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June, 2014



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Cournot duopoly and environmental R&D under regulator's precommitment to an emissions tax*

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Abstract

This paper presents examination of environmental R&D of Cournot duopolists with end-of-pipe technology under a regulator's precommitment to an emissions tax. Results show that, in the presence of technological spillover effect, the government invariably prefers environmental R&D cartelization to environmental R&D competition. In addition, this paper, in stark contrast to those presenting earlier studies, reveals that consumer surplus is not necessarily maximized by environmental research joint venture (ERJV) cartelization, although there invariably exist private incentives to firms for ERJV cartelization as well as social incentives for it.

JEL classification: O32; L13; Q55; Q58.

Keywords: R&D coordination; Environmental R&D; End-of-pipe technology; Precommitment ability; Emission tax

*The authors are grateful to Makoto Okamura for his constructive comments. Needless to say, all remaining errors are ours. The authors are also grateful to the Research Grant on Environmental Policy Studies of the Ministry of the Environment of Japan, No. 6, 2009–2011. In addition, this research is partially supported by KAKENHI (Grants-in-Aid for Scientific Research), No. 22730200 and No. 25380303.

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1 Introduction

Credible precommitment ability is an extremely important factor underpinning policy implementation in an oligopolistic market. However, the government does not invariably have a precommitment ability for any regulatory circumstance. In the context of environmental regulation, such ability is noted to a considerable degree as an important keyword. Requate (2005) surveys related studies that specifically address development of advanced emissions-reducing technology and the timing of environmental policy.

Chiou and Hu (2001) develop the environmental R&D model of Cournot duopolists with cleaner production technology when the regulator has a precommitment ability to an emissions tax. Poyago-Theotoky and Teerasuwannajak (2002) specifically examine the non-cooperative environmental R&D investment of Cournot duopolists with end-of-pipe technology, and also specifically investigate the effect of emissions taxation both in the presence and absence of a regulator's credible precommitment ability.¹

Nevertheless, no study reveals the effect of regulator's precommitment to an emissions tax on social welfare and other economic variables under cooperative environmental R&D of Cournot duopolists with end-of-pipe technology. Furthermore, no report presents a comparison of the equilibrium values under cooperative and non-co-operative environmental R&D when the government has a precommitment ability. This paper therefore presents a normative examination of whether the coordination of environmental R&D investment should be socially allowed or not under government's precommitment to an emissions tax.

This paper proceeds as follows. Section 2 introduces the model.² Section 3 and 4 examine quantity-setting duopolists' non-cooperative and cooperative environmental R&D. Section 5 presents a description of comparisons of equilibrium outcomes. Section 6 explains a comparative static analysis of the equilibrium outcome to derive policy implications. The final section presents concluding remarks.

2 The Model

Presuming an industry composed of two firms engaging in quantity competition, with the same cost structure and emissions-reducing technology. The value of q_i ($i = 1, 2$) denotes firm i 's production level and the utility function of a representative consumer is represented as

$$U(q_i, q_j, m) \equiv a(q_i + q_j) - (1/2)(q_i^2 + 2\theta q_i q_j + q_j^2) + m, \quad (i, j = 1, 2; i \neq j).$$

Therein, the value of m signifies the consumption of a numeraire good. The value of a (> 0) is a parameter of market size. Product differentiation is captured by $\theta \in [0, 1]$. Consumer's utility maximization yields the inverse demand function of good i as

$$p_i(q_i, q_j) = a - (q_i + \theta q_j), \quad (i, j = 1, 2; i \neq j).$$

The regulator has the ability to precommit to an emissions tax rate t (> 0). Under an emissions tax, a firm has an incentive for emissions reduction. Each firm's emissions per unit output is one. Firm i 's environmental R&D effort is given as z_i . Two firms use end-of-pipe technology in pollution abatement. Although this technology is insufficient to reduce emissions per unit output, it abates emissions by adsorbing pollution at the end of production processes.

Firm i receives benefits not only from its own environmental R&D efforts but also from rivals' efforts. R&D expenditure $(\gamma/2)z_i^2$, ($\gamma > 0$) enables firm i to reduce its emissions from q_i to $e_i(q_i, z_i) \equiv q_i - z_i - \beta z_j$. Symmetric parameter $\beta \in [0, 1]$ denotes a spillover effect of environmental R&D. When $0 < \beta \leq 1$, positive externalities from a rival's R&D are expressed by βz_j . No fixed costs for pollution abatement are required. In addition, firm i 's total cost function is additively separable with respect to R&D expenditure, $(\gamma/2)z_i^2$, and production cost, $C(q_i) = cq_i$, ($c > 0$).

