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Optimal Operational Strategy for Power Producers in Korea Considering Renewable Portfolio Standards and Emissions Trading Schemes

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Abstract: Globally, many countries are experiencing economic growth while concurrently increasing their energy consumption. Several have begun to consider a low-carbon energy mix to mitigate the environmental impacts caused by increased fossil fuel consumption. In terms of maximizing profits, however, power producers are not sufficiently motivated to expand capacity due to high costs. Thus, the Korean government initiated the Renewable Portfolio Standard (RPS), an obligation to generate a certain proportion of a producer's total generation using renewable energy for power producers with capacities of 500 MW or more, and the Emissions Trading Scheme (ETS), designed to attain a carbon emissions reduction goal. We propose a mathematical model to derive the optimal operational strategy for maximizing power producer profits with a capacity expansion plan that meets both regulations. As such, the main purpose of this study was to obtain the optimal operational strategy for each obligatory power producer. To that end, we defined a 2×2 matrix to classify their types and to conduct scenario-based analyses to assess the impact of major factor changes on solutions for each type of power producer. Finally, for the power generation industry to operate in a sustainable and eco-friendly manner, we extracted policy implications that the Korean government could consider for each type of power producer.

Keywords: renewable portfolio standards; emissions trading scheme; optimal operational strategy; generation expansion plan; energy planning

1. Introduction

Globally, interest in future-oriented values such as sustainability or green growth is rising steadily [1,2]. Many countries experiencing economic growth have an accompanying increase in energy consumption [3]. In recent decades, these countries have been considering environmental threats and the risks of depletion of traditional energy sources.

As part of this effort, a new climate regime was launched under the United Nations Framework Convention on Climate Change (UNFCCC) in 2015. At this meeting, each country voluntarily established greenhouse gas (GHG) reduction targets, and adjusted policies are being established to achieve these targets [4]. The main policies include the Renewable Portfolio Standard (RPS) and the Emissions Trading Scheme (ETS), which reduces fossil fuel consumption and carbon emissions.

Korea is the eighth largest energy and electricity consuming country in the world [5,6], as its main industries are energy-intensive, including steel and semiconductor manufacturing. The energy consumption of Korea's main industries is increasing continuously, and electricity consumption represents a large portion of this. However, the Korean generation industry's dependence on highly non-renewable energy (NRE) sources has been an issue. To solve this problem, in 2012, the government

implemented RPS, which obligates power producers with 500 MW or more of NRE generation capacity to produce a certain percentage of the previous year's NRE generation capacity from renewable energy (RE) sources. The government aims to have more than 10% of electric power generation come from RE sources by 2023.

At the 21st Conference of Parties, Korea, whose GHG emissions were 7th among Organization for Economic Co-operation and Development (OECD) countries in 2016, declared a national reduction target of 37% compared to business as usual (BAU) by 2030 [4]. In order to achieve this, in 2015, the government started ETS, which assigns companies Carbon Emissions Reductions (CER) based on annual and sectoral GHG reduction targets. Each company complies with this regulation by buying CER surplus, selling CER shortage, or paying penalties for excess emissions.

Korea's major producers in the power generation industry, which accounts for more than one-third of national GHG emissions [7], must follow both regulations. RPS and ETS act as means to implement international commitments, from a national viewpoint, and to create a new paradigm that can affect operations, from an enterprise perspective. Therefore, obligatory power producers (hereafter, power producers) should be aware of the mechanisms of both regulations. They should also provide a stable power supply and establish an efficient future operational strategy.

Korea's power industry is moving towards increasing the private-sector share from the nation-led sector. Thus, from a corporate management perspective, RPS and ETS will affect revenues and costs. Most previous studies have derived energy plans that expand generation capacity and minimize the total cost from a national perspective [1,3,5,8–11]. Therefore, our study aimed at maximizing the profit of power producers that are required to meet electricity demand while operating under both regulations. As such, we developed a mathematical model to maximize profits and provide optimal operational strategies, including capacity expansion plans and RPS/ETS implementation plans, for each power producer. In addition, we proposed a 2×2 matrix to classify them for analysis from the power producer's perspective and to analyze the optimal operational strategy for each scenario according to type using this matrix.

The rest of the paper is organized as follows. In Section 2, we review previous studies on both regulations in other countries and on quantitative studies on generation expansion planning (GEP) optimization. Differences between our study and previous studies are highlighted here. Section 3 examines the RPS and ETS mechanisms in Korea in detail and derives an operational scheme oriented towards the power producers regulated by both systems. Mathematical models for deciding operational strategies are developed in Section 4. In Section 5, a scenario-based analysis is conducted to assess how major factor changes affect solutions for power producers in each scenario. Finally, meaningful insights and political implications are provided in Section 6.

2. Literature Review

2.1. Associated with Government Policy

The expansion of RE sources is necessary for sustainable generation in the future. However, the insufficient incentive to expand the RE capacities for a power producer is a problem because it requires a lot of capital for new capacity expansion. Thus, the Korean government implemented RPS and ETS in order to reduce carbon emissions by increasing the proportion of RE power generation.

2.1.1. Renewable Portfolio Standards (RPS)

Many studies on RPS have been conducted including studies on the effects and contributions of an RPS introduction, policy proposals for effective RPS implementation, and portfolio design that reflects RPS uncertainty.

First, some researchers conducted studies analyzing the effect of introducing RPS in the United States (US) [12,13]. The study in Reference [14] found that the introduction of RPS contributed 4.2% and 6.1% to the adoption of wind and solar power, respectively, as a result of excluding political and

economic factors. In addition, References [15,16] evaluated the introduction of RPS in consideration of new variables.

Some studies on implementing RPS have been conducted in Korea. First, Reference [17] conducted a preliminary evaluation of Korea's RPS introduction by comparing Feed-in tariffs (FIT) and RPS in terms of capacity expansion, technological progress, cost-effectiveness, and market risk. Furthermore, References [4,18] investigated the current RPS policy in Korea, identified problems, and derived a future outlook based on quantitative indicators. Reference [18] conducted a virtual evaluation of current RPS policy in Korea based on a bottom-up model. Reference [4] analyzed an optimal portfolio for 2050 in the Korean power sector.

Some studies addressed the implementation of RPS in the European Union (EU). The study in Reference [19] proposed an optimization model to increase power supply stability and sustainability. It analyzed the EU policy to compare the benefits of RE sources to traditional energy sources from a cost, risk, and pollutant emissions perspective. In order to minimize costs and risks, the study analyzed the EU RPS status by year and derived the indicators, such as pollutant emissions and target achievement rates. In addition, Reference [20] conducted a study to evaluate the policy coordination impact when implementing RPS and carbon cap-and-trade according to the effective policy mix interval.

2.1.2. Emission Trading Scheme (ETS)

Existing studies on ETS derive a framework for ETS adoption, evaluate the effectiveness of specific state and country ETS policies, and evaluate the impact of ETS on social surplus.

Some researchers have been conducted on ETS framework designs and implementation schemes. First, Reference [21] focused on the development of the ETS regulatory framework in Shenzhen, China, including economic aspects and GHG emissions. An overview of key elements and progress of the Shanghai ETS design was presented in Reference [22]. In addition, Reference [23] conducted an overall evaluation of the ETS framework implemented in Korea in 2015 and analyzed the main points of policy design for consistent policy development. Reference [24] analyzed a scenario-based analysis and simulation for establishing a multi-regional integrated ETS scheme using computable general models in China, the US, Europe, Australia, Japan, and Korea.

Many studies regarding implementing ETS schemes have been conducted lately. The study in Reference [25] investigated the problems that arise when implementing an ETS scheme, which considered the decision making of power generation companies in the management areas of local government. References [26,27] studied the price effects of carbon credits.

On the other hand, some studies discussed the risks of introducing ETS and the factors that hinder the cost-effectiveness of ETS. Reference [28] classified risks (market risk, policy risk, green investment risk, etc.) from the supply chain perspective when implementing ETS and derived a strategic portfolio for risk mitigation. In addition, Reference [29] evaluated Korean ETS based on factors that actually limit the cost-effectiveness of ETS and established an operational strategy to control them. Establishing an operating system for ETS that takes into account realistic constraints and risks can be used as a sustainable policy tool.

2.2. Generation Expansion Planning (GEP) Optimization

Generation Expansion Planning (GEP) optimization is a research area that derives the optimal power generation portfolio composition. This research area includes many studies, mainly focused on the development of expansion plans for power generation capacities using mixed-integer programming, and on considering uncertainty in expansion plans. In addition, many studies have analyzed the effects of various factors (incentive systems, climate change, decentralized development, etc.) in the models.

Some researchers have presented a new framework for considering uncertainties in GEP. First, Reference [8] proposed a model based on mixed-integer programming that reflected the uncertainties of electricity demand, investment, and operating costs using robust optimization

techniques. Reference [30] derived an expansion plan that included stability and reliability constraints, and Reference [9] presented a GEP model that considered input variables uncertainty.

References [31,32] studied a power plant expansion problem using mixed-integer programming models. Reference [32] included both supply-side and demand-side approaches. The study in Reference [33] solved the problem by considering three objective functions: project lifetime economic return, minimization of CO₂ emissions, and minimization of fuel price uncertainty. Reference [34] presented a multistage expansion planning problem of a distribution system that considered both distribution networks and distributed generation. That model was based on cost minimization considering investment cost, maintenance cost, production cost, loss cost, and residual energy cost, and the energy loss cost reflected by piecewise linear approximation. Reference [35] studied generation expansion planning to expand the share of RE. This study developed a multi-objective (minimizing the total cost, maximizing generation at the peak load, and maximizing the contribution of RE) optimization model and analyzed the Brazilian case based on a scenario.

