Profiting from regulation: The effects of emissions standards on abatement R&D

Johanna-Sophia Hardt* Heidrun Hoppe-Wewetzer†
Felix B. Klapper‡

March 19, 2025

Abstract

This paper explores the impact of emissions standards on a firm's output and abatement R&D investment decisions in a duopoly model, extending the work of Amir et al. (2023). It is shown that high upper limits on total emissions remove the firms' incentives to invest in abatement R&D. This helps firms to coordinate on profit-increasing output levels relative to unregulated markets. Moreover, sudsidies for abatement R&D may hurt firms.

Keywords: Environmental regulation; emissions standard; Cournot; emissions abatement; abatement R&D

JEL-Codes: Q55, Q58, L13

---

*Leibniz University Hannover, Economics Dept, hardt@mik.uni-hannover.de
†Leibniz University Hannover, Economics Dept, and CEPR, hoppe@mik.uni-hannover.de
‡Leibniz University Hannover, Economics Dept, klapper@mik.uni-hannover.de

1 Introduction

Environmental regulation, such as the Clean Air Act in the United States, sets specific limits on pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_X), particulate matter (PM), and volatile organic compounds (VOCs). In the petrochemical industry, plants must adhere to specific standards for emissions of VOCs. In the power generation sector, coal-fired plants must keep SO_2 emissions below a certain tonnage per year depending on their capacity, while NOx emissions are also capped to reduce acid rain and ozone formation. The aluminum smelting industry faces limits on perfluorocarbon (PFC) emissions due to their global warming potential. To comply with these emissions limits, firms might choose to reduce production, or they might invest in new technology to expand their production capacity with additional low-emission facilities.[1] In fact, according to the recent report of the United Nations Environment Programme (2024), there is unexplored technological potential for emission reduction in the context of abatement research and development (R&D).

In this paper, we examine the impact of emissions standards on a firm's output and abatement R&D investment decisions in a duopoly model, as recently introduced by Amir et al. (2023). In this model, the firms face Cournot competition with pollution-generating production. There is a cap on total pollution, and abating emissions beyond this limit is costly. The firms simultaneously choose outputs and investments in R&D to reduce the unit cost of abating emissions that exceed the permissible limit. We extend the analysis of Amir et al. to scenarios where the emissions limit is unbounded.

We find that higher upper limits on emissions remove the firms' incentives to invest in abatement R&D: Rather than abate any emissions that exceed the permissible limit, firms restrict their output to exactly meet the emissions standard. Interestingly, our

---

[1] For empirical studies on the effect of emissions standards on new technology adoption and plant opening decisions of multi-plant firms, see, e.g., Gray (1997), Gray and Shadbegian (1998), Campbell and Levkoff (2025).

analysis reveals that firms may achieve higher profits under the regulation compared to a scenario without it, potentially even replicating the outcome of collusion in the unregulated output market. This advantage from implementing higher prices in the market outweighs the benefits from investing in abatement R&D. In a nutshell, we show that lax enough emissions standards induce firms to choose to not invest in abatement R&D, and thus forego the expansion of capacity with low-emission technology. Moreover, investigating the effects of subsidies for abatement R&D, we find that, when the upper limit on emissions is low enough, the subsidy always increases outputs but may hurt firms.

There is a growing literature on the impact of emissions standards on firms' incentives for abatement R&D and adopting cleaner technology.[2] Nevertheless, the effect of these standards on firms' profits compared to unregulated markets has still received scant attention. Exceptions are Anand and Giraud-Carrier (2020) and Deng et al. (2023), who recently observed in different settings that emissions standards may not always hurt firms. The main difference to the present paper is that, in our model, firms not only choose output levels, but may also invest in R&D to lower the cost of abating any excessive emissions beyond a fixed limit. In contrast, the previous papers focus on production decisions that require the adoption of new technology to reduce the ratio of emissions to output in order to meet a traded emissions quota.[3] The authors recognize the profit-enhancing effects of an emissions cap on the firms' output in a Cournot duopoly, but abstract from the possibility to reduce the cost of abating any emissions that exceed the permissible limit. In this paper, we go a step further and show that the emissions cap may help firms coordinate on profit-increasing output levels, even

---

[2] See, e.g., Montero (2002), Requate (2005), Tarui and Polasky (2005), Perino and Requate (2012). See Kellogg and Reguant (2021) for a comprehensive survey of industrial organization contributions to environmental regulation within energy markets and transportation.

[3] That is, for a given quota of permissible emissions, the abatement level is not endogenous in these models, but implied by the output choice.

though they are able to reduce the costs of expanding their capacity with low-emission facilities. The critical impact of an emissions standard, when not strict enough, is the removal of any incentive for the firms to invest in cost-reducing abatement R&D, as this influences their cost of deviating to higher output levels.

Related is also the work by Amir et al. (2008) who consider different ways of modeling abatement R&D of a single price-taking firm. Menezes and Pereira (2017) investigate the mix of R&D subsidy and emissions tax in a duopoly model with differentiated goods and emissions-reducing R&D. Empirical evidence supporting our results is provided by Bushnell et al. (2013) on emissions caps in the European Union. For manufacturing firms in the United States, King and Lenox (2001) find evidence for a connection between lower pollution and higher financial performance.

