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The organization of R&D and environmental policy: So does emission subsidy reduce emissions?

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Abstract

This paper reexamines the Poyago-Theotoky model and provides additional investigation that was conducted under a corrected environmental damage parameter. As new findings, we obtain the following. First, social welfare under a time-consistent emission tax (emission subsidy) policy is always welfare-enhancing rather than the case of *laissez-faire*. Second, if the environmental damage parameter is sufficiently small, then the equilibrium emission tax rate is invariably negative. It is therefore an emission subsidy. Moreover, total emissions under the emission subsidy become smaller than those under *laissez-faire* if the damage parameter is sufficiently small, and if the R&D cost is low. However, total emissions under the emission subsidy become greater than those under *laissez-faire* if the damage parameter is sufficiently small, and if the R&D cost is high.

JEL Classification: O32; L13; Q55; Q58.

Keywords: Emission subsidy; Emission tax; Emission reduction; Environmental R&D; Cournot duopoly

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1 Introduction

In an industrialized economy in which giant firms dominate markets, perpetual innovation continuously drives the rate of growth in living standards. Particularly, it is true that the petroleum and chemical industries have both been oligopolistic, routinizing corporate and environmental innovations, and contributing to economic growth with some environmental friendliness. These industries typically have developed pollution abatement instruments such as desulfurization equipment and denitrification equipment, which are categorized into *end-of-pipe* technologies.

Poyago-Theotoky (2007) presents pioneering work on emission tax policy and competition policy related to quantity-setting duopolists with *end-of-pipe* technology. Particularly, that investigation examines whether polluting Cournot duopolists' coordination of behavior in environmental R&D is socially allowable when the government has no precommitment ability for emission taxes. The study finds important policy implications for socially desirable R&D formation under time-consistent emission taxes. Furthermore, Poyago-Theotoky (2010) announces a corrigendum showing that the negative emission tax (emission subsidy) might be partially justified if it considerably improves the market inefficiency caused by Cournot duopolists. Indeed, this is a surprising result, but the essential question remains. That is "When does an emission subsidy reduce (or increase) emissions?" The answer is fervently sought by policy designers.

Many developed countries must confront the obligation of emissions reduction, along with the necessity of building a low-carbon society. In addition, most developing countries seek both industrialization and environmental improvement. Therefore, it is quite necessary for social planners to investigate the regulatory circumstances under which a time-consistent emissions subsidy reduces (or increases) emissions. This study examines that question carefully.

The arguments presented in this paper proceed as follows. Section 2 introduces the Poyago-Theotoky (2007) model and equilibrium outcomes. Section 3 presents an examination of the sign of the equilibrium emission tax rate and effects on total emissions. Section 4 presents policy implications and conclusions.

2 Model and equilibrium outcomes

This section presents the model and its equilibrium outcomes.

2.1 The model

Market structure:

Considering an industry comprising two homogeneous firms – firm i and firm j – engaging in quantity competition with the same cost structure and emissions-reducing technology, q_i is assumed to denote firm i's output. Inverse demand is given as $p(q_i, q_j) = a - (q_i + q_j),\ (i, j =$

$1, 2;\ i \neq j$), where $a(> 0)$ is a market size parameter.

Environmental R&D and cost structure:

The value of each firm's emissions per unit output is assumed to be one. Firm i's environmental R&D effort is denoted as z_i. Both firms use end-of-pipe technology for pollution abatement. Although this abatement technology is insufficient for reducing emissions per unit output, it mitigates emissions by adsorbing emissions at the end of the production process.

Firm i receives benefits not only from its own environmental R&D efforts but also from the efforts of its rival. When firm i's production level is q_i, then the R&D expenditures $(\gamma/2)z_i^2, (\gamma > 0)$ enable firm i to abate its emissions from q_i to $e_i(q_i, z_i) \equiv q_i - z_i - \beta z_j$. A lower value of γ implies higher efficiency of the environmental R&D cost. Symmetric parameter $\beta \in [0, 1]$ denotes the spillover effects of R&D. Firm i's positive externality from rival's R&D efforts is denoted as βz_j. No fixed costs for pollution abatement are necessary. In addition, firm i's total cost function is additively separable with respect to production costs and R&D expenditures: $C(q_i, z_i) = cq_i + (\gamma/2)z_i^2, (c > 0, A \equiv a - c > 0)$.

