Research Article

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Voluntary Green Commitment and Optimal Privatization Policy in a Mixed Eco-Industry

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Abstract: This study investigates the impact of target emissions from polluting firms on the production of green technology and the optimal policy decisions of privatization on the eco-industry under their voluntary commitments. For this, we formulate a vertical structure consisting of a downstream polluting industry and an upstream mixed eco-industry where private and public eco-firms produce emission abatement goods. The results show a U-shaped non-monotone relationship between environmental damage and the optimal degree of privatization, that is, welfare-maximizing public ownership is full nationalization or full or partial privatization, depending on the environmental damage. It supports that the government should have large ownership of partially privatized eco-firms for environmental protection, especially when environmental damage is serious.

Keywords: abatement goods, commitments on target emissions, eco-industry, mixed oligopoly, partial privatization

JEL Classification: D43, L13, Q58

1 Introduction

Global concerns on climate change require strong environmental protection and significant government interventions. Stricter environmental regulations have contributed to the emergence of eco-industries such as waste-water treatment and

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air pollution control. Environmentally specialized eco-firms provide abatement goods and services to mitigate pollution and manage environmental resources efficiently.[1] As these environmental products and clean technologies are largely supplied by the eco-industry, pollution management using the abatement goods has become more important in the policy-making process. Many governments have recognized the importance of the eco-industry and enacted various policies to encourage them; particularly, they have significantly increased policy attention toward public institutions and organizations for public firms to be key players in this eco-industry. For example, the Korean eco-industry market increasingly imports environmental technology: 22% by the public sector and 78% by the private sector in 2012. Recently, many governments in advanced countries also invested in the research and development (R&D) of eco-technology, such as CleanTECH San Diego in the USA, Lahti Regional Development Company in Finland, Solar Valley Mitteldeutschland in Germany, Water Cluster in Israel, and so on. Accordingly, policy consequences of privatizing public eco-firms or nationalizing private eco-firms in mixed oligopolies where public eco-firms compete with private ones have gained the attention of policymakers.[2]

The recent literature on environmental policy in mixed oligopolies has intensively analyzed the impact of nationalization or privatization on the environment. Since Matsumura (1998), the partial privatization approach has been popular in examining mixed oligopolies and is extensively used in many contexts, including environmental issues.[3] 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

1 The importance of the eco-industry has been recognized by numerous national and international institutions and researchers such as Berg, Ferrier, and Paugh 1998; Ecotec 2002; Kennett and Steenblik 2005; OECD 1996. For a recent analysis of the eco-industry, see David and Sinclair-Desgagné (2005, 2009), Canton, Soubeyran, and Stahn (2008, 2012), David, Nimubona, and Sinclair-Desgagné (2011), Lee and Park (2011, 2019, 2021a), Kim and Lee (2014, 2016), and Kim, Lee, and Matsumura (2018) among others.

2 In mixed oligopolies, public firms compete with private firms in a broad range of industries such as oil, gas, automobiles, steel, chemicals, electricity, power plants, and hospitals, among which the pollution problem is significantly relevant. In an OECD report, Kowalski et al. (2013) noted that, among the 2000 largest public companies in the world, over 10% are either public firms or have significant government ownership, and their sales are equivalent to approximately 6% of the global GDP.

3 It has been shown that neither full nationalization nor full privatization is optimal under moderate conditions in a homogenous mixed duopoly. Recent research has been conducted on the optimality of partial privatization policies with a focus on different aspects of economic phenomena. Some important topics are included in Lee and Hwang (2003), Heywood and Ye (2009), Lee, Xu, and Chen (2013), Nakamura and Takami (2015), and Kim, Lee, and Matsumura (2019) among others.

policy instruments. Pal and Saha (2015) and Xu, Cho, and Lee (2016) examined a differentiated mixed duopoly with external costs and supported the optimality of partial privatization under emission taxes. They also showed an inverted U-shaped relationship between environmental damage and the optimal degree of privatization. Further, Xing et al. (2020) and Xing and Tan (2021) considered environmental R&D of clean technology for reducing emissions in a polluting mixed duopoly and analyzed the optimal policy decision of partial privatization.

However, fully nationalized firms exist in mixed markets and emerge in the eco-industry with large market shares, even during privatization waves. Thus, there is an urgent need to investigate the importance of public ownership in the eco-industry and understand the optimality of full nationalization. This study presents an insightful analysis of the non-optimality of partial privatization in mixed eco-oligopolies in aligning the private and social concerns on the environmental problem.

