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Analysis on Renewable Energy Certificate Market in Korea Based on Simulation Models

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Abstract

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Following the global trend of reducing carbon emissions to prevent further effects of global warming, the Korean government announced the "Implementation plan of Renewable Energy 3020" to increase the national share of renewable energy (RE) and decrease carbon emissions in the country. The Renewable Portfolio Standard (RPS) is one of the policies designed to achieve the Renewable Energy plan, forcing some large electricity generators to generate a certain amount of power from renewable energy sources. The Renewable Energy Certificate (REC) is a certification that demonstrates a supplier generated 1 MWh of electricity with RE sources, which can then be traded and used to satisfy the requirements of RPS participants. Since the REC market appeared attractive to investors, as the government encouraged renewable energy, the problem of price decline due to oversupply occurred in the spots of the REC market.

In this study, five simulations were generated concerning the REC market, with one base scenario prediction and four alternative scenarios, using a multi-agent simulation approach. Our base scenario predicted that the current system would fail to achieve the goal in 2030. Among the alternative scenarios, adjusting the conditions of increased share, entry delay, and self-generation limit, we revealed that the market must be accomplished with less limiting conditions in the first periods. However, although policy changes in late periods do not make the policy possible to attain the goal in 2030, we observed that they could relay some positive signals to encourage potential investors to enter the market.

Although there are some acknowledged limitations, this study shows that the prediction of macro-level results of the REC market can be accomplished with micro-level decisions of supplying and demanding agents in the market.

Keywords: Renewable Portfolio Standard, Renewable Energy Certificate, Multi-agent simulation, Implementation plan of Renewable Energy 3020

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Chapter 1. Introduction

1.1 Research Background

As a result of the obvious effects of global warming, it has been recognized that our modern human civilization based on fossil fuels is producing an excessive amount of green-house gases which is subsequently destroying the ecosystem of the Earth. The Paris Agreement of 2015, wherein 195 countries around the world agreed to not allow the global temperature to increase more than 2 Celsius per year, is one of the actions following global demands to decrease carbon emissions. Making a transition in our energy consumption from fossil fuel-based energy to the green energy is unquestionably a global trend.

In this context, as it is clear that the successful development of renewable energy technologies will reduce carbon dioxide emissions by replacing fossil fuels in the power generation industry with economic feasibility in some technologies (Abolhosseini, Heshmati, Altmann, 2014), the government of Republic of Korea announced the "Implementation plan of Renewable Energy 3020". The government emphasized that the share of renewable energy generation in Korea is quite low in comparison to other major countries like Germany, the United Kingdom, France, Japan, and the USA, and most of the share of existing sources of RE generation in the nation consist of waste and bioenergy. The goal of the 3020 plan is to increase the share of the electricity generation based on RE, which was just about 7% in 2016, to at least 20%. Another goal of the plan is to build more than 95% of new RE generation plants in solar and wind power generation resulting in more than 85% of RE generation from solar and wind, which the Korean government particularly selected as “Clean Energy” out of all renewable energy options. The focus of this paper is the first goal of the plan, generating 20% of total generation capacity with RE energy sources.

To promote the increase of electric generation from RE energy sources, since 2012, the Korean government has enforced Renewable Portfolio Standard (RPS), compulsorily requiring electricity suppliers with a generation facility capacity of over 500MW to supply a certain percentage of generated electricity with renewable energy. Suppliers’ quota began as 2% in 2012, and increased to 7% in 2020. To achieve the goal of 20% RE generation in total, RPS requirements is planned to reach 28% by 2030.

The Renewable Energy Certificate (REC) is a certification that demonstrates a supplier’s generation of electricity from renewable energy sources and is given for every 1MWh of generated electricity. Suppliers can select to generate electricity independently or to buy REC from other, small-scale, suppliers to satisfy the quota.

In Korea, there are two markets in which REC can be traded; the spots market and the contract market. There are several differences between two markets. First, the contract market is where private generators can sell their REC combined with electricity, which is priced based on System Marginal Price (SMP) for 20 years, with fixed price by the contract, which is held only twice a year by the government. It can also be held randomly by each RPS participant when they choose.

Conversely, only the RECs are traded on the spots market, which is held by the government twice per week. In this market, the trades occur following the rule of supply and demand. As mentioned above, since the Korean government is encouraging RE generation, particularly through solar and wind energy, the RE electricity market appears to be an attractive market for the investigation of public operators. In addition, with the price decrease of solar panels to generate electricity and less difficulty in geographical conditions in comparison to wind power generation, a number of small-scale public solar power generators entered the market and started to supply REC. As a result, starting in 2017, REC supply started to exceed mandatory demand and the price began to fall.

As the price of the spots market decreased by more than 65%, the profitability of public generators faced critical challenges and arguing that the government should protect sustainable profits since the government encouraged people to participate the market to achieve the goal of 20% RE generation in total when announcing the implementation plan. To solve the problem, the Korean government chose to accelerate the increase of obligatory quota beginning in 2021, advancing the future plans by 1 year. It had been planned to increase 1%p per year, making the scheduled mandatory share of RPS participants in 2021 8% of total generation capacity initially, but this was adjusted upward to 9%.

As selling REC on the market is one of the main sources of profit for public generators, the falling price of the current market can cause critical institutional damage. Also, in such situation, generating renewable energy and selling REC to RPS participants would cease to be an attractive business model for potential investors. As a result, if there are not enough new entrants in the market, there would be possibility of a lack of supply in the future market, as the RPS requirements will continue to increase at an accelerated rate annually until the mandatory share of RPS participants reaches 28% in 2030. It is necessary for the government to ensure that the market will have enough economic efficiency to provide the continuous investment of public generators to reach the policy's goals. Forecast of the price of REC and supply in the market will provide useful information for the government to practically address this challenge.

1.2 Research Purpose and Method

Given these circumstances, this study proposes to forecast the future spots market price of REC and simulate whether there would be any problem to achieve the government's goal of 20% of RE generation in total, 28% in RPS, as scheduled.

Research goal 1: Forecast the price of the REC market to determine whether the current system will successfully achieve the goal of RPS in 2030.

If it is revealed to not to be on track to achieve the goal, this study also aims to determine some alternative policies that the Korean government can adopt to attain the goal.

Research goal 2: Pursue alternative policies if it is determined that the current system is not on track to achieve the goal of RPS in 2030.

This study will simulate the REC trading market of the Republic of Korea using a multi-agent simulation (MAS) built with python programming. In the study, mandatory suppliers will be cast as the buyer agents and public generators will act as supplier agents in the REC market simulation. Although the complex interactions and interdependencies between electricity market participants are similar to those studied in game theory, they are often too complex to be managed with the application of traditional game theory (Picker, 1997). Since agent-based simulation is a method focused on "clarity through simplicity" (Sallach and Macal, 2001), we expect that the simulation will be able to intuitively forecast the future of the market. Such characteristics can also make MAS meaningful, as there are arguments that cloud marketplaces similar to those of electricity, water, and stocks cannot adapt to changing market conditions (Breskovic, Altmann, and Brandic, 2012).

In the study, the literature review explores agent-based simulations as applied in various economic contexts, including the traditional market, the electricity market, and emissions trading schemes to demonstrate the usefulness of simulation tools for application to economic research. Using a MAS, this study will test various scenarios based on adjustments to RPS policy conditions and compare the results to produce insights to support the research goals of this study.

The empirical data of past market conditions is collected from a renewable one-stop information portal that is operated by the Korean government.

1.3 Outline of the Study

This study consists of five chapters. In chapter 2, an overview of the Renewable

Portfolio Standard policy and Renewable Energy Certificate will be provided, along with information on the current market system wherein the REC is being traded. Literature reviews regarding the Korean REC market's price change and price prediction, and research on agent-based simulations in various economic contexts will also be presented in the chapter.

Chapter 3 provides a description and rationale for the MAS used in this study. Displaying the pseudo codes of the simulation will present the logic behind how the simulation is coded and a flow chart is also provided for computational pricing sequence, supply and demand side agents and potential investors' decision logic, to help uncover how and in what situations the agents intuitively make decisions.

Chapter 4 shows the simulation results of the method described in Chapter 3, for the base scenario as well as several alternative scenarios made based on applied policy adjustments to RPS conditions. The results will be presented with our interpretation to present the answers to our research questions. All the results of alternative scenarios will be represented in one figure, along with the result of the base scenario, to clearly display the differences in results of scenarios.

Finally, chapter 5 summarizes the implications of the study, discusses the limitations of the study, and offers recommendations for further research that could be done to improve on and expand this study.

Chapter 2. Policy and Literature Review

2.1 Policy and Current System

2.1.1 Renewable Portfolio Standard

The Renewable Portfolio Standard (RPS) is a policy of the Korean government that is intended to promote the development, use, and supply of renewable energy. Electricity producers with a capacity of over 500MW, not excluding RE energy, are considered mandatory suppliers. The amount of electricity each producer must supply with RE energy is determined through calculating a combination of their facility capacity and the mandatory share for the year. After each year ends, the Korea Energy Agency assesses participants' achievement and for any unsupplied mandatory amounts imposes penalty surcharges in range of 150% of average traded price of the certificate, which will be introduced next. To secure flexibility in the policy, RPS participants can buy certificates from other entrepreneurs to achieve their requirement, and if any overachievement occurs, the amount exceeded can be applied to satisfy the following year's requirement. In addition, under the limit of 20% of requirements, participants can postpone accomplishment of mandatory amounts up to 3 years. The mandatory share of RPS participants, which was 7% in 2020, is planned to increase to 10% in 2022, and will be same in 2023. The plan for increasing mandatory share is not yet decided for the period between 2024~2030, but what is decided is that mandatory share will increase to 28% in 2030.

2.1.2 Renewable Energy Certificate

The Renewable Energy Certificate (REC) provides confirmation that a producer made or purchased shares of electricity from a renewable energy source, and is given for every 1MWh of electricity. The time period of validity for a given REC is 3 years from the date of issue and the certificate applies to various renewable energy sources such as solar, wind, tidal, bio waste, wood waste, etc. Most suppliers of REC are small-scale producers who generate electricity with renewable sources and receive profit by selling electricity and REC to the market.

2.1.3 The REC market

As mentioned above, REC can be traded through the market and there are two types of markets in Korea. The contract market is one type of market wherein private electricity entrepreneurs sell REC combined with electricity. There are two types of contract markets. One is private market, which can be held when RPS participants think they need to establish a contract to achieve RPS requirements. The other is a public market known as the "Fixed Price Market," which is held by the Korea Energy Agency, wherein participants establish a contract with six generating affiliates of the Korea Electric Power Corporation (KEPCO). While the private market is held randomly when demanders decide to open, the fixed price market is held regularly twice per year. Prices of fixed price market are appropriated as a sum of REC and System Marginal Price (SMP), which is a price of electricity from plants dependent on time throughout the day. A contract is executed for a 20-year period, so if an entrepreneur succeeds in establishing a contract in the fixed price market, they can earn stable profits by selling electricity and REC even when fluctuations in price of REC occur in the spots market. For that reason, most entrepreneurs prefer to sell REC in the fixed price market, so the competition for contracts is quite intense. In the last fixed price market held in the first half of 2020, while the announced recruitment capacity was 1,200,000 kW, entrepreneurs representing a total generation amount of 5,866,954 kW applied for contracts, so the competition rate was about 4.89:1. Due to dramatic increase in the amount of recruitment capacity compare to the second half of 2019, from 500,000 kW to 1,200,000 kW, the competition for contract plummeted quite significantly, from 7.3:1 to 4.89:1, although the total application capacity was increased from 3,652,174 kW to 5,866,954 kW. However, although the competition rate decreased, the total amount of applicants that failed to make a contract increased to 4,666,954 kW from 3,152,174 kW, the highest record in the history of the fixed price market.

The mean price of SMP+REC of the fixed price market was ₩159,269 in the second half of 2019 and it decreased a bit to ₩151.439 in the first half of 2020. Since the reference price of SMP is given as ₩89,980 in the announcement, we can estimate that the value of REC in the contract market is about to be ₩63,289.

The spots market is another type of market wherein RPS participants and public electricity entrepreneurs can trade REC following the rule of supply and demand. One characteristic of this market that differs from the normal market for goods is the fixed number of demanding agents and the amount of demand is also determined based on the rule of RPS. Unlike the contract market, in this scenario, agents can only trade REC not combined with SMP. The spots market is held twice a week on Tuesdays and Thursdays.

Since the supply of REC in the spots market first exceeded the demand of RPS participants in 2017, the oversupply of REC was considered to be the main reason of the issue of the price drop in the spots market. While the REC price of the contract market was assumed to be about ₩63,289 in 2020, the mean of the REC price in the spots market was ₩43,025 for the 11 months from January to November of 2020, and it is expected to fall even further at the end of the year, since REC is being traded at under ₩40,000 in December, as announced on the information website of Korean government. The fact that there are more than 6,000 MW of electricity from solar power plants waiting supply to access the grid, although the REC from small solar-generation entrepreneurs is oversupplied might make the situation worse in the future. As the supply and demand must remain balanced at all times to prevent power outages, the problem of oversupply in the Korean REC market should be solved to maintain an acceptable market for REC suppliers (Heshmati, Abolhosseini, and Altmann, 2015).

2.2 Literature Review

2.2.1 Research on the REC

A number of studies examine REC, as summarized in [Table 2-1] below. Lee's (2016) study, published by Korea Energy Economics Institute, attempted to predict the price of

REC by applying 2 types of models; Bayesian normal multiple regression model and a model based on Levelized cost of energy (LCOE). According to several scenarios related to the share of solar energy in RE generation and the achievement of a basic plan for power supply and demand, Lee (2016) expected the price of REC will be formed between approximately ₩53,000 ~ ₩83,000 when the basic plan is achieved and ₩48,000 ~ ₩75,000 when failing, in the period of 2024. Lee (2016) concluded suggesting obligatorily moving REC from electric generators to suppliers and establishing a fixed price of SMP+REC for long-term contracts, which allowed too little to reduce the uncertainty for the future.

