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Hiroaki Ino
(School of Economics, Kwansei Gakuin University)

Toshihiro Matsumura
(Institute of Social Science, The University of Tokyo)

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SCHOOL OF ECONOMICS

KWANSEI GAKUIN UNIVERSITY

1-155 Uegahara Ichiban-cho
Nishinomiya 662-8501, Japan

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

Hiroaki Ino†
School of Economics, Kwansei Gakuin University
and
Toshihiro Matsumura‡
Institute of Social Science, The University of Tokyo

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Abstract

This study shows the first-best optimality of an emission tax based on emission intensity targets. Emissions are taxed when a firm's emission intensity exceeds the targeted level. The literature on environmental tax shows that Pigovian tax, which internalizes negative externality, yields the first-best optimum under perfect competition, whereas the same is not true under imperfect competition. We show that even under imperfect competition, the combination of uniform emission tax and non-uniform emission intensity targets leads to the first best. The first-best uniform tax rate is always equal to the Pigovian tax. This principle can also apply to the policy combination of tradable emission permits and emission intensity targets.

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

JEL Classification: Q58, Q48, H23, L51

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†Address: 1-1-155 Uegahara, Nishinomiya, Hyogo 662-8501, Japan. E-mail: hiroakiino@04.alumni.u-tokyo.ac.jp.

‡Address: 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. E-mail: matsumur@iss.u-tokyo.ac.jp

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 result that the second-best tax rate is lower than its Pigovian counterpart may not hold in oligopoly markets. Simpson (1995) investigated Cournot oligopolies. He showed that the optimal tax rate is lower than the Pigovian if firms are symmetric, and 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.[1] However, whether the optimal tax rate is higher or lower than the Pigovian, the first best is not achieved by the emission tax policy.[2]

In this study, we propose a new emission pricing policy based on emission intensity targets. The government imposes an emission intensity (emission per output) target on

[1] For the general principle of welfare-improving production substitution, see also Lahiri and Ono (1988).

[2] 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.

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, based on the emission intensity target leads to the first-best optimality under imperfect competition. In other words, we show the optimality of the policy combination of emission tax and emission intensity regulation.

Emission intensity regulation has a production expansion effect (Ino and Matsumura, 2019),[3] and production reduction effect by the Pigovian tax can be offset by choosing adequate emission intensity targets.[4] Our result suggests that the government should set the tax rate to be marginal social cost of emission (Pigovian tax) without taking into account the competition structure of each market. The government should consider industry- or firm-specific conditions only at the stage of imposing emission intensity targets, not at that 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). For example, the Japanese government imposes environmental taxes in Japanese energy markets including Japanese electric power market as well as emission intensity targets in Japanese electric power market, both of 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 whereas the emission intensity regulation does not. However, under imperfect competition, the

[3] They showed that this production expansion effect is equivalent to the effect of refunding the emission tax revenue to consumers.

[4] 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 in efficient implementation of emission intensity regulation.

emission intensity regulations may be superior to the emission pricing policies for welfare, which become the second-best policies (Besanko, 1987; Helfand, 1991; Montero, 2002; Lahiri and Ono; 2007; Kiyono and Ishikawa, 2013; Hirose and Matsumura, 2017; Amir et al., 2018). 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 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.[5]

The remainder of this paper is organized as follows. Section 2 formulates the basic model in a homogeneous product market. Section 3 derives our main result. Section 4 discusses how the government can test the optimality of the policy. Section 5 presents three extensions, namely on the quantity and price competition with product differentiation, on the tradable permit market across industries and on the portfolio standards. Section 6 concludes this paper.

[5] 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`).

2 The model

We consider an oligopoly market wherein n firms choose their outputs (Cournot competition) and abatement levels. For $i = 1, \ldots, n$, $q_i \geq 0$ is firm i's output, and $a_i \geq 0$ is the level of firm i's abatement activity. The firms' products are homogeneous, and the inverse 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, $\partial c_i/\partial q_i > 0$, $\partial c_i/\partial a_i > 0$,[6] 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 $D' > 0$. We assume a unique interior social optimum and market equilibrium.[7]

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

3 Optimal policy

We consider the following emission intensity targets, $(\theta_1, \ldots, \theta_n) \geq \mathbf{0}$. Firm i's emission intensity is targeted by the government as $\theta_i = e_i/q_i$. If firm i emits over (below) this

[6] We relax this assumption in Section 5.3.

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

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

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

where $t \geq 0$ is the tax (subsidy) level.

