An Advantage of Emission Intensity Regulation for Emission Cap Regulation in a Near-Zero Emission Industry

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Abstract

We revisit command-and-control regulations and compare their efficiencies, in particular, an emission cap regulation that restricts total emissions and an emission intensity regulation that restricts emissions per unit of output under emission equivalence. We find that in both the most stringent target case, when the target emission level is close to zero, and the weakest target case, when the target emission level is close to business as usual, emission intensity yields greater welfare, although the same may not be true in moderate target cases.

JEL classification codes: Q52, L13, L51

Keywords: near-zero emission industry, emission cap, emission intensity, emission equivalence

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1 Introduction

Global warming is one of the most serious risks that society faces, and many countries have recently voluntary committed to reducing CO2 emissions under the Paris Agreement on climate change. A standard policy for reducing CO2 emissions is the introduction of so-called "market-based instruments," such as a carbon tax or an emission tax. A number of theoretical studies in environmental economics encourage the use of indirect regulations rather than command-and-control approaches from the perspective of cost-effectiveness. However, in practice, command-and-control instruments are now at the center of the regulatory debate for several reasons: political difficulty of introducing the optimal tax; provision of a simple, certain way to achieve a desirable goal; and incomplete enforcement and high monitoring costs for market-based instruments.[1] In such a case, direct regulations can play an important role.

In this study, we compare two direct regulations, an emission cap regulation that restricts total emissions and an emission intensity regulation that restricts emissions per unit of output, and we examine their efficiency. Many studies have shown that different policy instruments have different welfare and environmental consequences, because different instruments provide different incentives for firms (Besanko, 1987; Helfand, 1991; Lahiri and Ono; 2007; Kiyono and Ishikawa, 2013; Amir et al., 2018). For example, Montero (2002) focused only on firms' incentive under four regulations, including an emission cap and an emission intensity regulation, and evaluated environmental R&D rankings in a symmetric duopoly model with general demand. As for social welfare, Lahiri and Ono (2007) compared an emission intensity regulation and an emission tax under a Cournot oligopoly and showed the advantage of the emission intensity regulation over the emission tax in the weakest target case (the target emission level is close to business as usual). Amir et al. (2018) extended

[1] For a more detailed argument, see Bőhringer et al. (2017), Cohen and Keiser (2017), and Demirel et al. (2018).

Montero's (2002) analysis to rank regulatory instruments with respect to social welfare but provided numerical examples by using simple specification.

Under the oligopolistic market, we show that the emission intensity regulation yields greater welfare than the emission cap regulation does in the most stringent target case, in which the target emission level is close to zero (Propositions 2 and 2B). Although the target level is extreme, the hypothetical target plays a relevant role. For example, under the Paris climate agreement, many countries, such as the UK, France, Germany, and Japan, plan to reduce CO2 emissions drastically by 2050 (about 80% reduction at least against a business-as-usual scenario). To achieve this goal, in several industries, such as electric power and transportation, authorities may impose an emission constraint that is close to zero emissions. Thus, the most stringent case we discuss must be important. Japanese electric power companies have committed to CO2 emissions per kilowatt-hour, not total emissions, and our result suggests that this could be an efficient commitment. In addition, we examine the opposite case, in which the emission target is significantly weak. Again, we show that the emission intensity regulation improves social welfare more than the emission cap regulation does (Propositions 3 and 3B). However, we find that the welfare ranking may be reversed, meaning that the emission cap regulation may yield greater welfare than the emission cap regulation under a moderate emission target (Proposition 4).

We also show that under an emission intensity regulation, the stricter regulation may reduce abatement investment, whereas the stricter regulation always increases abatement investment under an emission cap regulation. In other words, the relationship between the degree of regulation and emission abatement activity depends on the regulation measure. This result suggests that a larger abatement investment might not imply stricter regulation in the industry.[2]

[2]For empirical work on the relationship between abatement investment and environmental performance, see Gutiérrez and Teshima (2018).

The rest of this paper is organized as follows. Section 2 formulates the model of quantity competition, and Section 3 compares emission intensity regulation and emission cap regulation. Section 4 presents results under price competition as a robustness check. Section 5 concludes.

2 The Model

We consider an industry with n symmetric polluting firms. The firm produces a single commodity for which the inverse demand function is given by $P : \mathbb{R}_+ \mapsto \mathbb{R}_+$. We assume that $P(Q)$ is twice continuously differentiable and $P'(Q) < 0$ for all Q as long as $P > 0$. Let $C(q_i) : \mathbb{R}_+ \mapsto \mathbb{R}_+$ be the cost function of each firm, where q_i $(i = 1, 2., ..., n)$ is the output of firm i $(i = 1, 2, ..., n)$. We suppose C is twice continuously differentiable, increasing, and convex for all q_i.[3] We assume that the marginal revenue is decreasing in rivals' outputs (i.e., $P'(Q)+P''(Q)q_i < 0$). These assumptions are standard and guarantee that the second-order condition is satisfied.

Emissions are associated with production, which yields a negative externality. After emissions have been generated, they can be reduced through investment in abatement technologies.[4] Thus, firm i's net emissions are $e_i := g(q_i) - x_i$, where $g : \mathbb{R}_+ \mapsto \mathbb{R}_+$ represents emissions associated with production and $x_i (\in \mathbb{R}_+)$ is firm i's abatement level. We assume that g is twice continuously differentiable, increasing, and convex for all q_i.

The firm's profit is $P(Q)q_i - C(q_i) - K(x_i)$, where the third term represents the abatement cost. We suppose that K is twice continuously differentiable, increasing, and strictly convex for $x_i > 0$. We further assume that $K(0) = K'(0) = 0$.[5] This assumption guarantees that

[3] We can relax this assumption. Our results hold if $C'' - P' > 0$ for all Q as long as $P > 0$.

[4] These are called end-of-pipe technologies. An alternative approach to reduce emissions is to change the production process. For a recent discussion of the relationship between mandatory regulation and this type of innovation, see Matsumura and Yamagishi (2017).

[5] The form of the abatement (R&D) cost function is a standard assumption in industrial organization and environmental economics (D'Aspremont and Jacquemin, 1998; Amir et al., 2018).

the social optimal level of abatement is never zero and that the profit function is smooth.

Total social surplus (firms' profits plus consumer surplus minus the loss caused by the externality) is given by

$$W(q_1, ..., q_n) = \sum_{i=1}^{n} \pi_i + CS - \eta(E) = \int_0^Q P(z)dz - \sum_{i=1}^{n} (C(q_i) + K(x_i)) - \eta(E),$$

where $\eta : \mathbb{R}_+ \mapsto \mathbb{R}_+$ is the welfare loss of emissions, and $E = \sum_{i=1}^n e_i$.

We assume that the environmental target $\bar{E}$ for total emissions is exogenously given (regulated by the government). $\bar{E}$ may depend on the administrative cost, political pressure, or international commitment, and thus, for simplicity, we treat the target as an exogenous variable. We assume that $\bar{E} \in (0, E^B)$ where E^B is the profit-maximizing emission level without a binding emission target (business-as-usual level). Let q^B be the profit-maximizing output without a binding emission target. $\bar{E}$ is attained through an emission intensity or emission cap.

Because there is no heterogeneity among firms, we focus on the symmetric equilibrium in which all firms choose the same actions in equilibrium.

