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Abstract

We formulate the vertical market structure with a downstream polluting industry and an upstream eco-industry, where both private and public eco-firms produce abatement goods. We then investigate the voluntary commitments on target emissions from polluting firms and their impacts on the optimal decisions of privatization policies. We provide the conditions for the non-optimality of partial privatization and show that, depending on the environmental damage, full nationalization, full privatization or partial privatization can be optimal. In particular, it is shown that there is a U-shaped relationship between environmental damage and the optimal degree of privatization. It supports that government should have large ownership of privatized eco-firms for environmental protection when environmental damage is serious.

JEL classification: D90; E21

Keywords: Abatement Goods; Commitments; Eco-Industry; Mixed Oligopoly; Partial Privatization

1. Introduction

Global concerns on climate change have required strong environmental protection and significant government interventions. Traditional environmental policies have taken the governmental regulations with the form of command-and-control (such as standards and quotas) and market-based incentive instruments (such as taxes/subsidies and tradable permits systems). Recently, a third approach of environmental policy instruments has emerged with the name of voluntary agreements. Voluntary agreements are commitments on abatement activities from polluting firms in improving their environmental performances beyond the required regulation level. They are practically implemented in accompany with other environmental policy instruments, which can induce polluting firms to participate in improving environmental quality.[1]

On the other hand, tighter environmental regulations have also contributed to the emergence of the eco-industry, in which eco-firms provide abatement goods and services to mitigate pollution and manage environmental resources efficiently.[2] Thus, many governments have recently recognized the importance of the eco-industry and have enacted various policies to encourage the industry. In particular, governments are significantly increasing policy attentions toward public institutions and organizations so that public firms can be key players in this eco-industry. The policy consequences of whether privatizing public eco-firms or nationalizing private eco-

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[1] In general, they have potential cost savings advantages to solve informational problems while credibility and capture problems also exist. See the literatures in Alberni and Segerson (2002), Lyon and Maxwell (2003), David (2005) and Hirose et al. (2017)..

[2] The importance of eco-industry has been recognized by numerous reports from national and international institutions such as OECD (1996), Berg et al (1998), Ecotech Research and Consulting Ltd (2002) and Kennett and Steenblik (2005). For the recent analysis of the eco-industry, see David and Sinclair-Desgagne (2005, 2009), Canton, et al. (2008, 2012), David et al. (2011), Lee and Park (2011, 2017).

firms in mixed oligopolies will draw the important attention of policymakers.[3]

Recent literature on environmental policy in mixed oligopolies, where public firm competes with private firms has intensively analyzed the impact of nationalization on the environment. For example, Ohori (2006) and Xu and Lee (2015) showed that partial privatization is socially optimal in an international mixed duopoly. Naito and Ogawa (2009) and Kato (2013) also argued that partial privatization improves the environment without allowing for any environmental policy instruments. Pal and Saha (2015) and Xu, et al. (2016) examined a differentiated mixed duopoly with external costs and supported the optimality of partial privatization under emission taxes.

As a matter of fact, since the seminal contribution by Matsumura (1998), who shows that neither full nationalization nor full privatization is optimal under moderate conditions in a homogenous mixed duopoly with the same technology, much research has been done on the optimality of partial privatization policies with a focus on different aspects of economic phenomena.[4] Most papers in the literature showed that various factors affect the optimal degree of privatization, but the non-optimality of full nationalization is quite robust even under environmental externality, as we described in the above, or under the two related market structures.[5]

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[3] In mixed oligopolies, public firm competes with private firms in a broad range of industries such as oil, gas, automobiles, steel, chemicals, electricity, power plants, and hospitals, in which pollution problem is significantly relevant.

[4] In the recent literature on mixed oligopolies, the partial privatization approach is popular and extensively used in many contexts. Some important topics are included in Heywood and Ye (2009), Lee et al. (2013) and Nakamura and Takami (2015), among others.

[5] As exceptional works, Matsumura and Kanda (2005) and Cato (2008) provided the rationale on full nationalization policy in free entry market with mixed oligopoly. However, Cato and Matsumura (2012, 2015) showed that partial privatization is always optimal when the competitors are foreign.

For instance, taking the two related market structures into consideration, Lee et al. (2013) investigated the privatization and strategic trade policies between the two international mixed markets, and Yang, et al. (2014) and Wu et al. (2016) examined a privatization policy in a vertically related market in which the downstream industry or upstream industry is a mixed market. They demonstrated that partial privatization is optimal depending upon the cost efficiency gap, but full privatization is never optimal. This represents that the non-optimality of full privatization is strikingly robust even under two related market structures. In reality, however, fully-nationalized firms exist in mixed markets and also emerge in the eco-industry with large market shares, even during privatization waves. Thus, it is urgent to investigate the importance of the public ownership in the eco-industry and shed light on the understanding the existence of full nationalization.

This paper investigates alternative policy instrument to regulate pollution, which is largely overlooked in the academic literature, namely, voluntary commitments on target emissions and public ownership of an abatement technologies. The objective of this paper is to present an insightful analysis of the non-optimality of partial privatization in mixed oligopolies in aligning the private and social concerns on the environmental problem.

In this paper, we consider an environment-related vertical market structure with polluting industry and eco-industry, in which both private and (possibly partially-privatized) public eco-firms produce abatement goods in a mixed duopoly market. We then formulate the voluntary commitments on target emissions from polluting firms under government regulations on abatement technologies. Under the commitment with abatement goods, we show that the optimality of full privatization or full nationality holds even under the same cost efficiency between the two eco-firms. This result sharply contrasts the previous results on the optimality of partial privatization.

Specifically, we show that, depending on the level of environmental damage, full nationalization, full privatization or partial privatization can be optimal. As the damage level increases, the optimal privatization policy decreases to zero, hence, full nationalization becomes optimal to decrease the total production of final goods and to increase the production of abatement goods. If the damage level becomes very serious, however, we also show that the government needs to privatize the fully-nationalized public eco-firm again to improve the cost efficiency of the public firm. Further, we find that a higher damage level requires an implicit subsidy for a public eco-firm. Thus, the government should kick out the private eco-firm under optimal privatization policy. These observations constitute a U-shaped relationship between environmental damage and the optimal degree of partial privatization.[6] This finding partially explains the reality that the government should have significant ownership of a privatized eco-firm for specific purposes, such as environmental protection.

The rest of the paper is organized as follows. Section 2 describes a vertically related industry between polluting firms and eco-firms. Section 3 analyzes the effect of privatization policy. Section 4 presents concluding remarks.

2. The model

Consider a model that consists of two vertically related industries: private, polluting firms in the downstream industry produce final goods with emitting pollutants while public and private eco-firms in the upstream industry produce abatement goods that reduce the emissions created by the downstream industry. We consider strategic interactions in both industries. In what follows, without loss of generality, the duopoly case will be investigated for each industry.[7]

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[6] Pal and Saha (2015) and Xu et al. (2016) examined a differentiated mixed duopoly with emission taxes, and showed that environmental damage will be non-monotone in degree of privatization and that optimal privatization is always partial privatization.

[7] This is to simplify the analysis. Most of our results remain true, even under a general mixed oligopoly.