This study considers an environment-related vertical market structure of polluting and eco-industries. Private and (possibly partially privatized) public eco-firms produce abatement goods in a mixed duopoly configuration and provide abatement goods and services to polluting firms. We then formulate the polluting firms' environmental concerns on target emissions when they consume abatement technologies and examine the optimality of partial privatization policy in a mixed eco-industry.

Regarding environmental concerns by the polluting firms, traditional approaches have considered governmental regulations as command-and-control (such as standards and quotas) and market-based incentive instruments (such as taxes/subsidies and tradable permits systems). Further, the third approach of environmental policy instruments has emerged with environmental corporate social responsibility (ECSR).[4] Voluntary commitment is a kind of ECSR wherein polluting firms commit abatement activities to improve their environmental performances beyond the required regulation level. They are practically implemented with other environmental policy instruments, inducing polluting firms to improve environmental quality.[5]

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4 With the increasing prominence of environmental issues owing to climate change and global warming, many listed firms in the G250 Fortune Index (a list of the largest 250 multinational companies) reveal concerns regarding ECSR. For example, KPMG (2019) reported that 78% of the world's top 25 companies undertook corporate responsibility and reported relative data to attract investors, while 67% of them also set interval carbon reduction targets in 2017. For recent theoretical works, see Liu, Wang, and Lee (2015), Hirose, Lee, and Matsumura (2017, 2020), Lee and Park (2019, 2021b), Fukuda and Ouchida (2020), Xu, Chen, and Lee (2022), and Xu and Lee (2022).

5 They also have potential cost savings advantages to solve informational problems while credibility and capture problems also exist. See Alberini and Segerson (2002), Lyon and Maxwell (2003), and David (2005).

We investigate the impact of target emissions from polluting firms on the production of green technology and welfare-maximizing public ownership under their voluntary commitments. We show that full privatization or full nationality can be optimal in the mixed eco-industry where two eco-firms have the same cost efficiency in producing abatement goods. This result sharply contrasts the previous results on the optimality of partial privatization. That is, most studies in the literature have shown that various factors affect the optimal degree of privatization, but the non-optimality of full nationalization is quite robust even under environmental externality or the two related market structures. For instance, Yang, Wu, and Hu (2014) and Wu, Chang, and Chen (2016) examined a privatization policy in a vertically connected market in which the downstream or upstream industry is a mixed market and demonstrated that partial privatization is optimal depending upon the cost efficiency gap, but full privatization is never optimal.[6] This represents that our findings on the optimality of full nationalization or full privatization are quite interesting under vertical market structure in the presence of environmental concerns.

We also provide a U-shaped (non-monotone) relationship between environmental damage and the optimal degree of partial privatization in a mixed eco-industry. That is, depending on the level of environmental damage, we find that full nationalization, full privatization, or partial privatization can be optimal. Further, as the damage level increases, the optimal degree of privatization decreases to zero and thus, full nationalization becomes optimal policy which reduces the total production of final goods and increases the production of abatement goods. However, when the damage level becomes serious, the government needs to privatize the fully nationalized public eco-firm again to improve its cost-efficiency. Furthermore, a higher damage level requires an implicit subsidy for a public eco-firm.

This result contrasts the previous relations between partial privatization and environmental damage. For example, Pal and Saha (2015) and Xu, Cho, and Lee (2016) examined a single-tier mixed duopoly with emission taxes. They showed an inverted U-shape relation with the degree of privatization, while the optimal privatization is always partial. Therefore, considering a vertical market structure with a mixed eco-industry, we find the reverse effect on the degree of privatization. It can partially explain the reality that the government should have significant ownership of a privatized eco-firm for specific purposes, such as environmental protection. Our findings show that with an increasing environmental problem, the government should reconsider the role of public eco-firm since the privatization of a public eco-firm may affect downstream polluting firms' emission level, and

6 See also, Lee (1996) and Zhang and Lee (2022) for related policy discussion in a model of vertical structure.

implement an appropriate level of partial privatization policy in addition to environmental policy measures such as emissions standards or emissions taxes.

The rest of the paper is organized as follows. Section 2 describes a model of vertically related industry between polluting firms and eco-firms. Section 3 analyzes the equilibrium outcomes and derives the optimal privatization policy. Section 4 presents some policy-relevant discussion in the analysis, and Section 5 concludes the paper.

