DISCUSSION PAPER
November 2010

No.45

A Model for Recycling Target Policy under Imperfect Competition With and Without Cooperation Between Firms

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Abstract: The purpose of this paper is to develop a general theoretical model that describes production and recycling in an n-firm oligopoly market in which firms can cooperate for recycling. We use a three-stage game to analyze a specific recycling issue. In stage 0, the government sets a target recycling rate as well as virgin material and final disposal tax rates. In stage 1, *n* identical firms simultaneously invest to reduce the cost of recycling given the recycling target. Here we treat this activity as a type of R&D. Furthermore, we consider three kinds of R&D activities depending on what firms maximize in stage 1, namely, industry-wide cooperation, within-group cooperation, and non-cooperation. In stage 2, firms engage in a Cournot competition.

Surprisingly, positive virgin material taxes or positive final disposal taxes discourage firms from engaging in recycling R&D efforts in normal situations, regardless of whether R&D cooperation takes place. We compare second-best social welfare levels under the three regimes described above. We find that both non-cooperation and within-group

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cooperation are inferior from a welfare perspective to industry-wide cooperation. Furthermore, in the case of within-group cooperation, the symmetric division of firms induces the lowest welfare for all ranges of a given spillover parameter.

Keywords: Recycling, Cooperation, Cournot Competition.

JEL Classification Q53, L13, O32

1. Introduction

In recent decades, the amount of electrical and electronic equipment (EEE) produced worldwide has significantly increased. The resulting increase in the amount of waste electrical and electronic equipment (WEEE) has lead to a major increase in environmental pollution. In 2005, the European Union implemented an environmental directive named 2002/96/EC to management WEEE. This regulation requires manufacturers to charge a fee when they help consumers dispose of WEEE that originates from their own products. However, the earliest implementation of a WEEE recycling system occurred not in the EU but in Japan. The Japanese WEEE recycling system was initiated in 2001. According to Japan's Recycling Law, the Japanese WEEE recycling system only recycles six types of home appliances.[1] In contrast, the EU WEEE directive encompasses a wider variety of products.

[1] In 2001, the designated appliances were CRT-based televisions, air conditioners, refrigerators and freezers, and washing machines. Liquid crystal and plasma televisions and clothes driers were added in 2009.

In both the EU and Japan, it is the responsibility of the manufacturers to recycle their own products. To promote the efficiency of the recycling system, the EU WEEE directive encourages each manufacturer to participate in a collective scheme called the Producer Responsibility Organization (PRO). The WEEE Directive states that "the producer can choose to fulfill this financing obligation either individually or by joining a collective scheme" (Article 8.2). PROs have been established in many EU countries. Under Japan's recycling system, manufacturers have formed two recycling groups. Both of them have independent recycling systems for the collection and handling of WEEE. Although Japan's recycling law does not regulate any type of competition between these two groups, the Japanese government likes to see cooperative environmental R&D aimed at reducing recycling costs occurring between these two groups. These two recycling groups in Japan are comprised of 24 firms ("group A") and 21 firms ("group B"). In Japan's recycling regime, each group establishes its own recycling systems, but they cooperate to collect and recycle WEEE. The most critical problem in the WEEE recycling systems of both the EU and Japan is that the cost of recycling is high. High recycling costs not only discourage manufacturers from investing in a recycling system but also lead to lower social welfare. In this paper, we establish an environment R&D model to analyze firm behavior in reducing the costs of recycling.

Many theoretical articles have investigated the issue of waste recycling given a perfect competition market, including Walls and Palmer (2001), Shinkuma (2007) and Koide (2008). However, the market structure of WEEE recycling regimes in the EU and Japan is an oligopoly market rather than a perfect competition market. Fleckinger and Glachant

(2010) investigated the government's waste policy in a product-differentiated duopoly model. They compared the results between competitive and cooperative PRO models and revealed some collusion problems in PROs. In this paper, we also discuss the issue of WEEE recycling in an imperfect competition market structure. A crucial difference between their model and our own is that in their model, firms have a responsibility to recycle their own products that are thrown out, but they do not use the waste as an input material in their model. In our model, we assume that firms not only collect their own waste but also use the waste as an input material. Furthermore, we assume that the percentage of recycled material used is in concordance with the government's target recycling rate. These assumptions match the current situation in Japan. For example, Sony electronics usually uses the waste plastic extracted from their own waste products such as TVs, washing machines, air conditioners, and refrigerators as input in the production process. Generally, this recycled material is used on the inside of new products. For exaple, waste plastic from old TVs is used as an input to produce new TVs. Additionally, and in keeping with our assumptions, all Japanese electronics firms must comply with the regulated target recycling rate that is set by the government.

