Profit-enhancing emissions taxes in near-zero-emissions industries

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Abstract

Motivated by the recent global trend of net-zero-emissions environmental regulations, we investigate the relationship between emissions tax rates and firm profits in oligopolies. Our result indicates that when the resulting emission levels are approximately zero, a marginal increase in the tax rate enhances firms' profits except in monopoly markets. This finding suggests that firms might not resist a further increase in environmental tax if the target emissions level is sufficiently low. Moreover, we present parametric numerical examples suggesting that the profit-enhancing range is large and not limited to near-zero emissions.

JEL classification codes: Q52, L13, L51

Keywords: net-zero-emissions industries, emissions tax, oligopolies

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1 Introduction

Severe climate change has elevated the urgency of achieving a net-zero-emissions society as a critical policy issue. European countries, along with China and Japan, have declared their intentions to achieve this goal.[1] Consequently, industries with significant CO2 emissions, such as electric power, steel, and transportation, are likely to face near-zero-emissions constraints imposed by regulatory authorities. Earlier research has examined the effects of emissions taxes on market outcomes and derived optimal levels under various settings (Buchanan, 1969; Barnett, 1980; Misiolek, 1980; Baumol and Oates, 1988; Simpson, 1995; Katsoulacos and Xepapadeas, 1995; Lee, 1999; Ino and Matsumura, 2021; Xu et al., 2022). However, firms may resist environmental regulations, particularly when these regulations adversely affect their profits.[2]

This study investigates the impact of emissions taxes on firm profits in oligopolistic markets, providing insights into the difficulty of implementing near-zero-emissions regulations. We find that a marginal decrease in the tax rate from the rate yielding zero-emissions reduces firms' profits except in monopoly industries. This implies that emissions taxes enhance firms' profits in near-zero-emissions industries, and thus, it is possible that oligopolists (non-monopolists) might not strongly resist emissions taxes.

This study contributes to the literature on the relationship between emissions taxes and firm profitability. Simpson (1995) and Carraro and Soubeyran (1996) indicate that firms may benefit from taxation if they are sufficiently heterogeneous. Pang (2019) considers bargaining between the government and firms, examining equilibrium emissions and profit taxes. Li and Fu (2022) examine the dynamic aspects of abatement technology innovation. However, studies on the profitability of emissions taxes focusing on near-zero-emissions

[1] Reuters (https://jp.reuters.com/article/japan-politics-suga/japan-aims-for-zero-emissions-carbon-neutral-society-by-2050-pm-idUSKBN27B0FB).

[2] Meng and Rode (2019) show that firms lobbied against the Waxman–Markey Bill, altering the likelihood of its implementation. See also Hirose et al. (2024).

industries remain scarce. Our study demonstrates that emissions taxes consistently enhance firm profits in near-zero-emissions industries except in monopoly markets.[3]

Moreover, this study contributes to the general literature on the relationship between taxes and firm profitability. The literature has already shown that taxes can raise profits in Cournot oligopolies (Katz and Rosen, 1985). Our new finding is that emissions taxes *always* raise profits in near-zero-emissions industries except monopolies, which has important implications for energy and environmental policies. In other words, we present a sufficient condition for profit-enhancing taxes in the context of emissions taxes. In addition, we discuss how the competitiveness of the market enhances or weakens this profit-enhancing effect.[4]

Regarding profit-enhancing environmental policies, Porter (1991) argues that strict environmental regulations encourage innovation, which may improve competitiveness and increase profits under stricter regulations (the Porter hypothesis). Various studies have found that stricter environmental regulations stimulate innovation (Ambec et al., 2013). Our study provides a different view from the Porter hypothesis in that emissions taxes can enhance profits even without innovation.

2 The Model

We consider an industry with n symmetric firms, where $n \geq 1$. Firms produce a single commodity with an inverse demand function given by: $P : \mathbb{R}_+ \mapsto \mathbb{R}_+$. Let $C(q_i, x_i) : \mathbb{R}_+^2 \mapsto \mathbb{R}_+$ be firm i's cost function, where q_i and x_i are firm i's output and abatement level, respectively. Furthermore, let $e(q_i, x_i) : \mathbb{R}_+^2 \mapsto \mathbb{R}$ be the emission level. We assume that P, C, and e are twice continuously differentiable and satisfy the following conditions: $P' < 0$

[3] Our analysis can be applied to cases in which a combination of policies, including an emissions tax, rather than the emissions tax alone, leads to zero-emissions industries. For examples of policy combinations, see Ino and Matsumura (2021, 2024).

