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Examination of excess electricity generation based on the 8th Basic Plan for long-term electricity supply and demand in South Korea

Philseo Kim[1a], So-Bin Cho[2a], Man-Sung Yim[1*]

1 Department of Nuclear and Quantum Engineering, KAIST, South Korea

2 Nuclear Engineering & Radiological Sciences, University of Michigan, United States
* Corresponding Author
[a] These authors contributed equally

ABSTRACT

According to the *Renewable Energy 3020 Implementation Plan* announced in 2017 by the South Korean administration, the electricity share of renewable energy will be expanded to 20% of the total electricity generation by 2030. Given the intermittency of electricity generation from renewable energy, the realization of such a plan implies potentially large excess electricity generation in certain situations. The purpose of this study is to propose a model to accurately simulate the effects of excess energy generation from renewables which would arise during the transition to South Korea's 8th Basic Plan for Long-term Electricity Supply and Demand. Our results show that the existence of excess power is highly likely when significant increases in generating capacity from PV and wind capacity are introduced, specifically in spring and fall. In addition, the planned ability to ramp down LNG plants will not be sufficient to cope with the excess energy produced by renewable intermittency. In this case, the role of coal-fired power plants through daily load-following operations could be essential to provide the grid system with additional operational flexibility. In addition, the role of nuclear energy would be vital to achieving both CO_2 emissions and electricity cost reductions as an alternative to the fossil fuel generation capacity (i.e., LNG and Coal) outlined in the 8th Basic Plan.

Keywords: renewable energy resources, nuclear energy, energy system modeling, excess electricity

NONMENCLATURE

Abbreviations

LNG	Liquified Natural Gas
EEC	Excess Energy Consumers
KPX	Korea Power Exchange
PV	Photovoltaics

Symbols

$P_{load,t}$	The electrical demand
$P_{Nuc,t}$ $P_{Coal,t}$ $P_{LNG,t}$ $P_{Ren,t}$	The generation (MW) at time t for each energy source: nuclear, coal, LNG and renewable, respectively
$P_{EEC,t}$	The number of participating Excess Energy Consumers (industrial loads) at time t
C_{Nuc} C_{Coal} C_{LNG}	The electricity cost (KRW/MWh) associated with nuclear, coal, LNG, and renewables, respectively
L_s	The minimum generation level
U_s	The maximum generation level
TC_s	The total installed capacity of each energy source s
r_s	The ramp rate of dispatchable generation technology of each energy source s
N_s	The total unit of generation resource s

1. INTRODUCTION

With its energy-intensive industrial structure, South Korea is being engaged with the challenging task of greenhouse gas emission reduction without encumbering continued economic growth. South Korea has committed to a 37% reduction in the forecasted greenhouse gas emissions, as outlined in the *Intended Nationally Determined Contribution* (INDC) in 2016 [1]. In this context, nuclear energy is well suited to provide the backbone of a non-emitting electricity generation system at all hours of the day and in all seasonal conditions.

However, according to the 2017 *Renewable Energy 3020 Implementation Plan* and the *8th Basic Plan for Long-term Electricity Supply and Demand* (8th Basic Plan), 20 % of the electricity demand is expected to be met by 58.5GW of renewable energy plants by 2030 [2,3]. This scenario poses challenges to the role of nuclear energy in South Korea's electricity sector as a baseload. The demand for flexible operation of nuclear power plants arises due to the fact that the maneuverability of liquefied natural gas (LNG) generators is insufficient to balance the demand and supply during the implementation of Korea's energy transition. Thus, when the target renewable capacity is deployed to the electricity mix, nuclear power plants may have to operate flexibly to accommodate both seasonal demand changes and net-load.

A recent study conducted by MIT indicates that the cost of achieving bold emission reduction goals increases significantly without the contribution of nuclear energy, and the least cost portfolios in the study always include a meaningful share of nuclear energy [4]. Moreover, a number of studies have shown that electricity generation with high renewable penetration is more economically and environmentally competitive when effective utilization of excess generation is exercised during some hours, rather than never allowing excess electricity generation [5,6]. This option is viable because significant energy demands and emissions associated with industrial and transportation sectors could be addressed by utilizing excess electricity. Since 2010 the U.S. has sponsored related research focusing on the potential link between nuclear and renewable energy sources. The Idaho National Laboratory (INL) has been conducting research since 2014 on how to better utilize excess energy from renewable energy sources to directly support the operation of energy-intensive industrial processes [7].

