Optimality of Emission Pricing Policies Based on Emission Intensity Targets under Imperfect Competition*

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Abstract

This study proposes a policy solution for negative environmental externality in oligopoly markets, in the form of an emission tax based on emission intensity targets. Emissions are taxed when firms' emission intensities exceed their targeted levels. We show that even under imperfect competition, this emission pricing policy leads to the first-best outcome. The optimal uniform tax rate is equal to the Pigovian level. We also discuss how to test the optimal non-uniform target levels. This principle can also apply to tradable emission permits traded based on emission intensity targets.

Keywords: optimal taxation, environmental regulation, Cournot competition, Bertrand competition, renewable portfolio standard

JEL Classification: Q58, Q48, H23, L51

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1 Introduction

Since Pigou's (1932) seminal work, it is well known that in perfectly competitive markets, the optimal emission tax rate on a harmful emission is equal to the marginal environmental damage caused by the emission, and that this tax policy leads to the first-best optimality. The tax that internalizes the negative externality of emission is known as "Pigovian tax." In imperfectly competitive markets, however, this Pigovian tax is not optimal (Buchanan, 1969; Barnett, 1980; Misiolek, 1980; Baumol and Oates, 1988). In a monopoly market, the monopolist's production level falls short of the optimal. To mitigate the welfare loss due to suboptimal production level, the emission tax rate in monopoly markets should be lower than the Pigovian rate. However, this low tax rate distorts the incentive for the monopolists' emission abatement activities, and thus reduces welfare. Therefore, the first-best optimality is not achieved by the emission tax (the second-best optimality). Recently, Fowlie et al. (2016) estimated and structurally simulated the welfare impacts of the Pigovian (first-best) level of carbon pricing in the US cement industry (a typical imperfectly competitive market), and showed that its impact on total welfare is negative and substantial.[1] This evidence implies that it is important to mitigate the welfare loss caused by market power when the emission is priced.

The result that the second-best tax rate is lower than its Pigovian counterpart may not hold in oligopoly markets. Levin (1985) showed that market power can exacerbate the negative externality in the asymmetric Cournot model and Simpson (1995) showed that the optimal tax rate can be higher than the Pigovian if firms are asymmetric and the degree of heterogeneity among firms is large. The latter result was derived because distribution of production among firms as well as the total production level affect welfare when firms are asymmetric. A higher tax rate induces production substitution from the firm with inferior emission abatement technology to the firms with superior emission abatement technology, thus improving welfare.[2] However, whether the optimal tax rate

[1] Welfare loss occurs when the social cost of carbon is below \$40 per ton of CO_2; the magnitude is over \$10 billion when the social cost of carbon is \$30 (see Fig 4B in their paper).

[2] For the general principle of welfare-improving production substitution, see also Lahiri and Ono

is higher or lower than the Pigovian, the optimal level intricately depends on abatement technologies and the individual demands of firms. Moreover, the first best is not achieved by the emission tax policy.[3]

In this study, we propose a new policy solution for oligopoly markets, an emission pricing policy based on emission intensity targets. Governments impose a firm-specific emission intensity (emission per output) target on each firm. Firms that fall short of the target pay the emission tax (or procure emission permits) according to the extent of shortfall, and firms that overachieve the target receive the subsidy (or can sell emission permits). We show that the Pigovian tax, whose rate is the marginal environmental damage, leads to the first-best optimality under imperfect competition when each firm's tax base is appropriately adjusted by its emission intensity target. Although the optimal target levels will be non-uniform among firms if the firms are asymmetric, they do not depend on emission functions and can be tested by the market and government information.

The first-best optimality is shown because this pricing policy can be viewed as the policy combination of emission tax and emission intensity regulation. Emission intensity regulation has a production expansion effect (Holland et al., 2009; Ino and Matsumura, 2019).[4] The production reduction effect by the Pigovian tax can be offset by choosing adequate emission intensity targets.[5] In other words, our policy provides enough instruments working in combination. An emission tax works to derive pollution levels; setting each different intensity target is therefore enough to effectively correct each firm's output level.

(1988).

[3]Even if firms are symmetric, the optimal tax rate can be higher and lower than the Pigovian tax in free-entry markets. See Katsoulacos and Xepapadeas (1995) and Lee (1999). Nonetheless, the first best is not achieved in their models.

[4]Holland et al. showed that a limit on the carbon intensity (low carbon fuel standard) may increase total energy because of the production expansion effect, and calibrated the model to understand the realistic impacts of the standard. Ino and Matsumura showed that the production expansion effect of emission intensity regulation is equivalent to the effect of refunding emission tax revenue to consumers generally.

[5]For the general property of emission intensity regulation, see Helfand (1991), Farzin (2003), and Lahiri and Ono (2007). Bőhringer *et al.* (2017) showed the difficulty inherent to the efficient implementation of emission intensity regulation.

Our result suggests that governments can set the tax rate to be the marginal social cost of the emission (Pigovian tax) without taking into account the competition structure of each market. The government can consider industry- or firm-specific conditions only at the stage of imposing emission intensity targets, rather than at the point of choosing the tax rate.

Both emission pricing policies (such as environmental taxes or tradable permit policies) and emission intensity regulations are widely observed (Helfand, 1991, Bushnell et al., 2017). For example, the Japanese government imposes environmental taxes as well as emission intensity targets in Japanese energy markets, which are typical oligopoly markets. In addition, several intensity regulations are imposed as per the Energy Conservation Act, such as the Japanese Act of the Rational Use of Energy enacted in 1979 (Matsumura and Yamagishi, 2017). In the literature, many works have compared emission pricing policies and emission intensity regulation policies in various contexts such as in free-entry markets and non-free-entry markets, in open economies and closed economies, and so on. It is known that under perfect competition, the emission pricing policy leads to the first-best outcome whereas the emission intensity regulation does not (Holland et al., 2009; Holland, 2012). However, under imperfect competition, the emission intensity regulations may be superior to the emission pricing policies for welfare, which become the second-best policies[6] (Besanko, 1987; Helfand, 1991; Montero, 2002; Lahiri and Ono; 2007; Kiyono and Ishikawa, 2013; Amir et al., 2018; Hirose and Matsumura, 2020). In contrast, we show the first-best optimality of the combination of two such standard policies.

Our principle can also apply to portfolio standard policies such as renewable portfolio standards (RPS), which have been introduced in the electricity markets of many countries. In an electricity market, the government can regulate the ratio of zero-emission or renewable power sources, and then open the markets to trading quotas or introduce

[6] Fowlie et.al (2016) also empirically measured the welfare impacts of the policy that allocates free permits in proportion to production, and showed that the policy improves welfare substantially. This result is consistent with the theory of the second best.

taxes. Similarly, the government can set the ratio of zero-emission or ultra-low emission vehicles in the vehicle manufacturing industry. If a firm does not meet (overachieves) the target, the firm must buy (sell) the permits or pay (receive) the tax. If the marginal social damage due to the use of non-renewable power sources or gasoline and diesel vehicles equals the price of the quotas or tax, the first-best optimum can be achieved with appropriate targets.[7]

The remainder of this paper is organized as follows. Section 2 formulates the basic model in a homogeneous product market. Section 3 presents our main result and derives the optimal levels of emission tax and intensity targets. Section 4 discusses the two problems in implementing the policy, the ways in which governments can test the optimality of the intensity target levels and the possibility that the tax revenue obtained from the optimal policy is negative. Section 5 presents two applications for the tradable permit market across industries and for the portfolio standards. Section 6 concludes this paper. In the appendix, we provide a theoretical extension on quantity and price competition with product differentiation.