Firm i 's net emissions $e_i(q_i, z_i)$ depend on both output and environmental R&D efforts. Total emissions $E \equiv \sum_{i=1}^2 e_i(q_i, z_i)$ cause environmental damage $D(E) \equiv (d/2)E^2$, ($d > 1/2$).³ Here, d is a damage

¹For details of environmental R&D model of Cournot duopolists under a time-consistent emissions tax/subsidy, see Poyago-Theotoky (2007) and Ouchida and Goto (2014).

²The model in the current paper is based on the analytical framework developed by Chiou and Hu (2001), and Poyago-Theotoky and Teerasuwannajak (2002).

³To guarantee the positive value of emissions abatement in equilibrium, this paper assumes that $d > 1/2$.

coefficient. Social welfare SW is defined as the sum of consumer surplus, $CS \equiv (1/2)(q_i^2 + 2\theta q_i q_j + q_j^2)$, and the sum of producer profit, $\pi_i + \pi_j$, total tax revenues $T \equiv tE$, minus environmental damage $D(E)$:

$$SW \equiv CS + \pi_i + \pi_j + T - D(E). \quad (1)$$

The time structure is the following.

- Stage 1: The regulator precommits an emissions tax rate to maximize social welfare, and also determines whether cooperative environmental R&D is allowed or not.
- Stage 2: Each firm determines the environmental R&D efforts.
- Stage 3: Each firm determines the output level non-cooperatively.

We examine the following two scenarios: environmental R&D competition and environmental R&D cartelization. In sections 3 and 4, we seek the subgame-perfect Nash equilibrium (SPNE) using backward induction.

3 Environmental R&D competition

This section presents derivation of the SPNE of the case of environmental R&D competition. In stage 3 firm i determines q_i to maximize its own profit:

$$\pi_i(q_i, q_j) = p_i(q_i, q_j)q_i - cq_i - t\{q_i - z_i - \beta z_j\} - (\gamma/2)z_i^2.$$

From first-order conditions, the symmetric equilibrium production level is yielded as $q_i(t) = (A - t)/(2 + \theta) \equiv q(t)$, ($A \equiv a - c > 0$).

At the second stage, firm i non-cooperatively chooses z_i to maximize its own profit:

$$\pi_i(z_i, z_j) = [q(t)]^2 + t\{z_i + \beta z_j\} - (\gamma/2)z_i^2.$$

The first-order condition engenders the subgame equilibrium R&D efforts $z_i(t) = z_j(t) = t/\gamma$. Using this result and (1), social welfare is calculated as

$$\begin{aligned} SW(t) &= CS(t) + \pi_i(t) + \pi_j(t) + T(t) - D(t) \\ &= GSS(t) - D(t) - I(t), \end{aligned}$$

where $GSS(t) \equiv \{2A - (1 + \theta)q(t)\}q(t)$, $D(t) = (d/2)\{2q(t) - (1 + \beta)\{z_i(t) + z_j(t)\}\}^2$, and $I(t) = (\gamma/2)\{[z_i(t)]^2 + [z_j(t)]^2\}$. Hereinafter, $GSS(t)$ expresses the gross social surplus, which is the sum of consumers and producers surplus generated by production. $I(t)$ denotes total R&D expenditures. The regulator maximizes social welfare by choosing t that satisfies $dSW/dt = 0$. Then the first-order condition yields the equilibrium tax rate:

$$t_N = \frac{\gamma[(2d - 1)\gamma + 2d(2 + \theta)(1 + \beta)]A}{\Delta_N},$$

where $\Delta_N \equiv 2d[\gamma + (2 + \theta)(1 + \beta)]^2 + (1 + \theta)\gamma^2 + (2 + \theta)^2\gamma > 0$. Hereinafter, subscript N denotes the case of environmental R&D competition. As a result, the equilibrium R&D efforts are derived as follows.

$$z_N = \frac{[(2d - 1)\gamma + 2d(2 + \theta)(1 + \beta)]A}{\Delta_N}.$$

Similarly, in SPNE, production per firm, emissions per firm, profit, consumer surplus, and social welfare are the following.

$$\begin{aligned} q_N &= (A - t_N)/(2 + \theta), \\ e_N &= q_N - (1 + \beta)z_N, \\ \pi_N &= [q_N]^2 + t_N(1 + \beta)z_N - (\gamma/2)[z_N]^2, \\ CS_N &= (1 + \theta)[q_N]^2, \\ SW_N &= 2Aq_N - (1 + \theta)[q_N]^2 - 2d[e_N]^2 - \gamma[z_N]^2. \end{aligned}$$

4 Environmental R&D cartelization

Next, the case of environmental R&D cartelization is examined. Contrary to the R&D scenario presented in the previous section, each firm cooperatively maximizes joint profits, $\Pi \equiv \pi_i + \pi_j$, at stage 2. The examination during the third stage is identical to that of the case of R&D competition.