3 Analysis

3.1 Emission Intensity Regulation

Let α be the upper bound of the emission per unit of output. Firm i chooses its output, q_i, and abatement level, x_i, to maximize its profit subject to

$$\alpha \geq \frac{e_i}{q_i} = \frac{g(q_i) - x_i}{q_i}. \tag{1}$$

When the constraint is binding,[6] firm i's optimization problem is

$$\max_{q_i} P(Q)q_i - C(q_i) - K(g(q_i) - \alpha q_i). \tag{2}$$

[6]The constraint is always binding because $\bar{E} < E^B$.

Let superscript EI denote the equilibrium outcomes under emission intensity regulation. Define $\pi_i^{EI}(q_i, Q_{-i}) := P(Q)q_i - C(q_i) - K(g(q_i) - \alpha q_i)$. Focusing on the symmetric equilibrium, the equilibrium output, $q^{EI}(\alpha)$, is characterized by the following first-order condition:

$$\frac{\partial \pi_i^{EI}}{\partial q_i} = P'(nq^{EI})q^{EI} + P(nq^{EI}) - C'(q^{EI}) - K'(x^{EI})\big(g'(q^{EI}) - \alpha\big) = 0. \tag{3}$$

The second-order condition is satisfied. We obtain $x^{EI}(\alpha) = g(q^{EI}(\alpha)) - \alpha q^{EI}(\alpha)$ and $e^{EI}(\alpha) = g(q^{EI}(\alpha)) - x^{EI}(\alpha) = \alpha q^{EI}(\alpha)$.

Differentiating (3) yields

$$\frac{dq^{EI}}{d\alpha} = -\frac{\partial^2 \pi_i^{EI}/\partial q_i \partial \alpha}{\partial^2 \pi_i^{EI}/\partial {q_i}^2 + \sum_{j \neq i} \partial^2 \pi_i^{EI}/\partial q_i \partial q_j} > 0, \tag{4}$$

where we use $\partial^2 \pi_i^{EI}/\partial q_i \partial \alpha = K' + (g' - \alpha)K'' q_i > 0$ and $\partial^2 \pi_i^{EI}/\partial {q_i}^2 + \sum_{j \neq i} \partial^2 \pi_i^{EI}/\partial q_i \partial q_j = P' - C'' - g''K' - (g' - \alpha)^2 K'' + n(P' + P'' q_i) < 0$. An increase in α relaxes the emission restriction and reduces the marginal cost of production, which increases q^{EI}.

The government sets the emission intensity $\alpha = \bar{\alpha}$ such that $ne^{EI}(\bar{\alpha}) = \bar{E}$. Let $(q^{EI}(\bar{E}), x^{EI}(\bar{E}))$ be the pair of equilibrium output and abatement and $W^{EI}(\bar{E})$ be the equilibrium welfare under emission intensity regulation when $\alpha = \bar{\alpha}$.

3.2 Emission Cap Regulation

Next, we consider the case under an emission cap regulation. Firms are symmetric and the number of permits is uniformly allocated, $\bar{E}/n$. Let superscript EC denote the equilibrium outcomes under emission cap regulation. Then, the profit function of firm i under the emission cap regulation is defined by $\pi_i^{EC}(q_i, Q_{-i}) := P(Q)q_i - C(q_i) - K(g(q_i) - \bar{E}/n)$. The equilibrium output, $q^{EC}(\bar{E})$, is characterized by the following first-order condition:

$$\frac{\partial \pi_i^{EC}}{\partial q} = P'(nq^{EC})q^{EC} + P(nq^{EC}) - C'(q^{EC}) - K'(x^{EC})g'(q^{EC}) = 0. \tag{5}$$

The second-order condition is satisfied. We obtain $x^{EC}(\bar{E}) = g(q^{EC}(\bar{E})) - \bar{E}/n$. Differentiating (5) yields

$$\frac{dq^{EC}}{d\bar{E}} = -\frac{\partial^2 \pi_i^{EC}/\partial q_i \partial \bar{E}}{\partial^2 \pi_i^{EC}/\partial {q_i}^2 + \sum_{j \neq i} \partial^2 \pi_i^{EC}/\partial q_i \partial q_j} > 0, \tag{6}$$

where we use $\partial^2 \pi_i^{EC}/\partial q_i \partial \bar{E} = (K'' g')/n > 0$ and $\partial^2 \pi_i^{EC}/\partial {q_i}^2 + \sum_{j \neq i} \partial^2 \pi_i^{EC}/\partial q_i \partial q_j = P' - C'' - g'' K' - g'^2 K'' + n(P' + P'' q_i) < 0$. Similar to the emission intensity case, an increase in $\bar{E}$ increases q^{EC}.

3.3 Comparison

In this subsection, we compare the two instruments. As expected, the equilibrium output is larger under the emission intensity regulation than under the emission cap regulation.

Result 1 $q^{EI}(\bar{E}) > q^{EC}(\bar{E})$.

Proof. See the Appendix.

Result 1 suggests that the equilibrium output under emission intensity regulation is larger than that under emission cap regulation. This result implies that the emission intensity regulation yields greater consumer surplus than the emission cap regulation does.

We now present our result on each firm's profit. Let $\pi^l(\bar{E}) := \pi_i^l\left(q^l(\bar{E}), (n-1)q^l(\bar{E})\right)$ denote each firm's equilibrium profit, $l = EI, EC$.

Proposition 1 *The emission cap regulation yields higher profit than the emission intensity regulation does; that is,* $\pi^{EC}(\bar{E}) > \pi^{EI}(\bar{E})$.

Proof. See the Appendix.

We explain the intuition behind Result 1 and Proposition 1. Under the emission intensity regulation, given α, an increase in q_i increases the upper limit of emissions. Therefore, each firm has a stronger incentive to increase its output under the emission intensity regulation than under the emission cap regulation, resulting in the larger equilibrium output (Result 1). However, anticipating this behavior of each firm, the government sets a stricter regulation to meet the emission target $\bar{E}$, which reduces the firms' profit.

We now discuss the welfare comparison. The emission intensity regulation is superior for consumer welfare to the emission cap regulation, but is less profitable for the firms. Thus, it is generally ambiguous which regulation is socially preferable. Let $W^{EI}(\bar{E})$ and $W^{EC}(\bar{E})$ be the equilibrium welfare under the emission intensity regulation and emission cap regulation, respectively. We present two cases in which the emission intensity regulation yields greater welfare than the emission cap regulation does; that is, $W^{EI}(\bar{E}) > W^{EC}(\bar{E})$. First, we consider the case with the most stringent target case ($\bar{E}$ is close to zero). When the firms are not allowed to pollute in the process of producing output (i.e., $\bar{E} = \bar{\alpha} = 0$), all emissions are reduced by the abatement activities and there are no emissions in the industry. Regardless of output level, the total emissions are zero if and only if the emissions per unit of output are zero. Therefore, when $\bar{E} = 0$, the emission cap regulation and emission intensity regulation yield the same outcome. Let q^Z and x^Z be common q and x under the zero-emission constraint (i.e., when $\bar{E} = 0$).

We now present the result when $\bar{E}$ is close to zero.

Proposition 2 *If $\bar{E}$ is sufficiently close to zero, the emission intensity regulation yields greater welfare than the emission cap regulation does.*

Proof. See the Appendix.

The intuition behind the result is as follows. As explained after Proposition 1, given $\bar{\alpha} > 0$, each firm has a stronger incentive to expand its output under the emission intensity regulation than under the emission cap regulation, because under the former regulation, each firm can increase the upper limit of emissions. However, this problem does not exist when $\bar{E} = \bar{\alpha} = 0$. Therefore, $q^{EC} = q^{EI}$ and $x^{EC} = x^{EI}$ when $\bar{E} = \bar{\alpha} = 0$.