The remainder of this paper is organized as follows: In Section 2, we present the model. The impact of emissions caps on the output and abatement R&D investment decisions of the firms is analyzed in Section 3. Section 4 considers the effects of an R&D subsidy. Section 5 concludes.

2 The model

We consider a duopoly model, as introduced by Amir et al. (2023). There are two firms, indexed by $i = 1, 2$, who produce a homogenous good and engage in Cournot competition in the output market. Production is costless for the firms, but generates pollution in the environment. Specifically, each firm i's output, q_i, produces exactly q_i units of pollution emissions. The inverse demand is given by $P(Q) = a - bQ$ for $Q \leq a/b$, where $a, b > 0$, and $Q = q_1 + q_2$ is the total output produced in the market.

The amount of total emissions permissible in the market is limited by an emissions standard. For simplicity, we assume that each firm faces the same emissions limit, denoted by ξ.[4] Abating emissions beyond this limit is costly with constant unit cost $c > 0$. Each firm i can invest in abatement R&D in order to reduce the unit cost of abatement to $c - x_i$. The cost of abatement R&D is given by $\gamma x_i^2/2$, where $\gamma > 0$ is a parameter inversely related to the efficiency of R&D.[5]

The following assumptions regarding the relationships between the abatement unit cost, the market size, and the efficiency of abatement R&D are maintained from the model of Amir et al. (2023):

A1(i) $a > 2c$

A1(ii) $3b\gamma > a/c$

The first assumption is standard in the linear Cournot model with production costs and states here that the market is sufficiently large relative to the abatement costs. The second assumption implies that maximal abatement R&D, i.e., $x = c$, is unattractive.

Contrary to Amir et al., we assume the emissions limit ξ is not bounded from above.[6]

Each firm i simultaneously chooses its investment in abatement R&D, x_i, and output, q_i.[7] The payoff of firm i is thus given by

$$\Pi_i = \begin{cases} \left(a - bq_i - bq_j\right) q_i - \left(c - x_i\right)\left(q_i - \xi\right) - \frac{1}{2}\gamma x_i^2 & , q_i > \xi \\ \left(a - bq_i - bq_j\right) q_i - \frac{1}{2}\gamma x_i^2 & , q_i \leq \xi, \end{cases}$$

where $j \neq i$.

---

[4] One can verify that the results of the paper extend with only slight modifications to the case of asymmetric limits, as considered in Amir et al. (2023), and tradable limits, as in Anand and Giraud-Carrier (2020), and Deng et al. (2023).

[5] This form of R&D cost function is standard in the R&D literature. See, for instance, d'Aspremont and Jacquemin (1988) and Amir (2000).

[6] Amir et al. (2023) consider the case of $0 < \xi < (a - c)/3b$.

[7] As noted by Amir et al. (2023), the one-stage game seems particularly suited for situations when firms cannot observe each other's R&D investment or when they cannot commit to their R&D choices. A two-stage version of the game is considered by Amir et al. (2018).

We use the Nash equilibrium in pure strategies as the solution for the game.

3 Abatement R&D and output choice

In this section, we will analyze the equilibrium choice of abatement R&D and output. Each firm i maximizes its payoff Π_i by choosing q_i and x_i under an exogenous emissions standard. The following proposition describes the equilibrium.

Proposition 1 *In equilibrium, each firm i chooses output*

$$q_i = \begin{cases} \frac{\gamma(a-c)-\xi}{3b\gamma-1} & , 0 \leq \xi < \frac{a-c}{3b} \\ \xi & , \frac{a-c}{3b} \leq \xi < \frac{a}{3b} \\ \frac{a}{3b} & , \xi \geq \frac{a}{3b} \end{cases}$$

and invests in abatement R&D

$$x_i = \begin{cases} \frac{a-c-3b\xi}{3b\gamma-1} & , 0 \leq \xi < \frac{a-c}{3b} \\ 0 & , \xi \geq \frac{a-c}{3b}. \end{cases}$$

Proof. *See Appendix A.1.*

When the emissions limit is not binding, i.e., for $\xi \geq a/(3b)$, there is no investment in abatement R&D, and firms choose their pre-regulation Cournot equilibrium output $a/(3b)$. For lower levels of ξ, i.e., $(a-c)/(3b) \leq \xi < a/(3b)$, we find that the firms still do not invest in abatement R&D, but choose outputs to exactly meet the emissions cap (see Figure 1). For this range of ξ, it is not optimal to produce a higher output $q_i > \xi$ and abate emissions that exceed the limit, even though the cost of abatement for excess output could be reduced via abatement R&D. The analysis reveals that the

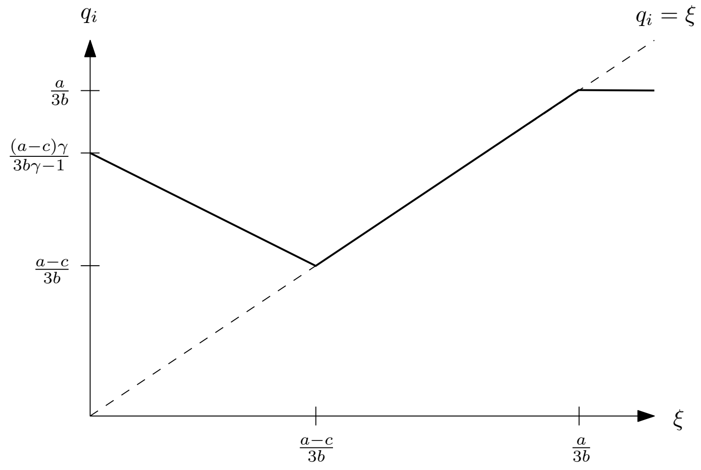

Figure 1: Equilibrium output of a single firm for varying emissions caps.