2 The model

We consider an oligopoly market wherein $n \in \mathbb{N}$ firms choose their outputs (Cournot competition) and emission abatement levels. This study focuses on the problem between negative externality and market power and thus assumes a market with no uncertainty and with no other market distortions such as any pre-existing distortional taxes on inputs and outputs. For $i = 1, \ldots, n$, $q_i \in \mathbb{R}_+$ is firm i's output, and $a_i \in \mathbb{R}_+$ is the level of firm i's abatement activity. The firms' products are homogeneous, and the inverse

[7] The Japanese government set up such schemes in energy markets. The government introduced targets pertaining to zero-emission power source ratios and a trading quota in the electric power market. It assigned different targets among firms, and a common price is imposed on all firms in the trading market (Advisory Committee for Natural Resources and Energy, Ministry of Economy, Trade, and Industry, 2019). The Zero-Emission Vehicle (ZEV) Program in California also uses a similar pricing mechanism. This program was introduced as part of a California state regulation that requires automakers to sell zero-emission vehicles such as electric or fuel cell vehicles in California and 10 other states, and the required number of zero-emission vehicles is linked to the automaker's overall sales of gasoline and diesel vehicles within the state (`https://ww2.arb.ca.gov/our-work/programs/zero-emission-vehicle-program`).

demand function is $p(Q)$, where $Q = \sum_{i=1}^{n} q_i$. We assume that $p(Q)$ is twice continuously differentiable and $p'(Q) < 0$ for all Q as long as $p > 0$. Firm i's cost function is $c_i(q_i, a_i)$. We assume that $c_i(q_i, a_i)$ is twice continuously differentiable, $\partial c_i/\partial q_i > 0$, $\partial c_i/\partial a_i > 0$,[8] and that the function is convex. Firm i's emission function is $e_i(q_i, a_i)$. We assume that $e_i(q_i, a_i)$ is twice continuously differentiable, $\partial e_i/\partial q_i > 0$ and $\partial e_i/\partial a_i < 0$, and that the function is convex. The social welfare is defined by

$$W = \int_0^Q p(q)dq - \sum_{i=1}^{n} c_i(q_i, a_i) - D\left(\sum_{i=1}^{n} e_i(q_i, a_i)\right),$$

where $D(\cdot)$ is the environmental damage function, which is twice continuously differentiable and convex, and $D' > 0$. Note that the first term in this definition includes both consumer surplus and the revenues of the firms. We assume a unique interior social optimum and market equilibrium.[9]

We denote the outcomes at the social optimal by the superscript o. Assuming the interior solution (i.e., $q_i^o > 0$ and $a_i^o > 0$), the first-order conditions for the welfare-maximizing problem are

$$p(Q^o) = \frac{\partial c_i}{\partial q_i}(q_i^o, a_i^o) + D'(E^o)\frac{\partial e_i}{\partial q_i}(q_i^o, a_i^o), \tag{1}$$

$$-D'(E^o)\frac{\partial e_i}{\partial a_i}(q_i^o, a_i^o) = \frac{\partial c_i}{\partial a_i}(q_i^o, a_i^o), \tag{2}$$

where $E^o = \sum_{i=1}^{n} e_i^o$ with $e_i^o = e_i(q_i^o, a_i^o)$. The second-order conditions are satisfied.

3 Optimal policy

We consider the following emission intensity targets, $(\theta_1, \ldots, \theta_n) \in \mathbb{R}_+^n$. Firm i's emission intensity e_i/q_i is targeted by the government as $\theta_i = e_i/q_i$. If firm i emits over (below) this level, or in other words, $e_i > \theta_i q_i$ ($e_i < \theta_i q_i$), it pays (receives) the tax (subsidy) for the difference. Firm i's profit maximization problem is described as

$$\max_{q_i, a_i} \; p(Q)q_i - c_i(q_i, a_i) - t[e_i(q_i, a_i) - \theta_i q_i], \tag{3}$$

[8] We relax this assumption in Section 5.2.

[9] A sufficient condition for the uniqueness is that $p'' \leq 0$, and e_i and c_i are strictly convex.

where $t \in \mathbb{R}_+$ is the tax (subsidy) level.[10]

We denote the outcomes at the market equilibrium by the superscript $*$. Assuming the interior solution (i.e., $q_i^* > 0$ and $a_i^* > 0$), the first-order conditions for firm i are

$$\begin{aligned} p'(Q^*)q_i^* + p(Q^*) + t\theta_i &= \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) + t\frac{\partial e_i}{\partial q_i}(q_i^*, a_i^*), \quad (4) \\ -t\frac{\partial e_i}{\partial a_i}(q_i^*, a_i^*) &= \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*). \quad (5) \end{aligned}$$

We assume that the second-order conditions are satisfied.[11]

By comparing (4)–(5) with (1)–(2), we obtain the optimal levels of the emission tax and emission intensity targets as

$$t^o = D'(E^o) > 0,\ \theta_i^o = -\frac{p'(Q^o)q_i^o}{D'(E^o)} > 0. \quad (6)$$

Proposition 1 *Suppose the Cournot oligopoly in a homogeneous product market that is presented here. There exists* $(\theta_1, \ldots, \theta_n)$ *such that the policy attains the first-best optimality (i.e.,* $q_i^* = q_i^o$ *and* $a_i^* = a_i^o$*) if and only if the tax rate is Pigovian (i.e.,* $t = D'(E^o)$*).*

Proof. For sufficiency, suppose that $t = t^o$ and set $(\theta_1, \ldots, \theta_n) = (\theta_1^o, \ldots, \theta_n^o)$ as defined in (6). Substitute (6) into the market conditions (4) and (5). Then, by (1) and (2), we find that (4) and (5) are satisfied when $q_i^* = q_i^o$ and $a_i^* = a_i^o$.

To prove necessity, we show the contraposition. Suppose that $t \neq D'(E^o)$ and take $(\theta_1, \ldots, \theta_n)$ arbitrarily. Then, by (5) and (2),

$$\frac{\partial c_i(q_i^*, a_i^*)/\partial a_i}{\partial e_i(q_i^*, a_i^*)/\partial a_i} = -t \neq -D'(E^o) = \frac{\partial c_i(q_i^o, a_i^o)/\partial a_i}{\partial e_i(q_i^o, a_i^o)/\partial a_i}.$$

Therefore, (q_i^*, a_i^*) never equates to (q_i^o, a_i^o) since the first and last terms are not equal. **Q.E.D.**

[10] Alternatively, the government may measure the obedience of the firm based on its emission intensity. If firm i's realized emission intensity e_i/q_i is above (below) the regulated level θ_i, i.e., $e_i/q_i > \theta_i$ ($e_i/q_i < \theta_i$), it is penalized (rewarded) by the rate tq_i (i.e., t per production q_i) for the difference $e_i/q_i - \theta_i$.

[11] A sufficient condition for it is $p'' \leq 0$.

The emission pricing policy based on emission intensity targets attains the first-best outcome in an oligopoly market. Moreover, the optimal tax rate is the traditional Pigovian level, that is, the marginal environmental damage at the optimal level of total emission. Emission intensity regulation gives producers an incentive to expand their production to relieve the regulatory constraint (Ino and Matsumura, 2019). Adjusting for this production expansion effect, the firm-specific emission intensity target can cancel out the effect of each firm's market power (and as a result, promote consumption). Thus, the emission tax can uniformly correct the negative externality at the Pigovian level. In the appendix, we show that this result is robust even under more general oligopoly markets including product differentiation and price competition.

As an important application of the intensity-based emission tax provided here, we can replace the emission tax with tradable emission permits. If a market exists for tradable permits across industries, the government can achieve the first best as long as firms are price takers in the tradable permit market. We formally discuss this application in Section 5.1. As stated in Introduction, our principle can also apply to portfolio standard policies. We formally discuss this application in Section 5.2.