Environmental damage and social welfare:

Net emissions from i, $e_i(q_i, z_i)$, depend both on the output and on environmental R&D efforts. Total emissions $E \equiv \sum_{i=1}^{2} e_i(q_i, z_i)$ cause environmental damage $D(E) \equiv dE^2/2$; $d(> \underline{d} \equiv (-1 + \sqrt{3})/2)$ is the damage parameter.[1] Social welfare SW is defined as the sum of consumers' surplus and producer's surplus less environmental damage $D(E)$ and total R&D expenditures, $\sum_{i=1}^{2}(\gamma/2)z_i^2$.

Timing:

The regulator has no precommitment ability for emission tax rate t. The time structure is the following.

<u>*Stage 1*</u>: Firm i determines z_i to maximize its own profit (π_i) or joint profits $(\pi_i + \pi_j)$.

<u>*Stage 2*</u>: The regulator determines emission tax rate (t) to maximize social welfare.

<u>*Stage 3*</u>: Firm i noncooperatively determines output level (q_i) to maximize its own profit.

2.2 Equilibrium outcomes

Poyago-Theotoky (2007) examines two environmental R&D scenarios (R&D competition and R&D cartelization) and derives the subgame-perfect Nash equilibrium (SPNE) under a time-consistent emission tax.[2]

[1] Poyago-Theotoky (2007, 2010) assumes $d > 1/2$, which is unnecessarily strict. An interior solution for environmental R&D efforts is guaranteed by the following relaxed assumption: $d > \underline{d} \equiv (-1 + \sqrt{3})/2$. In fact, two equilibrium values of R&D efforts in Table 1 ($z_{\rm N}$ and $z_{\rm C}$) are both positive if $d > \underline{d}$. For details, see Ouchida and Goto (2012).

[2] For detailed solution procedures, see Poyago-Theotoky (2007).

To begin with, let us explore the case of R&D competition. In stage 3, firm i's profit is $\pi_i(q_i, q_j) = \{a - (q_i + q_j)\}q_i - cq_i - t\{q_i - z_i - \beta z_j\}\} - (\gamma/2)z_i^2$. From the first-order conditions, the equilibrium output is calculated as $q(t) = (A - t)/3$. Consequently, social welfare in stage 2 is derived as $SW(t) = 2Aq(t) - 2[q(t)]^2 - (d/2)\{2q(t) - (1+\beta)\{z_i + z_j\}\}^2 - \sum_{i=1}^{2}(\gamma/2)z_i^2$. The subgame equilibrium emission tax rate is

$$t(z_i, z_j) = \frac{(2d-1)A - 3d(1+\beta)\{z_i + z_j\}}{2(1+d)}. \tag{1}$$

In the first stage, firm i's profit is $\pi_i(z_i, z_j) = [q(t(z_i, z_j))]^2 + t(z_i, z_j)\{z_i + \beta z_j\} - (\gamma/2)z_i^2$. Each firm determines its environmental R&D efforts noncooperatively. From the first-order conditions $\partial \pi_i(z_i, z_j)/\partial z_i = 0$, $(i, j = 1, 2; i \neq j)$, we are able to obtain the equilibrium R&D efforts z_{N} and the equilibrium values of other variables. The results are presented in Table 1.[3]

Environmental R&D cartelization implies that each firm determines its environmental R&D effort to maximize joint profits $(\pi_i(z_i, z_j) + \pi_j(z_i, z_j))$ during the first stage. Each equilibrium value under R&D cartelization is also reported in Table 1.

[3]Subscript "N" stands for the case of R&D competition. Subscript "C" denotes the case of environmental R&D cartelization.