Other researchers have presented two-step decision-making methods. Reference [36] addressed the maximization of investor returns at the upper level and the maximization of social surplus at the lower level. In addition, Reference [37] suggested heuristic-based dynamic programming for expansion plans. The study in Reference [10] defined the GEP problem of a restructured power system reflecting multi-period uncertainty for facility investment decisions in terms of price maker and suggested a framework accordingly. Reference [1] presented a power generation expansion (PGE) model incorporating various low-carbon elements for low-carbon economic growth. For the scenario-based experiments considering a low carbon situation, a compromised modeling approach was used to reduce model complexity.

A study on the optimum operational strategy for a power producer considering the sales and purchasing of renewable energy certificates (REC)/CER, penalty cost, and capacity investment cost under the simultaneous regulation of the RPS and ETS systems has not yet been conducted. Specifically, most quantitative studies considering RPS or ETS were conducted from a country perspective (cost minimize) [38]. However, this study proposes a mathematical model for maximizing power producer profits. This is because the viewpoint of the study is likely to be more effective in achieving power producer sustainability, given that the role of private power producers is expanding.

3. An Operational Scheme Considering a Combined Regulatory Environment

This section examines the RPS and ETS mechanisms in Korea's power generation industry. It defines an integrated operational scheme for power producers under both regulations.

- Renewable Portfolio Standards (RPS)

Sixteen countries around the world implemented the RPS [39], and the Korean government made it mandatory for power producers with 500MW or more of generation capacity (18 companies in 2017) to supply a certain proportion of RE. Table 1 shows the yearly RPS target ratio in Korea's power generation industry.

Table 1. RPS target ratio. (RPS: Renewable Portfolio Standard).

Year	2017	2018	2019	2020	2021	2022	2023 on
RPS target ratio (%)	4	5	6	7	8	9	10

The government assigned the REC targets, calculated by multiplying the amount of electric power from NRE in the previous year and the yearly target ratio to power producers. REC targets are satisfied in three ways: self-generation, purchase of RECs in the market, or penalty payment. Figure 1 is a diagram of the RPS mechanism with the power producer in the center.

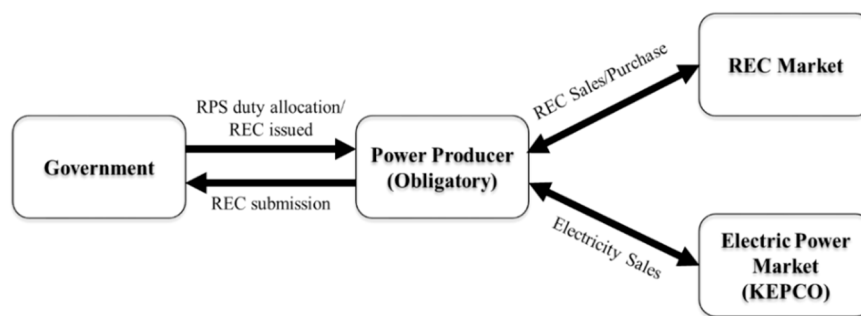


Figure 1. Diagram of the RPS mechanism. (KEPCO: Korea Electric Power Corporation).

As shown in Figure 1, power producers need to satisfy their obligations either by electric power generation using RE or by purchasing RECs in the market. To deal with the RECs themselves, the addition of RE capacity is necessary. However, since the investment cost for each RE source differs, the issue is that, if the same weight is given, the investment of power producers in a certain RE source can be biased. In order to prevent such biases, the Korean government has set REC weights differentiated for each energy source. Therefore, each power producer has to consider different weights when deciding how much of an energy source to add and which RECs to buy and sell in the REC market.

- Emissions Trading Scheme (ETS)

The Korean government has set a carbon emissions reduction target of 37% versus BAU by 2030, and it began implementing the ETS in January 2015. Because reduction goal in the power generation sector is very high according to the National Emissions Allocation Plan [7], the government assign the annual CERs to the power producers Figure 2 diagrams the ETS operation mechanism for power producers reflecting the situation described below.

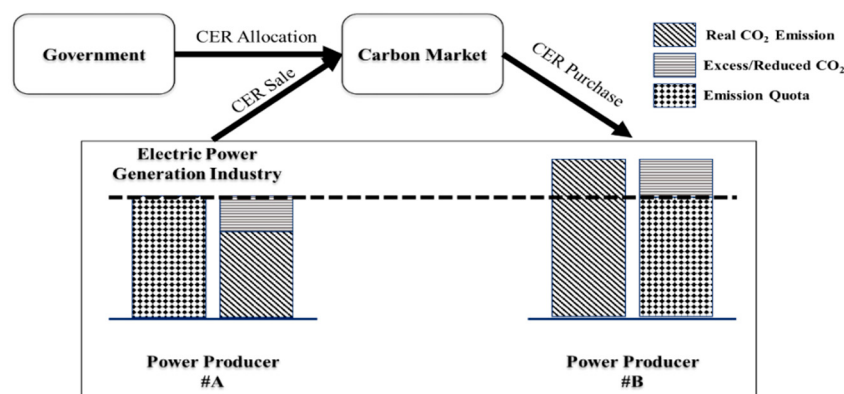


Figure 2. Diagram of the ETS mechanism. (ETS: Emissions Trading Scheme).

- Operational Scheme Considering a Combined Regulatory Environment

While most countries that implement RPS are obliged to supply RE to electricity sellers, Korea is uniquely obliged to supply each power producer because the government monopolizes the electricity market. Korea's power producers must comply with RPS duties and ETS emissions quotas. Therefore, a decision-making system that maximizes profits by considering REC/CER price changes, different power generation and operating costs for each energy source, new capacity investment costs, periodic obligations, and emission quotas is necessary. This study designed an operational scheme for Korea's power producers regulated by RPS and ETS simultaneously, shown in Figure 3.

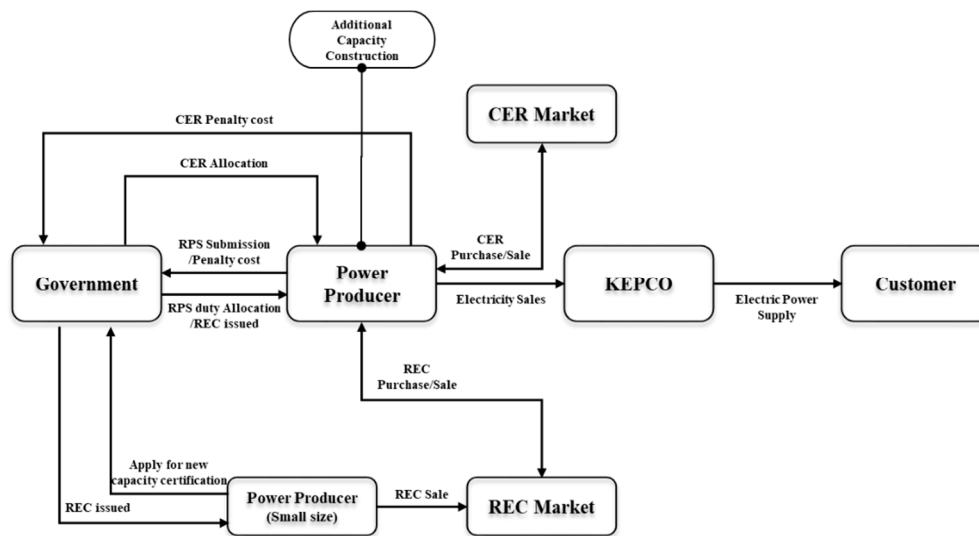


Figure 3. Integrated operational scheme for Korean power producers.

- Input Parameter Estimation for the Mathematical Model

For use as input values in the mathematical model, we first must estimate SMP, REC, and CER prices that change in the market.

First, this study uses the SMP estimation method in the previous study [40]. For REC and CER, forecasting is somewhat difficult due to the lack of existing data because the market operation period is short. Therefore, we use the average change rates of REC/CER to predict each price for the planning horizon to simplify parameter estimation.

Additionally, the total number of power producers considered in this study is 18 companies in Korea, which accounts for about 90% of Korea's total power generation capacity. This proportion (θ) will be a parameter to adjust the annual demand and emissions quota. For example, if the forecasting demand for 2018 is 100 TWh, the demand for power producers will be 90 TWh. These values are used as input values in our model.

4. Mathematical Modeling

4.1. Problem Structure and Definition

This study proposes a mathematical model based on mixed-integer linear programming to derive optimal operation strategies for Korea's power producers to maximize profit. Section 3 addressed the integrated operational scheme. The operational strategy corresponds to the value of the arrows derived from the power producers, composed of the decision variables of the proposed mathematical model. The decision variables are $X_{e,m,t}$, denotes the new generation capacity completed by each period, $x_{e,m,t,k}$, constructs the generation capacity of each period to achieve, and $X_{e,m,t}$ and $Y_{e,m,t,k}$, the binary variables for establishing the power generation plan. To calculate various revenue/cost values, the model uses the sale/purchase/non-fulfillment of REC and CER as variables. Figure 4 shows the structure of the problem proposed in this study. The blue variables have a positive effect on profit, while the red variables have a negative effect on profit.