An increase in $\bar{\alpha}$ relaxes the restriction on emissions. This leads to an increase in emissions, resulting in larger disutility from the emissions (emission effect). However, by the assumption of emission equivalence between two regimes, the emission effect is the same for the regimes. An increase in $\bar{E}$ and $\bar{\alpha}$ affects the per-firm output, q, and the per-firm abatement, x, (allocation effect). As stated above, the emission intensity regulation yields larger q and x than the emission cap regulation does.

Given the emission level, under the emission cap regulation, the marginal social cost of the reduction of emissions by the reduction of q is P/g' and that by the increase of x is K'. The marginal private cost for meeting the constraint by the reduction of q is $(P + P'q)/g'$ and that by the increase of x is K'. Thus, both x and q chosen by the firms are too small from the welfare viewpoint. Given the emission level, under emission intensity regulation, the marginal private cost for meeting the constraint by the reduction of q for each firm is $(P + P'q)/(g' - \alpha)$ and that by the increase of x is K'. When α is small, both x and q chosen by the firms are still too small from the welfare viewpoint, but both are larger than under the emission cap regulation. Therefore, the emission intensity regulation is better for welfare than the emission cap regulation is.

We believe that the most stringent case discussed in Proposition 2 is important. As mentioned in the introduction, under the Paris climate agreement, many countries, including the UK, China, France, Germany, and Japan, aim to reduce CO2 emissions drastically by 2050 (about an 80% reduction against a business-as-usual scenario). To achieve this goal, in several industries, such as electric power and transportation, a severe constraint that is close to zero emissions might be imposed. Thus, our result in the most stringent case has important implications for the debate on regulation.

Next, we examine the opposite (loosest constraint) case in which $\bar{E}$ is close to E^B.

Proposition 3 *Suppose that $\bar{E}$ is sufficiently close to E^B. The emission intensity regulation yields greater welfare than the emission cap regulation does.*

Proof. See the Appendix.

We explain the intuition. Because of emission equivalence, the emission effect is the same between two regimes. When $\bar{E} = E^B$, $q^{EC} = q^{EI} = q^B$ and $x^{EC} = x^{EI} = 0$. Because

$K'(0) = 0$, this abatement level is too low for welfare, and a marginal reduction of emissions by an increase in x is much more efficient than that by a reduction in q for welfare. In other words, given the emission, q is too large and x is too small for welfare. A marginal decrease in $\bar{\alpha}$ increases x and reduces q under both the emission cap regulation and emission intensity regulation, which improves welfare. The magnitude of this effect is stronger under the emission intensity regulation. Note that $q^{EI} > q^{EC}$ and thus, $x^{EI} > x^{EC}$ for $\bar{E} \in (0, E^B)$.

In Propositions 2 and 3, we show that when the target level is close to the strictest and loosest cases, the emission intensity regulation is better for welfare than the emission cap regulation is. The emission intensity regulation stimulates production and mitigates the problem of suboptimal production and abatement investment, which improves welfare under emission equivalence. Because the emission intensity regulation is better for welfare in the two polar cases, it might be natural to consider that the emission intensity regulation is better for any $\bar{E} \in (0, E^B)$. However, this is not true.

Let $(x^*(\bar{E}), q^*(\bar{E}))$ be the pair of the second-best abatement and output level (social optimum x and q given $E = \bar{E}$). The derivation is as follows. Let $\mathbf{q} = [q_1, q_2, ..., q_n]$ and $\mathbf{x} = [x_1, x_2, ..., x_n]$ denote an output profile and abatement profile, respectively. Given $\bar{E}$, the problem is

$$\begin{aligned} \max_{(\mathbf{q},\mathbf{x})} \quad & W = \int_0^Q P(z)dz - \sum_{i=1}^{n} (C(q_i) - K(x_i)) - \eta(\bar{E}) \\ s.t. \quad & \bar{E}/n = g(q_i) - x_i. \end{aligned}$$

The second-best output level, $q^*(\bar{E})$, is characterized by the following first-order condition:

$$\frac{\partial W}{\partial q_i} = P(nq^*(\bar{E})) - C'(q^*(\bar{E})) - K'(x^*(\bar{E}))g'(q^*(\bar{E})) = 0 \quad (i = 1, 2, ..., n). \tag{7}$$

$x^*(\bar{E})$ is derived from $\bar{E} = n\left(g(q^*) - x^*\right)$. Differentiating (7) yields

$$\frac{dq^*}{d\bar{E}} = -\frac{\partial^2 W(q^*, ..., q^*)/\partial q_i \partial \bar{E}}{\partial^2 W(q^*, ..., q^*)/\partial q_i^2 + \sum_{j \neq i} \partial^2 W(q^*, ..., q^*)/\partial q_i \partial q_j} > 0, \tag{8}$$

where we use $\partial^2 W/\partial q_i \partial \bar{E} = (g' K'')/n > 0$, $\partial^2 W/\partial q_i^2 = P' - C'' - g'' K' - g'^2 K'' < 0$, and $\partial^2 W/\partial q_i \partial q_j = P' < 0$.

As discussed above, $q^{EC}(\bar{E}) < q^*(\bar{E})$ and thus, $x^{EC}(\bar{E}) < x^*(\bar{E})$. In the two polar cases (strictest and loosest cases), $(x^{EC}(\bar{E}), q^{EC}(\bar{E})) = (x^{EI}(\bar{E}), q^{EI}(\bar{E}))$. Except for the two polar cases, $(x^{EC}(\bar{E}), q^{EC}(\bar{E})) < (x^{EI}(\bar{E}), q^{EI}(\bar{E}))$ holds (Result 1). As long as $(x^{EC}(\bar{E}), q^{EC}(\bar{E})) < (x^{EI}(\bar{E}), q^{EI}(\bar{E})) < (x^*(\bar{E}), q^*(\bar{E}))$, the outcome under the emission intensity regulation is closer to the second-best outcome than that under the emission cap regulation, and thus, the emission intensity regulation naturally yields greater welfare than the emission intensity regulation does. However, it is possible that $(x^{EI}(\bar{E}), q^{EI}(\bar{E})) > (x^*(\bar{E}), q^*(\bar{E}))$. Because the emission intensity can yield excessive production and excessive abatement investment, the emission cap regulation might be better than the emission intensity regulation for welfare.

We present the case wherein the emission cap regulation could be better than the emission intensity regulation for welfare.

Proposition 4 *Suppose that $P = a - bQ$, $C = 0$, $g = eq_i$, and $K = kx_i^2/2$. Then,*

$$W^{EI} > (<) W^{EC} \quad \text{if} \quad k < (>) \tilde{k},$$

where $\tilde{k} :=$

$$\frac{b\left(2e^2 - \bar{\alpha}e(n+2) + \bar{\alpha}^2(n+2) - \sqrt{4e^4 + 4\bar{\alpha}e^3 n + \bar{\alpha}^2 e^2\left(n^2+4\right) - 2\bar{\alpha}^3 e(n+2)^2 + \bar{\alpha}^4(n+2)^2}\right)}{2\bar{\alpha}e^2(e-\bar{\alpha})},$$

$\lim_{\bar{E}\to 0} \tilde{k} = \lim_{\bar{E}\to E^B} \tilde{k} = \infty$, *$\tilde{k}$ is U-shaped with respect to $\bar{E}$, and $\tilde{k} \geq \underline{k} := (b(6-n) + b\sqrt{68 + 20n + n^2})/2e^2$ for any $\bar{E} \in (0, E^B)$.*

Proof See the Appendix.

