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ORIGINAL ARTICLE

Analysis on Configuration Scheme of Power Sources in Future Power System of Korea

Heesung Moon[1] · Yoonsung Cho[2] · Gilsoo Jang[1]

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Abstract
The global energy system is moving toward sustainability to address critical challenges such as climate change, environmental pollution, and energy security. A key aspect of this transformation is shifting to renewable energy sources and reducing carbon emissions. However, integrating renewable energy into the power grid poses challenges for stability due to variability and intermittency. South Korea, with its high dependence on fossil fuels and an industrial-based economy, exemplifies the complexities of this transition. This study aims to support South Korea's energy transition by estimating future power demand and analyzing the power mix required to achieve the 2050 carbon-neutral target. The study employs linear regression and sigmoid-type logistic functions to forecast future demand and generation capacity, analyzing generator configurations based on seasonal and hourly usage patterns. Furthermore, the study calculates annual energy production and designs seasonal and hourly scenarios to provide insights into renewable energy integration strategies. The study also emphasizes the importance of Long-Duration Energy Storage (LDES) systems in addressing the variability of renewable energy and ensuring stable grid operation. It presents a stable grid operation model that minimizes fluctuations in the output of conventional generators while storing PV output and redistributing load during other time periods.

Keywords Carbon-neutral · Renewable energy sources · Power systems

1 Introduction

Global energy systems are undergoing a profound transformation driven by the urgency to address challenges like climate change, pollution, and energy security. At the heart of this transformation is a focus on sustainability and reducing carbon emissions.

The 2021 World Energy Outlook by the International Energy Agency emphasizes the urgent need to accelerate clean energy innovations and expand renewable energy to meet 2050 climate targets. This shift has driven the development of energy systems in countries rich in renewable resources, laying the foundation for energy revolutions worldwide. These developments reflect a global trend to reshape power generation and consumption, aligning them with sustainability and carbon neutrality goals [1].

Despite the increasing deployment of renewable energy sources worldwide, the transition to clean energy systems presents significant challenges. Renewable sources like solar and wind are inherently variable, causing fluctuations in electricity output that directly impact grid stability. Traditionally, coal and natural gas plants have played a crucial role in compensating for these fluctuations. However, as countries reduce their reliance on fossil fuel-based generators to align with carbon-neutral policies, the diminished capacity of these systems further exacerbates grid instability. This dual challenge of renewable energy variability and reduced backup capacity underscores the complexity of integrating large-scale renewable sources into power systems, necessitating innovative solutions and strategic planning to ensure grid reliability and resilience.

✉ Gilsoo Jang
gjang@korea.ac.kr

Heesung Moon
mhksun@korea.ac.kr

Yoonsung Cho
philos@cu.ac.kr

1 Department of Electrical Engineering, Korea University, Seoul, Korea

2 Department of Electrical Engineering, Catholic University of Deagu, Deagu, Korea

South Korea, with its high dependence on fossil fuels and a manufacturing-driven industrial economy, exemplifies the challenges and opportunities of this global energy transition. Over the past 30 years, South Korea's average temperature has risen by 1.4 °C, reflecting the accelerating impacts of climate change. In response, the South Korean government has announced two major policy agendas: the 2050 Carbon Neutral Scenario and the enhanced 2030 Nationally Determined Contribution (NDC). These initiatives aim to reduce greenhouse gas emissions by 40% from 2018 levels by 2030 and achieve net-zero emissions by 2050. Meeting these targets will require a comprehensive transformation of South Korea's power system [2].

The future of South Korea's energy system hinges on the integration of renewable energy sources, particularly solar and wind, into its power grid. However, the variability and intermittency of these sources pose significant challenges to the stable operation of the grid. To address these challenges, it is essential to analyze renewable energy generation characteristics and develop strategies that account for seasonal and hourly variations in supply. Detailed scenarios are necessary to ensure that renewable energy generation aligns with demand patterns, maintaining grid stability while meeting energy needs.

Long-duration energy storage (LDES) systems play a key role in mitigating the variability of renewable energy. These systems can store excess energy generated during peak production periods and release it during low-output periods, addressing imbalances between supply and demand. By enhancing grid flexibility and reliability, LDES can facilitate the integration of renewable energy and ensure a stable transition to a low-carbon energy system.