2.1. Profits in final goods industry

Consider a Cournot duopoly model in the final goods industry with two private firms. Both firms produce homogeneous goods with linear demand and zero marginal production cost. Then, each firm has a profit function as follows:

$$\pi_i = (A - Q)q_i - va_i \quad \text{for } i = 1,2 \tag{1}$$

where $P = A - Q$ is market price, $Q = q_1 + q_2$ is the total output, q_i is firm i's output, a_i is firm i's purchase of abatement goods and v is the price of the abatement goods.

In the production process, each firm emits the same types of pollutants. Denoting $\tilde{e}_i$ as firm i's emissions and $\tilde{e}_i = q_i$ without abatement technologies. If, however, the firm purchases a_i amounts of abatement goods from eco-firms, then it can reduce the emission by a_i. We assume that the abatement technology takes end-of-pipe clean technology and thus, the amount of emissions that are harmful to the environment e_i is,

$$e_i = \tilde{e}_i - a_i = q_i - a_i. \tag{2}$$

Using the abatement technology where polluting firms purchase positive abatement goods, the profit function in (1) can be rewritten as:[8]

$$\pi_i = (A - Q - v)q_i + ve_i \quad \text{for } i = 1,2 \tag{3}$$

Two important things should be noted in the above equations with positive abatement goods. One is that v is the additional unit cost for production while it is also the unit benefit from the emission. The other is that the decision on the purchase of abatement goods, a_i, is the same as

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[8] For the justification of positive abatement goods in the analysis, see the structure of the game in the below description and footnote 9.

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the choice of outputs q_i if the target emissions, e_i, are given.

2.2. Profits in eco-industry

Consider a Cournot duopoly model in the eco-industry with a private firm and a (possibly partially-privatized) public firm. Both firms produce homogeneous abatement goods with the same quadratic cost as follows:

$$c(a_j) = a_j^2/2 \quad \text{for } j = r, p \tag{4}$$

where r stands for "private," and p stands for "public." Hence, the profits of the eco-firms become:

$$\pi_r = va_r - a_r^2/2 \tag{5}$$

$$\pi_p = va_p - a_p^2/2 \tag{6}$$

2.3. The total surplus

The total surplus W in the two industries is defined as the sum of the consumer surplus and producer surplus minus the environmental damages. Namely,

$$W = \int_0^Q (A - u)du - \frac{{a_r}^2}{2} - \frac{{a_p}^2}{2} - d(e_1 + e_2) \tag{7}$$

where d stands for the social cost per emission or the marginal environmental damage, which is assumed as constant and positive.

Following Matsumura (1998), the privatized eco-firm maximizes the weighted sum of its own profits and the total surplus. Then, the objective function T_p becomes:

$$T_p = \alpha\pi_p + (1-\alpha)W \tag{8}$$

where α denotes the ownership share of the private sector that corresponds to the degree of privatization, which is determined by total surplus-maximizing government.

2.4. The structure of the game

The market equilibria can be analyzed by the outcome of the sequential game that consists of four stages. At the first stage, the government determines the degree of privatization of public eco-firm, α, to maximize the total surplus, W. At the same time, the government announces a subsidy policy that polluting firm will receive an appropriate subsidy when it chooses abatement technologies. That is, privatization policy in eco-industry will be implemented in combination with subsidy policy, which can induce polluting firms to purchase abatement goods from the eco-industry. At the second stage, each polluting firm commits to the amount of target emissions, e_i, and the choice of abatement technologies, a_i. At the third stage, the private and public eco-firms engage in a Cournot competition over the abatement goods, in which the private eco-firm maximizes its own profits and the public eco-firm maximizes the weighted sum of its own profits and total surplus. At the fourth stage, the polluting firms engage in a Cournot competition over the final goods and abatement goods. All of the games are solved by backward induction and the possible outcome is a subgame perfect equilibrium.

In the game sequence on commitment, each polluting firm determines the amount of target emissions in the second stage before the actual purchase of abatement goods is determined in the fourth stage, as a result of the Cournot competition between the eco-firms in the third stage. Thus, their commitments on target emissions influence the eco-firms' behavior (i.e., the market price of abatement goods). It implies that the polluting firms in the second stage should choose to either reduce the production of final goods or to engage in abatement activities (i.e., the intention of purchasing abatement goods in the fourth stage) after observing government subsidy policy on abatement technologies of the first stage. For the sake of simplicity, we assume that the subsidy amount on abatement technologies is sufficiently large so that polluting firms always choose to engage in abatement activities in the second stage.[9] Therefore, we can focus on the privatization policy in the eco-industry in the following analysis.

3. The equilibrium and main proposition

3.1. Fourth stage: Competition in final good industry

To characterize the Cournot-Nash equilibrium when choosing final goods at the fourth stage, we assume that downstream firms are price takers on abatement goods. Note that given the voluntary commitments on target emissions, e_i in the second stage, the amount of purchase of abatement goods, a_i, will be solely determined by the choice of q_i. Thus, the best-response function for each firm in the final goods industry can be derived from the first order condition for the maximization of firm i's profit in (3) with respect to q_i as follows:

$$\frac{\partial \pi_i}{\partial q_i} = A - Q - q_i - v = 0 \quad \text{for} \quad i = 1,2 \tag{9}$$

Solving the above two equations, we have the following equilibrium outputs:

$$q_i = \frac{A - v}{3} \quad \text{for} \quad i = 1,2 \tag{10}$$

Substituting equation (10) into equation (2) gives the derived demand function of abatement goods as follows:

$$a_i = \frac{A - v - 3e_i}{3} \quad \text{for} \quad i = 1,2 \tag{11}$$

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[9] Each firm will choose abatement technologies and engage in abatement activities if and only if it can earn higher profit under subsidization than no abatement activities. Hence, government can propose a subsidy policy that yields larger profit in the subgame perfect equilibrium of the game than the profit without abatement goods, in which private incentive to adopt abatement technologies should be greater than no abatement technologies.

3.2. Third stage: Competition in eco-industry

To investigate the Cournot-Nash equilibrium when choosing abatement goods at the third stage, the market demand function for the abatement goods, a_U , is needed. As David and Sinclair-Desgagne (2005, 2009), Canton et al. (2008) and Lee and Park (2011, 2017) adopted, we assume that the eco-industry market-clearing price for abatement goods will be set at equilibrium. Then, from equation (11) we have the followings:

$$a_r + a_p = a_U = a_1 + a_2 = \frac{2A - 2v - 3(e_1 + e_2)}{3} \tag{12}$$

Solving the above equation for v gives the following inverse demand function for abatement goods:

$$v(a_U) = A - \frac{3}{2}(e_1 + e_2 + a_U) \tag{13}$$

Substituting the above equation into equation (5), the objective function for the private firm, π_r can be rewritten as:

$$\pi_r = v(a_U)a_r - a_r^2/2 \tag{14}$$

Similarly, the objective function for the public firm can be rewritten as:

$$T_p = \alpha[v(a_U)a_p - a_p^2/2] + (1-\alpha)W \tag{15}$$

The first-order conditions for private and public firms give corresponding best-response functions as follows:

$$\frac{\partial \pi_r}{\partial a_r} = v(a_r + a_p) + v'(a_r + a_p)a_r - a_r = 0 \tag{16}$$

$$\frac{\partial T_p}{\partial a_p} = \alpha\{v(a_r + a_p) + v'(a_r + a_p)a_p - a_p\} + (1-\alpha)(d - a_p) = 0 \tag{17}$$