advantage of maintaining higher prices in the output market outweighs the benefits from abatement R&D. Put differently, zero R&D investments render deviations to higher output levels unattractive. Finally, for $0 \leq \xi < (a-c)/(3b)$, each firm invests in abatement R&D, $x_i > 0$, and produces an output above the limit, $q_i > \xi$. Note that the benefit from an abatement cost reduction increases in the amount of excess emissions such that the investment in abatement R&D and output increase as the emissions cap decreases. Nevertheless, the corresponding output does not reach the unregulated output level (see Figure 1).

The following proposition states that emissions limits can increase the firms' payoffs compared to unregulated markets.

Proposition 2 *There is a unique* $\hat{\xi} < (a-c)/(3b)$*, such for* $\hat{\xi} < \xi < a/(3b)$*, each firm's equilibrium payoff exceeds the payoff obtainable in the unregulated market.*

Proof. *See Appendix A.2.*

For $(a-c)/(3b) < \xi < a/(3b)$, there is no investment in abatement R&D, and firms coordinate on profit-increasing output levels relative to unregulated markets. Interestingly, our analysis reveals that, if $a \leq 4c$, i.e., when the initial marginal cost of

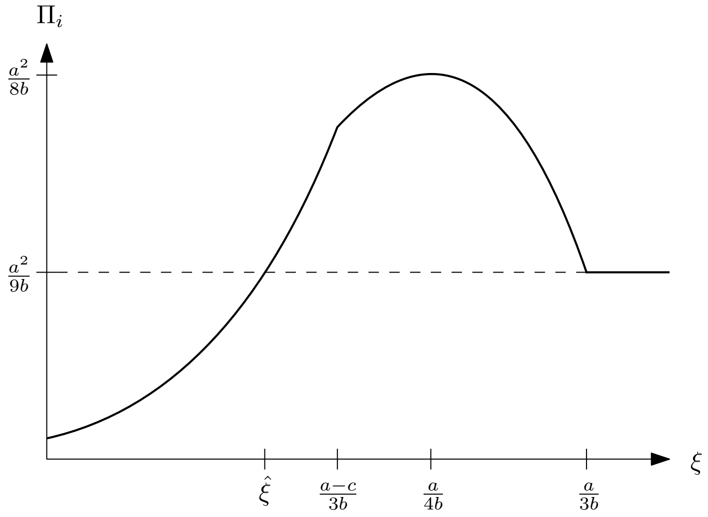

Figure 2: Equilibrium payoff of a single firm for varying emissions caps, and $a \leq 4c$.

abatement is sufficiently high, the firms' profits in the product market potentially even reach the level that is otherwise obtainable only through collusion in the unregulated market, $\Pi_i = a^2/(8b)$. As described above, these emissions standards render unilateral deviations to higher output levels unprofitable. For $\hat{\xi} < \xi < (a-c)/(3b)$, firms invest in abatement R&D but still realize higher equilibrium payoffs compared to an unregulated market. Here, the benefit from higher prices still outweighs the cost of abatement and abatement R&D. Finally, for $\xi < \hat{\xi}$, payoffs fall below the pre-regulation level due to higher cost of abatement and abatement R&D. Figure 2 illustrates Proposition 2 by depicting the equilibrium payoff Π_i of each firm i under varying emissions caps for the case of $a \leq 4c$. The dashed line indicates the pre-regulation payoff level.

Moreover, it can be easily verified that for each emissions cap $\max\{a/(4b), (a-c)/(3b)\} < \xi < a/(3b)$, there is always a smaller cap that results in the same equilibrium payoffs but involves strictly less pollution. This finding has interesting implications for the design of environmental regulation.

4 Subsidy for abatement R&D

In what follows, we consider a subsidy for abatement R&D that reduces the marginal cost of abatement R&D directly or, for instance, through a lump-sum governmental investment in the R&D capabilities of firms, thereby enhancing the efficiency of their R&D activities. More formally, we perform comparative statics with respect to γ and reverse the sign to capture the effect of a an R&D subsidy. The following proposition describes the effect of an R&D subsidy on equilibrium outcomes.

Proposition 3 *For all* $\xi < (a-c)/(3b)$*, the subsidy for abatement R&D increases output and investments in abatement R&D, and it reduces the firms' payoffs if* $b\gamma \leq 1$*. If* $b\gamma > 1$*, there exists a unique threshold value* $\xi' < \hat{\xi}$*, where* $\hat{\xi}$ *is defined in Proposition 2, such that the subsidy for abatement R&D increases payoffs for* $\xi < \xi'$ *and decreases payoffs for* $\xi > \xi'$*. For* $\xi \geq (a-c)/(3b)$*, the subsidy for abatement R&D does not affect equilibrium outcomes.*

Proof. *See Appendix A.3.*

The proposition states that, for $\xi \geq (a-c)/(3b)$, equilibrium strategies and payoffs are not affected by the R&D subsidy. For lower levels of ξ, i.e., $0 < \xi < (a-c)/(3b)$, the R&D subsidy increases equilibrium outputs and investments in abatement R&D, whereas the effect on payoffs turns out to be ambiguous: The R&D subsidy decreases the firms' payoffs if $b\gamma \leq 1$. Otherwise, there exists a threshold value $\xi' < \hat{\xi}$, such that payoffs are increased [reduced] depending on whether $\xi < [>]\xi'$.