In the second stage, firm i determines z_i to maximize joint profits:

$$\Pi = 2[q(t)]^2 + t(1 + \beta)\{z_i + z_j\} - (\gamma/2)z_i^2 - (\gamma/2)z_j^2.$$

The first-order condition ($\partial\Pi/\partial z_i = 0 = \partial\Pi/\partial z_j$) yields to the subgame equilibrium R&D efforts $z_i(t) = z_j(t) = (1 + \beta)t/r$. By comparing the subgame equilibrium profits under two scenarios, it is apparent that the equilibrium profit under R&D cartelization is greater than that under R&D competition. The difference between those values is $\beta^2 t^2 / 2\gamma$. Therefore, for a given tax rate, both firms invariably have a private incentive for R&D cooperation unless $\beta = 0$. Furthermore, if forming a research joint venture (RJV) is allowable, then each firm fully shares technological information at stage 2 to maximize joint profits.

By substituting $z_i(t)$, $z_j(t)$ and $q(t)$ into (1), we obtain the social welfare in subgame equilibrium. To maximize social welfare, the regulator determines the optimum tax rate that satisfies $dSW/dt = 0$. After some manipulation, the equilibrium tax rate is obtained as

$$t_C = \frac{\gamma[(2d - 1)\gamma + 2d(2 + \theta)(1 + \beta)^2]A}{\Delta_C},$$

where $\Delta_C \equiv 2d[\gamma + (2 + \theta)(1 + \beta)^2]^2 + (1 + \theta)\gamma^2 + (2 + \theta)^2(1 + \beta)^2\gamma > 0$. Subscript C expresses the case of environmental R&D cartelization. Therefore, the other SPNE outcomes are the following.⁴

$$\begin{aligned} z_C &= \frac{(1 + \beta)[(2d - 1)\gamma + 2d(2 + \theta)(1 + \beta)^2]A}{\Delta_C}, \\ q_C &= (A - t_C)/(2 + \theta), \\ e_C &= q_C - (1 + \beta)z_C, \\ \pi_C &= [q_C]^2 + t_C(1 + \beta)z_C - (\gamma/2)[z_C]^2, \\ CS_C &= (1 + \theta)[q_C]^2, \\ SW_C &= 2Aq_C - (1 + \theta)[q_C]^2 - 2d[e_C]^2 - \gamma[z_C]^2. \end{aligned}$$

5 Comparison

This section presents a comparison of the SPNE outcomes under two R&D scenarios.

5.1 Case of no spillover effect

First, we investigate the case of no spillover effect. If $\beta = 0$, then no benefit is yielded by R&D coordination at stage 2. Therefore, the following result is obtained straightforwardly.

Lemma 1. *If at least $\beta = 0$, then $t_N = t_C$, $z_N = z_C$, $q_N = q_C$, $e_N = e_C$, $\pi_N = \pi_C$, $CS_N = CS_C$, and $SW_N = SW_C$ for all $d > 1/2$, $\gamma > 0$, and $\theta \in [0, 1]$.*

(Proof): Omitted. \square

5.2 Emission tax rate

The difference between t_N and t_C is calculated as

$$t_N - t_C = \frac{\beta(2 + \theta)\gamma GA}{\Delta_N \Delta_C} \begin{matrix} \geq \\ < \end{matrix} 0,$$

⁴The assumption of $d > 1/2$ guarantees that $\min\{z_N, z_C\} > 0$ for all $\gamma > 0$, $\beta \in [0, 1]$, and $\theta \in [0, 1]$.

where $G \equiv 4(1 + \beta)[\gamma + (2 + \theta)(1 + \beta)][\gamma + (2 + \theta)(1 + \beta)^2]d^2 + 2\gamma\{[1 + \theta - \beta]\gamma + (2 + \theta)(1 + \beta)^2(\theta - \beta)\}d - \gamma^2(2 + \theta)(2 + \beta) \geq 0$. Now, we define $\hat{d} \equiv \{d(> 1/2) | G = 0\}$. The value of \hat{d} depends on γ , β , and θ . When $\gamma \rightarrow +\infty$, the limit value of \hat{d} is derived as

$$\begin{aligned}\hat{d}_L(\beta, \theta) &\equiv \lim_{\gamma \rightarrow +\infty} \hat{d}(\gamma; \beta, \theta) \\ &= \frac{-[1 + \theta - \beta] + \sqrt{H}}{4(1 + \beta)},\end{aligned}$$