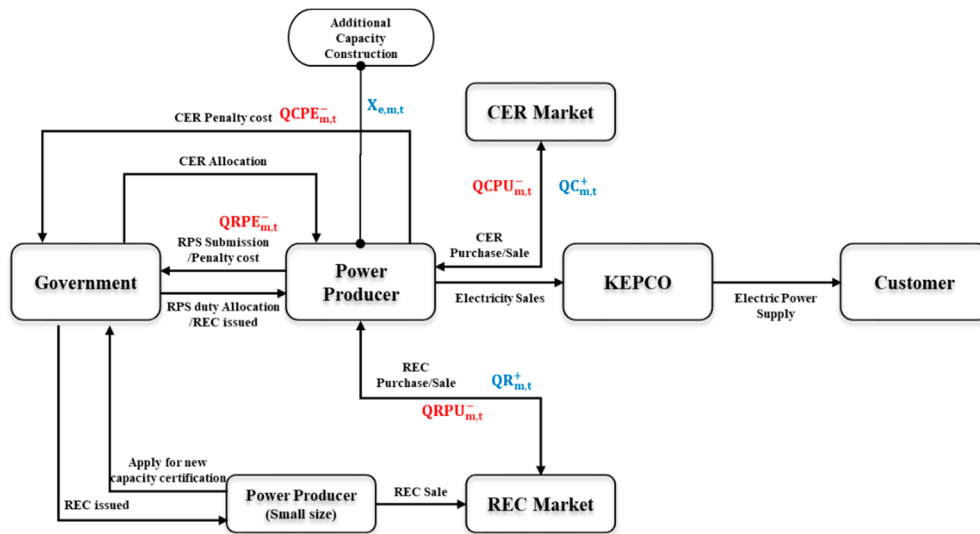


Figure 4. Problem structure.

4.2. Mathematical Model for Operational Strategy

This study uses the electricity demand and reserve margin of each planning period, based on data from the 7th basic plan for long-term electricity supply and demand [41]. This study considers 18 power producers (called M1 to M18) with capacities of 500 MW or more, which is the RPS standard. In addition, the capacity expiration and expansion plans included in the 7th basic plan are known, and power producers can sell their generated electric power to KEPCO, and the extra REC and CER can be sold to the market without limitation. However, this study assumes that the amount of additional REC/CER purchases are different depending on the size of the power producer. The annual unit generating and operating costs are known for all planning periods for each generation source [3,42–46]. Lastly, power plant expiration has not been confirmed in the 7th basic plan for the whole period, and the lifetimes of newly added power plants are not considered in this study.

4.2.1. Objective Function

The purpose of this model is to maximize the total profit of Korea's power producers. Power producers generate electricity to meet annual demand, sell it to KEPCO, and earn revenue by selling additional REC and CER. In terms of cost, additional costs for purchasing REC and CER, penalty costs, power generation and operation costs, and investment costs for new capacity expansion are taken into account. The objective function is expressed as Equation (1).

Minimize Total Profit (TP):

$$TP = \left\{ \sum_{m,t} (ES_{m,t} + QR_{m,t}^+ PR_t + QC_{m,t}^+ PC_t) \right\} - \left\{ \sum_{m,t} (QRPU_{m,t}^- PR_t + QCPU_{m,t}^- PC_t + REC_{m,t}^{pen} + CER_{m,t}^{pen} + GOC_{m,t} + Inv_{m,t}) \right\}. \quad (1)$$

To simplify the objective function, the model used the expressions such as $ES_{m,t}$, $REC_{m,t}^{pen}$, $GOC_{m,t}$, $Inv_{m,t}$ and calculated as follows:

$$ES_{m,t} = \varepsilon \sum_e Hr_e Eff_e Capa_{e,m,t} PE_t, \forall m, t \quad (2)$$

$$REC_{m,t}^{pen} = 1.5 PR_t \times \max(0, QRPE_{m,t}^-), \forall m, t \quad (3)$$

$$CER_{m,t}^{pen} = 3 PC_t \times \max(0, QCPE_{m,t}^-), \forall m, t \quad (4)$$

$$GOC_{m,t} = \varepsilon \sum_e (Hr_e Eff_e Capa_{e,m,t} genc_{e,t}), \forall m, t \quad (5)$$

$$\text{Inv}_{m,t} = \sum_e \sum_{k=1}^{t-1} (1 + \gamma)^{-k} (\text{IC}_e x_{e,m,t,k}), \forall m, t. \quad (6)$$

Equation (2) is the electricity sales of each power producer in period t , and Equations (3) and (4) are the penalty costs due to failing to achieve REC and CER targets. Equation (5) is the generation and operation cost of each power producer in period t , and Equation (6) is the investment cost for the expansion capacity.

4.2.2. Constraints

This chapter considers the following constraints.

$$\text{Capa}_{e,m,t} = \text{Capa}_{e,m,t-1} + X_{e,m,t} - \text{exp}_{e,m,t-1} + \text{add}_{e,m,t}, \forall e, m, t \quad (7)$$

$$\varepsilon \left(\sum_{e,m} \text{Hr}_e \text{Eff}_e \text{Capa}_{e,m,t} \right) \geq \theta (1 + \text{RM}_t) D_t, \forall t \quad (8)$$

$$x_{e,m,t,k} \leq \delta_e Y_{e,m,t,k}, \forall e, m, t, k \quad (9)$$

$$X_{e,m,t} = \sum_{k=1}^{t-1} x_{e,m,t,k}, \forall e, m, t \quad (10)$$

$$\sum_m X_{e,m,t} \leq \text{Capa}_{i \in e, t}^P, \forall i \in e, t \quad (11)$$

$$\text{Inv}_{m,t} \leq \text{Budget}_{m,t}, \forall m, t \quad (12)$$

$$\text{ETS}_{m,t}^{\text{Quota}} + \text{QC}_{m,t}^- = \sum_e (\text{Hr}_e \text{Eff}_e \text{Capa}_{e,m,t} \text{CF}_e) + \text{QC}_{m,t}^+, \forall m, t \quad (13)$$

$$\text{QCPE}_{m,t}^- + \text{QCPU}_{m,t}^- = \text{QC}_{m,t}^-, \forall m, t \quad (14)$$

$$\text{QCPU}_{m,t}^- \leq \text{CUL}_m, \forall m, t \quad (15)$$

$$\sum_{e,m} (\text{Hr}_e \text{Eff}_e \text{Capa}_{e,m,T} \text{CF}_e) \leq \sum_m \text{ETS}_{m,T}^{\text{Quota}}, \text{ where } t = T \quad (16)$$

$$\text{RPS}_{m,t}^{\text{Target}} \times \varepsilon \sum_{j \in e} (\text{Hr}_j \text{Eff}_j \text{Capa}_{j,m,t-1}) + \text{QR}_{m,t}^+ = \varepsilon \sum_{i \in e} (\text{Hr}_i \text{Eff}_i \text{Capa}_{i,m,t} \text{WR}_{i \in e}) + \text{QR}_{m,t}^-, \forall m, t \quad (17)$$

$$\text{QRPE}_{m,t}^- + \text{QRPU}_{m,t}^- = \text{QR}_{m,t}^-, \forall m, t \quad (18)$$

$$\text{QRPU}_{m,t}^- \leq \text{RUL}_m, \forall m, t \quad (19)$$

$$\sum_{i \in e, m} (\text{Hr}_i \text{Eff}_i \text{Capa}_{i,m,t} \times \text{WR}_{i \in e}) \leq \sum_m \left(\text{RPS}_{m,t}^{\text{Target}} \times \sum_{j \in e} (\text{Hr}_j \text{Eff}_j \text{Capa}_{j,m,t-1}) \right), \text{ where } t = T \quad (20)$$

$$\text{All variables are non-negative, } \forall e, m, t, k. \quad (21)$$

Equation (7) represents the cumulative capacity updating formula for each energy source by power producer and period, including new capacity to be completed during the period, planned capacity increases during the period, and expired capacity in the previous period. Equation (8) is a constraint for meeting demand, and Equation (9) represents the feasible expansion amount that can be added in period k . Equation (10) expresses that the sum, up to the amount of $(t - 1)$ period added by period k , is completed in t period. Equation (11) is used to set the RE potential capacity upper limit, and Equation (12) is an expression that shows the investment budget constraints for each company.

Equations (13) through (16) reflect the ETS policy. Equation (13) is the CER balance equation for each power producer. $\text{QC}_{m,t}^-$ denotes the CER shortage and expresses the sum of additional purchase

amounts and the penalty amounts from Equation (14). However, Equation (15) represents an upper limit on the number of additional purchases. Equation (16) expresses constraints on achieving the goals set by the country in the final year of the planning horizon.

Equations (17) through (20) reflect the RPS policy. Equation (17) is the REC balance equation for each power producer. $QR_{m,t}^-$ used in this equation means that REC shortage and can be expressed as the sum of the additional purchases and the penalty amounts given by Equation (18). Equation (19) is used to set an additional purchase upper limit. Equation (20) represents the constraints for achieving the goal set by the country in the final year of the planning horizon. Finally, Equation (21) implies that all variables used in this model should be non-negative.

Section 5 will perform scenario-based analyses, and the mathematical models applied to all scenarios are basically identical. However, this study can discover some differences in input parameters for each factor considered in each scenario, and the constraints may require changes. For example, consider Equations (22) and (23) below.

$$\begin{cases} X_{e,m,t} = 0, & \text{where } e = 10 \text{ and } m \neq 1, \forall t \\ X_{e,m,t} = 0, & \text{where } e = 8 \text{ or } e = 10, \forall m, t \end{cases}$$

Equation (22) is a constraint that makes it impossible for other companies to expand nuclear power plants, as nuclear power plant expansion in Korea is only possible for M1. Equation (23) is a restriction that makes it impossible to add new coal-fired and nuclear power plants.