Oligopoly firms, such as EEE manufacturers, always compete in the product market, though it is possible for them to cooperate in R&D activities. A pioneering study by d'Aspremont and Jacquemin (1988) showed that if a spillover effect is large, then the output level, R&D level, and social welfare in the case of R&D cooperation are larger than in the case of R&D non-cooperation. Other studies that have investigated the connection between R&D and social welfare include articles by Suzumura (1992) and Leathy and

Neary (1997). Some articles on environmental economics have focused on the role of R&D in reducing pollution emissions rather than reducing production costs. Katsoulacos and Xepapadeas (1996) showed that firms engage in environmental R&D when emission taxes are introduced. They also found that the optimal emission tax rate is lower than the marginal environmental damage. Chiou and Hu (2001) examined environment R&D levels and spillover effects in several different cooperation models. Poyago-Theotoky (2007) showed that the level of social welfare in the case of an R&D cartel is larger (smaller) than that in the case of independent R&D if the amount of environmental damage is small (large).

Based on the above articles, it is clear that many studies have investigated the effect of firm R&D on reducing pollution. However, to the best of our knowledge, no studies have investigated the effects of firm R&D on reducing recycling costs. Undoubtedly, the government's target recycling rate also affect firm R&D efforts that are aimed at reducing recycling costs. Therefore, the competitive regime of firm R&D influences both firm-level recycling performance as well as social welfare. Furthermore, because most previous models dealing with environmental R&D assume duopolies, the effect of cooperation on environmental R&D within each group, rather than in an entire industry, has not been examined.

The purpose of this paper is to examine how cooperation affects social welfare and recycling. Our model provides a general recycling framework in an n-firm oligopoly, of which theoretical studies are still quite scarce. We also consider how taxes and subsidies affect firm eagerness to engage in recycling programs.

In this paper, we use a three-stage game to analyze the issue of recycling. In stage 0, the government sets a recycling target rate in addition to virgin material and final disposal tax rates. In stage 1, n identical firms simultaneously invest to reduce recycling costs given the government-set recycling target. We consider this activity to be a type of R&D. We also consider three kinds of R&D activity depending on what firms chose to maximize in stage 1, namely, industry-wide cooperation, within-group cooperation, and non-cooperation. In stage 2, firms engage in a Cournot competition. The equilibrium level of R&D under a cooperative strategy is always larger than under a non-cooperative strategy. Surprisingly, virgin material and final disposal taxes discourage firm R&D efforts relating to recycling in usual cases, regardless of whether R&D cooperation takes place. This is because higher virgin material or final disposal tax rates raise firm marginal costs. Consequently, such taxes decrease output, thus decreasing firm incentives to invest in recycling. Accordingly, the government should instead use virgin material or final disposal subsidies to achieve an optimal outcome, the rates of which are derived in our theoretical analysis under both cooperation and non-cooperation. The inefficiency and high recycling fees of Japan's current recycling scheme have been noted previously.[2] Our numerical simulation compares welfare under conditions of industry-wide cooperation and within-group cooperation. The latter describes the current Japanese recycling regime in which firms are divided into two groups and chose R&D levels aimed at maximizing the joint profit of the group. This result suggests that welfare under the two-group regime is smaller than what would occur under industry-wide cooperation because the latter

[2] See Hosoda (2008) and Koide (2008).

generates more spillover effects and R&D incentives than the former. Moreover, a symmetric two-group case of within-group cooperation results in the lowest welfare because of an oligopoly-specific phenomenon. Therefore, the current two-group regime in Japan should be changed to an industry-wide regime. Our results shed light on the effect of group formations for cooperative recycling on social welfare.

The remainder of this paper is organized as follows. Section 2 presents the model set-up. Section 3 discusses equilibrium R&D expenditures and outputs. Section 4 provides numerical results. Finally, Section 5 concludes the paper.

2. Model Setup

We use a three-stage game to explore the Cournot competition between n identical firms working under a recycling target policy, where $n \geq 2$. In stage 0, the government sets a target recycling rate that is defined as $\mu \in [0, 1]$. Target recycling policies dictate that each firm has to recycle their own products that are collected after consumption[3]. The firm-level waste recycling ratio is defined as the amount (in weight) of recycled waste divided by the total input (the sum of the amount of virgin material and waste recycling), which must meet μ at a minimum.