We should remark that it is not as easy to implement our policy as the theory suggests. In discussing this problem, it is useful to clarify the advantages and disadvantages of the intensity-based emission tax to the second-best emission tax policy. The second-best emission tax policy is given by solving[12]

$$\max_t \ W^* = \int_0^{Q^*} p(q)dq - \sum_{i=1}^{n} c_i(q_i^*, a_i^*) - D\left(\sum_{i=1}^{n} e_i^*\right),$$

with assuming $\theta_i = 0$, where $e_i^* = e_i(q_i^*, a_i^*)$. From the first-order condition of this

[12]We assume a uniform tax t, that is, we do not allow firm-specific emission tax t_i. In this sense, the optimal emission tax considered here may be the third best. Note that for the intensity-based emission tax, the optimal tax level is uniform, i.e., $t_i = D'$ for all i, even if we take firm specific emission taxes into consideration.

problem, the second-best emission tax t^{oo} must satisfy[13]

$$t^{oo} = D'(E^*) + p'(Q^*)\frac{\sum_{i=1}^n q_i^* dq_i^*/dt}{\sum_{i=1}^n de_i^*/dt}, \tag{7}$$

where $E^* = \sum_{i=1}^n e_i^*$.[14]

Remark 1 When firms are asymmetric, the government should set n emission intensity targets. This is because in order to attain the first-best outcomes, the policy requires $n+1$ policy instruments for fixing one negative externality and the market power of n firms. Thus, if too many and too wide a variety of firms are in the market, the government faces an informational problem for setting intensity targets. However, we have to note that this informational problem is not unique to our policy since the required informational components in (6), D', p', and q_i, are also included in the second-best policy (7). Further, our policy does not require the estimation of dq_i^*/dt and dE^*/dt as in (7). Thus, the optimal levels of the targets may be tested more easily than the second-best policy in some methods, even in asymmetric cases. We discuss these methods in Section 4.1.

Remark 2 To correct the market power along with the externality, the government must provide some subsidy to mitigate the penalty to consumers. However, institutionally and politically, it is difficult to explicitly subsidize monopolists.[15] The second-best emission tax could avoid this problem by reducing the tax level from the first and implicitly subsidizing the firms by this reduction, which is equal to the second term in the left-hand side on (7). Similarly, intensity-based emission tax could avoid the problem by reducing the tax *base* from the first. This reduction is expressed by $\theta_i q_i$ in (3) and

[13] If the firms are identical, the expression is reduced to

$$t^{oo} = D'(E^*) + p'(Q^*)q_i^* \frac{dq_i^*/dt}{de_i^*/dt},$$

which is the well-known formula in the literature. See Barnett (1980) for the monopoly case (i.e., $n = 1$ and thus, $q_i^* = Q^*$). See Ebert (1991/2) and Katsoulacos and Xepapadeas (1996) for the extension to the symmetric oligopoly case.

[14] Note that this equation is not an explicit solution for t^{oo} since the market equilibrium outcomes on the right-hand side also depend on t^{oo}. In contrast, for the intensity-based emission tax, (6) is the explicit solution evaluated by the social optimal outcomes.

[15] "The environmental agency, however, will typically have neither the authority nor the inclination to offer subsidies to monopolists" (Baumol and Oates, 1988, p.82).

implicitly subsidizes the firms by $t\theta_i q_i$. However, even in these policies, if the tax revenue becomes negative, the included subsidy is no more "implicit" and would be difficult to implement institutionally and politically. In particular, because our policy attains the first-best outcomes, it is expected that the tax revenue is smaller than the second-best policy. We discuss this problem in Section 4.2 by simulating the tax revenue of our policy. Consequently, if the abatement cost is low, the market is highly concentrated, and the environmental damage is insignificant, then the tax revenue might be negative.

These two remarks suggest to us that our intensity-based policy would work well in the industries in which the number of firms is neither too large (i.e., not close to a perfectly competitive market) nor too small (i.e., not close to a monopoly market), such as the cement, automobile, and electric power industries.

4 Consideration for implementation

4.1 Testing the optimal levels of emission intensity

The government may be aware of the optimal emission price, $d = D'(E^o)$, and imposes the emission tax according to this level ($t = d$). However, the government needs to set the optimal target levels of emission intensity $(\theta_1^o, \ldots, \theta_n^o)$. In order to test whether the targets are optimal or not, two approaches may be used: (i) the conventional approach following Lerner's (1934) rule, which relates to the demand elasticity, and (ii) the new approach following Weyl and Fabinger's (2013) idea, which relates to the pass-through rate. The government can check the optimality of θ_i by testing whether Eq. (8) or (9) is satisfied or not.

Lerner's approach If θ_i is optimal for $i = 1, 2..., n$, the market outcomes are consistent to the social optimal, $q_i^* = q_i^o$ and $a_i^* = a_i^o$, as seen in Proposition 1. Thus, using the well-known Lerner's rule, (6) yields

$$\theta_i = -\frac{p^*}{d}\left(\frac{dp}{dQ}\frac{Q^*}{p^*}\right)\frac{q_i^*}{Q^*} = -\frac{p^*}{d}\frac{s_i^*}{\epsilon^*}, \tag{8}$$

where $p^* = p(Q^*)$ is the market price, $\epsilon^* = (p^*/Q^*)/(dp/dQ)$ is the market demand elasticity, and $s_i^* = q_i^*/Q^*$ is the market share of the firm i at equilibrium. Note that the data for p^* and s_i^* are available in the current market, and ϵ^* can be estimated under a sufficient volatility in market prices and quantities.

If all firms are symmetric, then $s_i = 1/n$. Then, the above equation implies that $\lim_{n\to\infty} \theta_i^o = 0$. In other words, if the market is sufficiently competitive, the optimal policy converges to traditional Pigovian tax.

Weyl and Fabinger's approach Weyl and Fabinger (2013) argued that the pass-through rate of tax is an important and a tractable welfare indicator under imperfect competition. The pass-through rate is observed or estimated by measuring the change in the market price (market information) when a tax rate (government information) is altered. Therefore, from an empirical point of view, it is useful to characterize the economic effects using such measurable indicators.[16] Following their spirit and decomposing the second equation in (6), if the given levels of θ_i's are optimal, it must be satisfied that

$$\theta_i = -\frac{dp^*/dt}{t}\frac{q_i^*}{dQ^*/dt}, \tag{9}$$

where dp^*/dt and dQ^*/dt approximate the ratio of the differences in the market price and the market size (market information) to the difference in our tax level (government information), respectively.[17] Thus, if we have sufficient experience in policy alteration or related data, we can test whether (9) is satisfied.

4.2 Tax revenue

To discuss whether the tax revenue generated by our intensity-based emission tax is positive or negative, we provide a simulation by specifying the functions in this subsection.

Suppose that $p(Q) = Y - Q$ and $D(E) = dE$ where $Y > 0$, $d > 0$, and $Y > d$. Consider that the firms are symmetric and assume $c_i(q_i, a_i) = n\alpha a_i^2/2$ where $\alpha > 0$ and

[16] Using this idea, Weyl and Fabinger (2013) investigated tax incidence, and Häckner and Herzing (2016) studied the marginal cost of public funds. Adachi and Fabinger (2017) extended these ideas to quite general oligopoly models.

[17] If we adopt the tradable permit scheme, the tax level is replaced by the price of the permits.

	social optimal	market equilibrium
output	$q^o = \frac{Y-d}{n}$	$q^* = \frac{Y-t(1-\theta)}{n+1}$
abatement	$a^o = \frac{d}{n\alpha}$	$a^* = \frac{t}{n\alpha}$

Table 1: Optimal and Market outcomes

$e_i(q_i, a_i) = q_i - a_i$. In other words, the marginal cost of production $\partial c_i/\partial q_i$ is constant and normalized to zero. Each firm's abatement cost is proportional to the number of firms, n. We adopt this setting because in this formulation, the industry abatement cost, $nc_i(q, a) = \alpha A^2/2$ (and thus its marginal cost αA), is independent of n and depends on the aggregate abatement $A = na$ only.