[4] We show that the profit-enhancing effect is stronger when the number of firms is larger (Proposition 2), when the degree of product differentiation is smaller (Proposition 3), and when under Bertrand competition rather than Cournot competition (Proposition 4).

as long as $P > 0$, $P' + P''q < 0$, $C_q \geq 0$, $C_x \geq 0$, $C_{qq} \geq 0$, $C_{xx} > 0$, $e_q > 0$, $e_x < 0$, $e_{qq} \geq 0$, and $e_{xx} \geq 0$ for $q, x > 0$, where the subscripts denote derivatives (e.g., $C_q = \partial C/\partial q_i$ and $C_{qq} = \partial^2 C/\partial q_i^2$). We also assume that $P(0) - C_q(0, x)$ is sufficiently large and $C_x(q, 0)$ is sufficiently small. Additionally, $|C_{qx}|$ and $|e_{qx}|$ are sufficiently small relative to C_{qq}, C_{xx}, e_{qq}, or e_{xx}. These assumptions ensure that the solutions remain interior and stable, with second-order conditions satisfied. These are standard assumptions in the literature (Carraro and Soubeyran, 1996).

The government imposes a per-unit emissions tax $t \geq 0$, which is given exogenously.[5] The profit function of firm i is defined by $\pi_i := P(Q)q_i - C(q_i, x_i) - te(q_i, x_i)$, where $Q := \sum_{i=1}^n q_i$ is the total output. Let superscript $*$ denote the symmetric equilibrium outcomes. The equilibrium outputs $(q^*(t), x^*(t))$ are characterized by the following first-order conditions:

$$\frac{\partial \pi_i}{\partial q_i} = P'(nq^*)q^* + P(nq^*) - C_q - te_q = 0, \quad (1)$$

$$\frac{\partial \pi_i}{\partial x_i} = -C_x - te_x = 0, \quad (2)$$

where the second-order conditions are satisfied based on the assumptions of P and C.

Subsequently, we investigate the marginal effect of the tax rate on firm profits when the target emission level is approximately zero. If a slight reduction in the tax rate improves the firm's profit, the firm is willing to lobby for reducing the tax rate. By contrast, if a marginal decrease in the tax rate reduces the firm's profit, the firm is more likely to accept such tax rates rather than resist them.

[5]This assumption implies that the emissions tax is beyond the regulators' control. Several scenarios are consistent with this assumption. First, taxation measures can be implemented at the supranational level, such as within the European Union (Petrakis and Poyago-Theotoky, 2002). Another interpretation relates to the emissions permit program, whereby firms must pay a price t for all emissions, with no free quota. In the program, the tax rates (permit prices) are not allowed to be industry specific. Third, although the government may want to select a welfare-maximizing emissions tax (Ino and Matsumura, 2021; Xu et al., 2022), firms' lobbying activities prevent the government from setting such rates (Hirose et al., 2024).

3 Results

Let $e^*(t) := e(q^*(t), x^*(t))$ be the emission level in the symmetric equilibrium and $E^*(t) := ne^*(t)$ be the equilibrium total emission level. The standard application of the implicit function theorem shows that q^* decreases with t and x^* increases with t, which implies that E^* decreases with t.

Let t^0 denote the emissions tax yielding net-zero emissions (i.e., $E^*(t^0) = 0$). We present our main result.

Proposition 1 *The firm's equilibrium profit strictly increases with t at $t = t^0$ if and only if $n > 1$.*

Proof We have

$$\frac{d\pi^*}{dt} = \frac{\partial \pi_i}{\partial q^*}\frac{dq^*}{dt} + \frac{\partial \pi_i}{\partial x^*}\frac{dx^*}{dt} + \frac{\partial \pi_i}{\partial t} = (n-1)P'(nq^*)q^*\frac{dq^*}{dt} - e(q^*, x^*), \tag{3}$$

where the second equality is due to (1) and (2). Because $e(q^*, x^*) = 0$ at $t = t^0$, we obtain

$$\left.\frac{d\pi^*}{dt}\right|_{t=t^0} = (n-1)P'q^*\left.\frac{dq^*}{dt}\right|_{t=t^0}, \tag{4}$$

which is strictly positive if and only if $n > 1$. ■

The right-hand side of equation (3) captures the trade-off between the positive and negative effects of taxation on the profit. The first term $(n-1)P'(nq^*)q^*(dq^*/dt)$ describes the moderation of market competition through increasing the emissions tax. A marginal increase in the tax rate increases the marginal costs for all the firms. Therefore, given the existence of rival firms, the market competition is moderated by an increase in the tax rate, which has a positive effect on the firm's profit. Obviously, this effect exists whenever there are rival firms. The second term $e(q^*, x^*)$ describes the increase in tax payments. Nevertheless, when the resulting emissions approach zero, the tax base also approaches zero, making the marginal increase in tax payment negligible. Consequently, except in the monopoly case, the first effect dominates the second, and a marginal increase in the emissions tax rate from the zero-emissions tax is always profitable for each firm.