Then, we have the reaction functions of private and public eco-firms as follows:

$$a_r(a_p) = \frac{2A - 3(e_1 + e_2) - 3a_p}{8} \tag{18}$$

$$a_p(a_r) = \frac{2(\alpha A + d(1-\alpha)) - 3\alpha(e_1 + e_2) - 3\alpha a_r}{2 + 6\alpha} \tag{19}$$

Note that the reaction functions are downward-sloping and thus, the abatement goods are strategic substitutes between the two eco-firms. Also, the slope of the reaction function of the public firm is higher than that of the private firm and thus, the public firm is less sensitive. Solving equations (18) and (19) gives the equilibrium amounts of abatements, a_r and a_p, and the equilibrium price v, all of which are functions of the emissions committed by the polluting firms at the second stage, e_1 and e_2

$$a_r = \frac{4A - 6d + 6(A+d)\alpha - 3(2+3\alpha)(e_1 + e_2)}{16 + 39\alpha} \tag{20}$$

$$a_p = \frac{2(5\alpha A + 8d(1-\alpha)) - 15\alpha(e_1 + e_2)}{16 + 39\alpha} \tag{21}$$

$$a_U = \frac{2(2A(1+4\alpha) + 5d(1-\alpha) - 3(1+4\alpha)(e_1 + e_2))}{16 + 39\alpha} \tag{22}$$

$$v = \frac{5\{(4A - 6(\alpha A - (1-\alpha)d) - 3(2+3\alpha)(e_1 + e_2)\}}{32 + 78\alpha} \tag{23}$$

3.3. Second stage: Commitments on target emissions

Now we can define the profit of the polluting duopoly at the second stage as a function of emissions, e_1 and e_2:

$$\pi_i = \frac{\{2(5d(1-\alpha) + A(2+8\alpha)) + 5(2+3\alpha)e_j\}^2 - 5(2+3\alpha)(86+219\alpha)e_i^2}{4(16+39\alpha)^2}$$
$$+ \frac{20e_i(A(2+3\alpha)(18+47\alpha) - 2d(1-\alpha)(19+51\alpha) - (2+3\alpha)(19+51\alpha)e_j}{4(16+39\alpha)^2}$$

for $i = 1,2$ and $i \neq j$ (24)

To examine commitment levels on target emissions, the best-response function for each firm can be found from the first-order conditions for the profit maximization with respect to the level of emissions as follows:

$$\frac{\partial \pi_i}{\partial e_i} = \frac{5\{(A(2+3\alpha)(18+47\alpha) - d(1-\alpha)(19+51\alpha)\}}{(16+39\alpha)^2}$$
$$-\frac{5\{(2+3\alpha)(19+51\alpha)e_j + (2+3\alpha)(86+219\alpha)e_i)\}}{2(16+39\alpha)^2} = 0, \text{ for } i = 1,2 \text{ and } i \neq j. \quad (25)$$

The above equations give the emission levels that maximize polluting firms' profits, which are a function of the degree of privatization:

$$e_1 = e_2 = \frac{2A(2+3\alpha)(18+47\alpha) - 4d(1-\alpha)(19+51\alpha)}{(2+3\alpha)(124+321\alpha)} \quad (26)$$

3.4. Upper bounds of damage level

Now all of the decision variables are functions of the degree of privatization, α, and the exogenous parameters are as follows:

$$e_1 = e_2 = \frac{2A(2+3\alpha)(18+47\alpha) - 4d(1-\alpha)(19+51\alpha)}{(2+3\alpha)(124+321\alpha)} \quad (27)$$

$$q_1 = q_2 = \frac{2A(19+51\alpha) + 15d(1-\alpha)}{(124+321\alpha)} \quad (28)$$

$$a_1 = a_2 = \frac{A(4+22\alpha+24\alpha^2) + d(106+143\alpha-249\alpha^2)}{(2+3\alpha)(124+321\alpha)} \quad (29)$$

$$a_p = \frac{10\alpha A(2+3\alpha) + 8d(31+38\alpha-69\alpha^2)}{(2+3\alpha)(124+321\alpha)} \quad (30)$$

$$a_r = \frac{2\{A(2+3\alpha) - 9d(1-\alpha)\}}{124+321\alpha} \quad (31)$$

$$a_U = \frac{2d(106+143\alpha-249\alpha^2) + A(8+44\alpha+48\alpha^2)}{(2+3\alpha)(124+321\alpha)} \quad (32)$$

$$v = \frac{5\{A(2+3\alpha) - 9d(1-\alpha)\}}{124+321\alpha} \quad (33)$$

$$P = A - Q = \frac{3A(16+39\alpha) - 30d(1-\alpha)}{124+321\alpha} \quad (34)$$

Independently of the parameter values, the outputs of final goods (q_1 and q_2), the purchases of abatement goods (a_1 and a_2), and the production of the public eco-firm (a_p) are all positive when the degree of partial privatization, α , takes a value between zero and unity. However, depending on the damage level, the emission levels committed to by the polluting firms (e_1 and e_2), the production of the private eco-firm (a_r), the price of abatement goods (v), and the price of final goods (P) can be either positive or negative. Since those variables must be non-negative in equilibrium, the following restrictions should be considered:

$$e_1 = e_2 \geq 0 \quad \text{when} \quad d \leq \overline{d}_e = \frac{A(2+3\alpha)(18+47\alpha)}{2(1-\alpha)(19+51\alpha)}$$

$$a_r \geq 0 \ \ \& \ v \geq 0 \quad \text{when} \quad d \leq \overline{d}_v = \frac{A(2+3\alpha)}{9(1-\alpha)},$$

$$P \geq 0 \quad \text{when} \quad d \leq \overline{d}_P = \frac{A(16+39\alpha)}{10(1-\alpha)}.$$

Since $\lim_{\alpha \to 1} \overline{d}_e = \lim_{\alpha \to 1} \overline{d}_v = \lim_{\alpha \to 1} \overline{d}_v = \infty$, the variables are surely positive under full privatization (i.e., $\alpha = 1$), regardless of the damage level. On the other hand, under partial privatization and full nationalization ($0 \leq \alpha < 1$), they can be negative. Since the inequality $\overline{d}_P > \overline{d}_{e_i} > \overline{d}_v$ holds when $0 \leq \alpha < 1$, the damage level d must be smaller than or equal to $\overline{d}_v$ for the non-trivial equilibrium to exist. Put differently, $\overline{d}_v$ is the upper bound of the damage level when $0 \leq \alpha < 1$.

