Market Power in Emissions Trading and Renewable Energy Policy

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Abstract: Policies for reducing greenhouse gas emissions, e.g., cap-and-trade (C&T) as emissions permits trading and renewable portfolio standards (RPS) as renewable energy policies, have recently been introduced in various countries. In this study, we examine market equilibria under C&T and RPS in a bi-level optimization framework. For the lower level, generation of outputs of renewable and non-renewable sectors and electricity prices are decided by maximizing their profits. For the upper level, the policy maker chooses optimal policy level in an attempt to maximize the social welfare. Our results indicate that C&T is the best scheme for both increasing social welfare and reducing greenhouse gas emissions.

1 INTRODUCTION

In recent years, greenhouse gas emissions (i.e., carbon dioxide (CO_2) and methane) have been implicated as contributing to global warming. A number of measures to control those emissions have been proposed in various countries. IEA (2018) examines the effectiveness of policy and support scheme for renewable energy in various countries. The support and target schemes have increased generation capacity of renewables significantly: in 2010, 61 countries had a feed-in tariff (FIT), renewable portfolio standards (RPS) or auction system in place. Additionally, by 2017, the scheme had expanded to 121 countries, not only in US and EU but also in Asia and Sub-Saharan Africa.

Two commonly implemented policy instruments are the cap-and-trade (C&T) scheme and a policy for promoting renewable energy technologies known as RPS. Under C&T, CO_2 emission quotas are set for each country, region, or sector. The non-renewable energy sectors are required to achieve CO_2 reductions. Some sectors are successful, exceeding CO_2 emission quotas. By contrast, there are unsuccessful ones. C&T is a system of trading through a market where successful and unsuccessful sectors buy to cover shortages or sell excess capacity emissions quotas. By contrast, RPS requires a certain percentage of electricity generation to originate from renewable energy sources. In most cases, producers are allowed to meet RPS by self-generation, procuring power from renewable energy sources via bi-lateral contracts, and purchasing renewable energy certificates/credits (RECs) from secondary markets. The REC price is endogenously determined by supply and demand conditions in the REC market.

Some countries have introduced C&T and RPS (ICAP, 2017; REN21, 2017). We assume that C&T and RPS are both adequate policy schemes viewed from the aspect of CO_2 reductions, but we do not know which is preferable and how each one impacts social welfare. Hibiki and Kurakawa (2013) discussed whether FIT or RPS as renewable energy policies is preferable from the aspect of social welfare. Their findings indicated that governments should introduce RPS when marginal damage cost is relatively high. They did not evaluate whether C&T as emissions permits trading or RPS as renewable energy policies is preferable from the aspect of social welfare.

Market power in the electricity market greatly influences electricity prices and production (Siddiqui et al., 2016). Modeling market power in electricity markets using a Cournot oligopoly structure has already been done. For example, Siddiqui et al. (2016) analyze market power in electricity markets under RPS. The result of their research showed welfare losses are actually higher when there is less potential for exercising market power. Tanaka and Chen (2012) analyze the impact of C&T on the electricity market. They show the relationship between emission cap levels and market equilibrium, however they do not show socially optimal emission cap, to be given exogenously as parameters.

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Our study develops an analytical model to determine an optimal policy level in a Cournot oligopoly structure for both C&T and RPS. We extend the model of Tanaka and Chen (2012) by considering the optimal policy level (i.e., the rate of emission cap and the rate of RPS). All sectors may then strategically determine output quantities to maximize profits. We then apply the model to analyze a relationship between market equilibria and energy and environmental policy as C&T and RPS. Thus, the analytical model is used to generate contestable hypotheses, while the numerical experiment gives us a more meaningful and intuitive interpretation of the results. We highlight the effect on electricity prices, social welfare, and CO_2 emissions under C&T and RPS.