5. Scenario-Based Analysis

This study examines how various factor changes affect the optimal operational strategy of power producers using the proposed model. First, we define four scenarios, and basic information for each scenario is shown in Table 2. In summary, Scenario 1 aims at creating a reference case by deriving operational strategy based on the current situation in Korea as an input value. Scenario 2 analyzes the impact of strengthening RPS duty ratio through nuclear and coal phase-out, and Scenario 3 aims to analyze the impact of tightening the carbon emissions regulations by increasing CER prices. Lastly, Scenario 4 is to analyze the impact of reaching the RE grid parity.

Table 2. Basic information for each scenario.

No	Description	Control Factor			
		Enhanced RPS Duty	Nuclear Option	CER Price	Generation Cost
SC1	Reference case	-	-	-	-
SC2	Nuclear and coal phase-out scenario: Considering strengthened RPS duty ratio	O	O	-	-
SC3	Impact of increasing the unit CER prices	-	-	O	-
SC4	Influence of reaching grid parity: Changing the generation and operation cost of RE sources	-	-	-	O

5.1. Input Data

In this model, it is assumed that the electricity demand and reserve margin in the entire planning horizon are already known, beginning in 2017 [41]. However, the demand is scaled using the initial generation capacity ratio of power producers under both regulations in Korea. (See Table 3)

The initial generation capacity data for each power producer is collected from the total generation capacity report. It is assumed a 3.59% transmission and distribution loss factor, constant during the entire period [43]. In addition, planned expanded and expired generation capacity amounts for each

power producer were gathered from the 7th basic plan [41], and the realizable potential of each RE source was obtained from previous research and statistics [42,47].

Table 3. Demand (TWh) and reserve margin (%).

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Demand (TWh)	498	522	544	563	580	597	612	627	642	657	671	684	698
Reserve Margin (%)	26.3	24.9	23.7	23.2	26.8	27.7	25.3	22.4	21.2	21.3	21.4	21.5	21.6

Next, the annual investment budget of each power producer during the planning horizon is deterministic. In this case, it is assumed that this value starts from 7% of initial sales and increases by an annual average of 3%. Data such as the capacity factor for each energy source, the investment cost per unit capacity addition, carbon emissions coefficients, generation and operation costs, and historical price data to use for estimation were collected from previous research [3,6,42,44–49] and the Electric Power Statistics Information System (EPSIS) (see Table 4) [43]. In scenario 4, considering the attainment of grid parity, it is assumed that the generation and operation costs of RE decrease linearly, lower than that of the lowest among NRE after 2021.

Table 4. Investment, capacity factor, generation and operation costs, and CO₂ emissions coefficient.

Type	Energy Source	Investment Cost (M KRW/MW)	Capacity Factor (h)	Generation and Operation Costs (KRW/MWh)		CO ₂ Emissions Coefficient (kgCO ₂ /MWh)
				Low	High	
Renewable Energy (RE)	Solar PV	3500	1314	65,000	271,000	33
	Wind	2500	2891	35,000	83,000	12
	Hydro	1170	4643	32,000	108,000	4
	Biomass	3500	7271	83,000	119,000	18
	Fuel cell	5680	7446	115,000	181,000	221
	Ocean	3824	1752	249,000	271,000	37
Non-renewable Energy (NRE)	LNG	620	6132	54,000	87,000	450
	Coal	540	7446	70,000	162,000	950
	Oil	1908	7621	114,000	129,000	680
	Nuclear	1562	7884	60,000	147,000	16

Lastly, the annual RPS target ratio uses the values specified in the regulations. Scenario 2 assumes a planned annual target ratio that can achieve 20% in the last period to reflect the government's intent to increase the proportion of RE through the implementation of a nuclear and coal phase-out roadmap (See Table 5).

Table 5. Strengthened RPS target ratio plan.

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
RPS Target Ratio (%)	4.0	6.0	8.0	10.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0

Table 6 shows the annual carbon emissions targets for the power generation industry, obtained by applying a linear interpolation method to the initial and final year target values.

Table 6. Total CO₂ emissions targets.

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
CO ₂ Target (MCO ₂ ton)	247	249	250	252	254	255	257	259	260	262	264	265	267

5.2. Results

5.2.1. Scenario 1: Reference Case

Figure 5 presents the amount of newly installed capacity of each energy source over the planning horizon. First, it seems that biomass generation capacity steadily expands, though the investment cost is high. This is because biomass generation is an attractive means to fulfill the RPS obligations, in that it has a higher capacity factor than other RE sources and can receive a REC. Second, wind and fuel cell generation tend to expand more after 2023, after most power producers have achieved their obligations. This preference increase is to improve profits by adding more energy sources with higher REC weights after eliminating the RPS penalty from not satisfying the RPS regulation conditions. Lastly, hydropower generation consistently increases. This happens because it has advantages such as low generation and operation costs, low carbon emissions, and RECs can be issued in the case of small-hydro generation.

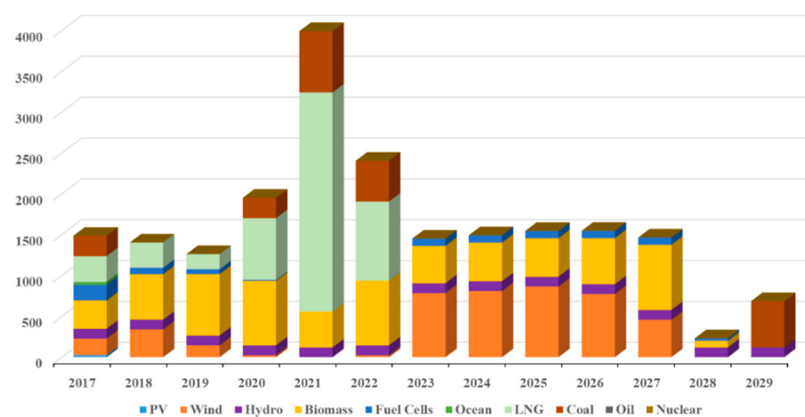


Figure 5. Newly installed capacity of each energy source in SC1.

Figure 6b presents the changes in capacity and generation share of RE/NRE from 2016 to 2029, respectively. In 2029, 12.6% of the power producer's total installed capacity will be comprised of RE sources, accounting for 9.7% of generation. In addition, the rates of capacity and generation increase from 2016 to 2029 show that RE increases more rapidly than NRE. As such, the government's regulations (RPS and ETS) have an effective impact on the expansion of RE proportion in the power producer's energy mix.

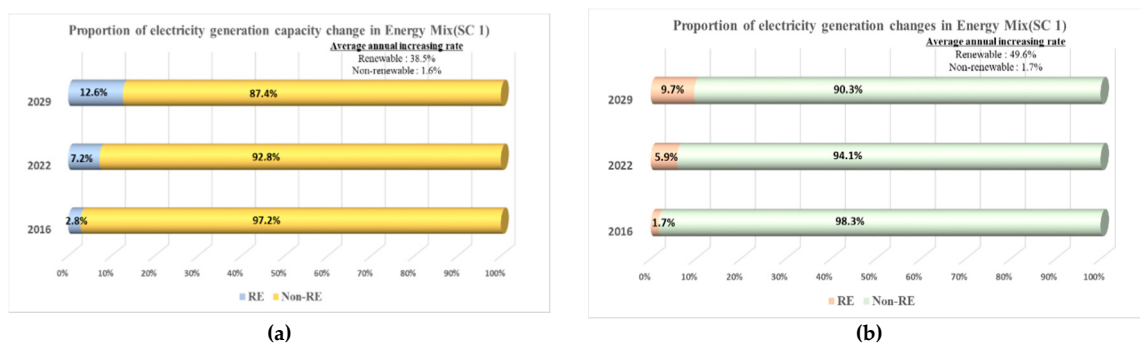


Figure 6. The proportion of RE/NRE capacity and generation. (a) Trends in the proportion of RE/NRE capacity (SC1); (b) trends in the proportion of RE/NRE generation (SC1). (RE: Renewable Energy, NRE: Non-renewable Energy).

The main purpose of this study was to derive an optimal operational strategy for each power producer. In order to analyze from each individual power producer's perspective, we created a power producer classification matrix. This matrix classified power producers into four types, with

initial RE capacity proportion and initial sales as two axes. Clockwise from the right top in Figure 7, the quadrants are defined as industry leaders (IL), reliable supporters (RS), industry followers (IF), and aggressive participants (AP). Characteristics of each segment are described in Table 7.

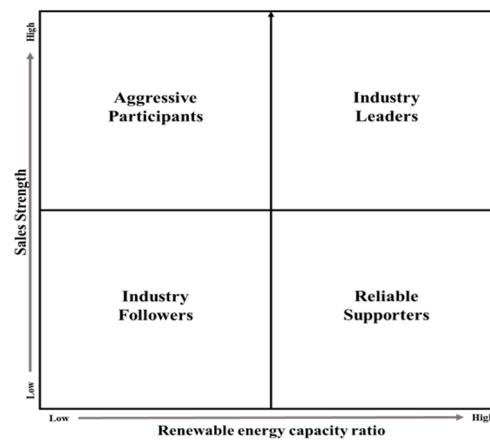


Figure 7. Power producer type matrix.

Table 7. Characteristics of each segment.

Segment	Characteristics
Industry Leaders	Power producers whose initial RE capacity proportion and initial sales are both high The group with the largest installed capacity share in the entire group
Reliable Supporters	Although initial RE capacity retention ratios are high, power generation is less than that of IL, and with lesser sales Power producers with a reliable response to government regulation
Industry Followers	The group with the largest number of producers Relatively low initial sales and initial RE capacity share Power producers who accommodate requests slowly to minimize the damage caused by government regulations
Aggressive Participants	The group with higher sales but low RE capacity retention ratio Power producers with a motive force to maximize profit through aggressive additional RE investments

In order to analyze the power producer's behavior in each segment, we first divided 18 power producers into four categories and analyzed the change in RPS duty achievement. First, since the IL segment has a large amount of installed capacity, it takes time to achieve RE duty. Therefore, instead of investing heavily in the early period, it also maximizes profits by combining appropriate long-term investment and profitable activities, such as selling electricity and excess CER.

