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Environmental Regulations on Vertical Oligopolies with Eco-Industry

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This article investigates optimal environmental regulations on vertical oligopolies where the upstream eco-industry produces abatement goods reducing pollutants and the downstream polluting industry produces consumption goods emitting pollutants. Under Cournot competition with blockaded entry, we analyze the environmental tax for externality and abatement subsidy for abatement activity. We also incorporate free entry case to examine the equilibrium number of firms in each industry, and then propose an entry fee for downstream polluting industry to lessen excessive entry and an entry subsidy for upstream eco-industry to increase insufficient entry when market concentration in eco-industry is significant. Finally, we show that under the two-part system with entry fee/subsidy and environmental tax/subsidy, the regulator can achieve the first-best market performance and fiscal equivalence with the Pigouvian rule.

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I. Introduction

Recent concerns over the environmental policy in the eco-industry have been increasing in part due to the importance of environmental technology innovation on pollution abatements. However, imperfect competition among environmental firms in the eco-industry can restrict the production of abatement goods and thus have a direct negative impact on the environmental problem. Thus, appropriate industrial regulation on the eco-industry has also become an important topic for

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environmental policy in lessening gross emissions.

The basic framework for environmental taxation on environmental firms in the eco-industry was first introduced by David and Sinclair-Desgagne (2005). They formulated the concept of vertical structure, in which pollution abatement goods are delivered to polluting firms by an environmental monopoly. They showed that the market power of the eco-industry would bring about a higher pollution tax than the marginal social cost of damage.[1] Canton, et al. (2008) extended the analysis to the vertical Cournot oligopolies, in which the downstream industry producing consumption goods and emitting environmental pollutants, and the upstream industry producing abatement goods for the downstream industry are limited by imperfect competition. They showed that if the environmental tax is the only available instrument used to regulate these distortions, the second-best optimality of higher taxation depends on the market power between the eco-industry and the polluting industry in the vertical structure.

However, from the viewpoint of policy coordination, it is beneficial to have a combination of instruments to remedy different market failures, such as an environmental policy for externality, a competition policy for imperfect competition, and a market structure policy for excessive (or insufficient) entry. Therefore, if the government can use multiple environmental instruments, such as taxation, subsidy, and entry fee, the first-best optimality of the Pigouvian rule might be obtained. For example, Schott (2008) and Park and Lee (2010) considered a single market model for polluting oligopolists and compared several regulatory instruments to find the optimal combinations when there are many different market failures. But, they focused on the environmental policy on the polluting industry without considering abatement technology and the eco-industry in a vertical relation.

This article considers the eco-industry and its effect on environmental regulation under vertical oligopolies with two industries, the upstream eco-industry that produces abatement goods, supported by a production subsidy, and the downstream polluting industry that produces consumption goods emitting pollutants, regulated by an environmental tax. We then devise the optimal combination of appropriate policy instruments.

We first specify what an optimal environmental tax and abatement subsidy should be when both industries are imperfectly competitive under blockaded entry.

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[1] The idea of environmental taxation on polluting firms in an imperfect competition was firstly introduced by Buchanan (1969), in which the optimal tax on monopoly should be less than the marginal social damage. This logic of the optimality of lower taxation was also applied to the monopoly in abatement technology (Barnett, 1980). More recent research on imperfect competition extended this analysis to the Cournot oligopoly (Levin, 1985; Simpson, 1995) and the endogenous market structure (Katsoulacos and Xepapadeas, 1995; Lee, 1999). Requate (2007) synthesized important works on pollution tax under imperfect competition. All these research provided the rationale for the second-best solution of a higher/lower optimal tax level, depending upon the relative effects of distortions, such as market power, excessive entry, and externality.

We show that an optimal environmental tax should be used for the negative externality and output restrictions in final production, and an optimal abatement subsidy should incorporate the effect of upstream market restrictions on abatement activity. We also examine the relationship between the environmental tax and the subsidy rate and show that the production subsidy for abatement goods has a similar form to an environmental tax with some weights on each distortion. Therefore, when environmental damage is serious under moderate conditions, the optimal policy is a positive tax on consumption goods and a positive subsidy on abatement goods.

We next extend the model to the free entry case in which the number of firms in each market is determined at the zero profit condition endogenously. We then provide the optimality of the equilibrium number of firms in each industry and specify what an optimal entry fee should be in both markets under free entry. In particular, we show that the regulator should impose an entry fee on the downstream industry to lessen excessive entry and, when market power in the eco-industry is significant, he should provide entry subsidy to the upstream industry to increase insufficient entry. Therefore, the policy combination of an environmental tax, an abatement subsidy, and an entrance fee or subsidy achieves the first-best optimum for many different market failures.