where $H \equiv [1 + \theta - \beta]^2 + 4(2 + \theta)(1 + \beta)(2 + \beta) > 0$. For a given set of β and θ , if $d \geq \hat{d}_L(\beta, \theta)$, then $t_N > t_C$ for all $\gamma > 0$. In contrast, if $d < \hat{d}_L(\beta, \theta)$, then $t_N > (\leq) t_C$ for all $\gamma < (\geq) \bar{\gamma} \equiv \{\gamma(> 0) | G = 0\}$. With respect to $\hat{d}_L(\beta, \theta)$, we find the following facts. When $\beta = 1 = \theta$, then $\hat{d}_L(\beta, \theta)$ has the maximum value $\hat{d}_L^{\max} \equiv \hat{d}_L(1, 1) = (-1 + \sqrt{73})/8 \approx 0.943$. However, when $\beta = 0 = \theta$, then $\hat{d}_L(\beta, \theta)$ has the minimum value $\hat{d}_L^{\min} \equiv \hat{d}_L(0, 0) = (-1 + \sqrt{17})/4 \approx 0.780 (> 1/2)$. Therefore, $t_N > t_C$ for all $d \geq \hat{d}_L^{\max}$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$. Consequently, the following results are derived.

Proposition 1. *Given a set of $\beta \in (0, 1]$ and $\theta \in [0, 1]$,*

- (i) $t_N > t_C$ for all $d \geq \hat{d}_L(\beta, \theta)$ and $\gamma > 0$.
- (ii) $t_N \geq t_C$ for all $d < \hat{d}_L(\beta, \theta)$ and $\gamma \leq \bar{\gamma}$.
- (iii) $t_N < t_C$ for all $d < \hat{d}_L(\beta, \theta)$ and $\gamma > \bar{\gamma}$.

Corollary 1. $t_N > t_C$ for all $d \geq \hat{d}_L^{\max}$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$.

Hereinafter, we define the sum of environmental damage ($D(E)$) and total R&D expenditures (I) as total non-production (TNP) cost. Then, the optimum emissions tax rate is satisfied with the equimarginal principle between the marginal gross social surplus ($GSS'(t)$) and the marginal TNP cost. The marginal increase of t reduces social surplus. We have readily ascertained that $GSS'(t) < 0$ and $GSS''(t) < 0$. In fact, $GSS'(t)$ is independent of d and γ . However, the marginal increase of t reduces environmental damage through emissions abatement, although it increases R&D expenditures. The effect of the marginal increase of t on TNP cost is the summation of the damage-reducing effect and R&D expenditure-increasing effect. Precisely, R&D cartelization enables internalization of the free-riding effect between two firms. In the second stage, each firm invariably has an incentive for R&D cartelization. The government reads it in decision making at stage 1. If the value of d is sufficiently large, then the damage-reducing effect is sufficiently large. In such circumstances, we have that $t_C < t_N$ because the marginal TNP cost under R&D cooperation becomes greater at a lower tax rate than the marginal TNP cost under R&D competition by larger emissions abatement through R&D cartelization. However, given a sufficiently small d , when γ is also sufficiently small, then the marginal increase of tax rate engenders a large damage-reduction effect through greater emissions abatement. It also brings larger R&D expenditures. Consequently, we find that $t_C < t_N$. Furthermore, given a sufficiently small d , when γ is also sufficiently large, then the marginal increase of the tax rate engenders a small damage-reducing effect through smaller emissions abatement, and also brings smaller R&D expenditures. Therefore, under such circumstance, the equimarginal principle engenders two equilibrium tax rates which share the relationship of $t_C > t_N$.

5.3 Production level

The difference between q_N and q_C is calculated as

$$q_C - q_N = \frac{t_N - t_C}{2 + \theta} = \frac{\beta\gamma GA}{\Delta_N \Delta_C} \geq 0. \quad (2)$$

Equation (2) shows that $\text{sign}\{q_C - q_N\}$ is opposite to $\text{sign}\{t_C - t_N\}$. Consequently, the following results are obtained.

Proposition 2. *Given a set of $\beta \in (0, 1]$ and $\theta \in [0, 1]$,*

- (i) $q_N < q_C$ for all $d \geq \hat{d}_L(\beta, \theta)$ and $\gamma > 0$.
- (ii) $q_N \leq q_C$ for all $d < \hat{d}_L(\beta, \theta)$ and $\gamma \leq \bar{\gamma}$.
- (iii) $q_N > q_C$ for all $d < \hat{d}_L(\beta, \theta)$ and $\gamma > \bar{\gamma}$.