The right-hand sides of equations (3) and (4) indicate that the positive effect of an increase in the tax rate on profits is not necessarily limited to the net-zero-emissions regulation. Because the right-hand side of (4) is strictly positive and continuous with respect to t, a decrease in t may reduce industry profits, even when t is not close to t^0 (or equivalently, E^* is not close to 0). This argument can be further clarified by specifying the functional forms. We discuss this point in the next section.

4 Parametric analysis

In this section, we consider a standard parametric setup as follows: $P = a - bQ$, $C(q_i, x_i) = cq_i + \gamma x_i^2/2$, and $e = \kappa q_i - x_i$, where a, b, c, γ, and κ are positive constants and $a > c$.

4.1 Emission tax pass-through

First, we investigate how competitiveness influences the impact of a tax change on prices. Let

$$\rho := \left.\frac{dP/dt}{P}\right|_{t=t^0}$$

be the *emission tax pass-through semi-elasticity* when the tax rate is the zero-emission level, which may be interpreted as the strength of the price-raising effect of increasing the tax rate.[6]

Lemma 1 *ρ increases with n.*

Proof See Appendix.

[6] The pass-through semi-elasticity is used, like pass-through rate, to capture the impact of taxes. For example, Adachi and Fabinger (2017) examine the ad valorem pass-through semi-elasticity under a general oligopoly setting.

Lemma 1 demonstrates that an increase in n strengthens the price-raising effect of the emissions tax.

4.2 From laissez-faire to taxation

We next investigate a relationship between the profit-enhancing tax rate and the laissez-faire emission level. Let $\overline{E}(n)$ denote the equilibrium emissions level when $t = 0$ (i.e., the laissez-faire emission level). The following proposition provides a condition under which the profit increases with the tax rate.

Proposition 2 *(i) The firm's profit increases with t if and only if*

$$E^*(t) < E^P(n) := \frac{(a-c)n(n-1)\kappa}{b(1+n)^2 + 2\gamma\kappa^2}.$$

(ii) $E^P(n) < \overline{E}(n)$. (iii) $E^P(n)$ and $E^P(n)/\overline{E}(n)$ increase with n. (iv) $E^P(n)/\overline{E}(n) \to 1$ as $n \to \infty$.

Proof See Appendix.

Proposition 2 suggests that the positive effect of taxation on profits is amplified by increasing the number of firms. Note that E^P is the threshold emission level, below which a further reduction in the target emission level by an increase in t increases the industry profits. An increase in the emissions tax enhances firms' profits when the targeted emission-reduction level from the laissez-faire emission level is greater than $100(1-\theta)\%$, where

$$\theta := \frac{E^P(n)}{\overline{E}(n)} = \frac{b(n-1)(1+n)}{b(n+1)^2 + 2\gamma\kappa^2}. \tag{5}$$

Then, the size of the profit-enhancing range is measured by θ. As Proposition 2(iii) states that θ increases with n, the profit increases with t as long as there are many firms in the market.

The following numerical examples indicate that an increase in the tax rate may enhance profits even if n is not so large. Consider a numerical example where $b = 1$, $\gamma = 1$, and

$\kappa = 1$. Figure 1 illustrates the relationship between θ and n. As $\theta \simeq 0.27$ for $n = 2$, an increase in the emissions tax rate enhances the duopolists' profits if the targeted emission reduction from the laissez-faire emission level is greater than 73%. This percentage is lower when the number of firms is greater than two: 56% for $n = 3$ and 20% for $n = 10$.

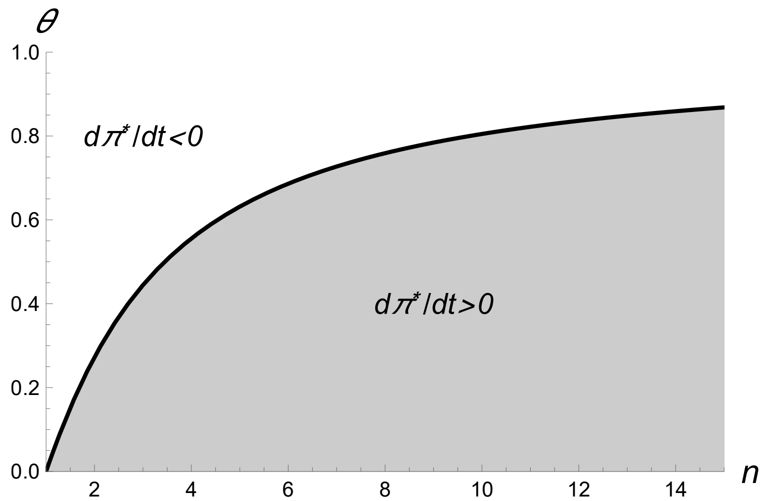


Figure 1: Profit-enhancing range

These numbers are plausible. For instance, the Japanese government committed to net-zero emissions by 2025 on October 26 in 2020. Before that, the Japanese government was less ambitious in its emissions reduction goals, committing to the 80% reduction of CO2 emissions by 2050 from emissions in 2013.[7] Given the oligopolistic nature of the heavy-emissions industries, this numerical exercise derives a realistic target level.