According to the model described by Higashida and Jinji (2006), firms can use one unit of virgin material, recycled material or a mix made from virgin and recycled materials to produce one unit of final good. We assume that the price of virgin material is w_v, which is

[3] In the real world, the government or retailers collect the waste products at designated collection sites. For simplification, we assume that a firm itself collects and recycles its own products that are discarded by consumers.

treated as a constant in this paper. The cost of recycling one unit of waste for firm i is defined as c_i, which is always higher than w_v, where $i = 1,\ldots,n$. Hence, the marginal cost for firm i is

$$MC_i = \mu c_i + (1 - \mu)w_v. \tag{1}$$

Equation (1) indicates that each firm bears an additional recycling cost $\mu(c_i - w_v)$ when the firm uses one unit of mixed material to produce one unit of final good. This recycling cost can be interpreted two ways. One interpretation is that it is the cost incurred when a firm collects waste products, extracts recycled material from them, and uses this material as an input in place of virgin material during the production process. Another interpretation is that the cost of easy recycling when a firm produces goods lowers the recycling cost. We admit that these interpretations lead to wider policy implications. In reality, consumers pay recycling fees when they purchase new appliances (i.e., an advanced disposal fee) or when they discard old ones. Obviously, the amount of recycling cost that firms can pass along to the consumers depends on the slope of the demand curve. Unless we assume illegal dumping occurs, a recycling hiding fee would be irrelevant. To focus specifically on recycling effort, we do not explicitly denote recycling fees and assume that firms load a part of the additional recycling cost.

Because we do not represent the reduced form of the optimal recycling target rate with respect to firm behavior, our model is essentially a two-stage game. In stage 1, firm i chooses a R&D investment level that is defined as x_i. For describing either a cooperative or non-cooperative R&D scenario among firms, we assume firm i's c_i is reduced by both its own R&D input factor and its rival's R&D input factor. Hence, c_i is defined as

$$c_i = \alpha - (x_i + \beta \sum_{j \neq i} x_j), \tag{2}$$

where $\alpha > 0$ is a constant, and $\beta \in [0, 1]$ is defined as a spillover coefficient. If n firms adopt a cooperative strategy, then the parameter β is equal to unity.[4] If firms in the industry use common stockyards for discarded products and operate using the same lines, it is reasonable to assume full spillover. In contrast, if firm i adopts a non-cooperative strategy with its rival firm j in a business operation, then the parameter β is a number between zero and unity that depends on the spillover effect. In this case, a firm operates its own recycling system, though each firm imperfectly learns recycling techniques and operations from other firms. Finally, the cost of R&D investment is defined as $\gamma x_i^2 / 2$, where $\gamma > 0$.

Although the term "R&D" may seem an odd choice to some readers, the reason we use it is to capture the increasing property of the cost of recycling efforts and to allow for comparison between existing environmental R&D models and our own.

In stage 2, n firms compete in a production market under Cournot competition. The inverse demand function is given by

$$P = a - bQ, \tag{3}$$

where $Q = q_1 + \cdots + q_n$, $a > 0$, $b > 0$, and q_i is an output level for firm i. Based on the model above, firm i's profit can be represented as

$$\pi_i = (P(Q) - MC_i)q_i - \gamma x_i^2 / 2. \tag{4}$$

We use backward induction to obtain the sub-game perfect Nash equilibrium (SPNE) of the game. It is important to note that though there is a time lag between the purchase of a

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4 This case can be called an environmental research joint venture as defined by Poyago-Theotoky (2007).

final good and waste recycling, we do not consider the time lag in this paper. If we consider such a time lag, then we should consider strategic behavior in an infinite Cournot competition. Without loss of generality, we assume that the market exists in a long-run, steady-state equilibrium. This kind of model setup is frequently employed in recycling studies (Palmer and Walls 2001; Higashida and Jinji, 2006).

3. The Model Analysis

In this section, we calculate the equilibrium R&D level and quantity for non- and full-cooperation, and then we examine how policy instruments affect social welfare in the two cases. Finally, we calculate the R&D level in the case of within-group cooperation.[5]

3.1 Non-cooperative Strategy in R&D and Output First, we consider a case of non-cooperation. In stage 2, each firm simultaneously chooses an output level to maximize its profit given the R&D investment level and other firm output levels. Maximizing Eq. (4) and solving the symmetric Nash-Cournot equilibrium, we obtain

$$q_i^n = \frac{a - nMC_i + \sum_{j \neq i} MC_j}{b(n+1)}. \tag{5}$$

Substituting Eq. (5) into Eq. (4) and differentiating it with respect to x_i, we obtain the first order condition

[5] Because studying R&D levels in the case of within-group cooperation is very complex, we only show the equilibrium level here.

$$\frac{d\pi_i}{dx_i} = \frac{\partial \pi_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} + \sum_{j \neq i} \frac{\partial \pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial \pi_i}{\partial x_i} = 0. \tag{6}$$

The first term on the right-hand side of Eq. (6) is zero because it is the first-order condition of the profit maximization. The second term is called the strategic effect. It shows that firm *i*'s profit is indirectly affected by its rivals' outputs and that the outputs of rivals are affected by firm *i*'s R&D investment. The third term is the profit effect, which shows that firm *i*'s profit is affected by its marginal cost and that firm *i*'s marginal cost is affected by its R&D investment level.

