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Environment Policy and Renewable Energy R&D Incentives in Cournot Competition*

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This paper studies how the policy choice between a command-and-control (CAC) system and an emission trading scheme (ETS) affects a firm's renewable energy R&D incentives in an oligopoly market when a renewable portfolio system (RPS) is introduced in conjunction with environmental regulation. An ETS with free allocation leads to greater renewable energy R&D incentives compared with a CAC or an ETS with auctioning. The difference in R&D incentives between a CAC and an ETS with auctioning is uncertain because the level of incentives depends on market conditions such as demand elasticity, abatement cost, and marginal R&D cost. This result contrasts with the results of previous studies in which a CAC or an ETS with auctioning leads to greater abatement R&D incentives than an ETS with free allocation.

JEL Classification: L13, L50, Q28

Keywords: R&D incentives, Cournot competition, environment regulations, emission trading scheme (ETS), command-and-control (CAC) system

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1. INTRODUCTION

In 2012, Korea introduced an obligatory national environmental regulation, the greenhouse gas target management system (GHG-TMS), as an emission reduction measure. The GHG-TMS is a command-and-control (CAC) policy that establishes GHG reduction targets for designated parties, which is also known as an emission standard in other countries. The GHG-TMS was transformed into an emission trading scheme (ETS) on January 1, 2015. In the ETS with free allocation (ETS-FA), 100% of the initial allocation is distributed free of charge, whereas in the ETS with auctioning (ETS-AU), permits are auctioned; thus, there is no initial free allocation of permits.

One of the key characteristics of the regulation is that it is implemented in conjunction with Korea's Renewable Portfolio System (RPS). The RPS is a renewable energy policy in which the government requires designated parties (utility firms in many countries) to generate minimum amounts of electricity from renewable sources. In many countries, an RPS or Feed-In-Tariff (FIT) is implemented in conjunction with an environmental regulation such as a carbon tax or an ETS. Renewable energy policies had been in place long before environmental regulations such as a TMS, a carbon tax, or an ETS were first introduced in the mid-2000s. R&D investments in new technologies will make it economically efficient to achieve established reduction targets. In this respect, governments are concerned with the degree to which they encourage long-term investments in product and process innovation or energy-efficiency-enhancing technologies and in renewable energy utilization. However, a few studies emphasize that the effect of environmental regulations on abatement technology investments is positive but limited (Leiter, Parolini, and Winner, 2011).

Energy and environmental regulations affect R&D incentives for developing emission reduction technologies and renewable energy technologies, but these incentives depend on environmental policy instruments and regulatory specifications. Therefore, it is important to determine whether a CAC or an ETS results in greater R&D incentives for emission reductions and renewable energy technologies. Environmental economists typically conclude that market-based policies such as an ETS with auctioning lead to greater abatement-related R&D investments than emission standards, carbon taxes, or an ETS with free allocation. In previous studies, R&D incentives regarding emission reduction technology have been compared across CAC systems, carbon taxes, and ETSs (Milliman and Prince, 1989; Downing and White, 1986; Jung *et al*., 1996). Milliman and Prince (1989) considered company-level R&D incentives, whereas Jung *et al*. (1996) studied incentives at the industry level, and both concluded that ETSs with auctioning and carbon taxes induce greater environment-related R&D investments than CAC systems in a perfectly competitive market.

In imperfectly competitive markets, however, Montero (2002a) found that emission standards induce greater environment R&D incentives for GHG-reduction technology using a game theory model. The key feature of that study is that in an imperfectly competitive market, there are an indirect or strategic effect of environment-related R&D investment and a direct effect of the investment. The strategic effect can be positive or negative. It is positive if R&D investments are pure, cost-reducing strategic substitutes and negative if R&D investments are strategic complements, reducing marginal abatement costs and hence increasing a rival's production level. Montero (2002b) compared environment R&D incentives under both quantity and price competitions. Under quantity competition, emission standards, carbon taxes, and ETSs with auctioning generate higher R&D incentives, whereas under price competition, carbon taxes and ETSs with auctioning result in higher R&D incentives. In addition to environmental regulations, RPSs have been introduced to foster the renewable energy industry in many countries. Jeong (2011a) extended the studies of Montero (2002a, 2002b) by comparing R&D incentives across different carbon regulations when an RPS and an environmental regulation are simultaneously implemented in an oligopoly model.

However, none of the previous studies consider how different environmental regulations can affect renewable energy R&D incentives. Many countries have focused on the renewable energy industry to enhance energy security and environmental integrity, in addition to creating opportunities for domestic economic development by strengthening relevant technology. Thus, for countries implementing both an RPS and an environmental policy, it is important to evaluate how different types of environmental regulations affect renewable energy R&D investments and abatement technology R&D investments. In reality, many final goods markets are not perfectly competitive markets. Permit markets can be imperfectly competitive as well because the number of major players with significant GHG emission levels may be a few and they behave strategically like oligopoly in the permit market. In ETS, the designated parties can achieve GHG emissions targets by employing energy-efficient technology, participating permit markets, and using offsets and borrowing and saving measures. Permit markets, offsets, borrowing and saving are the carbon-related implementation measures in which major firms with significant GHG emission levels can play significant roles. In the industrial organization literature, firms in imperfectly competitive markets have different R&D incentives from perfectly competitive firms because R&D investments in an imperfectly competitive market can act as strategic substitutes or strategic complements. The typical cost-reducing R&D investment acts as strategic substitutes, reducing rival's production level. Therefore, this paper studies how the environment-policy choice among CAC, ETS with auction, and ETS with free allocation affects a firm's renewable energy R&D incentives in oligopoly.

In the present paper, characterization of the optimal R&D investment follows closely the framework put forward by Montero (2002a, 2002b), but differs from it in major ways. As stated previously, Montero (2002a, 2002b) compared environment R&D incentives under different environment regulations in imperfectly competitive markets, and argued that under quantity competition, emission standards, carbon taxes, and ETSs with auctioning generate higher R&D incentives than ETSs with free allocation. In this study, RPS as an energy policy is considered with three different environmental regulations, i.e., the CAC, ETS with free allocation, and ETS with auctioning. We analyze renewable energy R&D incentives in a quantity-based Cournot duopoly model; the renewable energy quota under the RPS is established as a proportion of total production quantity.