The following findings are provided in this paper. Under C&T, the electricity price influences renewable energy generation. Electricity prices are high because of low levels of non-renewable energy generation. The social surplus of C&T's electricity market becomes relatively large. C&T directly controls CO_2 emissions. Under RPS, renewable energy generation decreases along with non-renewable energy generation. Electricity prices are low due to the high level of renewable energy generation. RPS does not control CO_2 emissions comparatively because non-renewable energy generation also increases when renewable energy generation increases.

The remaining part of this paper is organized as follows: Section 2 introduces one single-level model and two bi-level models. After laying out our numerical data in Section 3, we use the proposed model to conduct experiments. Section 4 contains concluding remarks along with suggestions for future research.

2 MODEL

In this study, we assume that there are one renewable energy sector and two non-renewable energy sectors possessing thermal power in the electricity industry.

We adopt a complementary approach to the models' interaction between a deregulated electricity industry and a policymaker by assuming that the policymaker's objective is to maximize social welfare inclusive of damages. In order to explore the variation of outcomes, we allow for the following market settings:

> **Benchmark Setting (BM).** This benchmark setting has a policymaker operating all power plants in order to maximize social welfare, considering damage from emissions. This setup results in a single-level program.
>
> **C&T.** The C&T is a market-based scheme for reducing the emission of CO_2 effectively in a region. Policymaker imposes upper-limit of the emissions, that is, "cap" on power producers. The power producers then trade a difference between the upper-limit and actual emissions in the market of the emission permit. If actual emission for a power producer is fewer (more) than upper-limit, the producer might be able to sell (buy) the emission permit. Energy sectors' decisions at the lower level are made by price-taking renewable and non-renewable energy sectors that take the rate of emission cap as given and maximize their profits inclusive of emission revenues or costs, the shadow price of the emission cap constraint. At the upper level, the policy maker decides the emission cap percentage in order maximize social welfare constrained by the lower level.
>
> **RPS.** The RPS scheme is one for encouraging power producers to supply a certain minimum share of their electricity from renewable energy sources. In countries or regions where the RPS scheme is introduced there is usually secondary market for REC. If the producers can not meet the RPS target, in order to meet the target they might be able to purchase the certificates in the REC market. Energy sectors' decisions at the lower level are made by renewable energy and non-renewable energy sectors that take the RPS percentage target as given and maximize their profits inclusive of REC revenues or costs determined by the shadow price of the RPS constraint.

Each sector is dominant and behaves in Cournot fashion (i.e., it is able to influence the electricity price). Since we will examine three settings, we denote $\cdot^*$, $\cdot^\dagger$, and $\cdot^\diamond$ as the optimal values for the decision variables under BM, C&T, and RPS, respectively.

2.1 Notation

The parameters, and variables adopted in this study are:

Parameters.

a**:** Intercept of the linear inverse demand function (U.S. Dollars/MWh)

b**:** Slope of the linear inverse demand function (U.S. Dollars/MWh^2)

c_1**:** Cost of non-renewable energy production 1 (U.S. Dollars/MWh)

c_2**:** Cost of non-renewable energy production 2 (U.S. Dollars/MWh)

c_r**:** Cost of renewable energy production (U.S. Dollars/MWh)

r_1**:** Emissions factor for non-renewable energy sector 1 (t- CO_2)

r_2**:** Emissions factor for non-renewable energy sector 2 (t- CO_2)

e_{cap}**:** Emission cap (t-CO_2)

e_1^b**:** Emissions for the non-renewable energy sector 1 determined in benchmark setting (t-CO_2)

e_2^b**:** Emissions for the non-renewable energy sector 2 determined in benchmark setting (t-CO_2)

k**:** Rate of increase in the marginal cost of CO_2 emissions (U.S. Dollars/MWh^2)

Variables.

q_1**:** Non-renewable energy 1 production (MWh)

q_2**:** Non-renewable energy 2 production (MWh)

q_r**:** Renewable energy production (MWh)

p**:** Electricity price (U.S. Dollars)

p^{REC}**:** Market-clearing price for RECs (U.S. Dollars/MWh)

p^e**:** Emission price (U.S. Dollars)