Based on developing a model to simulate the effects of increased use of renewable energy, this paper analyzed the excess energy generation profiles in South Korea based on using historical data from the Korea Power Exchange (KPX) along with the 8th Basic Plan.

2. METHODOLOGY

2.1 Scenarios

To simulate the possible excess energy generation behavior in Korea's declared electricity supply plan, four scenarios were defined to compare possible excess electricity generation management strategies, depending on the quantity and time distribution of surplus generation.

2.1.1 Scenario 1 – the base case

The reference scenario is to closely reflect the changes expected in Korea's evolving electric grid towards 2030. The monthly-averaged generation profiles are developed by scaling historical data of 2017 to renewable capacities envisioned in the 8th Basic Plan. This scenario evaluates seasonal variations in the excess energy generation pattern on a monthly basis. Then the results from April, July, October, and December are presented, illustrating changes in demand and supply of electricity along with weather conditions. The ramp-rate of baseload generations (i.e., nuclear and coal) is set at zero, while LNG plants are set to have ramping capabilities.

2.1.2 Scenario 2 - high and low renewable penetration case

The second scenario endeavors to capture the uncertainty and possible ranges of excess electricity generation on a monthly basis by recognizing Korea's distinct weather conditions throughout all seasons. The monthly-maximum and minimum renewable penetration data were used in this case. The comparison of excess energy generation between scenario 1 and 2 was conducted.

2.1.3 Scenario 3 - semi flexible operation of coal-fired generation/generators

The semi-flexible operation of coal power plants is considered in this scenario and compared to the scenario 1 to describe the option of reducing excess electricity from the baseload generation units. In Korea, to meet seasonal variations in electricity demand, coal power plants ramp down to minimum load, which is typically 50% of full power output [8]. This scenario explores the effectiveness of utilizing existing coal power plants along with LNG power plants in managing excess generation.

2.1.4 Scenario 4 - nuclear resurgence

The last scenario is to examine how Korea might reduce fossil fuel and CO_2 emissions from the industrial sector processes. In this scenario, the use of nuclear power as a reliable low carbon energy generator was considered. This nuclear resurgence scenario is compared with the base scenario with regards to the difference in electricity cost and CO_2 emissions.

2.2 Data and layout assumptions

In order to describe four different scenarios selected, different values of variables (i.e., hourly wind and solar generation profile, coal ramp rate, and installed nuclear capacity) were applied to each scenario. Table 1 describes the main components and assumptions used in this study.

Table 1 Description of study components and assumptions

Layout	Description / Assumption
Electrical Demand Load	• The electrical load pattern of South Korea in 2030 was defined by inflating the hourly average load profile for each month (April, July, October, and December) in 2017 by 30 %, considering how the electricity demand was formulated in the 8th Basic Plan
Electrical Grid	• The power grid was evaluated using the centralized dispatch approach, where full transmission of electricity is available. Electricity loss during transmission and distribution were not considered in this study. • The grid represents a system where all dispatchable and non-dispatchable units are electrically coupled and sell electricity into a single wholesale market.
Renewable Sources (Non-Dispatchable)	• The PV and wind target values of the 8th Basic Plan were used, and other renewable sources were neglected • The generation profile for 33.53GW of PV was evaluated by scaling up the hourly generation profile from the 3.5MW Hadong PV station in South Korea [9]. • The generation profile for 17.7 GW of Wind was evaluated by scaling up the hourly generation profile from the Seongsan Wind 8 MW Unit in Jeju, South Korea [10].
Dispatchable Energy Sources	• Coal total installed capacity: 39.9 GW/70 units • LNG total installed capacity: 44.3GW/200 units • Nuclear total installed capacity: 20.4GW/18 units • Unlike nuclear, the exact number of planned coal and LNG generation units for 2030 has not been fixed, so we estimated the number of units by dividing target capacity values by typical generation capacity values per unit (i.e., 500MW/coal generation unit and 200MW/LNG generation unit). • We assumed 20MW/min LNG and 10MW/min Coal power plants would be ramped, reflecting the current operation of these generation technologies in South Korea [8]. • In scenario 4, each energy total capacity/power plants units are: 34.06GW/30units (Nuclear), 29.9GW/50units (Coal), and 34.3GW/150units (LNG)
Excess Energy Consumers (EEC)	• To manage the time mismatch that can occur between fluctuating production and demand, Excess Energy Consumers (EEC) were assumed. • EECs are end-users whose industrial loads are traditionally met by baseload energy sources. • Each EEC is assumed to require 20 MW of grid frequency regulation following Cho and Yim [6]. • It is assumed that there is no limit to the capacity of EECs available at each time interval, allowing us to assess the excess electricity that can be consumed in this simulation.
Electricity Cost	• To represent the current cost of electricity generated by different sources in Korea for the simulation, wholesale electricity price data is obtained from KPX [11]. • The collected data were averaged over January 2017 to December 2019.

