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Environmental taxes and the effects of partial privatization on environmental R&D, environment and welfare

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ABSTRACT
This paper considers environmental R&D (ER&D) of clean technology for reducing pollutant emissions in a polluting mixed duopoly and analyzes partial privatization's impacts on ER&D, environment and welfare. In the situation that environmental taxes are exogenously given, it finds that the impacts of privatization policy on ER&D and environment critically depend on the level of environmental damage. However, regardless of the marginal damage, an appropriate partial-privatization policy can increase social welfare. In addition, it also considers an endogenously determined optimal environmental tax and shows that if the marginal damage is high, partial privatization's impacts on ER&D, environment and social welfare may be not the same as the exogenous environmental tax situation.

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1. Introduction

In many countries, state-owned and private firms coexist in such as electricity, petroleum, chemical, steel and other high pollution industries (Xing et al., 2019; Xu et al., 2016). In recent years, partial privatization has become an important reform method for state-owned firms in many developing (e.g., China and India) and developed countries (e.g., Japan) (Kato, 2013; Maw, 2002; Pal & Saha, 2015). With the increasingly prominent environmental pollution, people pay more and more attention to environmental quality. In this context, whether the implementation of partial privatization policies will change firms' environmental R&D (ER&D) behavior in the pollution industry, and whether it will impact environment (or welfare), have been the focuses of economists and policymakers.

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As an important environmental regulation tool to solve environmental problems, environmental taxation has been used in some developed countries since the 1970s, and has achieved remarkable results (Aghion et al., 2016; Pearce, 1991; Yang, 2018). In recent years, more and more developing countries have begun to control enterprise pollutant emissions by imposing environmental tax in the process of economic transformation (Chen & Nie, 2016). At present, many countries implement partial privatization and environmental tax policies in some polluting industries at the same time. For example, the government is promoting the mixed ownership reform in many polluting industries in China[1], while it has started to levy environmental taxes on polluting enterprises[2]. In the context of this policy mix, a practical problem is whether different environmental tax policies (e.g., taxes are exogenous or endogenous)[3] will change the impacts of partial privatization policies on ER&D, environment and welfare.

Here, we consider the polluting mixed duopoly and analyze the impacts of environmental tax policies on the relationship between partial privatization and ER&D (environment or social welfare). Firms use clean technology to reduce emissions. They invest in ER&D to develop their technology. We examine the following two cases. The environmental tax is exogenous (case (a)) and it is endogenous (case (b)). We find that: (i) partial privatization can affect public firm's ER&D, environment and social welfare and in most situations it can also affect private firm's ER&D in both cases. However, by comparing with the situation that firms adopt end-of-pipe technology, partial privatization's impacts on them may be different; (ii) when the marginal damage (i.e., marginal environmental damage) is high, partial privatization's impacts on ER&D (or environment) are different in the situations of low and high tax rate in case (a); and (iii) partial privatization's impacts on ER&D, environment and social welfare might be not the same under exogenous and endogenous tax policies. The above results suggest that when policy makers analyze how the partial privatization's impacts on ER&D (environment or welfare) in pollution industry, they should first identify the types of emission reduction technology adopted by firms in this industry and the types of environmental tax policy adopted by the government.

The rest is as follows. Section 2 reviews the related literature. Section 3 sets up the model. Sections 4 and 5 solve equilibrium results for situations of exogenous and endogenous environmental tax respectively. Section 6 concludes.

2. Literature review

In order to reduce pollutant emissions, more and more firms adopt pollution abatement technologies. There are two types of abatement technologies in related literature: end-of-pipe and clean technologies (Requate, 2005; Skea, 1995; Tsai et al., 2016). The former technology curbs pollution emissions by implementing add-on measures, but the later technology reduces pollution at the source by using cleaner production methods (Frondel et al., 2007).

In the literature related to the impacts of full (or partial) privatization on ER&D (environment and/or social welfare), most scholars assume that firms adopt end-of-pipe technology. Under the assumption of endogenous environmental taxes, Wang

and Wang (2009), Ferreira and Ferreira (2013), and Haruna and Goel (2019) examine how full privatization affects them. Some of other scholars focus on partial privatization's impacts on them (Ouattara, 2019; Pal & Saha, 2010, 2015; Wang et al., 2009; Xu et al., 2016). Different from above studies, Xing et al. (2020) take into account exogenous environmental taxes and analyze full privatization's impacts on ER&D and environment. However, all of above studies ignore clean technology and both situations of exogenous and endogenous environmental taxes when examining the effects of privatization.

In terms of environment and economy, clean technologies are often more advantageous than end-of-pipe technologies (Frondel et al., 2007). Under the assumption of exogenous environmental taxes, several scholars consider clean technology and analyze how full privatization affects ER&D (environment and/or social welfare) (Gil-Moltó & Varvarigos, 2014; Tsai et al., 2016; Xing & Tan, 2021). The partial privatization is a popular academic and realistic policy issue in mixed oligopolies (Lee et al., 2017). When determining ER&D (or output), a fully privatized firm generally pursues profit maximization, while a partially privatized firm also takes into account consumer surplus and environment. This difference may lead to different effects of partial and full privatization on ER&D (environment and welfare). However, Gil-Moltó and Varvarigos (2014), Tsai et al. (2016) and Xing and Tan (2021) ignore partial privatization, and therefore fail to investigate partial privatization's impacts on ER&D (environment and welfare).

When a firm adopts end-of-pipe technology, this technology can reduce its gross pollution but leave its output unchanged, whereas if it adopts clean technology, this technology can reduce pollution per output, and therefore firms' output and abatement (or ER&D) decisions are intertwined (Tsai et al., 2016). This difference may lead to different effects of partial privatization on ER&D (environment or welfare) when firms adopt above two types of technology. Empirical studies have shown that the ER&D investment in clean technologies is much more than that in end-of-pipe technologies in many countries (Frondel et al., 2007). However, most of the related studies assume that firms adopt end-of-pipe technology.

Compared with the previous literature, the main contributions are: (i) we examine how partial privatization impacts ER&D (environment and welfare) when firms use clean technology. The results suggest that in some situations partial privatization's impacts on public firm's ER&D (or social welfare) present an inverted 'U' pattern, which is not the same as full privatization's impacts (see Xing & Tan, 2021). Xing and Tan (2021) think full privatization's impacts on public firm's ER&D (or social welfare) is monotonic; (ii) when analyzing partial privatization's impacts, we allow the environmental taxes to be exogenous and distinguish the situations of low tax rate and high tax rate; and (iii) we compare exogenous and endogenous environmental taxes, and find that partial privatization's impacts may depend on the level of marginal damage, especially when the marginal damage is high[4].

3. The model

We consider a duopoly market where firms 0 and 1 produce a homogeneous product. The former is a (partially) public firm, but the latter is a (entirely) private firm (Xu

et al., 2016). Let q_i $(i = 0, 1)$ represent firm i's output. The inverse market demand for the product is: $P(Q) = 1-Q$, in which Q $(Q = q_0 + q_1)$ denotes total output. Following most mixed oligopoly literature (Gil-Moltó et al., 2011; Garcia et al., 2018; Pi & Guan, 2018; Haruna & Goel, 2019; Xing et al., 2020; and so on), both firms have quadratic production cost function form, which can be described by: $C(q_i) = q_i^2/2$.

Production processes in firms pollute the environment (Pal & Saha, 2015). We assume that per unit output brings about one unit of pollution. However, both firms can reduce pollution by using clean technology. The level of this technology depends on firm's ER&D investments. After environmental R&D, the pollution emission per unit output of firm i changes from 1 to $1-\eta_i$, in which η_i is the ER&D effort of firm i $(\eta_i \in [0, 1])$ (Tsai et al., 2016). The firm i's ER&D cost is: $I(\eta_i) = \eta_i^2/2$[5]. It follows that the pollution generated by firm i is: $E_i = (1-\eta_i)q_i$ and the total pollution generated by firms is: $E = E_0 + E_1 = \sum_{i=0}^{1}(1 - \eta_i)q_i$. It is worth noting that, the ER&D leads to pollution reduction per output here, which is different from studies on ER&D that take into account end-of-pipe technology (Poyago-Thotoky 2007; Haruna & Goel, 2019).