2. MODEL

There are two utility firms (F1, F2) competing in a traditional Cournot model and subject to an environmental regulation and a renewable energy policy, the RPS. Three types of environmental policies are considered: CAC, ETS with free allocation (ETS-FA), and ETS with auctioning (ETS-AU). We assume that firms and the government have complete information and therefore, correctly anticipate the Nash output/permit equilibrium in Cournot competition. The firms are symmetric in all respects including emission standard and permit allocation. They produce homogeneous products with identical marginal production costs and are engaged in the same renewable energy R&D investments.

Firm *i* has an inverse demand function $P = P(Q)$, where *P* is the price of the final goods and *Q* is the sum of the firms' products, $Q = q_1 + q_2$. Firms may use fossil fuels and renewable energy as intermediate goods but use only fossil fuels when the RPS is not adopted because the costs of renewable energy are higher than those of fossil fuels. For simplicity, it is assumed that firm *i*'s marginal cost of production other than the cost of renewable energy is zero, and the cost of renewable energy is $G_i(\bar{q}_{Ri}),\ i = 1,\ 2,$ where $G_i' > 0,\ G_i'' > 0.$ The renewable energy quota, $\bar{q}_{Ri}$, is set at $\bar{\alpha} q_i$, where $0 \le \bar{\alpha} \le 1,$ a renewable energy portion of total energy determined by the government under the RPS. The parameter $\bar{\alpha}$ denotes the renewable energy target rate for F1 and F2, which is specified in the RPS implementation plan published by the government, and is public knowledge.

Absent any environmental regulation, it is assumed that firm *i* emits as much as its production quantity minus the renewable energy quota,

$q_i - \bar{q}_{Ri} = (1-\bar{\alpha})q_i$. On the other hand, emission level set by firm *i* is defined as e_i after emission reduction in the presence of environmental regulations. Hence, firm *i* must determine levels of emissions, e_i, given the abatement cost, $W_i(r)$ with $W_i' > 0$ and $W_i'' > 0$, where r denotes the emission reductions and can be expressed as $(1-\bar{\alpha})q_i - e_i$. By investing in renewable energy R&D, firm *i* is able to reduce the cost of renewable energy from $G_i(\bar{\alpha}q_i)$ to $s_i G_i(\bar{\alpha}q_i)$, where $s_i = g_i(V_i)$ and $0 \le s_i \le 1$. The function g_i declines as the renewable energy R&D investment level, V_i, increases, $g_i(0) = 1,\ g_i(\infty) > 0,\ g_i' < 0,\ g_i'' > 0$. The level of emission reductions, r, declines as $\bar{\alpha}$ and e_i become large. It is also assumed that the marginal renewable energy cost is greater than the marginal abatement cost, $s_i G_i' > W_i'$, where $G_i' > 0$ and $W_i' > 0$.[1] For this reason, F1 and F2 would not meet their reduction targets through trading renewable energy quotas. Under an environmental regulation, F1 and F2 can meet the reduction targets by directly reducing emissions through adopting low-carbon technology or by trading pollution permits. V_i is a pure cost-reducing investment in renewable energy technology, but it does not reduce the marginal abatement cost. It is also assumed that the emission reduction and renewable energy goals are fixed at $\bar{E}$ and $\bar{q}_R$, respectively, under any environmental regulatory scheme, where $\bar{E} = e_1 + e_2$ and $\bar{q}_R = \bar{q}_{R1} + \bar{q}_{R2}$.

Depending on the type of environmental regulations in place, the game has two or three stages. Under the CAC, the renewable energy R&D investment level, V_i, is set in the first stage, and the firms compete on quantity in the second stage. In contrast, the ETS has three stages. Firms determine their renewable energy R&D investments in the first stage; they set their emission levels, e_1 and e_2, in the second stage, and the price of a permit, σ, is also decided in this stage. In the third stage, F1 and F2 compete on quantity.

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[1] It is generally known that adopting renewable energy, emitting zero emissions, costs more than developing abatement technology. In this respect, firms would meet their established reduction targets first by developing abatement technology with low costs and then adopting more expensive technology such as renewable energy. If $s_1 G_1' < W_1'$, the firms would go above the renewable energy quota to meet their reduction targets.

Firm i maximizes its profit function, $\pi_i(V_i) - z_i V_i$, where $\pi_i(V_i)$ is firm i's profit at a renewable energy R&D level of V_i, and z_i is the constant marginal cost of the renewable energy R&D investment. The optimum value of R&D investment V_i must satisfy the condition $d\pi_i / dV_i = z_i$, where $d\pi_i / dV_i$ is the total derivative of $\pi_i(V_i)$ with respect to V_i. Following Montero (2002a, 2002b), we compare the absolute values of $d\pi_i / ds_i$ of environmental instruments, where $d\pi_i / dV_i = (d\pi_i / ds_i) g_i'(V_i) = z_i$ to rank renewable energy R&D incentives. The equation $d\pi_i / dV_i = (d\pi_i / ds_i) g_i'(V_i) = z_i$ that the optimal amount of renewable energy R&D investment, V_i, increases as $|d\pi_i / ds_i|$ increases. This is clear from the assumption regarding the g_i function, $g_i(0) = 1$, $g_i(\infty) > 0$, $g_i' < 0$, $g_i'' > 0$. For all s_i, if the absolute value of additional profit $(d\pi_i)$ obtained from additional cost reduction (ds_i) of policy A is larger than that of policy B, then policy A generates greater renewable energy R&D incentives than policy B $(|d\pi_i^A / ds_i| > |d\pi_i^B / ds_i|)$.

We solve the firm's profit maximization problem by backward induction. Under a CAC scheme, the optimal production quantity, q_1 and q_2, is determined in the second stage, and then the renewable energy R&D investment, V_1 and V_2 is decided in the first stage. Under an ETS, after solving for the optimal quantity of q_i, the level of emissions, e_i, and the permit price, σ, are decided in the second stage. The renewable energy R&D investment, V_i, is determined in the first stage.