2.3 Optimization Calculation

The calculation model performs two tasks. First, it simulates the balance of electricity (i.e., supply and demand of electricity) over each hour throughout the day (i.e., 24 hours), prioritizing the use of renewables up to their installed capacity. The balance equation used was:

$$P_{load,t} + 20 \cdot P_{EG,t} = P_{Nuc,t} + P_{Coal,t} + P_{LNG,t} \quad (1)$$

$$\min Cost = \sum_t [P_{Nuc,t} \cdot C_{Nuc} + P_{Coal,t} \cdot C_{Coal} + P_{LNG,t} \cdot C_{LNG}] \quad (2)$$

$$P_{Net,t} = P_{load,t} - P_{Ren,t} = P_{Nuc,t} + P_{Coal,t} + P_{LNG,t} - 20 \cdot P_{EEC,t} \quad (3)$$

$$P_{Nuc,t}, P_{LNG,t}, P_{Coal,t} \in R,\ P_{EEC,t} \in Z \text{ for all } \forall t \quad (4)$$

$$L_s \cdot TC_s \le P_{s,t} \le U_s \cdot TC_s \text{ for all } \forall t, \forall s \quad (5)$$

$$|P_{s,t+1} - P_{s,t}| \le r_s \times N_s \ \ \forall t, \forall s \quad (6)$$

Second, optimization calculation was made with the calculation model by using mixed-integer linear programming. The calculation was to determine optimal operation strategies for a given set of generation sources and operational constraints, while minimizing total cost. The model also includes the consideration of excess generation consumers. Table 2 shows the variables and their values for each scenario.

Table 2 Summary of the variables and their values in each scenario of energy mix

Energy Sources	Variables	Scenarios 1	2	3	4
Coal	TC_s / N_s	39.9 / 70	39.9 / 70	39.9 / 70	29.9 / 50
	r_s (MW/min)	0	0	10	0
	L_s (%)	80	80	50	80
	U_s (%)	80	80	80	80
LNG	TC_s / N_s	44.3 / 200	44.3 / 200	44.3 / 200	34.3 / 150
	r_s (MW/min)	20	20	20	20
	L_s (%)	30	30	30	30
	U_s (%)	100	100	100	100
Nuclear	TC_s / N_s	20.4 / 18	20.4 / 18	20.4 / 18	34.06 / 30
	r_s (MW/min)	0	0	0	0

	L_s (%)	85	85	85	85
	U_s (%)	85	85	85	85
Renewable Energy	Statistical Data	Average	Max and Min	Average	Average

3. RESULTS

3.1 The base case

Fig.1 shows how a combination of energy sources accommodates the demand of April, July, October, and December under Scenario 1 (hourly resolution), representing four distinct seasons in South Korea. The highest level of renewable electricity penetration (~15%) occurred in the spring (April) and fall (October), while the summer and winter have the lowest (~8%). Regarding the demand trend, the lowest electricity demand peak occurs in the Spring (April) and Fall (October) at about 75GW, and the highest electricity demand peak is in the summer (July) and winter (December) at over 90GW for the predicted 2030 demand.

The results show that a mismatch between renewable penetration and electrical demand leads to variations in excess energy production (see Fig.1.) As shown in the spring and fall, cost-effective grid management is imperative to incorporate a large generating capacity of clean energy.

3.2 High and low renewable penetration

Fig.2 presents the excess energy evaluated from three different penetration levels (i.e., maximum, average, and minimum penetration of renewable energy that occurs during each month of the year). Oversupply from PV is highly likely in fall as Korea has favorable weather conditions (e.g., fewer rain clouds and moderate temperature) for PV in fall, thereby increasing excess electricity even when the combined renewable penetration (wind plus PV) is at the lowest (see the fall case in Fig.2.).

When the penetration of renewable energy is at its maximum, excess electricity becomes dominant across seasons.