Following Poyago-Thotoky (2003), Youssef and Dinar (2011) and Xing and Tan (2021), we consider the following environmental damage function:

$$D(E) = D(E_0 + E_1) = d\sum_{i=0}^{1}(1 - \eta_i)q_i \tag{1}$$

Where d $(d>0)$ denotes the marginal damage[6]. The government levies an environmental tax t $(t \geq 0)$ on firms' per unit pollutant (Pal & Saha, 2015). t denotes the environmental tax rate, which is assumed to satisfy inequality $0 \leq t \leq d$[7]. The resulting environmental tax paid by firm i is: $T_i = t(1-\eta_i)q_i$. Now, we can give firms' profit functions:

$$\pi_0 = P(Q)q_0 - C(q_0) - T_0 - I(\eta_0) \tag{2}$$

$$\pi_1 = P(Q)q_1 - C(q_1) - T_1 - I(\eta_1) \tag{3}$$

We define social welfare as the sum of producer surplus $(\pi_0 + \pi_1)$, consumer surplus $(CS = \frac{1}{2}Q^2)$ and environmental tax revenues $(T = T_0 + T_1)$, minus total environmental damage (D), which is expressed as (Xing et al., 2020):

$$SW = CS + \pi_0 + \pi_1 + T - D \tag{4}$$

Now, we give firms' objective functions. For firm 1, it is a private firm and pursues profit maximization. Its objective function is π_1 (see (3)). In addition, for firm 0 it may be partially privatized (fully state-owned or fully privatized) and pursues the weighted sum maximization of π_0 and SW (Kato, 2013; Matsumura, 1998; Wang et al., 2009). Its objective function is:

$$\Phi = \lambda\pi_0 + (1-\lambda)\,SW,\ \ \lambda \in [0,1] \tag{5}$$

According to (5), as λ increases, firm 0 will give a larger weight to the profit. If $\lambda = 0$, firm 0 is a fully public firm and pursues to maximize social welfare, and if $\lambda = 1$, it is a fully privatized firm and pursues to maximize the profit. However, if $0<\lambda<1$, firm 0 is a partially public (or partially privatized) firm and takes into account both the profit and social welfare. In this situation, λ denotes the degree of partial privatization. Note that, (i) some scholars think of this parameter as the share of a previously public firm sold to its private parties (Heywood & Ye, 2009; Matsumura, 1998); and (ii) for the convenience of expression, we still call firm 0 a public firm after partial privatization.

We consider two cases in this study. In case (a), the environmental tax is exogenous and the tax rate is allowed to be taken within a certain range. In case (b), it is endogenous and its optimal value is given by maximizing social welfare. The timing of the game is: firms simultaneously and independently determine their ER&D efforts (outputs) in stage 1 (stage 2) in case (a); and the government decides on optimal tax rate in stage 1 and firms determine their ER&D efforts (outputs) in stage 2 (stage 3) in case (b).

4. Case (a): *t* is exogenous

Here, the environmental tax is exogenously given. We start by examining the output stage. When two firms choose their optimal outputs, firm 0 maximizes the weighted sum of π_0 and SW (i.e., Φ), while firm 1 maximizes its profit (i.e., π_1). By differentiating (5) and (3) with respect to q_0 and q_1 respectively, we give first order conditions (i.e., FOCs):

$$\begin{aligned}\frac{\partial\Phi}{\partial q_0} &= \lambda\left[P(Q) + P'(Q)q_0 - C'(q_0) - T_0{}'\right] + (1-\lambda)\left[P(Q) - C'(q_0) - (1-\eta_0)D'(E)\right] \\ &= \lambda\left[1 - t(1-\eta_0) - q_1 - 3q_0\right] + (1-\lambda)\left[1 - d(1-\eta_0) - 2q_0 - q_1\right] = 0\end{aligned} \tag{6}$$

$$\begin{aligned}\frac{\partial\pi_1}{\partial q_1} &= P(Q) + P'(Q)q_1 - C'(q_1) - T_1{}' \\ &= 1 - t(1-\eta_1) - q_0 - 3q_1 = 0\end{aligned} \tag{7}$$

Due to $\frac{\partial^2\Phi}{\partial q_0^2} = -(2+\lambda)<0$ and $\frac{\partial^2\pi_1}{\partial q_1^2} = -3<0$, second order conditions (i.e., SOCs) are met. According to (6) and (7), there exists a substitution relationship between the outputs of firms. Solving (6) and (7) gives the outputs for firms:

$$q_0^* = \frac{2 - 3[\lambda t + (1-\lambda)d](1-\eta_0) + t(1-\eta_1)}{5+3\lambda} \tag{8}$$

$$q_1^* = \frac{(1+\lambda) + [\lambda t + (1-\lambda)d](1-\eta_0) - (2+\lambda)t(1-\eta_1)}{5+3\lambda} \tag{9}$$

Now, we turn to the ER&D stage. In this stage, two firms determine their optimal ER&D efforts. We can derive FOCs:

$$\begin{aligned}\frac{\partial\Phi(\eta_0,\eta_1)}{\partial\eta_0} &= \{\lambda P'(Q^*)q_0^* + (1-\lambda)\big[\underbrace{-P'(Q^*)q_1^*-(1-\eta_1)(D'(E^*)-t)}_{strategic\ effect}\big]\}\frac{\partial q_1^*}{\partial\eta_0} + \underbrace{\lambda t q_0^*}_{tax-saving\ effect} + \underbrace{(1-\lambda)D'(E^*)q_0^*}_{environmental\ effect} - I'(\eta_0)\\ &= \frac{\tau}{(5+3\lambda)^2}\{(9+8\lambda+\lambda^2)-\tau(16+11\lambda)(1-\eta_0)+\big[(2+5\lambda+2\lambda^2)t+(5-2\lambda-3\lambda^2)d\big](1-\eta_1)\}-\eta_0 = 0\end{aligned} \tag{10}$$

$$\begin{aligned}\frac{\partial\pi_1(\eta_0,\eta_1)}{\partial\eta_1} &= \underbrace{P'(Q^*)q_1^*\frac{\partial q_0^*}{\partial\eta_1}}_{strategic\ effect} + \underbrace{t q_1^*}_{tax-saving\ effect} - I'(\eta_1)\\ &= \frac{3(2+\lambda)t}{(5+3\lambda)^2}\{(1+\lambda)+\tau(1-\eta_0)-(2+\lambda)t(1-\eta_1)\}-\eta_1 = 0\end{aligned} \tag{11}$$

In (10) and (11), $\tau = \lambda t + (1-\lambda)d$. Because $0 \le t \le d \le 0.55$ and $0 \le \lambda \le 1$, $\frac{\partial^2\Phi}{\partial\eta_0^2} = \frac{(16+11\lambda)\tau^2}{(5+3\lambda)^2} - 1 < 0$ and $\frac{\partial^2\pi_1}{\partial\eta_1^2} = \frac{3(2+\lambda)^2t^2}{(5+3\lambda)^2} - 1 < 0$, Thus, SOCs are met.

We consider the marginal cost and marginal benefit of ER&D. Obviously, firm i's marginal cost from ER&D is $I'(\eta_i)$. On the marginal benefit from ER&D, for firm 0 it is determined by three effects: strategic effect (may be non-negative (or non-positive), i.e., $\{\lambda P'(Q^*)q_0^* + (1-\lambda)[-P'(Q^*)q_1^*-(1-\eta_1)(D'(E^*)-t)]\}\frac{\partial q_1^*}{\partial\eta_0} \ge (or \le) 0)$, tax-saving effect (is non-negative, i.e., $\lambda t q_0^* \ge 0$) and environmental effect (is non-negative, i.e., $(1-\lambda)D'(E^*)q_0^* \ge 0$). However, for firm 1 it is determined by two effects: strategic effect (is non-negative, i.e., $P'(Q^*)q_1^*\frac{\partial q_0^*}{\partial\eta_1} \ge 0$) and tax-saving effect (is non-negative, i.e., $t q_1^* \ge 0$) (Tsai et al., 2016). Tsai et al. (2016) also take into account these effects. However, unlike their study, in this study (i) the marginal benefit of firm 0 contains all of strategic effect, tax-saving effect and environmental effect; (ii) all of three effects have one more parameter λ in the marginal benefit of firm 0; and (iii) the tax-saving effect (environmental effect) does not contain ER&D's marginal cost in firm 1's (firm 0's) marginal benefit.

Solving (10) and (11) can give equilibrium ER&D efforts:

$$\eta_0^* = \frac{\varpi}{\zeta} \tag{12}$$

$$\eta_1^* = \frac{\phi}{\zeta} \tag{13}$$

In (12) and (13), $\varpi = \left\{\begin{array}{c}\tau[9+8\lambda+\lambda^2+(2-11\lambda-9\lambda^2)t+(-11+3\lambda+8\lambda^2)d]\times[(5+3\lambda)^2-3(2+\lambda)^2\\ \times t^2]-3(2+\lambda)\tau t[(2+5\lambda+2\lambda^2)t+(5-2\lambda-3\lambda^2)d]\times[1+\lambda+\tau-(2+\lambda)t]\end{array}\right\}$,

$\phi = 3(2+\lambda)t\left\{\begin{array}{c}[(5+3\lambda)^2-(16+11\lambda)\tau^2]\times[1+\lambda+\tau-(2+\lambda)t]-\tau^2\times\\ [9+8\lambda+\lambda^2+(2-11\lambda-9\lambda^2)t+(-11+3\lambda+8\lambda^2)d]\end{array}\right\}$

and $\zeta = \left\{\begin{array}{c}[(5+3\lambda)^2-(16+11\lambda)\tau^2]\times[(5+3\lambda)^2-3(2+\lambda)^2\times\\ t^2]-3(2+\lambda)t\tau^2[(2+5\lambda+2\lambda^2)t+(5-2\lambda-3\lambda^2)d]\end{array}\right\}$.