2 The Model

We consider a model of vertically related industries where private polluting firms in the downstream industry produce final goods with pollutant emissions. In contrast, public and private eco-firms compete in the upstream industry to produce abatement goods that reduce emissions created by the downstream industry. The duopoly case will be investigated for each industry without loss of generality in the following sections.[7]

2.1 Profits in the Final Goods Industry

We consider a Cournot duopoly in the final goods industry where two private 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 the inverse market demand function is given as $P = A - Q$. P is the market price; $Q = q_1 + q_2$ is the total output; q_i is the firm i's output; a_i is the 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 type of pollutants. $\tilde{e}_i$ denotes firm i's emissions, and $\tilde{e}_i = q_i$ without abatement technologies. However, if the firm purchases a_i amounts of abatement goods from eco-firms, then it can reduce emissions 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,[8]

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

8 Notably, no interaction term between the outputs and the abatement goods exists and thus, the reduction in gross emissions simplifies the analytical treatment According to all empirical reports, end-of-pipe abatement goods currently account for more than 70% of the pollution-treatment

$$e_i = \tilde{e}_i - a_i = q_i - a_i \quad (2)$$

When polluting firms purchase positive abatement goods (that is, $a_i > 0$), the profit function in (1) can be rewritten as:

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

Then, v is the additional unit cost for production while the unit benefits from the emission. Further, the decision on the purchase of abatement goods a_i, is the same as the choice of outputs q_i if the target emissions, e_i, are given.

2.2 Profits in Eco-Industry

Additionally, we consider a Cournot duopoly 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:[9]

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

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

$$\pi_j = va_j - a_j^2/2 \quad (5)$$

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 as follows,

$$W = \int_0^Q (A - u)du - \frac{a_r^2}{2} - \frac{a_p^2}{2} - d(e_1 + e_2) \quad (6)$$

segment of the eco-industry. See Lee and Park (2011, 2017, 2021), Kim and Lee (2014, 2016), and Kim, Lee, and Matsumura (2018).

9 The model with linear demand and quadratic cost functions is a standard formulation and popularly used in the literature on mixed oligopolies in order to rule out the uninteresting case of a public monopoly under the same constant marginal cost. See, for example, De Fraja and Delbono (1989), Wang and Chen (2010), and Kim, Lee, and Matsumura (2019). Instead, we can also impose asymmetric constant marginal cost between the public and private eco-firms and find the effects of cost gap between the firms on the optimal degree of privatization. provided the economic rationale behind this formulation.

where d represents the social cost per emission or the marginal environmental damage, assumed as constant and positive.[10]

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

$$T_p = \alpha\pi_p + (1-\alpha)W \tag{7}$$

where α denotes the ownership share of the private sector that corresponds to the degree of privatization, determined by the 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. First, the government determines the degree of privatization of the public eco-firm, α, to maximize the total surplus, W. Second, each polluting firm commits to the amount of target emissions, e_i. Third, the private and public eco-firms engage in a Cournot competition over the abatement goods. Therefore, the private eco-firm maximizes its profits, and the public eco-firm maximizes the weighted sum of its profits and total surplus. In the final fourth stage, the polluting firms engage in a Cournot competition over the final goods and abatement goods. All games are solved by backward induction, and the possible outcome is a subgame perfect equilibrium.[11]

3 The Equilibrium Analysis

3.1 Fourth Stage: Competition in the Final Goods Industry

We assume downstream firms are price takers on abatement goods, characterizing the Cournot-Nash equilibrium when choosing final goods at the fourth stage. 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

10 Note that environmental damage is proportional to the total emissions, used in Youssef and Dinar (2011), Tsai et al. (2016), Xing et al. (2021), Xu, Chen, and Lee (2022), and Xu and Lee (2022). However, if we use an increasing damage function, the analysis is quite complicated for deriving explicit solutions even though our main findings have not changed much.

11 In the below analysis, we implicitly assume that polluting firms always engage in abatement activities and focus on the analysis of optimal privatization policy in the eco-industry. In Section 4, we further discuss government policies which support these regulatory environments.

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:

$$\frac{\partial \pi_i}{\partial q_i} = A - Q - q_i - v = 0 \quad \text{for } i = 1, 2 \tag{8}$$

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

$$q_i = \frac{A - v}{3} \quad \text{for } i = 1, 2 \tag{9}$$

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

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

3.2 Third Stage: Competition in Eco-Industry

The market demand function for the abatement goods a_U is needed to investigate the Cournot-Nash equilibrium when choosing abatement goods at the third stage. As David and Sinclair-Desgagné (2005, 2010), Canton, Soubeyran, and Stahn (2008), and Lee and Park (2011, 2019) (Nimubona and Sinclair-Desgagne 2011) adopted, we assume that the eco-industry market-clearing price for abatement goods will be set at equilibrium. Then, from Equation (10), we have the following:

$$a_r + a_p = a_U = a_1 + a_2 = \frac{2A - 2v - 3(e_1 + e_2)}{3} \tag{11}$$

Solving Equation (12) for v gives the following inverse demand function for abatement goods:

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

Substituting Equation (13) into Equation (5), the objective function for the private firm π_r can be rewritten as:

$$\pi_r = v(a_U)a_r - a_r^2/2 \tag{13}$$

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

$$T_p = \alpha\left[v(a_U)a_p - a_p^2/2 + (1 - \alpha)W\right] \tag{14}$$

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

$$\frac{\partial \pi_r}{\partial a_r} = v(a_r + a_p) + v'(a_r + a_p)a_r - a_r = 0 \tag{15}$$

$$\frac{\partial T_p}{\partial a_p} = \alpha\{v(a_r + a_p) + v'(a_r + a_p)a_p - a_p\} + (1-\alpha)(d - a_p) = 0 \tag{16}$$

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

$$a_r(a_p) = \frac{2A - 3(e_1 + e_2) - 3a_p}{8} \tag{17}$$

$$a_p(a_r) = \frac{2(\alpha A + d(1-\alpha)) - 3\alpha(e_1 + e_2) - 3\alpha a_r}{2 + 6\alpha} \tag{18}$$

Note that the reaction functions are downward-sloping, and thus, the abatement goods are strategic substitutes between the two eco-firms. Additionally, 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. By solving Equations (17) and (18), we get the equilibrium amounts of abatements a_r and a_p and the equilibrium price v, all of which are functions of the emissions of the polluting firms at the second stage, e_1 and e_2

$$a_r = \frac{4A - 6d + 6(A + d)\alpha - 3(2 + 3\alpha) + (e_1 + e_2)}{16 + 39\alpha} \tag{19}$$

$$a_r = \frac{2(5\alpha A + 8d(1-\alpha)) - 15\alpha(e_1 + e_2)}{16 + 39\alpha} \tag{20}$$

$$a_U = \frac{2(2A(1 + 4\alpha) + 5d(1-\alpha) - 3(1 + 4\alpha(e_1 + e_2)))}{16 + 39\alpha} \tag{21}$$

$$v = \frac{5\{(4A - 6(\alpha A - (1-\alpha)d) - 3(2 + 3\alpha)(e_1 + e_2)\}}{32 + 78\alpha} \tag{22}$$

3.3 Second Stage: Commitments on Target Emissions

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

$$\pi_i = \frac{\{2(5d(1-\alpha) + 2A(1 + 4\alpha)) + 5(2 + 3\alpha)e_j)^2 - 5(2 + 3 + \alpha)(86 + 219\alpha)e_i^2}{4(16 + 39\alpha)^2} + \frac{20e_i(A(2 + 3\alpha)(18 + 47\alpha) - 2d(1-\alpha)(19 + 51\alpha) - (2 + 3\alpha)(19 + 51\alpha)e_j\}}{4(16 + 39\alpha)^2} \text{ for } i = 1,\ 2 \text{ and } i \neq j \tag{23}$$

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

$$\frac{\partial \pi_i}{\partial e_i} = \frac{5\{(A(2+3\alpha)(18+47\alpha) - d(1-\alpha)(19+51\alpha)\}}{(16+39\alpha)^2} - \frac{5\{(2+3\alpha)(19+51\alpha)e_j + (2+3\alpha)(86+219\alpha)e_i)\}}{2(16+39\alpha)^2} = 0, \text{ for } i = 1,\ 2 \text{ and } i \neq j \tag{24}$$

Then, if interior solutions exist, we have the emission levels that maximize polluting firms' profits, which are a function of the degree of privatization:

$$e_1 = e_2 = \frac{2A(2+3\alpha)(18+47\alpha) - 4d(1-\alpha)(19+51\alpha)}{(2+3\alpha)(124+321\alpha)} \tag{25}$$

Then, all decision variables are functions of the degree of privatization, α, as follows:

$$q_1 = q_2 = \frac{2A(19+51\alpha) + 15d(1-\alpha)}{(124+321\alpha)} \tag{26}$$

$$a_1 = a_2 = \frac{A\left(4+22\alpha+24\alpha^2\right) + d\left(106+143\alpha-249\alpha^2\right)}{(2+3\alpha)(124+321\alpha)} \tag{27}$$

$$a_p = \frac{10\alpha A(2+3\alpha) + 8d\left(31+38\alpha-69\alpha^2\right)}{(2+3\alpha)(124+321\alpha)} \tag{28}$$