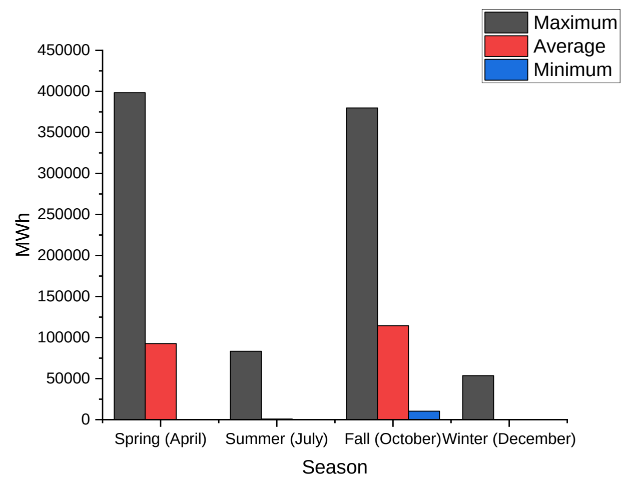

Fig.2. Excess energy generation from different renewable penetration

3.3 Semi flexible operation of coal-fired generation

In this scenario, the excess energy generation was significantly reduced, compared to the previous results from Scenario 1 and 2. As shown in Fig.3, the amount of excess energy generation occurring in April highly depends on coal-fired power plants' load following capabilities. Fig.3(b) indicates that the amount of excess power in April can be reduced by ramping down coal-

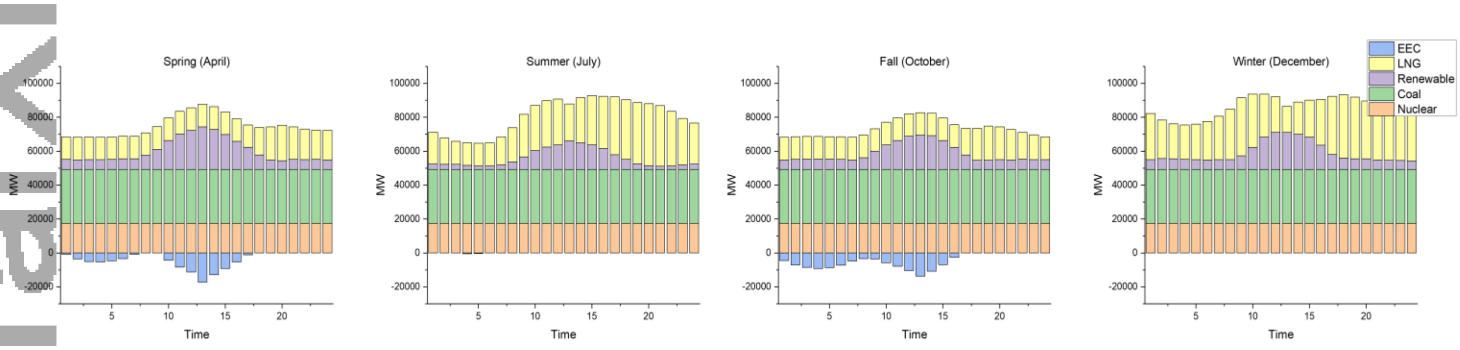

Fig.1. The seasonal variations in the estimated excess electricity generation under Scenario 1

fired power plants at a rate of about 10 MW/min to a 50% level. However, it is hard to completely eliminate excess energy generation. This strategy implies how the Korean electric power system can be managed by leveraging existing generation resources. As indicated in the 8th Basic Plan, coal and LNG power plants are expected to power down when low electricity demand or high renewable penetration is expected. However, though coal is regarded as one of the flexibility providers, it is insufficient to completely eliminate excess energy generated. As such, it is necessary to identify additional industrial end-users that could benefit from excess electricity utilization.

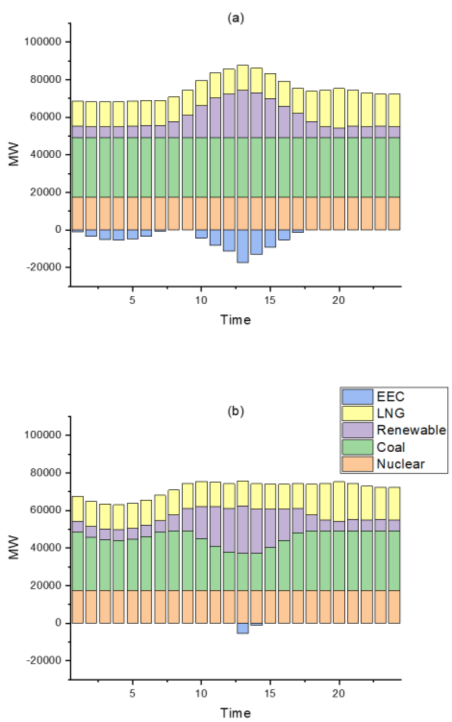

Fig.3. Simulation reuslts of scenario 3 in Spring (April)
(a) Spring result in scenario 1 (without coal ramp)
(b) Spring result in scenario 3 (with coal ramp)