Denoting $(q_i^o, a_i^o) = (q^o, a^o)$ and $(q_i^*, a_i^*) = (q^*, a^*)$ under $\theta_i = \theta$ by symmetry, we have the social optimal and market equilibrium outcomes as in Table 1. By (6), the optimal policy levels are

$$t^o = d,\ \theta_i^o = \frac{Y-d}{nd}.$$

Under this optimal policy set, we obtain $(q^*, a^*) = (q^o, a^o)$ as shown in Proposition 1.

The tax revenue under this optimal policy set, TR^o, is calculated as

$$\begin{aligned} TR^o &= \sum_{i=1}^{n} t^o[e_i(q_i^*, a_i^*) - \theta_i^o q_i^*] \\ &= nt^o[e_i(q^o, a^o) - \theta_i^o q^o] \\ &= d\left[Y - \frac{(\alpha+1)d}{\alpha} - \frac{(Y-d)^2}{nd}\right]. \end{aligned} \tag{10}$$

In the last line, the sign of the terms in the brackets determines whether TR^o is positive or negative. Thus, what reduces the tax revenue is represented by the second and third terms in the brackets. The second term is related to the abatement cost α, the third term is related to the number of firms n, and both terms are affected by d.

Abatement cost Because the term $(\alpha+1)d/\alpha$ in (10) decreases in α, the tax revenue increases in α. Panels A, B, C, and D in Figure 1 depict the cases when $n = 1$, $n = 2$, $n = 3$, and $n = 4$, respectively. As seen here, the tax revenue is more likely to be positive when the abatement is less efficient (i.e., α is larger).

Note that when $\alpha \to \infty$, the tax revenue under our intensity-based policy converges to that under the second-best emission tax t^{oo}. More concretely, from (7), t^{oo} satisfies

$$t^{oo} = d - \frac{Y - t^{oo}}{n+1} \frac{n\alpha}{n\alpha + n + 1}, \tag{11}$$

since $q^* = (Y - t)/(n+1)$ and $a^* = t/(n\alpha)$ are derived by assuming $\theta = 0$ in Table 1 and $e_i^* = q^* - a^*$. This yields the second-best level t^{oo} as

$$\begin{aligned} t^{oo} &= \frac{\{nd - (Y-d)\}n\alpha + d(n+1)^2}{n^2\alpha + (n+2)n + 1} \\ &\to d - \frac{Y-d}{n} \qquad (\text{as } \alpha \to \infty). \end{aligned}$$

Thus, it can be seen that the tax revenue under the second-best emission tax, $TR^{oo} = \sum_{i=1}^{n} t^{oo} e_i^*$ converges as

$$TR^{oo} = nt^{oo}\left(\frac{Y-t}{n+1} - \frac{t^{oo}}{n\alpha}\right) \to d\left[Y - d - \frac{(Y-d)^2}{nd}\right] \qquad (\text{as } \alpha \to \infty),$$

where the last expression is equal to $\lim_{\alpha\to\infty} TR^o$ by (10).

Figure 2 depicts how TR^o converges to TR^{oo} by extending the rage of α (horizontal axis) of Figure 1. The dotted lines are the graphs of TR^{oo}. If α is large, then TR^o is close to TR^{oo}. In this respect, if the second-best taxation is realistic, so is the intensity-based taxation. However, it should be noted that when α is small, as seen in the figure, TR^o can be substantially smaller than TR^{oo}. As a result, we have a case where TR^{oo} is not but TR^o is negative.

The number of firms Because the term $(Y-d)^2/nd$ in (10) decreases in n,[18] the tax revenue increases in n. Panels A, B, C, and D in Figure 3 depict the cases when $\alpha = 2$, $\alpha = 4$, $\alpha = 6$, and $\alpha = 8$, respectively.[19] As seen here, the tax revenue can be negative; it is more likely to be positive when the market is more competitive (i.e., n is larger). For instance in the simulation results, duopoly or triopoly is enough to make TR^o positive.

[18]Note that when $n \to \infty$, this term converges to 0 and thus, TR^o converges to $d[(Y-d) - d/\alpha]$. This is consistent with the first-best tax revenue that is obtained from the perfectly competitive market under $t = d$ and $\theta = 0$.

[19]In these cases, the ratio of abatement given by a^o/q^o are approximately 33%, 17%, 11%, and 8% (75%, 38%, 25%, and 19%) when $d = 2$ ($d = 3$), respectively.

Therefore, both abatement cost and competition positively affect tax revenue. Because of the latter effect of competition, the graphs of TR^o shift upward when we compare Panels B to A, C to B, and so on in Figure 1. Similarly, because of the former effect of the abatement cost, the graphs of TR^o shift upward when we compare Panels B to A, C to B, and so on in Figure 3

Environmental damage Interestingly, as for the environmental damage d, the term $(\alpha + 1)d/\alpha$ in (10) increases in d but the term $(Y - d)^2/nd$ decreases in d. While environmental damage amplifies the effect of the abatement cost, it diminishes the effect of competition. Thus, whereas the graphs in Figure 1 shift upward (downward) for *higher* d when α is relatively large (small) given n, the graphs in Figure 3 shift upward (downward) for *lower* d when n is relatively large (small) given α.

Hence, as seen in Figure 4, the tax revenues are not monotone but are inverted U-shaped in d. On the one hand, if d is close to 0, since the tax payment of a firm is $t(e_i - \theta_i q_i) \to p' q_i$ under the optimal policy, our policy becomes a set of pure subsidies fixing the market power of oligopolists. Thus, when environmental damage is insignificant,[20] the tax revenue is small and tends to be negative. On the other hand, if d is close to Y, since $t(e_i - \theta_i q_i) \to -da_i$ by $q_i \to 0$ under the optimal policy, our policy becomes pure subsidy for abatement activity. Thus, when environmental damage is significant,[21] the tax revenue also tends to be negative.

5 Applications

5.1 Tradable permit market based on emission intensity targets

In this subsection, we replace the emission tax with the tradable emission permits.

There are $N \in \mathbb{N}$ industries, each of which replicates[22] the Cournot competition

[20]For instance, when $d = 1$, the ratio of abatement a^o/q^o are approximately 12.5% for $\alpha = 2$, 6.3% for $\alpha = 4$, 4.2% for $\alpha = 6$, and 3.1% for $\alpha = 8$.

[21]For instance, when $d = 4$, the ratio of abatement a^o/q^o are about 200% for $\alpha = 2$ (including absorption), 100% for $\alpha = 4$, 67% for $\alpha = 6$, and 50% for $\alpha = 8$.

[22]This assumption is for notational simplicity, and we can easily extend the analysis here to the case with asymmetric industries.

of n firms, which is presented in Section 2. We denote each variable in the industry $j = 1, 2, \ldots, N$ by superscript j. The social welfare is modified by

$$W = \sum_{j=1}^{N} \left(\int_0^{Q^j} p(q)dq - \sum_{i=1}^{n} c_i(q_i^j, a_i^j) \right) - D \left(\sum_{j=1}^{N} \sum_{i=1}^{n} e_i(q_i^j, a_i^j) \right).$$

Since the outcomes at the social optimal are the same across the industries by symmetry, we drop superscript j from them. The first-order conditions for the welfare-maximizing problem are (1) and (2), where $E^o = N \sum_{i=1}^{n} e_i^o$ with $e_i^o = e_i^o(q_i^o, a_i^o)$. The second-order conditions are satisfied.

Consider the market for tradable permits across industries. We assume that the number of firms $n \times N$ is sufficiently large for the behavior of each firm to approximate a price taker in the permit market. The government sets emission intensity targets, $(\theta_1, \ldots, \theta_n) \in \mathbb{R}_+^n$, and if a firm does not meet (overachieves) its target, the firm must purchase (can sell) permits. The profit maximization problem of firm i in industry j is described as

$$\max_{q_i^j, a_i^j} \; p(Q^j)q_i^j - c_i(q_i^j, a_i^j) - r[e_i(q_i^j, a_i^j) - \theta_i q_i^j],$$

where $r \in \mathbb{R}_+$ is the price of the permits.