Then, we obtain firms' output and total output in equilibrium:

$$q_0^* = \frac{2\zeta - 3\tau(\zeta - \varpi) + t(\zeta - \phi)}{(5 + 3\lambda)\zeta} \tag{14}$$

$$q_1^* = \frac{(1 + \lambda)\zeta + \tau(\zeta - \varpi) - (2 + \lambda)t(\zeta - \phi)}{(5 + 3\lambda)\zeta} \tag{15}$$

$$Q^* = \frac{(3 + \lambda)\zeta - 2\tau(\zeta - \varpi) - (1 + \lambda)t(\zeta - \phi)}{(5 + 3\lambda)\zeta} \tag{16}$$

Using the equilibrium outputs (see (14), (15) and (16)), we obtain the following lemma.

Lemma 1. When t is exogenous, (i) q_0^* and $q_0^* + q_1^*$ (q_1^*) decrease (increases) with λ in the case of low d (or high d and high t); and (ii) q_0^* and $q_0^* + q_1^*$ (q_1^*) increase (decreases) with λ in the case of high d and low t.

Proof. See Appendix A.

The intuition is as below. If d is low (or both d and t are high), the damage caused by firms' production to the environment is small (or the marginal damage is large but pollution externality is mostly internalized by environmental taxes). When $\lambda = 0$, firm 0 seeks maximized social welfare in production. It can thus focus on increasing consumer surplus instead of reducing environmental damage (Kato, 2010; Tsai et al., 2016). With an increase of λ, firm 0 has an incentive to produce less because it focuses less on increasing consumer surplus, while firm 1 produces more due to strategic substitutes. Because the impact of λ on q_0 dominates its impact on q_1, total output decreases as λ increases. In addition, if d is high and t is low, pollution externality is poorly internalized. When $\lambda = 0$, firm 0 pursues the maximization of social welfare in production. It thus focuses on reducing environmental damage instead of increasing consumer surplus (Tsai et al., 2016). With an increase of λ, firm 0 has an incentive to produce more because it focuses less on reducing environmental damage. Thus, firm 1 produces less because of strategic substitutes. Due to the impact of λ on q_0 dominates its impact on q_1, total output increases with λ.

Using equilibrium ER&D efforts (see (12) and (13)), we can prove Proposition 1.

Proposition 1. When t is exogenous, (i) η_0^* decreases with λ in the case of low d (or high d and high t), and increases first and then decreases with λ in the case of high d and low t; and (ii) η_1^* is not affected by λ in the case of $t = 0$, increases with λ in the case of low d (t>0) (or high d and high t), and decreases with λ in the case of high d and low t (t>0).

Proof. See Appendix A.

The first part of above proposition indicates that in some situations, partial privatization's impacts on public firm's ER&D may be inverted 'U' pattern. Gil-Moltó and Varvarigos (2014), Tsai et al. (2016) and Xing and Tan (2021) also take into account

clean technology and exogenous t, whereas they study how full privatization affects public firms' ER&D. These scholars think that their relationship is monotonic. Obviously, our result is different. This implies that under certain conditions partial and full privatization's impacts on public firm's ER&D are different. In addition, Gil-Moltó and Varvarigos (2014) think that full privatization always does not affect private firms' ER&D. However, the second part of Proposition 1 shows that, depending on d and t, partial privatization can increase or reduce private firm's ER&D. Comparing parts (i) and (ii) of Proposition 1, the impacts of partial privatization on private and public firms' ER&D are different in some situations.

The reason for Proposition 1 is as below. Although the marginal benefit of ER&D for firm 0 (firm 1) is determined by strategic effect, tax-saving effect and environmental effect (strategic effect and tax-saving effect), the impact of λ on which is mainly determined by its impact on environmental effect (tax-saving effect) in the cases of low d, high d and high t, or high d and low t. First, we interpret the part (i). If d is low or both d and t are high, with an increase of λ, q_0^* decreases (see Lemma 1), and thus firm 0's environmental effect $((1-\lambda)D'(E^*)q_0^*)$ weakens. It follows that the marginal benefit of ER&D for firm 0 decreases with λ. In addition, if d is high but t is low, q_0^* increases with λ (see Lemma 1). For firm 0, its environmental effect $((1-\lambda)D'(E^*)q_0^*)$ strengthens first and then weakens as λ increases due to the effect of λ on q_0^* dominates (is dominated by) its effect on $1-\lambda$ if λ is small (large). Thus, firm 0's the marginal benefit from ER&D increases first and then decreases with λ. In sum, public firm's ER&D incentive will decrease (increase first and then decrease) as λ increases in cases of low d or high d and high t (the case of high d and low t). Second, we interpret the part (ii). If $t = 0$, for firm 1 its strategic effect and tax-saving effect disappear (i.e., $P'(Q^*)q_1^*(\partial q_0^*/\partial \eta_1) = 0$ and $tq_1^* = 0$). Obviously, firm 1's marginal benefit from ER&D is not affected by λ. Thus, its ER&D incentive will not change as λ increases. In cases of low d ($t>0$) or high d and high t (the case of high d and low t ($t>0$)),q_1^* increases (decreases) with λ (see Lemma 1), and thus tax-saving effect (tq_1^*) strengthens (weakens) as λ increases. It follows that firm 1's marginal benefit from ER&D increases (decreases) with λ. Thus, firm 1's ER&D incentive will increase (decrease) as λ increases.

Submitting (12)∼(15) into (1)∼(4) respectively, we derive:

$$\pi_0^* = \frac{[2\zeta-3\tau(\zeta-\varpi)+t(\zeta-\phi)]}{2(5+3\lambda)^2\zeta^2}\{2(1+2\lambda)\zeta+[7\tau-2(5+3\lambda)t](\zeta-\varpi) + (1+2\lambda)t(\zeta-\phi)\}-\frac{1}{2}(\frac{\varpi}{\zeta})^2 \tag{17}$$

$$\pi_1^* = \frac{(1+\lambda)\zeta+\tau(\zeta-\varpi)-(2+\lambda)t(\zeta-\phi)}{2(5+3\lambda)^2\zeta^2}\{3(1+\lambda)\zeta+3\tau(\zeta-\varpi)-3(2+\lambda)t(\zeta-\phi)\}-\frac{1}{2}(\frac{\phi}{\zeta})^2 \tag{18}$$

$$D^* = \frac{d}{(5+3\lambda)\zeta^2}\{(\zeta-\varpi)[2\zeta-3\tau(\zeta-\varpi)+t(\zeta-\phi)]+(\zeta-\phi)[(1+\lambda)\zeta+\tau(\zeta-\varpi)-(2+\lambda)t(\zeta-\phi)]\} \tag{19}$$

$$CS^* = \frac{1}{2}\left[\frac{(3+\lambda)\zeta - 2\tau(\zeta-\varpi) - (1+\lambda)t(\zeta-\phi)}{(5+3\lambda)\zeta}\right]^2 \tag{20}$$

$$SW^* = \frac{1}{2(5+3\lambda)^2\zeta^2}\left\{\begin{array}{l} 2(5+3\lambda)\zeta[(3+\lambda)\zeta-2\tau(\zeta-\varpi)-(1+\lambda)t(\zeta-\phi)]-[(3+\lambda)\zeta-2\tau(\zeta-\varpi) \\ -(1+\lambda)t(\zeta-\phi)]^2-[2\zeta-3\tau(\zeta-\varpi)+t(\zeta-\phi)]^2-[(1+\lambda)\zeta+\tau(\zeta-\varpi) \\ -(2+\lambda)t(\zeta-\phi]^2-2(5+3\lambda)d\{(\zeta-\varpi)[2\zeta-3\tau(\zeta-\varpi)+t(\zeta-\phi)] \\ +(\zeta-\phi)[(1+\lambda)\zeta+\tau(\zeta-\varpi)-(2+\lambda)t(\zeta-\phi)]\}-(5+3\lambda)^2(\varpi^2+\phi^2) \end{array}\right\} \tag{21}$$

According to the environmental damage in equilibrium (see (19)), we can prove the following proposition.

Proposition 2. When t is exogenous, (i) D^* decreases with λ in the case of low d (or high d and high t); and (ii) D^* increases with λ in the case of high d and low t.

Proof. See Appendix A.

There is no consistent conclusion on how partial privatization affects environment. By considering end-of-pipe technology and endogenous t, Wang et al. (2009) (Ouattara (2019)) show that partial privatization betters (damages) environment, while Pal and Saha (2010; 2015) and Xu et al. (2016) find that their relationship presents non-monotone pattern. Unlike the above studies, we consider clean technology and exogenous t, and obtain a different result.