$$a_r = \frac{2\{A(2+3\alpha) - 9d(1-\alpha)\}}{124+321\alpha} \tag{29}$$

$$a_U = \frac{2d\left(106+143\alpha-249\alpha^2\right) + A\left(8+44\alpha+48\alpha^2\right)}{(2+3\alpha)(124+321\alpha)} \tag{30}$$

$$v = \frac{5\{A(2+3\alpha) - 9d(1-\alpha)\}}{124+321\alpha} \tag{31}$$

$$P = A - Q = \frac{3A(16+39\alpha) - 30d(1-\alpha)}{124+321\alpha} \tag{32}$$

Independent 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. As those variables must be non-negative in equilibrium, the following restrictions (R1, R2, and R3) on the upper-bound of d should be imposed in the analysis:

$$\text{(R1)}\, e_1 = e_2 \geq 0 \text{ when } d \leq \overline{d}_e = \frac{A(2+3\alpha)(18+47\alpha)}{2(1-\alpha)(19+51\alpha)}$$

$$\text{(R2)}\, a_r \geq 0 \;\&\; v \geq 0 \text{ when } d \leq \overline{d}_v = \frac{A(2+3\alpha)}{9(1-\alpha)},$$

$$\text{(R3)}\, P \geq 0 \text{ when } d \leq \overline{d}_p = \frac{A(16+39\alpha)}{10(1-\alpha)}.$$

Since $\lim_{\alpha\to1}\overline{d}_e = \lim_{\alpha\to1}\overline{d}_v = \lim_{\alpha\to1}\overline{d}_v = \infty$, the variables are positive under full privatization (i.e., $\alpha = 1$), regardless of the damage level. However, the variables can be negative under partial privatization and full nationalization ($0 \leq \alpha<1$) as 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. In other words, $\overline{d}_v$ 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 emissions and outputs levels even if environmental damage is near zero, i.e., $a_i>0$ even if $d = 0$. Thus, output restriction of downstream firms under the commitment to total emission targets can be harmful to society when the environmental damage is not serious. Second, as damage increases, the emission levels decrease, i.e., $\frac{\partial e_i}{\partial d}<0$, benefitting environmental quality. 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 level, i.e., $a_p>a_r \Leftrightarrow d > \frac{2A(2+3\alpha)}{142+303\alpha}$ and $\alpha \in [0,1)$.

3.4 First Stage: Decisions on Privatization

The total surplus can now be expressed as a function of only one endogenous variable, that is, the degree of privatization α as follows:

$$\begin{aligned} W = \frac{1}{(2+3\alpha)^2(124+321\alpha)^2} & \left\{4A^2(2+3\alpha)^2\{1632+\alpha(8541+11152\alpha)\right\} \\ & + 4d^2(1-\alpha)\{1124+\alpha(36068+3\alpha(45539+45897\alpha))\} \\ & - 2Ad(2+3\alpha)\{7461+\alpha(56682+3\alpha(131963+93189\alpha))\}. \end{aligned} \tag{33}$$

The government chooses an optimal degree of privatization to maximize the total surplus under the restrictions on d. In general, the optimal degree of privatization has the following relationships:

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

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

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

Furthermore, the first derivative of the total surplus W, with respect to the degree of privatization α, provides the following relationships:

$$\frac{\partial W}{\partial \alpha}\Big|_{\alpha=1} > 0 \Leftrightarrow 0 < d < d_1 = \frac{A(\sqrt{773049} - 373)}{9968} \; (\approx 0.0507A) \tag{34}$$

$$\frac{\partial W}{\partial \alpha}\Big|_{\alpha=0} < 0 \Leftrightarrow d_2 = \frac{6A}{89} \; (\approx 0.0674A) < d < d_3 = \frac{63A}{299} \; (\approx 0.2107A) \tag{35}$$

The above relationships can be displayed in Figure 1, leading us to Proposition 1.

Proposition 1. Suppose that the total surplus is either monotonic or single-peaked over the degree of privatization. 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., $d_1 < d < d_2$), 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., $d > d_3$), partial privatization is optimal again.