3. OUTCOMES

3.1. RPS and CAC

When an RPS and a CAC are implemented simultaneously, in the second stage, F1 solves its maximization problem with respect to q_1:

$$\pi_1 = P(Q)q_1 - W_1(q_1 - \bar{q}_{R1} - e_1) - s_1 G_1(\bar{q}_{R1}), \tag{1}$$

where $Q = q_1 + q_2$ and $e_1 \le \bar{e}_1$. $\bar{e}_1$ is the emission standard of F1 under the CAC. q_2 denotes F2's production level. The optimal emission level of F1 is $\bar{e}_1$, the maximum level of emissions that F1 is able to emit under the CAC. Under the RPS, F1 is obligated to supply a quota of renewable energy, $\bar{q}_{R1} = \bar{\alpha} q_1$, which generates no emissions. By employing $e_1 = \bar{e}_1$ and $\bar{q}_{R1} = \bar{\alpha} q_1$ in equation (1), the first-order condition of equation (1) can be described as $P(Q) + P'(Q)q_1 - (1-\bar{\alpha})W_1'(\cdot) - \bar{\alpha} s_1 G_1'(\cdot) = 0.$ The term $(1-\bar{\alpha})W_1'(\cdot)$ indicates that with an introduction of CAC marginal production costs increase by an amount equal to the marginal abatement cost at $e_1 = \bar{e}_1$. The term $\bar{\alpha} s_1 G_1'(\cdot)$ indicates that with an introduction of renewable energy policy, marginal production costs increase by an amount equal to the marginal renewable energy cost at $\bar{q}_{R1} = \bar{\alpha} q_1$.

In the first stage, using the envelope theorem, the derivative of F1' profit function with respect to s_1 at the optimum output level and emission level is $d\pi_1 / ds_1 = P'(Q)q_1(dq_2 / ds_1) - G(\bar{\alpha} q_1)$.

And therefore

$$\left|\frac{d\pi_1}{ds_1}\right| = G_1(\bar{\alpha} q_1) - \frac{P' q_1 (\bar{\alpha} G_1'(P' + P'' q_1))}{((1-\bar{\alpha})W_1'' + \bar{\alpha}^2 s_1 G_1'' - P')(3P' + 2P'' q_1 - (1-\bar{\alpha})W_1'' - \bar{\alpha}^2 s_1 G_1'')}. \quad (2)$$

The first component of the right-hand side of equation (2) is the direct effect of the renewable energy R&D investment on F1's profit. The second component of the right-hand side of equation (2) is the indirect (or strategic) effect of the renewable energy R&D investment on the final goods market. Assuming that $P' + P'' q_i < 0$, the value of dq_2 / ds_1 is positive, indicating that renewable energy R&D investments are a strategic substitute. The interaction in the duopoly output market results in a positive strategic effect from reducing a rival's output. The reason is that renewable energy R&D investments made by F1 generate lower marginal renewable energy costs of F1, thereby increasing F2's relative costs and reducing F2's output level.

The sum of the direct and strategic effects of renewable R&D investments in equation (2) is positive; thus, the overall effect of R&D investments in an oligopoly market is greater than in a perfectly competitive market, where the strategic effects of R&D investments do not play a role.

3.2. RPS and ETS with Free Allocation

Now, we consider the case where both an RPS and an ETS with free allocation are introduced simultaneously. While firms under CAC are obligated to meet their emission standards $(e_1 \le \bar{e}_1,\ e_2 \le \bar{e}_2)$, where $\bar{e}_1 + \bar{e}_2 = \bar{E}$, only by reducing their emissions, firms under ETS can achieve their emission targets in two ways: by reducing their emissions and by purchasing permits from the permit market. Under ETS, the designated firms, F1 and F2, decide their renewable energy R&D level (V_i) in the first stage, emission levels in the second stage, and output levels in the third stage.

In the third stage, F1 solves its maximization problem with respect to q_1:

$$\pi_1 = P(Q)q_1 - W_1((1-\bar{\alpha})q_1 - e_1) - s_1 G_1(\bar{\alpha}q_1) - \sigma(e_1 - \varepsilon_1), \tag{3}$$

where ε_1 represents initial allowances allocated to F1 free of charge and σ is the unit price of permits after the government distributes a total number of permit $\bar{E}$ free of charge to the designated firms. $\bar{\alpha}q_1$ is the quota of renewable energy, $\bar{q}_{R1}$, under the RPS. F1 has the following first-order condition: $P(Q) + P'(Q)q_1 - (1-\bar{\alpha})W_1'(\cdot) - \bar{\alpha}s_1 G_1'(\cdot) = 0.$

In the second stage, F1 determines its emission level, e_1. Given the optimal production quantity, q_1, using the envelope theorem and by differentiating $\pi_1 = P(Q)q_1 - W_1((1-\bar{\alpha})q_1 - e_1) - s_1 G_1(\bar{\alpha}q_1) - \sigma(e_1 - \varepsilon_1)$, subject to $e_1 + e_2 \le \bar{E}$, with respect to e_1, the Nash equilibrium in permit market is derived from $W_1'((1-\bar{\alpha})q_1 - e_1) = \sigma$. It can be rewritten as $W_1'((1-\bar{\alpha})q_1 - e_1) = W_2'((1-\bar{\alpha})q_2 - e_2) = \sigma$ where $e_1 + e_2 \le \bar{E}$. While the firms anticipate correctly output levels, they trade permit until further trade is not mutually beneficial. This implies that the market clearing price of permits, σ, is the marginal abatement cost $W_i'(\cdot)$.