Table 1 Results of annual demand forecast using linear regression method

Year	Gross load (GW)	Power generation (TWh)
2035	132.6	690.7
2036	135.6	703.2
2037	136	742.4
2038	137.8	754.3
2039	140.3	766.1
2040	142.7	778
2041	145.2	789.8
2042	147.7	801.7
2043	150.1	813.6
2044	152.6	825.4
2045	155.1	837.3
2046	157.5	849.2
2047	160	861
2048	162.5	872.9
2049	165	884.8
2050	167.4	896.6

This study aims to support Korea's energy transition by estimating the future electricity demand needed to achieve the 2050 carbon neutrality goal and analyzing the electricity mix. Future demand was predicted using linear regression methods, and the capacity was analyzed according to trends of existing generators and changes in renewable energy sources. In addition, the problem was derived by calculating the seasonal hourly power generation of generators according to demand and emphasized the importance of LDES systems in resolving the imbalance in energy volume over seasonal time and ensuring stable power grid operation.

2 Analysis on Configuration of Load and Power Sources

2.1 Load Prediction

Based on the data from the 10th Basic Plan for Long-Term Electricity Supply and Demand, the projected demand for 2022–2036 is derived from the standard demand outlined in the plan. Since this refers to electricity consumption over time rather than total generation capacity, it was converted into the required generation capacity. In this study, linear regression was used to estimate the demand capacity.

Linear regression models the relationship between a dependent variable y and one or more independent variables X. Historical data on generation and demand capacity from 1996 to 2022 was analyzed to predict future power demand [3]. The method assumes a linear correlation between the variables, which was confirmed using Pearson's correlation coefficient and scatterplot analysis [4].

Pearson's correlation coefficient, calculated as shown in Eq. (1), was preferred over Spearman's rank correlation coefficient. A correlation of 0.994 indicates 99.4% linearity between generation capacity and peak demand, validated further by consistent scatterplot patterns [5, 6] Table 1.

Forecasts for 2036 align with the requirements of the 10th Basic Plan. From 2036 to 2050, future power demand was projected based on the trendline derived from the linear regression analysis.

$$\rho = \frac{\sum_i^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_i^n (X_i - \bar{X})^2}\sqrt{\sum_i^n (Y_i - \bar{Y})^2}} \tag{1}$$

To achieve carbon neutrality, the configuration of power generators must also change considerably. As the demand capacity for 2050 is predicted, the capacity of the synchronous generators must also be appropriately selected.

Regarding seasonal and hourly utilization rates, generators other than renewable energy sources generally vary based on the demand. The seasonal and hourly utilization rates were determined by calculating the ratios based on the seasonal and hourly demand based on the annual capacity factor of the currently operated generators. For solar and wind power, which will account for many future renewable energy sources, the output does not follow the demand but varies with the surrounding environment, which includes the effect of seasonal and hourly factors. Historical data on the output relative to the installed capacity of solar and wind power were used to determine the seasonal and hourly utilization rates [7–10].

2.2 Power Sources Prediction

Achieving carbon neutrality necessitates a comprehensive transformation of power generation configurations, with particular attention to appropriately determining the capacity of synchronous generators in alignment with the forecasted demand for 2050.

Seasonal and hourly utilization rates for non-renewable power sources are predominantly driven by fluctuations in demand. These rates were calculated using the annual capacity factors of currently operational generators, adjusted proportionally to seasonal and hourly demand variations.

For conventional power generation, capacity projections were based on existing plans and energy output forecasts for 2050. The envisioned future power grid prioritizes nuclear energy and carbon-free turbines as its central components to meet carbon neutrality objectives. In the case of cogeneration units, configurations were constrained to maintain only the minimum levels required for addressing current thermal constraints.

With power demand and synchronous generator capacity calculated, the capacity of renewable energy generators must also be determined, considering power supply and demand. While there is limited data on renewable energy compared to demand and synchronous generators, renewable capacity is expected to grow significantly to achieve carbon neutrality targets. This study estimates the future capacity of renewable energy by predicting facility capacities for each energy source.

To forecast renewable energy capacity, data on regional growth rates and constraints is essential. Growth rates encompass variables such as grid integration capacity, Levelized Cost of Electricity (LCOE) for renewable projects, and external factors like delays, community opposition, or litigation. Growth constraints, meanwhile, define the theoretical or market-based maximum capacity for renewable energy generation within a region. By analyzing correlations between actual performance data and these regional variables, the study identifies key relationships, leveraging them as weighted inputs to predict regional capacities [11].