The explanation for Proposition 2 is as below. Partial privatization can affect a firm's ER&D and output (see Lemma 1 and Proposition 1), thus can also affect this firm's pollutant emissions ($E_i = (1-\eta_i)q_i$) and environmental damage ($D_i = d(1-\eta_i)q_i$). In the situation of low d (or high d and low (or high) t), the effect of λ on E_i (or D_i) mostly depends on its effect on q_i. Consider the cases of low d or high d and high t (the case of high d and low t). On the one hand, partial privatization has the negative (positive) effect on q_0 (see Lemma 1), which will reduce (increase) the environmental damage. On the other hand, it has the opposite effect on q_1 and the environmental damage. The former effect dominates the latter effect. Therefore, partial privatization will reduce (increase) total environmental damage.

Using (21), we derive Proposition 3.

Proposition 3. When t is exogenous, SW^* increases first and then decreases with λ in the case of low d (high d and high t ($t<d$), or high d and low t).

Proof. See Appendix A.

By considering end-of-pipe technology and endogenous t, several scholars think that the appropriate partial-privatization policy will enhance social welfare (Ouattara, 2019; Pal & Saha, 2010, 2015; Xu et al., 2016). Our result suggests that, if firms use clean technology and t is exogenous, their result still holds. In addition, some studies think that full privatization's effect on social welfare is monotonic (Ferreira & Ferreira, 2013; Wang & Wang, 2009; Xing & Tan, 2021). However, Proposition 3 implies that partial privatization affects social welfare non-monotonously.

The reason for Proposition 3 is as below. Consider the cases of low d or high d and high t ($t<d$). In these cases, the effect of λ on consumer surplus is negative because the total output decreases with λ (see Lemma 1). However, it has positive effect on producer surplus. Because $T = tE$, $D = dE$ and $d>t$, and D^* decreases with λ (see Proposition 2), the effect of λ on $D^*-T^* = (d-t)E^*$ is negative. It follows that partial privatization has positive effect on T^*-D^*. When λ is small (large), with an increase of λ, the positive effect (i.e., higher $\pi_0^* + \pi_1^*$ and T^*-D^*) dominates (is dominated by) the negative effect (i.e., lower consumer surplus), and thus social welfare will increase (reduce). If d is high and t is low, we can do a similar analysis.

5. Case (b): *t* is endogenous

Some studies related to mixed oligopoly analyze the impacts of optimal environmental taxes and privatization policies on ER&D (environment and/or welfare) (Ferreira & Ferreira, 2013; Haruna & Goel, 2019; Ouattara, 2019; Pal & Saha, 2015; Xu & Lee, 2018). However, most of them consider end-of-pipe technology. By considering clean technology and endogenous t, we examine how partial privatization affects ER&D, environment and welfare here (case (b)). There are three stages of the game in case (b). The government determines the environmental tax rate in stage 1, and firms choose their ER&D efforts (outputs) in stage 2 (stage 3).

5.1. The effects of partial privatization on ER&D, environment and social welfare

Similarly as in case (a), we can derive equilibrium outputs (ER&D efforts) in stage 3 (stage 2). They are given by (8) and (9) ((12) and (13)) respectively. Further, we get the social welfare function on variable t, which is given by (21). Now, we take into account stage 1, in which the government determines optimal environmental tax rate (i.e., $t^{\#}$) by maximizing (21). We separate with two sub-cases (i) where d is low and (ii) where d is high. First, we consider the sub-case (i). We obtain $t^{\#} = 0$. Submitting $t^{\#} = 0$ into (12) and (13) can give equilibrium ER&D efforts: $\eta_0 = \frac{\vartheta}{\psi}$ and $\eta_1 = 0$, in which $\vartheta = d[9-\lambda-7\lambda^2-\lambda^3-(11-14\lambda-5\lambda^2+8\lambda^3)d]$ and $\psi = 25+30\lambda+9\lambda^2-(16-21\lambda-6\lambda^2+11\lambda^3)d^2$. Then, we derive environmental damage and social welfare in equilibrium:

$$D^{\#} = \frac{d}{(5+3\lambda)\psi^2}\left\{(\psi-\vartheta)[2\psi-3(1-\lambda)d(\psi-\vartheta)]+\psi[(1+\lambda)\psi+(1-\lambda)d(\psi-\vartheta)]\right\} \tag{22}$$

$$SW^{\#} = \frac{1}{2(5+3\lambda)^2\psi^2}\left\{\begin{array}{l}2(5+3\lambda)\psi[(3+\lambda)\psi-2(1-\lambda)d(\psi-\vartheta)]-[(3+\lambda)\psi-2(1-\lambda)d(\psi-\vartheta)]^2\\-[2\psi-3(1-\lambda)d(\psi-\vartheta)]^2-[(1+\lambda)\psi+(1-\lambda)d(\psi-\vartheta)]^2-2d(5+3\lambda)\{(\psi\\-\vartheta)[2\psi-3(1-\lambda)d(\psi-\vartheta)]+\psi[(1+\lambda)\psi+(1-\lambda)d(\psi-\vartheta)]\}-(5+3\lambda)^2\vartheta^2\end{array}\right\} \tag{23}$$

Proposition 4. When t is endogenous, in the case of low d, (i) $\eta_0^{\#}$ decreases with λ; (ii) $\eta_1^{\#}$ does not depend on λ; (iii) $D^{\#}$ decreases with λ; and (iv) $SW^{\#}$ increases first and then decreases with λ[8].

Proof. See Appendix A.

The intuition of this proposition can be similarly given as that in Propositions 1∼3 when d is low and $t = 0$. Compared with case (a), most of the results are the same in the situation of low d except for the impact of λ on private firm's ER&D. When t is exogenous, $\eta_1^{\#}$ increases with λ if $t>0$, but when t is endogenous, $\eta_1^{\#}$ is not affected by λ. The reason for this difference is that, partial privatization has the positive effect on tax-saving effect if t is exogenous and $t \neq 0$. However, this positive effect disappears if t is endogenous.

According to Propositions 2∼4, we derive Proposition 5[9].

Proposition 5. When d is low, compared with the situation of pre-privatization, the appropriate implementation of the partial privatization policy brings both environmental improvement and social welfare increase in both situations of exogenous and endogenous environmental tax.

Proof. See Appendix A.

Second, we consider the sub-case (ii). Due to the expression of $t^{\#}$ is very complex, we do not give its form here. The first line in each column d of Table 1 gives the numerical results of $t^{\#}$ with different values of λ. For example, if $d = 0.55$, $0.37<t^{\#}<0.39$ for all $\lambda \in [0, 1]$ (see the first line in column $d = 0.55$ of Table 1). Obviously, $t^{\#}$ is moderate and satisfies $0<t^{\#}<d$ if d is high. Submitting $t^{\#}$ into (12), (13), (19) and (21), we obtain the equilibrium results: $\eta_0^{\#}$, $\eta_1^{\#}$, $D^{\#}$ and $SW^{\#}$. The second to fifth lines of each d column in Table 1 respectively give the numerical results of them with different values of λ. According to the results of numerical simulation in Table 1 (see column $d = 0.55$ of Table 1), we find that when d is sufficiently high, $\eta_0^{\#}$, $\eta_1^{\#}$, $D^{\#}$ and $SW^{\#}$ decrease with λ. To sum up, we give the following observation[10].

Observation 1. When t is endogenous, in the case of high d, (i) $\eta_0^{\#}$ decreases with λ; (ii) $\eta_1^{\#}$ decreases with λ; (iii) $D^{\#}$ decreases with λ; and (iv) $SW^{\#}$ decreases with λ[11].

Ouattara (2019) shows that partial privatization makes environment worse, while Pal and Saha (2010; 2015) (Xu et al., 2016) find that partial privatization's impacts on environment are non-monotonic. In addition, all of them think that its impacts on social welfare are inversed 'U' pattern. The above scholars also take into account endogenous t. However, firms use end-of-pipe technology in their studies. Observation 1 shows that partial privatization may have different impacts on environment (or social welfare) when firms use clean technology.

Now we take a comparison of main results in cases (a) and (b) in the situation of high d. If t is endogenous, the increase of the partial privatization level certainly reduces firms' ER&D (or social welfare) and improves environmental quality. However, if it is exogenous, under certain conditions public firm's ER&D (or social

Table 1. When t is endogenous, the effects of λ on t, $\eta_0^{\#}$, $\eta_1^{\#}$, $D^{\#}$ and $SW^{\#}$.