Dropping superscript j by symmetry, the first-order conditions for firm i are

$$p'(Q^*)q_i^* + p(Q^*) + r\theta_i = \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) + r\frac{\partial e_i}{\partial q_i}(q_i^*, a_i^*), \quad (12)$$

$$-r\frac{\partial e_i}{\partial a_i}(q_i^*, a_i^*) = \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*). \quad (13)$$

Further, the market clear condition of the permit market is

$$N \sum_{i=1}^{n} [e_i(q_i^*, a_i^*) - \theta_i q_i^*] = E_G, \quad (14)$$

where $E_G \in \mathbb{R}$ is the amount of permits that the government sells.[23] We assume a unique equilibrium price for the permit market.

[23] If E_G is negative, the government purchases $-E^G$ from the market. If E_G is positive, the government may allocate E_G among firms instead of selling quota in the permit market. As for the sign of E_G at the optimal level, see Remark 3 below.

Suppose that the government sets the level of θ_i as

$$\theta_i^o = -\frac{p'(Q^o)q_i^o}{D'(E^o)} > 0, \tag{15}$$

and adjusts E_G as

$$E_G^o = N\sum_{i=1}^{n}(e_i^o - \theta_i^o q_i^o) = N\left[E^o + \sum_{i=1}^{n}\frac{p'(Q^o)(q_i^o)^2}{D'(E^o)}\right]. \tag{16}$$

We show that this policy combination makes the equilibrium price of permits r^* equal to the social marginal cost of emission and achieves the first-best outcome.

Proposition 2 *Suppose the N Cournot oligopolies in homogeneous product markets that are presented here. Assume that the firms are price takers in the tradable permit market. Then, the tradable permit market based on the emission intensity target presented by (15)–(16) attains the first-best optimality (i.e., $q_i^* = q_i^o$ and $a_i^* = a_i^o$) under $r^* = D'(E^o)$.*

Proof. Suppose that $r = D'(E^o) > 0$ under the targets (15). Then, by the optimal conditions (1)–(2), the market conditions (12)–(13) are satisfied with $q_i^* = q_i^o$ and $a_i^* = a_i^o$. Hence, if $r = D'(E^o)$, we have $q_i^* = q_i^o$ and $a_i^* = a_i^o$, and thus, $e_i^* = e_i^o$. Then, it must be held that

$$N\sum_{i=1}^{n}[e_i(q_i^*, a_i^*) - \theta_i q_i^*] = N\sum_{i=1}^{n}(e_i^o - \theta_i^o q_i^o) = E_G^o,$$

where the first equality is derived from $\theta_i = \theta_i^o$ and $e_i^* = e_i^o$, and the second one, from (16). Therefore, if $r = D'(E^o)$, the market clear condition (14) is satisfied, that is, $r^* = D'(E^o)$. **Q.E.D.**

The key assumption of this result is that firms are price takers in the permit market. To restrict the market power in the permit market, it is important to create a common permit market across industries and/or regions and provide incentives for a sufficiently large number of firms to join this market. One idea for that is making an oligopoly industry to which our intensity-based permit trading is applied join in the general permit market where the other firms have already been trading competitively. Another idea relates to government monitoring, which restricts firms' market power in the permit market.

Remark 3 At the optimal policy levels, the government's revenue obtained from selling the permits is $(r^* E_G^o)/N = \sum_{i=1}^n d(e_i^o - \theta_i^o q_i^o)$ per industry by (16) and $r^* = d$, where $d = D'(E^o)$. This revenue is equal to that obtained from the optimal intensity-based emission tax discussed in Sections 3. Since the sign of E_G^o follows the sign of the revenue, it can be negative as discussed in Section 4.2. If E_G^o is negative, the government has to commit to purchase the amount $-E^G$ from the market to induce firms to overachieve.

5.2 Portfolio standards

As stated previously, our principle can apply to portfolio standard policies. Examples of portfolio standard policies are RPS, which was introduced in many countries, the zero-emission power plant regulation in the Japanese electricity market, and the ZEV Program in California. To show the efficiency and limitation of portfolio standard policies, we investigate a green portfolio standard in the electricity market.

Suppose the electricity that each firm i produces, namely q_i, is decomposed into the brown output $b_i \geq 0$ and the green output $g_i \geq 0$ as $q_i = b_i + g_i$. The brown output is the electricity produced by non-green power sources such as fossil-fired power plants. Green output is the electricity produced by green power sources such as renewable power plants. We assume that the brown power sources yield negative externality, and the welfare loss is denoted by $D(B)$ with $D' > 0$ and $D'' \geq 0$, where $B = \sum_{i=1}^n b_i$.

The government regulates the ratio of green output as

$$\frac{g_i}{q_i} \geq 1 - \theta_i \;\Leftrightarrow\; \frac{b_i}{q_i} \leq \theta_i \quad \therefore (1-\theta_i) b_i \leq \theta_i g_i.$$

Firms that fall short of the green output targets pay the fee (or procure permits) according to the level of shortage, and firms that overachieve the targets receive the subsidy (or sell permits). Firm i's profit is

$$p(Q) q_i - \gamma_i(b_i, g_i) + \beta_i(b_i, g_i) - t((1-\theta_i) b_i - \theta_i g_i),$$

where γ_i is the production cost function, which is convex and satisfies $\partial \gamma_i / \partial b_i > 0$ and $\partial \gamma_i / \partial g_i > 0$. β_i is the private benefit function from the green output. We assume that

$\beta_i(b_i, g_i)$ is concave and satisfies $\partial\beta_i/\partial b_i \leq 0$ and $\partial\beta_i/\partial g_i \geq 0$. A firm may be able to sell green electricity at a price higher than the market price (the green electricity premium).[24] If the green electricity premium is $\beta > 0$ per green power output, then $\beta_i(b_i, g_i) = \beta g_i$.

If we regard $a_i = g_i$, $e_i(q_i, a_i) = q_i - a_i = b_i$, and $c_i(q_i, a_i) = \gamma_i(b_i, g_i) - \beta_i(b_i, g_i)$, the framework presented here becomes a special case of our basic model except for three minor points. Then, the analyses in the previous sections can be applied to this portfolio standard policy, and the first best is achieved by the policy. The three differences between the model in this subsection and the basic model are discussed below.

First, regarding the cost function, we drop the assumption that $\partial c_i/\partial a_i > 0$ when a_i is small, and assume that $\partial c_i/\partial a_i > 0$ only for a sufficiently large a_i. Indeed, even under this extension, our analyses in the previous sections are robust.[25] The assumption $\partial c_i/\partial a_i > 0$ is not natural for the portfolio standards model. Because $c_i(q_i, a_i) = \gamma_i(q_i - a_i, a_i) - \beta_i(q_i - a_i, a_i)$, we obtain $\partial c_i/\partial q_i = \partial\gamma_i/\partial b_i - \partial\beta_i/\partial b_i > 0$ and

$$\frac{\partial c_i}{\partial a_i} = \left(\frac{\partial \gamma_i}{\partial g_i} - \frac{\partial \gamma_i}{\partial b_i}\right) - \left(\frac{\partial \beta_i}{\partial g_i} - \frac{\partial \beta_i}{\partial b_i}\right).$$

Thus, $\partial c_i/\partial q_i$ is positive but $\partial c_i/\partial a_i$ can be negative if $\partial\beta_i/\partial g_i - \partial\beta_i/\partial b_i > 0$ is large. Moreover, even if $\beta_i = 0$, $\partial c_i/\partial a_i$ can be negative, especially for small a_i. The first parenthesis can be negative if γ_i is strictly convex, because for a given q_i, a marginal shift from b_i to g_i saves a cost if $\partial\gamma_i/\partial g_i < \partial\gamma_i/\partial b_i$. Therefore, we should allow that $\partial c_i(q_i, a_i)/\partial a_i < 0$, especially when a_i/q_i or g_i/b_i is small.