Next, we use Eq. (6) to solve the symmetric equilibrium R&D investment level in stage 1. Here we let $d\pi_i / dx_i = 0$ and obtain the symmetric solutions for R&D investment levels.[6] They are represented as follows.[7]

$$x_i^n = \frac{2\mu\omega(n(1-\beta)+\beta)}{\Delta_1 + \Delta_2}, \tag{7}$$

where $\omega = a - \mu\alpha - (1 - \mu)w_v$, $\Delta_1 = b\gamma(n+1)^2 - 2n^2\mu^2$, and

$$\Delta_2 = 2\mu^2(n-1)\left[n((\beta - \frac{1}{2})^2 + \frac{3}{4}) + \beta(1-\beta)\right] > 0.$$[8]

If no R&D is performed, the Nash-Cournot equilibrium output is given by $\omega/b(n+1)$. In the second stage, firm *i*'s output can be rewritten as

$$q_i^n = \frac{(1+n)\gamma\omega}{\Delta_1 + \Delta_2} \quad . \tag{8}$$

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[6] We assume that firm *i*'s profit function satisfies the second-order condition, i.e., $2(n\mu - \beta\mu(n-1))^2 - \gamma b(n+1)^2 < 0$.

[7] At first glance, Eq. (7) seems to be complex; however, if we set μ=1, w_v=0, and n=2, it corresponds to the non-cooperative solution x^* in the study by d'Aspremont and Jacquemin (1988, p.1134). Here, the first two substitutions essentially reduce our recycling model to the ordinary cost-reducing R&D model, and the last substitution reduces our model to a duopoly.

[8] This is the case if we assume the interior solution of R&D level under the cooperative case as solved in the next subsection (i.e., the sign of Δ_1) is positive.

If $\beta = 0$, this indicates R&D in recycling technology with no spillover effects. Hence, Eqs. (7) and (8) are, respectively, reduced to

$$x_i^n = \frac{2\mu n\omega}{\gamma b(n+1)^2 - 2\mu^2 n} \tag{9}$$

and

$$q_i^n = \frac{\gamma\omega(n+1)}{\gamma b(n+1)^2 - 2\mu^2 n}. \tag{10}$$

3.2 Cooperative Strategy R&D but Non-cooperative Strategy in Output (Industry-wide Cooperation Case)

In this case, n firms in the industry maximize joint profits to reach the equilibrium R&D level in stage 1, but they have a non-cooperative strategy in stage 2. We define this case as industry-wide cooperation. Letting $d\sum_j \pi_j / dx_i = 0$, the equilibrium R&D level can be obtained as follows.[9,10]

$$x_i^c = \frac{2n\mu\omega}{\Delta_1}. \tag{11}$$

We assume there is an interior solution in the model; therefore, the term Δ_1 should be positive. In stage 2, firm i's output can be rewritten as

$$q_i^c = \frac{\gamma\omega(1+n)}{\Delta_1}. \tag{12}$$

3.3 Comparison of the Equilibrium R&D Level

We compare the equilibrium R&D investment level between x_i^c and x_i^n by subtraction x_i^n

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9 We assume that firm i's profit function satisfies the second-order condition, i.e., $2n\mu^2 - b\gamma(1+n)^2 < 0$.

10 As stated in footnote 6, if we set $\mu=1$, $w_v=0$, and $n=2$, Eq. (11) corresponds with the cooperative solution $\hat{x}$, as shown in the study by d'Aspremont and Jacquemin (1988, p.1134).

from x_i^c. Because the numerator of Eq. (11) is larger than the numerator of Eq. (7) and the denominator of Eq. (11) is smaller than the denominator of Eq. (7), we conclude that x_i^c is always larger than x_i^n. Thus, we can obtain the following proposition.

Proposition 1 *For a given recycling target rate, if we assume interior solutions, the equilibrium R&D investment level in the case of industry-wide cooperation is always larger than that in the case of non-cooperation.*

The explanation behind Proposition 1 are that the full spillover effect in the case of cooperative regimes encourages each firm to invest in more R&D than in a case of non-cooperation, and this effect dominates the incentive that a firm free-rides with respect to R&D recycling.

3.4 Social welfare

Because social welfare is defined as the sum of consumer surplus (CS), producer surplus (PS), and environmental damage (D) from un-recycled products, social welfare can be defined as follows

$$W = \int_0^Q P(u)du - P(Q)Q + \sum_{i=1}^{n}((P(Q) - MC_i)q_i - \frac{\gamma x_i^2}{2}) - D(E), \tag{13}$$

where $E = (1 - \mu)Q$ is the amount of un-recycled product. Because environmental damage depends on the amount of un-recycled product, we assume that the environmental damage function is $D = \delta E^2/2$, where $\delta(\delta > 0)$ is a positive parameter related to marginal environmental damage. Given the above assumptions, Eq.(13) can be re-written as

$$W = (a - \frac{bQ}{2})Q - (\mu(\alpha - x - (n-1)\beta x) + (1-\mu)w_v)Q - \frac{n\gamma x^2}{2} - \frac{\delta}{2}((1-\mu)Q)^2. \tag{14}$$

Note that social welfare in situations of industry-wide cooperation is given by Eq. (14) when $\beta = 1$.