4.3 Taxation for net-zero emissions

We now discuss how a change in the tax rate to zero emission level influences the profit. Let t^X denote the emissions tax yielding emissions $E^*(t^X) = X\overline{E}(n)$, where $X \in [0, 1]$. Then,

[7]https://www.enecho.meti.go.jp/about/whitepaper/2021/html/1-2-0.html.

from (20) in the appendix, we obtain

$$t^X = \frac{\gamma((a-c)n\kappa - b(1+n)X\bar{E})}{n(b(1+n)+\gamma\kappa^2)}.$$

Suppose that the government changes the emissions target from $X\overline{E}(n)$ to zero, so that the tax rate increases from t^X to t^0. Then, the rate of change in profit is

$$\frac{\pi^*(n,t^0)}{\pi^*(n,t^X)} = \frac{b(n+1)^2\left(2b+\gamma\kappa^2\right)}{2b^2(n+1)^2 + b\gamma\kappa^2(n+1)\left(n(1-X)^2+(X+1)^2\right)+2\gamma^2\kappa^4X^2}.$$

From this, we see that the tax change from t^X to t^0 increases profits if and only if $\pi^*(n,t^0)/\pi^*(n,t^X) > 1$, or equivalently

$$X < \frac{2b(n^2-1)}{b(n+1)^2+2\gamma\kappa}.$$

As the right-hand side is increasing in n, the tax change to t^0 tends to be profitable when there are many firms in the industry.

Figure 2 illustrates the relationship between X and $\pi^*(n,t^0)/\pi^*(n,t^X)$ in the case with $b=1$, $\kappa=1$, and $\gamma=1$ and 7. As Figure 2 demonstrates, the rate of change in profit is greater than 1 as long as n is sufficiently large.

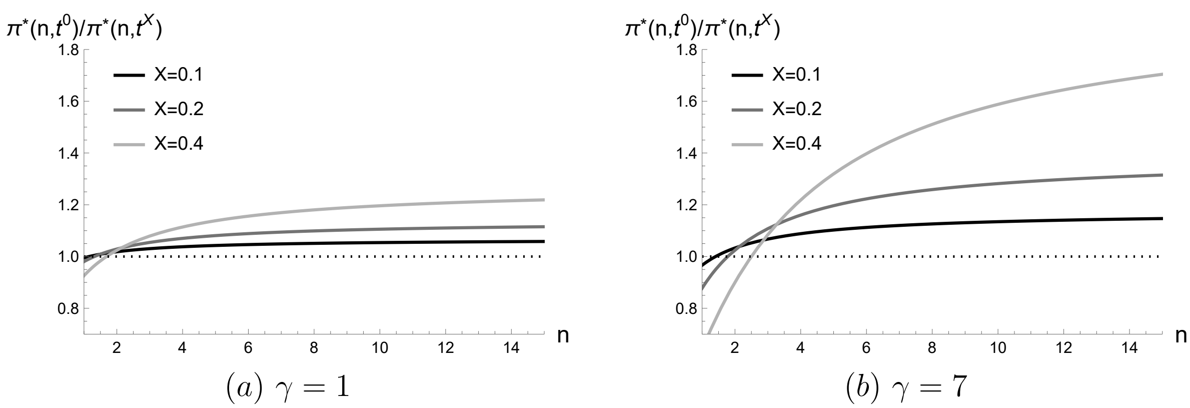
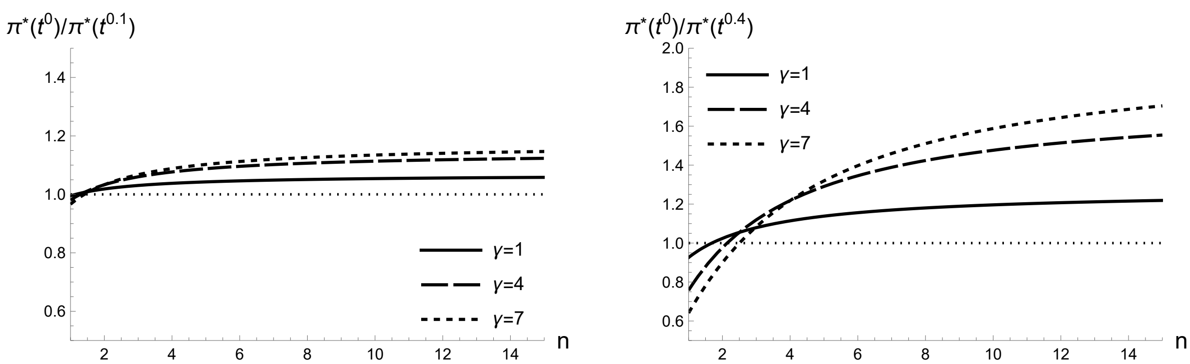