Figure 1 shows this result graphically (the case in which $a = 5$, $b = 1$, $k = 3$, $e = 2$, and $n = 3$). If k is not large, the emission intensity regulation yields greater welfare regardless of $\bar{E}$. However, if k is larger at a certain level, the emission cap regulation yields greater welfare at some target level.

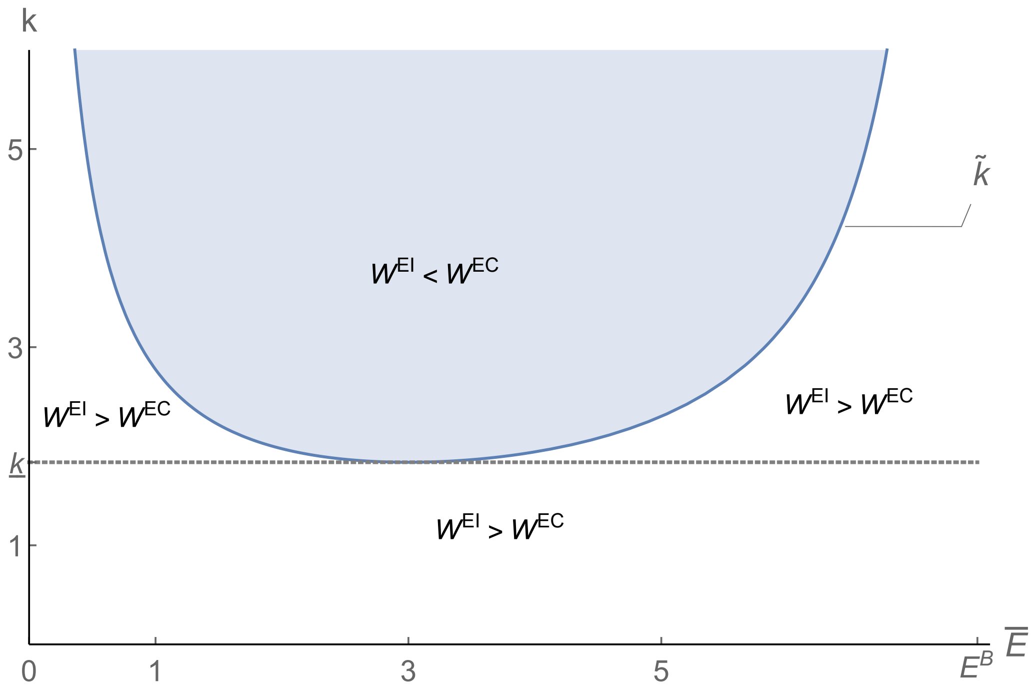

Figure 1: Welfare Comparison

As discussed above, the excessive production and abatement under the emission intensity regulation are the key factors behind Proposition 4. Figure 2 shows that x^* can be smaller than x^{EI}, although x^* is always larger than x^{EI} regardless of $\bar{E}$ (the case in which $a = 5$, $b = 1$, $k = 3$, $e = 2$, and $n = 3$). In other words, the abatement level under the emission intensity regulation can be too large (and the output level is also too large) to achieve the target level of emissions.

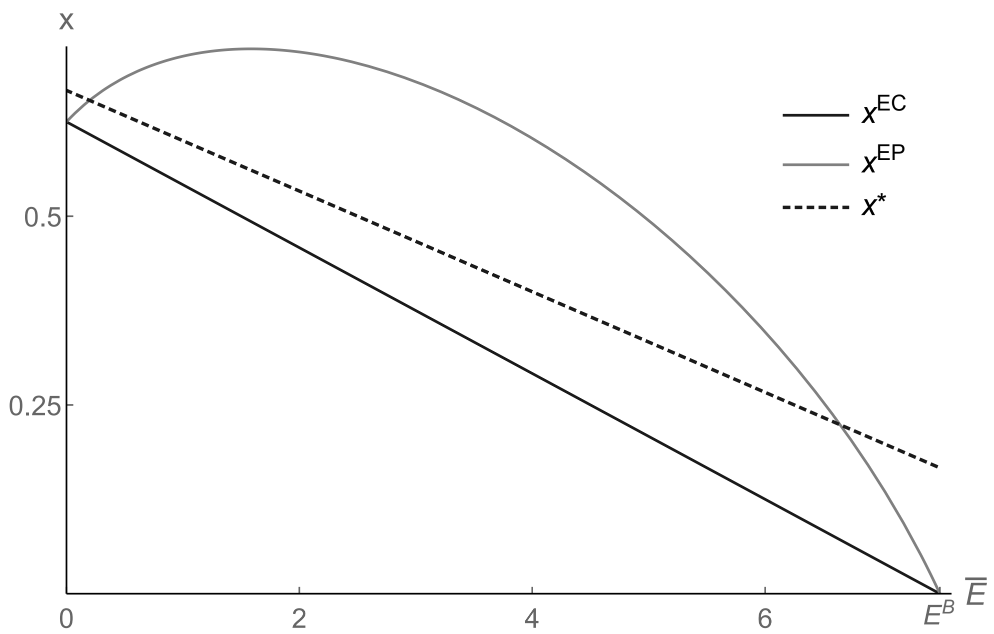

Figure 2: Abatement Level Comparison

We summarize the properties of the equilibrium abatement in the following. From Figure 2, we observe that x^* and x^{EC} are decreasing in $\bar{E}$. This is intuitive. A stricter regulation (smaller $\bar{E}$) stimulates emission abatement. By contrast, Figure 2 suggests that x^{EI} can be increasing in $\bar{E}$. This is because an increase in $\bar{E}$ relaxes the emission constraint, thereby naturally reducing abatement. However, an increase in $\bar{E}$ enlarges the output, which leads to the large abatement. Because the output expansion effect is strong under the emission intensity constraint, the latter effect might dominate the former effect, and thus, x^{EI} can be increasing in $\bar{E}$.

Under the general conditions, this discussion can be reduced to the following proposition.

Proposition 5 *(i) x^* and x^{EC} are decreasing in $\bar{E}$. (ii) x^{EI} is decreasing in $\bar{E}$ if $\bar{E}$ is sufficiently close to E^B. (iii) x^{EI} is nonmonotone with respect to $\bar{E}$ if $g'K' > -q^Z(P' - C'' - g''K' + n(P' + P''q^Z))$.*

Proof See the Appendix.

Proposition 5 suggests that the effect of emission regulation on the abatement activity depends on the regulatory regimes. With regard to Proposition 5(iii), it is difficult to judge under which conditions this inequality is satisfied. Here, we again specify the model as we did in Proposition 4 and derive the conditions.

Proposition 6 *Suppose that $P = a - bQ$, $C = 0$, $g = eq_i$, and $K = kx_i^2/2$. Then, x^{EI} is nonmonotone with respect to $\bar{E}$ if $ke^2 > (n+1)b$ and decreasing in $\bar{E}$ otherwise.*

Proof See the Appendix.

When e is larger, an increase in q increases the emission level more. An increase in $\bar{E}$ substantially increases the output under the emission intensity regulation, which induces larger abatement to offset the increase in emissions. The output expansion effect is stronger when b or n is smaller. Specifically, if the demand is elastic or the number of firms is small, a firm's output is more sensitive to a change in the emission regulation. Therefore, an increase in $\bar{E}$ more likely increases x when b or n are smaller. When k is larger, an increase in $\bar{E}$ reduces the marginal cost of production, including the emission abatement cost, more significantly, and thus, an increase in $\bar{E}$ more significantly increases the output. Therefore, an increase in $\bar{E}$ more likely increases x when k is larger.