The method of predicting the capacity of the region based on the collected data is based on a sigmoid-type logistic function, and the formula is as follows [12].

$$f(x) = \frac{1}{1 + e^{-t}} \tag{2}$$

The two main factors influencing renewable energy capacity in a region are the Growth Ceiling (the maximum renewable energy capacity achievable in a region) and the Pace of Growth (the speed at which renewable energy capacity can grow). These two factors incorporate the regional characteristics of renewable energy. The Growth Ceiling reflects the elements affecting the renewable energy capacity of a region, acting as the attainable maximum capacity when multiplied by the market potential Fig. 1.

This predictive model estimates renewable energy capacity within a range defined by an Ideal Logistic value and a Reference Logistic value, considering regional characteristic variables. The Ideal Logistic value represents the theoretical maximum capacity required to achieve the full market potential of solar energy by 2050. In contrast, the Reference Logistic value is derived from the observed solar generation performance as of December 2021, serving as a baseline for comparison. To enhance accuracy, the model incorporates regional factors, which are analyzed and weighted based on specific characteristics unique to each region, such as geographic conditions, economic development levels, and existing energy infrastructure.

When irregularities in data, such as missing information, inconsistencies, or insignificant trends in actual capacity or potential growth, are identified, the model defaults to an arithmetic mean growth estimate. This fallback approach ensures that projections remain reasonable and reliable even when data quality is compromised.

In this study, the predictive model was applied to estimate the future capacity of renewable energy sources, specifically solar and wind power. The results indicated that the solar power capacity is expected to reach 119.81 GW by 2050, representing significant growth driven by advancements in technology and policy support. Similarly, wind power capacity was predicted to grow to 68.4 GW by 2050, reflecting its increasing role in the renewable energy mix. These projections highlight the potential for substantial expansion in renewable energy generation, supporting global efforts toward achieving a sustainable and low-carbon energy future.

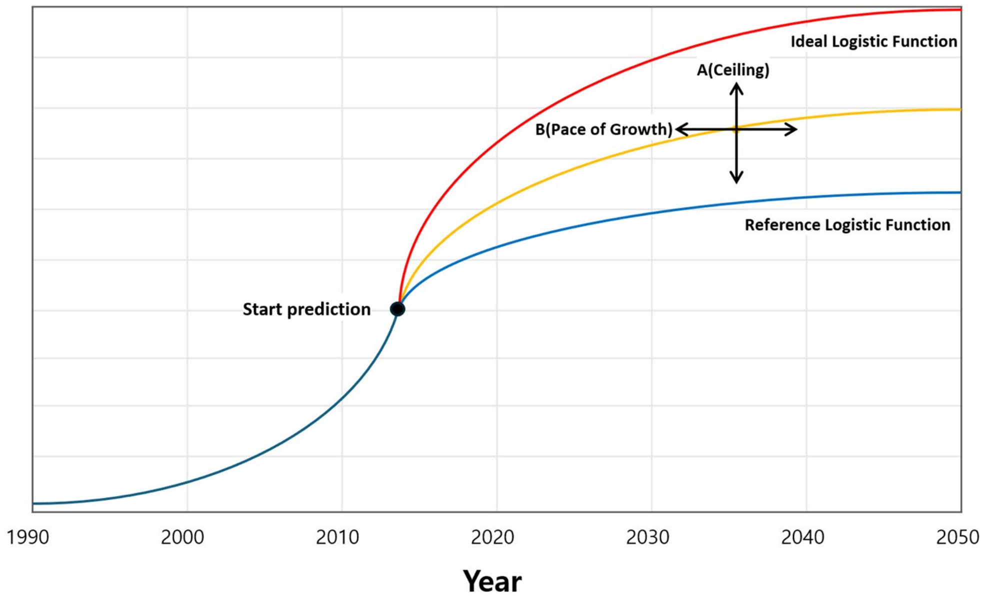


Fig. 1 Facility capacity calculation method of renewable energy area forecasting model

Table 2 Table of facility capacity by power source

Source	Facility capacity (GW)
PV	119.81
Onshore wind	22.4
Offshore wind	46
Nuclear	19.2
LNG & Carbon-free power	84.6
Coal	0
hydropower and pumping	10
Combined heat & power	11.1