Second, in this subsection's model, we must assume that $g_i \leq q_i$ (i.e., $e_i = b_i \geq 0$). If $\lim_{g_i \to q_i} \partial(\gamma_i - \beta_i)/\partial g_i$ is sufficiently large, this constraint does not bind, and the earlier analyses can be applied as well. However, this case excludes the possibility of a 100% renewable electricity player, and it might be too restrictive.[26] If $\partial(\gamma_i - \beta_i)/\partial g_i$ is small for any g_i, it is possible that $g_i = q_i$ (i.e., $b_i = 0$) is the optimal abatement level.

[24] For example, Tokyo Electric Power Company sells the electricity produced from hydropower at a premium.

[25] This is because it is necessary to satisfy $\partial c_i/\partial a_i > 0$ at the interior equilibrium by the first-order condition with respect to a_i. Thus, the range $\partial c_i/\partial a_i < 0$ is irrelevant to the analyses.

[26] Electricity markets contain 100% renewable electricity players. The vehicle manufacturing industry contains companies that only manufacture electrical vehicles, such as Tesla and many small Chinese manufactures.

Thus, we should consider the possible corner solution. The first-order conditions for the welfare-maximizing problem under the constraint $a_i \le q_i$ are[27]

$$p(Q^o) - \frac{\partial c_i}{\partial q_i}(q_i^o, a_i^o) - D'(E^o) + \lambda_i^o = 0, \tag{17}$$

$$D'(E^o) - \frac{\partial c_i}{\partial a_i}(q_i^o, a_i^o) - \lambda_i^o = 0, \tag{18}$$

$$\lambda_i^o \ge 0,\ q_i^o - a_i^o \ge 0,\ \lambda_i^o(q_i^o - a_i^o) = 0, \tag{19}$$

where we use $\partial e_i/\partial q_i = 1$ and $\partial e_i/\partial a_i = -1$ in this model. The first-order conditions for a profit-maximizing problem of firm i under the constraint $a_i \le q_i$ are[28]

$$p'(Q^*)q_i^* + p(Q^*) + t\theta_i - \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) - t + \lambda_i^* = 0, \tag{20}$$

$$t - \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*) - \lambda_i^* = 0, \tag{21}$$

$$\lambda_i^* \ge 0,\ q_i^* - a_i^* \ge 0,\ \lambda_i^*(q_i^* - a_i^*) = 0. \tag{22}$$

Note that λ^o and λ^* are the Lagrange multipliers. Comparing (17)–(19) and (20)–(22), we find that the first best is achieved if the government chooses

$$t^o = D'(E^o) > 0,\ \theta_i^o = -\frac{p'(Q^o)q_i^o}{D'(E^o)} > 0. \tag{23}$$

The final difference relates to the range of θ_i. In the portfolio standard case, it is realistic to assume that $\theta_i \in [0, 1]$, not $\in [0, \infty)$. From the expression θ_i^o in (23), as long as $D'(B^o) \ge -p'q_i^o$ for all i (i.e., the negative externality of non-green sources is large, or the output of each firm is small), this constraint is not binding, and the portfolio standard policy yields the first-best outcome. However, if the negative externality of non-green sources is small, or there exists a dominant firm with a large q_i^o in the market, this constraint can bind, and thus, the efficient outcome is not achieved by the portfolio standard policy. Therefore, the portfolio standard policy might not be optimal if the negative externality is insignificant and the market is highly concentrated.

[27] From the concavity of welfare, these are necessary and sufficient conditions for the global maximum.

[28] Since the (global) second-order condition in the unconstrained case implies the concavity of the profit, these first-order conditions are necessary and sufficient conditions.

6 Concluding remarks

In this study, we showed that the first-best optimality is achieved by the combination of two traditional and standard policy tools, emission tax (or tradable permit) and emission intensity targets. In other words, uniform emission pricing policies based on non-uniform emission intensity targets yield the first-best outcomes. The literature on environmental tax shows that Pigovian tax internalizing the negative externality yields the first best under perfect competition, whereas it does not under imperfect competition. We proposed a new policy solution under imperfect competition, a tax on emissions intensity above targets, leading to the first best. We also showed that the first-best tax rate will never be other than the Pigovian tax rate in our policy.

Emission taxes and tradable permits were intensively discussed in the context of carbon pricing, and many countries have introduced one of the two to mitigate global warming. Emission intensity regulations are also widely observed. Emission taxes raise the marginal cost of production and increase the distortion of suboptimal production under imperfect competition. Emission intensity regulation serves to stimulate production and mitigates the problem of insufficient production. Thus, the policy combination of two standard and widespread environmental policies is ideal.

Our model assumed that the number of firms is exogenous. If we consider the free-entry market, the first best will not be achieved by the combination of emission tax and emission intensity targets. However, if we introduce the appropriate level of entry license tax, the first-best optimality will be achieved by our policy.

In this study, we focused on imperfect competition and ignored other possible distortions that would put the economy back into a second-best world. For instance, we did not consider pre-existing distortions from other taxes on labor, capital, or output, which are intensively discussed in the literature. We also did not consider any kind of uncertainty. However, in the context of global warming, uncertainties with regard to the supply side, demand side, and social costs of emissions are quite important. Our analysis should be extended in these directions in future research.[29]

Appendix

Product differentiation and Bertrand competition

We extend the basic model in Section 2 by considering an oligopoly market wherein each firm $i = 1, \ldots, n$ produces differentiated products and chooses its output q_i (Cournot competition) or its price p_i (Bertrand competition) along with its abatement level a_i. Let $\mathbf{q} = (q_1, q_2, \ldots, q_n)$ and $\mathbf{p} = (p_1, p_2, \ldots, p_n)$. Again, we assume a unique interior social optimum and market equilibrium.

Demand system Following Vives (1999),[30] we formulate the demand system, which is obtained by the representative consumer's problem, as follows:

$$\max_{\mathbf{q}} U(\mathbf{q}) - \mathbf{pq},$$

where U is the sub-utility function for these n products. We assume that the Hessian of U is negative definite (U is strictly concave). From the first-order conditions for $q_i > 0$,

$$p_i = \frac{\partial U}{\partial q_i}(\mathbf{q}) \qquad i = 1, \ldots, n, \tag{24}$$

that is, we obtain the inverse demand system, $\mathbf{p}(\mathbf{q}) = (p_1(\mathbf{q}), p_2(\mathbf{q}), \ldots, p_n(\mathbf{q}))$. From the strict concavity of U, the demands are downward-sloping (i.e., $\partial p_i/\partial q_i < 0$ for all i), and the system can include both the substitute goods case (i.e., $\partial p_i/\partial q_j \leq 0$ for $j \neq i$) and the complement goods case (i.e., $\partial p_i/\partial q_j \geq 0$). Because the Jacobian of $\mathbf{p}(\mathbf{q})$ (the Hessian of U), which is denoted as $D\mathbf{p}$, is negative definite, $\mathbf{p}(\mathbf{q})$ is one-to-one by the

[29] Ellerman and Sue Wing (2003) established an important contribution in this context. They considered a macro-level emission cap and considered absolute and intensity-based emission caps, which were indexed to the gross domestic product (GDP). They showed the equivalence of absolute and intensity-based emission caps without the uncertainty in the GDP, and the equivalence result did not hold with uncertainty. Their results suggest the importance of uncertainty. Their result differs from ours because they examined macro-level caps and considered efficient carbon pricing policies to achieve this goal under perfect competition. However, we discussed how an efficient outcome may be achieved under imperfect competition.

[30] See Chapter 6. The model is a partial equilibrium model based on quasi-linear utility.

Gale–Nikaido theorem. Thus, as the inverted system of $\mathbf{p}(\mathbf{q})$, we can obtain the direct demand system $\mathbf{q}(\mathbf{p}) = (q_1(\mathbf{p}), q_2(\mathbf{p}), \ldots, q_n(\mathbf{p}))$.