The intuition behind these results is as follows. Implementing the R&D subsidy reduces the marginal cost of abatement R&D. Consequently, firms have an incentive to increase abatement R&D, which in turn reduces marginal abatement costs, leading firms to expand their production. Thus, the R&D subsidy makes deviations to higher output levels more attractive. If this effect outweighs the benefits of a reduction of the marginal abatement cost, equilibrium payoffs decrease. When the emissions standard is lower than ξ', the benefit from a reduction of marginal abatement cost compensates for the reduction in revenues due to lower prices in the output market.

Taken together, the output reducing effect of binding emissions standards can be reduced by implementing an R&D subsidy. This may harm firms.

5 Conclusion

We studied the effects of emissions standards on firms' output and abatement R&D investment decisions in a duopoly model, extending the work of Amir et al. (2023) to the case where the emissions limit is unbounded. Our analysis revealed that high emissions limits eliminate the firms' incentives to invest in abatement R&D. We have identified conditions under which emissions standards yield higher payoffs for the firms than in unregulated markets. Furthermore, we have demonstrated that subsidizing abatement R&D may hurt firms by making higher output levels in the product market more attractive.

Our findings have implications for setting emissions standards. In particular, we demonstrate that appropriately set standards can, in fact, reduce emissions without harming firms. Moreover, emissions standards may only stimulate investments in abatement R&D if they are sufficiently strict. Regulators might accompany emissions standards with an R&D subsidy to mitigate reductions in outputs.

A Appendix

A.1 Proof of Proposition 1

In what follows, we characterize the unique equilibrium. For this proof, define functions $\Pi_i^A(q_i, x_i; q_j)$ and $\Pi_i^{\overline{A}}(q_i, x_i; q_j)$, where superscripts A and $\overline{A}$ indicate payoffs with abatement ($q_i > \xi$) and without ($q_i \leq \xi$), respectively.

$$\begin{aligned}\Pi_i^A(q_i, x_i; q_j) &= (a - bq_i - bq_j)\, q_i - (c - x_i)\,(q_i - \xi) - \frac{1}{2}\gamma x_i^2 \\ \Pi_i^{\overline{A}}(q_i, x_i; q_j) &= (a - bq_i - bq_j)\, q_i - \frac{1}{2}\gamma x_i^2\end{aligned}$$

Suppose that both firms choose outputs such that they have to abate excess emissions. As shown by Amir et al. (2023), in the unique equilibrium, each firm i chooses output and abatement R&D investment

$$q_i^A = \frac{\gamma(a-c) - \xi}{3b\gamma - 1} \quad \text{and} \quad x_i^A = \frac{(a-c) - 3b\xi}{3b\gamma - 1}, \tag{A.1}$$

respectively. Note that q_i^A is decreasing in ξ, i.e., $\partial q_i^A/\partial \xi < 0$. The interior solution leads to an optimal output that exceeds the cap if $q_i^A > \xi$, which is equivalent to $\xi < (a-c)/(3b)$.

Suppose that firms choose outputs such that they do not have to abate excess emissions. Note that $\partial \Pi_i^{\overline{A}}/\partial x_i < 0$ for all $x_i > 0$. Consequently, the optimal x_i is always zero. Firm i's problem then simplifies to $\max_{q_i}[(a - b(q_i + q_j))q_i]$. The first-order condition is given by $a - 2bq_i - bq_j = 0$. Each firm i chooses output and abatement R&D investment in the unique equilibrium according to

$$q_i^{\overline{A}} = \frac{a}{3b} \quad \text{and} \quad x_i^{\overline{A}} = 0, \tag{A.2}$$

respectively. $q_i^{\overline{A}}$ is constant in ξ. The interior solution leads to an optimal output that does not exceed the cap if $q_i^{\overline{A}} \leq \xi$, which is equivalent to $\xi \geq a/(3b)$.

In what follows we show that for $\xi \in [\frac{a-c}{3b}, \frac{a}{3b})$, the combination $q_i^{\hat{A}} = \xi$, $x_i^{\hat{A}} = 0$ describes the equilibrium strategy of both firms by demonstrating that neither firm has an incentive to unilaterally deviate from that strategy. Denote the corresponding payoffs of each firm i as $\Pi_i^{\hat{A}} = \Pi_i^{\overline{A}}(\xi, 0; \xi) = a\xi - 2b\xi^2$.

- It must not be profitable for firm i to unilaterally deviate to any $q_i < \xi$ and/or $x_i \geq 0$, given firm j chooses $q_j = \xi$, $x_j = 0$.