	Variables	$\lambda = 0$	$\lambda = 0.1$	$\lambda = 0.2$	$\lambda = 0.3$	$\lambda = 0.4$	$\lambda = 0.5$	$\lambda = 0.6$	$\lambda = 0.7$	$\lambda = 0.8$	$\lambda = 0.9$	$\lambda = 1$
$d = 0.05$	t	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	$\eta_0^{\#}$	0.016927	0.014883	0.012941	0.011089	0.009318	0.007621	0.005989	0.004417	0.002898	0.001427	0.000000
	$\eta_1^{\#}$	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	$D^{\#}$	0.028703	0.028147	0.027649	0.027201	0.026796	0.026429	0.026093	0.025785	0.025502	0.025241	0.025000
	$SW^{\#}$	0.292443	0.293153	0.293348	0.293171	0.292726	0.292086	0.291309	0.290434	0.289493	0.288509	0.287500
$d = 0.15$	$t^{\#}$	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	$\eta_0^{\#}$	0.044744	0.039934	0.035223	0.030601	0.026058	0.021585	0.017174	0.012816	0.008505	0.004235	0.000000
	$\eta_1^{\#}$	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	$D^{\#}$	0.079295	0.078579	0.077953	0.077404	0.076922	0.076496	0.076120	0.075787	0.075492	0.075231	0.075000
	$SW^{\#}$	0.239687	0.239856	0.239864	0.239754	0.239559	0.239300	0.238995	0.238655	0.238288	0.237902	0.237500
$d = 0.25$	$t^{\#}$	0.047769	0.051329	0.053002	0.053351	0.053032	0.052597	0.052417	0.052684	0.053458	0.054717	0.056396
	$\eta_0^{\#}$	0.065916	0.060768	0.055640	0.050486	0.045288	0.040063	0.034849	0.029693	0.024639	0.019726	0.014980
	$\eta_1^{\#}$	0.013061	0.013928	0.014322	0.014387	0.014284	0.014151	0.014081	0.014123	0.014293	0.014584	0.014980
	$D^{\#}$	0.119109	0.118395	0.117864	0.117508	0.117283	0.117137	0.117019	0.116893	0.116736	0.116536	0.116288
	$SW^{\#}$	0.189988	0.190003	0.189964	0.189879	0.189758	0.189604	0.189424	0.189218	0.188989	0.188737	0.188465
$d = 0.35$	$t^{\#}$	0.153473	0.156429	0.157741	0.157941	0.157634	0.157304	0.157261	0.157650	0.158506	0.159795	0.161454
	$\eta_0^{\#}$	0.081715	0.077437	0.073113	0.068741	0.064324	0.059880	0.055440	0.051037	0.046706	0.042473	0.038359
	$\eta_1^{\#}$	0.037793	0.038209	0.038345	0.038286	0.038135	0.037980	0.037881	0.037866	0.037946	0.038114	0.038359
	$D^{\#}$	0.145183	0.144434	0.143885	0.143522	0.143297	0.143147	0.143018	0.142873	0.142688	0.142451	0.142159
	$SW^{\#}$	0.145962	0.145959	0.145927	0.145869	0.145789	0.145689	0.145572	0.145438	0.145288	0.145122	0.144942
$d = 0.45$	$t^{\#}$	0.263633	0.265899	0.266825	0.266888	0.266605	0.266376	0.266435	0.266884	0.267734	0.268949	0.270474
	$\eta_0^{\#}$	0.091344	0.088102	0.084739	0.081292	0.077782	0.074232	0.070662	0.067098	0.063564	0.060079	0.056661
	$\eta_1^{\#}$	0.057708	0.057691	0.057566	0.057363	0.057130	0.056911	0.056738	0.056625	0.056578	0.056592	0.056661
	$D^{\#}$	0.160905	0.160233	0.159746	0.159432	0.159239	0.159107	0.158985	0.158838	0.158645	0.158398	0.158096
	$SW^{\#}$	0.107710	0.107701	0.107678	0.107642	0.107595	0.107537	0.107469	0.107390	0.107301	0.107202	0.107094
$d = 0.55$	$t^{\#}$	0.379827	0.381363	0.381949	0.381940	0.381725	0.381591	0.381699	0.382110	0.382827	0.383820	0.385050
	$\eta_0^{\#}$	0.094280	0.092266	0.090038	0.087672	0.085206	0.082666	0.080071	0.077439	0.074788	0.072135	0.069494
	$\eta_1^{\#}$	0.072328	0.071904	0.071519	0.071152	0.070805	0.070485	0.070202	0.069961	0.069764	0.069609	0.069494
	$D^{\#}$	0.166439	0.165943	0.165583	0.165354	0.165215	0.165114	0.165012	0.164881	0.164706	0.164482	0.164206
	$SW^{\#}$	0.074921	0.074912	0.074898	0.074880	0.074857	0.074829	0.074796	0.074758	0.074714	0.074664	0.074608

Source: Authors' Calculations.

welfare) can increase first and then decrease with λ, and private firm's ER&D and environmental damage can increase with λ. The reason for this difference is as follows. If t is endogenous, its value cannot be sufficiently low (or sufficiently high) when d is high. In fact, it is moderate. However, if t is exogenous, its value can be sufficiently low (or sufficiently high). The difference of t in cases (a) and (b) can change the effects of λ on ER&D, environment and welfare.

According to Propositions 2 and 3, and Observation 1, we derive Proposition 6.

Proposition 6. When d is high, compared with the situation of pre-privatization, the appropriate implementation of the partial privatization policy betters (damages) environment and improves social welfare if t is exogenous and its value is high (low); However, the partial privatization policy generally betters environment but decreases social welfare in the situation of endogenous t.

Proof. See Appendix A.

In contrast to the result in the situation of low d (see Proposition 5), the partial privatization policy may not achieve a win-win result of improving both environmental quality and welfare in the situation of high d. When investigating the impacts of implementing the partial privatization policy on environment (or welfare), we should first clarify the marginal damage and environmental tax policies. Otherwise, we may get incorrect conclusions.

5.2. The effects of partial privatization on optimal environmental tax

First, we analyze how partial privatization impacts optimal environmental tax policy. When d is low, $t^{\#} = 0$. Obviously, $t^{\#}$ does not depend on λ in this situation. Now, we turn to investigate the effects of λ on $t^{\#}$ in the situation of high d. Combining values of $t^{\#}$ in the first line corresponding to $d = 0.55$ in Table 1, we find that with an increase of λ, $t^{\#}$ increases if $0 \leq \lambda \leq 0.2$ (or $0.5 \leq \lambda \leq 1$) and decreases if $0.2 \leq \lambda \leq 0.5$. We conclude that if d is high, $t^{\#}$ is non-monotone in the level of partial privatization, and further it first increases, then decreases and then increases with λ. Thus, in a high pollution industry, if the current level of privatization is sufficiently low (or sufficiently high), the government needs to raise the environmental tax rate when it continues to raise partial privatization level. However, if the current level of privatization is moderate, the government may lower the environmental tax rate when it continues to raise partial privatization level. For example, in China, with the deepening of mixed ownership reform, the partial privatization level of state-owned firms in some high pollution industries is improving. In this situation, the government needs to be aware of the possible impacts of partial privatization on environmental tax policies and adjust tax rates appropriately. The policy implication is given as follows.

Proposition 7. When d is low, the government does not need to change the optimal environmental tax policy if it carries out the higher privatization level in the polluting mixed duopoly. However, when d is high, it should appropriately adjust the optimal environmental tax policy according to the privatization level.

Proof. See Appendix A.

Second, we consider optimal policy mix case when the government can utilize optimal environmental taxes and optimal privatization together[12]. We can find optimal privatization levels, given optimal environmental taxes, in Table 1. Using the data of Table 1, the value of social welfare is maximized at $(t, \lambda) = (0, 0.2)$ in the situation of $d = 0.05$ (or $d = 0.15$), and it is maximized at $(t, \lambda) = (0.263633, 0)$ ($(t, \lambda) = (0.379827, 0)$) in the situation of $d = 0.45$ ($d = 0.55$). To sum up, we give the following observation.

Observation 2. When d is low, the optimal policy mix of the government is to choose not to levy environmental tax and to partially privatize public firm, while when d is high, it is to choose to levy environmental tax (its rate value is smaller than marginal damage) and not to privatize public firm.

The above observation indicates that the degree of marginal damage plays a key role in determining the policy mix between optimal environmental taxes and optimal privatization levels.

6. Conclusions

This study investigates the impacts of partial privatization on ER&D, environment and welfare in the polluting mixed duopoly. The government imposes an environmental tax on the firms' pollutant emissions. The environmental tax may be exogenous (case (a)) or endogenous (case (b)). Each firm uses clean technology and raises its technology through ER&D. The main findings obtained are as follows. In the situation of low marginal damage, as the partial privatization level increases, public firm's ER&D and environmental damage (social welfare) will reduce (increase first and then decrease) in both cases (a) and (b). While private firm's ER&D may increase in case (a) and it does not change in case (b). Moreover, in the situation of high marginal damage, partial privatization's impacts on public firm's ER&D (environmental damage or social welfare) can also be different. For example, partial privatization has the negative effect on them in case (b), but it can have the positive effect on environmental damage and the non-monotonic effect on public firm's ER&D (or social welfare) in case (a).