	Two environmental R&D scenarios	
	Environmental R&D competition	Environmental R&D cartelization
Environmental R&D efforts	$z_{\mathrm{N}} = \dfrac{[(1+d)(2d-1)+d(1+\beta)]A}{2\gamma(1+d)^2+d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$z_{\mathrm{C}} = \dfrac{(1+\beta)[(1+d)(2d-1)+2d]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Emission tax rate	$t_{\mathrm{N}} = \dfrac{[d(2d-3)(1+\beta)^2+2\gamma(2d^2+d-1)]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$t_{\mathrm{C}} = \dfrac{[d(2d-3)(1+\beta)^2+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Output level	$q_{\mathrm{N}} = \dfrac{[2(1+d)\gamma+d(1+\beta)(7+4d+3\beta)]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$q_{\mathrm{C}} = \dfrac{[d(5+2d)(1+\beta)^2+\gamma(1+d)]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Emissions	$e_{\mathrm{N}} = \dfrac{[2(1+d)\gamma+(1+\beta)\{(3+\beta)d+2\}]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$e_{\mathrm{C}} = \dfrac{[(1+d)\gamma+2d(1+\beta)^2]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Profits	$\pi_{\mathrm{N}} = q_{\mathrm{N}}^2+t_{\mathrm{N}}(1+\beta)z_{\mathrm{N}}-(\gamma/2)z_{\mathrm{N}}^2$	$\pi_{\mathrm{C}} = q_{\mathrm{C}}^2+t_{\mathrm{C}}(1+\beta)z_{\mathrm{C}}-(\gamma/2)z_{\mathrm{C}}^2$
Social welfare	$SW_{\mathrm{N}} = 2Aq_{\mathrm{N}}-2q_{\mathrm{N}}^2-2d\{q_{\mathrm{N}}-(1+\beta)z_{\mathrm{N}}\}^2-\gamma z_{\mathrm{N}}^2$	$SW_{\mathrm{C}} = 2Aq_{\mathrm{C}}-2q_{\mathrm{C}}^2-2d\{q_{\mathrm{C}}-(1+\beta)z_{\mathrm{C}}\}^2-\gamma z_{\mathrm{C}}^2$

Table 1: Equilibrium outcomes under two environmental R&D scenarios.

3 Further investigations and results

This section presents examination of the sign of the equilibrium emission tax rate and the effects on total emissions.

3.1 Sign of emission tax rate

Poyago-Theotoky (2007) proves that each firm always has some incentive for R&D cooperation, that is $\pi_{\mathrm{C}} \geq \pi_{\mathrm{N}}$, and that $SW_{\mathrm{C}} > SW_{\mathrm{N}}$ if $1/2 < d < 3/2$.[4] Furthermore, if $d \geq 3/2$, then $SW_{\mathrm{C}} \geq (<) SW_{\mathrm{N}}$ for all $\gamma \geq (<) \gamma_{\varphi}$.[5] However, strictly speaking, as pointed out by Ouchida and Goto (2012), these results still hold under relaxed assumptions: $d > \underline{d} \equiv (-1+\sqrt{3})/2$. Therefore, if $\underline{d} < d < 3/2$, then cooperative environmental R&D is always socially allowable, which implies that the government permits firms to undertake R&D cooperation, and also determines the emission tax rate t_{C} during stage 2 if $\underline{d} < d < 3/2$. In addition, from Table 1, it is readily apparent that $t_{\mathrm{C}} > 0$ and $t_{\mathrm{N}} > 0$ if $d \geq 3/2$.

Poyago-Theotoky (2010) points out that the emission tax rate in SPNE can be negative.[6] The sign of the denominator of t_{C} in Table 1 is positive. Therefore, we specifically examine the sign of the numerator. The sign of t_{C} depends on the following condition:

$$\gamma < (\geq)\ \gamma_{\mathrm{C}}^{t} \equiv \frac{d(3-2d)(1+\beta)^2}{(2d-1)(d+1)} \iff t_{\mathrm{C}} < (\geq)\ 0. \tag{2}$$

The critical value γ_{C}^{t} is presented in Figure 1.[7] The asymptotic line of γ_{C}^{t} is $d = 1/2$. If d is in the interval $(\underline{d}, 1/2]$, then $t_{\mathrm{C}} < 0$ for all $\beta \in [0,1]$. In Regions I and II in Figure 1, $t_{\mathrm{C}} < 0$. In contrast, in Regions III and IV, $t_{\mathrm{C}} > 0$. When $d > 3/2$, then $t_{\mathrm{C}} > 0$ for all $\gamma > 0$ and $\beta \in [0,1]$. Proposition 1 summarizes these results on t_{C}.