Table 3 Results of demand and electricity calculations by period

Season	Time	Hour	Load (GW)	Power Output (GWh)
Spring	Morning	456	110.63	50,499
	Daytime	639	118.94	76,002
	Evening	456	122.13	55,692
	Night	639	110.44	70,572
Summer	Morning	456	113.13	51,587
	Daytime	639	137.94	88,145
	Evening	456	139.5	63,610
	Night	639	115.92	74,073
Autumn	Morning	456	110.79	50,520
	Daytime	639	122.17	78,065
	Evening	456	127.16	57,984
	Night	639	110.62	70,683
Winter	Morning	456	126.9	57,865
	Daytime	639	137.51	87,866
	Evening	456	137.75	62,814
	Night	639	124.99	79,871

2.3 Summary of Facility Capacity, and Capacity Factor Rates

The previously studied content, facility capacity, and capacity factor of the power source are summarized in Table 2. According to the carbon-neutral scenario, the facility size of renewable energy sources will increase significantly, and other power plants will likely be implemented by maintaining their status or changing to power plants that do not emit carbon.

The capacity factor of renewable energy sources is low because it changes depending on the season and time. In the case of nuclear power plants, LNG, and carbon-free power sources, the capacity factor is high because continuous output is possible if there is sufficient raw material.

3 Methodology

Traditional long-term grid planning methodologies have historically focused on developing annual base cases for future systems centered around peak load scenarios. These assessments typically involved examining various load levels, such as 100%-80% of peak load, under the assumption that power generation sources remained stable while only load variability was considered.

However, with the growing dominance of renewable energy sources like wind and solar, characterized by their intermittent nature, new challenges emerge, including heightened variability and uncertainty. Addressing these complexities necessitates a paradigm shift in the development of annual base cases for future grids, incorporating the unique dynamics of renewable energy systems.

This study identifies significant seasonal and hourly problems by evaluating energy patterns on an hourly basis by considering the fluctuating nature of renewables and describes a strategic path to achieving improved grid stability and integration in renewable energy-centric energy systems.

Based on previous studies, a carbon-neutral scenario was analyzed to calculate the annual energy consumption of the power source using the power load, power generation facility capacity, and capacity factor of the power source. To derive the scenario by time, each season and time were classified into four groups, and the classification conditions by group were as follows [13].

Seasons:

- Spring (March, April, May).
- Summer (June, July, August).
- Fall (September, October, November).
- Winter (December, January, February).

Times of Day:

- Morning (5 AM −9 AM).
- Daytime (10 AM −4 PM).
- Evening (5 PM −9 PM).
- Night (10 PM −4 AM).

The amount of energy multiplied by the required demand, the number of hours, and demand according to the classified time zone and the corresponding time, and the required demand level is shown in the following table.

The demand for each period was expressed by multiplying the maximum demand, 167.4 GW, by the demand level for each period, and the amount of power for each period was calculated by multiplying the demand by the number of hours.

4 Case Study

4.1 Base Case

In cases where seasonal and hourly power generation falls short, additional generators can be deployed to balance supply and demand. However, this study aligned annual power generation with demand, demonstrating that the sum of curtailed renewable energy and the shortfall in generation equals zero. This implies that if the curtailed energy is stored and utilized to address the shortfall, it would be possible to achieve an annual energy balance, ensuring efficient energy management.

Figure 2 highlights that other generators produce substantial output in response to demand, primarily due to the large installed capacity of photovoltaic systems during daylight hours, resulting in supply-demand imbalances. To assess this dynamic, the required load and actual power generation were analyzed. The results indicate that LNG generators and carbon-free generators play a critical role in managing the variability of renewable energy, ramping down as solar output peaks during the day. Despite a significant increase in the installed capacity of future renewable energy sources, LNG and carbon-free generators continue to handle a substantial share of the energy supply. However, their output exhibits considerable fluctuations over time, driven by the inherent variability of renewable energy generation.

Figure 3 shows a graph excluding the amount of power generation from demand to see if supply and demand are aligned in all seasons and time zones.

In Fig. 3 clearly demonstrate a significant surplus of electricity during the spring season, driven by a notably higher output from photovoltaic (PV) systems compared to other seasons. This seasonal advantage suggests that a strategic adjustment of LNG and carbon-free generators in response to the heightened PV output could potentially facilitate a balanced supply and demand scenario on an hourly basis.