A few remarks are in order. First, each polluting firm purchases abatement goods to reduce both the emissions and outputs levels even if environmental damage is zero (i.e., $a_i > 0$ even if $d = 0$). However, in the case of zero damage, the polluting firms' commitment on emission levels under government subsidy worsens welfare. This implies that output restriction of downstream firms can be harmful to society when the environmental damage is not serious.[10]

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[10] In that case, the government can either eliminate subsidy policy or shut down the eco-industry to

Second, as damage increases, the emission levels decrease (i.e., $\frac{\partial e_i}{\partial d} < 0$). Third, the production of a public eco-firm is greater than that of a private eco-firm when the damage level is greater than a certain damage level[11] (i.e., $a_p > a_r \Leftrightarrow d > \frac{2A(2+3\alpha)}{142+303\alpha}$ and $\alpha \in [0,1)$).

3.5. First stage: Decisions on privatization

The total surplus can now be expressed as a function of only one endogenous variable, α, (i.e., the degree of privatization) as follows:

$$
\begin{aligned}
W = \frac{1}{(2+3\alpha)^2(124+321\alpha)^2} & \left\{ 4A^2(2+3\alpha)^2\{1632+\alpha(8541+11152\alpha)\right\} \\
& + 4d^2(1-\alpha)\{1124+\alpha(36068+3\alpha(45539+45897\alpha))\} \\
& - 2Ad(2+3\alpha)\{7416+\alpha(56682+3\alpha(131963+93189\alpha))\}. \qquad (35)
\end{aligned}
$$

The government chooses a degree of privatization so as to maximize the total surplus. Thus, we can check the optimal degree of privatization from the following relationships:[12]

i) If $\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=0} \leq 0$ then $\alpha^* = 0$ is optimal (corner solution).

ii) If $\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} \geq 0$ then $\alpha^* = 1$ is optimal (corner solution).

iii) If $\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=0} > 0$ and $\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} < 0$ then α^* has an interior optimum value between 0 and 1.

The first derivative of the total surplus, W, with respect to the degree of privatization, α,

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protect the welfare from the strategic behavior of the output restrictions by the downstream firms if the sunk cos is not so high.

[11] In particular, we can show that the production of a public eco-firm is always higher than that of a private eco-firm when the damage level is greater than d_1 in the following analysis.

[12] In Appendix C, we will provide numerical examples for the validity of the analysis and show that the total surplus is monotonic or single-peaked over the degree of privatization when it takes a value between 0 and 1.

provides the following relationships:

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} > 0 \Leftrightarrow 0 < d < d_1 = \frac{A(\sqrt{773049}-373)}{9968} (\approx 0.0507A) \tag{36}$$

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=0} < 0 \Leftrightarrow d_2 = \frac{6A}{89} (\approx 0.0674A) < d < d_3 = \frac{63A}{299} (\approx 0.2107A) \tag{37}$$

The above relationships can be displayed in Fig.1, which leads us to Proposition 1.

Proposition 1

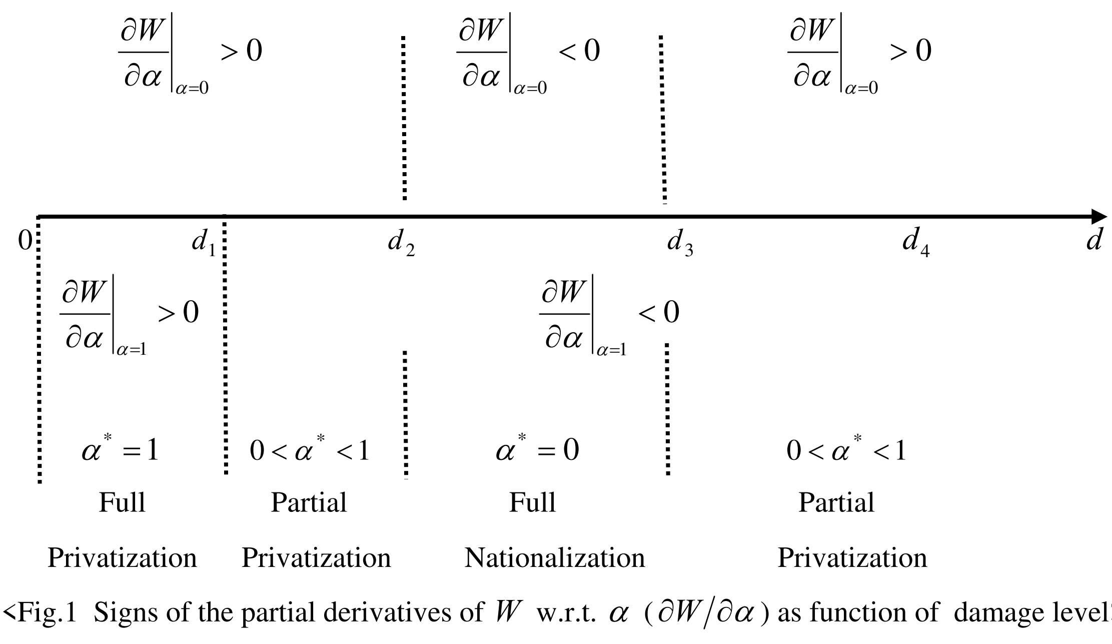
Suppose that the total surplus is either monotonic or single-peaked over the degree of privatization when it takes a value between zero and unity. Then, the optimal privatization policy crucially depends on the level of damage as follows:

(i) If the damage is small (i.e., $0 \le d \le d_1$), then full privatization is optimal.

(ii) If the damage is medium (i.e., $d_1 < d < d_2$), then partial privatization is optimal.

(iii) If the damage is large (i.e., $d_2 \le d \le d_3$), then full nationalization is optimal.

(iv) If the damage is too large (i.e., $d > d_3$), then partial privatization is again optimal.



<Fig.1 Signs of the partial derivatives of W w.r.t. α ($\partial W/\partial \alpha$) as function of damage level>

Proposition 1 states that the damage level (d) relative to the market size (A) plays a crucial role in determining the optimal privatization policy. With a relatively low level of damage, full privatization is optimal, while, with a relatively high level of damage, full nationalization is optimal. With a medium level of damage, partial privatization emerges as the optimal policy. These findings are consistent with our intuition. When the damage is low, then the government does not have to intervene in the eco-market to preserve the environment. When the damage level increases to some level (d_1), it has to reduce the emission. Through the privatization of an eco-firm, the government lowers the price of abatement goods to let the emitting firms buy more of the abatement goods. With severe environmental damage (larger than d_2), the government fully nationalizes the eco-firm so that it supplies abatement goods at a low price. Surprisingly, however, when the damage reaches a very high level (d_3), then the government starts privatizing the public eco-firm again.

