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

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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, subsidies for abatement R&D may hurt firms, but improve welfare when the regulation is strict enough.

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

JEL-Codes: Q55, Q58, L13

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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,

[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).

our 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 and welfare 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. The section also discusses welfare effects. 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 assumption regarding the relationships between the abatement unit cost, the market size, and the efficiency of abatement R&D is maintained from the model of Amir et al. (2023): Assumption (A1)(i) $a > 2c$, (ii) $3b\gamma > a/c$.

(A1)(i) is standard in the linear Cournot model with production costs and states here that the market is sufficiently large relative to the abatement costs. (A1)(ii) implies that maximal abatement R&D, i.e., $x = c$, will be unattractive in equilibrium.

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

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

where $j \neq i$.

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

[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 leave the analysis of the two-stage version for unbounded emissions standards for future research.

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*

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

and invests in abatement R&D

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

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 $q_i = a/3b$. For lower levels of ξ, we find that there is a range of ξ, i.e., $(a-c)/3b \leq \xi < a/3b$, where firms still do not invest in abatement R&D and choose their output levels to exactly meet the emissions cap, $q_i = \xi$ (see Figure 1). For this range of ξ, it is not optimal to produce a higher output by abating emissions that exceed the limit, even though the cost of abatement for excess output could be reduced via abatement R&D. Our analysis reveals that the advantage of maintaining a higher price in the output market outweighs the benefits from abatement R&D. Note that zero R&D investments render deviations to higher output levels unattractive. Finally, for even lower emissions

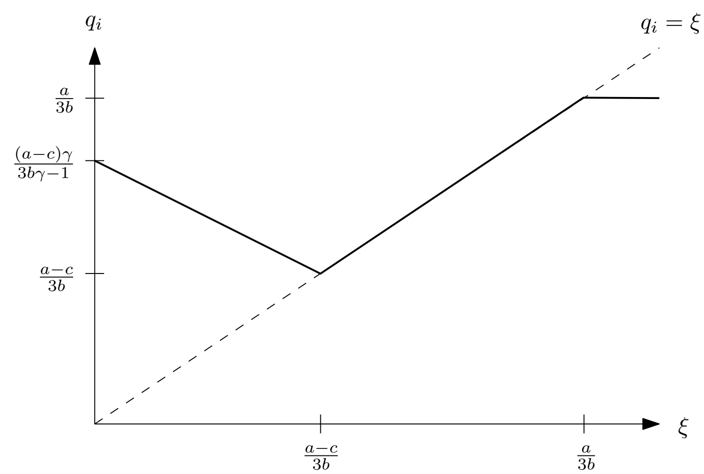

Figure 1: Equilibrium output of a single firm for varying emissions caps.

limits, i.e., $0 \leq \xi < (a-c)/3b$, each firm now has an incentive to invest in abatement R&D, $x_i > 0$, and consequently to increase output by abating all emissions above the limit, $q_i > \xi$. To see the intuition note that, as the emissions cap decreases, the benefit from an abatement cost reduction increases in the amount of excess emissions. This results in higher investment in abatement R&D and hence also higher output. However, note that the output level 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. The equilibrium involves*

$$q_i = \xi \text{ and } x_i = 0, \quad \text{if } \tfrac{a-c}{3b} \leq \xi < \tfrac{a}{3b}$$
$$q_i > \xi \text{ and } x_i > 0, \quad \text{if } \hat{\xi} < \xi < \tfrac{a-c}{3b}.$$

Proof. *See Appendix A.2.*

The equilibrium with higher firms' profits under regulation is sustained by the following considerations. Recall that any emissions limit $\xi \geq a/3b$ would not be binding. When ξ is reduced below $a/3b$, the firms have to either abate any excess emissions or reduce their output level to meet the cap. However, note that a reduction in output leads to a higher price and higher duopoly profits in the market. Hence, it is optimal for each firm to reduce its output to meet the cap, up to the point $(a-c)/3b$, beyond which an increase in price would result in too large a loss in sales, and refrain from investing in abatement R&D, given its rival also reduces its output so as to meet the cap.[8] Notice that any positive investment in abatement R&D would make a higher output level, $q_i > \xi$, more attractive. It is also interesting to note that within this particular range of caps, firms' profits can potentially reach the level that would otherwise be obtainable only through collusion in the unregulated market, i.e., $\bar{\Pi}_i = a^2/8b$, whenever $a \leq 4c$, i.e., the initial marginal cost of abatement is sufficiently high.