When policy makers adopt privatization policies, they care for their impacts on environment (or welfare). This study gives the following policy implication. If the environmental tax can be endogenously chosen when partially privatizing a polluting public firm in the mixed duopoly, the partial privatization policy undoubtedly will better the environment in both low and high marginal damage. However, if it is exogenously given and its rate is low, the partial privatization policy in a high pollution industry may make the environment worse. In some developing countries, due to the government imposes very low environmental taxes, partial privatization in high pollution industries can deteriorate the environment. In addition, if the environmental tax is exogenous, partial privatization's impacts on social welfare present an inverted 'U' pattern, and thus the appropriate partial-privatization policy can enhance social welfare. However, if it is endogenously chosen, the partial privatization policy in a high pollution industry may reduce social welfare.

This study uses a very simple framework to examine partial privatization's impacts. Some extensions may be possible. One is that the (partially) public firm is unconcerned about environment and pursuits the maximization of the weighted sum of the profit and consumer surplus (Ouattara, 2019). The other extension is that the government subsidizes the firm's ER&D activity rather than imposes environmental taxes (Xing et al., 2019). We will consider these extensions in the future.

Notes

1. The mixed ownership reform in China is characterized by partial privatization of state-owned firms.
2. China started to levy environmental tax since January 1, 2018.
3. Generally there are two typical ways to deal with environmental tax rate. One is that it is exogenous (Tsai et al., 2016; Xing et al., 2020). In this situation, the tax rate is usually allowed to be taken within a certain range. The other is that it is endogenous and its optimal value is usually given by maximizing social welfare (Haruna & Goel, 2019; Pal & Saha, 2015).
4. We assume that the environmental damage is linear to the output production, and thus our results may also depend on the environmental damage function.
5. Note that if we relax the assumption of ER&D cost as $I(\eta_i) = \kappa\eta_i^2/2$ $(\kappa>0)$, we do not find that full privatization can maximize social welfare.
6. To guarantee $0 \leq \eta_i \leq 1$, $q_i \geq 0$, $\pi_i \geq 0$ and $SW \geq 0$ in equilibrium for all $\lambda \in [0,1]$, this study assumes that d is not sufficiently high and meets inequality $0<d \leq 0.55$.
7. The reason for the assumption of $t \leq d$ is that, it is generally believed that in an imperfect market structure the environmental tax rate should not exceed the marginal damage (Ohori, 2006; Tsai et al., 2016; Xing & Tan, 2021). Some scholars compare the size of optimal environmental tax and marginal damage in the mixed oligopoly and they show that the former can't be larger than the latter (Lee & Xu, 2018; Ohori, 2014; Pal & Saha, 2015). However, Lee (1999) thinks that in some situations $t>d$ under a free entry Cournot oligopoly market.
8. Partial privatization is optimal if the government also decides on λ by maximizing $SW^{\#}$. For example, according to the fifth line of column $d = 0.05$ in Table 1, the value of social welfare is the largest when $\lambda = 0.2$.
9. Note that this result focuses on the comparison of post-privatization and pre-privatization.
10. Although this observation has been verified by numerical method, it cannot be proved strictly. Thus, we give it in the form of "observation" not in the form of "proposition".
11. Full nationalization is optimal if the government also chooses λ by maximizing $SW^{\#}$. For example, according to the fifth line of column $d = 0.55$ in Table 1, the value of social welfare is the largest when $\lambda = 0$.
12. Some related studies see Garcia et al. (2018, 2019).
13. Unlike clean technology, the adoption of end-of-pipe technology by firms leads to the reduction of gross emissions, rather than the reduction of emissions per unit output.
14. The derivation process and main results of Appendix B are given as online supplementary materials.
15. Most of them consider end-of-pipe technology, but we consider clean technology here.
16. The derivation process and main results of Appendix C are given as online supplementary materials.

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References

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, *124*(1), 1–51. https://doi.org/10.1086/684581

Chen, Z. Y., & Nie, P. Y. (2016). Effects of carbon tax on social welfare: A case study of China. *Applied Energy*, *183*, 1607–1615. https://doi.org/10.1016/j.apenergy.2016.09.111

Ferreira, F. A., & Ferreira, F. (2013). Privatization in a mixed duopoly with environmental taxes. In *AIP Conference Proceedings* (pp. 1558–1561).

Frondel, M., Horbach, J., & Rennings, K. (2007). End-of-pipe or cleaner production? An empirical comparison of environmental innovation decisions across OECD countries. *Business Strategy and the Environment*, *16*(8), 571–584. [Database] https://doi.org/10.1002/bse.496

Garcia, A., Leal, M., & Lee, S. H. (2018). Optimal policy mix in an endogenous timing with a consumer-friendly public firm. *Economics Bulletin*, *38*(3), 1438–1445.

Garcia, A., Leal, M., & Lee, S. H. (2018). Time-inconsistent environmental policies with a consumer-friendly firm: Tradable permits versus emission tax. *International Review of Economics & Finance*, *58*, 523–537. https://doi.org/10.1016/j.iref.2018.06.001

Garcia, A., Leal, M., & Lee, S. H. (2019). Endogenous timing with a socially responsible firm. *Korean Economic Review*, *35*(2), 345–370.

Gil-Moltó, M. J., Poyago-Theotoky, J., & Zikos, V. (2011). R&D subsidies, spillovers and privatization in mixed markets. *Southern Economic Journal*, *78*(1), 233–255. https://doi.org/10.4284/0038-4038-78.1.233

Gil-Moltó, M. J., & Varvarigos, D. (2014). *Environmental investments in mixed vs private oligopoly: What are the implications of privatization?* Working Papers 2014018. The University of Sheffield, Department of Economics.

Haruna, S., & Goel, R. K. (2019). Optimal pollution control in a mixed oligopoly with research spillovers. *Australian Economic Papers*, *58*(1), 21–40. https://doi.org/10.1111/1467-8454.12138

Heywood, J. S., & Ye, G. L. (2009). Partial privatization in a mixed duopoly with an R&D rivalry. *Bulletin of Economic Research*, *61*(2), 165–178. https://doi.org/10.1111/j.1467-8586.2008.00301.x

Kato, K. (2013). Optimal degree of privatization and the environmental problem. *Journal of Economics*, *110*(2), 165–180. https://doi.org/10.1007/s00712-012-0316-2

Kato, K. (2010). *Partial privatization and environmental policies*. MPRA Paper 27630. University Library of Munich.

Leal, M., Garcia, A., & Lee, S. H. (2018). The timing of environmental tax policy with a consumer-friendly firm. *Hitotsubashi Journal of Economics*, *59*(1), 25–43.

Lee, S. H. (1999). Optimal taxation for polluting oligopolists with endogenous market structure. *Journal of Regulatory Economics*, *15*(3), 293–308. https://doi.org/10.1023/A:1008034415251

Lee, S. H., Muminov, T. K., & Tomaru, Y. (2017). Partial privatization and subsidization in a mixed duopoly: R&D versus output subsidies. *Hitotsubashi Journal of Economics*, *58*(2), 163–177.

Lee, S. H., & Park, C. H. (2021). Environmental regulations in private and mixed duopolies: Taxes on emissions versus green R&D subsidies. *Economic Systems*, *45*(1), 100852. https://doi.org/10.1016/j.ecosys.2020.100852

Lee, S. H., & Xu, L. L. (2018). Endogenous timing in private and mixed duopolies with emission taxes. *Journal of Economics*, *124*(2), 175–201. https://doi.org/10.1007/s00712-017-0565-1

Matsumura, T. (1998). Partial privatization in mixed duopoly. *Journal of Public Economics*, *70*(3), 473–483. https://doi.org/10.1016/S0047-2727(98)00051-6

Maw, J. (2002). Partial privatization in transition economies. *Economic Systems*, *26*(3), 271–282. https://doi.org/10.1016/S0939-3625(02)00047-X

Ohori, S. (2006). Optimal environmental tax and level of privatization in an international duopoly. *Journal of Regulatory Economics*, *29*(2), 225–233. https://doi.org/10.1007/s11149-006-6037-0

Ohori, S. (2014). Price and quantity competition in a mixed duopoly with emission tax. *Theoretical Economics Letters*, *04*(02), 133–138. https://doi.org/10.4236/tel.2014.42020

Ouattara, K. S. (2019). Pollution abatement and partial privatization. *Economics Bulletin*, *39*(3), 1887–1897.

Pal, R., & Saha, B. (2015). Pollution tax, partial privatization and environment. *Resource and Energy Economics*, *40*, 19–35. https://doi.org/10.1016/j.reseneeco.2015.01.004

Pal, R., & Saha, B. (2010). *Does partial privatization improve the environment*. Mumbai Working Papers, 2010–2018. Indira Gandhi Institute of Development Research.