To understand the behavior of optimal degree of partial privatization, let us look at the effects of the degree of the privatization, α . Differentiating equations (27) to (32) with respect to the degree of privatization, we know the effects as follows:

$$\frac{\partial q_i}{\partial \alpha} = \frac{75(6A-89d)}{(124+321\alpha)^2} \gtreqless 0 \Leftrightarrow d \lesseqgtr \frac{6A}{89} = d_2 \tag{38}$$

$$\frac{\partial a_r}{\partial \alpha} = -\frac{90(6A-89d)}{(124+321\alpha)^2} \gtreqless 0 \Leftrightarrow d \gtreqless \frac{6A}{89} = d_2 \tag{39}$$

$$\frac{\partial a_p}{\partial \alpha} < 0 \Leftrightarrow d > \frac{31A(2+3\alpha)^2}{4402+18786\alpha+21312\alpha^2} < d_1 \tag{40}$$

$$\frac{\partial a_i}{\partial \alpha} < 0 \Leftrightarrow d > \frac{70A(2+3\alpha)^2}{14404+65532\alpha+78039\alpha^2} < d_1 \tag{41}$$

$$\frac{\partial e_i}{\partial \alpha} = \frac{20(5A(2+3\alpha)^2 + 2d(1133+6189\alpha+8253\alpha^2))}{(2+3\alpha)^2(124+3\alpha 21)^2} > 0 \tag{42}$$

A few remarks are in order. First, as shown in equations (38) and (39), the effects on the production of private firms in upstream and downstream markets are reversed when the damage level reaches d_2, at which full nationalization policy becomes optimal. However, when the damage level is greater than d_1 but below when full privatization is optimal, the effects on the production of an upstream public eco-firm are always negative, as shown in equation (40), and its effects outweigh the effects on the private eco-firm, as shown in equation (41). Note also that the production of a public eco-firm is always higher than that of a private eco-firm when the damage level is greater than d_1. Thus, the emission levels are always decreasing, as shown in equation (42).

The economic intuition is as follows. As equation (38) shows, downstream firms choose to produce more (less) final goods as the degree of privatization increases, when the damage level is low (high). An increase in the production of final goods increases consumer surplus (i.e., it has a positive effect on the economy). However, the final goods emit the pollutants in the production process (i.e., it also has a negative effect on the economy). Hence, there is a trade-off between the gain from consumer surplus and the loss from environmental damage depending upon the level of damage. Furthermore, the production of a public eco-firm is always higher than that of a private eco-firm and it decreases, as the degree of privatization increases, when the damage level is greater than d_1. Thus, cost efficiency exists with a privatization policy.

Detailed explanations can be provided in each case. First, when the environmental damage is trivial, $d < d_1$, the government does not have to deal with the environmental issues, hence choosing full privatization.[13] Second, when the damage is moderate, which is neither trivial nor serious (i.e., $d_1 < d < d_2$), then the government needs to reduce the production of final goods via partial nationalization (i.e., a decrease in α). It however, needs to not reduce the production

[13] As mentioned in footnote 10, government can shut down the eco-industry to protect the welfare from the strategic behavior of downstream firms. However, we will not fully investigate this issue in this paper in order to focus only on the optimal privatization policy of the government in the eco-industry.

by a large amount because a decrease in α partially offsets the negative effect of environmental damage by increasing a_i

Third, if the environmental damage level is serious, $d > d_2$, then the government has to reduce emissions through either decreasing the production of final goods, increasing the production of abatement goods, or both. When the damage is not very serious (i.e., $d \le d_3$), however, the government does not have to commit to the privatization policy. Since the government can fully nationalize one of the eco-firms when the damage level reaches d_3, it can increase abatement goods as the damage level increases, directly through the nationalized eco-firm. As a result, the optimal degree of privatization, α^*, remains unchanged at zero for $d_2 \le d \le d_3$.

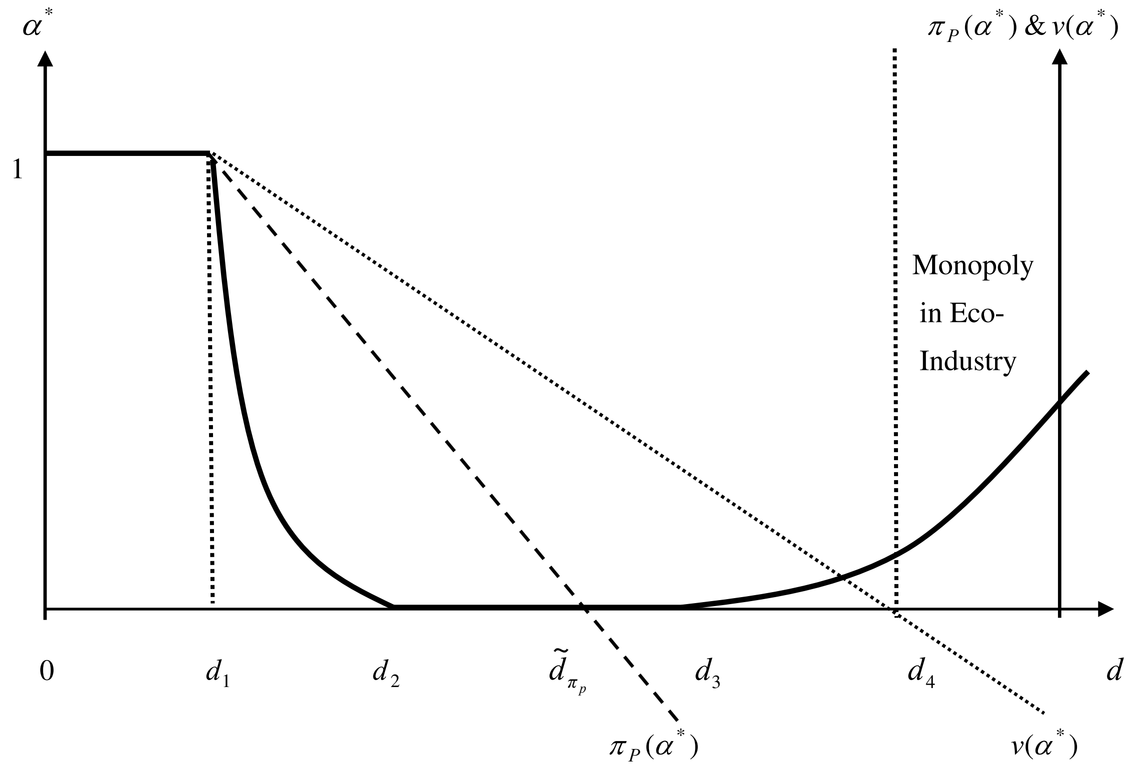
Finally, when the environmental damage level becomes very serious, when $d_3 > d$, then the government has to reduce the production of final goods to decrease the pollutants emitted in the production process. It can be done by increasing α (i.e., privatizing the eco-firm again). An increase in α increases a_r, the production of abatement goods by the private eco-firm, but induces the decrease of the production of the public eco-firm, a_p. This implies that there exists cost efficiency between the substitutable abatement goods. Hence, the degree of privatization policy increases as the damage level increases.

3.6. Implicit subsidies for public eco-firm and kick-out of private eco-firm[14]

Let us look at the profits of the public eco-firm with an optimal degree of privatization, $\pi_P(\alpha^*)$. As Fig. 2 shows, $\pi_P(\alpha^*)$ decreases with d, with $\pi_P(\alpha^*) = 0$ at $d = \tilde{d}_{\pi_p}$. The government fully nationalizes the eco-firm when the damage level reaches d_2. No problem arises, even without government support, when the damage level lies between d_2 and $\tilde{d}_{\pi_p}$. Without

[14] Appendix A shows the condition for the negative value of $\pi_P(\alpha^*)$ and $v(a^*)$.

government subsidies, however, the firm cannot operate when the damage level is greater than $\tilde{d}$. In other words, although the government subsidies are not explicitly considered, they should exist in the model. As Fig. 2 also shows, the price of the abatement goods, $v(\alpha^*)$, decreases with an optimal degree of privatization. Since this price is negative when the damage level is larger than d_4, the profit of the private eco-firm cannot be positive.