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

$$p'(Q^*)q_i^* + p(Q^*) + t\theta_i = \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) + t\frac{\partial e_i}{\partial q_i}(q_i^*, a_i^*), \tag{3}$$

$$-t\frac{\partial e_i}{\partial a_i}(q_i^*, a_i^*) = \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*). \tag{4}$$

We assume that the second-order condition is satisfied.[8]

By comparing (3)–(4) with (1)–(2), we obtain the optimal levels of the emission tax and emission intensity targets as

$$t^o = D'(E^o) > 0, \; \theta_i^o = -\frac{p'(Q^*)q_i^*}{D'(E^o)} > 0. \tag{5}$$

Proposition 1 *Consider a Cournot oligopoly in a homogeneous product market. 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. Sufficiency is obvious since (3) and (4) coincide (1) and (2) when $t = t^o$ and $(\theta_1, \ldots, \theta_n) = (\theta_1^o, \ldots, \theta_n^o)$. To prove necessity, we show the contraposition. Suppose that $t \neq D'(E^o)$ and take $(\theta_1, \ldots, \theta_n)$ arbitrarily. Then, by (4) 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.**

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

The emission pricing policy based on emission intensity targets attains the first-best outcome. Moreover, the optimal tax rate is always 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. Thus, the emission tax uniformly corrects the negative externality at the Pigovian level. In Section 5.1, we show that this result is robust even under more general oligopoly markets including product differentiation and price competition.

We considered an emission tax based on emission intensity targets. However, we can replace the emission tax with tradable emission permits. Suppose that a market exists for tradable permits across industries. The government sets an emission intensity target, and if a firm does not meet (overachieves) the target, the firm must purchase (can sell) permits. The government adjusts the total number of permits to equalize the equilibrium price of the permit to the marginal social cost of emission. Then, the first best is achieved as long as firms are price takers in the tradable permit market. We formally discuss this mechanism in Section 5.2. As stated previously, our principle can also apply to portfolio standard policies. We formally discuss this application in Section 5.3.

4 Testing the optimal level of emission intensity

The government may be aware of the desirable level of the emission price, $d = D'(E^o)$, and imposes the emission tax according to this level ($t = d$). However, the government needs to know 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. (6)

or (7) is satisfied or not.

Lerner's approach If the given level of θ_i is optimal, using the well-known Lerner's rule, (5) yields

$$\theta_i^o = -\frac{p^*}{d}\left(\frac{dp}{dQ}\frac{Q^*}{p^*}\right)\frac{q_i^*}{Q^*} = -\frac{p^*}{d}\frac{s_i^*}{\epsilon^*}, \tag{6}$$

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 result 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. Since 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, from an empirical point of view, it is useful to characterize economic effects using such measurable indicators.[9] Following their spirit and decomposing the second equation in (5),

$$\theta_i^o = -\frac{dp^*/dt}{t}\frac{q_i^*}{dQ^*/dt}, \tag{7}$$

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.[10] Thus, if we have sufficient experience in policy alteration or related data, we can test whether (7) is satisfied.

[9] 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.

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

5 Extensions

5.1 Product differentiation and Bertrand competition

We extend the basic model 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),[11] 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 $q_i > 0$,

$$p_i = \frac{\partial U}{\partial q_i}(\mathbf{q}) \qquad i = 1, \ldots, n, \tag{8}$$

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 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

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

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

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

$$\frac{\partial U}{\partial q_i}(\mathbf{q}^o) = \frac{\partial c_i}{\partial q_i}(q_i^o, a_i^o) + D'(E^o)\frac{\partial e_i}{\partial q_i}(q_i^o, a_i^o), \tag{9}$$

$$-D'(E^o)\frac{\partial e_i}{\partial a_i}(q_i^o, a_i^o) = \frac{\partial c_i}{\partial a_i}(q_i^o, a_i^o), \tag{10}$$

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

Cournot competition First, we consider the Cournot competition. Under the emission intensity targets, $(\theta_1, \ldots, \theta_n) \geq \mathbf{0}$, 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

$$\frac{\partial p_i(\mathbf{q}^*)}{\partial q_i}q_i^* + p_i(\mathbf{q}^*) + t\theta_i = \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) + t\frac{\partial e_i}{\partial q_i}(q_i^*, a_i^*), \tag{11}$$

$$-t\frac{\partial e_i}{\partial a_i}(q_i^*, a_i^*) = \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*). \tag{12}$$

We assume that the second-order condition is satisfied. Note that $p_i(\mathbf{q}^*) = \partial U(\mathbf{q}^*)/\partial q_i$ by (8). Thus, by comparing (11)–(12) with (9)–(10), we obtain the optimality by setting

$$t = D'(E^o) > 0, \;\; \theta_i = -\frac{q_i^*}{D'(E^o)}\frac{\partial p_i(\mathbf{q}^*)}{\partial q_i} > 0. \tag{13}$$