When emissions caps are set below $(a-c)/3b$, firms can no longer benefit from the higher prices associated with an output level of $q_i = \xi$. Instead, each firm now finds it optimal to produce at a level where $q_i > \xi$ and to abate any excess emissions. Since abatement is costly, the firms now have an incentive to invest in cost-reducing R&D, $x_i > 0$. It may seem surprising that firms' equilibrium payoffs exceed the pre-regulation payoffs even for emissions caps below $(a-c)/3b$. To understand the intuition, note that firms can still effectively coordinate on reduced output levels compared to the pre-regulation level, because abatement R&D is costly, and obtain higher profits, up to the threshold $\hat{\xi}$. For $\xi < \hat{\xi}$, firms' equilibrium payoffs fall below the pre-regulation levels due to increased costs of abatement and abatement R&D.

Figure 2 illustrates Proposition 2 by depicting firm i's equilibrium payoff Π_i for varying emissions caps under the condition $a \leq 4c$. The dashed line indicates the

[8]The equilibrium strategies are given in Proposition 1.

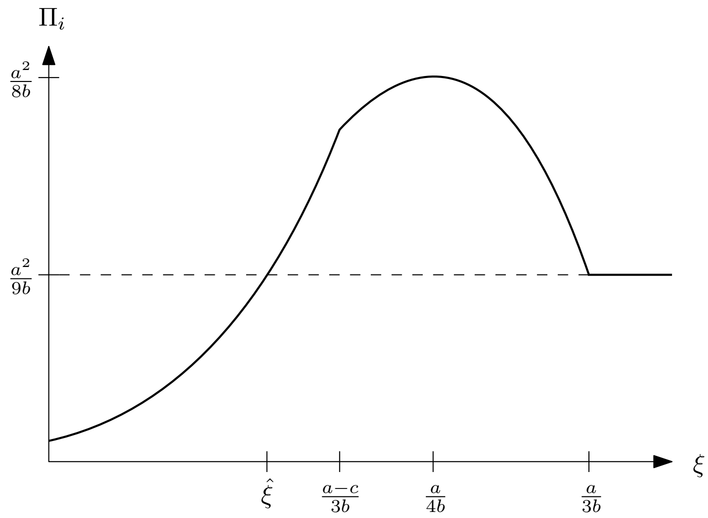

Figure 2: Equilibrium payoff of a single firm for varying emissions caps, and $a \leq 4c$.

pre-regulation payoff level.[9]

It is straightforward to verify the following corollary.

Corollary 1 *For each emissions cap*

$$\xi > \max\left\{\frac{a}{4b}, \frac{a-c}{3b}\right\},$$

there exists a strictly smaller cap that results in the same equilibrium payoffs for the firms, but involves strictly less pollution.

Corollary 1 has interesting implications for the design of environmental regulations aimed at reducing emissions. However, conducting a comprehensive normative assessment of emissions cap policies proves to be non-trivial. As Weitzman (2009, 2011) argues, there is 'deep structural uncertainty about unknown unknowns' such as the climate change response to changes in emissions. It is not clear how reductions in the amount of total emissions are be translated into utility changes via an appropriate

[9]The threshold $\hat{\xi}$ is given by (A.12) in the appendix.

'damage function', and the way in which this uncertainty is formalized should influence the outcome of any social welfare analysis of environmental regulation.

In the following, we measure welfare simply as the sum of the firms' profits and consumer surplus. Hence, in the equilibrium of our model, welfare is given by $W = 2\Pi_i + (a - P(2q_i))\, q_i$, where q_i denotes the equilibrium output of firm i. We find that every emissions cap below $a/3b$ - that is, every binding cap - reduces welfare below the level obtainable in the unregulated market, which is $4a^2/9b$.