Figure 2: Profit-enhancing impacts

Comparing the diagrams in Figure 2 suggests another important implication regarding the parameter of abatement costs γ. The range in which the profit is enhanced by targeting zero emissions shrinks with a larger γ. Nevertheless, the profit-enhancing effect itself can be greater when γ is larger.

Figure 3 highlights this point. In both diagrams ($X = 0.1$ and 0.7), the range in which $\pi^*(n, t^0)/\pi^*(n, t^X) > 1$ is smaller when $\gamma = 7$ than when $\gamma = 1$. Nevertheless, given that n is sufficiently large, the rate of change $\pi^*(n, t^0)/\pi^*(n, t^X)$ itself is rather greater when $\gamma = 7$ than when $\gamma = 1$.

The interpretation is as follows. Higher abatement costs lead to the higher emissions tax ensuring the target emission level. Thus, the target emission level is less likely to reach profit-enhancing emission level when γ is larger. However, once the target emission level reaches the critical level, a further reduction of emissions caused by a higher emissions tax more significantly enhances firms' profits, because competition is more restricted owing to the higher emissions tax when γ is larger. Therefore, a larger γ has a more significant impact on profits, especially when n and X are large.[8]



$(a)\ X = 0.1$ $(b)\ X = 0.4$

Figure 3: Profit-enhancing impacts and X

[8]We obtain a similar implication regarding parameter κ. The profit-enhancing range shrinks with a larger κ, whereas the profit-enhancing effect can be greater when κ is larger. The intuition behind these results are common with the results on γ.

5 Competition mode

In the previous analysis, we assume quantity competition (Cournot competition) with homogeneous goods. In this section, we consider differentiated goods and compare quantity competition and price competition (Bertrand competition).

We adopt a standard duopoly model with differentiated goods and linear demand (Dixit,1979; Singh and Vives, 1984). The quasi-linear utility function of the representative consumer is

$$U(q_i, q_j, y) = \alpha(q_i + q_j) - \frac{\beta}{2}(q_i^2 + 2\delta q_i q_j + q_j^2) + y, \tag{6}$$

where q_i is the consumption of good i produced by the firm i and y is the consumption of an outside good provided competitively (with a unitary price). Parameters α and β are positive constants and $\delta \in (0, 1)$ reflects the degree of product differentiation (a larger δ represents a smaller degree of product differentiation). The direct and inverse demand functions for goods $i = 1, 2$ with $i \neq j$ are, respectively,

$$\hat{q}_i(p_i, p_j) := \frac{\alpha(1-\delta) - p_i + \delta p_j}{\beta\,(1-\delta^2)} \quad \text{and} \quad \hat{p}_i(q_i, q_j) := \alpha - \beta q_i - \beta\delta q_j, \tag{7}$$

where p_i is the price of firm i. We adopt the same functional forms except for the demand function as those in Section 4. Note that the assumption made in Section 2 implies $\alpha > c$.

5.1 Bertrand competition

Under Bertrand competition, each firm i independently chooses $(p_i,\ x_i)$ to maximize its profit $\pi_i^B := p_i\hat{q}_i(p_i, p_j) - C(\hat{q}_i(p_i, p_j), x_i) - te(\hat{q}_i(p_i, p_j), x_i)$. The first-order conditions for firm i are

$$\frac{\partial \pi_i^B}{\partial p_i} = \frac{\alpha(1-\delta) - 2p_i + \delta p_j}{\beta\,(1-\delta^2)} + \frac{c}{\beta\,(1-\delta^2)} + \frac{\kappa t}{\beta\,(1-\delta^2)} = 0, \tag{8}$$

$$\frac{\partial \pi_i^B}{\partial x_i} = -\gamma x_i + t = 0. \tag{9}$$

Let superscript B denote the equilibrium outcomes under Bertrand competition. From the first-order conditions, we have

$$\begin{aligned} p^B &= \frac{\alpha - \alpha\delta + c + \kappa t}{2-\delta},\ x^B = \frac{t}{\gamma},\ e^B = \frac{\gamma\kappa(\alpha - c) - \beta\left(-\delta^2 + \delta + 2\right)t - \gamma\kappa^2 t}{\beta\gamma(2-\delta)(\delta\ +1)}, \\ \pi^B &= \frac{2\gamma(\alpha - c - \kappa t)^2 + \beta(\delta+2)^2 t^2}{2\beta\gamma(\delta+2)^2}. \end{aligned} \tag{10}$$