Corollary 2. $q_N < q_C$ for all $d \geq \hat{d}_L^{\max}$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$.

5.4 Environmental R&D efforts

The difference between z_N and z_C is expressed as

$$z_C - z_N = \frac{\beta\gamma JA}{\Delta_N \Delta_C} > 0, \quad (3)$$

where $J \equiv (2d-1)\{2d+(1+\theta)\}\gamma^2 + (2+\theta)(1+\beta)\{4d^2(2+\beta) + 2(\theta d+1) + 2d\beta(1+\theta) + \theta\}\gamma + 2d(2d+1)(2+\theta)^2(1+\beta)^3 > 0$. Therefore, from Lemma 1 and equation (3), we have the following proposition.

Proposition 3. (i) *Only when $\beta = 0$, then $z_C = z_N$ for all $d > 1/2$, $\gamma > 0$, and $\theta \in [0, 1]$.*
(ii) *$z_C > z_N$ for all $d > 1/2$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$.*

The intuition underlying proposition 3 is that, in the presence of spillover effect, R&D cartelization reduces free-ride effects. In fact, the following becomes apparent.

$$\left. \frac{\partial \pi_i}{\partial z_i} \right|_{\substack{t=t_C \\ z_i=z_C \\ z_j=z_C}} = t_C - \gamma z_C = -\beta t_C < 0 \quad (4)$$

That equation is true for all $d > 1/2$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$. Equation (4) shows that the increasing effect of R&D expenditures dominates the tax-avoidance effect. d'Aspremont and Jacquemin (1988, 1990) reveal, in the context of cost-reduction R&D in Cournot duopoly, that R&D cartelization engenders more R&D effort than the case of R&D competition if the spillover effect is large. Proposition 3 differs from their well-known result.

5.5 Consumer surplus and social welfare

We next consider consumer surplus and social welfare. The difference between CS_C and CS_N is

$$CS_C - CS_N = (1+\theta)\{q_C + q_N\}\{q_C - q_N\} \geq 0. \quad (5)$$

Equation (5) states that $\text{sign}\{CS_C - CS_N\}$ is identical to $\text{sign}\{q_C - q_N\}$. Therefore, the results related to consumer surplus are closely related to Proposition 2 and Corollary 2.

Proposition 4. *Given a set of $\beta \in (0, 1]$ and $\theta \in [0, 1]$,*

- (i) *$CS_N < CS_C$ for all $d \geq \hat{d}_L(\beta, \theta)$ and $\gamma > 0$.*
- (ii) *$CS_N \leq CS_C$ for all $d < \hat{d}_L(\beta, \theta)$ and $\gamma \leq \bar{\gamma}$.*
- (iii) *$CS_N > CS_C$ for all $d < \hat{d}_L(\beta, \theta)$ and $\gamma > \bar{\gamma}$.*

Corollary 3. *$CS_N < CS_C$ for all $d \geq \hat{d}_L^{\max}$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$.*

In addition, the difference between SW_C and SW_N is

$$SW_C - SW_N = \frac{\beta\gamma FA^2}{\Delta_N \Delta_C} > 0, \quad (6)$$

where $F \equiv (2d-1)[2\beta d + (2+\beta)]\gamma^2 + 2d(1+\beta)^2\{[2(4-\theta) + \beta(11+3\theta)]d + 3 + 4\theta - 2\beta\}\gamma + 8d^2(2+\theta)(1+\beta)^4 > 0$. From equation (6) and Lemma 1, we have the following proposition.⁵

Proposition 5. (i) *Only when $\beta = 0$, then $SW_C = SW_N$ for all $d > 1/2$, $\gamma > 0$, and $\theta \in [0, 1]$.*
(ii) *$SW_C > SW_N$ for all $d > 1/2$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$.*

Proposition 5 shows that, in the presence of spillover effect, the government should allow environmental R&D cartelization in any case, and also set the emissions tax rate t_C at the first stage.⁶

⁵Proposition 5 and Proposition 6(iii) still hold, even if the production cost function is $C(q_i) = q_i^2$. For details, see Appendix A. Appendix A is the extended analysis of Section 4 presented in Wang and Wang (2009).

⁶When $\beta \neq 0$, then $\text{sign}\{\pi_C - \pi_N\}$ is arbitrary for all $d > 1/2$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$. Consequently, firms do not necessarily prefer environmental R&D cartelization under precommitment to an emissions tax.