Proposition 3 *For every* $0 \leq \xi < a/3b$, $W < 4a^2/9b$.

Proof. *See Appendix A.3.*

We have demonstrated above that every emissions cap below $a/3b$ reduces total industry output compared to unregulated markets (Proposition 1). This corresponds to a reduction in consumer surplus due to higher prices. As we know from Proposition 2, firms' profits are also reduced whenever emissions caps are set below the threshold $\hat{\xi}$, where $\hat{\xi} < a/3b$, resulting in an overall welfare loss as compared to the unregulated markets. For emissions caps in the range of $\hat{\xi} < \xi < a/3b$, we have found that firms' profits are higher than without regulation. Proposition 3 reveals that these gains in profits do not outweigh the losses in consumer surplus.

4 Subsidy for abatement R&D

The analysis in the previous section suggests that welfare decreases under binding emissions caps. Therefore, it may be appropriate to conclude that, where feasible, abatement R&D should be subsidized when emissions caps are implemented to reduce emissions. Initiatives such as those supported by the Advanced Research Projects Agency-Energy (ARPA-E) in the United States serve as examples of subsidizing abatement R&D in industries regulated by emissions caps. Although a comprehensive welfare analysis of this policy measure, including the costs incurred by the government, is beyond the scope of this paper, we examine in this section the effects of a subsidy on the marginal cost of abatement R&D on firms' equilibrium payoffs and consumer surplus.[10] 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 a reduction in γ on the firms' equilibrium payoffs, consumer surplus, and welfare W, as defined in Section 3.

Proposition 4 *Suppose $\xi \geq (a-c)/3b$. Then a reduction in γ does not affect firms' equilibrium payoffs, consumer surplus, and welfare.*

Suppose $\xi < (a-c)/3b$. Then, for $\gamma \leq 1/b$, a reduction in γ reduces firms' equilibrium payoffs, whereas for $\gamma > 1/b$, there exists a unique $\xi' < \hat{\xi}$, where $\hat{\xi}$ is defined in Proposition 2, such that a reduction in γ increases firms' equilibrium payoffs if $\xi < \xi'$, and decreases these payoffs if $\xi > \xi'$. Consumer surplus and welfare are decreasing in γ for all $\gamma > 0$.

Proof. *See Appendix A.4.*

We find that for emissions caps $\xi \geq (a-c)/3b$, firm's equilibrium strategies and payoffs are not affected by changes in γ. Hence, consumer surplus and welfare are not affected either. By contrast, for a stricter regulation with $0 \leq \xi < (a-c)/3b$, our results suggest that a subsidy on abatement R&D improves consumer surplus and welfare, whereas the effect on firms' equilibrium payoffs turns out to be ambiguous: A reduction in γ decreases these payoffs for $\gamma \leq 1/b$. Otherwise, there exists a threshold value $\xi' < \hat{\xi}$, such that firms' equilibrium payoffs are increased [reduced] depending

[10] This includes subsidies through lump-sum governmental investments in the R&D capabilities of firms, thereby enhancing the efficiency of their R&D activities. Note that our analysis extends with only slight modifications to the case in which a subsidy reduces the cost of abatement R&D by sx_i, with $s > 0$.

on whether ξ is lower [higher] than ξ'.[11] The understand the intuition, note that we consider a subsidy on the marginal cost of abatement R&D. As a result, firms find it optimal to increase investments in abatement R&D, which reduces their marginal cost of abatement and leads them to expand production. The increased output, however, reduces the price and hence firms' profits in the market. Consumers clearly benefit from the reduced price. We find that firms are compensated for the loss in profits by the larger reduction in abatement costs associated with lower levels of emissions caps when $\xi < \xi'$. There is, however, a range of emissions caps, $\xi' < \xi < (a - c)/3b$, where the reduction in abatement costs is not enough. Thus, a subsidy for abatement R&D 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 but improve welfare 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

[11] The threshold ξ' is given by (A.15) in the appendix.