Sonu (2016) indicates that most early RPS research considered its political aspects. However, as the RPS policy carries the risk of price uncertainty since the introduction of REC price and the risk of the market can result in a contraction in investment, the paper argues for an analysis of how REC price and price changes can affect micro-level investment prior to the adoption of changes in policy. Sonu (2016) assumes that increased market risk will decrease investment and that a long-term trend of price decrease will increase investment, as the investors will assume that their profit will decrease as slowly as they invest. Using a regression analysis of empirical data of monthly installed capacity of a solar power plant, REC price, and macro-economic indicators after the RPS had been adopted, Sonu's (2016) assumptions were confirmed.

Moon, Kwon, Woo, et al. (2020) note that previous research established economic evaluations that did not systematically consider the price fluctuations of REC and SMP.

In this regard, the paper attempts to offer a new economic evaluation of the solar-generation business from the entrepreneurs' perspective based on scenarios for price fluctuation of SMP and REC, also applying a sensitivity analysis. The paper calculates cost considering the lifetime of generators, construction cost, operation and maintenance cost, and cost to connect with Energy Storage System (ESS). For a price fluctuation scenario, the researchers selected cases in which the price of SMP and REC increase, maintain, and decrease simultaneously as the cases with different patterns can be predicted with intermediate values of the chosen three cases. Through cost-benefit analysis, the paper demonstrates that small solar generators around 100 kW have economic efficiency when only the price of SMP and REC both increase and large solar generators around 1 MW have economic efficiency when the price of SMP and REC both maintain or increase.

Kwak, Kim, and Shin, et al. (2020) argue that most previous research on REC price assumption methodologies was based on LCOE, however those methodologies carry theoretical limitations in that they are unable to reflect the market supply and demand situation. To address this problem, the authors attempt to build a mathematical model containing RPS policy mechanisms such as carry-over, borrowing, and default. The paper demonstrates that the marginal cost of REC will fall from ₩ 51,718 in 2020 to ₩ 23,786 by 2030 based on a model simulation with assumption that mandatory share will increase 2.6%p per year in order to reach the goal of 28% in 2030 and the empirical data of lifetime, install cost, capacity factor.

From previous research, we recognized that there were some attempts to predict the price of REC, but it actually fell faster than expected. We also noted that small solar generators are more sensitive to price changes of SMP and REC. In this context, this study aims to offer a novel approach for price prediction: multi-agent simulation.

Authors	Methodology	Contents
Lee (2016)	- Bayesian normal multiple regression model - Model based on LCOE	Prediction of REC price in the future.
Sonu (2016)	- Regression analysis based on investment theory	The effect of REC price change on investment to PV installation.
Moon, Kwon, Woo, et al. (2020)	- Benefit-Cost Ratio analysis	Evaluation of economic efficiency of solar PV generation based on fluctuation scenarios of SMP and REC price.
Kwak, Kim, Shin, et al. (2020)	- Mathematical model	Estimation on marginal price of REC

[Table 2-1] Research reviewed for REC.

2.2.2 Research on Simulation models

Multiple researchers have applied simulation models in their investigations, as summarized in [Table 2-2], with narrative details to follow. Conzelmann, Koritarov, Macal, et al. (2002) tested the possible effects of changing power plant outages and price setting rules on electricity market prices applying Electricity Markets Complex Adaptive Systems (EMCAS) to probe the potential of EMCAS as an electronic laboratory. To model the full range of time scales, EMCAS includes a large number of different agents.

The researchers probed its potential, demonstrating that the program is able to replicate the original market game and also allows for analysis of the effects of agent learning and adaptation. EMCAS revealed that human economic decisions dominate the model in a longer time scale, while physical laws dominate in a shorter time scale.

According to Rai and Henry (2016), agent-based modeling can manage a flexible architecture such as detailed representation of complex agent systems that include the behavior of agents, their social interactions, and the economic environments surrounding them. With those strengths noted, ABM is introduced as a suitable methodology to elicit insights related to policy design and evaluation, as well as system design and infrastructure planning. However, the lack of careful validation is the most critical weakness of ABM. As many studies forego the process due to data limitations, the best that can be achieved is a comparison model that yields outcomes in the real world, which is generally weak and indirect.

Mittal and Krejci (2017) applied an agent-based model developed with Net Logo to capture the decision making processes and interactions of heterogeneous individual residential electricity consumers given the option to adopt rooftop PV or participate in a community solar project. The paper indicates that the model will help utility companies to determine the right mix of alternative renewable energy models for their customers (as revenue will decrease if more customers adopt rooftop PV), and avoid imposing unfair financial burden on consumers who do not adopt rooftop PV as fair share of the cost of maintaining and upgrading the existing electricity infrastructure.

Veselka, Boyd, and Conzelmann, et al. (2002) introduce an agent-based approach as a novel tool to analyze electric markets restructured from a centralized decision making process to open markets intended to promote competition among suppliers. They set their agents as decision making units dependent only on imperfect local information. In the EMCAS model applied, an agent learns about market behavior and the actions of other agents. Thus, when dramatic market changes occur and their current strategy fails to maximize its utility, the agent explores new strategies to adapt to the evolving supply and demand forces in the dynamic market.

Jung, Ko, and Son (2016) apply ABM in modeling consumers' purchasing behaviors and market dynamics in terms of marketing strategy, as there are not many previous studies with regard to marketing with ABM to help understand the complex interactions between consumers' purchase decision making. Through their research on the diffusion of new products and spatial analyses of consumer behavior, they conclude that the power of ABM its allowing researchers to test several theories when it is difficult to collect personal-level data through the simulation.

Hui, Xin-gang, Ling-zhi, and Fan (2020) employed an agent-based approach to the analysis of the green certificate market of China that will be implemented in 2021. Since the tradable green certificate is considered a financial asset, they assume that the green certificate trading market could be regarded as kind of a financial market with some financial characteristics. Through agent-based modeling, they demonstrate that the value-trading strategy, which indicates that value traders will sell an asset when the market price is higher than the fundamental value and purchase otherwise, is the optimal strategy for renewable obligation subjects, including grid companies and electricity retail companies.

Zhang, Zhang, and Bi (2011) applied an agent-based approach to analyze the influence of transaction costs on the efficiency of the artificial sulfur dioxide (SO_2) emission trading market. They establish that ABM can provide behavioral simulation at the micro-level, and find that macro-level behavior emerged from interactions of micro-agents. From the simulation, they proved that transaction costs have negligible effect on market price, but it can block some small amount of trading, thus decreasing the total efficiency of the market.

Yu, Fan, Zhu, and Eichhammer (2020) note that the concept of an emission trading scheme (ETS) is distinguished from the typical financial market, as firms can choose among three options at a micro level: allowance trading, output adjustment, and low-carbon technology adoption. So, dynamic interactions related to the three options occur at a macro level. To manage the dynamic complexity of the model, they establish an agent-based model for the ETS, calibrating the model based on European data. They establish their own model to overcome the limitations of existing agent-based models, ignoring the fundamental characteristics of ETS such as the adoption of low-carbon technology. With the simulation, they show that after a certain level, a higher target leads to low price uncertainty.

Praca, Ramos, Vale, and Cordeiro (2003) define the electricity industry that was operated in a vertical structure is now becoming a competitive market and requires new modeling approaches that simulate the ways in which electricity markets might evolve over time and how participants might react to the changing market. They developed a Multi-Agent System for Competitive Electricity Markets (MASCEM) wherein agents represent market entities, such as generators, consumers, and operators. In MASCEM simulation, agents can establish their own objectives and decision rules and can adapt strategies based on previous successes and failures. Time-dependent strategies differ depending on the point in time when agents modify the price and how much it changes, whereas behavior-dependent strategies refer to agents adjusting their price between negotiation periods. They argue that simulating such a strategic decision behavior of the participants can elicit the potential effects of market rules and conditions.

Santos, Pinto, and Morais, et al. (2015) note that understanding the markets' principles and how to evaluate investments under the competitive environment of the electricity market is of critical importance and simulation tools can be used to predict how the involved players' interaction will potentially affect the outcomes of the markets. In the study, three multi-agent systems are applied, including the MASCEM, which provides agents with bidding strategies to enable the achievement of the best possible results depending on the market context. The Adaptive Learning Strategic Bidding System (ALBids) offers agents the capability to analyze the context of their current situation and automatically adapt their strategy according to the analysis. The Multi-Agent Smart Grid Simulation Platform (MASGriP) proposes a set of possible coalitions that facilitate the management of smart grid and microgrid modeling within the distribution network and among involved players. The study applies a multi-agent system integrating the three approaches in a case study of European regional market operators, proving that the use of such a combinations of simulation tools can offer advantages for market players in testing and adapting their strategic behavior to assess the complex and competitive market.

Authors	Methodology	Contents
Conzelmann, Koritarov, Macal, et al. (2002)	Electricity Markets Complex Adaptive Systems (EMCAS)	Show that EMCAS can replicate the original market game and that it allows analysis of the effects of agent learning and adaptation.
Rai and Henry (2016)	ABM on energy demand	Show that ABM can make detailed representation of complex agent system like their behavior social interaction so that it can be suit for policy design and evaluation.
Mittal, Huang and Krejci (2017)	ABM with NetLogo on PV adoption	Use ABM to capture the decision process and interaction of electric consumers who are given the options of adopting rooftop PV or participating in local solar project.
Veselka, Boyd, Conzelmann, et al. (2002)	EMCAS	Show that ABM can capture the agents' learning behavior to adapt to the dynamics of decentralized electric market.
Jung, Ko and Son (2016)	ABM on marketing	Show how to use ABM in marketing applying it to 1) Innovation diffusion and 2) Spatial analysis of consumer behavior.
Hui, Xin-gang, Ling-zhi, Fan (2020)	ABM on green certificate trading	Show that ABM can capture changing economic efficiency occurred from impact of market agents' various strategic behaviors.
Zhang, Zhang and Bi (2011)	ABM on emission trading	Show the influence of transaction costs on market efficiency with ABM approach. Prove that ABM can capture macro-level behavior from simulating micro-level behavior.
Yu, Fan, Zhu and Eichhammer (2020)	ABM on ETS	Show that ABM can contain effect of some fundamental characteristic of such non typical financial market.
Praca, Ramos, Vale and Cordeiro (2003)	MASCEM	Developed new simulation model, MASCEM to show how the markets evolve over time and participants adapt to the changes.
Santos, Pinto, Morais, et al.	MASCEM, ALBids, MASGriP	Develop multi-agent system integrating three systems to define best strategic behavior to adapt in the competitive market.

[Table 2-2] Research reviewed on simulation models.

As affirmed by the previous research above, agent-based simulation offers the ability to simulate agents' behavior and capture the dynamic complexity of various macro-level economic contexts based on the micro-level simulation of agents' behavior, which was an identified challenge of existing methodologies. This review confirmed the application of agent-based simulation as a suitable methodology for this study, as it aims to predict the future price of REC in the spots market of Korea based on individual agents' decisions in the market to identify the right approach for achieving the government's target.

Chapter 3. Methods

In this study, we endeavored to simulate the REC market of Korea by applying a multi-agent simulation methodology. To assess the credibility of our forecast regarding the future market, we first applied a simulation of the past market. We are interested in the market from 2016, as it was the first year that the markets for REC from solar power and REC from non-solar power, which had previously been separated, were integrated. To simplify the model, we assumed that all the RECs issued were traded in the spots market.

3.1 Demand side Agents

The agents of demand side in our model are mandatory suppliers that have to achieve a certain amount of RE generation to avoid penalty surcharges. The irregular property of these demanders is that total demands for REC are calculated by the government as a certain percentage of the total generation capacity of the facility due to RPS law. Since the unit of capacity is the amount of power in MWh, the mandatory demand of REC is determined by the following equation.

$$Mandatory(MWh) \times \frac{2month}{12months} \times 1 + Mandatory(MWh) \times \frac{10months}{12months} \times 1.16 \qquad (1)$$

Demand agents' input demands are calculated based on actual data from the announcement of mandatory REC requirements for 2020 by the Ministry of Trade, Industry and Energy. Calculating equation (1) backward, we can elicit the total amount of facility capacities of mandatory suppliers. Assuming that the total capacity of mandatory suppliers does not increase or decrease significantly, we can calculate the mandatory requirements of earlier periods from the 2020 data, and the requirements of the years were derived by multiplying the mandatory share of each year to total capacity of each mandatory supplier, as shown in [Table 3-1].

Year	‘12	‘13	‘14	‘15	‘16	‘17	‘18	‘19	‘20	‘21	‘22	‘23~
Mandatory Share (%)	2.0	2.5	3.0	3.0	3.5	4.0	5.0	6.0	7.0	9.0	10.0	10.0

[Table 3-1] Annual RPS mandatory requirements.

Source: 산업통상자원부, 2020, 그린뉴딜 지원을 위한 신재생에너지 관련법령 개정, 시행.