Bertrand competition Next, we consider the Bertrand competition. Under the emission intensity targets, $(\theta_1, \ldots, \theta_n) \geq \mathbf{0}$, 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

$$q_i(\mathbf{p}^*) + [p_i^* + t\theta_i]\frac{\partial q_i(\mathbf{p}^*)}{\partial p_i} = \left[\frac{\partial c_i}{\partial q_i}(q_i(\mathbf{p}^*), a_i^*) + t\frac{\partial e_i}{\partial q_i}(q_i(\mathbf{p}^*), a_i^*)\right]\frac{\partial q_i(\mathbf{p}^*)}{\partial p_i}, \tag{14}$$

$$-t\frac{\partial e_i}{\partial a_i}(q_i(\mathbf{p}^*), a_i^*) = \frac{\partial c_i}{\partial a_i}(q_i(\mathbf{p}^*), a_i^*). \tag{15}$$

We assume that the second-order condition is satisfied. By denoting $q_i^* = q_i(\mathbf{p}^*)$, (14) and (15) are rearranged as

$$\begin{aligned} \frac{q_i^*}{\partial q_i(\mathbf{p}^*)/\partial p_i} + p_i^* + t\theta_i &= \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) + t\frac{\partial e_i}{\partial q_i}(q_i^*, a_i^*), \qquad (16) \\ -t\frac{\partial e_i}{\partial a_i}(q_i^*, a_i^*) &= \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*). \qquad (17) \end{aligned}$$

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 (8). Thus, regarding (16)–(17) 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 (9)–(10) when we set

$$t = D'(E^o) > 0, \; \theta_i = -\frac{q_i(\mathbf{p}^*)}{D'(E^o)} \bigg/ \frac{\partial q_i(\mathbf{p}^*)}{\partial p_i} > 0. \qquad (18)$$

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 $D\mathbf{p}$).

Consequently, we obtain an extended result of Proposition 1.

Proposition 2 *Consider Cournot or Bertrand oligopoly in a differentiated product market. 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. Sufficiency is obvious since Eqs. (11)–(12) or (16)–(17) coincide (9)–(10) when t and $(\theta_1, \ldots, \theta_n)$ are as in (13) or (18). To prove necessity, we show the contraposition. Suppose that $t \neq D'(E^o)$ and take $(\theta_1, \ldots, \theta_n)$ arbitrarily. Then, by (12) or (17) and (10),

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

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 result (Proposition 1) does not depend on the assumption of a homogeneous product market and/or Cournot competition.

5.2 Tradable permit market based on emission intensity targets

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

There are N industries, each of which replicates[12] the Cournot competition of n firms, which is presented in Section 2. We denote each variable in the industry $j = 1, 2, \dots, N$ 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 $E^o = N \sum_{i=1}^{n} e_i(q_i^o, a_i^o)$. The second-order condition is 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, $(\theta_1, \dots, \theta_n) \geq \mathbf{0}$, 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 $r \geq 0$ is the price of the permits.

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

$$p'(Q^*)q_i^* + p(Q^*) + r\theta_i = \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) + r\frac{\partial e_i}{\partial q_i}(q_i^*, a_i^*), \tag{19}$$

$$-r\frac{\partial e_i}{\partial a_i}(q_i^*, a_i^*) = \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*). \tag{20}$$

Further, the market clear condition of the permit market is

$$N \sum_{i=1}^{n} [e_i(q_i^*, a_i^*) - \theta_i q_i^*] = E^G, \tag{21}$$

where E^G is the number of permits that the government sells.[13]

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

[13] If E^G is negative, the government commits to purchase $-E^G$ from the market to induce firms to overachieve. If E^G is positive, the government may allocate E^G among firms instead of selling quota in the permit market. The first best is achieved by any allocation as long as the total amount allocated to firms is E^G.

Suppose that the government sets the level of θ_i as

$$\theta_i = -\frac{p'(Q^*)q_i^*}{D'(E^o)} > 0, \tag{22}$$

and adjusts E^G as

$$E^G = N\left[E^o - \sum_{i=1}^{n} \theta_i q_i^*\right] = N\left[E^o + \sum_{i=1}^{n} \frac{p'(Q^*)(q_i^*)^2}{D'(E^o)}\right]. \tag{23}$$

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 3 *Consider N Cournot oligopolies in homogeneous product markets. Suppose that the firms are price takers in the tradable permit market. Then, the tradable permit market based on the emission intensity target presented by (22)–(23) 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 (22). Then, the market conditions (19)–(20) coincide with the optimal conditions (1)–(2). Hence, 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

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

where the first equality is derived from $e_i^* = e_i^o$, and the second one, from (23). Therefore, if $r = D'(E^o)$, the market clear condition (21) 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. Another idea relates to government monitoring, which restricts firms' market power in the permit market.