4 Differentiated Bertrand competition

In this section, we consider differentiated Bertrand competition instead of Cournot competition, meaning that firms compete in strategic complements. We show that our main results do not depend on the mode of competition.

Assume that there are n symmetric firms that produce differentiated products. The direct demand function for product i ($i = 1, 2, ..., n$) is given by $D_i(p_1, p_2, ..., p_n) : \mathbb{R}_+ \mapsto \mathbb{R}_+$. We assume that D is twice continuously differentiable for all $p_i > 0$. The demand is downward sloping, $\partial D_i/\partial p_i < 0$, and $\partial D_i/\partial p_j > 0, j \neq i$ as long as $D > 0$. The latter condition means that goods are substitutes. In addition, we assume that the direct effect of a price change dominates the indirect effect, $\sum_{m=1}^{n}(\partial D_i/\partial p_m) < 0$ and $\partial^2 D_i/(\partial p_i)^2 + \sum_{j\neq i}|\partial^2 D_i/\partial p_i \partial p_j| < 0$. We further assume that demand has increasing differences, $\partial^2 D_i/\partial p_i \partial p_j \geq 0$, which implies that the price-setting game is supermodular. These are standard assumptions in a price-setting oligopoly with differentiated products.[7] Except for the demand system, we follow the same structure in the quantity competition analysis. The firm $i's$ profit is $\pi_i = p_i D_i(p_i, p_{-i}) - C(D_i(p_i, p_{-i})) - K(x_i)$.

4.1 Emission Intensity regulation

Define the profit function of firm i under the emission intensity regulation as $\pi_i^{EI}(p_i, p_{-i}) := p_i D_i(p_i, p_{-i}) - C(D_i(p_i, p_{-i})) - K(g(D_i) - \alpha D_i)$. The first-order condition is

$$\frac{\partial \pi_i^{EI}}{\partial p_i} = D_i(p_i, p_{-i}) + (p_i - C' - K'(g' - \alpha))\frac{\partial D_i}{\partial p_i} = 0 \ (i = 1, 2, ..., n).$$

Focusing on the symmetric equilibrium ($p_i = p^{EI}(\alpha)$ for i) under the emission intensity regulation,

$$\frac{\partial \pi_i^{EI}(p^{EI}, ..., p^{EI})}{\partial p_i} = D^{EI} + \left(p^{EI} - C' - K'(g' - \alpha)\right)\frac{\partial D_i}{\partial p_i} = 0, \tag{9}$$

where $D^{EI}(\alpha) = D_i\left(p^{EI}(\alpha), ..., p^{EI}(\alpha)\right)$ and $x^{EI}(\alpha) = g\left(D^{EI}(\alpha)\right) - \alpha D^{EI}(\alpha)$. Using the implicit function theorem and differentiating (9) with respect to α yields

$$\frac{\partial D^{EI}}{\partial \alpha} + \left(\frac{\partial p^{EI}}{\partial \alpha} - C''\frac{\partial D^{EI}}{\partial \alpha} - K''\frac{\partial x^{EI}}{\partial \alpha}(g' - \alpha) - K'\left(g''\frac{\partial D^{EI}}{\partial \alpha} - 1\right)\right)\frac{\partial D_i}{\partial p_i}$$
$$+ \left(p^{EI} - C' - K'(g' - \alpha)\right)\sum_{m=1}^{n}\frac{\partial^2 D_i}{\partial p_i \partial p_m}\frac{\partial p^{EI}}{\partial \alpha} = 0$$

[7]Examples of the demand system include linear and constant elasticity of substitution demand and the logit demand model (see Vives, 1999; Anderson et al., 2001).

where

$$\frac{\partial D^{EI}}{\partial \alpha} = \sum_{m=1}^{n} \frac{\partial D_i}{\partial p_m}\frac{\partial p^{EI}}{\partial \alpha},$$
$$\frac{\partial x^{EI}}{\partial \alpha} = (g' - \alpha)\frac{\partial D^{EI}}{\partial \alpha} - D^{EI}.$$

Hence, using the assumptions for demand functions,

$$\frac{\partial p^{EI}}{\partial \alpha} = - \frac{(K' + K''(g' - \alpha)D^{EI})\frac{\partial D_i}{\partial p_i}}{\frac{\partial D_i}{\partial p_i} + \left(1 - \left(C'' - K''\left(g' - \alpha\right)^2 - K'g''\right)\frac{\partial D_i}{\partial p_i}\right)\sum_m \frac{\partial D_i}{\partial p_m} + (p^{EI} - C' - K'(g' - \alpha))\sum_m \frac{\partial^2 D_i}{\partial p_i \partial p_m}} < 0,$$

implying that

$$\frac{\partial D^{EI}}{\partial \alpha} > 0. \tag{10}$$

As well as the Cournot model, an increase in α relaxes the emission constraint and increases the per-firm output, $D^{EI}(\alpha)$.

We compare the equilibrium outcomes under emission equivalence. We redefine the equilibrium outcomes, satisfying $nD^{EI}(\widehat{\alpha}) = \widehat{E}$, as $p^{EI}(\widehat{E}) := p^{EI}(\widehat{\alpha})$. Let $(D^{EI}(\widehat{E}), x^{EI}(\widehat{E}))$ be the pair of equilibrium output and abatement and $W^{EI}(\widehat{E})$ be the equilibrium welfare under the emission intensity regulation when $\alpha = \widehat{\alpha}$.

4.2 Emission Cap Regulation

If the firms are subject to the emission cap, the profit function of firm i under the emission cap regulation can be written as $\pi_i^{EC}(p_i, p_{-i}) := p_i D_i(p_i, p_{-i}) - C(D_i(p_i, p_{-i})) - K(g(D_i) - \widehat{E}/n)$. Given the emission cap, $\widehat{E}/n$, the first-order condition is

$$\frac{\partial \pi_i^{EC}}{\partial p_i} = D_i(p_i, p_{-i}) + p_i\frac{\partial D_i}{\partial p_i} - C'\frac{\partial D_i}{\partial p_i} - K'g'\frac{\partial D_i}{\partial p_i} = 0 \ (i = 1, 2, ..., n).$$

Focusing on the symmetric equilibrium ($p_i = p^{EC}(\widehat{E})$ for all i),

$$\frac{\partial \pi_i^{EC}(p^{EC}, ..., p^{EC})}{\partial p_i} = D^{EC} + p^{EC}\frac{\partial D_i}{\partial p_i} - C'\frac{\partial D_i}{\partial p_i} - K'g'\frac{\partial D_i}{\partial p_i} = 0, \tag{11}$$

where $D^{EC}(\widehat{E}) = D_i(p^{EC}(\widehat{E}), ..., p^{EC}(\widehat{E}))$. Using the implicit function theorem and differentiating (11) with respect to $\widehat{E}$ yields

$$\frac{\partial D^{EC}}{\partial \widehat{E}} + \left(\frac{\partial p^{EC}}{\partial \widehat{E}} - C'' \frac{\partial D^{EC}}{\partial \widehat{E}} - K'' \frac{\partial x^{EC}}{\partial \widehat{E}} g' - K' g'' \frac{\partial D^{EC}}{\partial \widehat{E}} \right) \frac{\partial D_i}{\partial p_i} + \left(p^{EC} - C' - K' g' \right) \sum_{m=1}^{n} \frac{\partial^2 D_i}{\partial p_i \partial p_m} \frac{\partial p^{EC}}{\partial \widehat{E}} = 0$$

where

$$\begin{aligned} \frac{\partial D^{EC}}{\partial \widehat{E}} &= \sum_{m=1}^{n} \frac{\partial D_i}{\partial p_m} \frac{\partial p^{EC}}{\partial \widehat{E}} \\ \frac{\partial x^{EC}}{\partial \widehat{E}} &= g' \frac{\partial D^{EC}}{\partial \widehat{E}} - \frac{1}{n}. \end{aligned}$$

Hence, we obtain

$$\frac{\partial p^{EC}}{\partial \widehat{E}} = - \frac{K'' g' \frac{\partial D_i}{\partial p_i} \frac{1}{n}}{\frac{\partial D_i}{\partial p_i} + \left(1 - \left(C'' - K'' g'^2 - K' g'' \right) \frac{\partial D_i}{\partial p_i} \right) \sum_m \frac{\partial D_i}{\partial p_m} + \left(p^{EI} - C' - K' g' \right) \sum_m \frac{\partial^2 D_i}{\partial p_i \partial p_m}} < 0.$$

This also implies

$$\frac{\partial D^{EC}}{\partial \widehat{E}} > 0. \tag{12}$$

As in the case of emission intensity, the effect of the emission regulation on the per-firm output is the same as that under Cournot competition.