In the first stage, F1 determines its optimal renewable energy R&D investments. Using the envelope theorem, the derivative of F1's profit function with respect to s_1 at the Subgame Perfect Nash Equilibrium in the permits and output markets is:

$$-\frac{d\pi_1}{ds_1} = G_1(\bar{\alpha} q_1) - P'(Q) q_1 \frac{dq_2}{ds_1} + \frac{d\sigma}{ds_1}(e_1 - \varepsilon_1). \tag{4}$$

The first component of the right-hand side of equation (4) is the direct effect of renewable energy R&D investments, which is positive (as it was in the previous case under the CAC). The second term of the right-hand side of equation (4) is an indirect or strategic effect of the renewable energy R&D investments on the final goods market, which is positive because renewable energy R&D investments are a cost-reducing innovation and thus increase the rival's relative cost, thereby reducing the rival's production level (see Appendix (A2) for the derivation of $|dq_2 / ds_1|$). Renewable energy R&D investments made by F1 reduce the renewable energy cost to $s_1 G_1$, reducing F2's output level. Abatement R&D investments, which lead to lower marginal abatement costs, entail a lower permit price and hence an increase in the rival's output, $dq_2 / ds_1 < 0.$[2] On the other hand, renewable energy R&D investments do not provide lower marginal abatement costs, but induce lower marginal renewable energy costs and a larger total production quantity for the firms. This creates a greater demand for permits, thereby increasing the permit price. This suggests that renewable energy R&D investments

[2] At first glance, it is not intuitive that renewable energy R&D investments made by power companies would affect the permit price. However, note that the focus in this study is on the market structure, in particular an imperfectly competitive market in which two firms compete on quantity. It is well known that while the number of power companies is small in many countries, they are major players in the permit market because they have significant GHG emissions. For example, as of June 2013, among designated participants in Korea's TMS, emissions from the power generation sector represent 40.3% of the total, and energy consumption in the sector is 39.6%, whereas the number of power companies participating in Korea's TMS is only 5.9% (MOSF, 2014). This justifies the consideration that power companies may have market power in the permit market and affect the permit price.

under an ETS are a cost-reducing investment, as is the case under the CAC, and reduce the rival's output level further by raising the permit price. The third term on the right-hand side of equation (4) is another indirect or strategic effect of the renewable energy R&D investments on the permit market, but it is omitted due to the initial free allocation under the ETS with free allocation. Equation (4) can be rewritten as follows:

$$\left|\frac{d\pi_1}{ds_1}\right| = G_1(\bar{\alpha}q_1) - \frac{P'q_1\bar{\alpha}G_1'(P' + P''q_1 - \frac{1-\bar{\alpha}}{2}W_1'')}{(\bar{\alpha}^2 s_1 G_1'' - P')(3P' + 2P''q_1 - (1-\bar{\alpha})W_1'' - \bar{\alpha}^2 s_1 G_1'')}. \quad (5)$$

A comparison of equation (5) and (2) indicates that renewable energy R&D incentives under an ETS with free allocation are higher than under a CAC. The explanation is that renewable energy R&D investments are strategic substitutes, and as a result, there is a positive strategic effect of R&D investments on the final goods market. In addition to this strategic effect, under an ETS with free allocation, F1's renewable energy R&D investments increase the market price of permits and thus further reduce the rival's production level. In sum, F2's production quantity is reduced due to the renewable energy R&D investments made by F1 in two ways: first, through the relatively high production cost, and second, through an increase in the permit price.

Proposition 1: *Renewable energy R&D incentives under an ETS with free allocation are higher than under a CAC when an RPS is introduced simultaneously.*

Proof: If $|d\pi_1 / ds_1|$ in equation (2) is subtracted from $|d\pi_1 / ds_1|$ equation (5), this yields $P'q_1\bar{\alpha}G_1'(1-\bar{\alpha})W_1''/\,2(\bar{\alpha}^2 s_1 G_1'' - P')(P' - (1-\bar{\alpha})W_1'' - \bar{\alpha}^2 s_1 G_1'')$ > 0, since $G_i' > 0$, $G_i'' > 0$, $W_i' > 0$, $W_i'' > 0$.

The strategic effect of renewable energy R&D investments under an ETS with free allocation in an imperfectly competitive market is positive as in the case of a CAC because renewable energy R&D investments are independent of marginal abatement costs. The renewable energy R&D investments are a strategic substitute, reducing the firm's marginal renewable energy cost and raising its rival's relative production cost.

3.3. RPS and ETS with Auctioning

Under an ETS with auctioning, there will be zero initial allowances allocated free of charge, i.e., $\varepsilon_1 = 0$. F1 maximizes the following profit function with respect to q_1:

$$\pi_1 = P(Q)q_1 - W_1((1-\bar{\alpha})q_1 - e_1) - s_1 G_1(\bar{\alpha}q_1) - \sigma(e_1 - \varepsilon_1), \tag{6}$$

where σ is the unit price of permits, and the initial free allocation ε_1 is zero under an ETS with auctioning. $\bar{\alpha}q_1$ is the quota of renewable energy, $\bar{q}_{R1}$, under the RPS.

The first-order conditions of equation (6) with respect to q_1 and e_1 are identical to those under an ETS with free allocation. Given the optimal production and emission quantities, q_1 and e_1, using the envelope theorem, the absolute value of $d\pi_1 / ds_1$ is as follows:

$$\left|\frac{d\pi_1}{ds_1}\right| = G_1(\bar{\alpha}q_1) - \frac{P'q_1\bar{\alpha}G_1'(P' + P''q_1 - \frac{1-\bar{\alpha}}{2}W_1'')}{(\bar{\alpha}^2 s_1 G_1'' - P')(3P' + 2P''q_1 - (1-\bar{\alpha})W_1'' - \bar{\alpha}^2 s_1 G_1'')} + \frac{\bar{\alpha}G_1'(1-\bar{\alpha})W_1''e_1}{2(3P' + 2P''q_1 - (1-\bar{\alpha})W_1'' - \bar{\alpha}^2 s_1 G_1'')}. \tag{7}$$

Comparing equation (5) to equation (7), an ETS with free allocation leads to higher renewable energy R&D incentives than ETS with auctioning. The direct effect is identical under both regulatory schemes, whereas the strategic effects differ between the two schemes. The second term on the right-hand side of equation (7) is the strategic effect of the R&D investments on the final goods market, which is positive because the renewable energy R&D investments made by F1 lead to a lower F1's marginal renewable energy cost, increasing its rival's relative cost and thus reducing the rival's production level. The ETS generates a greater strategic effect of renewable energy R&D investments on the final goods market through the permit market than does the CAC. Unlike an ETS with free allocation, the third term on the right-hand side of equation (7) is not zero, representing another strategic effect of renewable energy R&D investments on the permit market. In fact, the third term is negative because renewable energy R&D investments increase the permit price (see Appendix (A3) for the derivation of $|d\sigma / ds_i|$). The explanation is that with a lower marginal renewable energy cost, F1 is able to increase its production quantity and hence its demand for permits, increasing the market clearing permit price.