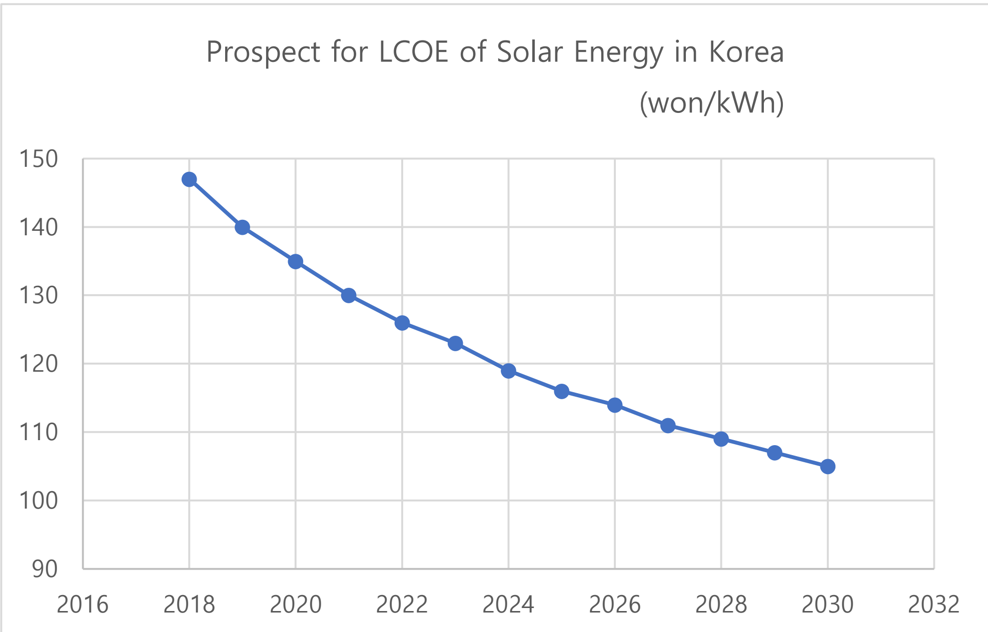
To satisfy the Renewable Portfolio Standard (RPS) requirements, mandatory suppliers can choose between two options. One is to generate electricity from a renewable energy source themselves and the other is to buy REC on the market. Based on the RPS rule, the maximum amount of self-generation is regulated to be under 50% of their requirements in order to protect small-scale public suppliers (Korea Energy Agency, 2011). In our simulation, the decision on whether or not to buy from the market is based on a comparison of the price of the market and the cost to self-generate, unless they are already producing 50% of the mandatory requirement themselves. If they decide to self-generate, their self-generation capacity will increase in the model and will be reflected in the following year’s simulation.

The cost of self-generation is calculated annually based on LCOE for solar power generation in Korea, which is the “ratio of lifetime costs to lifetime electricity generation”

(International Renewable Energy Agency, IRENA). Since buying REC from public generators does not mean that they are buying generated electricity either, we have to calculate only the cost of REC and that will be demand agents' willingness to pay (WTP) for REC. So, we subtracted System Marginal Price (SMP) from LCOE, and since REC is given for every 1 MWh, while LCOE and SMP is given for every unit of 1 kWh, the equation for mandatory suppliers' self-generation cost is given as below. Considering the limited land to install plants around RPS participants' locations, the units separated from same RPS participant were assumed to pay more land fee of 20won/kWh per each unit.

$$Cost = (LCOE - SMP) \times 1{,}000 + land\ fee_i \qquad (2)$$

The change of LCOE and its future expectation through the years is shown in [Figure 3-1] below.



[Figure 3-1] Outlook of LCOE for solar power generation in Korea.

Source: KEEI, 지역별 경제성을 고려한 태양광 시장 잠재량 산정 및 이행비용 분석.

Since SMP is a value that is affected by the world oil price, it was fixed at ₩86/kWh, the value of annual SMP of Korea recorded by the Korea Power Exchange (KPX) for period of 2016~2019.

Since there are huge gap between RPS participants, some of them are divided into several agents so each can have similar amount of mandatory electricity to supply under around 500,000 MWh, or about 572,000 REC in 2020, which is our reference year. Through this process, the total number of mandatory suppliers is set as 71, from original 22. Also, to reflect the increasing land fees when a participant decides to generate more REC themselves, additional costs are added to each agent that was originally separated from one participant.

At the end of the year, the amount of remaining demand is recorded and added to the total demand for the next year. So, except for the first year of simulation, the total demand of each mandatory supplier is calculated as $Demand + Demand_{left} - Production$.

3.2 Supply side Agents

The agents on the supply side of our model are public generators. We set 210 producers in initial market and the number is calibrated to the supplied REC in the first year of simulation, 2014. They are given a random generating facility capacity of around 30 kW, randomly distributed in range of ± 5, and the amount of annual REC they earn is calculated by assuming a 3.6-hour/day average of electricity generation through the year that is saved as inventory. As REC is given for every 1MWh, the amounts of inventory for each public generator are calculated as below.

$$Inventory = \frac{Capacity \times 3.6 \times 365}{1000} \qquad (3)$$

The cost to produce one unit of REC is calculated in the same manner as demand side agents, based on LCOE for solar power energy and SMP. The land fee is randomly added to the LCOE of each supply side agent in range of 18 to 22 based on the difference of LCOE estimated considering land fee and not considering land fee in the report of the Korea Energy Economics Institute (Cho and Lee, 2018). However, at the beginning period of the market, we set the desired price for REC more expensively compared to the produced cost in order to make it meet the empirical data of first year based on the assumption that producers would try to sell REC at least at the price of the contract market of that period. As public generators do not install facilities every year, their price is only affected by LCOE in the first year of installation and the price is adjusted based on market results in subsequent years. After the market, stocks of agents were recorded, and are added to the inventory for the next year.

While the number of agents on the demand side is fixed, there can be changes to the number of agents on the supply side, as potential investors can be observing the market and may enter when they think they can gain enough profit from making an investment. In the same as agents already in the market, potential investors consider their virtual capacity around 30 kW and assume their payback period based on the trading price and trade rate of the market as following equation.

$$Period_{payback} = \frac{(1{,}500{,}000 + Land\ fee) \times Capacity}{Capacity \times 3.6 \times 365 \times (SMP + \frac{MP}{1000} \times Trade\ rate)} \quad (4)$$

In the equation above, MP is the market price of the previous year and Trade rate is the total number of trades in the market divided by the total amount of REC produced for all public generators in the market in the previous year.

The number of potential investors is set at 400 each year, which is about twice the number of initial suppliers in the market. This number is assumed based on data of issued REC in total, as this study focuses on the REC market from 2016, when the markets of solar and non-solar REC generation were integrated. As the total REC in the market never increased as much as the supply of 2014, we assumed that it to be adequate to set the number of potential investors at about twice number of initial suppliers.

When they assume the payback period to be shorter than 8 years for the first 6 years and shorter than 11 years for the last, they will decide to make investment. When the potential investors decide to invest, there would be a 2-year delay before they enter the market, considering the time to construct the plant and obtain permission to do business with electricity.

3.3 Market

In our simulation, we assume that the market is held 12 times every year, as we believed that twice a week would cause the simulation to become too complex.

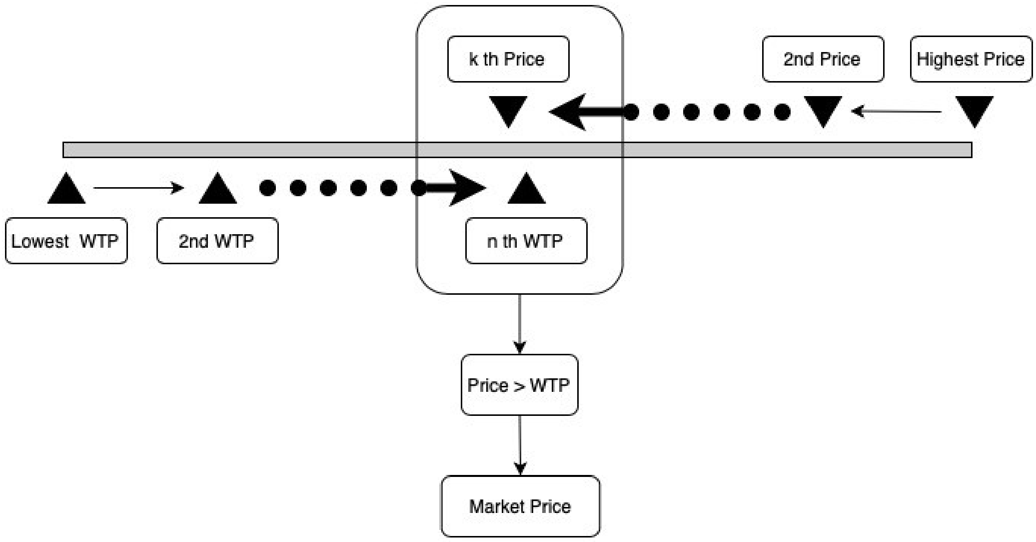
Since the amount of demand of the market is not totally based on the rule of supply and demand, as it is mandatory, to decide the first price of the market, we used a computational approach, comparing the prices suggested by both the demand side and the supply side. Starting with the lowest WTP from demand side and the highest price from supply side, the simulation endeavors to diminish the price gap between the demand side and the supply side by moving to the next level of price in the direction of low-to-high for the demand side and high-to-low for the supply side. Since the amount of demand of one demand agent is much larger than the amount of supply of one supply agent, when the price of the demand side moves one step, the price of the supply side is made to move multiple steps until the value of demand change exceeds the value of supply change. When the simulation reaches the point where the price suggested by the supply side agents first exceeds WTP of the demand side agents, the mean is appropriated as the market price. So, we can say that our computational pricing sequence finds the market price near the point at which the minimum price that a provider will accept meets the maximum price a buyer is willing to pay following such trading mechanisms in earlier research (Altmann, Courcoubetis, Risch, 2010).

The above is the explanation for the following [Figure 3-2] presents the pseudo code for the computational pricing sequence in the model and a picture of this logic is presented next.

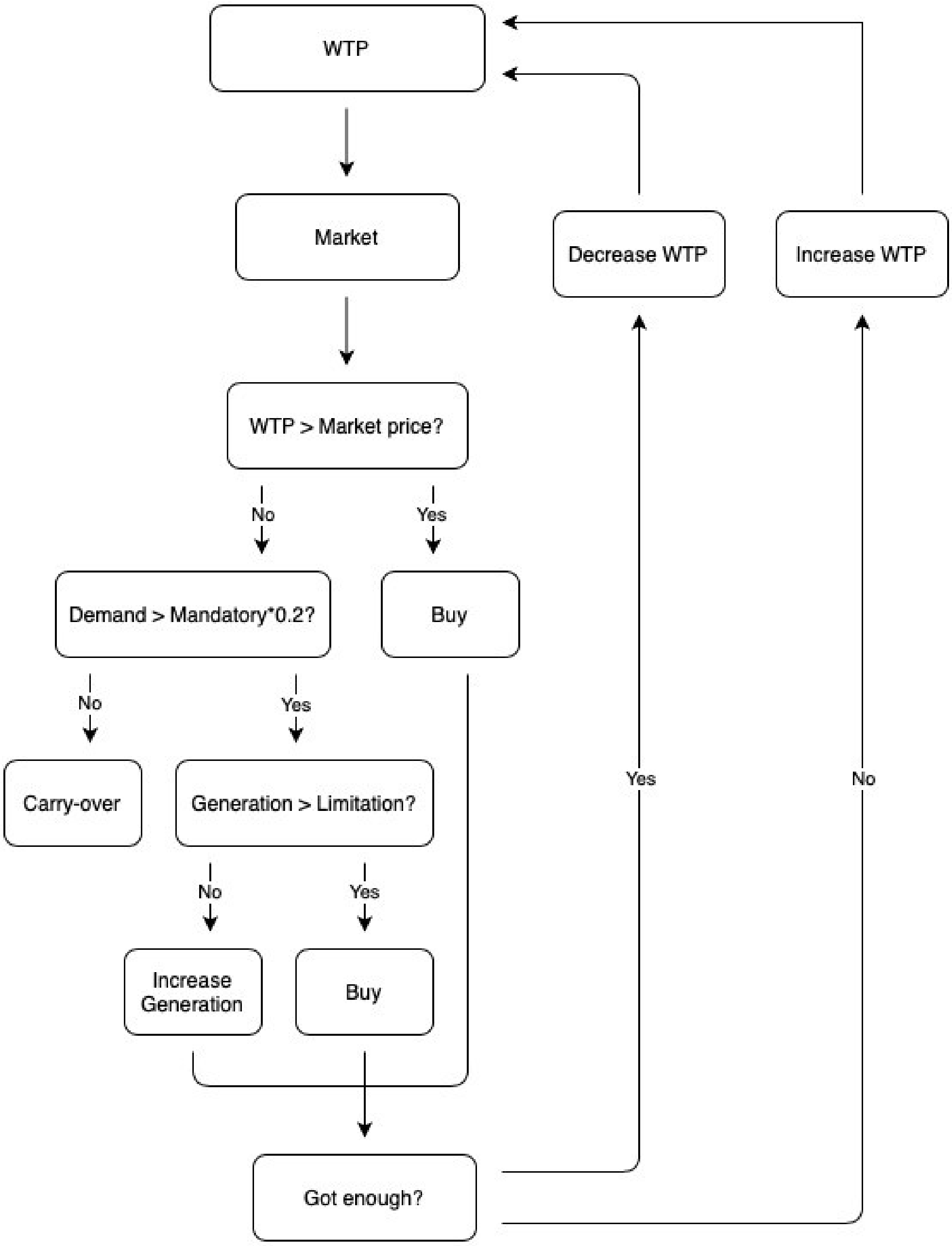
```
#WTP list sorted
#demandorder=0
#Price list sorted, reverse=True
#supplyorder=0

while WTP<Price do:
    demandorder+=1
    if demandorder=number of demand agents then:
        break
    end if
    while demand_for_passed_WTP > supply_for_passed_price do:
        supplyorder+=1
        if supplyorder=number of supply agents then:
            break
        end if
    end while
    if WTP>=Price do:
        marketprice=mp=(WTP+Price)/2
    end if
    return mp
end while
```

[Figure 3-2] Pseudo code for computational pricing sequence of the market.

To take WTP and Price in given order, they should be sorted in the list before the block of pricing sequence. Since 12 markets every year exist in our simulation, the code must be placed to be sure it runs before each market starts, not only once at the start of the first market of each year, as shown in [Figure 3-3].



[Figure 3-3] Computational pricing sequence of the market.



[Figure 3-4] Behavioral logic of demand side agents.