  For $q_i < \xi$, payoffs $\Pi_i^{\overline{A}}(q_i, x_i; \xi)$ decrease in x_i, i.e., $\mathrm{d}\Pi_i^{\overline{A}}/\mathrm{d}x_i < 0$ for all $q_i \geq 0$ and $x_i > 0$, such that $x_i > 0$ cannot be part of any equilibrium. Consequently, it is sufficient to show that there does not exist a profitable deviation to $q_i < \xi$ in combination with $x_i = 0$. Define

  $$\hat{\Pi}_i^{\overline{A}}(q_i; \xi) = \Pi_i^{\overline{A}}(q_i, 0; \xi).$$

  Then, there is no profitable deviation if

  $$\hat{\Pi}_i^{\overline{A}}(q_i; \xi) \leq \Pi_i^{\hat{A}} \quad , \forall q_i < \xi. \tag{A.3}$$

  Note that $\hat{\Pi}_i^{\overline{A}}(q_i; \xi)$ is continuous for $q_i < \xi$. (A.3) holds if the following conditions are satisfied:

  First, payoffs have to be monotonously increasing in q_i, i.e.,

  $$\left.\frac{\mathrm{d}\hat{\Pi}_i^{\overline{A}}}{\mathrm{d}q_i}\right|_{(q_i;\xi)} > 0 \quad , \forall q_i < \xi. \tag{A.4}$$

  Observe that $\mathrm{d}\hat{\Pi}_i^{\overline{A}}/\mathrm{d}q_i|_{(\xi;\xi)} = a - 3b\xi > 0$ for all $\xi \in [\frac{a-c}{3b}, \frac{a}{3b})$. Furthermore,

$\mathrm{d}^2\hat{\Pi}_i^{\overline{A}}/\mathrm{d}q_i^2|_{(q_i;\xi)} = -2b < 0$ for all $q_i < \xi$. Consequently, (A.4) holds, i.e., payoffs are monotonously increasing in q_i for $q_i < \xi$. Second, payoffs must never exceed $\Pi_i^{\hat{A}}$. Since payoffs monotonously increase in q_i, the maximum payoffs for $q_i < \xi$ are strictly below $\lim_{q_i \to \xi} \hat{\Pi}_i^{\overline{A}}(q_i;\xi) = \hat{\Pi}_i^{\overline{A}}(\xi;\xi) = \Pi_i^{\hat{A}}$. Thus, (A.3) is satisfied and firm i cannot profitably unilaterally deviate to any strategy $q_i < \xi$, $x_i \geq 0$. Because of symmetry, firm j can neither profitably unilaterally deviate to $q_j < \xi$, $x_j \geq 0$.

- It must not be profitable for firm i to unilaterally deviate to any $q_i > \xi$ and/or $x_i \geq 0$, given firm j chooses $q_j = \xi$, $x_j = 0$. For $q_i > \xi$, excess emissions have to be abated. For each output level, the payoff maximizing level of abatement R&D investment, denoted by $\hat{x}_i(q_i) \geq 0$, follows from the first-order condition $\partial \Pi_i^A / \partial x_i = 0$, which corresponds to

  $$\hat{x}_i(q_i) = \frac{q_i - \xi}{\gamma}. \tag{A.5}$$

  Consequently, no $x_i \neq \hat{x}_i(q_i)$ can be part of any equilibrium and it suffices to show that there does not exist a profitable deviation to $q_i > \xi$ with corresponding $0 < \hat{x}_i(q_i) < c$. Note that it is not profitable to choose $x_i = c$ under the model assumptions. Define

  $$\hat{\Pi}_i^A(q_i;\xi) = \Pi_i^A(q_i, \hat{x}_i(q_i); \xi).$$

  Then, there is no profitable deviation if

  $$\hat{\Pi}_i^A(q_i;\xi) \leq \Pi_i^{\hat{A}} \quad, \forall q_i > \xi. \tag{A.6}$$

  Note that $\hat{\Pi}_i^A(q_i;\xi)$ is continuous for $q_i > \xi$. (A.6) holds if the following conditions are satisfied:

First, payoffs have to be monotonously decreasing in q_i, i.e.,

$$\left.\frac{\mathrm{d}\hat{\Pi}_i^A}{\mathrm{d}q_i}\right|_{(q_i;\xi)} < 0 \quad , \forall q_i > \xi. \tag{A.7}$$

Observe that $\mathrm{d}\hat{\Pi}_i^A/\mathrm{d}q_i|_{(\xi;\xi)} = a - 3b\xi - c \leq 0$ for $\xi \in [\frac{a-c}{3b}, \frac{a}{3b})$, where equality holds for $\xi = (a-c)/(3b)$. In addition, $\mathrm{d}^2\hat{\Pi}_i^A/\mathrm{d}q_i^2|_{(q_i;\xi)} = 1/\gamma - 2b < 0$ for all $q_i > \xi$ under the model assumptions. Consequently, (A.7) holds, i.e., payoffs are monotonously decreasing in q_i for $q_i > \xi$. Second, payoffs must never exceed $\Pi_i^{\hat{A}}$. Since payoffs monotonously decrease in q_i, the maximum payoffs for $q_i > \xi$ are strictly below $\lim_{q_i \to \xi} \hat{\Pi}^A(q_i; \xi) = \hat{\Pi}^A(\xi; \xi) = \Pi_i^{\hat{A}}$. Thus, (A.6) is satisfied and firm i cannot profitably unilaterally deviate to any strategy $q_i > \xi$, $x_i \geq 0$. Because of symmetry, firm j can neither profitably unilaterally deviate to $q_j > \xi$, $x_j \geq 0$.