Let t^{0B} be the emissions tax rates yielding net-zero emissions under Bertrand competition. By using $e^B = 0$, we obtain the zero-emissions tax under Bertrand competition

$$t^{0B} = \frac{\gamma\kappa(\alpha - c)}{\beta\left(2 + \delta - \delta^2\right) + \gamma\kappa^2}.$$

5.2 Cournot competition

Next, consider Cournot competition. Each firm i independently chooses (q_i,x_i) to maximize its profit $\pi^C := \hat{p}_i(q_i, q_j)q_i - C(q_i, x_i) - te(q, x_i)$. The first-order conditions for firm i are

$$\frac{\partial \pi_i^C}{\partial q_i} = \alpha - c - \beta\left(q_i + \delta q_j\right) - \beta q_i - \kappa t = 0, \tag{11}$$

$$\frac{\partial \pi_i^C}{\partial x_i} = -\gamma x_i + t = 0. \tag{12}$$

Let superscript C denote the equilibrium outcomes under Cournot competition. From the first-order conditions, we have

$$\begin{aligned} q^C &= \frac{\alpha - c - \kappa t}{\beta\delta + 2\beta},\ x^C = \frac{t}{\gamma},\ e^C = \frac{\kappa(\alpha - c - \kappa t)}{\beta(\delta+2)} - \frac{t}{\gamma}, \\ \pi^C &= \frac{2\gamma(-\alpha + c + \kappa t)^2 + \beta(\delta+2)^2\ t^2}{2\beta\gamma(\delta+2)^2}. \end{aligned} \tag{13}$$

Let t^{0C} be the emissions tax rates yielding net-zero emissions under Cournot competition. By using $e^C = 0$, we obtain the zero-emissions tax under Cournot competition

$$t^{0C} = \frac{\gamma\kappa(\alpha - c)}{\beta(\delta+2) + \gamma\kappa^2}.$$

5.3 Comparison

As in Section 4, the emission tax pass-through semi-elasticity is

$$\rho^B := \left.\frac{dp^B/dt}{p^B}\right|_{t=t^{0B}} = \frac{\kappa\left(\beta\left(-\delta^2+\delta+2\right)+\gamma\kappa^2\right)}{(2-\delta)\left(\alpha\gamma\kappa^2+\beta(\delta+1)(\alpha-\alpha\delta+c)\right)}, \tag{14}$$

$$\rho^C := \left.\frac{dp^C/dt}{p^C}\right|_{t=t^{0C}} = \frac{(\delta+1)\kappa\left(\beta(\delta+2)+\gamma\ \kappa^2\right)}{(2+\delta)\left(\alpha\left(\beta\ +\gamma\kappa^2\right)+\beta c(\delta+1)\right)}, \tag{15}$$

and the derivative of the profit with respect to t at the zero-emissions tax, interpreted as the profit-enhancing effect, is

$$\xi^B := \left.\frac{d\pi^B}{dt}\right|_{t=t^{0B}} = \frac{(\alpha-c)\delta\kappa}{(2-\delta)\left(\beta\left(2+\delta-\delta^2\right)+\gamma\kappa^2\right)}, \tag{16}$$

$$\xi^C := \left.\frac{d\pi^C}{dt}\right|_{t=t^{0C}} = \frac{(\alpha-c)\delta\kappa}{(2+\delta)\left(\beta(\delta+2)+\gamma\kappa^2\right)}. \tag{17}$$

We also obtain the profit-enhancing range measurements as

$$\theta^B = \frac{\beta(2-\delta)\delta(\delta+1)}{\beta(\delta+1)(2-\delta)^2+2\gamma(1-\delta)\kappa^2}, \tag{18}$$

$$\theta^C = \frac{\beta\delta(\delta+2)}{\beta(\delta+2)^2+2\gamma\kappa^2}. \tag{19}$$

First, we show the comparative statics result with respect to δ.

Proposition 3 *For each $\ell = B, C$, (i) ρ^ℓ increases with δ, and (ii) θ^ℓ increases with δ.*

Proof See Appendix.