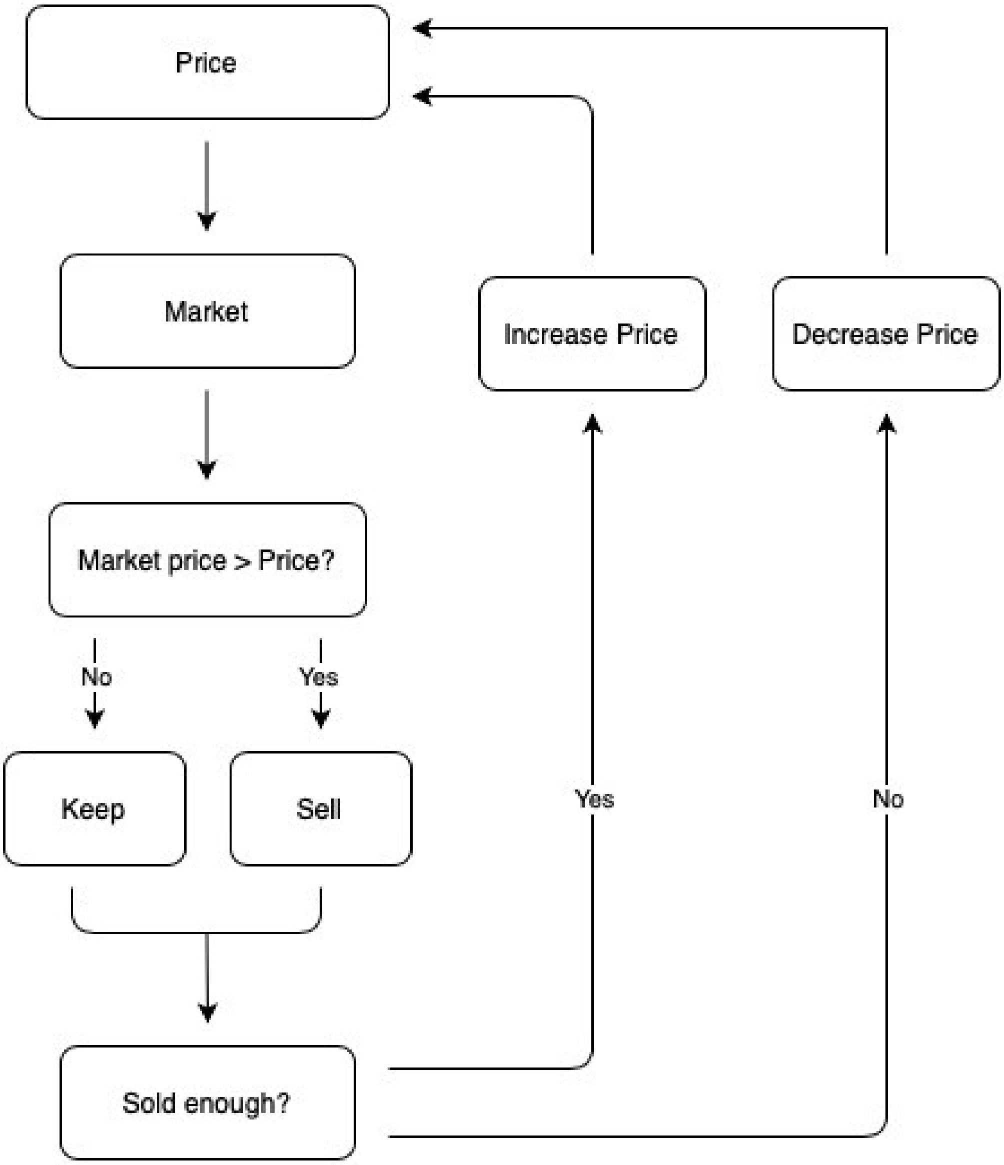
Demand side agents have behavioral logic in the market, as in [Figure 3-4] above. If their initial WTP is higher than the market price, they decide to purchase REC in the market. However, when their WTP is lower than price, they can make other decisions. If they already have enough REC and the demand left is less than 20% of their requirements, which they can carry-over into the next year, they decide to carry over these demands. If they have more demands left compare to the RPS carry-over limitation, they enter the phase of deciding to whether or not to increase their self-generation. If they are already generating the amount of limitation, 50% of mandatory requirements, they should buy REC from the market, although the market price is higher than their WTP. Another option, is to increase self-generation capacity in an effort to satisfy their quota.

After each market finishes, comparing existing demands and mandatory requirements, if they failed to get enough REC to satisfy their quota, they increase their WTP to buy more REC in the next market. Conversely, they may decrease their WTP when existing demands and requirements are low. The following pseudo code for WTP adjustment in [Figure 3-5] presents the logic above.

```
def offer_func:
    if demand left > initial demand*0.8 then:
        WTP + 2500 + random.randrange(-500,500,500)
    if demand left < initial demand*0.2 then:
        WTP - 1500 - random.randrange(-500,500,500)
    end if
```

[Figure 3-5] Pseudo code for WTP adjustment of demand side agents.

The gap in increasing and decreasing price range is applied in order to reflect the pressure of RPS participants to satisfy their mandatory share.



[Figure 3-6] Behavior logic of supply side agents.

Supply side agents have behavior logic, as presented in above [Figure 3-6]. When the market price is higher than the price at which they want to sell their REC, they decide to sell in the market. Conversely, they may decide to keep their REC. As the agents cannot know the exact and clear information of the whole market, their behavior after market is decided by their own status. If they still have more than half of their initial production for the year, they decide to lower the price they offer to the market in order to avoid having too much stock left. If they have less than 20% of their initial production, they may decide to offer a higher price in the market. The following code in [Figure 3-7] presents the logic of the price adjustment of supply agents.

```
def price_func:
    if stock left > initial inventory*0.5 then:
        Price - 2500 - random.randrange(-500,500,500)
    if stock left < initial inventory*0.2 then:
        Price + 1500 + random.randrange(-500,500,500)
    end if
```

[Figure 3-7] Pseudo code for Price adjustment of supply agents.

The price gap in decreasing and increasing is also applied for supply agents. In this case, the price gap is used to reflect the pressure on REC suppliers to sell the certificate before expiration, which is not certainly coded in our simulation.

As WTP and price is adjusted at the end of every market, as mentioned above, the pricing sequence presented in [Figure 3-2] and [Figure 3-3] should be executed before every market starts. The behavioral logic of agents in the market presented in [Figure 3-4] and [Figure 3-6] is coded in the market and generation block, and the logic of the code will be presented in the pseudo code presented in [Figure 3-8] below.

```
for time in range(total_demand) do:
    if no demand agents left then:
        break
    end if

    demand_agent_in_market = random.choice(demand_agent)
    supply_agent_in_market = random.choice(supply_agent)

    if demand_agent_in_market.demand=0 then:
        exit market queue
    end if
    if no more supply at the market then:
        if demand_agent_in_market.demand < carry-over limit then:
            select to carry-over
        else:
            if demand_agent_in_market.generation < generation limit then:
                generation+=1
            else:
                pass
            end if
        end if
    end if

    if supply_agent_in_market.inventory=0 then:
        exit market queue
    end if
    if supply_agent_in_market.price > market price then:
        exit market queue
    end if

    if demand_agent_in_market.WTP < market price then:
        if demand_agent_in_market.generation < generation limit then:
                generation+=1
        else:
            purchase
        end if
    else:
        purchase
    end if
end for

offer_func
price_func
```

[Figure 3-8] Pseudo code for the market and generation.

When all the markets of a year finished, potential investors decide whether or not to enter the market based on their observation of the market as their decision logic in [Figure 3-9] below.

```
if year < 2020 then:
    if payback period<8 then:
        attend entering queue
        get 1 year delay
    end if
else:
    if payback period<11 then:
        attend entering queue
        get 1 year delay
```

[Figure 3-9] Pseudo code for potential investors decision.

The rational payback period to enter is assumed based on several articles and an interview with the principal of the Korea Solar Energy Development Association (KOSEDA) in 2020, arguing that they now just want the payback period to be 10 years, as it is too long due to the price fall of the spots market. Since potential agents are set to have random capacity, they consider entering, while following the same logic as supply agents; each of them calculating their own payback period based on their capacity and the mean price of the market throughout the year.

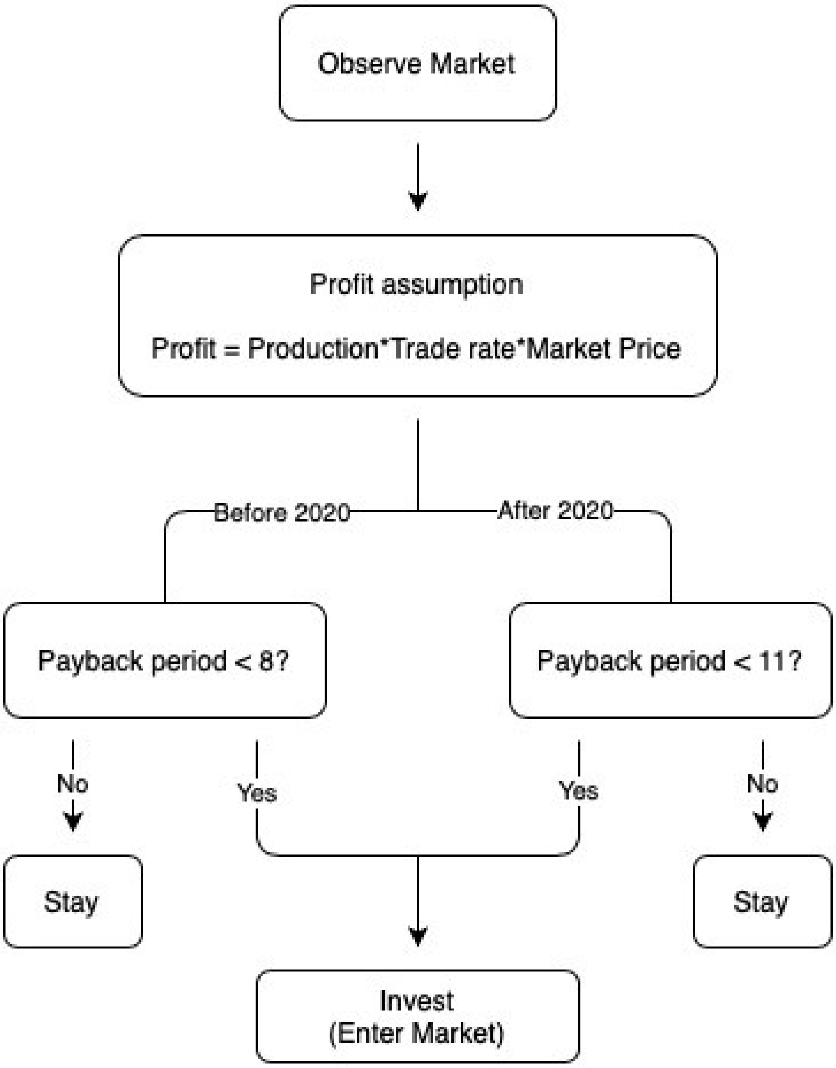
As shown in the pseudo code above, when the decision is made to enter the market, there is a delay in entry that is applied in consideration of the time to get licensed in electric business, the construction of a plant, and the connection to the grid. So, when deciding to enter the market, from the observation for the market in period T, they will first enter the market in period T+2 and the entry time sequence considering this delay is coded as in [Figure 3-10] below.

```
if entering_queue_investors.delay=1 then:
    delay-=1
if entering_queue_investors.delay=0 then:
    enter market
end if
```

[Figure 3-10] Pseudo code for entering sequence with delay.

The new entrants in the market follow same logic to get their price and inventory variable with the supply agents. For the last, the number of new entrants is added to the number of suppliers in the market.

The potential investors' decision logic is pictured in [Figure 3-5] below.



[Figure 3-5] Decision logic of potential investors

As the agents in the model decide their behavior based on profit and status, we can say that our model is general enough and might be able to reveal how the behavior of agents can be changed in several simulations adjusting for some exogeneous conditions.

For the last, the variables and keywords included in the simulation are summarized in the [Table 3-2] below.

Keywords	
Willingness to Pay (WTP)	Decided based on demand side agents' marginal cost for self-generation.
Price	Decided based on supply side agents' marginal cost to produce.
Demand_agent_in_market	A demand side agent randomly selected in a turn of trade.
Supply_agent_in_market	A supply side agent randomly selected in a turn of trade.
Payback period	Time required for investors to earn the amount of money they invested 8 years before 2020, 11 years from 2020.
Variables	
Suppliers' capacity (kW)	30 + random number (-5, 5)
Suppliers' land fee (won)	20 + random number (-2, 2)
WTP (Change after market)	Increase 2,500 + random (-500, 500), interval 500
	Decrease 1,500 + random (-500,500), interval 500
Price (Change after market)	Increase 1,500 + random (-500,500), interval 500
	Decrease 2,500 + random (-500, 500), interval 500

[Table 3-2] Variables and keywords in the simulation.

Chapter 4. Simulation and Results

4.1 Simulation

In our simulation, there are 71 demand side agents in the market, expanded into small scales from the original 22 Renewable Portfolio Standard (RPS) participants. There are also 210 public plants initially, with approximately 30 kW facility capacity each. The number of agents is calculated based on the REC supply of 2014, which was the reference year of our simulation, where the results are excluded, as 2014 and 2015 are dummy periods for delayed new entrants. The number of potential investors is set at 400 each year, assuming there might always be some investors who are interested in the market for about twice of initial entrants.

All of the policy adjustments in our alternative scenarios are assumed to occur after 2023, as the plan of RPS until 2023 has already been announced. However, for no delay and less limit scenarios, the assumption of the policy changes applied from the initial market is also simulated to assess the difference between running the market in such condition in the total period and only in later periods.

The results presented in this chapter represent an average of 100 simulation results for each scenario, since the randomness in some variables in our simulation resulted in a wide distribution of results. To show the distribution of the simulation, high 95% and low 95% results will be presented with the average results for baseline scenarios for both short and long term in dot line.

4.2 Base Scenario

To validate the simulation, we endeavored to reenact the empirical data from the market in the past. The empirical data of the past market are presented in [Table 4-1] below.