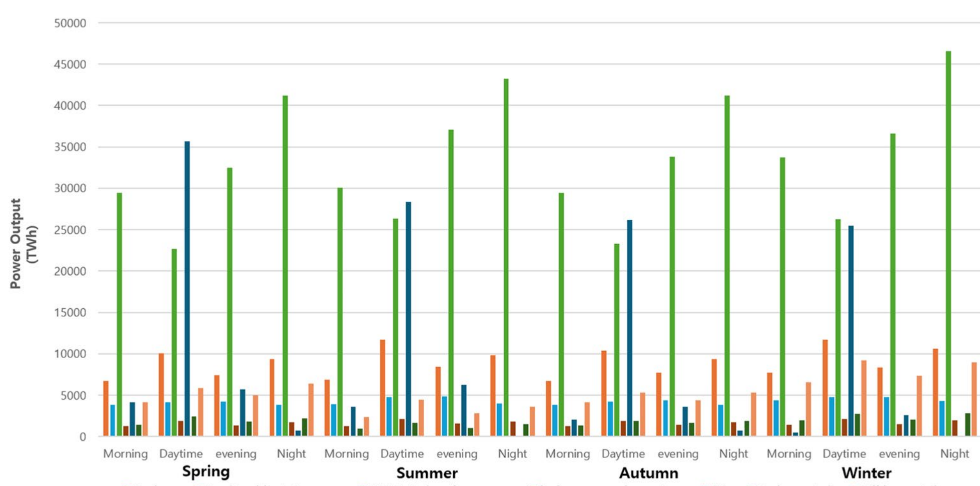


Fig. 2 Seasonal and hourly power generation calculation results (GWh)

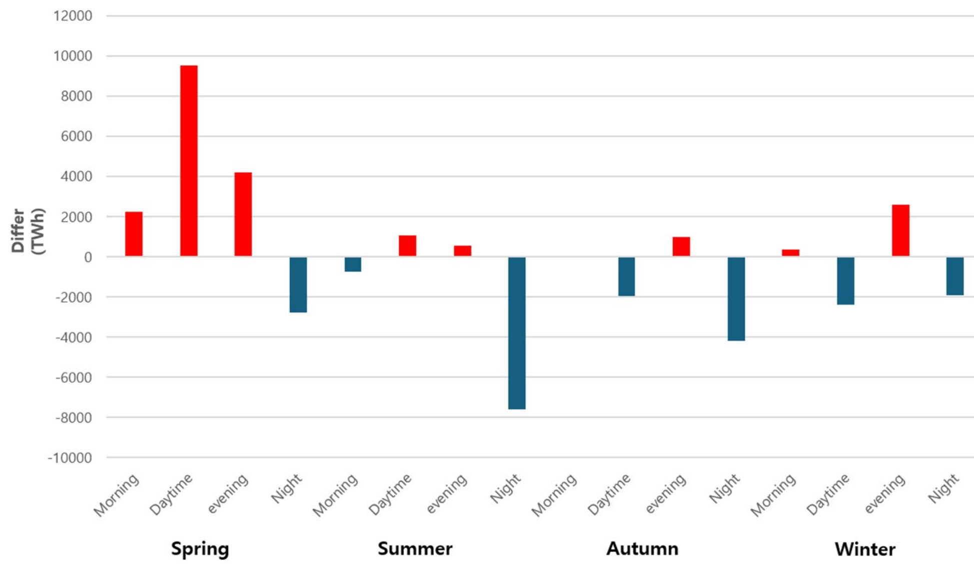


Fig. 3 Seasonal hourly energy surplus

However, to achieve such balance, several critical factors must be meticulously addressed. Notably, consideration must be given to the continuous operation of generators, which cannot be easily shut down or restarted. Furthermore, the ability of retrofitted carbon-free generators originally derived from traditional turbine plants to rapidly adjust their output in response to fluctuating demand must be carefully evaluated to determine their viability in handling such dynamic changes.

In the spring, the fluctuation in output from LNG and carbon-free generators during different times of the day—morning, daytime, and evening—reaches approximately 10,000 TWh. When examined on an hourly basis, this variability translates to a required output fluctuation capacity exceeding 30 GW. This underscores the substantial flexibility needed from the power generation fleet to accommodate such sharp changes. While adjusting the output of existing generators is one approach to addressing this variability, another critical strategy involves curtailing the excess PV output, which can experience significant spikes during certain hours. This curtailment, however, can lead to considerable energy waste, reducing the overall efficiency of the power system.