Taken together, for $\xi \in [\frac{a-c}{3b}, \frac{a}{3b})$, there is no profitable unilateral deviation for each firm i to any strategy involving $q_i \neq \xi$ in combination with $x_i \geq 0$. Consequently, each firm i chooses output and abatement R&D $q_i^{\hat{A}} = \xi$ and $x_i^{\hat{A}} = 0$ in the unique equilibrium for $\xi \in [\frac{a-c}{3b}, \frac{a}{3b})$.

■

A.2 Proof of Proposition 2

To prove the proposition we first establish that the firm's equilibrium payoff Π_i is a continuous function of the emissions limit ξ. Then, for the range $(a-c)/(3b) \leq \xi < a/(3b)$, the maximum of Π_i is defined as $\tilde{\xi}$, where $\tilde{\xi}$ is unique and shown to be the global maximum. Finally, for $\xi < (a-c)/(3b)$, we define $\hat{\xi}$ to be the emissions limit at which $\Pi_i(\hat{\xi})$ is equal to the firm's equilibrium payoff obtainable for $\xi \geq a/(3b)$, where $\hat{\xi}$ is shown to be unique. Noting that the firm's equilibrium payoff Π_i obtainable for $\xi \geq a/(3b)$ is equal to the firm's equilibrium payoff in an unregulated market, we then argue by the continuity of $\Pi_i(\xi)$ and since $\hat{\xi} < \tilde{\xi} < a/(3b)$ that $\Pi_i(\xi)$ exceeds the pre-regulation payoff for the range $\hat{\xi} < \xi < a/(3b)$.

By Proposition 1, firm i's equilibrium payoff is given by

$$\Pi_i(\xi) = \begin{cases} \frac{(a-c)^2\gamma(2b\gamma-1)+2(a-2ab\gamma+bc\gamma(9b\gamma-4))\xi+b(9b\gamma-4)\xi^2}{2(1-3b\gamma)^2} & ,\xi \in [0, \frac{a-c}{3b}) \\ a\xi - 2b\xi^2 & ,\xi \in [\frac{a-c}{3b}, \frac{a}{3b}) \\ \frac{a^2}{9b} & ,\xi \in [\frac{a}{3b}, \infty). \end{cases} \tag{A.8}$$

All pieces of $\Pi_i(\xi)$ are continuous functions of ξ at any point in their respective domain. Furthermore, the pieces are connected at $\xi = (a-c)/(3b)$ and $\xi = a/(3b)$. Consequently, $\Pi_i(\xi)$ is continuous for all $\xi \geq 0$.

Suppose $(a-c)/(3b) \leq \xi < a/(3b)$. We define the maximum of $\Pi_i(\xi)$ to be $\tilde{\xi}$. To see that $\tilde{\xi}$ is unique, note first that any interior maximum $\tilde{\xi}_1$ uniquely solves the first-order condition $\mathrm{d}\Pi_i/\mathrm{d}\xi = 0$, i.e.,

$$\tilde{\xi}_1 = \frac{a}{4b}, \tag{A.9}$$

with $(a-c)/(3b) \leq \tilde{\xi}_1 < a/(3b)$ if

$$a \leq 4c. \tag{A.10}$$

Suppose condition (A.10) holds. Then, $(a-c)/(3b) \leq \tilde{\xi}_1 < a/(3b)$ is a unique maximum since $\mathrm{d}^2\Pi_i/\mathrm{d}\xi^2 = -4b < 0$ for all $\xi \in [\frac{a-c}{3b}, \frac{a}{3b})$.

If condition (A.10) does not hold, $\mathrm{d}\Pi_i/\mathrm{d}\xi < 0$ for all $\xi \in [\frac{a-c}{3b}, \frac{a}{3b})$. Consequently, the local maximum is characterized by a corner solution, namely,

$$\tilde{\xi}_2 = \frac{a-c}{3b}. \tag{A.11}$$

We now show that this is maximum also global. For this, it is sufficient to show that, by the continuity of $\Pi_i(\xi)$, there cannot exist a higher payoff than $\Pi_i(\tilde{\xi})$ in the other cases described in (A.8), where $\tilde{\xi}$ is either given by $\tilde{\xi_1}$ or $\tilde{\xi_2}$. In order to rule out a global maximum in the first case of $\Pi_i(\xi)$, it suffices to show that $\Pi_i(\xi)$ strictly monotonically increases in ξ for $\xi < (a-c)/(3b)$, i.e., $\mathrm{d}\Pi_i/\mathrm{d}\xi|_{(\xi)} =$

$$\frac{a - 2ab\gamma + b(9b\gamma - 4)(c\gamma + \xi)}{(1-3b\gamma)^2} > 0 \quad , \forall \xi \in \left[0, \frac{a-c}{3b}\right),$$