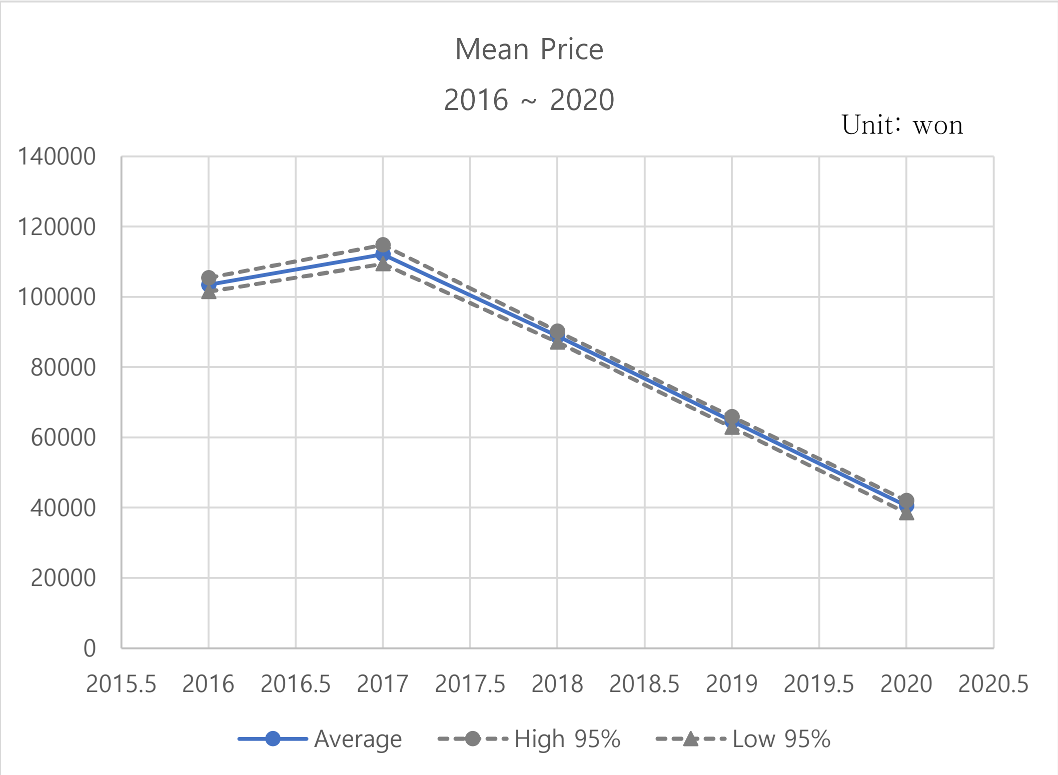
	Issued volume (REC)	Volume of transaction (REC)	Mean price
2016	14,599,281	7,466,954	₩134,588
2017	20,108,089	10,339,403	₩129,966
2018	25,862,989	15,275,671	₩98,370
2019	31,966,789	19,572,296	₩63,349
2020		25,380,007	₩43,025

[Table 4-1] Market data from 2014~2020 (November).

Although the simulation starts from 2014, since 2014 and 2015 were used as temporal dummies, to give potential investors enough time to enter the market, the market we are interested in exploring starts from 2016, when the markets of solar and non-solar RECs were integrated in March 2016. The results in this chapter will be presented from the simulation results of 2016. As the data are from the integrated market, [Table 4-1] presents the data collected from the sum of solar energy and non-solar energy. Also, as our simulation runs the market as a single market, not separating the contract market and the spots market, the volumes of issued and traded REC is also presented as total, not dividing the markets. In addition, to simplify the model, we adjusted the total size scale of data in 1/1000

4.2.1 Past market simulation

The simulation results for the market from 2014 to 2020 are as below in [Figure 4-1].



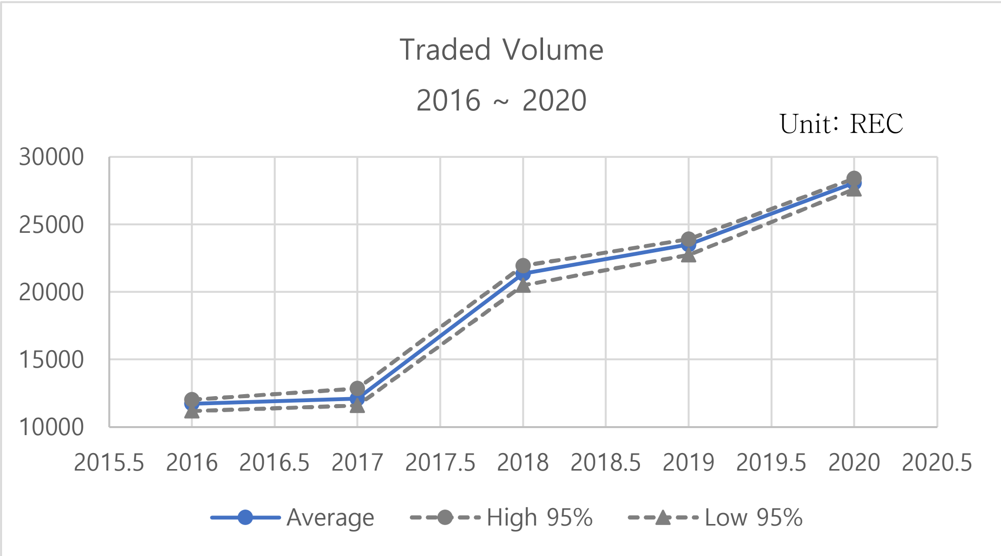
[Figure 4-1] Mean price of REC market for the short-term.

As happened in the actual market, the simulation shows that the mean price of the REC market results in a downward slope graph as time flows. Although it does not fit the empirical data perfectly, the simulation reveals a similar pattern of price fall as shown in [Table 4-2] below, although the data of 2020 is collected only up to November. The comparison between empirical data and simulated results is presented below in [Table 4-2], presenting the Root Mean Square Deviation (RMSE) of the error.

	Empirical mean price	Simulated mean price
2016	₩134,588	₩103,421
201	₩129,966	₩112,134
2018	₩98,370	₩88,900
2019	₩63,349	₩64,609
2020	₩43,025 (~11)	₩40,562
RMSE		16653.51

[Table 4-2] Compare of price change of empirical data and simulation.

The simulation presents a graph [Figure 4-2] of the annual amount of trade increasing as expected, since the demands of RPS participants increases every year based on the rise of mandatory share to supply with RE energy sources. It must be pointed out that that empirical data of 2020 presented in [Table 4-3] below is collected from only January to November.

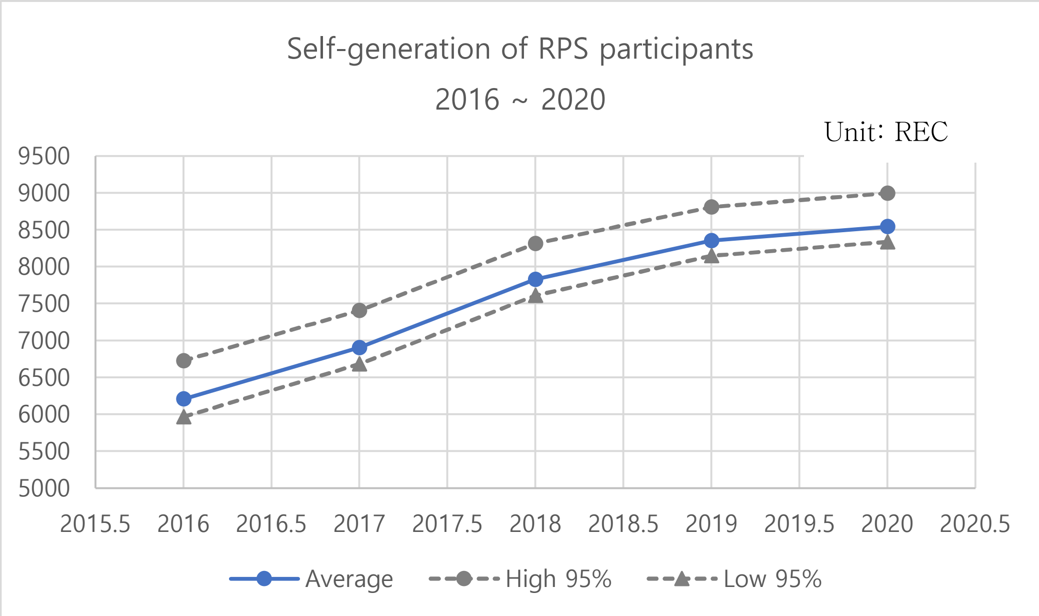


[Figure 4-2] Traded volume of REC market for the short-term.

	Volume of trade in empirical data (REC)	Volume of trade in simulation (REC) (*1000)
2016	7,466,954	11,727,890
2017	10,339,403	12,101,740
2018	15,275,671	21,347,320
2019	19,572,296	23,490,820
2020	25,380,007 (~11)	28,080,080
RMSE (1/1000)		4019.20

[Table 4-3] Compare of trade volume of empirical data and simulation.

The exact amount of RPS participants' self-generated electricity using renewable energy sources is unknown, as it is not an obligatory for RPS participants to provide this information publicly. Even KPX, the agency responsible for the REC trading market, does not provide any information about the self-generation, indicating that the decision to generate is a corporate secret of each RPS participant. As such, only data for a few self-generators that publicly post RE generation capacity was available, and the total amount of self-generation in whole market was estimated dependent on the characteristics of the agents when generating [Figure 4-3].

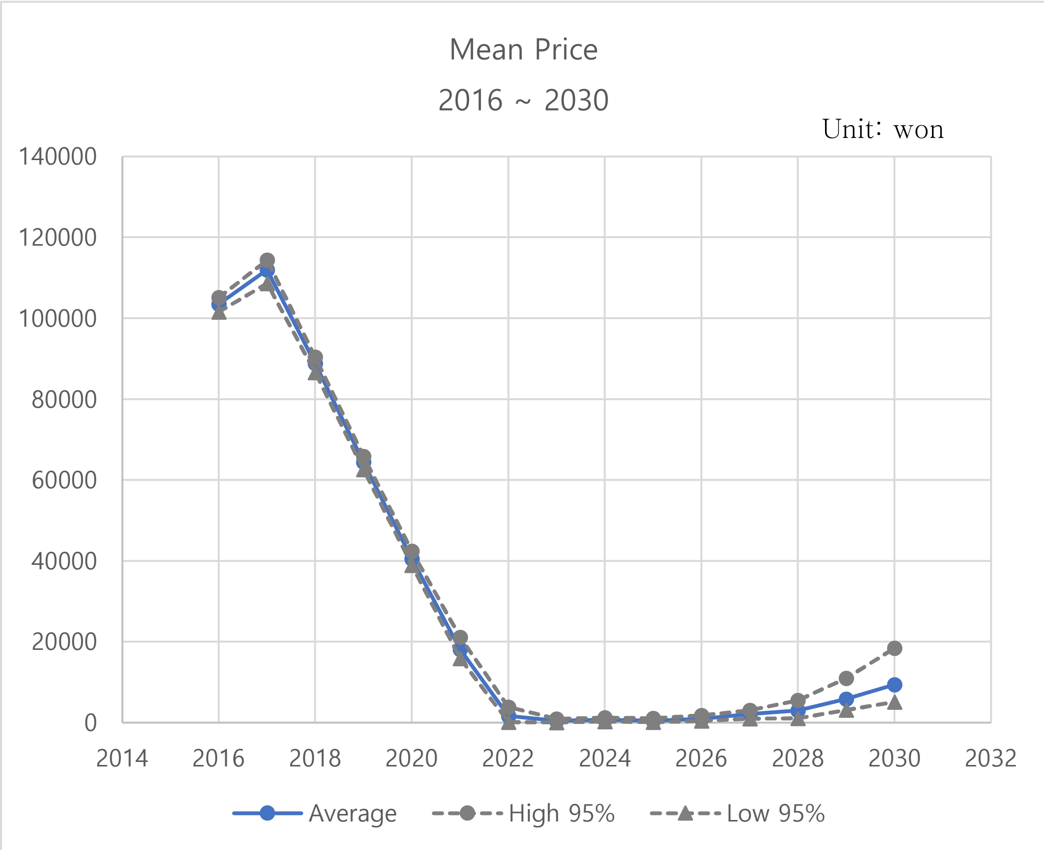


[Figure 4-3] Self-generation of RPS participants for the short-term.

Our simulation estimated that RPS participants will increase RE generation capacity in the short term and the speed of such increase seems to be slow down at the end of the period simulated. With the increasing traded volume of REC above, we can interpret that the demand agents in our simulation do make efforts to satisfy their requirements using both the options they can choose, buying and generating.

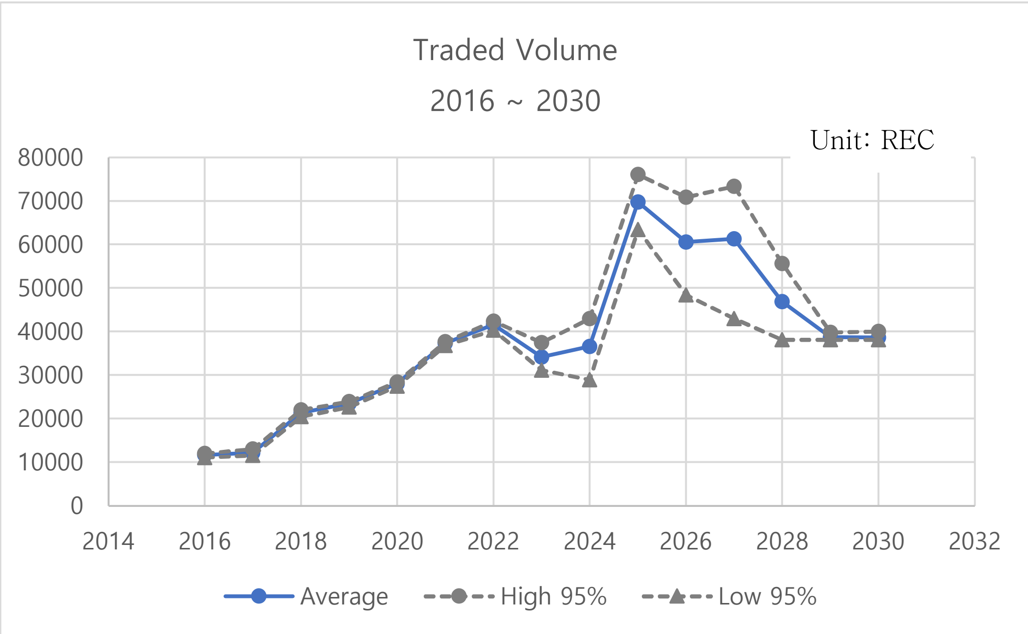
4.2.2 Long-term market (2016~2030)

The short-term simulation for the current market does not imply that our simulation model perfectly replicates the empirical market. However, since it does demonstrate a similar pattern of price fall, in line with the examined history of the empirical market, we believe that it is able to apply to the expectations for the future market's pattern of change, so we applied it for the long-term market simulation until 2030, the deadline year of Korean government's "Implementation plan of Renewable Energy 3020". Since the increasing plan of mandatory share after 2023 has not yet been announced, we assumed it to be increased 2%p per year for the first three years, then to speeds up to increasing 3%p per year for the last four years to meet the RPS policy goal of making the mandatory share of RPS participants 28% in 2030, as shown in [Figure 4-4].