4.2 Supply and Demand Balance Using LDES

LDES (Long-Duration Energy Storage) technology has the advantage of being able to store energy for periods ranging from several hours to days. This allows for better management of generation and consumption, reducing the need for fuel-based power plants during peak demand periods in electricity systems rich in renewable energy [15].

As a result, carbon emissions can be reduced, energy security can be strengthened, and consumer energy costs can be lowered. These benefits make LDES a key option for providing flexibility and stability in future decarbonized power systems [16, 17].

However, the development and implementation of LDES technologies, excluding pumped hydro storage, are still in the early stages and face challenges such as cost, scalability, and regulation. Nevertheless, the continued growth of renewable energy sources and the need to address climate change are expected to accelerate the decarbonization of the electricity sector using LDES technologies.

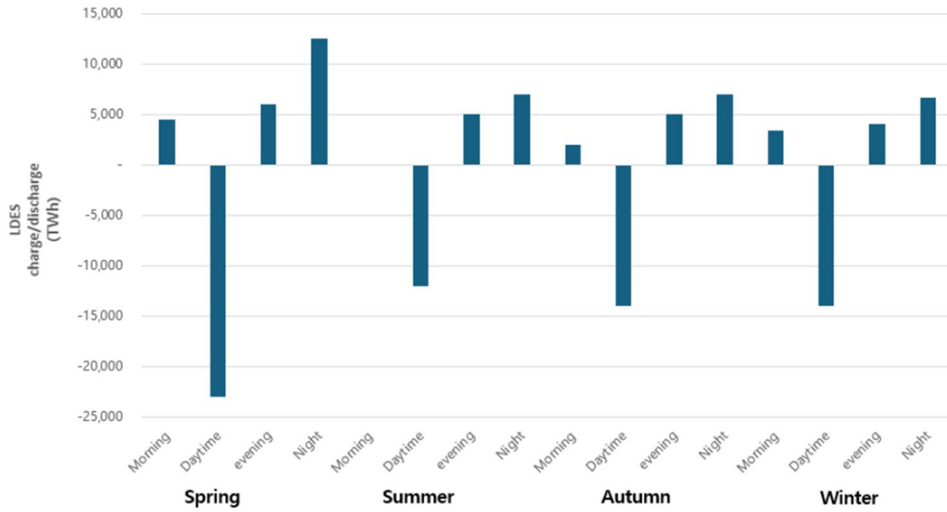
A LDES configuration is included to address the daily supply and demand imbalance. LDES capacity is expected to reach 20.85 GW/124.97 GWh by 2036, with a capacity estimated to be 32 GW/192 GWh by 2050.

In this study, the LDES control method was designed to minimize surplus energy within a season. The maximum amount of energy that can be recharged is determined by seasonal surplus or emissions within the capacity limits of the LDES.

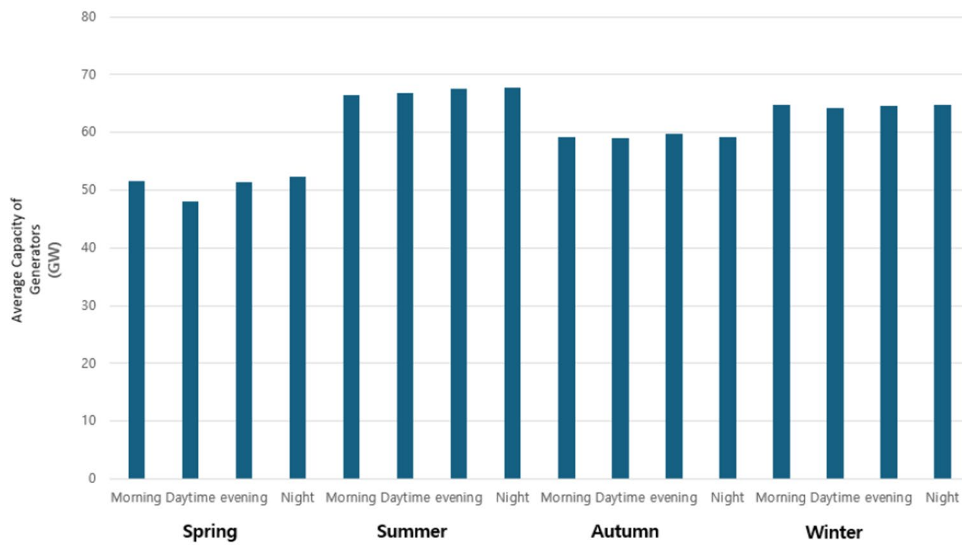
Figure 4 (a) illustrates the charge and discharge patterns of LDES used to redistribute surplus power generation. Fully utilizing the capacity of LDES minimizes PV generation curtailment, with stored energy offsetting other energy sources at different times to balance supply and demand. This approach significantly reduces temporal fluctuations in conventional generators, thereby alleviating operational stress. Additionally, minimizing curtailment enhances energy efficiency.