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.

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

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

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

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 $\Pi_i(\frac{a-c}{3b}) > \Pi_i(\frac{a}{3b})$, such that

$$\hat{\xi} = \frac{a-2ab\gamma}{4b-9b^2\gamma} - c\gamma + \frac{1}{3}\cdot\sqrt{\frac{(1-3b\gamma)^2(a^2+9bc^2\gamma(9b\gamma-4))}{b^2(4-9b\gamma)^2}}. \tag{A.12}$$

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 $\xi \geq a/3b$. By Proposition 1, it follows from $\hat{\xi} < (a-c)/3b$ that $q_i > \xi$ and $x_i > 0$ if $\hat{\xi} < \xi < (a-c)/3b$ and $q_i = \xi$ and $x_i = 0$ if $(a-c)/3b \leq \xi < a/3b$.

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A.3 Proof of Proposition 3

For equilibrium industry output $2q_i$, consumer surplus is $C(\xi) = (a - P(2q_i))q_i$. Substituting q_i, as defined in Proposition 1, yields

$$C(\xi) = \begin{cases} \frac{2b}{(3b\gamma-1)^2}((a-c)\gamma-\xi)^2, & \text{if } \xi \in [0, \frac{a-c}{3b}) \\ 2b\xi^2, & \text{if } \xi \in [\frac{a-c}{3b}, \frac{a}{3b}) \\ \frac{2a^2}{9b}, & \text{if } \xi \in [\frac{a}{3b}, \infty). \end{cases} \tag{A.13}$$

Denote welfare by $W(\xi) = 2\Pi_i(\xi) + C(\xi)$. By (A.8) and (A.13), welfare is given by

$$W(\xi) = \begin{cases} \frac{(a-c)^2\gamma(-1+4b\gamma)+2(a-4ab\gamma+bc\gamma(-2+9b\gamma))\xi+b(-2+9b\gamma)\xi^2}{(1-3b\gamma)^2}, & \text{if } \xi \in [0, \frac{a-c}{3b}) \\ 2\xi(a-b\xi), & \text{if } \xi \in [\frac{a-c}{3b}, \frac{a}{3b}) \\ \frac{4a^2}{9b}, & \text{if } \xi \in [\frac{a}{3b}, \infty). \end{cases} \tag{A.14}$$

To prove the proposition, we first establish that consumer surplus is reduced under binding emissions limits $0 \leq \xi < a/3b$ as compared to unregulated markets. By Proposition 2, this implies that $W(\xi)$ may only be enhanced for $\xi > \hat{\xi}$, where the threshold $\hat{\xi}$ is defined in (A.12). We then argue that this is not feasible by showing that $W(\xi)$ is a continuous function that monotonously increases for $\hat{\xi} \leq \xi < a/3b$ and is constant for $\xi \geq a/3b$, which proves the proposition.

By Proposition 1, binding emissions limits reduce equilibrium outputs as compared to unregulated markets, i.e., for $\xi < a/3b$, $q_i(\xi) < a/3b$. This corresponds to a higher price and a reduction of consumer surplus, such that, for all $0 \leq \xi < a/3b$, $C(\xi) < 2a^2/9b$.

Proposition 2 states that emissions limits $\hat{\xi} < \xi < a/3b$ increase equilibrium profits relative to unregulated markets. Consequently, emissions standards $\xi \leq \hat{\xi}$ can never be welfare increasing and, in order to prove the proposition, we only have to rule out welfare improvements through emissions standards $\hat{\xi} < \xi < a/3b$.

It is easy to verify that the pieces of $C(\xi)$ are connected at $\xi = (a-c)/3b$ and $\xi = a/3b$, ensuring that $C(\xi)$ is continuous. As stated in the proof of Proposition 2, $\Pi_i(\xi)$ is also continuous, which implies that $W(\xi)$ is continuous as well.