Proposition 1. (i) When $\underline{d} < d \leq 1/2$, then $t_{\mathrm{C}} < 0$ for all γ and $\beta \in [0,1]$.
(ii) When $1/2 < d \leq 3/2$, then $t_{\mathrm{C}} < 0$ for all $\gamma < \gamma_{\mathrm{C}}^{t}$.
(iii) When $1/2 < d \leq 3/2$, then $t_{\mathrm{C}} \geq 0$ for all $\gamma \geq \gamma_{\mathrm{C}}^{t}$.

In this model, a negative emission tax rate (emission subsidy) is fundamentally equivalent to a production subsidy because the value of each firm's emissions per unit output assumed to be one. Production subsidy has two effects. One is a damage increasing effect. The other is

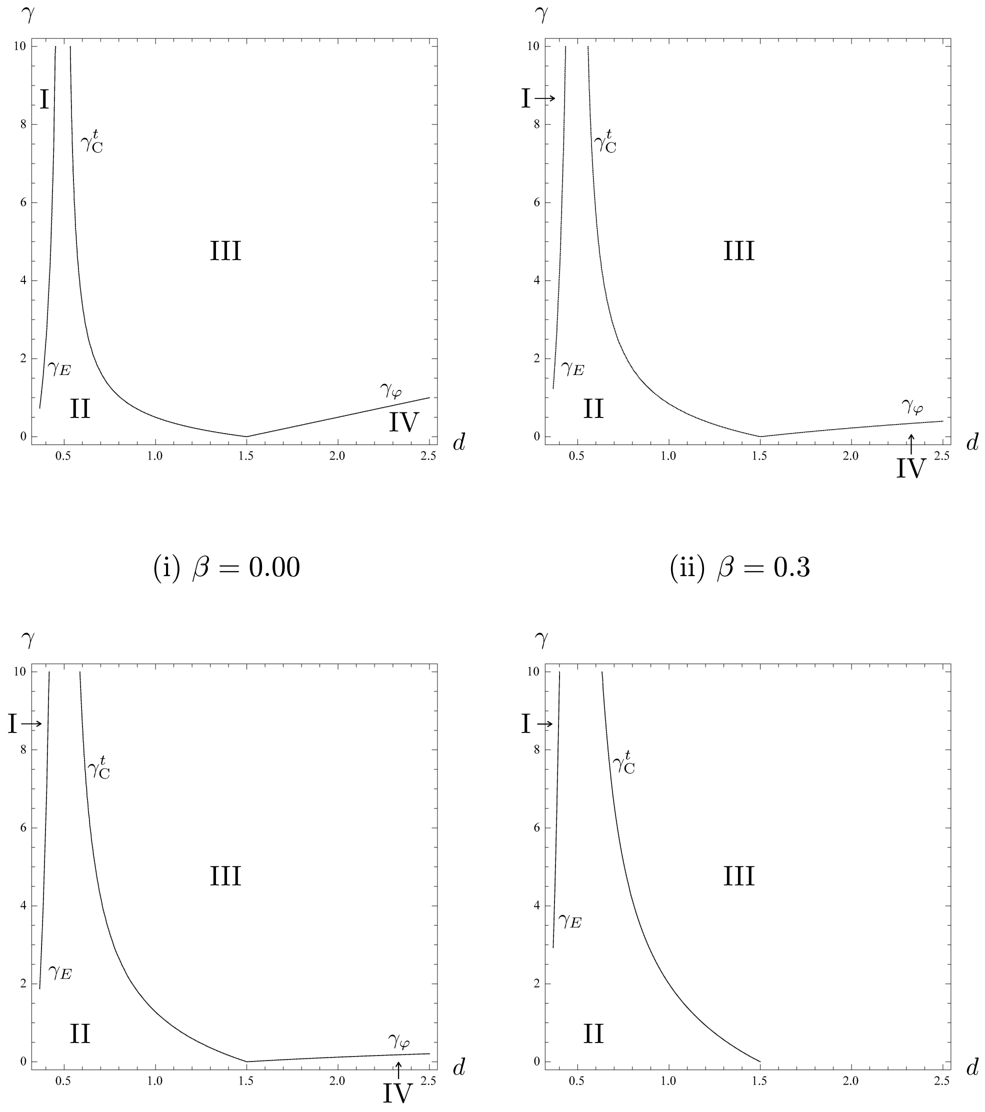
[4] For details, see Equation (16) and Part (i) of Proposition 2 in Poyago-Theotoky(2007)[respectively, p.70 and p.72].