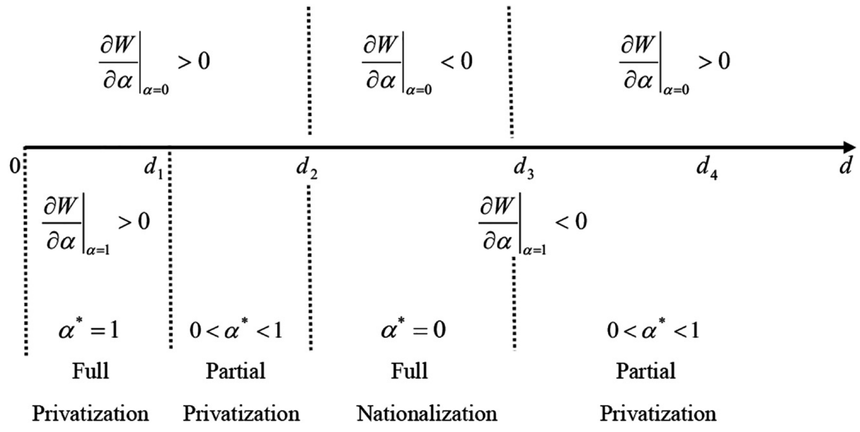

Figure 1: Signs of the partial derivatives of W w.r.t. α ($\partial W/\partial \alpha$) as function of damage level.

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 full nationalization is optimal with a relatively high level of damage. 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, 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 must 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 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. However, when the damage reaches a very high level (d_3), the government starts privatizing the public eco-firm again.

To understand the behavior of the optimal degree of partial privatization, let us look at the effects of the degree of privatization α. Differentiating Equations (26)–(29) with respect to the degree of privatization, we know the effects as follows:

$$\frac{\partial q_i}{\partial \alpha} = \frac{75\,(6A - 89d)}{(124 + 321\alpha)^2} \gtreqless 0 \Leftrightarrow d \lesseqgtr \frac{6A}{89} = d_2 \tag{36}$$

$$\frac{\partial a_r}{\partial \alpha} = -\frac{90\,(6A - 89d)}{(124 + 321\alpha)^2} \gtreqless 0 \Leftrightarrow d \gtreqless \frac{6A}{89} = d_2 \tag{37}$$

$$\frac{\partial a_p}{\partial \alpha} < 0 \Leftrightarrow d > \frac{31A\,(2 + 3\alpha)^2}{4402 + 18786\alpha + 21312\alpha^2} < d_1 \tag{38}$$

$$\frac{\partial a_i}{\partial \alpha} < 0 \Leftrightarrow d > \frac{70A\,(2 + 3\alpha)^2}{14404 + 65532\alpha + 78039\alpha^2} < d_1 \tag{39}$$

$$\frac{\partial e_i}{\partial \alpha} = \frac{20\left(5A\,(2 + 3\alpha)^2 + 2d\left(1133 + 6189\alpha + 8253\alpha^2\right)\right)}{(2 + 3\alpha)^2\,(124 + 3\alpha 21)^2} > 0 \tag{40}$$

A few remarks are in order. First, as shown in Equations (36) and (37), 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 the level when full privatization is optimal, the effects on the production of an upstream public eco-firm are always negative, as shown in Equation (38), and its effects outweigh the impact on the private eco-firm, as shown in Equation (37). Notably, 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 (40).

The economic intuition is as follows. As Equation (36) 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 positively affects the economy). However, the final goods emit pollutants in the production process (i.e., it also negatively affects the economy); hence, a trade-off between the gain from consumer surplus and the loss from environmental damage depends upon the level of damage. Furthermore, the production of a public eco-firm is always higher than that of a private eco-firm. 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 are provided for each case. First, when the environmental damage is trivial (i.e., $d < d_1$), the government does not have to deal with the environmental issues, hence choosing full privatization. Second, when the damage is moderate, 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). However, it need not reduce the output by a large amount because a reduction of 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 must reduce emissions by decreasing the production of final goods, increasing the output of abatement goods, or both. However, when the damage is not very serious (i.e., $d \le d_3$), the government does not have to commit to the privatization policy. Instead, as the government can 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. Therefore, 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 must reduce the production of final goods to decrease the pollutants emitted in the production process. This 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 a decrease in the production of the public eco-firm a_p. This implies cost efficiency between the substitutable abatement goods. Hence, the degree of privatization policy increases as the damage level increases.

4 Further Policy Discussions

4.1 Financial Support for Public Eco-Firm and Kick-Out of Private Eco-Firm[12]

Let us look at the profits of the public eco-firm with an optimal degree of privatization $\pi_p(\alpha^*)$. As Figure 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. In addition, even without government support, no problem arises when the damage level lies between d_2 and $\tilde{d}_{\pi_p}$. However, the firm cannot operate without government financial support when the damage level is greater than $\tilde{d}$. In other words, the government should provide financial support to the public firm. Furthermore, the government sets the degree of privatization to partial to maximize the total surplus when $d > d_3$ and the price of the abatement goods, $v(\alpha^*)$, decreases with an optimal degree of privatization. Thus, the price of abatement