If the R&D investment level in stage 1 is defined as $\hat{x} = x_1 = \ldots = x_n$, the Nash-Cournot equilibrium output for each firm in stage 2 is

$$\hat{q} = \frac{a - MC_i}{b(n+1)} = \frac{a - (\mu(\alpha - \hat{x} - (n-1)\beta\hat{x}) + (1-\mu)w_v)}{b(n+1)}. \tag{15}$$

It is important to note that each firm increases its output by $(1+\beta(n-1))\mu\hat{x}/(b(n+1))$ in comparison to the situation in which no R&D takes place. Substituting $Q = n\hat{q}$ into Eq. (14) and differentiating with respect to μ and x, the optimal recycling target μ^* and the second-best R&D investment level are obtained as follows.[11]

$$x^* = \frac{\mu\omega((\beta(n-1)+1)(b(n+2) - n\delta(1-\mu^*)^2)}{\gamma b^2(n+1)^2 + \mu^{*2}(\beta(n-1)+1)^2(n\delta(1-\mu^*)^2 - b(n+2))} \tag{16}$$

The optimal R&D level in the case of cooperation is simply x^* when $\beta = 1$. Substituting x^* into Eq. (15), we obtain the second-best output.

$$q^* = \frac{\gamma b(n+1)\omega}{\gamma b^2(n+1)^2 + \mu^{*2}(\beta(n-1)+1)^2(n\delta(1-\mu^*)^2 - b(n+2))} \tag{17}$$

Solving Eq. (17) for μ^* when $\hat{x} = x^*$ and $\hat{q} = q^*$, we can derive an implicit expression of the optimal recycling target as

[11] Hereafter, we assume the existence of the interior solution μ^*. We cannot analytically solve it, though we can implicitly show it.

$$\mu^* = \frac{w_v + (n+1)bq^* - a}{w_v + (1-\beta + n\beta)x^* - \alpha}. \qquad (18)$$

3.5 Policy Instruments with Optimal Recycling Target

In this section, we explore how to achieve the second-best R&D investment level. For a given μ, the number of firm i's choice variables is two (i.e., x_i and q_i.) Thus, the remaining variables (i.e., the recycled waste μq_i and the final disposal waste $(1-\mu)q_i$) are automatically determined. Because Tinbergen's rule requires that the number of instruments should not be less than the number of independent policy goals, the government needs at least one policy instrument other than a recycling target. Hence, we consider a virgin material tax and a final disposal waste tax.

First, we examine the effect of the introduction of a virgin material tax by replacing w_v with $w_v^n = w_v + t_v^n$ for cases of non-cooperation and w_v with $w_v^c = w_v + t_v^c$ for cases of industry-wide cooperation. The parameter t_v^h $(h = c, n)$ is defined as the tax rate, and the parameter w_v^h is the price of virgin material including the tax. A firm's profit can then be rewritten as

$$\pi_i = (P - \mu c_i - (1 - \mu)w_v^h)q_i - \gamma x_i^2 / 2. \qquad (19)$$

We can thus derive a virgin material tax rate to achieve optimal R&D investment for recycling. Solving t_v^n to satisfy $x_i^n = x^*$ and t_v^c to satisfy $x_i^c = x^*$, we obtain the optimal virgin material tax and subsidy rates as follows.

$$t_v^n = \frac{b\gamma\omega(n+1)^2(n\delta\Delta_3(1-\mu^*)^2 - b(\beta(n-1)(n+4)-(n-2)))}{2(n(1-\beta)+\beta)(1-\mu^*)(\gamma b^2(n+1)^2 - b\mu^{*2}\Delta_3^2(n+2) + n\mu^2\delta\Delta_3^2(1-\mu^*)^2)}, \qquad (20)$$

where $\Delta_3 = 1 + (n-1)\beta$, and

$$t_v^c = \frac{bn\gamma\omega(n+1)^2(\delta(1-\mu^*)^2 - b)}{2(1-\mu^*)(\gamma b^2(n+1)^2 - bn^2\mu^{*2}(n+2) + n^3\delta\mu^{*2}(1-\mu^*)^2)}. \tag{21}$$

The two rates shown above differ even if $\beta = 1$ because a firm's incentive for R&D differs depending on whether firms cooperate or not. The sign of t_v^h (h = c, n) can either be positive or negative, depending upon the parameters. In the case of cooperation,

$$t_v^c \geq 0 \Leftrightarrow \delta \geq b/(1-\mu^*)^2$$

and

$$t_v^c < 0 \Leftrightarrow \delta < b/(1-\mu^*)^2.$$

The sign of t_v^c is positive (negative) when environmental damage is relatively large (small). However, in the case of non-cooperation, the relation between the sign of t_v^n and the parameters is ambiguous.