[5] The critical value γ_{φ} is defined as $\gamma_{\varphi} \equiv \{\gamma > 0 | \varphi \equiv d(3-2d)(1+\beta)^2(1-\beta) + 2\gamma(2d^2\beta + 2d\beta - \beta + d) = 0, d > 3/2\}$. The definition of φ is given in Poyago-Theotoky (2007, p. 69). The critical value γ_{φ} is presented in Figure 1. When $\beta = 1$, Region IV disappears.

[6] Petrakis and Xepapadeas (2003) analyze the strategic emission tax policy when the monopolist can relocate abroad. Then, they point out that time-consistent emission tax rate in SPNE can be negative.

[7] The critical value γ_{C}^{t} is a monotonically decreasing function in $d \in (1/2, 3/2)$. In addition, the critical value γ_{φ} is a monotonically increasing function in $d \in (3/2, +\infty)$. Consequently, those two curves in Figure 1 apparently have a unique intersection at $(d, \gamma) = (3/2, 0)$.

the decreasing effect of market inefficiency. When d is sufficiently small, the increasing effect of environmental damage is dominated by the improving effect of the market inefficiency. This is the economic intuition underlying the negative emission tax rate.[8] Particularly, part (i) of Proposition 1 is obtained under the parameter range corrected by Ouchida and Goto (2012).



(i) $\beta = 0.00$ (ii) $\beta = 0.3$

(iii) $\beta = 0.6$ (iv) $\beta = 1.0$

Figure 1. Sign of the emission tax rate and total emissions.

[8]For details, see Poyago-Theotoky (2010) and Petrakis and Xepapadeas (2003, p.203).

3.2 Negative emission tax and total emissions

Next we calculate the effect of the time-consistent emission tax on the reduction of total emissions. The equilibrium emission per firm under *laissez-faire* is $A/3$. Therefore, total emissions under *laissez-faire* are $E^0 \equiv 2A/3$. Total emissions under environmental R&D cartelization are $E_{\mathrm{C}} \equiv 2e_{\mathrm{C}}$. After some manipulation, the difference between E^0 and E_{C} is obtained as follows.

$$E^0 - E_{\mathrm{C}} \geq (<)\ 0 \iff \gamma \leq (>)\ \gamma_E \equiv \frac{(1+\beta)^2\{-8d^2-6d+3\}}{(2d-1)(d+1)} \tag{3}$$

Therefore, the effect of time-consistent emission tax (or emission subsidy) on the reduction of total emissions is summarized in the following proposition and corollary.

Proposition 2. (i) When $\underline{d} < d < 1/2$, then $E_{\mathrm{C}} > E^0$ for all $\gamma > \gamma_E$.

(ii) When $\underline{d} < d < 1/2$, then $E_{\mathrm{C}} \leq E^0$ for all $\gamma \leq \gamma_E$.

(iii) When $d \geq 1/2$, then $E_{\mathrm{C}} < E^0$ for all γ and $\beta \in [0,1]$.

(iv) When $\gamma < (\sqrt{3}-1)(1+\beta)^2$, then $E_{\mathrm{C}} < E^0$ for all $d \in (\underline{d}, +\infty)$.