Finally, we examine the fiscal budget of environmental regulation and show that multiple instruments achieve the fiscal equivalence in which the regulator's revenue is exactly the same with the Pigouvian rule, which is the amount of marginal damage.

The organization of this paper is as follows. Section II constructs the basic model for the vertical structure, consisting of polluting firms in the downstream industry and environmental firms in the upstream industry. In Section III, we find the optimal environmental tax and abatement subsidy that maximize social welfare under blockaded entry. In Section IV, we extend the basic model to the free entry structure where the entry is determined endogenously and find the optimal entry fee/subsidy for each industry to obtain the first-best solution. The final section provides a conclusion.

II. The Basic Model

We consider a vertical industry structure with two Cournot oligopolies, in which the upstream eco-industry produces abatement goods for selling its products to the downstream industry, and the downstream polluting industry produces consumption goods for consumers. In that production process, we assume that consumption goods emit negative external effects, called environmental pollution, which is reduced only by abatement goods. We also assume that the regulator wants to employ an environmental tax and an abatement subsidy.

The followings are the timing of the game: (i) the regulator chooses an optimal environmental tax and an abatement subsidy to maximize social welfare; (ii) given the demand for abatement goods from downstream firms, the eco-firms in upstream industry compete in quantity in a Cournot manner; (iii) given the demand of consumption goods from consumers, the polluting firms in downstream industry choose its optimal level of production and usage of abatement goods with the mode of Cournot competition. This three-stage game will be solved by backward induction

1. Downstream Industry

There are n symmetric downstream firms, indexed by i, where the amount of production of the firm is q_i. Each firm's cost function is given by $C_d(q_i)$, where $C_d'(q_i) > 0$ and $C_d''(q_i) \geq 0$. The inverse market demand function of the consumption good is given by $P(Q)$ where $Q = \sum_{i=1}^{n} q_i$ and $P'(Q) < 0$ However, production activity generates some pollution, which is denoted by an emission function, $e(q_i)$. This is identical for all firms, and it is assumed that $e'(q_i) > 0$ and $e''(q_i) \geq 0$.

The downstream firms are regulated by environmental tax, t, levied on the amount of emissions. Thus, each firm has an incentive to reduce the environmental tax using a cleanup activity that requires purchase of some specific abatement goods a_i, sold by upstream firms at a market price of r.[2] The effectiveness of the abatement goods is given by a function, $w(a_i)$ which measures the amount of pollution reduced by the purchase of a_i. We assume that this pollution abatement technology is characterized by decreasing marginal productivity, i.e., $w'(a_i) > 0$ and $w''(a_i) \leq 0$; that is, more abatement goods consumed decrease the net amount of pollution with a decreasing rate. Then, the net amount of pollution can be defined as $y_i(q_i, a_i) = e(q_i) - w(a_i)$.[3]

Each downstream firm compete in a Cournot manner and wants to maximize its profit function over the two variables, q_i and a_i, the individual level of the

[2] We assume that the market-clearing price of abatement goods is determined by demand and supply in the eco-industry. That is, for analytic convenience, we eliminate the strategic interactions of the downstream firms and thus, they behave as price takers at the market equilibrium. On this assumption of market-clearing price in a vertical relation, see Ghosh and Morita (2007) and Canton et al. (2008).

[3] We focus on the end-of-pipe pollution abatement, in which abatement activities are additively separable from the production process. This assumption follows the analysis of David and Sinclair-Desgagne (2005) and Canton et al. (2008).

production and the amount of purchased abatement goods, respectively.

$$\max_{q_i, a_i} \Pi_i = P(Q)q_i - C_d(q_i) - r \cdot a_i - t \cdot y_i(q_i, a_i) \tag{1}$$

The first-order necessary conditions for Cournot-Nash equilibrium output of consumption goods and consumption of abatement goods are as follows:

$$\frac{\partial \Pi_i}{\partial q_i} = P(Q) + P(Q)' q_i - C_d'(q_i) - t \cdot e'(q_i) = 0 \tag{2}$$

$$\frac{\partial \Pi_i}{\partial a_i} = -r - t\left[-w'(a_i)\right] = 0 \Rightarrow r = t \cdot w'(a_i) \tag{3}$$

Because of the independency of the end-of-pipe pollution abatement technology, the production decision is separable from the abatement decision. In particular, from Equation (3), the abatement activity, a_i is determined as the function of the market price of abatement goods, r, and environmental tax, t. For instance, the higher the environmental tax, the less the output production and the more the abatement activities.