3.4 Nuclear resurgence

In this scenario, the base case scenario in 3.1 (Nuclear: 20.4 GW, Coal: 39.9 GW, LNG: 44.3 GW) was compared to the nuclear resurgence scenario (Nuclear: 34.06 GW, Coal: 29.9 GW, LNG: 34.3 GW). The comparison was concerning the purchase price of electricity (for KPX), greenhouse gas emissions, and excess energy generation.

Table 3 Comparison of the cost of electricity, CO2 emissions, and excess energy generation between the nuclear phase-out and the resurgence scenario

	Total Cost (Billion KRW)		CO_2 Emissions (Million ton)		Excess Energy Produced (MWh)	
Month	Scenario 1	Scenario 4	Scenario 1	Scenario 4	Scenario 1	Scenario 4
Spring (Apr.)	154.43	146.72	0.88	0.69	92640	102740
Summer (July)	172.77	164.12	1.00	0.80	760	2700
Fall (Oct.)	150.52	142.83	0.88	0.68	114400	124640
Winter (Dec.)	186.49	177.61	1.03	0.82	0	0

Table 3 compares how the results vary with four distinct seasons in terms of total cost, CO_2 emissions, and excess energy produced. As the capacity of nuclear energy is increased, the greenhouse gas emissions are significantly reduced. The price of electricity becomes competitive under the nuclear resurgence scenario compared to the base case. Excess energy generation also shows a similar pattern between scenario 1 and 4. The results confirm that nuclear energy is an energy source with lower greenhouse gas emissions and lower generation costs in comparison to other baseload energy sources.

3.5 Policy Implications of the results

The excess electricity generation in South Korea are expected to drive applications involving a symbiotic business relationship between a nuclear power company and an industrial demand response. In a carbon-constrained world, the industrial demand response (e.g., hydrogen production) at a nationwide scale will likely to considerably increase the required amount of low-carbon energy (i.e., nuclear and renewable) while meeting the industry's goals of carbon emission reductions and economic competitiveness. Our analysis shows that unsynchronized generation patterns formed from baseload nuclear plants and non-dispatchable renewables (mostly PV) will make up a majority of surplus generation in Korea's future grid. As such, the Korea Government may implement policies to trigger grid management technology innovations and regulatory arrangement that maximizes excess electricity utilization for all electricity suppliers and demand response markets. This regulatory arrangement could include: (1) join task force retaining authorities over plant licensing security and emergency planning, (2) flexibility in non-electric use of nuclear power generated energy, (3) rearrangement of ownership of business models. It will also be essential for market expansion to establish national standards for excess electricity production, transmission, and utilization.

4. CONCLUSION

This study analyzed potential excess energy generation in South Korea based on the 8th Basic Energy Plan, where renewable penetration becomes significant by 2030. The analysis examined the optimum use of nuclear, coal, and LNG resources to minimize electricity generation costs under the scenario of large-scale renewable energy penetration. A mixed-integer linear programming method was used to formulate an optimal dispatch schedule based on the capacity of available power generation sources. This optimization scheme included matching the hourly supply of all generation sources and electricity demand to minimize the total cost of electricity.

Our study on South Korea's renewable initiative for 2030 has led to following observations. First, there is a high probability of generating excess electricity when PV and wind output remains high, especially in spring and fall. Second, despite its cost and CO_2 emissions, LNG generation capacity in Korea will remain important to support the current renewable expansion policy. Our analysis, however, shows the flexibility of the LNG fleet will be insufficient to address intermittency and to handle the related excess energy produced by renewable sources. Subsequently, the load-following operation of coal-fired plants (or nuclear power plants) is expected to be necessary. Third, to achieve both CO_2 emissions reduction and minimizing electricity cost, it is crucial to recognize the value of reliable low-carbon generation technologies. Nuclear power would be the main beneficiary of such policy, as it is the only non-emitting baseload generator for South Korea. Lastly, our results suggest that South Korea should develop plans for and catalyze the practical use of excess electricity generation.

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