(Proof): See Appendix A. □

Corollary 1. When $\gamma < (\sqrt{3}-1)$, then $E_{\mathrm{C}} < E^0$ for all $d \in (\underline{d}, +\infty)$ and $\beta \in [0,1]$.

(Proof): Readily inferred from Proposition 2(iv). □

In Figure 1, γ_E is described as the borderline between Region I and Region II. In both Regions I and II, the sign of the equilibrium emission tax rate is negative: emission subsidy is realized in the equilibrium. Therefore, we can identify that in Region I, the emission subsidy yields greater total emissions than those under *laissez-faire*. In Region II, however, it yields less total emissions than those under *laissez-faire*, i.e., the emission subsidy reduces total emissions.

We now explore the intuition underlying the existence of Regions I and II. As environmental damage d decreases, the equilibrium tax rate t_{C}, R&D effort z_{C}, and accordingly R&D effort with a spillover effect $(1+\beta)z_{\mathrm{C}}$ respectively denote decreases. Additionally, as the R&D cost parameter γ becomes large, each value of z_{C} and $(1+\beta)z_{\mathrm{C}}$ decreases greatly. Ultimately, if the value of d is sufficiently small, then the sign of t_{C} becomes negative. However, as the value of d becomes small, the equilibrium production level per firm q_{C} becomes greater. Consequently, as shown by Region I, total emissions under emission subsidies become greater than that under *laissez-faire* if the damage parameter is sufficiently small, and if R&D cost is not low. In Region II, whereas the sign of equilibrium tax rate is negative, total emissions under an emission subsidy become smaller than the case of *laissez-faire* because the emission-increasing effect is dominated by the large abatement effect.[9]

[9]Unlike Region IV, Regions I and II still exist even if $\beta = 1$.

From the definitions of γ_{C}^{t} and γ_E in Equations (2) and (3), we obtain the following proposition with respect to Region II.

Proposition 3. The larger the spillover effect becomes, the broader the regulatory circumstances in which emission subsidies reduce total emissions.

(Proof): See Appendix B. □

Proposition 3 states that Region II is increasing in β. Figure 1 presents this result graphically. The value of β is regarded as the level of intellectual property rights protection. Therefore, a stronger protection level generates smaller Region II. When the spillover is perfect ($\beta = 1$), Region I becomes the smallest.

Next, we devote attention to the case of $d > 3/2$. Then, it is straightforward to verify that $t_{\mathrm{C}} > 0, t_{\mathrm{N}} > 0, E_{\mathrm{C}} < E^0$, and $E_{\mathrm{N}} \equiv 2e_{\mathrm{N}} < E^0$ if $d > 3/2$. Furthermore, because social welfare under *laissez-faire* is calculated as $SW^0 \equiv 2(2-d)A^2/9$, we obtain that $SW_{\mathrm{C}} > SW^0$ and $SW_{\mathrm{N}} > SW^0$ for all $d \in (\underline{d}, +\infty)$, $\gamma > 0$ and $\beta \in [0, 1]$. These results for social welfare imply that a time-consistent emission tax (emission subsidy) policy is invariably welfare-enhancing. From our examinations described above and Poyago-Theotoky's (2007, 2010) conclusions, the comparison results with regard to the sign of emission tax rate, total emissions, and social welfare are presented in Table 2.

Region	Emission tax	Total emissions	Social welfare
I	$t_{\mathrm{C}} < 0$	$E_{\mathrm{C}} > E^0$	$SW_{\mathrm{C}} > SW_{\mathrm{N}}$
II	$t_{\mathrm{C}} < 0$	$E_{\mathrm{C}} < E^0$	$SW_{\mathrm{C}} > SW_{\mathrm{N}}$
III	$t_{\mathrm{C}} > 0$	$E_{\mathrm{C}} < E^0$	$SW_{\mathrm{C}} > SW_{\mathrm{N}}$
IV	$t_{\mathrm{N}} > 0$	$E_{\mathrm{N}} < E^0$	$SW_{\mathrm{C}} < SW_{\mathrm{N}}$

Table 2. Emission tax rate, total emissions and social welfare.