Proposition 3(i) implies that the price-raising effect of the emissions tax is stronger when the degree of product differentiation is smaller. Proposition 3(ii) means that firms' profits are more likely to improve when the degree of product differentiation is smaller. Recall that in the previous sections, we show that the price-raising effect of the emissions tax is stronger and θ is larger when the number of firms is larger. An increase in the number of firms is interpreted as tougher competition among firms. Similarly, a smaller degree of product differentiation accelerates competition and strengthens the profit-enhancing effect of the emissions tax. Proposition 3 illuminates that this mechanism works regardless of whether the firms compete in price or quantity.

Next, we demonstrate the comparison of the effects as follows.

Proposition 4 *(i)* $\rho^B > \rho^C$. *(ii)* $\xi^B > \xi^C$. *(iii)* $\theta^B > \theta^C$.

Proof See Appendix.

Proposition 4(i) and (ii) suggest that the price-raising and profit-enhancing effects of the emissions tax are stronger under Bertrand competition than under Cournot competition when the resulting emission level in the industry is close to zero. Proposition 4(iii) implies that firms' profits are more likely to improve under Bertrand competition than under Cournot competition. Similar to Proposition 3, these results may be interpreted from the view point of the degree of the market competitiveness. According to Singh and Vives (1984), Bertrand competition is more competitive than Cournot competition. Recall that in the previous sections, we show that the price-raising effect of the emissions tax is stronger and θ is larger when the market is more competitive in the sense that the number of firms is larger. Proposition 4 is consistent with this interpretation, and suggests that our results do not depend on the specific competition mode (Cournot competition with homogeneous goods).[9]

6 Concluding remarks

This study examines the relationship between emissions taxes and firm profits. Many countries have expressed intent to realize a net-zero-emissions society, making a reduction of emission levels in high-emissions industries to net zero inevitable. This study demonstrates that in near-zero-emissions industries, a marginal increase in the tax rate enhances firms'

[9]However, a larger number of firms and a change of competition model from Cournot to Bertrand could have opposite implications, and thus, we think that this robustness check is important. For an example yielding opposite implications, see Matsumura et al. (2025), in which common ownership is less likely to improve welfare when the number of firms is larger while common ownership is more likely to improve welfare under Bertrand competition than under Cournot competition.

profits, except for monopoly industries. This profit-enhancing effect is stronger when market competition is tougher. We show this outcome by investigating how the number of firms, the degree of product differentiation, and the competition mode affect the profit-enhancing effect. We also present examples indicating that the profit-enhancing ranges are large.

This study assumes that firms maximize their own profits. However, the literature on environmental policies has paid attention to non-profit maximizing actions, such as environmental corporate social responsibility and collusive preference caused by overlapping ownership structure, reflecting recent changes in financial markets.[10] A systematic analysis of this issue should be considered in future research.

[10]The literature on the relationship between non-profit-maximizing objectives and environmental problems has become popular and diverse. For recent discussions on this topic, see Bárcena-Ruiz et al. (2017, 2023), Fukuda and Ouchida (2020), Hirose et al. (2020), Hirose and Matsumura (2022, 2023), Tomoda and Ouchida (2023), Xu et al. (2022), and Xing and Lee (2024a,b).

Appendix

Proof of Proposition 2

(i) From (1) and (2), we obtain

$$q^*(t) = \frac{a-c-\kappa t}{(1+n)b},\ x^*(t) = \frac{t}{\gamma},\ \pi^*(t) = \frac{2\gamma(a-c-\kappa t)^2 + b(1+n)^2t^2}{2b(1+n)^2\gamma}. \tag{20}$$

Differentiating the profit function, we obtain

$$\frac{d\pi^*}{dt} = \frac{-4\gamma\kappa(a-c-\kappa t) + b(1+n)^2 t}{2b(1+n)^2\gamma}, \tag{21}$$

where $d\pi^*/dt > 0$ if and only if

$$t > \frac{2(a-c)\gamma\kappa}{b(1+n)^2 + 2\gamma\kappa^2} =: t^P. \tag{22}$$

From (20) and t^P, we obtain the total emission at $t = t^P$

$$E^P(n) := ne^*(t^P) = \frac{(a-c)n(n-1)\kappa}{b(1+n)^2 + 2\gamma\kappa^2}. \tag{23}$$

Using (22), (23), and $dE^*(t)/dt < 0$, $d\pi^*/dt > 0$ holds if and only if $E^*(t) < E^P(n)$. ■

(ii) From (20) and $t = 0$, we obtain

$$\overline{E}(n) = \frac{\kappa(a-c)n}{b(1+n)}. \tag{24}$$

Hence, we have:

$$\overline{E}(n) - E^P(n) = \frac{2(a-c)n\kappa\left(b(1+n) + \gamma\kappa^2\right)}{b(1+n)\left(b(1+n)^2 + 2\gamma\kappa^2\right)} > 0. \ ■$$