One can verify that $W(\xi)$ monotonously increases for $\hat{\xi} \leq \xi < (a-c)/3b$, i.e.,

$$\left.\frac{\mathrm{d}W}{\mathrm{d}\xi}\right|_{(\xi)} = \frac{2\,(a - 4ab\gamma + b(-2+9b\gamma)(c\gamma+\xi))}{(1-3b\gamma)^2} > 0 \quad , \forall \xi \in \left[\hat{\xi}, \frac{a-c}{3b}\right),$$

and for $(a-c)/3b \leq \xi < a/3b$, i.e.,

$$\left.\frac{\mathrm{d}W}{\mathrm{d}\xi}\right|_{(\xi)} = 2(a - 2b\xi) > 0 \quad , \forall \xi \in \left[\frac{a-c}{3b}, \frac{a}{3b}\right).$$

Further, $W(\xi)$ is constant for $\xi \geq a/3b$. It follows that $W(\xi) < W(\frac{a}{3b}) = 4a^2/9b$ for all $0 \leq \xi < a/3b$.

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A.4 Proof of Proposition 4

In what follows, we investigate the effect of γ on each firm i's equilibrium payoff $\Pi_i(\xi)$, consumer surplus $C(\xi)$ and welfare $W(\xi)$, as given by (A.8), (A.13) and (A.14), respectively. To prove the proposition, we first establish that a reduction in γ only affects equilibrium outcomes under emissions limits such that $0 \leq \xi < (a-c)/3b$. For these limits, we then demonstrate that the effect of γ on the firms' equilibrium payoffs is positive if $\gamma \leq 1/b$, and ambiguous otherwise, before we show that consumer surplus and welfare are decreasing in γ.

It is straightforward to see that $\Pi_i(\xi)$, $C(\xi)$ and $W(\xi)$ only depend on γ under emissions limits $0 \leq \xi < (a-c)/3b$. Consequently, a reduction in γ does only affect equilibrium outcomes under these limits, and a change in γ has no effect for $\xi \geq (a-c)/3b$.

For $0 \leq \xi < (a-c)/3b$, the effect of γ on firm i's equilibrium payoff is

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

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

0. Furthermore, it holds that

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

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

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

which holds if $b\gamma \leq 1$, or rather, $\gamma \leq 1/b$. If $\gamma > 1/b$, $\mathrm{d}\Pi_i/\mathrm{d}\gamma|_{(0)} < 0$. Then, the shape of $\mathrm{d}\Pi_i/\mathrm{d}\gamma$ implies that there has to exist a unique value $\xi' \in (0, \frac{a-c}{3b})$ such that $\mathrm{d}\Pi_i/\mathrm{d}\gamma|_{(\xi')} = 0$. More specific,

$$\xi' = \frac{(a-c)(b\gamma-1)}{b(9b\gamma-5)}. \tag{A.15}$$

This implies that, for $\gamma > 1/b$, $\mathrm{d}\Pi_i/\mathrm{d}\gamma|_{(\xi)} < 0$ for all emissions limits such that $0 \leq \xi < \xi' < (a-c)/3b$ and $\mathrm{d}\Pi_i/\mathrm{d}\gamma|_{(\xi)} > 0$ for $\xi' < \xi < (a-c)/3b$.

For $0 \leq \xi < (a-c)/3b$, one can verify that the effect of γ on consumer surplus is negative, i.e.,

$$\left.\frac{\mathrm{d}C}{\mathrm{d}\gamma}\right|_{(\xi)} = \frac{4b((a-c)\gamma-\xi)(c-a+3b\xi)}{(3b\gamma-1)^3} < 0 \quad , \forall \xi \in \left[0, \frac{a-c}{3b}\right).$$

For $0 \leq \xi < (a-c)/3b$, one can further verify that the effect of γ on welfare is negative, i.e.,

$$\left.\frac{\mathrm{d}W}{\mathrm{d}\gamma}\right|_{(\xi)} = -\frac{(a-c-3b\xi)((a-c)(5b\gamma-1)+b(1-9b\gamma)\xi)}{(3b\gamma-1)^3} < 0 \quad , \forall \xi \in \left[0, \frac{a-c}{3b}\right).$$

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