An age-old policy debate has swirled around the issue of whether consumer surplus or social welfare should be the welfare standard for competition policy.⁷ This paper presents an investigation of two points of argument related to competition policy. One is whether coordination in environmental R&D investment should be allowable. The other is whether an environmental research joint venture (ERJV) should be socially permitted.⁸ With respect to the former, from Proposition 5(ii), cooperative R&D is socially efficient from the viewpoint of social welfare unless $\beta = 0$. However, from Proposition 4(iii), non-cooperative R&D is efficient from the viewpoint of consumer surplus only when $d < \hat{d}_L(\beta, \theta)$ and $\gamma > \bar{\gamma}$.

6 Comparative statics

Section 5 reveals that, in the presence of technological spillover effect and regulator's precommitment to an emissions tax, environmental R&D cartelization is socially more efficient than environmental R&D competition. This section presents a specific examination of the effects of technological spillover, and also produces comparative static analysis of the equilibrium outcomes under R&D cartelization.

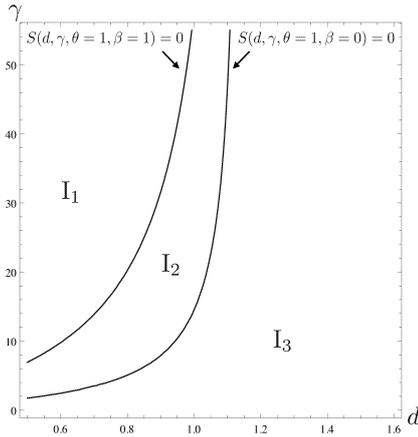
The results of comparative statics related to t_C , z_C and q_C can be summarized as follows.

Lemma 2. For all $d > 1/2$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$,

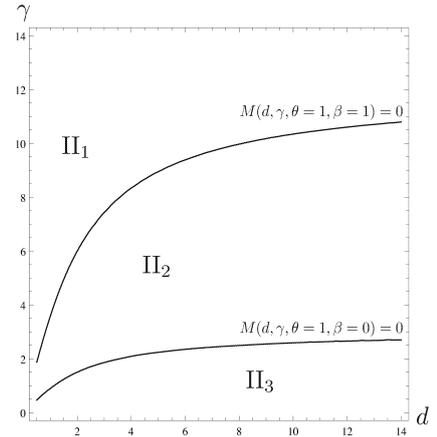
- (i) $\partial t_C / \partial \beta \gtrless 0$.
- (ii) $\partial z_C / \partial \beta \gtrless 0$.
- (iii) $\partial q_C / \partial \beta \gtrless 0$.

(Proof): Appendix B. \square

Figure 1 presents special case ($\theta = 1$) of Lemma 2. In Figure 1(a), Region I₁ (Region I₃) is the parameter set of (d, γ) that satisfies $\partial t_C / \partial \beta > (<)0$, whereas the parameter set in Region I₂ does not fix the sign $\{\partial t_C / \partial \beta\}$. Furthermore, Appendix B shows that $\partial q_C / \partial \beta = -(1/(2 + \theta))(\partial t_C / \partial \beta) \lesseqgtr 0$. Consequently, Region I₁ (Region I₃) is the parameter set that satisfies $\partial q_C / \partial \beta < (>)0$, whereas the parameter set in Region I₂ does not fix the sign $\{\partial q_C / \partial \beta\}$. Similarly, in Figure 1(b), Region II₁ (Region II₃) is the parameter set of (d, γ) that satisfies $\partial z_C / \partial \beta > (<)0$, although the parameter set in Region II₂ does not fix the sign $\{\partial z_C / \partial \beta\}$.



(a) The sign of $\partial t_C / \partial \beta$, $\partial q_C / \partial \beta$, and $\partial CS_C / \partial \beta$.



(b) The sign of $\partial z_C / \partial \beta$.

Figure 1: Results of partial differentiation.

⁷For details, see Nevena and Röller (2005), Farrell and Katz (2006), Carlton (2007), Salop (2010), Kaplow (2012) and others.

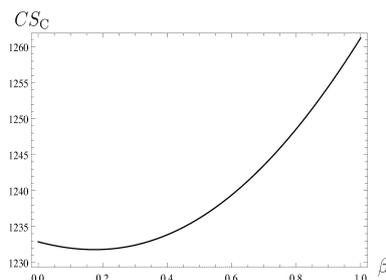
⁸For details, see Section 6.

d'Aspremont and Jacquemin (1988, 1990) show that the equilibrium value of R&D effort under cooperative R&D increases proportionally with technological spillover effects. In sharp contrast to that, it is newly revealed that emissions-reducing R&D effort under R&D coordination does not necessarily increase with the R&D spillover effect. Furthermore, we obtain the following Proposition.