Social optimal The social welfare is defined by

$$W = U(\mathbf{q}) - \sum_{i=1}^{n} c_i(q_i, a_i) - D\left(\sum_{i=1}^{n} e_i(q_i, a_i)\right).$$

Assuming the interior solution (i.e., $q_i^o > 0$ and $a_i^o > 0$), the first-order conditions for the welfare-maximizing problem are

$$\begin{aligned} \frac{\partial U}{\partial q_i}(\mathbf{q}^o) &= \frac{\partial c_i}{\partial q_i}(q_i^o, a_i^o) + D'(E^o)\frac{\partial e_i}{\partial q_i}(q_i^o, a_i^o), && (25) \\ -D'(E^o)\frac{\partial e_i}{\partial a_i}(q_i^o, a_i^o) &= \frac{\partial c_i}{\partial a_i}(q_i^o, a_i^o), && (26) \end{aligned}$$

where $\mathbf{q}^o = (q_1^o, q_2^o, \ldots, q_n^o)$ and $E^o = \sum_{i=1}^{n} e_i(q_i^o, a_i^o)$. The second-order conditions are satisfied. Let $\mathbf{p}^o = \mathbf{p}(\mathbf{q^o})$ and then, $\mathbf{q}(\mathbf{p^o}) = \mathbf{q}^o$ by the definition of inverse demand.

Cournot competition First, we consider the Cournot competition. Under the emission intensity targets, $(\theta_1, \ldots, \theta_n) \in \mathbb{R}_+^n$, firm i's profit maximization problem is

$$\max_{q_i, a_i} \; p_i(\mathbf{q})q_i - c_i(q_i, a_i) - t[e_i(q_i, a_i) - \theta_i q_i].$$

Assuming the interior solution (i.e., $q_i^* > 0$ and $a_i^* > 0$), the first-order conditions for firm i are

$$\begin{aligned} \frac{\partial p_i(\mathbf{q}^*)}{\partial q_i}q_i^* + p_i(\mathbf{q}^*) + t\theta_i &= \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) + t\frac{\partial e_i}{\partial q_i}(q_i^*, a_i^*), && (27) \\ -t\frac{\partial e_i}{\partial a_i}(q_i^*, a_i^*) &= \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*), && (28) \end{aligned}$$

where $\mathbf{q}^* = (q_1^*, q_2^*, \ldots, q_n^*)$. We assume that the second-order conditions are satisfied. Note that $p_i(\mathbf{q}^*) = \partial U(\mathbf{q}^*)/\partial q_i$ by (24). Thus, by comparing (27)–(28) with (25)–(26), we obtain the optimal policy levels as

$$t^o = D'(E^o) > 0, \;\; \theta_i^o = -\frac{q_i^o}{D'(E^o)}\frac{\partial p_i(\mathbf{q}^o)}{\partial q_i} > 0. \tag{29}$$

Bertrand competition Next, we consider the Bertrand competition. Under the emission intensity targets, $(\theta_1, \ldots, \theta_n) \in \mathbb{R}^n_+$, firm i's profit maximization problem is

$$\max_{p_i, a_i} \; p_i q_i(\mathbf{p}) - c_i(q_i(\mathbf{p}), a_i) - t[e_i(q_i(\mathbf{p}), a_i) - \theta_i q_i(\mathbf{p})].$$

Assuming the interior solution (i.e., $p_i^* > 0$ and $a_i^* > 0$), the first-order conditions for firm i are

$$\begin{aligned} q_i(\mathbf{p}^*) + [p_i^* + t\theta_i]\frac{\partial q_i(\mathbf{p}^*)}{\partial p_i} &= \left[\frac{\partial c_i}{\partial q_i}(q_i(\mathbf{p}^*), a_i^*) + t\frac{\partial e_i}{\partial q_i}(q_i(\mathbf{p}^*), a_i^*)\right]\frac{\partial q_i(\mathbf{p}^*)}{\partial p_i}, && (30) \\ -t\frac{\partial e_i}{\partial a_i}(q_i(\mathbf{p}^*), a_i^*) &= \frac{\partial c_i}{\partial a_i}(q_i(\mathbf{p}^*), a_i^*), && (31) \end{aligned}$$

where $\mathbf{p}^* = (p_1^*, p_2^*, \ldots, p_n^*)$. We assume that the second-order conditions are satisfied. By denoting $q_i^* = q_i(\mathbf{p}^*)$, (30) and (31) are rearranged as

$$\begin{aligned} \frac{q_i^*}{\partial q_i(\mathbf{p}^*)/\partial p_i} + p_i^* + t\theta_i &= \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) + t\frac{\partial e_i}{\partial q_i}(q_i^*, a_i^*), && (32) \\ -t\frac{\partial e_i}{\partial a_i}(q_i^*, a_i^*) &= \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*). && (33) \end{aligned}$$

Note that $p_i^* = p_i(\mathbf{q}(\mathbf{p}^*)) = \partial U(\mathbf{q}(\mathbf{p}^*))/\partial q_i$ by the definition of inverse demand and (24). Thus, regarding (32)–(33) as the system of $2n$ equations with respect to $2n$ variables of $(q_1^*, \ldots, q_n^*) = (\mathbf{q}(\mathbf{p}^*))$ and $(a_1^*, \ldots, a_n^*)$, the system coincides (25)–(26) when we set

$$t^o = D'(E^o) > 0, \; \theta_i^o = -\frac{q_i(\mathbf{p}^o)}{D'(E^o)} \Big/ \frac{\partial q_i(\mathbf{p}^o)}{\partial p_i} > 0. \tag{34}$$

Note that by the inverse function theorem, $\partial q_i(\mathbf{p})/\partial p_i$ is the same as the i-i'th element of $D\mathbf{p}^{-1}$ (the inverse matrix of Jacobian $D\mathbf{p}$).

Result Consequently, we obtain an extended result of Proposition 1.

Proposition 3 *Suppose the Cournot or the Bertrand oligopoly in a differentiated product market that is presented here. There exists $(\theta_1, \ldots, \theta_n)$ such that the policy attains the first-best optimality (i.e., $q_i^* = q_i^o$ and $a_i^* = a_i^o$) if and only if the tax rate is Pigovian (i.e., $t = D'(E^o)$).*

Proof. For sufficiency, suppose that $t = t^o$ and set $(\theta_1, \ldots, \theta_n) = (\theta_1^o, \ldots, \theta_n^o)$ as defined in (29) in the Cournot case or (34) in the Bertrand case. Substitute (29) or (34) into Eqs. (27)–(28) or (32)–(33). Then, by (25)–(26), we find that Eqs. (27)–(28) or (32)–(33) are satisfied when $q_i^* = q_i^o$ or $p_i^* = p_i^o$ and $a_i^* = a_i^o$. Note that in the Bertrand case, $p_i^* = p_i^o$ implies that $q_i^* = q_i(\mathbf{p}^o) = q_i^o$.

To prove necessity, we show the contraposition. Suppose that $t \neq D'(E^o)$ and take $(\theta_1, \ldots, \theta_n)$ arbitrarily. Then, by (28) or (33) and (26),

$$\frac{\partial c_i(q_i^*, a_i^*)/\partial a_i}{\partial e_i(q_i^*, a_i^*)/\partial a_i} = -t \neq -D'(E^o) = \frac{\partial c_i(q_i^o, a_i^o)/\partial a_i}{\partial e_i(q_i^o, a_i^o)/\partial a_i}.$$

Therefore, (q_i^*, a_i^*) never equates to (q_i^o, a_i^o) since the first and last terms are not equal. **Q.E.D.**

This result suggests that our main principle (Proposition 1) does not depend on the assumption of a homogeneous product market and/or Cournot competition. However, it must be noted that in the case of differentiated products, the optimal policy requires the estimation of the individuals demands, $\partial p_i/\partial q_i$ or $\partial q_i/\partial p_i$.