Proposition 2: *When an RPS is introduced in conjunction with an environmental regulation in an imperfectly competitive market, an ETS with free allocation induces greater renewable energy R&D incentives than an ETS with auctioning.*

Proof: It is evident from the comparison of equation (5) and (7). The strategic effect of renewable energy R&D (RE-R&D) investments under an ETS with free allocation is greater than that under an ETS with auctioning. This is due to the difference of indirect or strategic effects between ETS-FA and ETS-AU. The indirect or strategic effect on the final goods market under ETS is positive as mentioned above, increasing cost competitiveness of a firm with RE-R&D investments over its rival. However the indirect or strategic effect on the permit market under ETS-AU is negative while the effect under ETS-FA is zero.

Renewable energy R&D investments under ETS-AU increase the permit price due to output increases with lower production cost of renewable energy.

Renewable energy R&D investments act as strategic substitutes in both the output and permit markets in the model.

Proposition 3: *When an RPS is introduced in conjunction with an environmental regulation in an imperfectly competitive market, if the amount of emission* (e_1) *is less than a certain emission level* $(\bar{M})$, *where* $\bar{M} = \left| \frac{P'q_i(3P' + 2P''q_i - (1-\bar{\alpha})W_i'' - \bar{\alpha}^2 s_i G_i'')}{(\bar{\alpha}^2 s_i G_i'' - P')(P' - (1-\bar{\alpha})W_i'' - \bar{\alpha}^2 s_i G_i'')} \right|$, *an ETS with auctioning induces greater renewable energy R&D incentives than a CAC. Conversely, if* $\bar{M} < e_i$, *a CAC induces greater renewable energy R&D incentives than an ETS with auctioning.*

Proof: By subtracting equation (2) from equation (7), it is easily determined that $(P'q_1\bar{\alpha}G_i'(1-\bar{\alpha})W_i'') / (2(\bar{\alpha}^2 s_i G_i'' - P')(P' + (1-\bar{\alpha})W_i'' - \bar{\alpha}^2 s_i G_i'')) + (\bar{\alpha}G_i'(1-\bar{\alpha})W_i'' e_i) / (2(3P' + 2P''q_i - (1-\bar{\alpha})W_i'' - \bar{\alpha}^2 s_i G_i'')) = \bar{H}$, which can be either positive or negative depending on the strategic effects of renewable energy R&D investments on both final goods and permit markets. The equation $\bar{H}$ can be simplified as $\frac{\bar{\alpha}G_i'(1-\bar{\alpha})W_i''}{2} \left(\frac{P'q_i}{(\bar{\alpha}^2 s_i G_i'' - P')(P' - (1-\bar{\alpha})W_i'' - \bar{\alpha}^2 s_i G_i'')} + \frac{e_i}{3P' + 2P''q_i - (1-\bar{\alpha})W_i'' - \bar{\alpha}^2 s_i G_i''} \right)$. With simple calculation, we derive that $\bar{H} > 0$ if $\bar{M} > e_i$, where $\bar{M} = \left| \frac{P'q_i(3P' + 2P''q_i - (1-\bar{\alpha})W_i'' - \bar{\alpha}^2 s_i G_i'')}{(\bar{\alpha}^2 s_i G_i'' - P')(P' - (1-\bar{\alpha})W_i'' - \bar{\alpha}^2 s_i G_i'')} \right|$. $\bar{M}$ is a threshold emission level at which the net strategic effects of RE-R&D investments on both output and permit markets under ETS with auctioning are the same as the strategic effect on output market under CAC.

According to Proposition 3, an ETS with auctioning induces greater renewable energy R&D investments than a CAC under certain conditions. If the strategic effect of output markets under an ETS with auctioning is greater than that under a CAC and the difference of the strategic effects of output market between an ETS with auctioning and a CAC is greater than the negative strategic effect of permit market under an ETS with auctioning, an ETS with auctioning leads to greater renewable energy R&D incentives than does a CAC. Conversely, if the difference is less than the negative strategic effect, $\bar{M} < e_i$, a CAC leads to greater renewable energy R&D incentives than an ETS with auctioning.

4. SIMULATIONS

Next, we compare the renewable energy R&D incentives given a specific demand function $P(Q) = a - b(q_1 + q_2)$, abatement costs $((1-\bar{\alpha})q_i - e_i)^2$, and renewable energy costs $0.5 + (\bar{\alpha}q_i)^2$. In this chapter, we omit the subscript *i* for the variables, q, s, g, V, and G, because we only consider a symmetric equilibrium. Renewable energy costs become $0.5 + s(\bar{\alpha}q)^2$, where $s = g(V)$, after renewable energy R&D investments are made. For simplification,[4] RE-R&D effects are set at three different values, $s = 0.5$, 0.75, and 1, and the renewable energy quotas are also set at three different values, $\bar{\alpha} = 0.1$, 0.2, and 0.5.

Table 1 presents the RE-R&D incentives with a general demand curve, $P(Q) = a - b(q_1 + q_2)$, where $a = 10$ and $b = 2$. Total emissions, $\bar{E}$, are capped at 2, which implies that by symmetry each firm is permitted to emit 1 unit at most under any environmental regulation before RE-R&D.[5] In this case, an ETS with free allocation leads to greater R&D incentives than a CAC or an ETS with auctioning. Given general elasticity of demand, an ETS with auctioning provides greater RE-R&D incentives than does a CAC.

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4) Even though RE-R&D level, V_i, is endogenously determined, we rank RE-R&D investment incentives between A policy and B policy by comparing $|d\pi_i / ds_i|$ of A policy with $|d\pi_i / ds_i|$ of B policy. In order to avoid numerical complications, *s* is exogenously given in simulations.

5) Total emission $\bar{E}$ is 2 in the simulation. If a different value is given for the total emission, the value of direct and strategic effect would not be the same. However, the size of emission cap $(\bar{E})$ would not affect the RE-R&D rank among environment regulations. Equations (2), (5), (7) do not include emission cap $(\bar{E})$.