4 Policy implication and concluding remarks

In this section, we derive policy implications from our above analysis. Part (i) of Proposition 2 provides the following new policy recommendation. Here, we presume that the government faces with the obligation of emission reduction. If the environmental damage parameter is sufficiently small, and if R&D cost is sufficiently high (i.e., Region I in Figure 1), then the government should not introduce a time-consistent emission subsidy that yields greater emissions than those under *laissez-faire* in Cournot duopoly. In other words, in regulatory circumstances such as Region I in Figure 1, the government should adopt another policy instrument. From the social welfare ranking in Table 2, environmental R&D cartelization is socially desirable in Region I. Furthermore, Proposition 3 implies that the perfect spillover minimizes Region I. These results indicate that environmental research joint venture cartelization shrinks the regulatory environment of the emission-increasing outcome.

Many countries are carrying out environmental regulations to reduce greenhouse gas emissions. Particularly major developed countries must act as "abatement leaders". At the same time, many developing countries seek emissions abatement as well as economic growth. This research sends an important message to policy-makers in such countries. As pointed out by Petrakis and Xepapadeas (2003) and Poyago-Theotoky (2010), negative emission tax (emission subsidy) can be partially justified if market power mitigation effect yielded by emission subsidy dominates the damage-increasing effect. In this model, an emissions subsidy is feasible as an output subsidy. However, if the policy goal is to achieve the obligation of emission reduction, then an emission-increasing outcome is a policy failure. The petroleum refining industry and the petrochemical industry are examples of polluting industries with desulfurization equipment and denitrification equipment. Those industries are applicable to the this model. Such industries emit plenty of greenhouse gases. Therefore, the near impossibility of emissions reduction obligations has a strong impact on the enforcement of international environmental treaties such as the United Nations Framework Convention on Climate Change. This study provides fundamental results that are expected to be useful in avoiding policy failure when the regulator's policy variable is a time-consistent emission tax.

As described in this paper, these new findings have two points of particular significance.[10] One is derivation of incremental policy implications. Another is to give a further theoretical foundation for time-consistent emission tax policy in quantity-setting duopoly. This research plays an indispensable complementary role for contributions by Poyago-Theotoky (2007, 2010).

Appendix A

Proof of Proposition 2: Difference between $E^0 = 2A/3$ and $E_{\mathrm{C}} = 2e_{\mathrm{C}}$ is calculated as shown below.

$$E^0 - E_{\mathrm{C}} \geq (<)\ 0 \iff \gamma \leq (>)\ \gamma_E \equiv \frac{(1+\beta)^2\{-8d^2 - 6d + 3\}}{(2d-1)(d+1)}$$

The critical value γ_E is the increasing function in the interval $(\underline{d}, 1/2)$. In addition, $\gamma_E > 0$ for all $d \in (\underline{d}, 1/2)$. Consequently, the value of γ_E at the γ-intercept is obtained as $\gamma_E|_{d=\underline{d}} = (\sqrt{3}-1)(1+\beta)^2$. The value of $\gamma_E|_{d=\underline{d}}$ is increasing in $\beta \in [0, 1]$. Furthermore, the asymptotic line of γ_E is $d = 1/2$. If $d \geq 1/2$, then $E^0 - E_{\mathrm{C}} > 0$. □

[10] That is $d > 1/2$, we can not obtain the new findings if we adopt the unnecessarily strict assumption for the environmental damage parameter by Poyago-Theotoky (2007, 2010). Our results are generated by further investigations under the corrected damage parameter.

Appendix B

Proof of Proposition 3: From (2), we have straightforwardly $\partial\gamma_C^t/\partial\beta > 0$ for all $d \in (1/2, 3/2)$, $\gamma > 0$, and $\beta \in [0,1]$. Similarly, from (3), $\partial\gamma_E/\partial\beta > 0$ for all $d \in (\underline{d}, 1/2)$, $\gamma > 0$, and $\beta \in [0,1]$. Therefore, Region II becomes larger as β becomes larger. $\square$

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