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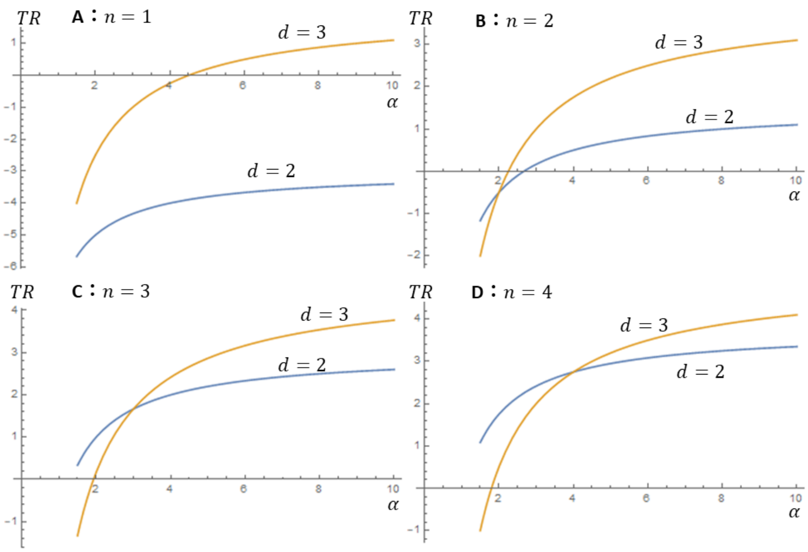

Figure 1: Tax revenue (vertical axis) under the optimal policy with $Y = 5$ and $d = 2, 3$. Panel **A** depicts the revenue in the case where $n = 1$ for $1.5 < \alpha < 10$ (horizontal axis). Panel **B** depicts the revenue in the case where $n = 2$ for $1.5 < \alpha < 10$ (horizontal axis). Panel **C** depicts the revenue in the case where $n = 3$ for $1.5 < \alpha < 10$ (horizontal axis). Panel **D** depicts the revenue in the case where $n = 4$ for $1.5 < \alpha < 10$ (horizontal axis).

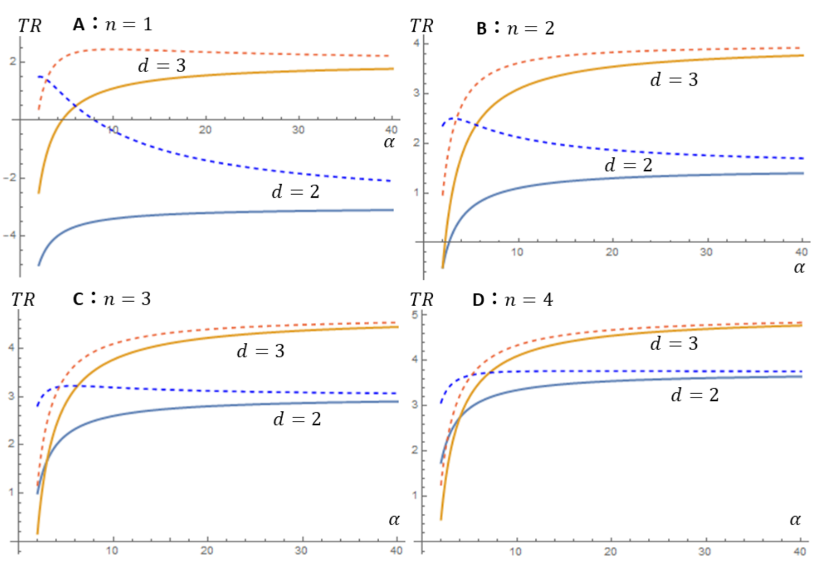

Figure 2: Tax revenues (vertical axis) from the intensity-based emission tax and the second-best emission tax with $Y = 5$ and $d = 2, 3$. The real (dotted) line depicts the former (latter) revenue for various α up to 40 (horizontal axis).

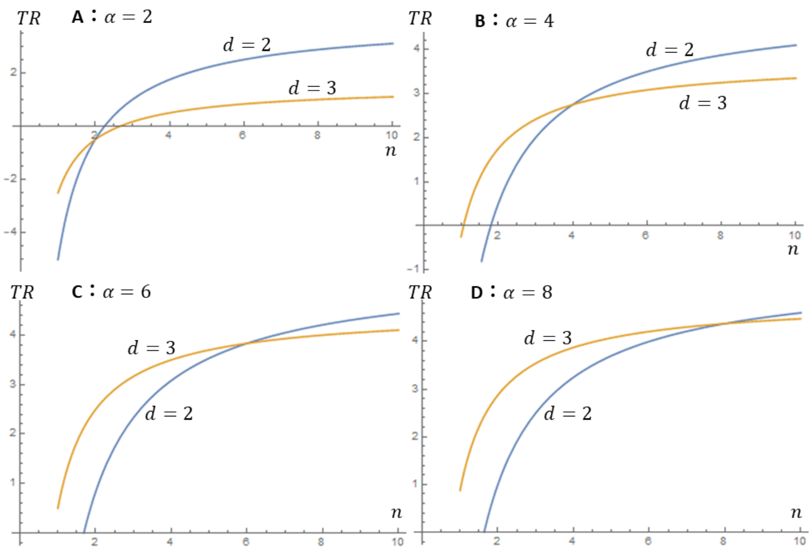

Figure 3: Tax revenue (vertical axis) under the optimal policy with $Y = 5$ and $d = 2, 3$. Panel **A** depicts the revenue in the case where $\alpha = 2$ for $1 \leq n \leq 10$ (horizontal axis). Panel **B** depicts the revenue in the case where $\alpha = 4$ for $1 \leq n \leq 10$ (horizontal axis). Panel **C** depicts the revenue in the case where $\alpha = 6$ for $1 \leq n \leq 10$ (horizontal axis). Panel **D** depicts the revenue in the case where $\alpha = 8$ for $1 \leq n \leq 10$ (horizontal axis).

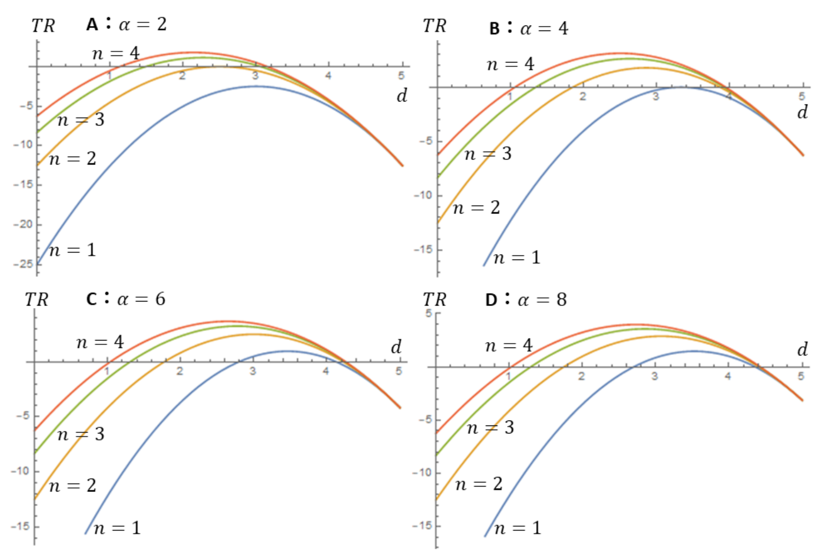

Figure 4: Tax revenue (vertical axis) under the optimal policy with $Y = 5$ and $n = 1, 2, 3, 4$. Panel **A**, **B**, **C**, and **D** depict the revenue in the case where $\alpha = 2$, $\alpha = 4$, $\alpha = 6$, and $\alpha = 8$, for $0 < d < 5$ (horizontal axis), respectively.