[Figure 4-4] Mean price of REC market for the long-term.

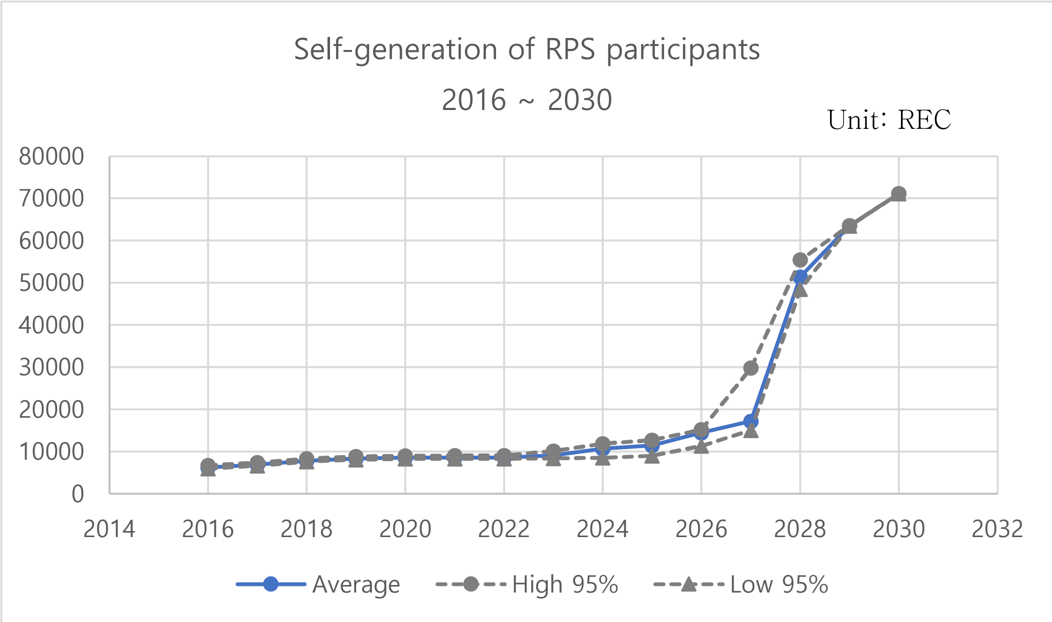
In the long-term, our simulation predicts that the price of REC will continue to fall until the mid-2020s and begin to recover in the late 2020s. From the rule of supply and demand, we can expect that the point at which the price begins to increase again is the time when the demand of RPS participants will follow the remaining supplies in the market, which are oversupplied in the early years.



[Figure 4-5] Traded volume of REC market for the long-term.

As expected from the results of mean price, we can observe that the lack of supply to be traded occurs from the period when the mean price begins to increase from not increasing in traded volume. From the results in [Figure 4-5], we can expect that there would be no merit for potential investors to enter the market because if there were new entrants supplying REC to the market, the volume traded would not seem to be stable.

Since there must be demands of RPS participants to satisfy their mandatory share in these periods, they must choose to self-generate renewable energy and earn REC themselves when there is not enough supply. [Figure 4-5] below reveals the effort of RPS participant agents to satisfy their requirements.



[Figure 4-6] Self-generation of RPS participants for the long-term.

Our simulation predicts that self-generation of RPS participants will steeply increase in the periods when a lack of REC supply occurs in the market to achieve their goal almost to the limitation 50% they can generate themselves. The steep increasing figure above also proves that there is no option to buy for the RPS participants due to the lack of supply in the market.

4.2.3 Interpretation and implication

In our simulation, the market consequently failed to achieve the goal of 28% RE generation through RPS in 2030, although the participants tried their best to achieve it by increasing their RE generation capacity near to the limit of the amount allowed under the limitation of the RPS rule. We can interpret this result as the current system not being expected to successfully achieve its goals and from the lack of supply in late markets, we can say that potential investors are not getting positive signals to enter the market after the mid-2020s. Also, imposing too much burden on RPS participants might be a problem, since several RPS participants are the affiliates of KEPCO, the governmental electricity supplier of Korea. As the Korean electric market is in the second stage in the evolution of its electric power industry, where there is competition in generation with a single buyer, KPX in case of Korea (Shim, Kim, Altmann, 2018), large self-generation of governmental RPS participants can be claimed as an imbalanced resource allocation problem.

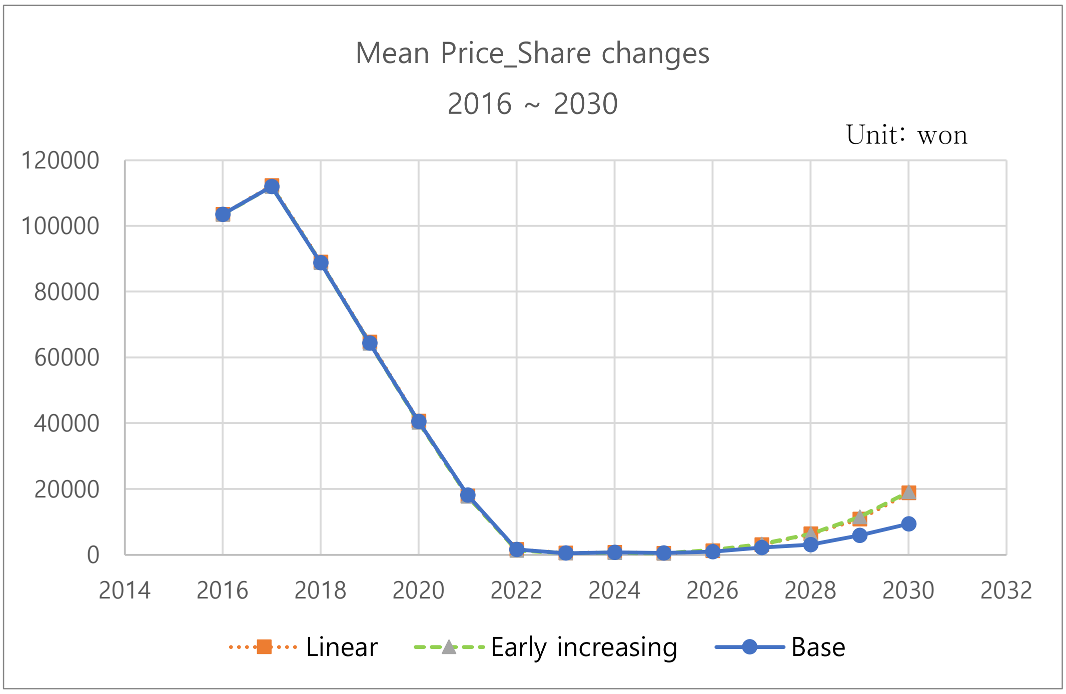
To identify a more efficient scenario to successfully reach the 2030 goal and not to give much share to RPS participants, we executed some other simulations for the scenarios applying some changes in the original condition. To see the differences intuitively, we will present the results of alternative scenarios on the same plane as the results of the base scenario above.

4.3 Political Changes in Increasing Mandatory Share

As mentioned above, our base scenario assumes that the mandatory share of RPS participants will increase 2%p per year for three years after 2023 and will then increase 3%p per year in last four years to reach 28% in 2030. This assumption was based on records that the government did increased the share slowly in the early years and then sped up when they thought it was needed, as it is increased 1%p per year from 2017 and

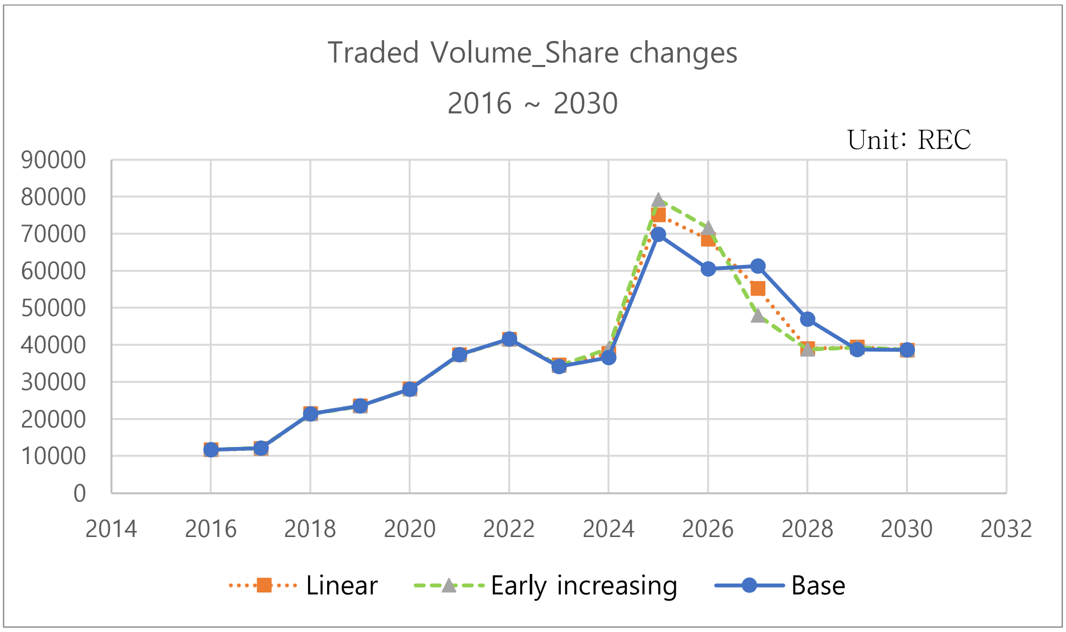
2%p between 2020 and 2021, as the need to increase demand for REC was identified, and then it returns to 1%p in 2021~2022.

We simulate two alternative scenarios; one that assumes the mandatory share increases 3%p per year in early four years after 2023 and then 2%p per year later, and the other assumes that the mandatory share increases linearly after 2023, 2.6%p per year to reach 20% in 2030. No other settings, including all the variables, are touched except the increasing pattern of the RPS policy's mandatory share.



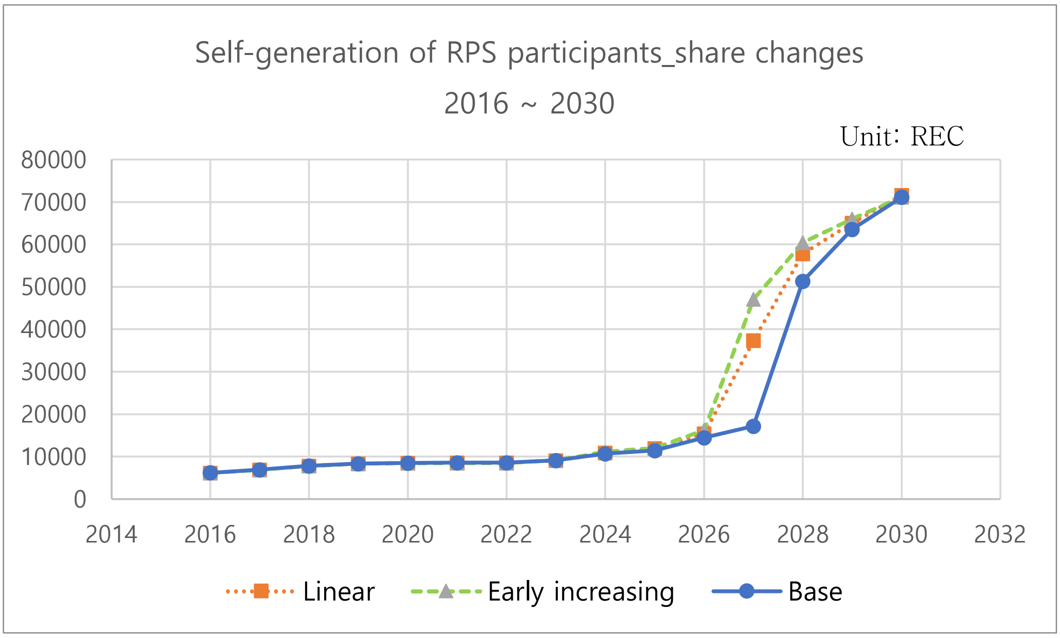
[Figure 4-7] Mean prices of share increasing scenarios.

From the graphs of mean price for each scenario in [Figure 4-7], we can see that there is not that many differences in the pattern of price change between share increasing scenarios. The faster demand increase of alternative scenarios seems to make the price a bit higher compared to that of the base scenario, but it is difficult to say whether there are significant differences between the scenarios simulated.



[Figure 4-8] Traded volumes of share increasing scenarios.

The graphs of traded volume in [Figure 4-8] reveal that although the results of mean price seemed to be similar in the scenarios, we can observe a larger volume of REC traded in the market due to the higher demand of alternative scenarios. However, we can see that the alternative scenarios also meet the lack of supply, as the graphs of traded volume fall even faster as more volume was traded earlier and became stable in the late market, in congruence with the base scenario. From the results above, we can say that in the alternative scenarios, more volume is traded lowering the stock of RES suppliers and causing the lack of supply to occur earlier, but the number of potential investors entering the market is similar to the base scenario.