Table 1 RE-R&D Incentives with General Demand

Policy	s	σ	e	q	$P(Q)$	Effects		
						Direct	Strategic	Total
$a=10,\ b=2,\ \bar{\alpha}=0.1$								
CAC	1	–	1	1.545	3.822	0.524	0.069	0.592
ETS-FA	1	1.09	1	1.545	3.822	0.524	0.174	0.698
ETS-AU	1	1.09	1	1.545	3.822	0.524	0.141	0.665
CAC	0.75	–	1	1.546	3.818	0.524	0.069	0.593
ETS-FA	0.75	1.09	1	1.546	3.818	0.524	0.175	0.698
ETS-AU	0.75	1.09	1	1.546	3.818	0.524	0.142	0.666
CAC	0.5	–	1	1.547	3.814	0.524	0.069	0.593
ETS-FA	0.5	1.09	1	1.547	3.814	0.524	0.175	0.699
ETS-AU	0.5	1.09	1	1.547	3.814	0.524	0.142	0.666
$a=10,\ b=2,\ \bar{\alpha}=0.2$								
CAC	1	–	1	1.576	3.696	0.599	0.161	0.760
ETS-FA	1	1.15	1	1.576	3.696	0.599	0.343	0.942
ETS-AU	1	1.15	1	1.576	3.696	0.599	0.288	0.887
CAC	0.75	–	1	1.580	3.678	0.600	0.163	0.763
ETS-FA	0.75	1.16	1	1.580	3.678	0.600	0.349	0.949
ETS-AU	0.75	1.16	1	1.580	3.678	0.600	0.294	0.894
CAC	0.5	–	1	1.585	3.661	0.600	0.165	0.766
ETS-FA	0.5	1.17	1	1.585	3.661	0.600	0.355	0.956
ETS-AU	0.5	1.17	1	1.585	3.661	0.600	0.300	0.900
$a=10,\ b=2,\ \bar{\alpha}=0.5$								
CAC	1	–	1	1.571	3.714	1.117	0.470	1.588
ETS-FA	1	1.14	1	1.571	3.714	1.117	0.635	1.752
ETS-AU	1	1.14	1	1.571	3.714	1.117	0.579	1.696
CAC	0.75	–	1	1.600	3.600	1.140	0.518	1.658
ETS-FA	0.75	1.20	1	1.600	3.600	1.140	0.706	1.846
ETS-AU	0.75	1.20	1	1.600	3.600	1.140	0.647	1.787
CAC	0.5	–	1	1.630	3.481	1.164	0.572	1.736
ETS-FA	0.5	1.26	1	1.630	3.481	1.164	0.787	1.951
ETS-AU	0.5	1.26	1	1.630	3.481	1.164	0.727	1.890

Table 2 RE-R&D Incentives with Elastic Demand

Policy	s	σ	e	q	$P(Q)$	Effects		
						Direct	Strategic	Total
$a=10,\ b=0.05,\ \bar{\alpha}=0.1$								
CAC	1	–	8	13.631	8.637	2.358	0.031	2.389
ETS-FA	1	11.26	8	13.631	8.637	2.358	12.753	15.111
ETS-AU	1	11.26	8	13.631	8.637	2.358	2.884	5.242
CAC	0.75	–	8	13.670	8.633	2.369	0.031	2.400
ETS-FA	0.75	11.34	8	13.670	8.633	2.369	13.850	16.219
ETS-AU	0.75	11.34	8	13.670	8.633	2.369	3.925	6.294
CAC	0.5	–	8	13.708	8.629	2.379	0.031	2.410
ETS-FA	0.5	11.42	8	13.708	8.629	2.379	15.131	17.510
ETS-AU	0.5	11.42	8	13.708	8.629	2.379	5.150	7.529
$a=10,\ b=0.05,\ \bar{\alpha}=0.2$								
CAC	1	–	8	15.099	8.490	9.620	0.107	9.727
ETS-FA	1	14.20	8	15.099	8.490	9.620	16.028	25.647
ETS-AU	1	14.20	8	15.099	8.490	9.620	–4.451	5.168
CAC	0.75	–	8	15.302	8.470	9.866	0.113	9.979
ETS-FA	0.75	14.60	8	15.302	8.470	9.866	19.715	29.581
ETS-AU	0.75	14.60	8	15.302	8.470	9.866	–1.318	8.549
CAC	0.5	–	8	15.510	8.449	10.123	0.119	10.242
ETS-FA	0.5	15.02	8	15.510	8.449	10.123	25.093	35.216
ETS-AU	0.5	15.02	8	15.510	8.449	10.123	3.484	13.607
$a=10,\ b=0.05,\ \bar{\alpha}=0.5$								
CAC	1	–	8	15.652	8.435	61.748	0.507	62.255
ETS-FA	1	15.30	8	15.652	8.435	61.748	5.810	67.558
ETS-AU	1	15.30	8	15.652	8.435	61.748	–21.411	40.337
CAC	0.75	–	8	17.561	8.244	77.597	0.813	78.410
ETS-FA	0.75	19.12	8	17.561	8.244	77.597	10.619	88.216
ETS-AU	0.75	19.12	8	17.561	8.244	77.597	–23.647	53.951
CAC	0.5	–	8	20.000	8.000	100.500	1.389	101.889
ETS-FA	0.5	24.00	8	20.000	8.000	100.500	22.222	122.722
ETS-AU	0.5	24.00	8	20.000	8.000	100.500	–22.222	78.278

Table 2 reports RE-R&D incentives with an elastic demand curve, $P(Q) = a - b(q_1 + q_2)$, where $a = 10$ and $b = 0.05$, in which total emissions, $\bar{e}$, are capped at 16 units, indicating that a maximum of 8 units are permitted for each firm. An ETS with free allocation induces greater RE-R&D investments than does a CAC or an ETS with auctioning. Given elastic demand, it is inconclusive whether the RE-R&D incentives under an ETS with auctioning are greater than they would be under a CAC. For example, a CAC leads to greater RE-R&D incentives than an ETS with auctioning at $\bar{\alpha} = 0.2,\ 0.5,$ whereas an ETS with auctioning induces greater RE-R&D incentives at $\bar{\alpha} = 0.1.$ In sum, if the value of the indirect or strategic effects of RE-R&D investments is negative, RE-R&D incentive under a CAC are always greater than those under an ETS with auctioning.