The RS segment has a smaller generation capacity than the IL segment, and the RE capacity retention ratio is high, so they easily satisfy the RPS duty. Therefore, to minimize the penalty expenditure, they achieve the RPS duty from the beginning to maximize profits.

Finally, power producers in the IF segment usually maintain proper investment from the beginning, but it takes a while to achieve the RPS duty because of the low initial RE capacity retention ratio compared to the RS segment. Figure 8 shows the change of RPS duty ratio among 11 power producers in the IF segment. Unlike other power producers, M10 and M16 show a high achievement ratio from the beginning.

This is because M10 and M16 have larger sales per unit generation capacity (since they provide city gas or solar operations and maintenance business in addition to electric power generation) than other power producers in the same IF segment. This helped them pursue profit maximization through aggressive RE investments. Thus, it can be inferred that power producers with large sales per unit generation capacity (like M10 and M16) will be effective in maximizing profits by following the strategy corresponding to the AP segment because the same investment has a greater impact on the energy mix.

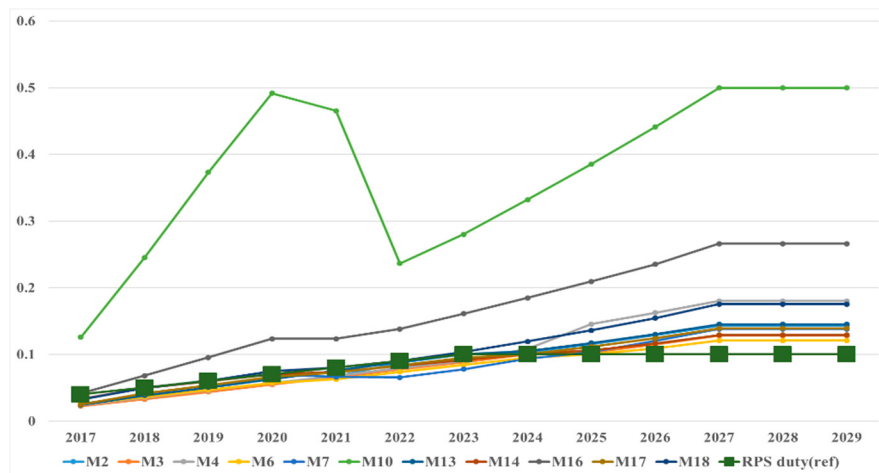


Figure 8. RPS ratio changes of each power producer in the IF segment.

A growing number of power producers will be regulated by RPS. Some of them will be able to make aggressive investments due to large sales, although the RE capacity ratio is low, and they are clearly distinguishable from the IF segment. Therefore, in order to consider such characteristics, it is more realistic and suitable to divide the group into four segments, as shown in Figure 9.

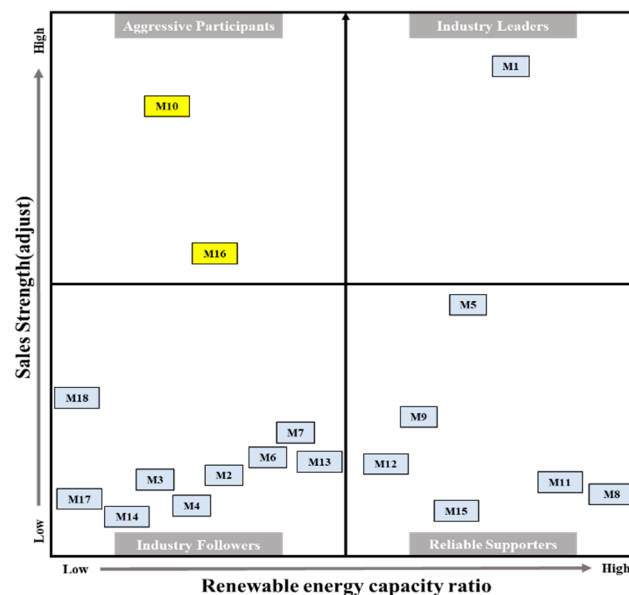


Figure 9. Power producer type matrix (adjusted).

5.2.2. Scenario 2: Nuclear and Coal Phase-out Scenario Considering a Strengthened RPS Duty Ratio

Scenario 2 considers the abolition of 6 nuclear power plants (totaling 8.8 GW) and 10 coal-fired power plants (totaling 3.34 GW), the prohibition on the addition of new nuclear and coal-fired power plants, and the strengthened RPS duty ratio as a constraint.

Compared with the reference scenario, this result shows the capacity of all RE sources increases more rapidly (see Figure 10). In particular, fuel cells with a higher REC weight are installed to meet the RPS duty ratio early on. In addition, wind and biomass generation capacity rise more than in the reference scenario. This indicates that RE sources, which can generate revenue through REC and can minimize penalties from excess carbon emissions, can play an alternative in a situation where nuclear power generation, which accounts for a very large proportion of the national energy mix and has very low carbon emissions, must be replaced. However, to meet the demand in the nuclear

and coal phase-out environment, there is a limit to the addition of solely RE sources. Thus, the new installation of competitive liquefied natural gas (LNG) generation capacities among NRE sources tends to increase quickly.

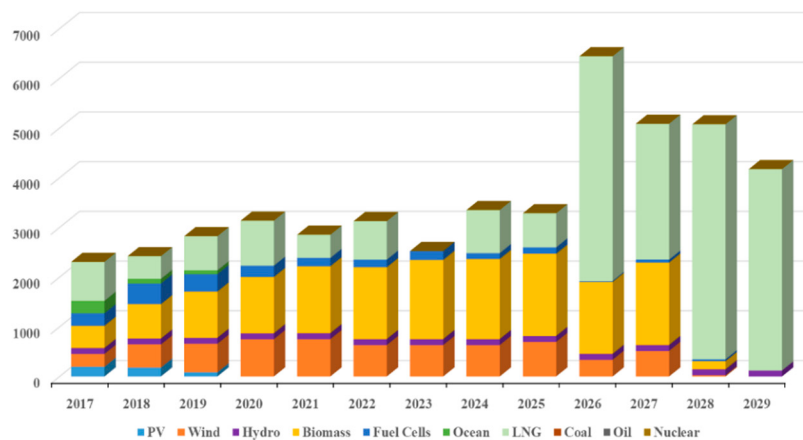


Figure 10. Newly installed capacity of each energy source in SC2.

Figure 11a,b shows that 20.8% of the total power producers generation capacity and 17.8% in terms of generation amount will be composed of RE sources in 2029 (see Figure 12). In addition, we increased the investment budget proportion by 15%, and most power producers tend to aggressively increase RE capacities to gain more REC sales. This tendency is most noticeable in the RS and AP segments. Furthermore, power producers with relatively large capacity in the IF segment continue to make better decisions between payment of penalties and additional investment in achieving their duties. In conclusion, in order to achieve the strengthened duty ratio, the government can use a policy that causes the IF segment (with the most power producers) to be more burdened with penalty payments. Additionally, the RS and AP segments, which are reliably responsive to government regulations, may apply supporting policies, such as loan interest benefits on investment expenditure.

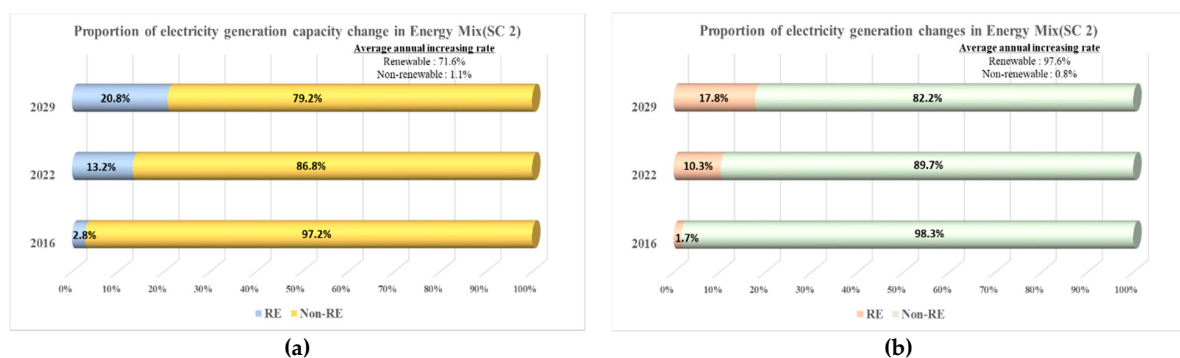


Figure 11. The proportion of RE/NRE capacity and generation. (a) Trends in the proportion of RE/NRE capacity (SC2); (b) trends in the proportion of RE/NRE generation (SC2).

5.2.3. Scenario 3: Impact of Increasing the Unit CER Prices

The CER price of Korea set in the reference scenario is somewhat low, and thus we considered this scenario with increasing CER price conditions (annual averages of 5%, 10%, and 15%) to more strongly regulate emissions. Ultimately, we examined how the power generation industry and power producers from each segment would react to such CER price increases.

First, the changes in RE/NRE generation amounts according to the CER price increases are shown in Figure 13.