Here, we find the surprising result that a virgin material subsidy may enhance recycling R&D. Introducing the regulation of the pair μ^* and t_v^h (h = c, n) can achieve the optimal state; however, the rate of t_v^h may not be positive.[12] Replacing w_v^h with w_v and differentiating Eq. (7) and Eq. (11) with respect to t_v, we obtain

$$\frac{dx_i^n}{dt_v^n} = \frac{dx_i^n}{dw_v^n}\frac{dw_v^n}{dt_v^n} = -\frac{2\mu(1-\mu)(n(1-\beta)+\beta)}{\Delta_1 + \Delta_2} < 0$$

and

$$\frac{dx_i^c}{dt_v^c} = \frac{dx_i^c}{dw_v^c}\frac{dw_v^c}{dt_v^c} = -\frac{2n\mu(1-\mu)}{\Delta_1} < 0. \tag{23}$$

When a firm's R&D for recycling represents an underinvestment with a virgin material tax of zero under a given recycling rate, which is a commonly observed situation in the real

[12] Note that the optimal recycling target is the same across both industry-wide cooperation and non-cooperation regimes.

world, a positive virgin material tax discourages recycling R&D investment. Therefore, we establish the following proposition, which concentrates on a counterintuitive result under the second-best recycling rate.

Proposition 2 *Suppose that* $x_i^c < x^{c*}$ $(x_i^n < x^{n*})$ *for each i under* $\mu = \mu^*$. *In this case, the optimal virgin material tax rate* t_v^c (t_v^n) *is negative. In other words, governments should not introduce a virgin material tax but rather a subsidy to achieve the optimal state.*

It is well known that if the government levies a virgin material tax in a perfect competition market, it will decrease the amount of virgin material used and increase the amount of recycled material used (Walls and Palmer, 2001). Proposition 2 states the opposite result in an oligopoly context. A high virgin material tax rate actually discourages environmental R&D investment under both cooperative and non-cooperative strategies when R&D levels are smaller than optimal; this is the normal situation. This implies that if the government levies a positive virgin material tax, then firms will reduce their R&D investment level. The reason for this is that a positive virgin material tax increases a firm’s marginal production cost. However, a higher marginal production cost results in a reduction in the firm’s output. In turn, this decrease in output leads to a decrease in the amount of recycling. It dampens a firm’s incentive to invest in R&D aimed at reducing the marginal cost of recycling.

We also consider a final disposal tax. Suppose that firms face a waste disposal tax rate t_e^h, with $h = c, n$, per unit of final waste. For this purpose, we examine the effect of the introduction of a waste disposal tax by replacing w_v with $w_e^n = w_v + t_e^n$ for cases of non-cooperation and w_v with $w_e^c = w_v + t_e^c$ for cases of industry-wide cooperation. Then a firm's profit can be re-written as

$$\pi_i = (P - \mu c_i - (1 - \mu) w_e^h) q_i - \gamma x_i^2 / 2. \tag{24}$$

The only difference between Eqs. (19) and (24) is the replacement of virgin material price, including the tax/subsidy w_w^h with w_e^h, which represents the virgin material price plus the disposal tax. In our steady state assumption, w_w^h and w_e^h have the same effect on a firm's profit. Solving $x_i^n = x^*$ and $x_i^c = x^*$ for t_e^n and t_e^c, respectively, we obtain the optimal disposal tax/subsidy rates. These are the same as Eqs (20) and (21), respectively.

$$t_e^n = \frac{b\gamma\omega(n+1)^2(n\delta\Delta_3(1-\mu^*)^2 - b(\beta(n-1)(n+4)-(n-2)))}{2(n(1-\beta)+\beta)(1-\mu^*)(\gamma b^2(n+1)^2 - b\mu^{*2}\Delta_3^2(n+2) + n\mu^2\delta\Delta_3^2(1-\mu^*)^2)} \tag{25}$$

and

$$t_e^c = \frac{bn\gamma\omega(n+1)^2(\delta(1-\mu^*)^2 - b)}{2(1-\mu^*)(\gamma b^2(n+1)^2 - bn^2\mu^{*2}(n+2) + n^3\delta\mu^{*2}(1-\mu^*)^2)}. \tag{26}$$

Proposition 3 *The optimal final disposal tax/subsidy rates for cases of industry-wide cooperation and non-cooperation (t_e^n and t_e^c, respectively) are the same as the optimal virgin material tax/subsidy rates (t_v^c and t_v^n, respectively).*

Proposition 3 shows that the optimal R&D levels can be obtained by either the virgin material tax/subsidy or the final disposal waste tax/subsidy together with a recycling target policy. Furthermore, because Proposition 3 ensures an equivalence between the two policy instruments, the following counterintuitive result holds.