5. CONCLUSION

This paper suggests that when a government determines its national implementation scheme for GHG reduction, renewable energy R&D incentives should be considered equally with abatement-related R&D incentives. When renewable energy is considered an important tool for economic growth and achieving a low-carbon society, environmental policies should be evaluated with respect to their effects on renewable energy technology development. In imperfectly competitive markets for final goods and permits, an ETS with free allocation leads to greater renewable energy R&D incentives than a CAC or an ETS with auctioning. This is because renewable energy R&D investments under an ETS with free allocation only induce positive strategic effects from cost-reducing innovation, whereas an ETS with auctioning has negative strategic effects resulting from an increasing permit price and positive strategic effects resulting from cost-reducing innovation. This result differs from those of previous studies. In studies considering perfectly competitive markets, an ETS with auctioning generally induces greater abatement-related R&D

incentives than other regulatory instruments. In imperfectly competitive markets, however, emission standards may offer greater environmental R&D incentives than an ETS due to the strategic effects of abatement-related R&D investments. The logic is that environmental R&D investments made under an ETS induce a negative strategic effect by lowering marginal abatement costs and hence increasing the rival's production level through the permit market.

Now, let's consider perfectly competitive markets for emissions and/or final goods. When competitive markets for both final goods and emissions and a perfectly competitive market for final goods with an imperfectly competitive permit market are assumed, renewable energy R&D incentives are identical under all regulatory schemes. This comes from the fact that there is no strategic effect of R&D investments in a competitive market for final goods. However, when an imperfectly competitive market for final goods with a perfectly competitive permit market is considered, an ETS with free allocation and an ETS with auctioning have identical R&D incentives, and ETS lead to greater incentives than under a CAC. This is because renewable energy R&D investment increases a rival's relative production costs and therefore reduces the rival's output.

The result of this paper may be affected if abatement-related R&D investments are also considered and if the relationship between V_i and e_i is structured differently. If e_i is related to V_i in such a way that renewable energy R&D investments reduce emissions, the direct effect is the sum of $G_i(\cdot)$ and $W_i'(\cdot)$, which is identical for all environmental instruments. However, the strategic effects of renewable energy R&D investments differ under each environmental policy, and hence, ranking the renewable energy R&D incentives of the various environmental instruments depends on the size of the strategic effects. If e_i is positively related to s_i, the strategic effects arise from two different channels through the permit market, producing negative and positive effects. The positive strategic effect arises from the decrease in the rival's production level through cost-reducing innovation that induces lower marginal renewable energy costs and a larger total output quantity, creating a greater demand for permits and hence increasing the permit price. The negative strategic effect is due to reduced abatement costs, which reduces the permit price and hence increases the rival's production level. The overall strategic effects of renewable energy R&D investments are inconclusive and depend on the size of the strategic effects. If firms in an oligopoly market make both abatement-related and renewable energy R&D investments simultaneously, a CAC may lead to less, more, or the same level of R&D incentives relative to an ETS with free allocation or an ETS with auctioning. The intuition is that the positive strategic effects of renewable energy R&D investments under an ETS with free allocation are offset by the negative strategic effects of abatement R&D investments. Thus, the overall strategic effect of both R&D investments under an ETS with free allocation may be less than or the same as under a CAC or an ETS with auctioning.

One extension of this study can be found in a model with a green certificate market. Renewable energy R&D investments reduce the price of the green certificate and therefore increase the rival's production level, which is a negative strategic effect that is inversely related to the positive strategic effect of cost-reducing innovation. Thus, when comparing environmental regulatory instruments in the presence of a green certificate market, the relative levels of abatement and renewable energy R&D incentives will depend on the overall size of the strategic effects.

APPENDIX

A1. RPS and CAC

The first-order conditions of firm 1 and 2, $d\pi_i / dq_i$ and $d\pi_j / dq_j$, are respectively,

$$P(Q) = P'(Q)q_1 - (1-\bar{\alpha})W_1'(\cdot) - \bar{\alpha}s_1G_1'(\bar{\alpha}q_1) = 0, \qquad \text{(A1)}$$

$$P(Q) = P'(Q)q_2 - (1-\bar{\alpha})W_2'(\cdot) - \bar{\alpha}s_2G_2'(\bar{\alpha}q_2) = 0. \qquad \text{(A2)}$$

Totally differentiating the equation (A1) and (A2) with respect to s_1 are respectively,

$$\begin{aligned} &P'\left(\frac{dq_1}{ds_1} + \frac{dq_2}{ds_1}\right) + P'\frac{dq_1}{ds_1} + P''q_1\left(\frac{dq_1}{ds_1} + \frac{dq_2}{ds_1}\right) \\ &-\alpha G_1' - ((1-\bar{\alpha})W_1'' + \bar{\alpha}^2 s_1 G_1'')\frac{dq_1}{ds_1} = 0, \end{aligned} \qquad \text{(A3)}$$

$$\begin{aligned} &P'\left(\frac{dq_1}{ds_1} + \frac{dq_2}{ds_1}\right) + P'\frac{dq_2}{ds_1} + P''q_2\left(\frac{dq_1}{ds_1} + \frac{dq_2}{ds_1}\right) \\ &-((1-\bar{\alpha})W_2'' + \bar{\alpha}^2 s_2 G_2'')\frac{dq_2}{ds_1} = 0. \end{aligned} \qquad \text{(A4)}$$

Subtract equation (A4) from equation (A3), and rearrange equation (A4); the following are derived:

$$(P' - (1-\bar{\alpha})W_1'' - \bar{\alpha}^2 s_1 G_1'')\frac{dq_1}{ds_1} - \bar{\alpha}G_1' - (P' - (1-\bar{\alpha})W_2'' - \bar{\alpha}^2 s_2 G_2'')\frac{dq_2}{ds_1} = 0, \qquad \text{(A5)}$$

$$(P' + P''q_2)\frac{dq_1}{ds_1} + (2P' + P''q_2 - (1-\bar{\alpha})W_2'' - \bar{\alpha}^2 s_2 G_2'')\frac{dq_2}{ds_1} = 0. \qquad \text{(A6)}$$