which holds under the model assumptions. Consequently, there cannot exist a global maximum $\xi \in [0, \frac{a-c}{3b})$. In order to rule out a global maximum in the third case of $\Pi_i(\xi)$, first note that $\Pi_i(\xi)$ is constant in ξ for all $\xi \geq a/(3b)$. Recall that $\tilde{\xi}$ characterizes a unique maximum of the second case of $\Pi_i(\xi)$ and that $\Pi_i(\xi)$ is continuous. It follows that $\Pi_i(\tilde{\xi}) > \Pi_i(\frac{a}{3b}) = \Pi_i(\xi)$ for all $\xi \geq a/(3b)$. Consequently, there cannot exist a global maximum $\xi \in [\frac{a}{3b}, \infty)$. Thus, the unique emissions limit $\tilde{\xi} = \max\{\tilde{\xi_1}, \tilde{\xi_2}\}$ is a global payoff maximum and either takes the value $\tilde{\xi_1} = a/(4b)$ if $a \leq 4c$ ((A.10) holds), or otherwise $\tilde{\xi_2} = (a-c)/(3b)$, such that $(a-c)/(3b) \leq \tilde{\xi} < a/(3b)$.

In order to show the existence of a unique emissions limit $\hat{\xi}$ with $0 < \hat{\xi} < \tilde{\xi}$ such that $\Pi_i(\hat{\xi}) = \Pi_i(\frac{a}{3b})$, we consider the Intermediate Value Theorem (IVT). First, recall that $\Pi_i(\xi)$ is continuous in $\xi \in (0, \tilde{\xi})$. Second, it has to hold that $\lim_{\xi \to 0} \Pi_i(\xi) < \Pi_i(\frac{a}{3b})$, i.e.,

$$\frac{(a-c)^2\gamma(2b\gamma - 1)}{2(1-3b\gamma)^2} < \frac{a^2}{9b},$$

which is satisfied under the model assumptions. Third, it has to hold that $\lim_{\xi \to \tilde{\xi}} \Pi_i(\xi) > \Pi_i(\frac{a}{3b})$. As stated above, $\tilde{\xi}$ characterizes a unique global maximum of $\Pi_i(\xi)$, suggesting that that the condition holds and that there exists at least one value $\hat{\xi}$. Furthermore, the equilibrium payoff is monotonically increasing for all $\xi \in (0, \tilde{\xi})$, which, according to the IVT, ensures that $\hat{\xi} \in (0, \tilde{\xi})$ is a unique value.

It is straightforward to show that $\hat{\xi} < (a-c)/(3b)$ if $\Pi_i(\frac{a-c}{3b}) > \Pi_i(\frac{a}{3b})$. Furthermore, $\Pi_i(\tilde{\xi}) > \Pi_i(\hat{\xi}) = \Pi_i(\frac{a}{3b})$. Since $\Pi_i(\xi)$ is continuous, it follows from the inequality $\hat{\xi} < \tilde{\xi} < a/(3b)$ that each limit $\xi \in (\hat{\xi}, \frac{a}{3b})$ results in strictly higher equilibrium payoffs than any non-binding emissions limit $\xi \geq a/(3b)$.

■

A.3 Proof of Proposition 3

To show the effect of a subsidy for abatement R&D, i.e., a decrease of γ, on equilibrium outcomes under varying emissions standards, we investigate the marginal effects of γ and reverse the sign. We first show that equilibrium outcomes are only affected under emissions limits $\xi < (a-c)/(3b)$. Then, we show that, under these limits, each firm i's equilibrium output and abatement R&D investment decrease in γ, before we demonstrate conditions under which the effect of γ on the firm's equilibrium payoff is either weakly positive, or ambiguous.

The equilibrium strategy of each firm i (as given by Proposition 1) and its equilibrium payoff Π_i (as given by (A.8)) only depend on γ under emissions limits $\xi < (a-c)/(3b)$, i.e., equilibrium outcomes are only affected under these emissions limits.

For $\xi < (a-c)/(3b)$, the equilibrium output and abatement R&D investment are $q_i^A(\xi)$ and $x_i^A(\xi)$, as defined in (A.1), respectively. Then, the effect of γ on the output and abatement R&D investment is strictly negative, i.e.,

$$\left.\frac{\partial q_i^A}{\partial \gamma}\right|_{(\xi)} = -\frac{a-c-3b\xi}{(3b\gamma-1)^2} < 0 \quad , \forall \xi \in \left[0, \frac{a-c}{3b}\right),$$

and

$$\left.\frac{\partial x_i^A}{\partial \gamma}\right|_{(\xi)} = -\frac{3b(a-c-3b\xi)}{(3b\gamma-1)^2} < 0 \quad , \forall \xi \in \left[0, \frac{a-c}{3b}\right).$$

Consequently, an R&D subsidy increases equilibrium outputs and abatement R&D

investments under emissions limits $\xi < (a-c)/(3b)$.