<Fig.2 Optimal degree of partial privatization as function of damage level>

Proposition 2

With the optimal partial degree of privatization, the private eco-firm will be kicked out when $d > d_4 = 2A/9$.

Proof: When $d > d_3$, the government sets the degree of privatization to partial to maximize the total surplus. However, with an optimal partial degree of privatization, when $d > d_4$, the price of abatement goods is negative. This means that the profit of a private eco-firm is negative and thus, it will be kicked out. **Q.e.d.**

Proposition 2 implies that when $d > d_4$, the government should decide the degree of privatization comparing the total surplus between a mixed eco-duopoly and a partially privatized eco-monopoly public firm. The economic explanation is as follows: The lowest value of the upper bound of the damage level with $\alpha^* = 0$ (i.e., full nationalization) is $d_4 = 2A/9$. However, the upper bound will increase as the degree of privatization increases. If $d > d_4$, then whether the private eco-firm produces abatement goods or not depends on the degree of privatization. The optimal degree of privatization is always lower than full privatization to guarantee the positive price of abatement goods. The government therefore needs to compare the total surplus of a monopoly eco-public firm with that of a mixed eco-duopoly.

For example, with $d = A/3$, the total surplus has a maximum value of α = 0.06, whereas the price of abatement goods, v, has a positive value with $\alpha > 1/6$. The total surplus, maximized by partial privatization, is not feasible because it includes the negative price of abatement goods. If only the public eco-firm exists in the market, then the total surplus has a higher maximum value with α = 0.021. If, hence, $d > d_4$, the government must kick out the private eco-firm with the privatization policy to achieve a higher total surplus.[15]

4. Concluding remarks

This paper investigates alternative policy instrument to regulate pollution, which is largely neglected in the academic literature, namely, voluntary commitments of polluting firms on target emissions in private market and partial public ownership of eco-firms in public domain. We then examine the welfare effect of commitments on emissions from polluting firms and its effect on the non-optimality of partial privatization. We show that both full nationalization and full privatization of the public eco-firm can be optimal, even with the same cost efficiency between the eco-firms, crucially depending on the environmental damage level.

Main findings are as follows: When the environmental damage is trivial, then the government does not have to concern the environmental problem and hence chooses full privatization without government subsidy. When, however, the damage level increases to a certain level, government need to (partially) nationalize the eco-firm under the government subsidy on abatement technologies, reducing emissions by increasing the supply of abatement goods through the (partially) privatized eco-firm. If the damage increases further, to reach a critical level, the government fully nationalizes the public eco-firm. Interestingly, when the environmental damage becomes very serious, the government needs to privatize the fully-nationalized public eco-firm again to decrease the total production of final goods and the production cost of abatement goods. These observations constitute a U-shaped relationship between the environmental damage level and the optimal degree of privatization. When the damage level is very high, a large amount of abatement goods should be supplied and purchased. The fully-nationalized firm can operate, even under a negative profit, because it can receive implicit government subsidies, while the private eco-firm can produce nothing with a non-positive price. This implies that the government kicks out the private eco-firm, under the optimal partial privatization policy, when the damage level is too high.

The objective of this paper is to present an insight on the non-optimality of partial privatization in mixed oligopolies in aligning the private and social concerns on the environmental problem. There still remain limitations. We used a simplified homogeneous duopoly model to focus on the relationship between the optimal degree of privatization and environmental damage level in the industries. More detailed analysis with general demand, cost, abatement technology and heterogeneous products in a mixed oligopoly will enhance our knowledge on the importance of public ownership in eco-industry. It is hoped that this paper stimulates future study.

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[15] Appendix B examines the public eco-monopoly case.

Appendix A: The values of $\pi_P(\alpha^*)$ and $v(\alpha^*)$

First, we will examine the value of $\pi_P(\alpha^*)$. At the first stage, the profit of a public firm is as follows:

$$\pi_p = \frac{2(5A\alpha(2+3\alpha)+4d(1-\alpha)(31+69\alpha))(10A(1+\alpha)(2+3\alpha)-d(1-\alpha)(214+441\alpha))}{(2+3\alpha)^2(124+321\alpha)^2}$$

Then, we can show that

$$\pi_p \gtreqless 0 \Leftrightarrow d \lesseqgtr d_{\pi_p=0} = \frac{10A(1+\alpha)(2+3\alpha)}{(1-\alpha)(214+441\alpha)}$$

First, we have $d_{\pi_p=0} > d_2$. Then, when full privatization or partial privatization is optimal, $0 < d < d_2$, the non-negative profit condition of the public firm is always satisfied, irrespective of the degree of privatization. But, when full nationalization is optimal, $d_2 < d < d_3$, $\pi_P(\alpha^*)$ decreases with d, where $\pi_P(\alpha^*) = 0$ at $d = \tilde{d}_{\pi_p}$. Thus, there exists a certain threshold for the zero profit of a public firm:

$$\pi_p\Big|_{\alpha=0} = \frac{d}{124}(10A \quad 107d) \gtreqless 0 \Leftrightarrow d \lesseqgtr \frac{10A}{107} \approx 0.0934A = \tilde{d}_{\pi_p}$$

Second, we will examine the value of $v(\alpha^*)$. From equation (33), the price of abatement goods has a negative slope and positive intercept and its sign depends on the damage level, $\tilde{d}_v$.

$$v\Big|_{d=0} = \frac{A(2+3\alpha)}{124+321\alpha} > 0, \ \frac{\partial v}{\partial d} = -\frac{45(1-\alpha)}{124+321\alpha} < 0 \text{ and } v(\alpha^*) \gtreqless 0 \Leftrightarrow d \lesseqgtr \tilde{d}_v = \frac{A(2+3\alpha)}{9(1-\alpha)}$$

Then, the threshold of the damage level which guarantees the positive price of abatement goods is greater than d_3.

$$\tilde{d}_v - d_3 = \frac{A(31+1464\alpha)}{2691(1-\alpha)} > 0$$

Appendix B: Public Eco-Monopoly

The fourth stage is the same with the mixed eco-duopoly case. Because the total consumption of abatement goods by downstream firms is the same as the total production of the public eco-monopoly, the market demand function is as follows:

$$a_1 + a_2 = \frac{2A - 2v - 3(e_1 + e_2)}{3} = a_p\,. \tag{A1}$$

Solving the above for v gives the following inverse demand function for abatement goods:

$$v(a_p) = A - \frac{3}{2}(e_1 + e_2 + a_p)\,. \tag{A2}$$

Then, the objective function for the public firm can be rewritten as:

$$T_p = \alpha\left\{v(a_p)a_p - a_p^2/2\right\} + (1-\alpha)W\,. \tag{A3}$$

The first-order condition for the public firm gives the corresponding best-response function as follows:

$$\frac{\partial T_p}{\partial a_p} = \alpha\left\{A - \frac{3}{2}(e_1 + e_2 + a_p) - \frac{3}{2}a_p - a_p\right\} + (1-\alpha)(d - a_p) = 0\,. \tag{A4}$$