2. Upstream Industry

There are m symmetric upstream firms, indexed by j, where the amount of abatement goods produced by the firm is a_j. Each firm's cost function is given by $C_u(a_j)$, where $C_u' > 0$ and $C_u'' \geq 0$. We assume that upstream firms are supported by an abatement subsidy, s, based on the sales of abatement goods.

Then, given the market price of r, each upstream firm competes with Cournot manner and wants to maximize its profit function over the variable a_j, the individual level of production.

$$\max \Pi_j = r \cdot a_j - C_u(a_j) + s \cdot a_j \tag{4}$$

Since all firms in the upstream industry are able to anticipate the behaviors of downstream firms in (2) and (3), which are separable decisions, the upstream firms can anticipate the demand of the abatement goods. So, the profit function of the upstream firm can be changed to

$$\max_{a_j} \Pi_j = t \cdot w'(a_i) \cdot a_j - C_u(a_j) + s \cdot a_j$$

Furthermore, from the assumption that downstream firms are price-takers in the trade, the eco-industry market-clearing price for the abatement goods will be set at $\sum_{i=1}^{n} a_i = \sum_{j=1}^{m} a_j$; that is, we have the amount of abatement goods consumed by *ith* downstream firm, $a_i = \frac{1}{n}\sum_{j=1}^{m} a_j$ at symmetric equilibrium in the downstream market. Then, the upstream firm's profit function can be changed as follows:

$$\max_{a_j} \Pi = t \cdot w'(\frac{1}{n}\sum_{j=1}^{m} a_j) \cdot a_j - C_u(a_j) + s \cdot a_j \qquad (4')$$

The first-order necessary condition for Cournot-Nash equilibrium output of abatement goods can be written as

$$\frac{\partial \Pi_j}{\partial a_j} = t \cdot w'(\frac{1}{n}\sum_{j=1}^{m} a_j) + t \cdot w''(\frac{1}{n}\sum_{j=1}^{m} a_j)\frac{a_j}{n} - C_u'(a_j) + s = 0 \qquad (5)$$

Then, the symmetric equilibrium for identical upstream firms, in which $n \cdot a_i = m \cdot a_j$, yields the following condition:

$$t\left(w'(\frac{1}{n}\sum_{j=1}^{m} a_j) + w''(\frac{1}{n}\sum_{j=1}^{m} a_j) \cdot \frac{a_j}{n} \right) + s = C_u'(a_j) \qquad (5')$$

From Equation (5'), the decision of abatement production is determined by the shape of the pollution abatement technology, the marginal cost of producing abatement goods, the number of firms in both upstream and downstream industries, and the regulator's two instruments—abatement subsidy, s , and environmental tax, t . Therefore, other things being equal, more abatement goods will be produced when (i) the environmental tax or abatement subsidy is higher, (ii) the pollution abatement technology is more efficient, (iii) the eco-industry production technology is efficient, (iv) the number of firms in the upstream market is smaller, and (v) the number of firms in the downstream market is greater.[4]

[4] For the existence of an unique m-firm Cournot-Nash equilibrium in the eco-industry market, the second-order sufficient conditions from (5) require that the concavity of the abatement function should not be too weak. The above comparative results on the number of firms come from the assumption that $w'''(a_i)$ is very small enough.

III. Optimal Regulation under Blockaded Entry

Let $D(Y)$ denote the environmental damages from pollution, where $D'(Y) > 0, D''(Y) \geq 0$ and $Y = ny_i$. Then, social welfare is defined as the sum of consumers' and producers' surplus less the environmental damages in (6).

The regulator's problem is to choose the levels of output of consumption and abatement goods, maximizing the following social welfare function:

$$\max_{q_i, a_j} W = \int_0^{nq_i} P(u)du - n \cdot C_d(q_i) - m \cdot C_u(a_j) - D(Y) \tag{6}$$

The first-order necessary conditions for interior solutions can be written for the optimal allocation as follows:

$$\frac{\partial W}{\partial q_i} = P(Q) - C_d'(q_i) - D'(Y) \cdot e'(q_i) = 0 \tag{7}$$

$$\frac{\partial W}{\partial a_j} = -C_u'(a_j) + D'(Y) \cdot w'(a_i) = 0 \tag{8}$$

or

$$P(Q) = C_d'(q_i) + D'(Y)e'(q_i) \tag{7'}$$

$$D'(Y) = w'(\frac{m}{n} a_j) = C_u'(a_j) \tag{8'}$$

Notice that where $Q = nq_i$ and $A = na_i = ma_j$ at the symmetric equilibrium. The solutions give the principle of marginal optimality, i.e., (7') says that market price of the consumption goods should be equal to marginal production cost of consumption goods plus marginal damage of production, and (8') says that marginal benefit of abatement goods on the environmental damage should be equal to the marginal cost of production of abatement goods.