(iii) We have:

$$\frac{dE^P(n)}{dn} = \frac{\kappa(a-c)\left(b\left(3n^2+2n-1\right) + 2\gamma\kappa^2(2n-1)\right)}{\left(b(n+1)^2 + 2\gamma\kappa^2\right)^2} > 0. \tag{25}$$

We also have

$$\frac{E^P(n)}{\overline{E}(n)} = \frac{b(n-1)(1+n)}{b(n+1)^2 + 2\gamma\kappa^2}. \tag{26}$$

Differentiating this with respect to n yields

$$\frac{d(E^P(n)/\overline{E}(n))}{dn} = \frac{2b\left(b(n+1)^2 + 2\gamma\kappa^2 n\right)}{\left(b(n+1)^2 + 2\gamma\kappa^2\right)^2} > 0. \blacksquare$$

(iv) We have

$$\lim_{n\to\infty} E^P(n) = \lim_{n\to\infty} \overline{E}(n) = \frac{(a-c)\kappa}{b}. \blacksquare$$

Proof of Lemma 1

We obtain

$$\frac{d\rho}{dn} = \frac{a\left(b^2\kappa(n+1)^2 + b\gamma\kappa^3\left(n^2+2n+2\right) + \gamma^2\kappa^5\right) - bc\gamma\kappa^3 n^2}{(n+1)^2\left(a\left(b+\gamma\kappa^2\right) + bcn\right)^2} > 0. \blacksquare$$

Proof of Proposition 3

Under the Bertrand competition, differentiating the profit function, we obtain (12) and (14). It is also routine to calculate (16).

Under the Cournot competition, differentiating the profit function, we obtain (13) and (15). It is also routine to calculate (17).

The proof of Proposition 3 is completed by deriving the derivative as follows:

$$\begin{aligned}
\frac{d\rho^B}{d\delta} &= \frac{\alpha\left(\beta^2\left(2+\delta-\delta^2\right)^2\kappa + \gamma^2\kappa^5\right) + \beta\gamma\left(2\alpha(1-\delta^2) + \alpha - c + 2(\alpha + c\delta)\right)\kappa^3}{(2-\delta)^2\left(\alpha\left(\beta - \beta\delta^2 + \gamma\kappa^2\right) + \beta c(\delta+1)\right)^2} > 0, \\
\frac{d\theta^B}{d\delta} &= \frac{2\beta\left(\beta\left(2+\delta-\delta^2\right)^2 + 2\gamma\left(\delta(1-\delta)^2+1\right)\kappa^2\right)}{\left(\beta(2-\delta)^2(\delta+1) - 2\gamma(1-\delta)\kappa^2\right)^2} > 0, \\
\frac{d\rho^C}{d\delta} &= \frac{\alpha\left(\beta^2\left(2+\delta\right)^2\kappa + \gamma^2\kappa^5\right) + \beta\gamma\left((1+\delta)^2(\alpha-c) + 2\alpha(\delta+2)\right)\kappa^3}{(2+\delta)^2\left(\alpha\left(\beta+\gamma\kappa^2\right) + \beta c(\delta+1)\right)^2} > 0, \\
\frac{d\theta^C}{d\delta} &= \frac{2\beta\left(\beta\left(2+\delta\right)^2 + 2\gamma\left(1+\delta\right)\kappa^2\right)}{\left(\beta(2+\delta)^2 + 2\gamma\kappa^2\right)^2} > 0. \blacksquare
\end{aligned}$$

Proof of Proposition 4

By (12) and (13),

$$\rho^B - \rho^C = \frac{\delta^2\kappa\left(\alpha\left(\beta^2\left(4-\delta^2\right)(1+\delta)+\beta\gamma\left(3+\delta(1-\delta)\right)\kappa^2+\gamma^2\kappa^4\right)+\beta c\gamma(\delta+1)\kappa^2\right)}{(2-\delta)(\delta+2)\left(\alpha\beta\left(1-\delta^2\right)+\alpha\gamma\kappa^2+\beta c(\delta+1)\right)\left(\alpha\left(\beta+\gamma\kappa^2\right)+\beta c(\delta+1)\right)} > 0.$$

Since the denominator in (14) is smaller than in (15), we obtain $\xi^B > \xi^C$. Finally, from (16) and (17), we have

$$\theta^B - \theta^C = \frac{2\beta\delta^2\left(\beta\left(4-\delta^2\right)(1+\delta)+2\gamma\kappa^2\right)}{\left(\beta(\delta+2)^2+2\gamma\kappa^2\right)\left(\beta(\delta+1)(2-\delta)^2+2\gamma(1-\delta)\kappa^2\right)} > 0. \blacksquare$$

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