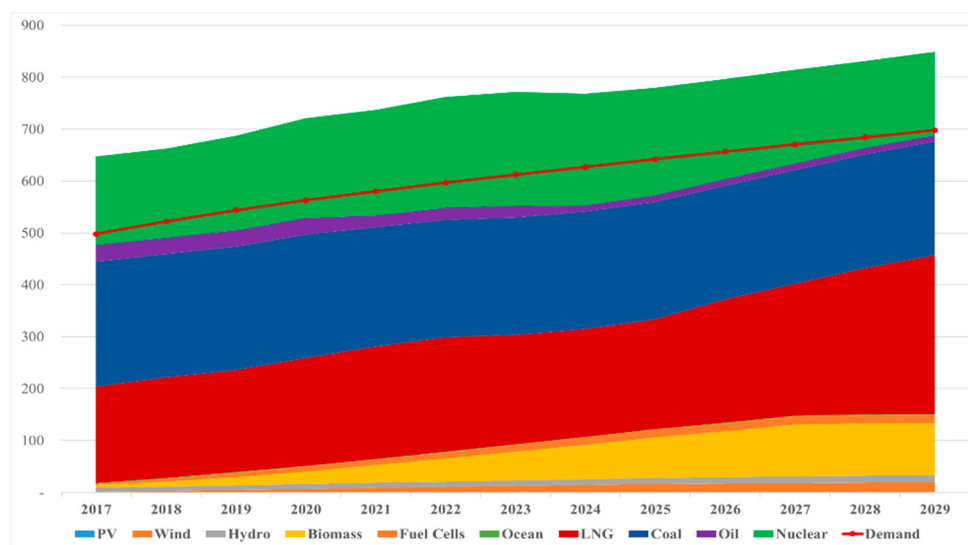


Figure 12. Power generation changes in SC 2 (TWh).

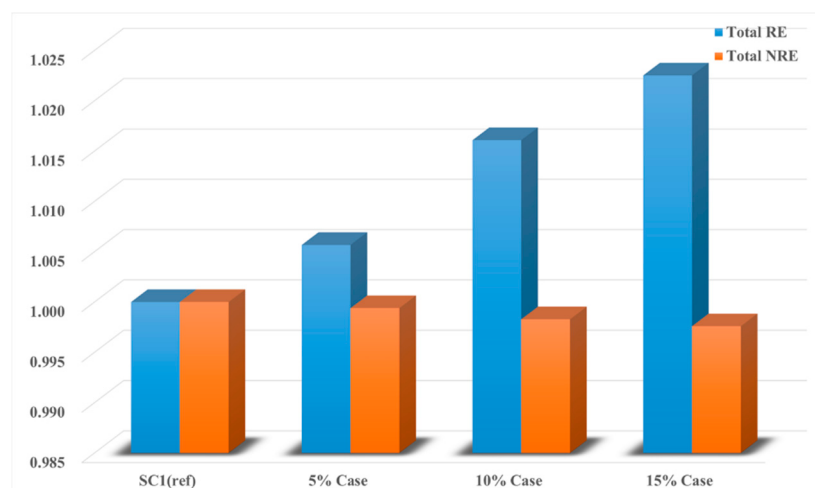


Figure 13. Power generation changes of RE/NRE considering CER price increases.

It shows the ratios of RE/NRE generation amounts by CER price increase level when the generation amount of the reference scenario is set to 1 in 2029. As the annual average increase rate rises, the total generation amount is the same in 2029, but the RE generation amount increases and the NRE generation amount tends to decrease. For instance, at an annual average CER price increase of 15%, the RE generation increases by 1800 GWh compared to the reference scenario, close to the amount of solar generation capacity (1400 MW). However, the generation capacity represents only a 0.1% difference. This means that power producers with the same energy mix will pursue a different power plant utilization strategy according to the CER price change.

Figure 14 shows the changes in RE/NRE generation changes for each segment according to the CER price change when the reference scenario power generation is set to 1 in 2029. As the price increase rate rises, the NRE power generation tends to decrease. Table 8 shows the actual generation (TWh) with CER price changes according to representative companies in each segment. In summary, since the IL segment accounts for a large share of the total installed capacity, additional NRE generation, the amount that is reduced by the power producers of other segments, tends to happen to satisfy the demands. In addition, the AP segment shows a tendency to increase the RE generation amount most sensitively as the CER price increases. Meanwhile, the RS segment steadily increases RE generation as the CER price increases, for up to a 5% increase, and the power producers of the IF segment do

not increase RE generation due to the small penalty, but they start responding at the 10% increase level. Therefore, a more effective approach would be to apply differentiated penalty rates to each segment, divided into more than and less than certain emissions amounts, at current low prices of the CER market.

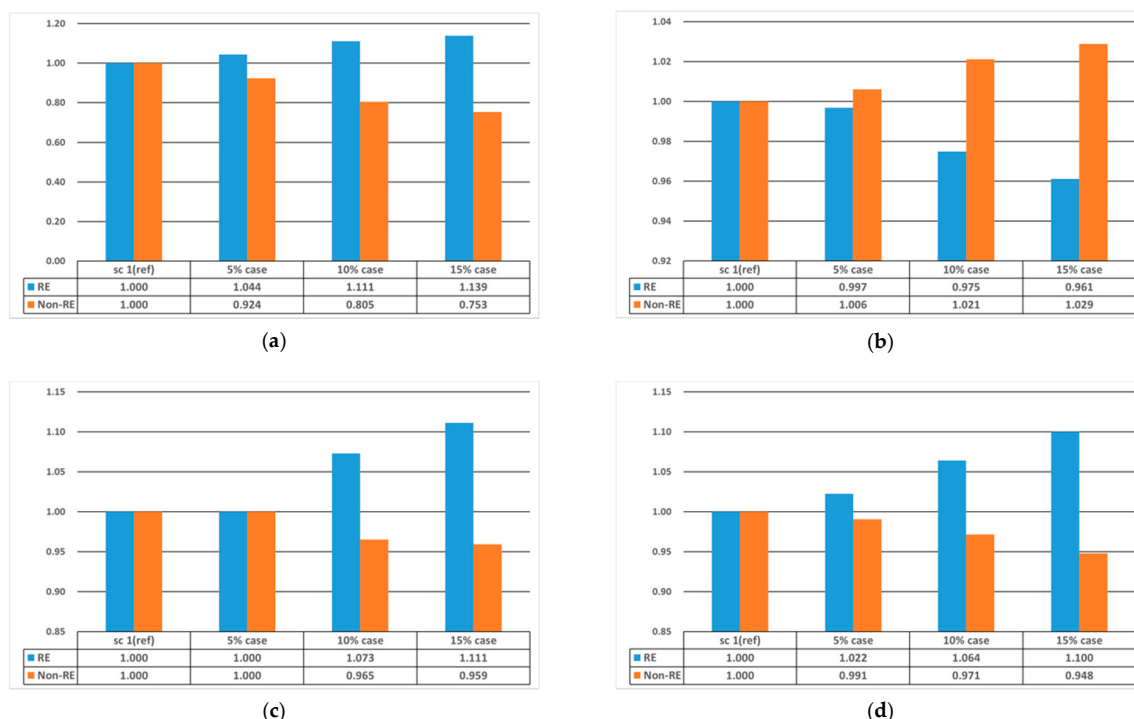


Figure 14. RE/NRE power generation changes with CER price increases in: (a) AP segment (M10); (b) IL segment (M1); (c) IF segment (M18); (d) RS segment (M5).

Table 8. RE/NRE power generation (TWh) with CER price changes for each segment.

RE/NRE Generation (TWh)		Scenario 1 (Reference)			5% Case			10% Case			15% Case		
		2017	2023	2029	2017	2023	2029	2017	2023	2029	2017	2023	2029
M1	RE	3.42	11.26	21.53	3.42	10.88	21.46	3.42	9.68	20.99	3.42	9.18	20.69
(IL)	NRE	174.4	262.1	310.7	174.4	264.2	312.6	174.4	269.7	317.3	174.4	272.6	319.7
M5	RE	1.65	5.27	8.38	1.65	5.46	8.56	1.65	5.77	8.92	1.68	6.07	9.21
(RS)	NRE	72.03	75.54	75.54	72.03	74.84	74.84	72.03	73.39	73.39	71.63	71.63	71.63
M10	RE	0.45	5.74	5.74	0.45	3.49	5.99	0.45	3.87	6.38	0.45	4.03	6.54
(AP)	NRE	5.85	15.62	15.62	5.85	14.44	14.44	5.85	12.57	12.57	5.85	11.76	11.76
M18	RE	0.18	1.41	1.41	0.18	0.88	1.41	0.18	0.96	1.52	0.18	0.97	1.57
(IF)	NRE	10.14	10.88	10.88	10.14	10.88	10.88	10.14	10.5	10.5	10.14	10.43	10.43

Next, we examine the emissions intensity trend (tCO_2/MWh) according to the CER price change from the power generation industry and power producer's side.

The IL segment, which accounts for more than 20% of total capacity, is the group with the highest reactivity according to the increase in demand, and the emissions intensities of companies in that group are similar to the increase in demand. The RS segment also shows an increase in emissions intensity versus the same year as CER price increases. What is unusual is that, even if the CER price increase rate rises, the emissions intensity increases. This has a logical explanation: the NRE generation capacity of the IL and RS segments increases to compensate for the decrease in NRE generation caused by the decrease in the AP and IF segment emissions (see Figure 15, Figure 16a–d).