Pearce, D. (1991). The role of carbon taxes in adjusting to global warming. *The Economic Journal*, *101*(407), 938–948. https://doi.org/10.2307/2233865

Pi, J. C., & Guan, Y. W. (2018). Privatization, pollution, and welfare in a mixed differentiated duopoly. *Panoeconomicus*, *65*(4), 395–410. https://doi.org/10.2298/PAN130909001P

Poyago-Thotoky, J. (2003). Optimal environmental taxation, R&D subsidization and the role of market conduct. *Finnish Economic Papers*, *16*(1), 15–26.

Poyago-Thotoky, J. (2007). The organization of R&D and environmental policy. *Journal of Economic Behavior & Organization*, *62*(1), 63–75.

Requate, T. (2005). Dynamic incentives by environmental policy instruments-a survey. *Ecological Economics*, *54*(2–3), 175–195. https://doi.org/10.1016/j.ecolecon.2004.12.028

Skea, J. (1995). Environmental technology. In H. Folmer, H. L. Gabel, & H. Opschoor (Eds.), *Principles of environmental and resource economics. A guide for students and decision-makers* (pp. 389–412). Edward Elgar Publishing Ltd.

Tsai, T. H., Wang, C. C., & Chiou, J. R. (2016). Can privatization be a catalyst for environmental R&D and result in a cleaner environment? *Resource and Energy Economics*, *43*, 1–13. https://doi.org/10.1016/j.reseneeco.2015.10.002

Wang, L. F. S., & Wang, J. (2009). Environmental taxes in a differentiated mixed duopoly. *Economic Systems*, *33*(4), 389–396. https://doi.org/10.1016/j.ecosys.2009.08.002

Wang, L. F. S., Wang, Y. C., & Zhao, L. H. (2009). Privatization and the environment in a mixed duopoly with pollution abatement. *Economics Bulletin*, *29*(4), 3112–3119.

Xing, M. Q., & Tan, T. T. (2021). Environmental attitudes and impacts of privatization on R&D, environment and welfare in a mixed duopoly. *Economic Research-Ekonomska Istraživanja*, *34*(1), 807–827. https://doi.org/10.1080/1331677X.2020.1804968

Xing, M. Q., Tan, T. T., & Xia, W. (2019). Environmental R&D subsidy, spillovers and privatization in a mixed duopoly. *Economic Research-Ekonomska Istraživanja*, *32*(1), 2995–3015. https://doi.org/10.1080/1331677X.2019.1658530

Xing, M. Q., Tan, T. T., Xia, W., & Liu, L. L. (2020). Environmental R&D and privatization in a mixed duopoly market. *Managerial and Decision Economics*, *41*(1), 93–105. https://doi.org/10.1002/mde.3095

Xu, L. L., Cho, S., & Lee, S. H. (2016). Emission tax and optimal privatization in Cournot-Bertrand comparison. *Economic Modelling*, *55*, 73–82. https://doi.org/10.1016/j.econmod.2016.02.008

Xu, L. L., & Lee, S. H. (2018). Environmental policies with excess burden of taxation in free entry mixed markets. *International Review of Economics & Finance*, *58*, 1–13. https://doi.org/10.1016/j.iref.2018.02.020

Yang, Z. N. (2018). Privatization of state-owned enterprises, environmental protection tax and social welfare. *Business & Economy*, *35*(4), 124–128.

Youssef, S. B., & Dinar, Z. (2011). Regulation of a duopoly and environmental R&D. *Environmental Economics*, *2*(3), 47–51.

Appendix

Appendix A. Proofs of lemma and propositions

Proof of Lemma 1: We can prove that $\frac{\partial q_0^*}{\partial \lambda}|_{d=0}<0$ for all $0 \le \lambda \le 1$. Because $\frac{\partial q_0^*}{\partial \lambda}$ is a continuous function of d on interval [0, 0.55], there exists a $\underline{d}$ ($0<\underline{d}<0.55$) making that $\frac{\partial q_0^*}{\partial \lambda}<0$ for all $0<d<\underline{d}$. Thus, q_0^* decreases with λ in the case of low d. If d is high, $\frac{\partial q_0^*}{\partial \lambda}|_{t=0}>0$ and $\frac{\partial q_0^*}{\partial \lambda}|_{t=d}<0$ for $0 \le \lambda \le 1$. Because $\frac{\partial q_0^*}{\partial \lambda}$ is a continuous function of t on interval [0, d], there exist $\underline{t}$ and $\bar{t}$ ($0<\underline{t} \le \bar{t}<d$) making that $\frac{\partial q_0^*}{\partial \lambda}>0$ for all $0 \le t<\underline{t}$, and making that $\frac{\partial q_0^*}{\partial \lambda}<0$ for all $\bar{t}<t \le d$. Thus, q_0^* increases (decreases) with λ if d is high and t is low (high). Similarly, $q_0^*+q_1^*$ (q_1^*) increases (decreases) with λ in the case of high d and low t, and decreases (increases) with λ in cases of low d or high d and high t.

Proof of Proposition 1: (i) We can prove that $\frac{\partial \eta_0^*}{\partial \lambda}|_{d=0}=0$ and $\frac{\partial \eta_0^*}{\partial \lambda}|_{d\to\Delta}<0$ for all $0 \le \lambda \le 1$ (Δ is a positive real number whose value can be arbitrarily small). Because $\frac{\partial \eta_0^*}{\partial \lambda}$ is a continuous function of d on interval [0, 0.55], there exists a $\underline{d}'$ ($0<\underline{d}'<0.55$) making that $\frac{\partial \eta_0^*}{\partial \lambda}<0$ for all $0<d<\underline{d}'$. Thus, η_0^* decreases with λ in the case of low d. if d is high, there exists $\tilde{\lambda}$ making that $\frac{\partial \eta_0^*}{\partial \lambda}|_{t=0}>(<)0$ for all $0 \le \lambda<\tilde{\lambda}$ ($\tilde{\lambda}<\lambda \le 1$) and $\frac{\partial \eta_0^*}{\partial \lambda}|_{t=d}<0$ for all $0 \le \lambda \le 1$. $\frac{\partial \eta_0^*}{\partial \lambda}$ is a continuous function of t on interval [0, d]. There exist $\underline{t}'$ and $\bar{t}'$ ($0<\underline{t}' \le \bar{t}'<d$) making that $\frac{\partial \eta_0^*}{\partial \lambda}>(<)0$ if $0 \le \lambda<\tilde{\lambda}(t)$ ($\tilde{\lambda}(t)<\lambda \le 1$ ($\tilde{\lambda}(t)$ meets $\frac{\partial \eta_0^*}{\partial \lambda}\Big|_{\lambda=\tilde{\lambda}(t)}=0$ and $\tilde{\lambda}(0)=\tilde{\lambda}$)) for all $0 \le t<\underline{t}'$, and making that $\frac{\partial \eta_0^*}{\partial \lambda}<0$ for all $\bar{t}'<t \le d$. Thus, η_0^* decreases (increases first and then decreases) as λ increases if d is high and t is high (low); and (ii) According to (13), $\eta_1^*=0$ if $t=0$. Obviously, η_1^* does not depend on λ if $t=0$. In addition, we can prove that $\frac{\partial \eta_1^*}{\partial \lambda}|_{d=0}=0$ and $\frac{\partial \eta_1^*}{\partial \lambda}|_{d\to\Delta \text{ and } t>0}>0$ for all $0 \le \lambda \le 1$ (Δ is a positive real number whose value can be arbitrarily small). Because $\frac{\partial \eta_1^*}{\partial \lambda}$ is a continuous function of d on interval [0, 0.55], there exists a $\underline{d}''$ ($0<\underline{d}''<0.55$) making that $\frac{\partial \eta_1^*}{\partial \lambda}>0$ for all $0<d<\underline{d}''$ if $t>0$. Thus, η_1^* increases with λ in the case of low d if $t>0$. In the case of high d, we can prove that $\frac{\partial \eta_1^*}{\partial \lambda}|_{t=0}=0$, $\frac{\partial \eta_1^*}{\partial \lambda}|_{t\to\Delta}<0$ (Δ is a positive real number whose value can be arbitrarily small), and $\frac{\partial \eta_1^*}{\partial \lambda}|_{t=d}>0$ for all $0 \le \lambda \le 1$. Because $\frac{\partial \eta_1^*}{\partial \lambda}$ is a continuous function of t on interval [0, d], there exist $\underline{t}''$ and $\bar{t}''$ ($0<\underline{t}'' \le \bar{t}''<d$) making that $\frac{\partial \eta_1^*}{\partial \lambda}<0$ for all $0<t<\underline{t}''$, and making that $\frac{\partial \eta_1^*}{\partial \lambda}>0$ for all $\bar{t}''<t \le d$. Thus, η_1^* decreases (increases) as λ increases if d is high and $t(t>0)$ is low (high).