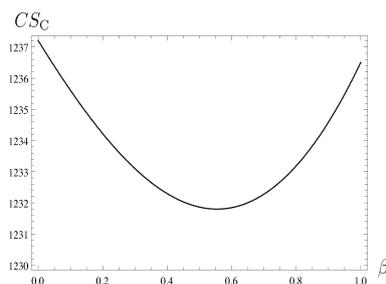
Proposition 6. For all $d > 1/2$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$,

- (i) $\partial e_C / \partial \beta < 0$.
- (ii) $\partial CS_C / \partial \beta \stackrel{>}{\leq} 0$.
- (iii) $\partial SW_C / \partial \beta > 0$.

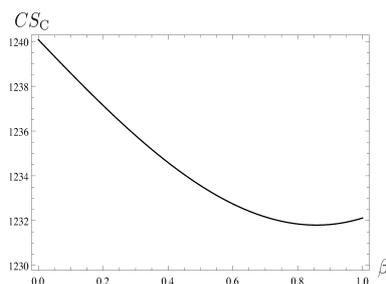
(Proof): Appendix C. \square



(a) J-shaped pattern ($\gamma = 20$).



(b) U-shaped pattern ($\gamma = 35$).



(c) Reverse J-shaped pattern ($\gamma = 50$).

Figure 2: Consumer surplus and spillover effect.

Full technological information exchange ($\beta = 1$) means the case of RJV. Proposition 6(i) and proposition 6(iii) report that ERJV cartelization engenders the lowest total emissions and the highest social welfare. In addition, Proposition 6(iii) is consistent with results reported by d'Aspremont and Jacquemin (1988, 1990) and Lambertini and Rossini (2009) show that social welfare under RJV cartelization yields superior performance compared to alternative R&D scenarios: R&D competition, R&D cartelization, and RJV competition.⁹ The widely known result in the literature of cost-reducing R&D is still robust. Its

⁹For details, see the R&D scenarios defined by Table 1 of Kamien *et al.*(1992).

policy implications are applicable as that for emissions-reducing R&D in the presence of precommitment ability. The government should always encourage ERJV cartelization in the horizontal relation. As an actual case corresponding to this model, we can exemplify the oil companies. They have huge oil refineries (plants) and also invest in improving the quality of catalyst for flue-gas desulfurization equipment for themselves.

Regarding R&D efforts, profits, consumer surplus and social welfare, Belleflamme and Peitz (2010, pp.498-499) state that RJV cartelization leads to superior performance to the case of R&D competition. Proposition 6(ii) differs greatly from typical results related to consumer surplus (e.g., Lambertini and Rossini (2009, Section 6)). Under the precommitment to an emissions tax, the results related to $\text{sign}\{\partial CS_C/\partial\beta\}$ are the following. Parameter set (d, γ) in Region I_1 (Region I_3) of Figure 1(a) engenders $\text{sign}\{\partial CS_C/\partial\beta\} < (>)0$. However, under the parameter set in Region I_2 , CS_C is U-shaped or (reverse-)J shaped in β . Figure 2 presents three representative patterns in Region I_2 in Figure 1(a) when $\theta = 1$, $d = 1$, and $A = 100$.

7 Concluding remarks

Under a regulator's ability of precommitment to an emissions tax, we examine the two scenarios of a quantity-setting duopolist's environmental R&D: R&D competition and R&D cartelization. This paper reveals that, in the presence of a technological spillover effect, the regulator always prefers environmental R&D cartelization to environmental R&D competition. In addition, consumer surplus is not necessarily maximized by ERJV cartelization, although there invariably exist private incentives to firms for ERJV cartelization as well as social incentives for it. Consequently, it is newly revealed that ERJV cartelization is socially efficient from both viewpoints of consumer surplus and social welfare if the damage coefficient is sufficiently large and the R&D cost parameter is small. Then, total emissions are minimized.

This study provides two contributions. One is to derive new theoretical findings and foundations in this field. The other is to give new insights for policy design. With regard to the design of competition policy, it is too difficult for antitrust authorities to evaluate firm profits and environmental damage precisely. Therefore, regulators in many countries might unwillingly employ consumer surplus the welfare standard. As referred in footnote 7, numerous policy debates have centred upon the welfare standard. For such arguments, this paper presents some theoretical foundations (Propositions 4, 5, and 6).

Appendix A.