Solving equation (A4) gives the equilibrium production of an eco-public firm, a_p, and the equilibrium price, v, all of which are functions of the emission committed by the polluting firms at the second stage, e_1 and e_2, and the degree of privatization committed by the government at the first stage, α.

$$a_p = \frac{2(\alpha(A-d)+d) - 3\alpha(e_1 + e_2)}{2 + 6\alpha}\,. \tag{A5}$$

$$v = \frac{4A - 6d + 6(A+d)\alpha - 3(2+3\alpha)(e_1 + e_2)}{4(1+3\alpha)}\,. \tag{A6}$$

Now we can define the profit of the polluting duopoly at the second stage as a function of only α, e_1 and e_2.

$$\pi_i = \frac{\{2(\alpha(A-d)+d) + (2+3\alpha)e_j\}^2 - (20 + 96\alpha + 99\alpha^2)e_i^2}{4(16+39\alpha)^2} + \frac{2e_i(A(8+40\alpha+42\alpha^2) - 2d(4+11\alpha-15\alpha^2) - (8+42\alpha+45\alpha^2)e_j}{4(16+39\alpha)^2}$$

$$\text{for } i = 1,2 \text{ and } i \neq j\,. \tag{A7}$$

The first-order condition for profit maximization with respect to the level of emissions is as follows:

$$\frac{\partial \pi_i}{\partial e_i} = \frac{2A(2+3\alpha)(2+7\alpha) - 2d(1-\alpha)(4+15\alpha)}{8(1+3\alpha)^2}$$

$$- \frac{(2+3\alpha)(10+33\alpha)e_i + (2+3\alpha)(4+15\alpha)e_j}{8(1+3\alpha)^2} = 0 \text{, for } i = 1,2 \text{ and } i \neq j. \quad \text{(A8)}$$

The above equation gives the emission levels that maximize a polluting firms' profit, which is a function of the degree of privatization:

$$e_1^M = e_2^M = \frac{2A(2+3\alpha)(2+7\alpha) - d(1-\alpha)(4+15\alpha)}{(2+3\alpha)(7+24\alpha)}. \quad \text{(A9)}$$

With the above emissions level, although the price of abatement goods of a public eco-monopoly is not same as that of a mixed eco-duopoly, the upper bound of damage level is the same.

$$v^M = \frac{A(2+3\alpha) - 9d(1-\alpha)}{14+48\alpha}$$

$$v^M > 0 \text{ when } d < \bar{d}_v = \frac{A(2+3\alpha)}{9(1-\alpha)}$$

At the first stage, with the above emissions level, the total surplus is as follows:

$$W = \frac{A^2(2+3\alpha)^2(20+141\alpha+247\alpha^2)}{(2+3\alpha)^2(7+24\alpha)^2} - \frac{d^2(4-492\alpha-1957\alpha^2-516\alpha^3+2961\alpha^4)}{(2+3\alpha)^2(7+24\alpha)^2}$$

$$- \frac{Ad(76+960\alpha+3827\alpha^2+5937\alpha^3+3150\alpha^4)}{(2+3\alpha)^2(7+24\alpha)^2}. \quad \text{(A10)}$$

The total surplus is also too complicated to analytically find the optimal degree of privatization. Following the same assumption, we can show that the optimal privatization policies depend on the level of damage.

$$\frac{\partial W}{\partial \alpha} = \frac{A^2(2+3\alpha)^3(27+74\alpha)}{(2+3\alpha)^3(7+24\alpha)^3} - \frac{Ad(2952+19028\alpha+41994\alpha^2+34965\alpha^3 7236\alpha^4)}{(2+3\alpha)^3(7+24\alpha)^3}$$

$$+ \frac{10d^2(744+2200\alpha-8460\alpha^2-41202\alpha^3-44577\alpha^4)}{(2+3\alpha)^3(7+24\alpha)^3}. \quad \text{(A11)}$$

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} > 0 \Leftrightarrow 0 < d < d_1^M = \frac{A(\sqrt{95529}-137)}{9968} (\approx 0.07303A). \quad \text{(A12)}$$

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=0} < 0 \Leftrightarrow d_2^M = \frac{3A}{31} (\approx 0.967A) < d < d_3^M = \frac{3A}{10} (= 0.3A). \quad \text{(A13)}$$

1. If the damage is small (i.e., $0 \leq d \leq d_1^M$), then full privatization is optimal

2. If it is medium (i.e., $d_1^M < d < d_2^M$), then partial privatization is optimal

3. If it is large (i.e., $d_2^M \le d \le d_3^M$), then full nationalization is optimal

4. If it is too large (i.e., $d > d_3^M$), then partial privatization is again optimal

where $d_1^M = \dfrac{A(\sqrt{95529} - 137)}{9968}$, $d_2^M = \dfrac{3A}{31}$ and $d_3^M = \dfrac{3A}{10}$.

Appendix C: Numerical examples

Using numerical examples, we draw the shape of the total surplus as a function of the degree of privatization and show that the main proposition can be verified by examples. Without a loss of generality, the market size A is normalized to unity in the following simulations.

1. With a low level of damage ($d = 2A/100$)

Let us assume $d = 2A/100$ for the case of a low level of damage. In this case, the following inequality holds:

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} \ge 0.$$

The total surplus, as a function of the degree of partial privatization, is depicted as a graph in Fig. A1. It shows that the total surplus increases monotonically with the degree of privatization in the domain of $0 \le \alpha \le 1$, and hence, full-privatization is optimal (i.e., $\alpha^* = 1$).

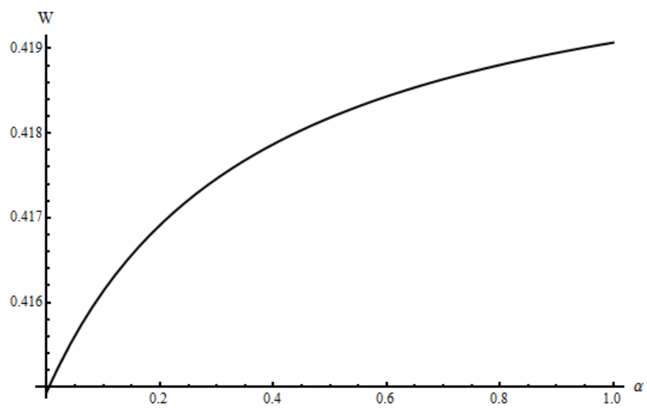

Fig. A1 Total surplus as a function of α when $d = A/50$

2. With a medium level of damage ($d = 6A/100$)

Let us assume $d = 6A/100$ for the case of a medium level of damage. In this case, the following inequality holds:

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=0} < 0, \left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} < 0.$$

The total surplus, as a function of the degree of partial privatization, is depicted as a graph in Fig. A2. It shows that the total surplus is a single-peaked function of the degree of privatization in the domain of $0 \le \alpha \le 1$, and hence, partial-privatization is optimal. In this example, the optimal degree of α^* is about 0.2057.