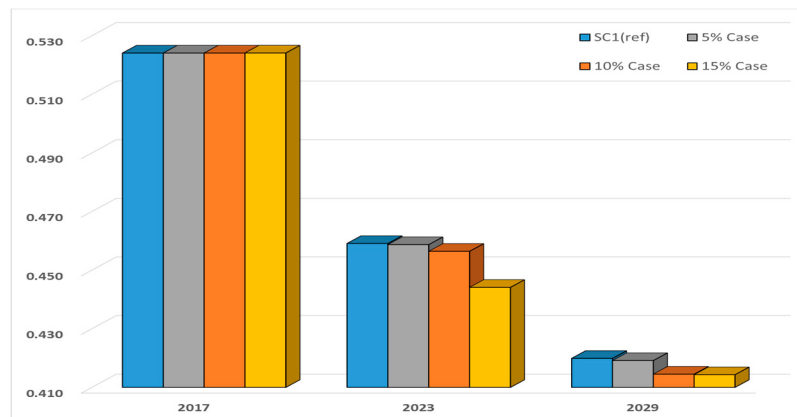


Figure 15. Changes in the emissions intensity (tCO₂/MWh) of the power generation industry with CER price increases.



Figure 16. Changes in the emissions intensity (tCO₂/MWh) with CER price increases in: (a) AP segment (M10); (b) IL segment (M1); (c) IF segment (M18); (d) RS segment (M5).

Next, we examined the change in the RPS duty ratio with CER price changes for each segment. Figure 17 shows the yearly RPS target ratio, and that the level of achievement differs for each segment. The AP segment presents the greatest increase in RPS ratio, and both the IF and RS segments increase steadily beyond the RPS target ratio. On the other hand, the IL segment is close to the target in the latter half of the planning horizon, and even if the CER price increases, it does not reach the goal. This can be understood in the same manner as for the emissions intensity and it is a phenomenon caused by the fact that power producers with a large share in the whole industry have to compensate for the decrease in NRE generation because of the increase in the RPS ratio of the remaining segments. This indicates that the government should not set RPS targets in a lump sum regardless of the power producer's type, but that differentiating the regulatory level based on capacity size and RE/NRE generation will be more effective in achieving the RPS goal.

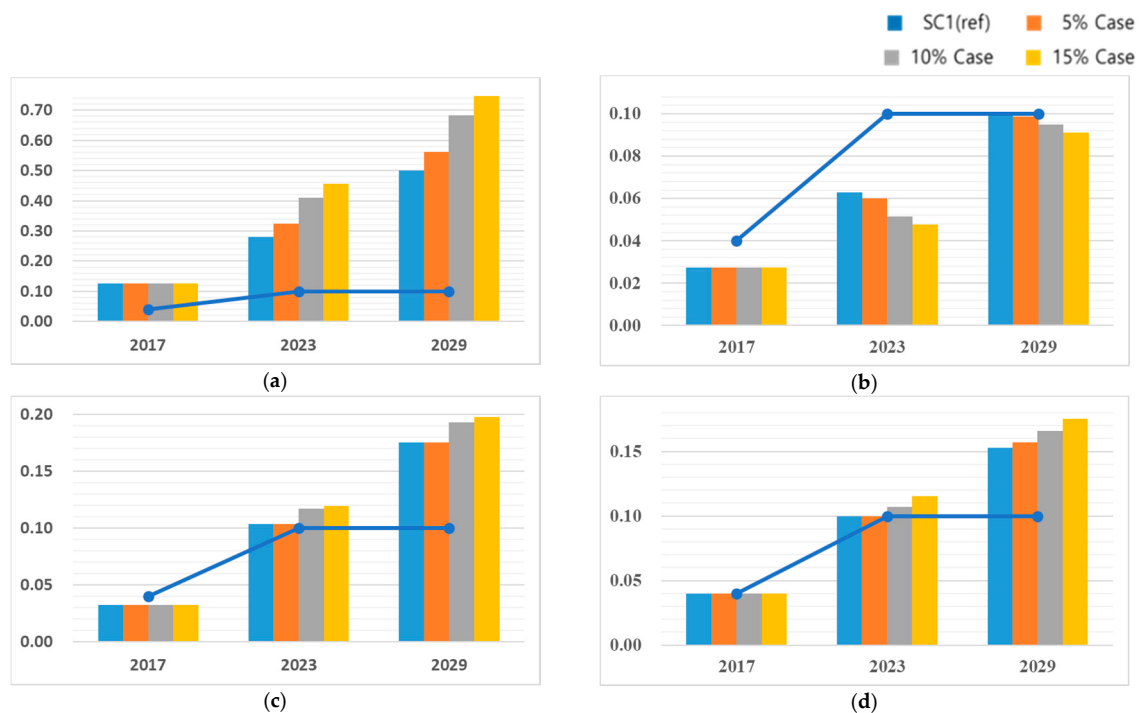


Figure 17. RPS ratio changes with CER price increases in: (a) AP segment (M10); (b) IL segment (M1); (c) IF segment (M18); (d) RS segment (M5).

In addition, except for SC2, achieving RPS targets through PV capacity expansion are rarely executed. It is due to the low capacity hours, low power generation efficiency and high generation and operation cost caused by the low amount of sunlight in Korea. Therefore, policy support (increasing power generation subsidies, improving REC weights, etc.) is needed to make the power producers consider solar energy as an attractive generation capacity expansion option in the future.

5.2.4. Scenario 4: The Influence of Reaching Grid Parity by Changing the Generation and Operation Costs of RE Sources

In the early stages of the planning horizon, the generation and operation costs of RE are higher than those of NRE, so there is a tendency to expand coal and LNG, which are both economically superior to other sources, and the RPS duty ratio is achieved primarily by using biomass and small hydropower. After reaching grid parity, profits seem to be created by increasing new capacity investments in fuel cells with high REC weights in order to maximize the cost-benefit of RE (see Figure 18).

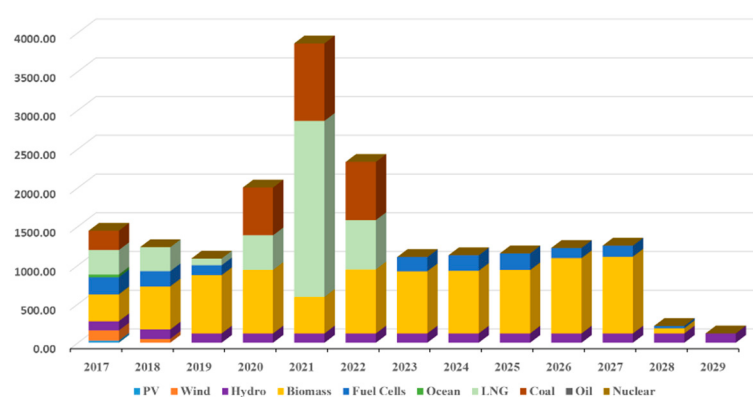


Figure 18. Newly installed capacity of each energy source in SC4.

Next, we checked to see how the RE/NRE generation capacity and power generation changes compare to the reference scenario. In terms of generation capacity and amount of generation, there is no difference from the reference scenario by 2022, but the proportion of RE generation exceeds 10% by 2029. In particular, the proportion of RE capacities decreases but the proportion of RE generation amount increases (see Table 9). This implies that power producers follow different utilization rates for RE/NRE capacity under the same energy mix after reaching grid parity. In this case, the increase in the RE capacity utilization rate is the force that drives up SMP prices. In other words, if grid parity is attained and the RE capacity utilization rate is increased, the profitability deterioration problem of power producers caused by SMPs being too low can be solved. However, when grid parity is attained without adopting the nuclear and coal phase-out option, it is difficult to attain an RE capacity and generation proportion of 20% or more nationally. This implication should be considered when the government intends to increase the RE proportion to achieve sustainability in the national energy mix.

Next, Figure 19 shows how the profit of each segment's representative power producers changed in the same year versus scenario 1. Profits are calculated as profit per MWh to compare on an equal basis, not on a total profit basis. Our results show that the AP segment shows the greatest profit increase per MWh during the planning horizon, as it further strengthened its aggressive investment propensity previously shown in the reference scenario. The IL segment shows a different behavior: a relatively small increase in profits, due to its role in supporting the industry.

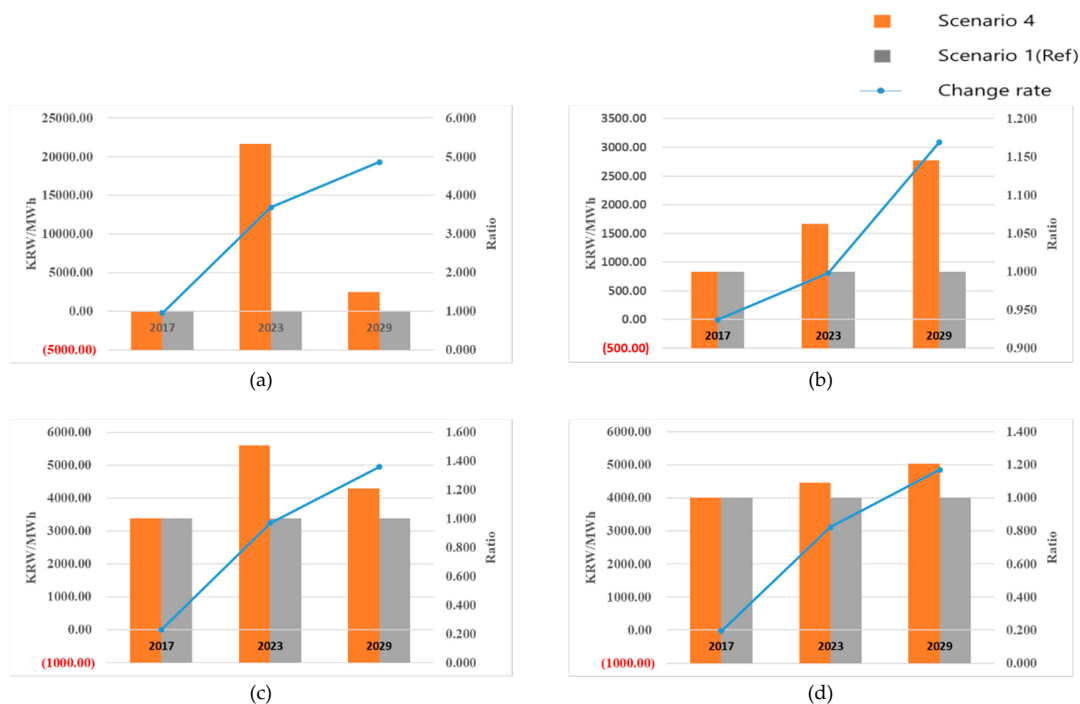


Figure 19. Profit change amount (KRW/MWh) and rate (%) of: (a) AP segment (M10); (b) IL segment (M1); (c) IF segment (M18); (d) RS segment (M5) (compared to SC1).