Using market equilibrium conditions in Equation (2) and the optimality conditions in (7), we have the optimal environmental tax:

$$t^* = D'(Y) + \frac{P'(Q)q_i}{e'(q_i)} = D'(Y) + \frac{P'(Q)Q}{ne'(q_i)} \tag{9}$$

If the regulator imposes an environmental tax in (9) to downstream polluting firms, each firm produces the social optimum production in (7). Then, the optimal environmental tax in (9) is the sum of the distortion from environmental damages and the distortion from the downstream firm's market power per marginal emission. As we can see, the first term of environmental distortion is positive and the second term of market distortion in downstream market is negative. Therefore, the environmental tax could be either positive or negative, depending on the relative size of the distortions from environmental damages and downstream firm's market power, where a negative value for the environmental tax would correspond to a subsidy.[5] Notice that when competition is perfect, i.e., $n \to \infty$, where the market power is insignificant, the optimal environmental tax is exactly the same as the social marginal damage.

Similarly, using market equilibrium conditions in Equation (5) and the optimality conditions in (8), we have the optimal environmental abatement subsidy:

$$s^* = D'(Y)w'(a_i) - t^*\left(w'(a_i) + w''(a_i)\frac{a_i}{m}\right) \tag{10}$$

If the regulator imposes a production subsidy in (10) to upstream firms in eco-industry, each firm produces the social optimum production in (8). Using the optimal environmental tax in (9), we then have the following optimal abatement subsidy:

$$s^* = -tw''(a_i)\frac{a_i}{m} - \frac{P'(Q)q_i}{e'(q_i)}w'(a_i) \tag{10'}$$

$$= D'(Y)w''(a_i)\frac{a_i}{m} - \frac{P(Q)q_i}{e'(q_i)}w'(a_i)\left[\frac{m-\varepsilon_{w'}}{m}\right] \tag{10''}$$

where $\varepsilon_{w'} = \dfrac{w''(a_i)}{w'(a_i)}a_i > 0$, which indicates the relative concavity of the abatement function.

A few remarks are in order. First, the optimal abatement subsidy in (10") is also the combination of two distortions—environmental damages and downstream firm's market power—with some weights on each distortion. This implies that the optimal abatement subsidy is closely related to the optimal environmental tax in (9). However, notice that t is solely determined irrespective of the size of s, while s should be adjusted according to the relative size of t. For example, if t^* is zero,

[5] On this result of two-fold type of tax/subsidy under imperfect competition, see Buchanan (1969) and Barnett (1980) regarding regulating monopolist, and Shaffer (1995) and Lee (1999) regarding regulating oligopolies under blockaded entry.

$s^* = D'(Y)w'(a_i)$, which is positive. In particular, if t^* is nonnegative, s is always positive from (10'). Therefore, under moderate conditions where the environmental damage effect is big enough, i.e., $D'(Y) \geq -P'(Q)q_i / e'(q_i)$, the optimal condition requires a positive tax on downstream firms and a positive subsidy on upstream firms.

However, if the market distortion effect is big enough, i.e., $D'(Y) < -P'(Q)q_i / e'(q_i)$, the optimal environmental tax is negative. For example, from (10), if $t^* = \dfrac{D'(Y)w'(a_i)}{w'(a_i) + w''(a_i)\dfrac{a_i}{m}}$, the optimal subsidy will be zero. Alternatively, zero subsidy at the equilibrium requires that $\varepsilon_{w'} = k \equiv \dfrac{mP'(Q)q_i / e'(q_i)}{D'(Y) + P'(Q)q_i / e'(q_i)}$, where $k \geq m$. That is, the subsidies on both industries are necessary only when $\varepsilon_{w'} < k$. Thus, when the concavity of the abatement function is not too weak, i.e., the value of $\varepsilon_{w'}$ is smaller than or equal to m ($0 < \varepsilon_{w'} \leq m$), the abatement subsidy is always positive.[6]

Second, when the downstream market is in a perfect competition, the optimal tax is positive, $t^* = D'(Y)$ and the optimal subsidy is also positive, $s^* = -\dfrac{D'(Y)w''(a_i)}{m}$. Notice that this subsidy decreases as the number of environmental firms increases. In particular, when the upstream market is in perfect competition, i.e, $m \to \infty$, the optimal subsidy is zero.