4.3 Comparison

We now compare equilibrium outcomes under two different regimes and reexamine Result 1 and Propositions 1–3. Under the regularity condition, the equilibrium output is larger under the emission intensity regulation than under the emission cap regulation.

Result 1B $D^{EI}(\widehat{E}) > D^{EC}(\widehat{E})$.

The proof is straightforward from (9), (11), and $\sum_{m=1}^{n} (\partial D_i / \partial p_m) < 0$. Using (9) and (11), we obtain $p^{EI}(\widehat{E}) < p^{EC}(\widehat{E})$. Because of the demand condition, we obtain this result.

Next, we present our result on the firm's profit. Let $\pi^l(\widehat{E}) := \pi_i^l(p^l(\widehat{E}), p^l(\widehat{E}))$ denote each firm's equilibrium profit under emission equivalence, $l = EI, EC$.

Proposition 1B *The emission cap regulation yields higher profit than does the emission intensity regulation; that is,* $\pi^{EC}(\widehat{E}) > \pi^{EI}(\widehat{E})$.

Proof. See the Appendix.

We now compare the resulting social welfare under both regulations. Let

$$W(p_i, p_{-i}) := U(D_i(p_i, p_{-i}), D_{-i}(p_i, p_{-i})) - \sum_{i=1}^{n} (C_i(D_i(p_i, p_{-i})) + K_i(x_i)) - \eta(E)$$

denote total social surplus under price competition. Denote the equilibrium welfare under emission equivalence by $W^l(\widehat{E}) := W^l(p^l(\widehat{E}), p^l(\widehat{E}))$, $l = EI, EC$. We consider the most stringent regulation, which imposes a near-zero emission.

Proposition 2B *If* $\widehat{E}$ *is sufficiently close to zero, the emission intensity regulation yields greater welfare than the emission cap regulation does.*

Proof. See the Appendix.

Likewise, we consider the opposite case when $\widehat{E}$ is close to E^B. We omit the proof because it is analogous to that of Proposition 2B.[8]

Proposition 3B *Suppose that* $\widehat{E}$ *is sufficiently close to* E^B. *The emission intensity regulation yields greater welfare than the emission cap regulation does.*

Provided that firms compete in strategic complements instead of strategic substitutes, our main results hold, that is, the emission intensity regulation leads to higher welfare in the extreme cases. This has important policy implications. The model that covers both quantity and differentiated Bertrand competition can be applicable across diverse industries, such as the energy, semiconductor, electric, and transportation industries. Thus, regulators should take into account the emission intensity regulation as an efficient regulatory instrument.

[8]The proof is available upon request from the authors.

5 Concluding Remarks

In this study, we compare two direct-regulation tools, an emission cap regulation and an emission intensity regulation. We find that profit-maximizing firms always prefer the emission cap regulation. However, the emission intensity regulation always yields greater consumer welfare and can yield greater welfare. Moreover, we present two cases in which the emission intensity regulation yields greater welfare than the emission cap regulation does: the case of the strictest target, which is close to a zero-emission target, and the case of the loosest target, which is close to business as usual. Our result suggests that the government should adopt the emission intensity regulation, especially to achieve a zero-emission society efficiently.

Our study neglects any uncertainty of demand or cost. If the government chooses the direct regulation before knowing the demand parameter, an increase of the degree of demand uncertainty increases the advantage of the emission intensity regulation over the emission cap regulation for both the welfare and profits of firms. This is because the firms can expand (shrink) their output more flexibly under the emission intensity regulation than under the emission cap regulation when demand is high (low). We consider this is the reason that some companies, such as Japanese electric power companies, choose emission intensity regulations as their favored form of self-regulation. Comparing the two tools after introducing demand uncertainty is left to future research.

Appendix

Proof of Result 1

$$\frac{\partial \pi_i^{EC}}{\partial q_i}\Big|_{q_i=q^{EI}} = K'(x^{EI})\left(g'(q^{EI}) - \bar{\alpha}\right) - K'(x^{EI})g'(q^{EI}) < 0.$$

This inequality implies that q_i^{EI} is excessive from firm i's profit-maximizing viewpoint under the price cap regulation. ■

Proof of Proposition 1

Using the resulting profit and emission equivalence, we obtain

$$\begin{aligned}
\pi^{EC}(\bar{E}) &= P(nq^{EC})q^{EC} - C(q^{EC}) - K(g(q^{EC}) - \bar{E}/n) \\
&> P(nq^{EI})q^{EI} - C(q^{EI}) - K(g(q^{EI}) - \bar{E}/n) \\
&= P(nq^{EI})q^{EI} - C(q^{EI}) - K(g(q^{EI}) - \bar{\alpha}q^{EI}) = \pi^{EI}(\bar{E}),
\end{aligned}$$

where the inequality follows from the fact that $q^{EC}(\bar{E}) = \arg\max_{\{q_i\}} P(Q)q_i - C(q_i) - K(g(q_i) - \bar{E}/n)$ and $q^{EI} \neq q^{EC}$. ■

Proof of Proposition 2

For $l = EC, EI$, we obtain

$$\begin{aligned}
\frac{dW^l}{d\bar{E}}\Big|_{\bar{E}=0} &= \sum_{i=1}^{n}\left(\frac{\partial W^l}{\partial q_i}\frac{dq^l}{d\bar{E}} + \frac{\partial W^l}{\partial x_i}\frac{dx^l}{d\bar{E}}\right) + \frac{\partial W^l}{\partial \bar{E}} \\
&= n(P(nq^Z) - C'(q^Z))\frac{dq^l}{d\bar{E}} - nK'(x^Z)\frac{dx^l}{d\bar{E}} - \eta'(0) \\
&= n(P(nq^Z) - C'(q^Z))\frac{dq^l}{d\bar{E}} - nK'(x^Z)\left(g'(q^Z)\frac{dq^l}{d\bar{E}} - \frac{1}{n}\right) - \eta'(0) \\
&= n(P(nq^Z) - C'(q^Z) - K'(x^Z)g'(q^Z))\frac{dq^l}{d\bar{E}} + K'(x^Z) - \eta'(0),
\end{aligned}$$

where we use $g(q_i) - x_i = \bar{E}/n$ (and thus, $dx^l/d\bar{E} = g'(dq^l/d\bar{E}) - 1/n$), and $(q^{EC}, x^{EC}) = (q^{EI}, x^{EI}) = (q^Z, x^Z)$ when $\bar{E} = 0$. Because $q^Z < q^{EC} < q^{EI}$ for all $\bar{E} > 0$, we obtain

$$\frac{dq^{EI}}{d\bar{E}}\Big|_{\bar{E}=0} > \frac{dq^{EC}}{d\bar{E}}\Big|_{\bar{E}=0} > 0.$$

