (set before abatement decisions) and a time-consistent fee (set afterward). When products are highly differentiated, the optimal time-consistent fee is less stringent than the pre-commitment tax. However, as products become more homogeneous, the ranking reverses—especially when R&D is efficient and pollution is severe.

They also show that equilibrium abatement is higher under time-consistent regulation when differentiation is strong, but may be lower when R&D costs are minimal. Welfare comparisons follow similar patterns, with pre-commitment regulation yielding higher welfare in markets with homogeneous products.

6.7.5 Mixed oligopolies

In mixed oligopolies, a public firm competes alongside private firms, but maximizes a weighted combination of profits and social welfare, including environmental damages. This structure allows the public firm to partially internalize externalities, improving overall welfare.

Bárcena-Ruiz and Garzón (2006) show that privatization can be welfare-reducing when emission taxes are present, as it exacerbates underproduction typical of oligopoly models. The public firm helps offset this distortion. Haruna and Goel (2009) find similar results, noting that the public firm's presence reduces output and emissions, potentially leading to emission subsidies when pollution is mild. In contrast, Pal and Saha (2014) demonstrate that first-best outcomes can be achieved through a combination of abatement subsidies and output taxes, without requiring privatization. For a comprehensive review, see Poyago-Theotoky (2023).

6.8 Case studies

6.8.1 Simultaneous abatement decisions: Hewlett-Packard and Dell

HP and Dell have both invested heavily in reducing emissions from their manufacturing processes and product lifecycles. HP was among the first to report its greenhouse gas emissions and launched aggressive recycling and toxic substance reduction programs. Dell followed with similar initiatives, including closed-loop recycling and energy-efficient product design. These simultaneous efforts were driven by emission-related compliance costs and competitive sustainability benchmarks.

A similar argument applies to European automakers. Facing tightening emission standards, companies like Volkswagen, BMW, and Stellantis have each committed billions to electrification and battery innovation. Volkswagen's IG Metall agreement freed up €15 billion in annual savings, much of which is being redirected to EV R&D and production realignment. Stellantis has pledged €30 billion for electrification by 2025, while BMW is investing heavily in next-generation battery technologies.

6.8.2 ERJVs: Canada's Oil Sands Innovation Alliance

Major oil sands producers in Canada—including Suncor, Cenovus, and Canadian Natural Resources—formed Canada's Oil Sands Innovation Alliance (COSIA) to jointly invest in environmental R&D. The alliance focuses on reducing greenhouse gas emissions, improving water use, and land reclamation. By pooling resources and sharing technology, these firms coordinate abatement efforts to meet regulatory requirements and reduce per-unit emission costs.

Similarly, Japanese refining companies—including JXTG Nippon Oil & Energy and Idemitsu—coordinate green R&D aimed at reducing emissions from refining operations. The association facilitates joint development of end-of-pipe technologies like scrubbers and catalytic converters.

6.8.3 Sequential abatement decisions: Manufacturing and US refining

A cross-country study of 33,500 manufacturing firms found that high-emission sectors with strong knowledge spillovers—such as cement and mineral products—saw early adopters invest in cleaner production technologies following the introduction of emission taxes; see Brown et al. (2022). These leaders used R&D not to develop new products, but to retool existing processes, prompting follower firms to later adopt similar technologies to remain cost-competitive under the new regulatory regime.

In the U.S. refining industry, firms like Chevron and ExxonMobil often act as leaders in green investments. Under state-level emission fees (e.g., California's carbon pricing), these firms have made high-profile investments in carbon capture and low-carbon fuels. Smaller refiners tend to follow their lead, especially when these strategies prove cost-effective under the emission fee regime.