For $\xi < (a-c)/(3b)$, the effect of γ on firm i's equilibrium payoff is

$$\left.\frac{\partial \Pi_i}{\partial \gamma}\right|_{(\xi)} = -\frac{(c-a+3b\xi)\left(a-ab\gamma+c(-1+b\gamma)+b(9b\gamma-5)\xi\right)}{2(3b\gamma-1)^3}.$$

Rearranging terms yields that, under our model assumptions, $\partial \Pi_i/\partial\gamma$ is a continuous quadratic function with respect to ξ with an inverted U-shape. Note that $\lim_{\xi \to \frac{a-c}{3b}} \partial\Pi_i/\partial\gamma|_{(\xi)} = 0$. Furthermore, it holds that

$$\lim_{\xi\to\frac{a-c}{3b}} \frac{\partial\left[\frac{\mathrm{d}\Pi_i}{\mathrm{d}\gamma}\right]}{\partial\xi} = \frac{b\left(c(4-6b\gamma)+a(6b\gamma-4)+(5-9b\gamma)(a-c)\right)}{(3b\gamma-1)^3} < 0.$$

Consequently, for all $0 \le \xi < (a-c)/(3b)$, the effect of γ on the equilibrium payoff is weakly positive if

$$\left.\frac{\partial \Pi_i}{\partial \gamma}\right|_{(0)} = \frac{(a-c)^2(1-b\gamma)}{2(3b\gamma-1)^3} \ge 0,$$

which holds if $b\gamma \le 1$. Then, the effect of γ on the payoff is weakly positive. If $b\gamma > 1$, $\mathrm{d}\Pi_i/\mathrm{d}\gamma|_{(0)} < 0$. Then, the shape of $\partial\Pi_i/\partial\gamma$ implies that there has to exist a unique value $\xi' \in (0, \frac{a-c}{3b})$ such that $\mathrm{d}\Pi_i/\mathrm{d}\gamma|_{(\xi')} = 0$. This implies that $\mathrm{d}\Pi_i/\mathrm{d}\gamma|_{(\xi)} < 0$ for all $\xi < \xi' < (a-c)/(3b)$ and $\mathrm{d}\Pi_i/\mathrm{d}\gamma|_{(\xi)} > 0$ for $\xi' < \xi < (a-c)/(3b)$. The effect of a subsidy for abatement R&D on each firm i's equilibrium payoff is weakly negative if $b\gamma \le 1$, and ambiguous otherwise. When the effect is ambiguous, there exists a unique threshold ξ' such that the effect is positive for all $\xi < \xi' < (a-c)/(3b)$ and negative for $\xi' < \xi < (a-c)/(3b)$. Note that it holds that $\xi' < \hat{\xi}$.

■

References

Amir, R. (2000), Modelling imperfectly appropriable R&D via spillovers, *International Journal of Industrial Organization* 18, 1013–1032

Amir, R., A. Gama, R. Lahmandi-Ayed, and K. Werner (2023), A one-stage model of abatement innovation in Cournot duopoly: emissions vs performance standards, *Environmental Modeling & Assessment* 28, 875–891

Amir, R., A. Gama, and K. Werner (2018), On environmental regulation of oligopoly markets: emission versus performance standards, *Environmental and Resource Economics* 70, 147–167

Amir, R., M. Germain, and V. Van Steenberghe (2008), On the impact of innovation on the marginal abatement cost curve, *Journal of Public Economic Theory* 10, 985–1010

Anand, K. S. and F. C. Giraud-Carrier (2020), Pollution regulation of competitive markets, *Management Science* 66, 4193–4206

Bushnell, J. B., H. Chong, and E. T. Mansur (2013), Profiting from regulation: Evidence from the European carbon market, *American Economic Journal: Economic Policy* 5, 78–106

Campbell, J. and S. Levkoff (2025), Assessing the productivity and abatement effects of the 1990 Clean Air Act Amendment, *Research Policy* 54, 105145

d'Aspremont, C. and A. Jacquemin (1988), Cooperative and noncooperative R&D in duopoly with spillovers, *The American Economic Review* 78, 1133–1137

Deng, Z., X. Fan, and T. Gao (2023), A blessing in disguise: Collusion equivalent phenomenon under environmental regulation, *Operations Research Letters* 51, 628–631

Gray, W. B. (1997), Manufacturing plant location: Does state pollution regulation matter?, *NBER Working Paper Series 5880*

Gray, W. B. and R. J. Shadbegian (1998), Environmental regulation, investment timing, and technology choice, *The Journal of Industrial Economics* 46, 235–256

Kellogg, R. and M. Reguant (2021), Energy and environmental markets, industrial organization, and regulation, *Handbook of Industrial Organization* 5, 615–742

King, A. A. and M. J. Lenox (2001), Does it really pay to be green? An empirical study of firm environmental and financial performance: An empirical study of firm environmental and financial performance, *Journal of Industrial Ecology* 5, 105–116

Menezes, F. M. and J. Pereira (2017), Emissions abatement R&D: Dynamic competition in supply schedules, *Journal of Public Economic Theory* 19, 841–859

Montero, J.-P. (2002), Permits, standards, and technology innovation, *Journal of Environmental Economics and Management* 44, 23–44

Perino, G. and T. Requate (2012), Does more stringent environmental regulation induce or reduce technology adoption? When the rate of technology adoption is inverted U-shaped, *Journal of Environmental Economics and Management* 64, 456–467

Requate, T. (2005), Dynamic incentives by environmental policy instruments—a survey, *Ecological Economics* 54, 175–195

Tarui, N. and S. Polasky (2005), Environmental regulation with technology adoption, learning and strategic behavior, *Journal of Environmental Economics and Management* 50, 447–467

United Nations Environment Programme (2024), *Emissions Gap Report 2024: No more hot air ... please! With a massive gap between rhetoric and reality, countries draft new climate commitments*, tech. rep., UNEP, URL: `https://www.unep.org/resources/emissions-gap-report-2024`