From (5), we obtain $P - C' - K'g' > P + P'q_i - C' - K'g' = 0$. Under these conditions, we obtain

$$\frac{dW^{EI}}{d\bar{E}}\bigg|_{\bar{E}=0} > \frac{dW^{EC}}{d\bar{E}}\bigg|_{\bar{E}=0} > 0.$$

Because $W^{EI} = W^{EC}$ when $\bar{E} = 0$, we obtain Proposition 2. ■

Proof of Proposition 3

For $l = EC, EI$, we obtain

$$\begin{aligned}
\frac{\partial W^l}{\partial \bar{E}}\bigg|_{\bar{E}=E^B} &= \sum_{i=1}^{n}\left(\frac{\partial W^l}{\partial q_i}\frac{dq^l}{d\bar{E}} + \frac{\partial W^l}{\partial x_i}\frac{dx^l}{d\bar{E}}\right) \\
&= n(P(nq^B) - C'(q^B))\frac{dq^l}{d\bar{E}} - nK'(x^B)\frac{dx^l}{d\bar{E}} - \eta'(E^B) \\
&= n(P(nq^B) - C'(q^B))\frac{dq^l}{d\bar{E}} - \eta',
\end{aligned}$$

where we use $q^{EC} = q^{EI} = q^B$ and $x^{EC} = x^{EI} = 0$ when $\bar{E} = E^B$ and $K'(0) = 0$. Because $q^{EC} < q^{EI} < q^B$ for all $\bar{E} < E^B$, we obtain

$$0 < \frac{dq^{EI}}{d\bar{E}}\bigg|_{\bar{E}=E^B} < \frac{dq^{EC}}{d\bar{E}}\bigg|_{\bar{E}=E^B}.$$

From (5), we obtain $P - C' > 0$. Under these conditions,

$$\frac{\partial W^{EI}}{\partial \bar{E}}\bigg|_{\bar{E}=E^B} < \frac{\partial W^{EC}}{\partial \bar{E}}\bigg|_{\bar{E}=E^B} < 0.$$

Because $W^{EI} = W^{EC}$ when $\bar{E} = E^B$, we obtain Proposition 3. ■

Proof of Proposition 4

First, we consider the equilibrium outputs for each regime. From (3) and (5), we obtain

$$q^{EI} = \frac{a}{(1+n)b + k(e-\alpha)^2}, \quad q^{EC} = \frac{a + ke\bar{E}}{(1+n)b + e^2k}.$$

Substituting the equilibrium outputs into total surplus, we obtain

$$\begin{aligned}
W^{EI}(\bar{\alpha}) &= \frac{an\left(a\left(b(n+2) + k(e-\bar{\alpha})^2\right) - 2\eta\bar{\alpha}\left(b(n+1) + k(e-\bar{\alpha})^2\right)\right)}{2\left(b(n+1) + k(e-\bar{\alpha})^2\right)^2}, \\
W^{EC}(\bar{E}) &= \frac{a^2n^2\left(b(n+2) + e^2k\right) + 2aekn\bar{E}\left(b(n+2) + e^2k\right) - bk\bar{E}^2\left(b(n+1)^2 + e^2kn\right)}{2n\left(bn + b + e^2k\right)^2} - \eta\bar{E}.
\end{aligned}$$

Using $E^{EI}(\bar{\alpha}) = \bar{\alpha} q^{EI} = \bar{E}$, $W^{EC}(\bar{E})$ can be rewritten as a function of $\bar{\alpha}$. Thus, we obtain

$$W^{EI}(\bar{\alpha}) - W^{EC}(\bar{E}) = \frac{a^2 kn\bar{\alpha}(e-\bar{\alpha})H}{2\left(bn+b+e^2k\right)^2\left(b(n+1)+k(e-\bar{\alpha})^2\right)^2},$$

where $H := 2b^2(n+1)+bk\left(2e^2 - e(n+2)\bar{\alpha} + (n+2)\bar{\alpha}^2\right)+e^2k^2\bar{\alpha}(\bar{\alpha}-e)$. $W^{EI}(\bar{\alpha})-W^{EC}(\bar{E})$ is positive if and only if $H > 0$ and

$$H > (<) 0 \ \text{ if } k < (>) \tilde{k},$$

where $\tilde{k} :=$

$$\frac{b\left(2e^2 - \bar{\alpha}e(n+2) + \bar{\alpha}^2(n+2) - \sqrt{4e^4 + 4\bar{\alpha}e^3 n + \bar{\alpha}^2 e^2\left(n^2+4\right) - 2\bar{\alpha}^3 e(n+2)^2 + \bar{\alpha}^4(n+2)^2}\right)}{2\bar{\alpha}e^2(e-\bar{\alpha})}.$$

Remember that $\bar{\alpha}$ is determined by $E^{EI}(\bar{\alpha}) = \bar{E}$, and thus, $\tilde{k}$ also depends on the emission target via $\bar{\alpha}$. This implies that $W^{EI}(\bar{\alpha}) > (<) W^{EC}(\bar{E})$ if $k < (>) \tilde{k}$. Because $\lim_{\bar{\alpha}\to 0}\tilde{k} = \lim_{\bar{\alpha}\to e}\tilde{k} = \infty$, we obtain $\lim_{\bar{E}\to 0}\tilde{k} = \lim_{\bar{E}\to E^B}\tilde{k} = \infty$.

Differentiating $\tilde{k}$ with $\bar{\alpha}$, we obtain

$$\frac{\partial \tilde{k}}{\partial \bar{\alpha}} = \frac{b(e-2\bar{\alpha})\left(2e^2 + \bar{\alpha}en - \bar{\alpha}^2 n - \sqrt{4e^4 + 4bar\alpha e^3 n + \bar{\alpha}^2 e^2\left(n^2+4\right) - 2\bar{\alpha}^3 e(n+2)^2 + \bar{\alpha}^4(n+2)^2}\right)}{\bar{\alpha}^2(e-\bar{\alpha})^2\sqrt{4e^4 + 4\bar{\alpha}e^3 n + \bar{\alpha}^2 e^2\left(n^2+4\right) - 2\bar{\alpha}^3 e(n+2)^2 + \bar{\alpha}^4(n+2)^2}}.$$

Because $\partial\tilde{k}/\partial\bar{\alpha}$ is negative (positive) when $\bar{\alpha} < \ (>)\ e/2$, $\tilde{k}(\bar{E})$ is U-shaped and minimized at $\bar{\alpha} = e/2$. Because $\tilde{k}$ is minimized when $\bar{\alpha} = e/2$, we obtain $\underline{k} = b(6-n+\sqrt{n^2+20n+68})/2e^2$. Note that $\bar{\alpha}(\bar{E})$ is increasing, $\bar{\alpha}(0) = 0$, and $\bar{\alpha}(E^B) = e$. ■

Proof of Proposition 5

(i) For $l = EC, EI$, and $*$, we have

$$\frac{dx^l}{d\bar{E}} = g'\frac{dq^l}{d\bar{E}} - \frac{1}{n},$$

where we use $g - x = \bar{E}$. Combining the equation with (8), we obtain

$$\begin{aligned}\frac{dx^*}{d\bar{E}} &= g'\left(-\frac{(g'K'')/n}{nP' + P''q - C'' - g''K' - g'^2K''}\right) - \frac{1}{n}\\ &= \frac{1}{n}\left(-\frac{g'^2K''}{nP' - C'' - g''K' - g'^2K''} - 1\right) < 0.\end{aligned}$$

Likewise, from (6), we obtain

$$\begin{aligned}\frac{dx^{EC}}{d\bar{E}} &= g'\left(-\frac{(K''g')/n}{P'-C''-g''K'-g'^2K''+n(P'+P''q_i)}\right)-\frac{1}{n}\\ &= \frac{1}{n}\left(-\frac{g'^2K''}{P'-C''-g''K'-g'^2K''+n(P'+P''q_i)}-1\right)<0.\end{aligned}$$

Therefore, x^* and x^{EC} are decreasing in $\bar{E}$ in general demand and cost functions.