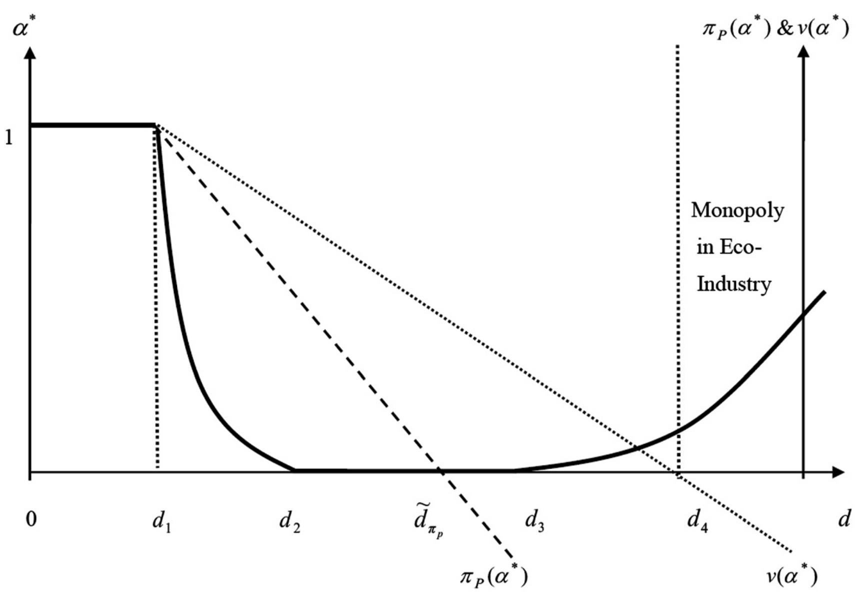

Figure 2: Optimal degree of partial privatization as function of damage level.

12 Appendix A shows the condition for the negative value of $\pi_p(\alpha^*)$ and $v(\alpha^*)$.

goods can be negative with an optimal partial degree of privatization when $d > d_4 = 2A/9$. This means that the profit of a private eco-firm is negative, and thus, it will be kicked out. Therefore, when $d > d_4$, the government should decide the degree of privatization by 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 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. Therefore, the government 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 $\alpha = 0.06$, 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 $\alpha = 0.021$. Hence, if $d > d_4$, the government must kick out the private eco-firm with the privatization policy to achieve a higher total surplus.[13]

4.2 Incentive Subsidies on the Abatement Goods for Polluting Firms

In the analysis of the game sequence on voluntary 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 commitment to target emissions influence the eco-firms' behavior (i.e., the market price of abatement goods). This affects the strategic choices of the polluting firms in the last stage, whether to engage in abatement activities after observing the actual market price of abatement goods. That is, the polluting firms might not engage in abatement activities if their choices are not profitable, compared to the non-commitment. Thus, it might be necessary for the government to provide an incentive subsidy on the abatement goods wherein polluting firms receive an appropriate subsidy when it chooses abatement technologies. This implies that the privatization policy in the eco-industry will be implemented in combination with the subsidy policy, inducing the polluting firms to purchase abatement goods from

13 Appendix B examines the public eco-monopoly case.

the eco-industry.[14] Following Lee and Park (2021), the government can propose an incentive subsidy policy that yields a larger profit with positive abatement goods in the subgame perfect equilibrium of the game than the profit without abatement goods. This guarantees that the private incentive to adopt abatement technologies under the commitment to the target emissions is profitable, compared to non-commitment. Therefore, our findings on the privatization policy in the eco-industry hold.

5 Concluding Remarks

This study investigates voluntary commitments of polluting firms on target emissions in the private market under the partial public ownership of eco-firms in a mixed eco-industry. We then examine the welfare effect of commitments on emissions from polluting firms and its impact on the non-optimality of partial privatization. We show that both full nationalization and 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. We find a U-shaped non-monotone relationship between environmental damage and the optimal degree of privatization policy in a mixed eco-industry. When the environmental damage is trivial, the government does not have to be concerned with the environmental problem and hence chooses full privatization without government subsidy. However, when the damage level increases to a certain level, governments 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, the government fully nationalizes the public eco-firm to reach a critical level. 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. When the damage level is very high, several abatement goods should be supplied and purchased. Therefore, the fully nationalized firm can operate, even under a negative profit, because it can receive implicit government subsidies. However, the private eco-firm cannot produce at a non-positive price,

14 If the subsidy amount on abatement technologies is sufficiently large, polluting firms always engage in abatement activities under the commitment of target emissions. That is, as the private firm can earn profits without abatement consumption at Cournot equilibrium, which is $A/3$, then the incentive-compatible subsidy should satisfy that the ex-post subsidy profit (i.e., the profits in (23) of the equilibrium outcome with the optimal degree of privatization plus a lump-sum subsidy amount) is higher than $A/3$.

which induces public monopoly under the optimal partial privatization policy when the damage level is too high.