Finally, let us examine government revenue calculated as the sum of taxes less subsidies:

$$\begin{aligned} R^B &= nty_i - msa_j \\ &= D'(Y)\left[Y + w''(a_i)a_i a_j \right] + \frac{P'(Q)q_i}{e'(q_i)}\left[Y + w''(a_i)a_i a_j + mw'(a_i)a_j \right] \end{aligned}$$

Government revenue is also composed of the two distortions—environmental damages and downstream firms' market power—with some weights on each distortion. Therefore, government revenue could be either positive or negative, depending on the relative size of the relative concavity of the abatement function. If the government revenue is negative, the government faces a financial budget problem from employing the environmental tax and the abatement subsidy under blockaded entry.

[6] Notice that from the second-order sufficient conditions, only when the concavity of the abatement function is not too weak, there exists a unique m-firm Cournot-Nash equilibrium in the eco-industry market.

IV. Optimal Regulation under Free Entry

In many industries under imperfect competition entry barriers are not sufficiently high. For instance, if the entry cost is small and a large number of potential entrants exist toward the industry, entry into the industry cannot be controllable as a certain fixed number. In this section, we relax the assumption of blockaded entry and consider an industry equilibrium where the output of individual firm and the number of firms in the industry are both endogenously determined by free entry and exit, in which the equilibrium number of firms is endogenously determined by the zero-profit condition.[7] We first focus on the asymmetric free entry case for each industry and we extend to the symmetric free entry case for both upstream and downstream industries and provide the optimal entry fee/subsidy under free entry.

1. Free Entry to Downstream Industry

When the number of firms in upstream sector is given as m, we first examine the welfare effect of free entry to downstream sector. If we consider the welfare function in (6) as a function of the number of firms in downstream sector, n, then total differentiation of this function yields:

$$\frac{dW}{dn} = \frac{dW}{dq_i}\frac{dq_i}{dn} + \frac{dW}{da_j}\frac{da_j}{dn} + \frac{\partial W}{\partial n} \tag{11}$$

If the government imposes an optimal emission tax in (9) and abatement subsidy in (10), the market equilibrium will achieve the social optimum in (7) and (8), in which $\left.\frac{dW}{dq_i}\right|_{t^*,s^*} = \left.\frac{dW}{da_j}\right|_{t^*,s^*} = 0$. Then, the equation (11) becomes:[8]

$$\left.\frac{dW}{dn}\right|_{t^*,s^*} = \left.\frac{\partial W}{\partial n}\right|_{t^*,s^*} = P(Q)q_i - C_d(q_i) - D'(Y)\left[y_i + \frac{mw'(a_i)a_j}{n}\right] \tag{12}$$

On the other hand, we have the following zero-profit condition of the

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[7] This issue is related to the analysis of endogenous market structure. For more discussion on endogenous market structure with free entry, see Shaffer (1995), Katsoulacos and Xepapadeas (1995), and Lee (1999). Schott (2008) compares several different environmental policy instruments, and Park and Lee (2010) suggest two-part system of entry fee and emission tax to achieve the first-best.

[8] Notice that $Y = ny_i = n\left[e(q_i) - w(a_i)\right] = n\left[e(q_i) - w(\frac{ma_j}{n})\right]$ since $na_i = ma_j$.

downstream firm in (1) under free entry:

$$\Pi_i = P(Q)q_i - C_d(q_i) - r \cdot a_i - t \cdot y_i(q_i, a_i) = 0 \tag{13}$$

Then, inserting the optimal emission tax in (9) and abatement subsidy in (10) gives the following relation:

$$P(Q)q_i - C_d(q_i) = \left[D'(Y) + \frac{P'(Q)q_i}{e'(q_i)} \right] \left[y_i + w'(a_i)a_i \right] \tag{13'}$$

Then, Equation (12) becomes

$$\left. \frac{dW}{dn} \right|_{t^*, s^*} = \left[\frac{P'(Q)q_i}{e'(q_i)} \right] \left[y_i + w'(a_i)a_i \right] < 0.$$

It implies that the number of downstream firms under free entry is greater than the socially optimal number of downstream firms: excessive entry theorem holds, provided by Mankiw and Whinston(1986) and Suzumura and Kiyono(1987). Therefore, there should be entry regulation for lessen the number of firms in the downstream sector. In particular, if the regulator imposes an lump-sum entry fee of $-\left(\frac{P'(Q)q_i}{e'(q_i)} \right) \left(y_i + w'(a_i)a_i \right)$, which is positive, on the entrant to downstream industry, the socially optimal number of firms will produce the consumption goods in the downstream industry.