α**:** Optimal proportion of electricity from renewable energy (%)

β**:** Rate of emission cap (%)

e_1**:** Emissions of non-renewable energy sector 1 (t-CO_2)

e_2**:** Emissions of non-renewable energy sector 2 (t-CO_2)

For non-renewable and renewable energy sectors, we assume the quadratic cost functions $C_1(q_1) = \frac{1}{2}c_1q_1^2$, $C_2(q_2) = \frac{1}{2}c_2q_2^2$, and $C_r(q_r) = \frac{1}{2}c_rq_r^2$, which reflect not only marginal costs of production but also amortized capital costs. As for the demand side, we also aggregate consumers' willingness to pay as a linear inverse demand function, i.e., $p = a - bq$ (in U.S. Dollars/MWh), where $q = q_1 + q_2 + q_r$ is total consumption. We assume that $b < c_i < c_r < \alpha$ in order to ensure that there is an equilibrium and to capture the general characteristic that renewable energy has a higher level of costs than non-renewable energy sources. Here, $a > 0$ (in U.S. Dollars/MWh) and $b > 0$ (in U.S. Dollars/MWh^2) are the intercept and slope of the inverse demand function, respectively. The externality from emissions is included via a damage function that is convex only in its production from the non-renewable energy sector, i.e., $d(q_1,q_2) = \frac{1}{2}k(q_1+q_2)^2$ for $k > 0$. Other types of damage functions may be posited but increasing marginal effects from emissions capture the fact that atmospheric concentrations of greenhouse gases are more difficult to reverse in greater abundance. In order to facilitate comparative statics of the resulting solutions, we assume that $k > b$.

2.2 Benchmark Setting

The benchmark setting selects generation of either type in order to maximize sectors' own profits by solving the following single-level problem:

$$\max_{q_1 \geq 0} \quad \pi_1 = \quad pq_1 - C_1(q_1), \tag{1}$$

$$\max_{q_2 \geq 0} \quad \pi_2 = \quad pq_2 - C_2(q_2), \tag{2}$$

$$\max_{q_r \geq 0} \quad \pi_r = \quad pq_r - C_r(q_r). \tag{3}$$

Eqs. (1)–(3) are transformed to Karush-Kuhn-Tucker (KKT) conditions because they are convex functions.

$$0 \leq q_1 \perp -a + bq_1 + c_1q_1 + bq \geq 0, \tag{4}$$

$$0 \leq q_2 \perp -a + bq_2 + c_2q_2 + bq \geq 0, \tag{5}$$

$$0 \leq q_r \perp -a + bq_r + c_rq_r + bq \geq 0. \tag{6}$$

We derive optimal generations q_1^*, q_2^*, and q_r^* by Eqs. (4)–(6). Social welfare is thus defined as follows:

$$\begin{aligned} aq^* - \frac{1}{2}b(q^*)^2 - C_1(q_1^*) - C_2(q_2^*) - C_r(q_r^*) \\ -d(q_1^* + q_2^*). \end{aligned} \tag{7}$$

We treat the emissions of non-renewable energy in the benchmark setting e_1^b and e_2^b as benchmark parameters for policies with emissions trading.