Corollary *Suppose that* $x_i^c < x^{c*}$ $(x_i^n < x^{n*})$ *for each i under* $\mu = \mu^*$. *In this case, the optimal final disposal waste tax rate* t_v^c (t_v^n) *is negative. In other words, the governments should not introduce a waste tax but rather a subsidy to achieve the optimal state.*

3.6 The case of within-group cooperation

In this section, we consider the case of within-group cooperation, which describes a joint PRO by several firms in the EU and the current Japanese recycling scheme. In this case, we assume that firms are divided into two groups, namely, group *A* and group *B*. Group *A* consists of firm 1 to *m*. Group *B* consists of firm *m+1* to *n*. If firm *i* and firm *j* belong to the same group, then firm *i*'s R&D investment level x_i will reduce firm *j*'s marginal recycling cost by x_i. In other words, if two firms are in the same group, then the spillover effect in the same group is equal to unity. This is because firms in the same group use the same collecting sites and recycling plants. In contrast, if two firms belong to different groups, then firm *i*'s R&D investment level x_i will reduce firm *j*'s marginal recycling cost by βx_i. In other words, the inter-group spillover effect is β. In summary, if firm *i* belongs to group *K*, with *K*=*A*, *B*, then the marginal recycling cost of firm *i* is $c_i = \alpha - x_i - \sum_{\substack{j \in K \\ j \neq i}} x_j - \beta \sum_{j \notin K} x_j$.

To avoid complexity, we only show the equilibrium R&D investment level in the second stage with respect to a typical case in which the two groups consist of the same number of firms ($m = n/2$).

$$x_i^g = \frac{2n\mu(n(1-\beta)+2)\omega}{4b\gamma(1+n)^2 - n^2\mu^2(1+\beta)(n(1-\beta)+2)} \qquad (27)$$

We can solve to obtain the second-best R&D level and policy instrument for the case of within-group cooperation. However, to avoid unnecessary complexity, we omit this calculation here[13].

4 Social Welfare Comparison

We employ a numerical analysis in this section because it is difficult to obtain a reduced form of the optimal recycling target rate. Introducing suitable policy instruments, such as a virgin material tax/subsidy or a final disposal waste tax/subsidy together with recycling target as denoted in the previous section, the second-best level of social welfare can be attained in each case. Accordingly, we compare second-best welfare levels in the case of industry-wide cooperation, within-group cooperation, and non-cooperation, and we consider the effect of varying group size in the case of within-group cooperation. Here we let $a = \alpha = 100$, $b = w_v = 1$, $\gamma = 10$, $\delta = 5$, $n = 10$ and $m = 5$. The numbers of parameters are not randomly selected but rather are chosen to emphasize the difference in the three kinds of R&D investment level.

[Insert Figure 1 here]

[Insert Figure 2 here]

[13] The authors can provide detailed results upon request.

As Figure 1 shows, the level of welfare in the case of industry-wide cooperation is constant for β and is always larger than the level of welfare in the case of both within-group cooperation and non-cooperation, except β = 1 where the welfare levels of all cases coincide. An increase in the spillover rate induces two opposite effects. One has a negative impact on R&D efforts because the benefit of free-riding on the R&D effort of other firms becomes more attractive. The other is positive because a higher spillover rate reduces the marginal recycling cost for firms; in turn, this leads to a larger output and larger recycling R&D effort. In the case of both within-group cooperation and non-cooperation, the latter effect dominates the former at equilibrium.

Figure 1 shows that the two-group regime is inferior in terms of welfare to the industry-wide cooperation regime. This suggests that the current Japanese recycling system, under which firms are divided into two groups, should be changed to an industry-wide cooperation system.

Until now, we have only considered a symmetric two-group case under within-group cooperation. Now, we examine what happens if the size of each group changes. Figure 2 shows the welfare levels for various spillover rates when the size of a group changes. Here we assume that the total number of firms between the two groups is fixed to ten, and we only change the number of firms in one group m. Obviously, once the value of m is determined, the number of firms in the other group size is automatically determined. When m = 0 or m = 10, the within-group cooperation regime reduces to the industry-wide cooperation regime. Figure 2 reveals a counterintuitive result in which the symmetric two-group case induces the lowest level of welfare. In other words, the level of welfare is concave with respect to group size. The more group size grows, the higher is the number of firms that benefit from full spillover with others in the same group. This reduces the marginal recycling cost and increases the production of each firm in the group. This is the reason why a more asymmetric group division leads to more welfare. This is similar to a phenomenon in which an unequal treatment of homogeneous firms within a oligopoly market generates an aggregate cost-saving effect. This was originally described by Bergstrom and Varian (1985a, 1985b) and was extended by Salant and Shaffer (1999), Amir and Nannerup (2004), and Honma (2009). To summarize the results shown in Figure 2, splitting groups into roughly equal sizes deteriorates social welfare through the effect described above that is specific to oligopolies. Thus, the government should encourage an industry-wide cooperation recycling regime.