2. Free Entry to Upstream Industry

Next, when the number of firms in downstream sector is given as n, we examine the welfare effect of free entry to upstream sector. Similarly, if we consider the welfare function in (6) as a function of the number of firms in upstream sector, m, then total differentiation of this function yields:

$$\frac{dW}{dm} = \frac{dW}{dq_i}\frac{dq_i}{dm} + \frac{dW}{da_j}\frac{da_j}{dm} + \frac{\partial W}{\partial m} \tag{14}$$

Again, if the government imposes an optimal emission tax in (9) and abatement subsidy in (10), the market equilibrium will achieve the social optimum in (7) and

(8), in which $\left.\frac{dW}{dq_i}\right|_{t^*,s^*} = \left.\frac{dW}{da_j}\right|_{t^*,s^*} = 0$. Then, the Equation (14) becomes:

$$\left.\frac{dW}{dm}\right|_{t^*,s^*} = \left.\frac{\partial W}{\partial m}\right|_{t^*,s^*} = -C_u(a_j) + D'(Y)w'(a_i)a_j \tag{15}$$

Notice that from the optimal condition of abatement goods in (8'), we have $C_u'(a_j) = D'(Y)w'(a_j)$. Then, combining this into (15) yields

$$\left.\frac{dW}{dm}\right|_{t^*,s^*} = C_u'(a_j) - \frac{C_u(a_j)}{a_j} \tag{15'}$$

Thus, with the optimal emission tax and abatement subsidy, the welfare distortion from the number of firms in the upstream industry depends on the scale of returns in production of abatement goods. First, under the increasing returns of scale where $MC_u(a_j) < AC_u(a_j)$, we have $\frac{dW}{dm} < 0$. That is, if the marginal cost of upstream industry is smaller than the average cost, from the viewpoint of socially optimal number of firms, the number of firms in upstream market is excessive. Second, under the decreasing returns of scale where $MC_u(a_j) > AC_u(a_j)$, we have $\frac{dW}{dm} > 0$. That is, if the marginal cost of upstream industry is greater than the average cost, the number of firms in upstream market is insufficient than the socially optimal number of firms. Finally, under the constant returns of scale where $MC_u(a_j) = AC_u(a_j)$, we have $\frac{dW}{dm} = 0$. Then, the number of firms in upstream market is the socially optimal.

Now, we will consider the equilibrium number of firms in upstream market under free entry. Then, we have the following zero-profit condition of the upstream firm in (4) under the free entry, $\Pi_j = r \cdot a_j - C_u(a_j) + s \cdot a_j = 0$, which yields:

$$C_u(a_j) = r \cdot a_j + s \cdot a_j \tag{16}$$

Then, inserting the optimal emission tax in (9) and abatement subsidy in (10) into Equation (15) gives the following relation:

$$\left.\frac{dW}{dm}\right|_{t^*,s^*} = tw''(a_i)\frac{a_i a_j}{m} = \left(D'(Y) + \frac{P'(Q)}{e'(q_i)}q_i\right)w''(a_i)\frac{a_i a_j}{m} \tag{17}$$

It implies that the number of upstream firms under free entry is not equal to the socially optimal number of firms,[9] and its result depends on the size of optimal emission tax in (9). If the emission tax is positive, where the effect of environmental damage is greater than the effect of market power in imperfect competition, the free entry equilibrium yields excessive entry. Then, there should be entry regulation for lessen the number of firms in upstream sector. In particular, the lump-sum entry fee of $-tw''\frac{a_i a_j}{m}$ yields the socially optimal number of firms in the upstream industry. However, if the emission tax is negative, where the market power in imperfect competition is serious than the environmental damage, the free entry equilibrium yields insufficient entry. Then, imposing the lump-sum entry subsidy increases the equilibrium number of firms in the upstream industry.

3. Optimal Entry Regulation under Free Entry

Finally, we will consider the free entry case for both upstream and downstream industries and examine the economic implications of the optimal entry fee in both industries. Attempting to find appropriative instruments to permit entry into an industry, we consider the two-part taxation system, the combined form of output tax/subsidy and entry fee/subsidy, and take a general approach to find the optimal system.

By denoting ϕ_d as the entry fee for the downstream firm and ϕ_u as the entry fee for the upstream firm, we get the following zero-profit conditions for each industry under free entry.

$$\Pi_i = P(Q)q_i - C_d(q_i) - r \cdot a_i - t \cdot y_i - \phi_d = 0 \tag{18}$$

$$\Pi_j = r \cdot a_j - C_u(a_j) + s \cdot a_j - \phi_u = 0 \tag{19}$$

Notice that the entry fee will determine the equilibrium number of firms in each market. From the equilibrium condition in (3) and (5) and the optimal environmental tax and subsidy in (9) and (10), we have the following zero-profit condition for the downstream and upstream markets:

[9] The economic issue of excessive entry under free entry is provided by Mankiw and Whinston (1986) and Suzumura and Kiyono (1987) under the single market analysis. Ghosh and Morita (2007) analyzed the vertical oligopoly model and showed free entry in upstream market may produce insufficient entry.

$$\Pi_i = P(Q)q_i - C_d(q_i) - \left(D'(Q) + \frac{P'(Q)q_i}{e'(q_i)} \right)\left(y_i + w'(a_i)\right) - \phi_d = 0 \tag{18'}$$

$$\Pi_j = D'(Y)w'(a_i)a_j - C_u(a_j) - \left(D'(Y) + \frac{P'(Q)q_i}{e'(q_i)} \right) w''(a_i)\frac{a_i a_j}{m} - \phi_u = 0 \tag{19'}$$

On the other hand, from the social welfare function in (6), we can derive the following first-order necessary conditions for the two variables, n and m, the number of firms in each industry:

$$\frac{\partial W}{\partial n} = P(Q)q_i - C_d(q_i) - D'(Y)\left[y_i + w'(a_i)a_i\right] = 0 \tag{20}$$

$$\frac{\partial W}{\partial m} = -C_u(a_j) + D'(Y)w'(a_i)a_j = 0 \tag{21}$$

Then, using the market equilibrium conditions and the optimality conditions in (18) and (20), and (19) and (21), the following optimal entry fee for each industry could be obtained:

$$\phi_d^* = -\frac{P'(Q)Q}{ne(q_i)}\left[y_i + w'(a_i)a_i\right] \tag{22}$$

$$\phi_u^* = -\left(D'(Y) + \frac{P'(Q)}{e'(q_i)}q_i \right) w''(a_i)\frac{a_i a_j}{m} = -tw''(a_i)\frac{a_i a_j}{m} \tag{23}$$

A few remarks are in order. First, from (22), the optimal entry fee for the downstream firm is always positive, as described in the previous section. And it approaches zero when the market is in perfect competition.

Second, from (23), the optimal entry fee for the upstream firms has a similar form to the environmental tax with some weights. Only when the optimal environmental tax for downstream firms is positive, the optimal entry fee for the upstream firms is also positive. But, when the optimal environmental tax for downstream firms is negative, which is a subsidy, the optimal entry fee for the upstream firms is also negative, which actually means the entry subsidy of upstream firms.

Third, the optimal rate of entry fee for the upstream firms is determined by the equilibrium number of firms in both downstream and upstream industries. For example, as $n \to \infty$, where the downstream market is in perfect competition, the optimal environmental tax is positive, $t^* = D'(Y)$, and thus the optimal entry fee for the upstream firms is also positive. But, the optimal entry fee for the upstream firms is decreasing as m is increasing. In particular, as $m \to \infty$, where the upstream market is in perfect competition, it approaches zero. In addition, as t approaches zero, ϕ_u^* approaches zero.

Fourth, total payment of a downstream firm under two-part system is as follows:

$$T_d = \phi_d^* + t^* y_i = D'(Y)y_i - \frac{P'(Q)q_i}{e'(q_i)} w'(a_i)a_i$$

The total payment of a downstream firm captures not only the environmental damage effect but the output distortion effect from the downstream firm's market power with some weights.

Fifth, total payment of an upstream firm under two-part system is as follows:

$$T_u = \phi_u^* - s^* a_j = \frac{P'(Q)q_i}{e'(q_i)} w'(a_i)a_j$$

Total payment of an upstream firm captures the output distortion effect from the downstream firm's market power with the same weights on the payment of the downstream firm, which will be cancelled out in an aggregated payment.

Finally, as an aggregation, the government revenue can be calculated as the sum of taxes less subsidies. Then, the regulator can raise the following revenues from the regulation:

$$R^F = nT_d + mT_u = n\left[e(q_i) - w(a_i)\right]D'(Y) = D'(Y)Y$$

Notice that the government revenue is always positive and is exactly the same with the Pigouvian rate, in which fiscal equivalence is achieved at the amount of marginal damage. That is, this regulation is financially feasible from the standpoint of the regulator. In particular, if $D(Y)'' \geq 0$ and thus, if environmental damages can be covered by the revenue, i.e., $R(Y) > D(Y)$ or $D'(Y) > \frac{D(Y)}{Y}$, the regulator does not need to construct the second-best Ramsey rule.[10]

[10] Under the Ramsey rule, the budget balance effect of the regulation should be taken into policy consideration. For the feasibility of the financial budget under environmental regulation, see Shaffer (1995) and Sugeta and Matsumoto (2005).