2.3 Cap-and-Trade

Lower-level Problem

At the lower level, each sector selects its production in order to maximize its profit, which consists of revenues from electricity sales minus costs.

$$\max_{q_1, p^e \geq 0} \quad \pi_1 = \quad pq_1 - C_1(q_1) - p^e(r_1q_1 - \beta e_1^b), \tag{8}$$

$$\max_{q_2, p^e \geq 0} \quad \pi_2 = \quad pq_2 - C_2(q_2) - p^e(r_2q_2 - \beta e_2^b), \tag{9}$$

$$\max_{q_r \geq 0} \quad \pi_r = \quad pq_r - C_r(q_r). \tag{10}$$

In Eqs. (8) and (9), non-renewable energy sectors determine production to maintain emission cap (e_{cap}) based on the emissions of non-renewable energy sector determined in benchmark setting (e_i^b) and the rate of emissions cap (β). Eqs. (8)–(10) are transformed to KKT conditions because they are convex optimization problems. The emission cap (e_{cap}) is defined as $e_{cap} = \beta e_1^b + \beta e_2^b$. Eq. (14) provide the adjustment conditions in the emissions trading market.

$$0 \leq q_1 \perp -a + bq_1 + c_1 q_1 + bq + p^e r_1 \geq 0, \quad (11)$$

$$0 \leq q_2 \perp -a + bq_2 + c_2 q_2 + bq + p^e r_2 \geq 0, \quad (12)$$

$$0 \leq q_r \perp -a + bq_r + c_r q_r + bq \geq 0, \quad (13)$$

$$0 \leq p^e \perp r_1 q_1 + r_2 q_2 - e_{cap} \geq 0. \quad (14)$$

We derive optimal generation $q_1^\dagger$, $q_2^\dagger$, and $q_r^\dagger$ by Eqs. (11)–(14).

Upper-level Problem

For the upper-level problem, the policymaker selects the optimal rate of emission cap, $\beta^\dagger$ in order to maximize social welfare using $q_1^\dagger$, $q_2^\dagger$, and $q_r^\dagger$ that are derived at the lower level:

$$\begin{aligned} \max_{\beta} \quad & aq^\dagger - \frac{1}{2} b (q^\dagger)^2 - C_1(q_1^\dagger) - C_2(q_2^\dagger) \\ & - C_r(q_r^\dagger) - d(q_1^\dagger, q_2^\dagger). \end{aligned} \quad (15)$$

2.4 Renewable Portfolio Standards

Lower-level Problem

At the lower level, each sector selects its production in order to maximize its profit, which consists of revenues from electricity sales minus costs.

$$\max_{q_1 \geq 0} \quad \pi_1 = \quad pq_1 - C_1(q_1) - \alpha p^{REC} q_1, \quad (16)$$

$$\max_{q_2 \geq 0} \quad \pi_2 = \quad pq_2 - C_2(q_2) - \alpha p^{REC} q_2, \quad (17)$$

$$\max_{q_r \geq 0} \quad \pi_r = pq_r - C_r(q_r) + (1 - \alpha) p^{REC} q_r. \quad (18)$$

In Eqs. (16) and (17), the RPS requirement results in an extra cost resulting from the obligation to purchase RECs at the equilibrium REC price, p^{REC} (in U.S. Dollars/MWh). In Eq. (18), the renewable energy sector earns revenues from RECs in proportion to p^{REC} and the RPS constraint. Since each of these problems is convex, it may be replaced by the KKT conditions. Hence, the lower-level problem in Eqs. (19)–(22) consists of each sector's KKT conditions for profit maximization and the RPS constraint:

$$0 \leq q_1 \perp -a - bq_1 - c_1 q_1 - bq - p^{REC} \alpha \geq 0, \quad (19)$$

$$0 \leq q_2 \perp -a - bq_2 - c_2 q_2 - bq - p^{REC} \alpha \geq 0, \quad (20)$$

$$\begin{aligned} 0 \leq q_r \perp & -a - bq_r - c_r q_r - bq \\ & + p^{REC} (1 - \alpha) \geq 0, \end{aligned} \quad (21)$$

$$0 \leq p^{REC} \perp (1 - \alpha) q_r - \alpha q_1 - \alpha q_2 \geq 0. \quad (22)$$

In Eq. (22), REC price satisfies REC market settlement condition. We derive optimal generation $q_1^\diamond$, $q_2^\diamond$, and $q_r^\diamond$ through Eqs. (19)–(22).