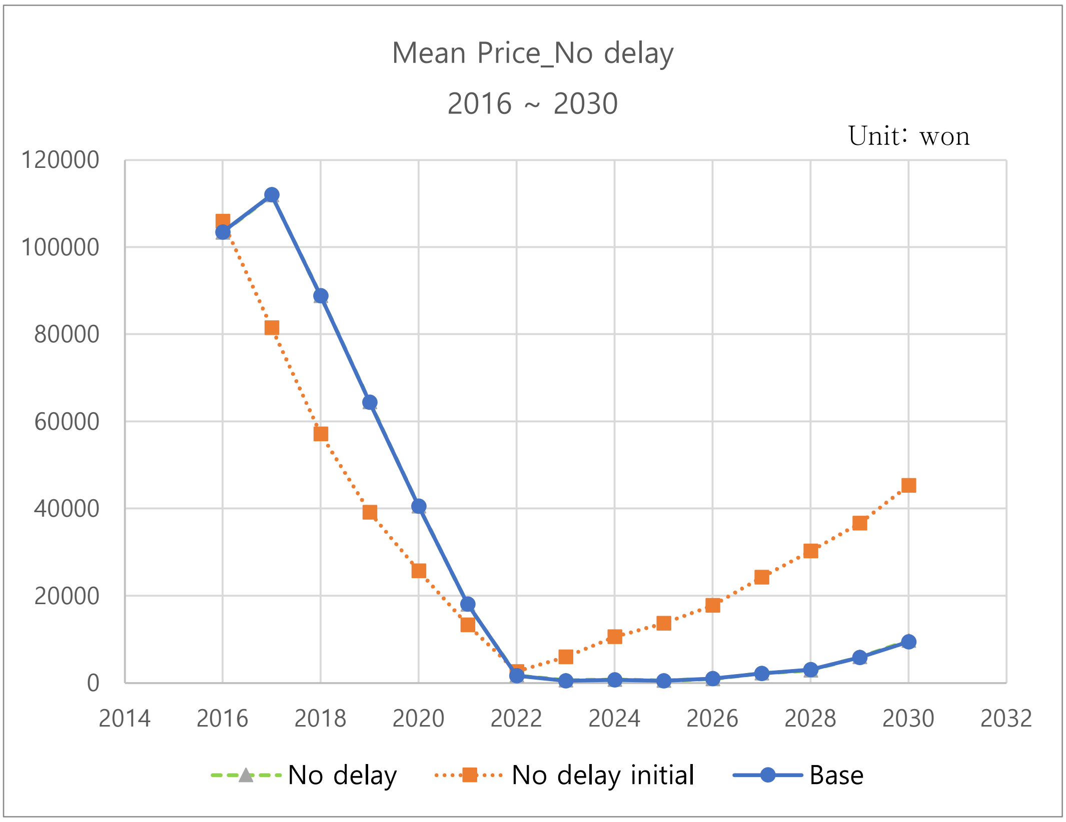
[Figure 4-9] Self-generation of RPS participants of share increasing scenarios.

The [Figure 4-9] graphs of self-generation of RPS participants reveal the same circumstances as the results of traded volume. Just as we find that lack of supply occurred more steeply in alternative scenarios, here we find the level of self-generation of RPS participants starts to increase steeply earlier. With the results from linear and base scenarios, we can see that the order of self-generation increases exactly following the order of whose demand is increased more. However, at the end, the RPS participants in every scenario increased their generation near the limitation level, as they are unable to buy enough REC from the market to satisfy their RPS requirements due to the lack of supply.

Based on the comparison between the three scenarios related to the timing and speed of mandatory share increase, we find that the alternative scenarios show almost similar results to the base scenario, increasing the volume of REC traded in the market. However, although more trade is occurred in the market in both the early increase and linear increase scenario, consequently, the amount of total REC in the market was not that different and all of the scenarios expect the system to fail to achieve the goal of 2030 although the RPS participants attempt to self-generate as much as they can. So, we next simulated the scenarios with changes in the delay of potential investors' market entry and restrictions on RPS participants' self-generation.

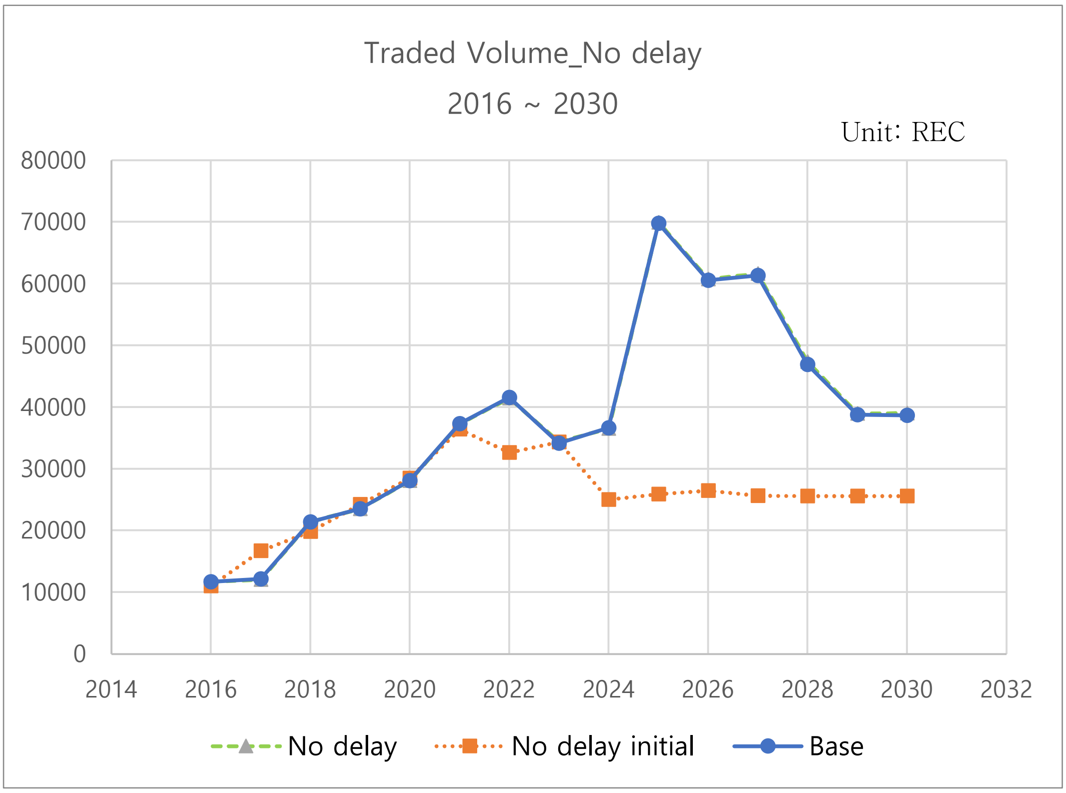
4.4 No Delay for New Entrants to the Market

To evaluate the effect of the immediate reaction of potential investors to the result of the market, in this scenario, we assume that investors can participate in the market of year T as soon as they decide to enter from the observation of market in year T-1. As in the case of the mandatory share increase scenario, only the delay condition is adjusted. Removing the delay to enter the market is applied in the code by changing the input of delay in [Figure 3-9] from 1 to 0. As the potential investors in the queue have a delay of 0, they will immediately enter the market following the logic presented in [Figure 3-10].



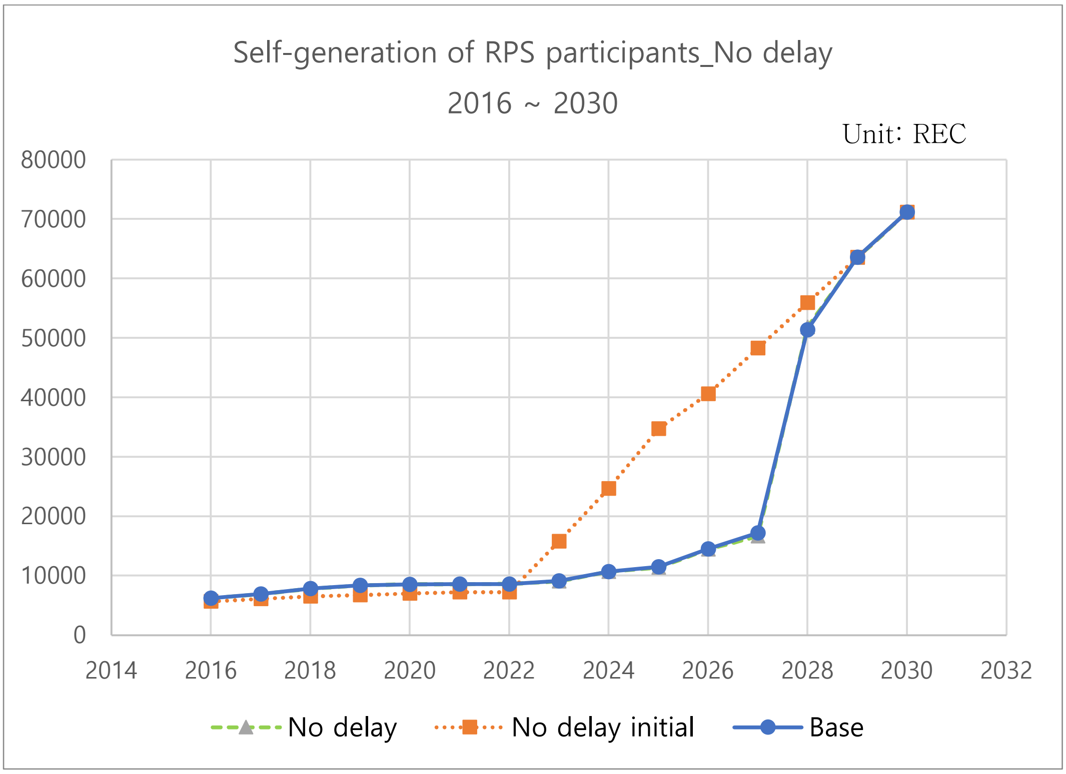
[Figure 4-10] Mean price of no-delay scenario.

In this scenario [Figure 4-10], our simulation expects that the no-delay scenario will show almost the same pattern of price change with base scenario; falling due to oversupply and recovering in the late 2020s due to lack of supply. With the assumption that there is no delay in entering from the start of the market, the mean price seemed to be less than the base scenario due to a faster increase of the supply and the lack of supply also occurs more quickly. However, from the initial higher price recovery of the no-delay scenario, we assume that the total amount of supply entering the market before the lack of supply in the scenario would be less compared to that of the base and no delay from 2023 scenarios.



[Figure 4-11] Traded volume of no-delay scenario.

From the graph above [Figure 4-11], as expected from the result of mean price, we can observe that the no-delay scenarios also show a stable pattern in traded volume in the late market due to a lack of REC supplied in the market. We can observe there is a bit more trade in earlier markets in the initial no-delay scenario and it results in an earlier lack of supply in the market with lower level REC supply compared to the other scenarios. It also matches our assumption from the price result that the higher recovery means lower supplies in the late market. The graph of no delay after 2023 scenario matches the result of mean price showing an almost similar pattern with the base scenario.



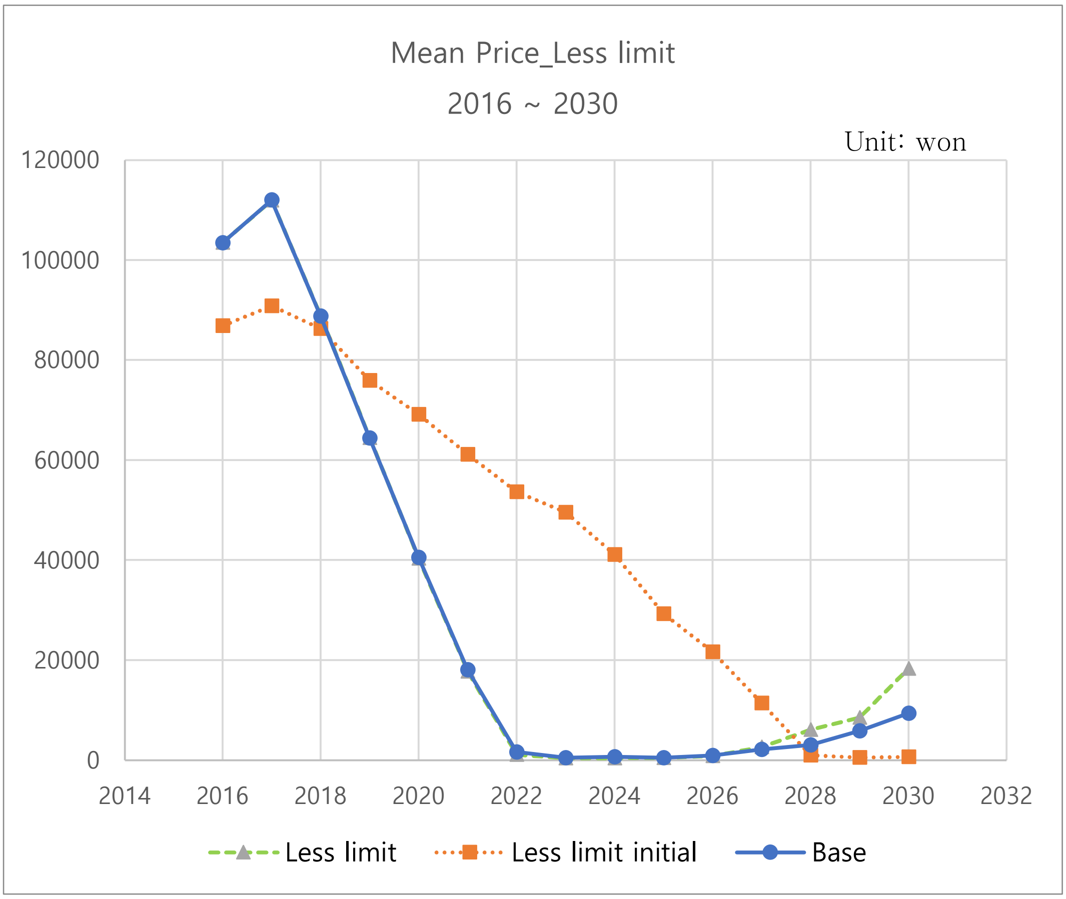
[Figure 4-12] Self-generation of RPS participants of no-delay scenario.