Table 9. Comparison of the ratio of RE/NRE by scenario (SC1 and SC4).

Year	Scenario 1 (Ref)				Scenario 4			
	% of Electricity Generation Capacity(A)		% of Electricity Generation(B)		% of Electricity Generation Capacity(A)		% of Electricity Generation(B)	
	RE	NRE	RE	NRE	RE	NRE	RE	NRE
2016	2.8	97.2	1.7	98.3	2.8	97.2	1.7	98.3
2022	7.2	92.8	5.9	94.1	7.1	92.9	5.9	94.1
2029	12.6	87.4	9.7	90.3	11.4	88.6	10.2	89.8

6. Discussion and Conclusions

6.1. Discussion and Political Implications

To enable the future power generation industry in Korea to operate in a sustainable and eco-friendly manner, this study derived optimal operational strategies for each power producer under the governmental policies (RPS and ETS). It considered 10 energy sources (six types of RE, four types of NRE) and 18 power producers under both regulations, and developed a mathematical model that included actual policy constraints along with other generation-related constraints. This study formulated the mathematical model intended to maximize the total profit for power producers, and to determine the capacity expansion plans, sales/purchase amounts of REC/CER, and penalty levels. Additionally, a scenario-based analysis was conducted to derive the optimal operational strategy for each power producer based on the scenario design that considered four different influential factors. Furthermore, this study proposed a matrix to analyze the behavior of each power producer in detail. The proposed matrix classified the types of power producers and analyzed how the influential factors of each scenario affect the strategies of power producers in each segment. Based on the analysis, this study drew some meaningful insights. First, the scenario-based analyses show that small hydropower generation adopts steadily, so it is necessary to consider the support policies specializing in small hydropower generation or policies that encourage technological research and the development for expanding realizable potential generation capacity. In addition, in order for the government to more rapidly increase the proportion of RE sources, it is worth targeting the IF segment, to which most power producers belong. Only for those IF segment's power producers that continue to make more favorable decisions between paying penalties and additional capacity investments to accomplish their RPS duties, the government will be able to set policies that increase the penalty rate from the beginning of the regulation to drive IF's decisions toward additional capacity investments. In addition, in the case of the RS and AP segment power producers that are faithfully responding to government regulations, it is possible to consider policies such as loan interest rate benefits and preferential treatment of REC weights depending on the number of successive years of achieving duty.

Plus, in terms of strengthening the carbon emissions regulations, the CER price, which is currently 20,000 KRW per unit CER, does not fulfill the effective regulatory function for reducing the carbon emissions of the power producers. However, the CER price cannot be intentionally increased. Thus, in order to achieve the national goal, the government must be able to establish policies for grading power producers according to the amount of power generation and applying differentiated penalties rate to each grade. Finally, this study expected that attaining grid parity can solve the power producer profitability deterioration problem caused by SMPs that are too low. However, reaching grid parity was not sufficient to achieve RE generation amounts greater than 20%. Therefore, the solution for this problem should contain the nuclear and coal phase-out roadmap, or the development of facility designs and generation technologies that are not biased toward one or two generation sources. In addition, if a power producer invests in energy sources with high investment costs and REC weights, greater support policy should provide for maximizing the effect of reaching grid parity. These insights are important implications that must be considered in order to maximize the effectiveness of the policy-making process and to enact policy that ensures the future sustainability of the national power generation industry. Additionally, in our analysis, one significant conclusion is that, for accomplishing the regulation goals at the national level and for achieving the sustainability of Korea's future power industry, implementing different policies that consider characteristics of each segment is more effective than implementing identical policies for every segment.

6.2. Limitations and Future Research

Despite the above implications, this study has some limitations. First, the research that determines the future energy mix of a country or a company needs to consider the electricity supply and demand uncertainty that changes over time. Our study does not take this into consideration because it mainly

aims at analyzing the operational strategies and behaviors of power producers under the RPS and ETS regulations. Second, some assumptions and parameter estimation methods described in this study make the model impractical. In particular, some parameters were inevitably estimated and used in the model due to the limitations regarding available data and data collection.

For future research, it is necessary to overcome these limitations. Such a study must consider uncertainties such as generation and operation costs and price data (for SMP, REC, and CER) to make the model more realistic. In addition, if the technical constraints associated with electric power generation were to further enhance and parameters were to be standardized to make it possible for their more accurate use, the results of our operational strategy optimization model will then become more reliable and more useful. In addition, in order to address various situations from the power producer perspective, it is necessary for the scenario-based analyses to consider fluctuations in electric power demand and fuel prices. Finally, the model could enhance by adding more sophisticated constraints regarding the RPS and ETS regulations.

Author Contributions: D.S. wrote the manuscript and participated in all phases. J.K. participated in scenario-based analysis and reviewed the related literature. B.J. conceived the theme of this study, guided the whole research process, and responded to the reviewers. All authors have read and approved the final manuscript.

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Abbreviations

RPS	Renewable Portfolio Standard
ETS	Emissions Trading Scheme
GHG	Greenhouse Gas
NRE	Non-renewable Energy
RE	Renewable Energy
CER	Carbon Emissions Reductions
REC	Renewable Energy Certificates
GEP	Generation Expansion Planning
BAU	Business as Usual
KEPCO	Korea Electric Power Corporation
EPSIS	Electric Power Statistics Information System
SMP	System Marginal Prices
LNG	Liquefied Natural Gas
IL	Industry Leaders
RS	Reliable Supporters
IF	Industry Followers
AP	Aggressive Participants

Indices

e	Power generation source index ($e = i \cup j, e = 1, 2, \dots, 10$)
i	Renewable energy (RE) source index ($i = 1, 2, \dots, 6$)
j	Non-renewable energy (NRE) source index ($j = 7, 8, 9, 10$)
m	Power Producer (PP) index ($m = M1, M2, \dots, M18$)
$t(\leftrightarrow k)$	Time Horizon (2017($t = 1$)~2029($t = T = 13$), 2029: Target year)

Decision Variables

$X_{e,m,t}$	New generation capacity of energy source e of each power producer in period t (MW)
$x_{e,m,t,k}$	Constructed new generation capacity of energy source e of each power producer in period k to complete in period t (MW)
$Y_{e,m,t}$	1 if the capacity expansion of energy source e is considered for each power producer in period k to complete in period t ($\in \{0,1\}$)
$QR_{m,t}^+$	Sales amount of Renewable Energy Certificate (REC) of each power producer in period t

$QRPU_{m,t}^-$	Additional purchasing amount of REC of each power producer in period t
$QRPE_{m,t}^-$	Non-fulfillment amount of REC of each power producer in period t
$QC_{m,t}^+$	Sales amount of Carbon Emission Reduction (CER) of each power producer in period t
$QCPU_{m,t}^-$	Additional purchasing amount of CER of each power producer in period t
$QCPE_{m,t}^-$	Non-fulfillment amount of CER of each power producer in period t
Parameters	
$add_{e,m,t}$	Planned expansion capacity of energy source e of each power producer in period t (MW)
$Budget_{m,t}$	Budget limitation of each power producer for capacity expansion in period t (KRW)
$Capa_{iee,t}^p$	Potential expansion capacity of energy source i in period t (MW)
$Capa_{e,m,0}$	Initial generation capacity of power producer of each energy source e (MW)
CF_e	CO ₂ emission coefficient of energy source e (kgCO ₂ /MWh)
CUL_m	Upper limit of additional purchasing amount of CER of each power producer in period t (tCO ₂)
D_t	Electric power demand in period t (MWh)
Eff_e	Power generation efficiency of energy source e (%)
$ETS_{m,t}^{Quota}$	CO ₂ emission limitation of each power producer in period t (tCO ₂)
$exp_{e,m,t}$	Planned expired capacity of energy source e of each power producer in period t (MW)
$genc_{e,t}$	Power generation and operation cost of energy source e in period t (KRW/MWh)
Hr_e	Annual generating hours of energy source e (hour)
IC_e	Investment cost of unit expansion capacity of energy source e (KRW/MW)
M	Big M
PC_t	Predicted CER in period t (KRW/MWh)
PE_t	Predicted SMP in period t (KRW/MWh)
PR_t	Predicted REC in period t (KRW/MWh)
RM_t	Reserve margin in period t (%)
$RPS_{m,t}^{Target}$	RPS target ratio of each power producer in period t (%)
RUL_m	Upper limit of additional purchasing amount of REC of each power producer in period t (tCO ₂)
WR_{iee}	Weight of REC issued of renewable energy source i
Γ	Interest rate (%)
δ_e	Available constructed capacity of energy source e in each period (MW/year)
ε	Net ratio of transmission and distribution
Θ	Capacity proportion of power producer (obligatory) compared to total capacity (%)

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