(ii) From (4), we obtain

$$\begin{aligned}\frac{dx^{EI}}{d\bar{E}} &= g'\frac{dq^{EI}}{d\alpha}\frac{d\bar{\alpha}}{d\bar{E}}-\frac{1}{n}\\ &= g'\frac{dq^{EI}}{d\alpha}\frac{1}{n}\left(q^{EI}+\bar{\alpha}\frac{dq^{EI}}{d\alpha}\right)^{-1}-\frac{1}{n},\\ &= \frac{1}{n}\left(g'\frac{dq^{EI}}{d\alpha}\left(q^{EI}+\bar{\alpha}\frac{dq^{EI}}{d\alpha}\right)^{-1}-1\right),\end{aligned}$$

where we use $\bar{E}/n=\bar{\alpha}q^{EI}(\bar{\alpha})$ when $\bar{E}>0$. Thus,

$$\frac{dx^{EI}}{d\bar{E}}>(<)0 \text{ if and only if } \Theta\equiv(g'-\bar{\alpha})\frac{dq^{EI}}{d\alpha}-q^{EI}>(<)0.$$

If $\bar{E}=E^B$, we obtain

$$\begin{aligned}\Theta\big|_{\bar{E}=E^B} &= (g'-\bar{\alpha})\frac{dq^{EI}}{d\alpha}-q^B\\ &= (g'-\bar{\alpha})\left(-\frac{(g'-\bar{\alpha})K''q^B}{P'-C''-g''K'-(g'-\alpha)^2K''+n(P'+P''q_i)}\right)-q^B\\ &= q^B\left(-\frac{(g'-\bar{\alpha})^2K''}{P'-C''-g''K'-(g'-\alpha)^2K''+n(P'+P''q_i)}-1\right)<0,\end{aligned}$$

where we use $q^{EI}=q^B, x^{EI}=0$, and $K'(0)=0$ when $\bar{E}=E^B$. Thus, x^{EI} is decreasing in $\bar{E}$ if $\bar{E}$ is sufficiently close to E^B.

(iii) If $\bar{E}=0$, we obtain

$$\begin{aligned}\Theta\big|_{\bar{E}=0} &= g'\frac{dq^{EI}}{d\alpha}-q^Z\\ &= g'\left(-\frac{K'+g'K''q^Z}{P'-C''-g''K'-g'^2K''+n(P'+P''q^Z)}\right)-q^Z,\end{aligned}$$

where we use $q^{EI} = q^Z$, $\bar{\alpha} = 0$ when $\bar{E} = 0$. Thus, we find

$$\Theta\Big|_{\bar{E}=0} > (<) 0 \text{ if and only if } g'K' > (<) - q^Z \left(P' - C'' - g''K' + n(P' + P''q^Z)\right). \quad (13)$$

■

Proof of Proposition 6

From (13), we obtain

$$\frac{dx^{EI}}{d\bar{E}}\Big|_{\bar{E}=0} > (<) 0 \text{ if and only if } ke^2 > (<)(n+1)b.$$

This and Proposition 5(ii) imply that x^{EI} is nonmonotone with respect to $\bar{E}$ if $ke^2 > (n+1)b$.

Suppose that $ke^2 \leq (n+1)b$. We show that x^{EI} is decreasing in $\bar{E}$, which is the latter part of Proposition 6. Remember that Θ is the key determinant of $dx^{EI}/d\bar{\bar{E}}$. Under the specific model, we obtain

$$\begin{aligned}\Theta = (g' - \bar{\alpha})\frac{dq^{EI}}{d\alpha} - q^{EI} &= (e - \bar{\alpha})\frac{2ak(e - \bar{\alpha})}{((n+1)b + k(e - \bar{\alpha})^2)^2} - \frac{a}{(n+1)b + k(e - \bar{\alpha})^2} \\ &= \frac{a(k(e - \bar{\alpha})^2 - (n+1)b)}{((n+1)b + k(e - \bar{\alpha})^2)^2} < 0. \quad ■\end{aligned}$$

Proof of Proposition 1B

Using the resulting profit and emission equivalence, we obtain

$$\begin{aligned}\pi^{EC}(\widehat{E}) &= p^{EC}D^{EC} - C(D^{EC}) - K(g(D^{EC}) - \widehat{E}/n) \\ &> p^{EI}D^{EI} - C(D^{EI}) - K(g(D^{EI}) - \widehat{E}/n) \\ &= p^{EI}D^{EI} - C(D^{EI}) - K(g(D^{EI}) - \bar{\alpha}D^{EI}) = \pi^{EI}(\widehat{E}),\end{aligned}$$

where the inequality follows from the fact that $p^{EC}(\widehat{E}) = \arg\max_{\{p_i\}} p_i D_i(p_i, p_{-i}) - C(D_i(p_i, p_{-i})) - K(g(D_i) - \widehat{E}/n)$ and $p^{EI} \neq p^{EC}$. ■

Proof of Proposition 2B

For $l = EC, EI$, we obtain

$$\begin{aligned}
\frac{dW^l}{d\widehat{E}}\Big|_{\widehat{E}=0} &= \sum_{i=1}^{n} \frac{\partial W}{\partial D_i}\frac{\partial D^l}{\partial \widehat{E}} + \sum_{i=1}^{n} \frac{\partial W}{\partial x_i}\frac{\partial x^l}{\partial \widehat{E}} + \frac{\partial W}{\partial \widehat{E}} \\
&= \sum_i (\frac{\partial U}{\partial D_i} - C'(D^Z))\frac{\partial D^k}{\partial \widehat{E}} - nK'(x^Z)\frac{\partial x^k}{\partial \widehat{E}} - \eta'(0) \\
&= n(p^Z - C'(D^Z))\frac{\partial D^k}{\partial \widehat{E}} - nK'(x^Z)\left(g'(D^Z)\frac{\partial D^k}{\partial \widehat{E}} - \frac{1}{n}\right) - \eta'(0) \\
&= n\left(p^Z - C'(D^Z) - K'(x^Z)g'(D^Z)\right)\frac{\partial D^k}{\partial \widehat{E}} + K'(x^Z) - \eta'(0).
\end{aligned}$$

Because $D^Z < D^{EC} < D^{EI}$ for all $\widehat{E} > 0$ and the equilibrium demand is monotonically increasing from (10) and (12), we obtain

$$\frac{\partial D^{EI}}{d\widehat{E}}\Big|_{\widehat{E}=0} > \frac{\partial D^{EC}}{d\widehat{E}}\Big|_{\widehat{E}=0}.$$

We obtain

$$\frac{dW^{EI}}{d\widehat{E}}\Big|_{\widehat{E}=0} > \frac{dW^{EC}}{d\widehat{E}}\Big|_{\widehat{E}=0}.$$

Because $W^{EI} = W^{EC}$ when $\widehat{E} = 0$, we obtain Proposition 2B. ■

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