5 **Concluding Remarks**

We have developed a general theoretical model that describes production and recycling in an n-firm oligopoly market in which firms can cooperate for recycling. We have shown that both a virgin material tax and a final disposal tax harms a firm's R&D effort with respect to recycling under normal parameter ranges, regardless of whether R&D cooperation takes place. Furthermore, using numerical simulations, we have compared levels of social welfare under three recycling regimes, including industry-wide cooperation, within-group cooperation, and non-cooperation. The comparison has demonstrated the superiority of the industry-wide cooperation scenario. It has shown that the symmetric division of firms induces the lowest welfare for all spillover parameter ranges under within-group cooperation. The results of the numerical simulation strongly support that industry-wide cooperation should be adopted as a country-level recycling regime.

This study suggests two lines of further research. First, post-consumer home appliances in developed countries, such as EU and Japan, are not only recycled within-country, but they are also exported to developing countries as second-hand products or recyclable resources. For simplicity, we focused only on domestic recycling in the present model. Incorporating the international trade of recyclable resources into the model could provide useful insights into cross-border recycling between developed and developing countries. Second, the concept of within-group cooperation presented in this paper can be extended to other environmental economic models, such as pollution emissions reduction and energy-saving models. Furthermore, various forms of cooperation can also be considered. Under our assumption of within-group cooperation, firms were divided into two groups. However, there are many possible situations in which three or more groups (i.e., coalitions) cooperatively undertake environmental R&D within each group. The remaining firms outside of these groups would then non-cooperatively and independently undertake R&D activity. It would be interesting to explore how the co-existence of cooperation and noncooperation as well as the spillover effects among groups and firms affect social welfare and environmental damage.

Acknowledgements

The authors thank Takayoshi Shinkuma, Hideo Koide, and the seminar participants in the Annual Meeting of the Japanese Economic Association and the Society for Environmental Economics and Policy Studies.

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Figure 1 Social welfare in the case of industry-wide cooperation, within-group cooperation, and non-cooperation

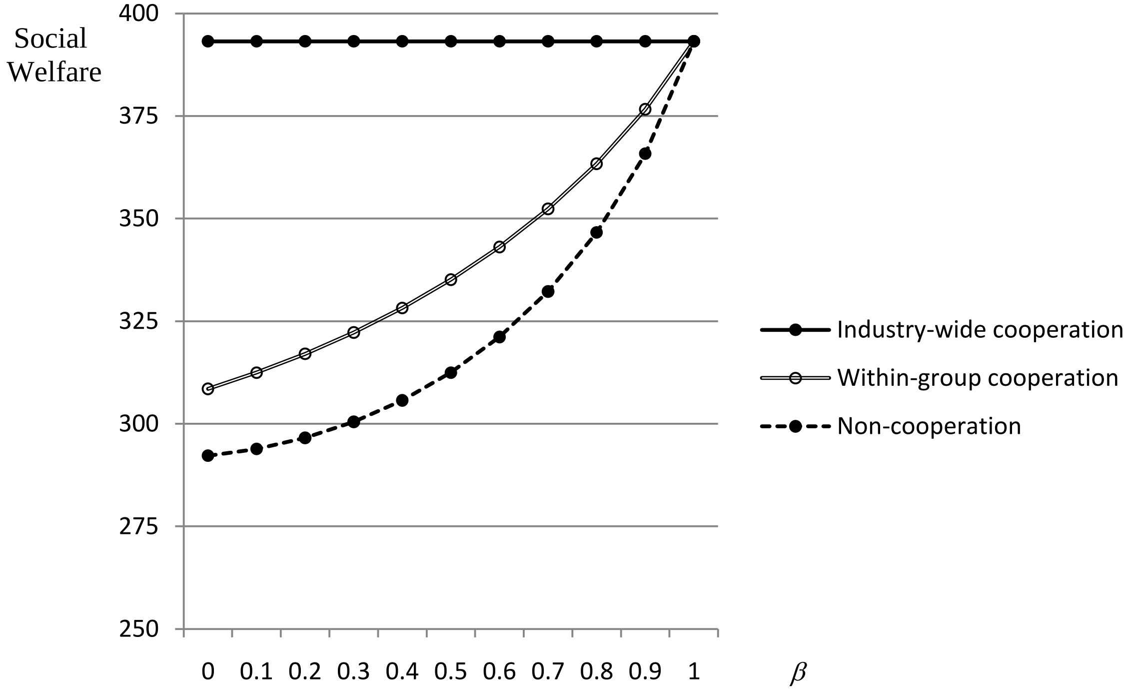

Figure 2 Social welfare under the within-group cooperation regime