From equation (A5) and (A6), dq_i / ds_i is derived as follows:

$$\frac{dq_2}{ds_1} = \frac{\bar{\alpha}G_1'(P' + P''q_1)}{((1-\bar{\alpha})W_1'' - \bar{\alpha}^2 s_1 G_1'' - P')(3P' + 2P''q_1 - (1-\bar{\alpha})W_1'' - \bar{\alpha}^2 s_1 G_1'')}. \qquad \text{(A7)}$$

Assuming that $P' + P''q_1 < 0,$ it is clear that $dq_2 / ds_1 > 0.$

A2. RPS & ETS with Free Allocation

Totally differentiating the first order conditions, $d\pi_i / dq_i$ and $d\pi_i / dq_i$, with respect to s_1, we find:

$$P'\left(\frac{dq_1}{ds_1}+\frac{dq_2}{ds_1}\right)+P'\frac{dq_1}{ds_1}+P''q_1\left(\frac{dq_1}{ds_1}+\frac{dq_2}{ds_1}\right)$$
$$-\ \alpha G_1' - W_1''\left(\frac{(1-\bar{\alpha})dq_1}{ds_1}-\frac{de_1}{ds_1}\right)-\bar{\alpha}^2 s_1 G_1''\frac{dq_1}{ds_1}=0, \tag{A8}$$

$$P'\left(\frac{dq_1}{ds_1}+\frac{dq_2}{ds_1}\right)+P'\frac{dq_2}{ds_1}+P''q_2\left(\frac{dq_1}{ds_1}+\frac{dq_2}{ds_1}\right)$$
$$-\ W_2''\left(\frac{(1-\bar{\alpha})dq_2}{ds_1}-\frac{de_2}{ds_1}\right)-\bar{\alpha}^2 s_2 G_2''\frac{dq_2}{ds_1}=0, \tag{A9}$$

$$W_1''\left((1-\bar{\alpha})\frac{dq_1}{ds_1}-\frac{de_1}{ds_1}\right)=W_2''\left((1-\bar{\alpha})\frac{dq_2}{ds_1}-\frac{de_2}{ds_1}\right)=0, \tag{A10}$$

$$\frac{de_1}{ds_1}+\frac{de_2}{ds_1}=0. \tag{A11}$$

Subtract equation (A9) from equation (A8) and rearrange equation (A9); then,

$$(P'-(1-\bar{\alpha})W_1''-\bar{\alpha}^2 s_1 G_1'')\frac{dq_1}{ds_1}-\bar{\alpha}G_1'+W_1''\left(\frac{de_1}{ds_1}\right)-W_2''\left(\frac{de_2}{ds_1}\right)$$
$$-\ (P'-(1-\bar{\alpha})W_2''-\bar{\alpha}^2 s_2 G_2'')\frac{dq_2}{ds_1}=0, \tag{A12}$$

$$(P'+P''q_2)\frac{dq_1}{ds_1}+W_2''(\frac{de_2}{ds_1})+(2P'+P''q_2-(1-\bar{\alpha})W_2''-\bar{\alpha}^2 s_2 G_2'')\frac{dq_2}{ds_1}=0. \tag{A13}$$

From equation (A10) and (A11), the following are derived:

$$\frac{de_1}{ds_1} = \frac{(1-\bar{\alpha})}{2}\left(\frac{dq_1}{ds_1} - \frac{dq_2}{ds_1}\right), \tag{A14}$$

$$\frac{de_2}{ds_1} = \frac{(1-\bar{\alpha})}{2}\left(\frac{dq_2}{ds_1} - \frac{dq_1}{ds_1}\right). \tag{A15}$$

By plugging equation (A14) and (A15) into equation (A12), the following are derived:

$$(P' - \bar{\alpha}^2 s_1 G_1'')\frac{dq_1}{ds_1} - (P' - \bar{\alpha}^2 s_1 G_1'')\frac{dq_2}{ds_1} + \bar{\alpha} G_1' = 0. \tag{A16}$$

By plugging equation (A16) and (A15) into equation (A13), the following are derived:

$$\begin{aligned}&(3P' + 2P''q_2 - (1-\bar{\alpha})W_2'' - \bar{\alpha}^2 s_2 G_2'')\left(\frac{dq_2}{ds_1}\right)\\ &\quad + \frac{\bar{\alpha} G_1'(P' + P''q_2 - \frac{(1-\bar{\alpha})}{2}W_2'')}{P' - \bar{\alpha}^2 s_1 G_1''} = 0,\end{aligned} \tag{A17}$$

$$\frac{dq_2}{ds_1} = \frac{\bar{\alpha} G_1'(P' + P''q_2 - \frac{1-\bar{\alpha}}{2}W_2'')}{(\bar{\alpha}^2 s_1 G_1'' - P')(3P' + 2P''q_2 - (1-\bar{\alpha})W_2'' - \bar{\alpha}^2 s_2 G_2'')}. \tag{A18}$$

By plugging equation (A18) into equation (8), equation (9) is derived.

A3. RPS & ETS with Auctioning

Totally differentiating equation (6) with respect to s_1, we find:

$$\frac{d\sigma}{ds_1} = W_1''\left((1-\bar{\alpha})\frac{dq_1}{ds_1} - \frac{de_1}{ds_1}\right) = W_2''\left((1-\bar{\alpha})\frac{dq_2}{ds_1} - \frac{de_2}{ds_1}\right). \qquad \text{(A19)}$$

Using equation (A19), (A16) and (A18), $d\sigma / ds_1$ is derived as follows:

$$\frac{d\sigma}{ds_1} = \frac{\bar{\alpha}G_1'(1-\bar{\alpha})W_2''}{2(3P' + 2P''q_2 - (1-\bar{\alpha})W_2'' - \bar{\alpha}^2 s_2 G_2'')}. \qquad \text{(A20)}$$

Assuming that $P' + P''q_i < 0$, renewable energy R&D investments made by firm 1, V_1, increase the permit price, σ: $d\sigma / V_1 > 0$. This can be rewritten as $d\sigma / ds_1 < 0$ because V_1 reduces renewable energy costs to $s_1 G_1$ but increases the permit price. By plugging equation (A20) into equation (4), equation (7) can be obtained.

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