V. Concluding Remarks

This article analyzed the relationship between pollution abatement technology and environmental policy in a vertical oligopoly structure, in which imperfect competitions among upstream environmental firms and downstream polluting firms are taken into consideration. In particular, we employed the appropriate combination of policy instruments, such as environmental tax, abatement subsidy, and entry fee, to correct simultaneously for the pollution externality, output distortion, and excessive (or insufficient) entry. We derived the optimal combination of instruments under blockaded entry and endogenous entry. The following are our main findings.

First, we considered the optimal environmental tax and abatement subsidy when both upstream and downstream industries are imperfectly competitive under blockaded entry. We showed that the optimal environmental tax should be used for negative externality and output restrictions in final production, and the optimal abatement subsidy should incorporate the tax effect of upstream market restrictions on abatement activity.

Second, we examined the relationship between the environmental tax and the subsidy rate and showed that the production subsidy for abatement goods has a similar form as the output/pollution tax, with some weights on each distortion. Therefore, when environmental damage is serious under moderate conditions, the optimal policy is a positive tax on consumption goods and a positive subsidy on abatement goods.

Third, we extended the model to the free entry case for both industries and examined the optimal two-part system with an entry fee. In particular, we showed that the regulator should impose an entry fee on downstream industry to lessen excessive entry and provide entry subsidy to upstream industry to increase insufficient entry when market power in eco-industry is significant. Furthermore, we showed that the regulator's revenue is exactly the same with the Pigouvian rule.

Finally, policy relevant implication of the analysis is that for the optimal policy combinations, environmental regulation should be paired with industrial regulation. In particular, when the multiple regulators are segregated and independent, policy coordination between various regulators in different government bodies—such as environmental protection and industrial antitrust agencies—deserves closer scrutiny. Moreover, specific mandates and lack information about other regulatory sectors may leave regulators with an incomplete set of instruments from which to choose. Thus, one of extensions of our analysis is to incorporate the insufficient tools for regulating industries, for example, where subsidy is unavailable and thus environmental tax is the only instrument. These issues are challenges for future research on optimal environmental policy.

References

Barnett, A. H. (1980), "The Pigouvian Tax Rule under Monopoly," *American Economic Review*, 70, 1037-1041.

Buchanan, J. M. (1969), "External Diseconomies, Corrective Taxes and Market Structures." *American Economic Review*, 59, 174-177.

Canton, J., A. Soubeyran. and H. Stahn (2008), "Environmental Taxation and Vertical Cournot Oligopolies: How Eco-Industries Matter," *Environmental and Resource Economics*, 40, 369-382.

David, M. and B. Sinclair-Desgagne (2005), "Environmental Regulation and the Eco-Industry," *Journal of Regulatory Economics*, 28(2), 141-155.

Ghosh, A. and H. Morita (2007), "Free Entry and Social Efficiency under Vertical Oligopoly," *RAND Journal of Economics*, 38(3), 541-554.

Katsoulacos, Y., and A. Xepapadeas (1995), "Environmental Policy under Oligopoly with Endogenous Market Structure," *Scandinavian Journal of Economics*, 97, 411-420.

Lee, S. H. (1999), "Optimal Taxation for Polluting Oligopolists with Endogenous Market Structure," *Journal of Regulatory Economics*, 15, 293-308.

Levin, D. (1985), "Taxation within Cournot Oligopoly," *Journal of Public Economics*, 27, 281-290.

Mankiw, N. G. and M. D. Whinston (1986), "Free Entry and Social Inefficiency," *RAND Journal of Economics*, 17, 48-58.

Park, C. H. and S. H. Lee. (2010), "Two-Part Tax for Polluting Oligopolist with Endogenous Entry," *Environmental and Resource Economics Review*, 19(3), 459-483.

Requate, T. (2007), "Environmental Policy under Imperfect Competition," In *The International Yearbook of Environmental and Resource Economics 2006/2007*, ed. T. Tietenberg and H. Folmer. Northampton, MA: Edward Elgar.

Schott, S. (2008), "Regulatory Coordination and Optimal Taxation of Polluters in Non-Competitive Markets," Working paper, Carleton University.

Shaffer, S. (1995), "Optimal Linear Ttaxation of Polluting Oligopolists," *Journal of Regulatory Economics*, 7, 85-100.

Simpson, R. (1995), "Optimal Pollution Tax in a Cournot Duopoly," *Environmental and Resource Economics*, 6, 359–369.

Sugeta, H., and S. Matsumoto (2005), "Green Tax Reform in an Oligopolistic Industry," *Environmental and Resource Economics*, 31, 253-274.

Suzumura, K. and K. Kiyono (1987), "Entry Barriers and Economic Welfare," *Review of Economic Studies*, 54, 157-167.