Figure 4 (b) depicts the average output of generators compensating for the variability of renewable energy sources. During the spring season, daytime PV output exceeds the capacity of LDES, leading to discrepancies relative to other periods. However, the maximum observed difference of 3 GW is expected to be manageable within the power system's

Fig. 4 (**a**) charge/discharge pattern of LDES / (**b**) Average Capacity of Volatility Control Generators



(a)



(b)

reserves. In unavoidable situations, minimal curtailment of PV generation may be necessary.

To effectively address and harness the intermittent nature of renewable energy, it would be advantageous to implement storage systems capable of retaining energy for extended periods. Such systems could redistribute the substantial energy generated during spring daytime hours to deficit periods in other seasons, leading to more efficient power management.

5 Conclusion

As renewable energy sources such as wind and solar, defined by their intermittent and variable nature, continue to dominate the energy landscape, the industry faces increasingly complex challenges, including amplified variability and uncertainty. Addressing these challenges requires a paradigm shift in how annual baseline models for future grids are developed, integrating the intricacies of renewable energy systems.

Traditionally, grid planning has focused on managing extreme conditions during peak and off-peak periods. However, with the accelerating integration of variable renewable energy, future systems must address challenges across all seasons, not just in summer and winter.

This study presents an advanced framework for analyzing seasonal and hourly energy patterns, offering critical insights into grid stability within renewable energy-centric systems. Designed to provide a holistic view of grid operations under diverse conditions, the simulations ensure energy demand is met consistently throughout the year while identifying potential bottlenecks.

Future energy demand and renewable energy capacities were projected using sophisticated methodologies, including linear regression and sigmoid-type logistic functions. These projections revealed critical challenges, such as seasonal and hourly mismatches between energy production and consumption.

Spring was identified as a particularly challenging season. While energy demand during this period is typically below average, significant surpluses arise during daytime hours due to peak solar generation. This underscores the difficulty of balancing supply and demand during spring, with daytime surpluses becoming increasingly pronounced as solar capacity expands to meet carbon-neutral goals. Effective strategies to manage this surplus are essential to prevent grid instability.

To address these challenges, the study highlights the strategic utilization and optimization of LDES. By redistributing surplus energy to periods of lower demand, such as nighttime or off-peak hours, LDES minimizes the need for curtailing solar energy while reducing operational stress on conventional generators. The optimization of LDES charge and discharge patterns ensures a more stable and reliable energy supply in the face of renewable energy variability.

This study also emphasizes the importance of advanced grid management systems, such as smart grids, that can dynamically allocate energy in real time. When integrated with LDES, the smart grid's predictive control could enable proactive load distribution, and load management could be further optimized through demand response. Beyond the installation of additional capacity, energy management can efficiently manage surplus power generation, while reducing fluctuations in generator output, thereby enabling more resilient and flexible operation of the power grid.

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Declarations

Conflict of Interest All authors state that there is no conflict of interest.

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Heesung Moon He received the B.S. from Hanyang University in Korea. The M.S. and Ph.D. candidate from Korea University, Korea, in 2020 and 2022. His research interests are renewable energy applications, power system planning.

Yoonsung Cho He received Ph.D. degree in Electrical Engineering from Korea University, Korea in 2008. At present, he is a professor of Deagu Catholic university. His research interests include power system analysis and operation.

Gilsoo Jang He received the B.S. and M.S. degrees from Korea University, South Korea, and the Ph.D. degree from Iowa State University, USA, in 1997. He weas a Visiting Scientist with the Electrical and Computer Engineering Department, Iowa State University for one year, and a Researcher with the Korea Electric Power Research Institute for two years. He is currently a Professor of the School of Electrical Engineering, Korea University. His research interests include power quality and power-system control.