The result of self-generation of RPS participants in the no-delay scenario [Figure 4-12] gives the same message as the result of traded volume. In the initial no-delay scenario, as the market meets a lack of supply in early period, the RPS participants start to steeply increase their self-generation earlier than they do in other scenarios. We can interpret this as the allowance of faster entrants of potential investors can result in making the oversupply problem even worse. In the no delay after 2023 assumption, the graph of self-generation seems to be similar to the base scenario, just like the results of price and trade.

From the results of no-delay scenario, as both assumption of from initial and from 2023 no delay fails to achieve the goal in 2030, we can assume that reducing the delay of new entrants after 2023 would not help the market to achieve the desired goal. Additionally, the initial assumption also seems not to solve the fundamental problem of the market, making the problem of oversupply even worse, so we can say that it is not a better option that could be selected in the past at the start of the market.

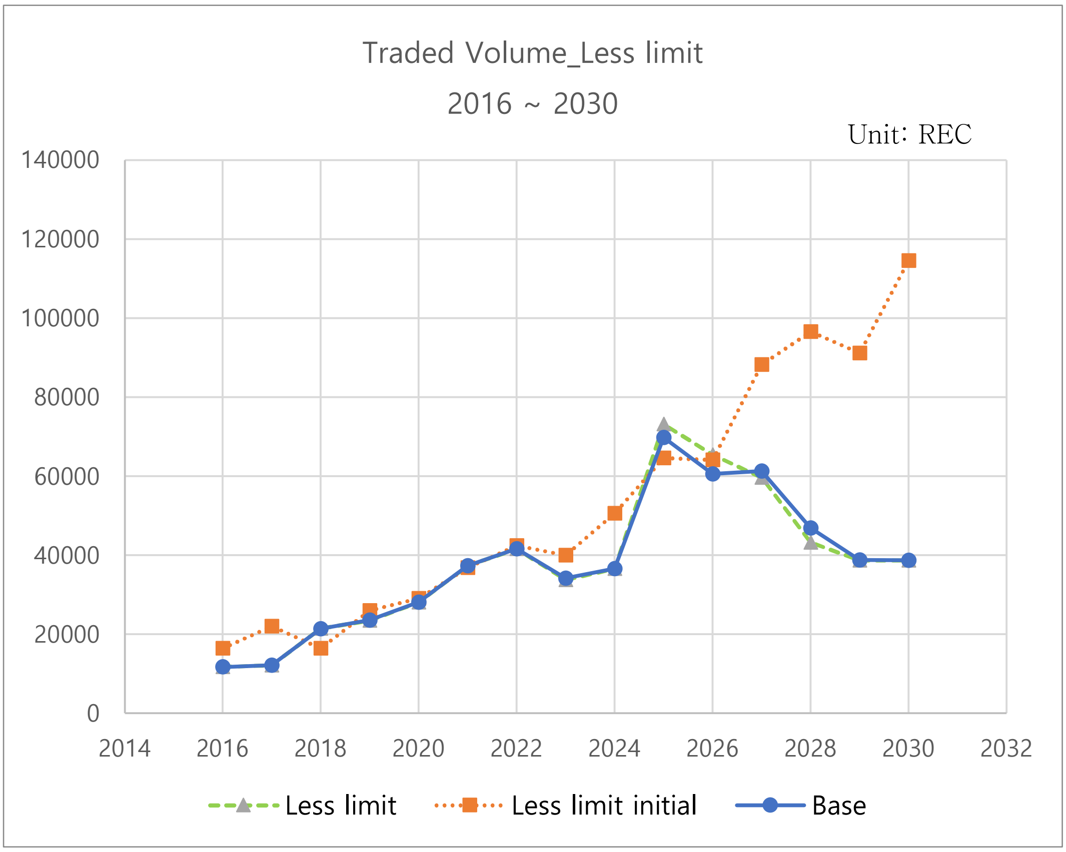
4.5 Less Limit for RPS Participants' Self-generation

For the other scenario, we simulated a market in which the limitation of RPS participants' self-generation to protect the small generation entrepreneurs moves to a lower level, meaning they should buy more from the market compared to the initial scenario. In this scenario, as shown in [Figure 4-13], the 50% limitation was adjusted to 30% in order to pressure RPS participants to buy more in the market rather than increasing their self-generation. This can be applied to the code by changing limitation in [Figure 3-8].



[Figure 4-13] Mean price of less limit scenario

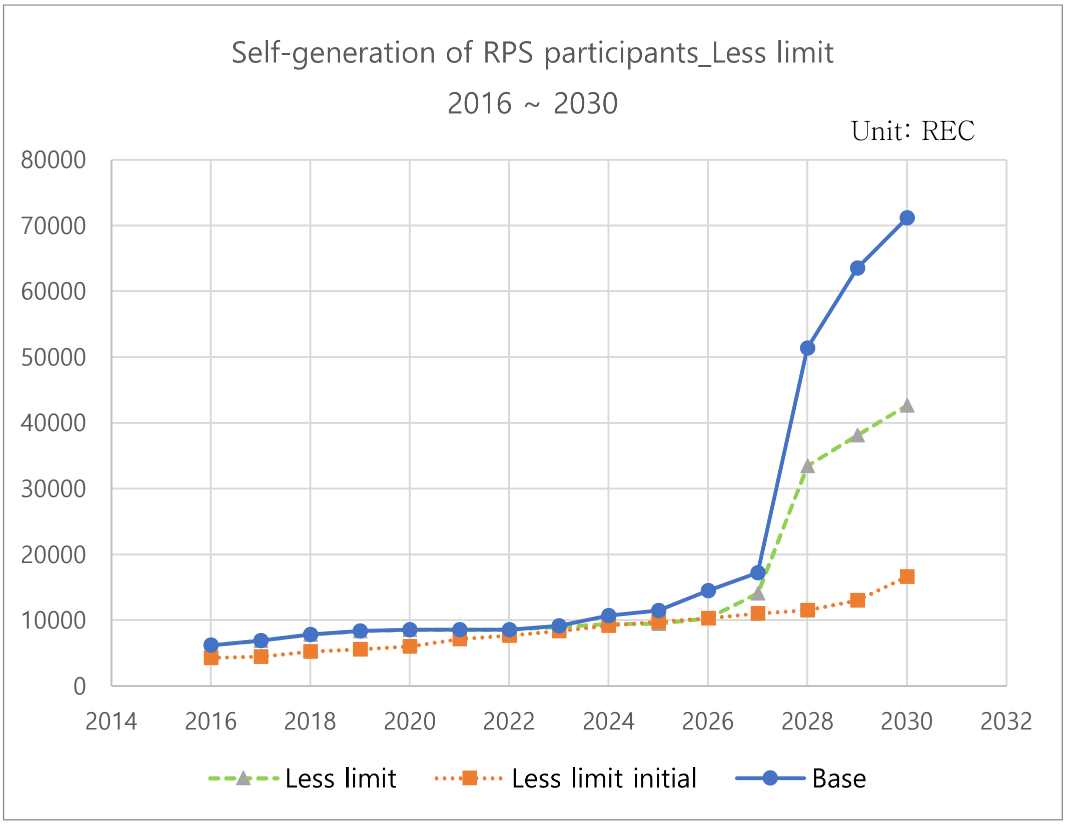
From the result, we can observe that the price seemed to be much higher in assumption of less limits from initial market. From the high price, we can expect that the potential investors may get positive signals from the market for a longer time compared to the base scenario. So, the price does not show the pattern of recovering, as the period when the demand exceeds the supply again does not come in the scenario and the price seems to keep falling even lower than the lowest price of the base scenario in the late 2020s. The result of scenario in which the limit goes lower after 2023 shows a similar pattern with the base scenario, but a bit higher price in the late market, which could occur from more demand in the less limit scenario as the RPS participants cannot generate as much as they can in the base scenario.



[Figure 4-14] Traded volume of less limit scenario

In the initial less limit scenario [Figure 4-14], we can observe that much more volume of REC compare to base scenario is traded in the market. As expected from the high price of the market, we can see that there are actually enough supplies to keep the graph of traded volume increase to significantly high peak than that of base scenario. For the falling pattern of traded volume here, it is expected to be occurred as there might be some suppliers do not want to sell their REC in the market since the price fell down to too low level at the last few years.

Alternatively, as expected from the results of price, we can observe the traded volume of less limit after 2023 scenario also seems similar to that of base scenario but a bit more volume is traded in the period of lack of supply. From the result, we can assume that lowering the RPS participants' generation limit can give positive signal to potential investors only for the short period after the policy adjustment, getting few new entrants in the market.



[Figure 4-15] Self-generation of RPS participants of less limit scenario

As they are used to buying a lot of REC in the market through long period, in [Figure

4-15], we can observe that initially in the less scenario, the self-generation of RPS participants increases very slowly, and not even half, compared to that of the base scenario and they still have a lot of spare capacity that they can increase to reach the goal of the last year if they are pressured not to make any carry-over.

Alternatively, the assumption of 2023 seems to fail to achieve the goal of 2030, as it meets lack of supply in congruence with the base scenario, but they generate less than the base scenario as they are blocked by the RPS rule of only generating 30% of their requirements. The later start of the steep increase of self-generation compared to the base scenario proves our assumption that there was positive signal to potential investors for a short period from the traded volume result.

As a result, we can assert that less limit conditions should be applied to the market from an earlier period to achieve the goal of 2030, and it might be already too late to make this possible. However, we observe that increasing the demand in the market by restricting self-generation of RPS participants will surely result in giving positive signals to potential investors from both scenarios related with the limitation.

Chapter 5. Conclusion

From the results of our simulations, we find the answer to our first research goal. According to our simulation, as we can see in the results of [Figure 4-5] and [Figure 4-6], the current market will fail to achieve the goal of Renewable Portfolio Standard (RPS), which will require RPS participants to supply renewable electricity in the amount of 28% of their facility capacity, not including RE generation. Although RPS participants take almost half of the total requirements with self-generation, which can be such a heavy burden for them, and some social challenges related to resource allocation also occur, they are consequently expected to fail.

According to our simulation, we can assert that to achieve the goal, the market should be started with more strict limitations on RPS participants' self-generation in order to push them to generate more demand in the market. From the results presented in [Figure 4-14] and [Figure 4-15], we can say that it might be too late, as the initial less limit scenario is the only scenario that demonstrates the possibility of achieving the goal with spare capacity to increase.

However, our simulation shows that some alternative scenarios, such as early increase and less limits after 2023 can give positive signals to potential investors so that they might decide to enter the market, although those scenarios consequently failed to achieve the goal. From those results, we can expect that such alternative scenarios can provide hints to policymakers endeavoring to make the policy possible to achieve the goal at the end, in 2030.

There are some limitations to this study. First, it considered only the spots market as the site where REC can be traded, but there are actually other options that solar generators can choose, like the contract market. Second, it only considered 12 markets per year, but the spots market is actually held twice a week, so there might be much more interaction effects that our simulation missed due to the small number of markets. Third, our simulation does not include the time pressure on the REC supplying agents that they must sell their REC in three years before the certificate expires. So, further study of this issue should be done trying to overcome the limitations above and to contain the full complexity of the actual REC market in Korea.

As mentioned earlier, due to the wide distribution of the results, the result figures are made with average value of 100 simulations for each scenario. For that reason, it is difficult to say that our simulation result is robust and clear. However, the meaning of this study is that we present a prefigurative simulation model for the renewable certificate market that can show the changing patterns of decision results of multiple agents in the market depending on the environmental conditions. The multi-agent simulation in this study can be developed into such an agent-based model for the REC market, adding more related agents who might have complex interactions with one another.

Beside to the limitations above, the development of a prefigurative simulation of the study to a robust methodology, controlling the randomness of variables and results is also recommended for further study.

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Abstract (Korean)

지구 온난화를 막기 위해 탄소 배출량을 저감하고자 하는 세계적인 추세에 따라, 한국 정부는 국내 재생 에너지의 비중을 늘리고 탄소배출량을 줄이기 위한 '재생에너지 3020 이행계획'을 발표한 바 있다. 신재생 에너지 공급 의무화(RPS)는 일부 대형 발전사에 대해 일정 비율 이상의 전력을 재생 에너지 발전으로 공급할 것을 강제하는 정책이다. 재생 에너지 공급 인증서 (REC)는 발전사가 재생에너지 발전을 통해 1MWh의 전력을 공급했음을 인정해주는 인증서로서 이는 거래를 통해 RPS 의무사들의 의무 충족에 활용될 수 있다. 이렇게 정부가 재생에너지를 장려하는 환경에서 많은 사람들이 발전 시장에 매력을 느껴 투자를 시작했고, 이는 결국 공급과잉으로 인한 REC 현물시장의 가격 하락 문제를 야기했다.

본 연구에서는 REC 시장에 대해 행위자 기반 모형 (ABM)을 사용하여 하나의 기준 시나리오와 4개의 대안 시나리오에 대한 예측 시뮬레이션을 수행하였다. 그 결과 기준 시나리오는 현재의 시스템이 2030년 달성하고자 하는 목표를 달성하지 못할 것으로 예측했다. 공급 의무, 시장 진입 지연, 자체 생산량

제한 등의 조건 변화를 통해 만들어진 시나리오에 대한 시뮬레이션을 통해 우리는 시장이 일찍부터 자체 생산량에 대해 더 강한 제약을 받고 있었어야 한다는 것을 확인할 수 있었다. 또한 앞으로의 정책 변화가 RPS 제도의 2030년 목표를 달성하는 모습을 보여주진 못했지만, 그러한 정책변화들이 잠재적 투자자들을 유인할 수 있는 긍정적 신호를 보낸다는 사실은 확인할 수 있었다.

시장을 온전히 재현하지 못했다는 한계점이 있으나, 본 연구는 REC 시장에 대한 거시 수준의 예측이 시장의 공급자 및 수요자들의 미시적인 결정에 대한 시뮬레이션으로 확인될 수 있다는 것을 보였다는 의의가 있다.

주요어 : 신재생 에너지 공급 의무화, 재생 에너지 공급 인증서, 다중 에이전트 시스템, 재생에너지 이행계획 3020

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