5.3 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 gray output $x_i \geq 0$ and the green output $y_i \geq 0$ as $q_i = x_i + y_i$. The gray output is the electricity produced by gray 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 gray power sources yield negative externality, and the welfare loss is denoted by $D(X)$ with $D' > 0$ and $D'' \geq 0$, where $X = \sum_{i=1}^{n} x_i$.

The government regulates the ratio of green output as

$$y_i/q_i \geq 1 - \theta_i \Longleftrightarrow x_i/q_i \leq \theta_i \quad \therefore (1-\theta_i)x_i \leq \theta_i y_i$$

. 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

$$p(Q)q_i - \gamma_i(x_i, y_i) + \beta_i(x_i, y_i) - t((1-\theta_i)x_i - \theta_i y_i),$$

where γ_i is the production cost function, which is convex and satisfies $\partial\gamma_i/\partial x_i > 0$ and $\partial\gamma_i/\partial y_i > 0$. β_i is the private benefit function from the green output. We assume that $\beta_i(x_i, y_i)$ is concave and satisfies $\partial\beta_i/\partial x_i \leq 0$ and $\partial\gamma_i/\partial y_i \geq 0$. A firm may be able to sell green electricity at a price higher than the market price (the green electricity premium).[14] If the green electricity premium is α per green power output, then $\beta_i(x_i, y_i) = \alpha y_i$.

If we regard $a_i = y_i$, $e_i(q_i, a_i) = q_i - a_i = x_i$, and $c_i(q_i, a_i) = \gamma_i(x_i, y_i) - \beta_i(x_i, y_i)$, 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

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

under this extension, our analyses in the previous sections are robust.[15] 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 $\partial c_i/\partial q_i = \partial\gamma_i/\partial x_i - \partial\beta_i/\partial x_i > 0$ and

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

Thus, $\partial c_i/\partial q_i$ is positive but $\partial c_i/\partial a_i$ can be negative if $\partial\beta_i/\partial y_i - \partial\beta_i/\partial x_i > 0$ 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 x_i to y_i saves a cost if $\partial\gamma_i/\partial y_i < \partial\gamma_i/\partial x_i$. Therefore, we should allow that $\partial c_i(q_i, a_i)/\partial a_i < 0$, especially when a_i/q_i or y_i/x_i is small.

Second, in this subsection's model, we must assume that $y_i \leq q_i$ (i.e., $e_i = x_i \geq 0$). If $\lim_{y_i \to q_i} \partial(\gamma_i - \beta_i)/\partial y_i$ 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.[16] If $\partial(\gamma_i - \beta_i)/\partial y_i$ is small for any y_i, it is possible that $y_i = q_i$ (i.e., $x_i = 0$) is the optimal abatement level. Thus, we should consider the possible corner solution. The first-order conditions for the welfare-maximizing problem under the constraint $a_i \leq q_i$ are[17]

$$p(Q^o) - \frac{\partial c_i}{\partial q_i}(q_i^o, a_i^o) - D'(E^o) + \lambda_i^o = 0, \tag{24}$$

$$D'(E^o) - \frac{\partial c_i}{\partial a_i}(q_i^o, a_i^o) - \lambda_i^o = 0, \tag{25}$$

$$\lambda_i^o \geq 0,\ q_i^o - a_i^o \geq 0,\ \lambda_i^o(q_i^o - a_i^o) = 0, \tag{26}$$

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

[15] 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.

[16] 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.

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

for a profit-maximizing problem of firm i under the constraint $a_i \leq q_i$ are[18]

$$p'(Q^*)q_i^* + p(Q^*) + t\theta_i - \frac{\partial c_i}{\partial q_i}(q_i^*, a_i^*) - t + \lambda_i^* = 0, \tag{27}$$

$$t - \frac{\partial c_i}{\partial a_i}(q_i^*, a_i^*) - \lambda_i^* = 0, \tag{28}$$

$$\lambda_i^* \geq 0, \ q_i^* - a_i^* \geq 0, \ \lambda_i^*(q_i^* - a_i^*) = 0. \tag{29}$$

Note that λ^o and λ^* are the Lagrange multipliers. Comparing (24)–(26) and (27)–(29), we find that the first best is achieved if the government chooses

$$t^o = D'(E^o) > 0, \ \theta_i^o = -\frac{p'(Q^*)q_i^*}{D'(E^o)} > 0. \tag{30}$$

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 (30), as long as $D'(X^o) \geq -p'q_i^o$ 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.

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, emission pricing policies based on 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 showed that the optimality is achieved by the combination of uniform emission tax and non-uniform

[18] 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.

emission intensity targets, leading to the first best. We also showed that the first-best uniform tax rate is always equal to the Pigovian tax rate.

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.

In this study, we 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 the policy discussed in this study. We also did not consider any kind of uncertainty in this study. 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 will be extended in this direction in future research.[19]

[19] 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.

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