Table 1: Evaluation conditions.

Intercept of inverse demand function	a	100
Slope of inverse demand function	b	0.01
Production cost of non-renewable energy sector 1	c_1	0.026
Production cost of non-renewable energy sector 2	c_2	0.024
Renewable energy production cost	c_r	0.25
Emission factor of non-renewable energy sector 1	r_1	0.5
Emission factor of non-renewable energy sector 2	r_2	0.8
Damage cost	k	[0, 0.1]

Upper-level Problem

At the upper-level problem, the policymaker selects the optimal RPS proportion, $\alpha^\diamond$ in order to maximize social welfare using $q_1^\diamond$, $q_2^\diamond$, and $q_r^\diamond$ derived at the lower level:

$$\begin{aligned} \max_{\alpha} \quad & aq^\diamond - \frac{1}{2} b (q^\diamond)^2 - C_1(q_1^\diamond) - C_2(q_2^\diamond) \\ & - C_r(q_r^\diamond) - d(q_1^\diamond, q_2^\diamond). \end{aligned} \quad (23)$$

3 NUMERICAL EXAMPLES

In this section, we compare the effect of C&T and RPS on renewable energy production, market price, social welfare, and CO_2 emissions using the proposed model. Table 1 shows the evaluation conditions. The parameter values are set by reference to Siddiqui et al. (2016) and Tanaka and Chen (2012).

Figure 1 shows the effect of the rate of increase in the marginal cost of CO_2 emissions, k, on renewable energy production, q_r, under a benchmark setting, C&T, and RPS. In the figure, the benchmark setting, the emissions trading by cap-and-trade, and the renewable energy policy as the renewable portfolio standards are denoted by BM, C&T, and RPS, respectively.

Renewable energy generation under C&T and RPS are almost the same as that under BM when k is low, whereas renewable energy generation under C&T and RPS increases when k increases. C&T has directly no influence on renewable energy generation due to the trading scheme between non-renewable energy generation. However, renewable energy generation under C&T has a tendency to increase when k becomes large. Renewable energy generation under RPS also increases quickly when k increases. This outcome might be because RPS is a direct policy of renewable energy. However, renewable energy generation decreases after $k = 0.03$, approximately. Intuitively, non-renewable energy generation decreases

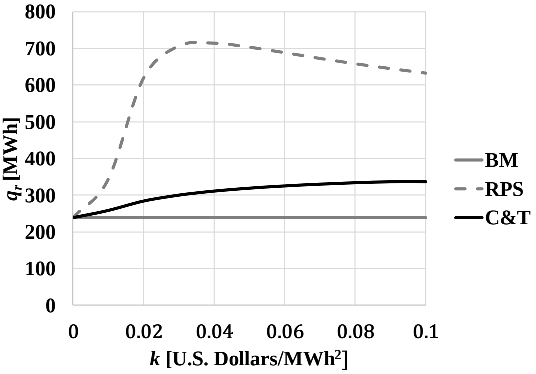

Figure 1: Renewable energy generation.

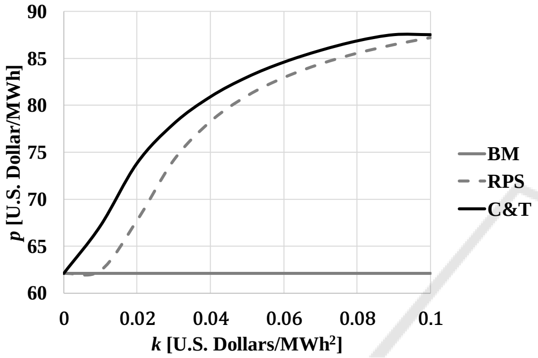

Figure 2: Electricity prices.

as k becomes large. Thus the decrease causes small generation of renewable energy due to characteristic of RPS scheme.