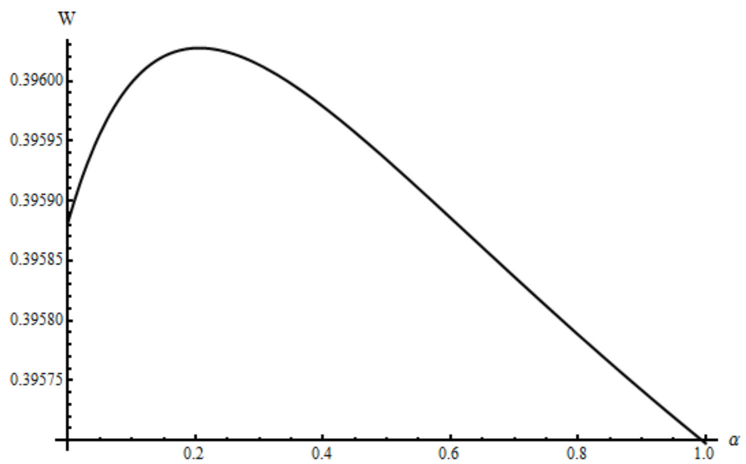

Fig. A2. Total surplus as a function of α when $d = 3A/50$

3. With a large level of damage ($d = 10A/100$)

Let us assume $d = 10A/100$ for the case of a large level of damage. In this case, the following inequality holds:

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=0} \le 0$$

The total surplus, as a function of the degree of partial privatization, is depicted as a graph in Fig. A3. It shows that the total surplus decreases monotonically with the degree of privatization in the domain of $0 \le \alpha \le 1$, and hence, full-privatization is optimal (i.e., $\alpha^* = 0$).

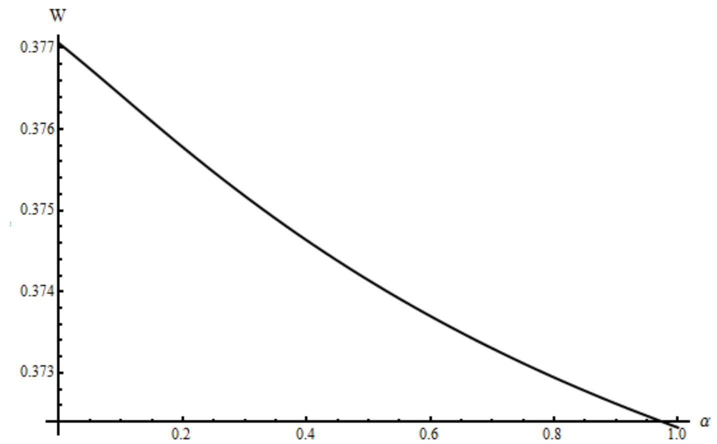

Fig. A3 Total surplus as a function of α when $d = 5A/50$

4. With too large of a level of damage ($d = 21.5A/100$)

Let us assume $d = 21.5A/100$ for the first case of too large of a level of damage. In this case, the following inequalities again hold:

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=0} > 0, \left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} < 0.$$

The total surplus as a function of the degree of partial privatization is depicted as a graph in Fig. A4. It shows that the total surplus is a single-peaked function of the degree of privatization in the domain of $0 \le \alpha \le 1$, and hence, partial-privatization is optimal. In this example, the optimal degree of α^* is about 0.0034.

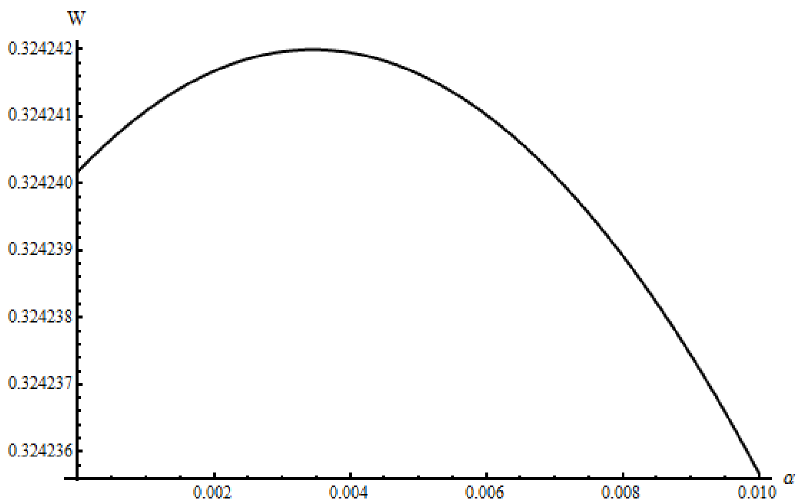

Fig. A4 Total surplus as a function of α when $d = 21.5A/100$

5. Private eco-firm kicked out by partial privatization policy ($d = 33A/100$)

Let us assume $d = 33A/100$ for the second case of too large of a level of damage. In this case, the following inequalities also again hold:

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=0} > 0, \quad \left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} < 0.$$

The total surplus as a function of the degree of partial privatization is depicted as a graph in Fig. A5. It shows that the total surplus is a single-peaked function of the degree of privatization in the domain of $0 \le \alpha \le 1$, and hence, partial-privatization is optimal. In this example, the optimal degree of α^* is about 0.0671. However, when $d = 33A/100$, the price of abatement is $v\Big|_{d=33A/100} = \dfrac{A(597\alpha - 97)}{2480 + 6420\alpha}$. For a positive price of abatement goods, the degree of privatization should be greater than $\dfrac{97}{597} \approx 0.1624$. So, if government sets the degree of privatization to maximize total surplus as 0.0671, then the private eco-firm will be kicked out.

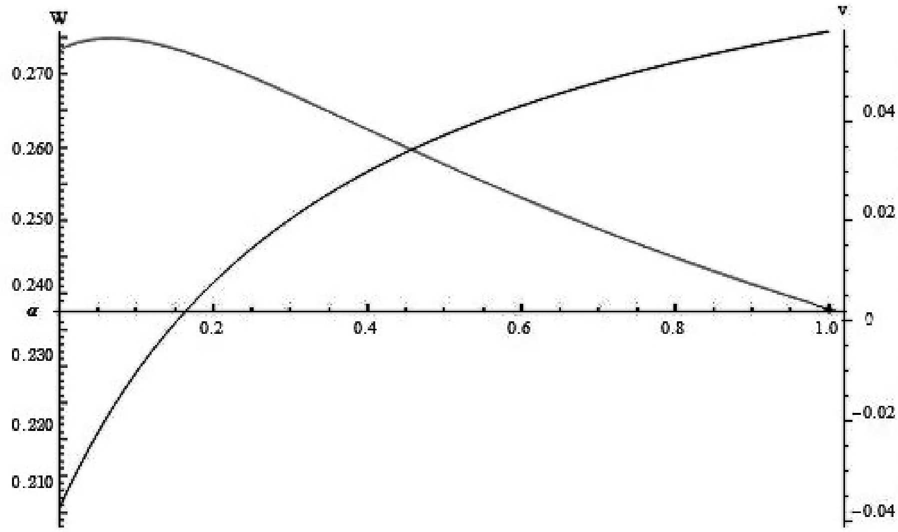

Fig. A5 Total surplus as a function of α when $d = 33A/100$

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