Proof of Proposition 2: We can prove that $\frac{\partial D^*}{\partial \lambda}|_{d=0}=0$ and $\frac{\partial D^*}{\partial \lambda}|_{d\to\Delta}<0$ (Δ is a positive real number whose value can be arbitrarily small) for all $0 \le \lambda \le 1$. Because $\frac{\partial D^*}{\partial \lambda}$ is a continuous function of d on interval [0, 0.55], there exists a $\underline{d}'''$ ($0<\underline{d}'''<0.55$) making that $\frac{\partial D^*}{\partial \lambda}<0$ for all $0<d<\underline{d}'''$. Thus, D^* decreases with λ in the case of low d. If d is high, $\frac{\partial D^*}{\partial \lambda}|_{t=0}>0$ and $\frac{\partial D^*}{\partial \lambda}|_{t=d}<0$ for $0 \le \lambda \le 1$. Because $\frac{\partial D^*}{\partial \lambda}$ is a continuous function of t on interval [0, d], there

exist $\underline{t}'''$ and $\overline{t}'''$ $(0<\underline{t}''' \leq \overline{t}'''<d)$ making that $\frac{\partial D^*}{\partial \lambda}>0$ for all $0 \leq t<\underline{t}'''$, and making that $\frac{\partial D^*}{\partial \lambda}<0$ for all $\overline{t}'''<t<d$. Thus, D^* increases (decreases) as λ increases if d is high and t is low (high).

Proof of Proposition 3: We can prove that $\frac{\partial SW^*}{\partial \lambda}|_{d=0}>(<)0$ for all $0 \leq \lambda<\widehat{\lambda}$ $(\widehat{\lambda}<\lambda \leq 1$ $(\widehat{\lambda}$ meets $\frac{\partial SW^*}{\partial \lambda}|_{d=0}=0))$. Because $\frac{\partial SW^*}{\partial \lambda}$ is a continuous function of d on interval [0, 0.55], there exists a $\underline{d}''''$ $(0<\underline{d}''''<0.55)$ making that $\frac{\partial SW^*}{\partial \lambda}>(<)0$ if $0 \leq \lambda<\widehat{\lambda}(t)$ $(\widehat{\lambda}(t)<\lambda \leq 1$ $(\widehat{\lambda}(t)$ meets $\left.\frac{\partial SW^*}{\partial \lambda}\right|_{\lambda=\widehat{\lambda}(t)}=0$ and $\widehat{\lambda}(0)=\widehat{\lambda}))$ for all $0<d<\underline{d}''''$. Thus, SW^* increases first and then decreases with λ in the case of low d. If d is high, there exists $\breve{\lambda}(t)$ $(\breve{\lambda}(t)$ meets $\left.\frac{\partial SW^*}{\partial \lambda}\right|_{\lambda=\breve{\lambda}(t)}=0)$ making that $\frac{\partial SW^*}{\partial \lambda}|_{t=0}>(<)0$ for $0 \leq \lambda<\breve{\lambda}(0)$ $(\breve{\lambda}(0)<\lambda \leq 1)$ and $\frac{\partial SW^*}{\partial \lambda}|_{t=d}>(<)0$ for all $0 \leq \lambda<\breve{\lambda}(d)$ $(\breve{\lambda}(d)<\lambda \leq 1)$. $\frac{\partial SW^*}{\partial \lambda}$ is a continuous function of t on interval $[0, d]$. There exist $\underline{t}''''$ and $\overline{t}''''$ $(0<\underline{t}''''<\overline{t}''''<d)$ making that $\frac{\partial SW^*}{\partial \lambda}>(<)0$ if $0 \leq \lambda<\breve{\lambda}(t)$ $(\breve{\lambda}(t)<\lambda \leq 1)$ for all $0 \leq t<\underline{t}''''$ or $\overline{t}''''<t<d$.

Proof of Proposition 4: When d is low, $t^{\#}=0$. In this situation, $\frac{\partial \eta_0^{\#}}{\partial \lambda}<0$, $\frac{\partial \eta_1^{\#}}{\partial \lambda}=0$ and $\frac{\partial D^{\#}}{\partial \lambda}<0$. In addition, there exists a $\dot{\lambda}$ $(0<\dot{\lambda}<1)$ making that $\frac{\partial SW^{\#}}{\partial \lambda}>(<)0$ if $0 \leq \lambda<\dot{\lambda}$ $(\dot{\lambda}<\lambda \leq 1$ $(\dot{\lambda}$ meets $\frac{\partial SW^{\#}}{\partial \lambda}|_{\lambda=\dot{\lambda}}=0))$. Thus, as λ increases, $\eta_0^{\#}$ and $D^{\#}$ will decrease, $\eta_1^{\#}$ will not change, and $SW^{\#}$ will increase first and then decrease.

Proof of Proposition 5: According to Proposition 3 (Proposition 4), SW^* $(SW^{\#})$ increases first and then decreases with λ when d is low. There exists a $\ddot{\lambda}$ $(0<\ddot{\lambda}<1)$ making that SW^* $(SW^{\#})$ increases with λ for all $\lambda \in [0, \ddot{\lambda}]$. In addition, according to Proposition 2 (Proposition 4), D^* $(D^{\#})$ always decreases with λ when d is low. Thus, when d is low, $SW^*|_{\lambda=0}<SW^*|_{\lambda\in(0,\ddot{\lambda}]}$, $SW^{\#}|_{\lambda=0}<SW^{\#}|_{\lambda\in(0,\ddot{\lambda}]}$, $D^*|_{\lambda=0}>D^*|_{\lambda\in(0,\ddot{\lambda}]}$ and $D^{\#}|_{\lambda=0}>D^{\#}|_{\lambda\in(0,\ddot{\lambda}]}$. It follows that Proposition 5 holds.

Proof of Proposition 6: The proof of this proposition is similar to Proposition 5, and we will not give it here.

Proof of Proposition 7: When d is low, $t^{\#}=0$. Obviously, it does not depend on λ. In addition, according to the numerical results of $t^{\#}$ with different values of λ in Table 1, $t^{\#}$ is affected by λ when d is high. Thus, Proposition 7 holds.

Appendix B. Firms adopt end-of-pipe technology

In basic model, we take into account clean technology. This section assumes that each firm uses end-of-pipe technology. Let y_i denote firm i's ER&D effort and $I(y_i)=y_i^2/2$ denote the ER&D cost. It follows that the pollution generated by firm i is: $E_i=q_i-y_i$, and the environmental tax paid by this firm is: $T_i=t(q_i-y_i)$[13]. Similar to the basic model, this section also considers the linear environmental damage function: $D(E_0+E_1)=d(E_0+E_1)$. Note that all other assumptions are the same as basic model. Furthermore, profit and social welfare functions are respectively given by: $\pi_i=P(Q)q_i-C(q_i)-T_i-I(y_i)$ and $SW=(q_0+q_1)^2/2+\pi_0+\pi_1+T_0+T_1-D(E_0+E_1)$. Therefore, firm 0's objective function has the same form as (5) and firm 1's objective function is π_1[14].

By analyzing the impacts of λ on the equilibrium results, we come to the following conclusions. First, consider exogenous t. Compared the findings with clean technology, the impacts

of λ on environment or welfare are similar, but its impacts on ER&D may be different. Specifically, when firms adopt end-of-pipe technology, public firm's ER&D decreases with (does not depend on) λ if $t<(=)d$, and private firm's ER&D is independent of λ. However, when firms adopt clean technology, public firm's ER&D may increase first and then decrease with λ, and private firm's ER&D may increase (or decrease) with λ.

Second, consider endogenous t. Comparing the findings with clean technology, the effects of λ on ER&D, environment and welfare are similar if d is low, but its effects on private firm's ER&D (or welfare) can be different if d is high. Specifically, when d is high, private firm's ER&D (social welfare) always increases (increases first and then decreases) with λ when firms adopt end-of-pipe technology. However, they can decrease with λ when firms adopt clean technology. The above results suggest that when we analyze partial privatization's impacts on ER&D and welfare in a pollution industry, we should first clarify the types of emission reducing technologies adopted by firms and the level of environmental damage caused by production in this industry.

Appendix C. The government determines environmental tax after firms' ER&D

In case (b) of basic model (see section 5), the government commits to its regulation from the beginning of the game in which the environmental tax rate can be set before each firm conducts ER&D. This section considers the time-consistent environmental tax policy framework. The government strategically chooses the optimal tax rate after observing firms' ER&D efforts (Garcia et al., 2018; Haruna & Goel, 2019; Leal et al., 2018; Lee & Park, 2021)[15]. The stages of the game are as follows. Each firm decides on its ER&D effort (output) in stage 1 (stage 3), and the government chooses the environmental tax rate in stage 2[16].

First, consider the situation of low d. In this situation, we obtain the same result as Proposition 4. Compared with the findings in case (a), we get the same conclusion as that in section 5.1. Second, consider the situation of high d. We show that as λ increases, public (private) firm's ER&D will increase (decrease), environmental damage will increase first and then decrease and social welfare will increase. Obviously, these results are different from those obtained in case (a). Thus, even the government strategically chooses t, partial privatization's impacts on ER&D (environment and welfare) can still be different under the situations of exogenous and endogenous t.