Figure 2 depicts the effect of the rate of increase in the marginal cost of CO$_2$ emissions, k, on electricity prices, p, under BM, C&T, and RPS. Under C&T, the electricity prices are high because of little non-renewable energy generation. The renewable energy sector is unaffected by k increases, using renewable energy generation to obtain higher profits (see Fig. 1). Under RPS, the electricity prices are low due to the higher usage of renewable energy generation.

Figure 3 exhibits the effect of the rate of increase in marginal cost of CO$_2$ emissions, k, on social welfare under BM, C&T, and RPS.

Social welfare decreases when k increases due to the impact of damages from increased CO$_2$ emissions. Comparing C&T and RPS, the social welfare attained from C&T is higher than from RPS. The reason for this outcome must greatly influence electricity prices (see Fig. 2). The social surplus of C&T's electricity market becomes relatively large.

Figure 4 shows the effect of the rate of increase in marginal cost of CO$_2$ emissions, k, on CO$_2$ emissions, e, under BM, C&T, and RPS.

On the one hand, C&T and RPS control CO$_2$ emissions when k increases. CO$_2$ emissions under C&T are lower than that of RPS because C&T is a policy aiming to directly control CO$_2$ emissions. On the other hand, CO$_2$ emissions under RPS is higher than those under C&T. RPS does not control CO$_2$ emissions as well, by comparison, because non-renewable energy generation also increases along with renewable energy generation. This means that the damage cost for RPS is larger than that for C&T. Thus, the effects of the damage cost as well as electricity prices lead to large social welfare for C&T.

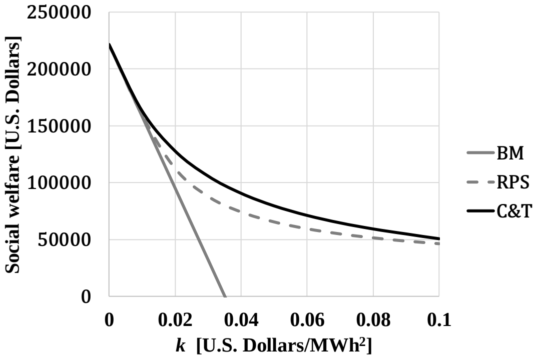

Figure 3: Social welfare.

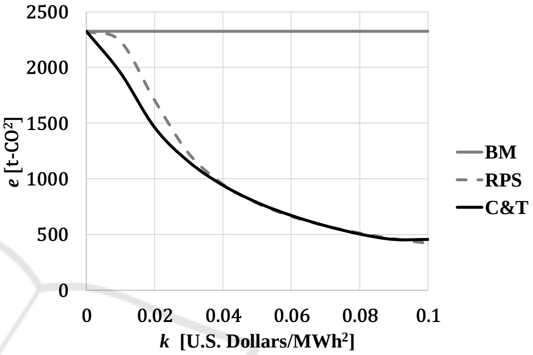

Figure 4: CO$_2$ emissions.

4 CONCLUDING REMARKS

In this study, we examine C&T and RPS aimed at reducing greenhouse gas emissions that cause global warming. We develop an analytical model for C&T and RPS and used it to decide the optimum level of power generation, electricity prices, rate for an emissions cap, and RPS requirement percentage. We analyze how the regulation level affects market equilibrium. Furthermore, we show how policymakers should decide the level of regulation for the purpose of maximizing social welfare. In the end, C&T's social welfare turns out being higher than that of the RPS. Naturally, enforcement of C&T is effective for controlling CO$_2$ emissions. From the viewpoint of social welfare and CO_2 reductions, the government enforces C&T.

We analyze the problem of a simple setting with two non-renewable energy sectors and one renewable energy sector in this study. In reality, the number of sectors and the ratio of renewable energy sectors to them, differ by country and world region. Future research should extend itself to models where the number of sectors may be set. We will also extend the model to introduce the policy mix scheme consisting of C&T and RPS in order to investigate the interaction between the schemes.

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