This study presents an insight into the non-optimality of partial privatization in mixed oligopolies in aligning the private and social concerns on the environmental problem. However, there are limitations. We used a simplified homogeneous duopoly model to focus on the relationship between the optimal degree of privatization and the environmental damage level in the industries. A more detailed analysis of the general demand or asymmetric costs, abatement technology, and heterogeneous products in a mixed oligopoly will enhance our knowledge of the importance of public ownership in the eco-industry. We hope that this paper stimulates future studies.

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

First, we will examine the value of $\pi_p(\alpha^*)$. In 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

$$\pi_p \underset{<}{\overset{>}{-}} 0 \Leftrightarrow d \underset{>}{\overset{<}{-}} d_{\pi_p=0} = \frac{10A(1+\alpha)(2+3\alpha)}{(1-\alpha)(214+441\alpha)}$$

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, a certain threshold for the zero profit of a public firm exists:

$$\pi_p\big|_{\alpha=0} = \frac{d}{124}(10A \quad 107d) \underset{<}{\overset{>}{-}} 0 \Leftrightarrow d \underset{>}{\overset{<}{-}} \frac{10A}{107} \approx 0.0934A = \quad d_{\pi_p}$$

Second, we 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, $\tilde{d}_v$.

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

Then, the threshold of the damage level that 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 as the mixed eco-duopoly case. As 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:

$$\alpha_1 + \alpha_2 = \frac{2A - 2v - 3(e_1 + e_2)}{3} = a_p. \quad \text{(A1)}$$

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

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

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

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

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

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

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

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

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

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

$$\pi_i = \frac{\{2(\alpha(A-d)+d) + (2+3\alpha)e_j\}^2 - (20+96\alpha+99\alpha^2)e_i^2}{4(16+39\alpha)^2} + \frac{2e_i(A(8+40\alpha+42\alpha^2) - 2d(4+11\alpha-15\alpha^2) - (8+42\alpha+45\alpha^2)e_j}{4(16+39\alpha)^2} \text{ for } i=1,2 \text{ and } i \neq j. \quad (A7)$$

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

$$\frac{\partial \pi_i}{\partial e_i} = \frac{2A(2+3\alpha)(2+7\alpha) - 2d(1-\alpha)(4+15\alpha)}{8(1+3\alpha)^2} - \frac{(2+3\alpha)(10+33\alpha)e_i + (2+3\alpha)(4+15\alpha)e_j}{8(1+3\alpha)^2} = 0, \text{ for } i=1,2 \text{ and } i \neq j. \quad (A8)$$

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

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

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

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

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

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

$$W = \frac{A^2(2+3\alpha)^2(20+141\alpha+247\alpha^2)}{(2+3\alpha)^2(7+24\alpha)^2} - \frac{d^2(4-492\alpha-1957\alpha^2-516\alpha^3+2961\alpha^4)}{(2+3\alpha)^2(7+24\alpha)^2} - \frac{Ad(76+960\alpha+3827\alpha^2+5937\alpha^3+3150\alpha^4)}{(2+3\alpha)^2(7+24\alpha)^2}. \quad (A10)$$

The total surplus is 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.

$$\frac{\partial W}{\partial \alpha} = \frac{A^2(2+3\alpha)^3(27+74\alpha)}{(2+3\alpha)^3(7+24\alpha)^3} - \frac{Ad\left(2952+19028\alpha+41994\alpha^2+34965\alpha^3 7236\alpha^4\right)}{(2+3\alpha)^3(7+24\alpha)^3} + \frac{10d^2\left(744+2200\alpha-8460\alpha^2-41202\alpha^3-44577\alpha^4\right)}{(2+3\alpha)^3(7+24\alpha)^3}. \quad \text{(A11)}$$

$$\left.\frac{\partial W}{\partial \alpha}\right|_{\alpha=1} > 0 \Leftrightarrow 0 < d < d_1^M = \frac{A\left(\sqrt{95529}-137\right)}{9968} \; (\approx 0-07303A). \quad \text{(A12)}$$

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

1. If the damage is small (i.e., $0 \le d \le d_1^M$), 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 $d_1^M = \frac{A(\sqrt{95529}-137)}{9968}$, $d_2^M = \frac{3A}{31}$ and $d_3^M = \frac{3A}{31}$.

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