In the case of $C(q_i) = q_i^2$, the difference between the two equilibrium values of social welfare is

$$SW_C^* - SW_N^* = \frac{\beta\gamma Za^2}{\Psi\Omega} > 0,$$

where $Z \equiv 8(1+\beta)^4(4+\theta)d^2 + 2d\gamma(1+\beta)^2\{6-\beta+2\theta+2d[2+\beta(5+\theta)]\} + (2d-1)[2+\beta(2d+1)]\gamma^2 > 0$, $\Psi \equiv 2d[(1+\beta)(4+\theta)+\gamma]^2 + \gamma[(4+\theta)^2 + \gamma(3+\theta)] > 0$, and $\Omega \equiv 2d[(1+\beta)^2(4+\theta)+\gamma]^2 + \gamma[(1+\beta)^2(4+\theta)^2 + \gamma(3+\theta)] > 0$ and $\beta \in (0, 1]$. The superscript asterisk expresses the case of quadratic cost function. The equation above invariably holds unless $\beta = 0$. If $\beta = 0$, then $SW_C^* = SW_N^*$.

In addition, after some manipulations, we have

$$\frac{\partial SW_C^*}{\partial\beta} = \frac{2(1+\beta)\gamma Va^2}{\Omega^2} > 0,$$

where $V \equiv 4d^2(1+\beta)^4(4+\theta)(6+\theta) + 4d\gamma(1+\beta)^2[2d(5+\theta)-1] + (2d+1)(2d-1)\gamma^2 > 0$.

The results presented above give an important message related to Wang and Wang's (2009) privatization model with emissions tax policy. In their model, the equilibrium outcomes under R&D competition are identical to those under R&D cartelization because no spillover effect is assumed. Therefore, examinations of the case of R&D coordination are indispensable if the technological spillover effect is newly added to the Wang and Wang's (2009) model.

Appendix B.

Proof of Lemma 2:

We have readily obtained the following result.

$$\frac{\partial t_C}{\partial \beta} = \frac{S(d, \gamma, \theta, \beta)\gamma A}{[\Delta_C]^2} \geq 0, \quad \frac{\partial z_C}{\partial \beta} = \frac{M(d, \gamma, \theta, \beta)A}{[\Delta_C]^2} \geq 0,$$

where $S(d, \gamma, \theta, \beta) \equiv -4d^2(1+\beta)^4(2+\theta)^2 - 4d(2d-1)(1+\beta)^2(2+\theta)\gamma + \{2+\theta - 2d(2d-1)\}\gamma^2 \geq 0$ and $M(d, \gamma, \theta, \beta) \equiv -4d^2(1+\beta)^6(2+\theta)^3 + 2d(5+\theta-2d)(1+\beta)^4(2+\theta)^2\gamma + [2+\theta + 2(2\theta+3)d + 4d^2](1+\beta)^2(2+\theta)\gamma^2 - (2d-1)(1+\theta+2d)\gamma^3 \geq 0$. Additionally, we obtain that $\partial q_C/\partial \beta = -(1/(2+\theta))(\partial t_C/\partial \beta) \leq 0$. Therefore, $\text{sign}\{\partial t_C/\partial \beta\}$, $\text{sign}\{\partial z_C/\partial \beta\}$, and $\text{sign}\{\partial q_C/\partial \beta\}$ are arbitrary for all $d > 1/2$, $\gamma > 0$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$. \square

Appendix C.

Proof of Proposition 6(i):

After some manipulations, we have $e_C = \{2d(1+\beta)^4(2+\theta) + (1+\beta)^2(3+\theta)\gamma + \gamma^2\}A/\Delta_C (> 0)$. Moreover, it is straightforward to obtain that

$$\frac{\partial e_C}{\partial \beta} = -\frac{2\gamma(1+\beta)KA}{(2+\theta)[\Delta_C]^2} < 0,$$

where $K \equiv 2d(1+\beta)^4(2+\theta)^2[3+3\theta+\theta^2] + 4d(1+\beta)^2(2+\theta)^3\gamma + [2d(2+\theta)^2 + (1+\theta)(2d-1)]\gamma^2 > 0$. \square

Proof of Proposition 6(ii):

The following result is readily obtained.

$$\frac{\partial CS_C}{\partial \beta} = -\frac{2(1+\theta)}{2+\theta} \left(\frac{\partial t_C}{\partial \beta} \right) q_C.$$

Consequently, from Lemma 2(i), we obtain that $\partial CS_C/\partial \beta \leq 0$. \square

Proof of Proposition 6(iii):

We obtain that, for all $\gamma > 0$, $d > 1/2$, $\beta \in (0, 1]$, and $\theta \in [0, 1]$,

$$\frac{\partial SW_C}{\partial \beta} = \frac{2\gamma(1+\beta)RA^2}{[\Delta_C]^2} > 0,$$

where $R \equiv (2d+1)(2d-1)[2d+(1+\theta)]\gamma^2 + 4d(2+\theta)(1+\beta)^2[2(3+\theta)d-1]\gamma + 4d^2(2+\theta)^2(4+\theta)(1+\beta)^4 > 0$. \square

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