Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Effect of Nuclear Power Load-Following Capability in Future Korean Electricity Grid

Gyudong Kim [a], Jeong Ik Lee [a*]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*

[*]*Corresponding author: jeongiklee@kaist.ac.kr*

***Keywords :** load-following capability, power generation mix, grid stability

1. Introduction

As the share of renewable energy in South Korea's energy mix increases, maintaining the stability and flexibility of the power grid is becoming an increasingly critical challenge. According to the officially announced 10th Basic Plan for Long-Term Electricity Supply and Demand, the proportion of renewable energy is expected to rise from the current 6.8% to 30.6% by 2036. However, the share of coal-fired power plants, which traditionally provide stable load balancing, is planned to be reduced to below 15% [1].

In a scenario where load stabilities are decreasing due to the rise in renewable energy, a reduction in the proportion of coal-fired power plants may exacerbate load-following within the remaining coal-fired generation capacity as well as nuclear power. This shift necessitates a reassessment of the role of nuclear power plants, which have traditionally served as reliable baseload generators. Moving forward, nuclear power plants must enhance their load-following capabilities to address the variability of renewable energy sources and reduce the burden of excessive load-following on coal-fired power plants. This study aims to analyze how much the load-following capabilities of nuclear power plants need to improve by 2036, based on data from the Korea Power Exchange [2].

2. Methods and Results

2.1 Data Analysis Methods

In this study, power generation data and load variability for nuclear power, coal-fired power generation, LNG, and renewable energy were analyzed using generation capacity and power trading volumes by fuel source for the period from 2018 to 2023, as provided by the Korea Power Exchange. To determine the trend in the contribution to supply of each power source to the overall power grid, the annual trading volume for each power source was aggregated and expressed as a percentage of the total trading volume(MWh). To evaluate the contribution of each power source to load-following, the hourly changes in power trading volumes for each source were calculated as a percentage of the total power trading volume, and the resulting values were averaged over the course of a year.

2.2 Share of Power Trading Volume

Fig. 1 shows the share of nuclear power in the electricity trading volume increased from 23.7% in 2018 to 31.5% in 2023. Similarly, the share of new and renewable energy rose from 5.5% to 6.9%. In contrast, coal-fired power generation's share decreased from 43.3% to 32.7%, while LNG power generation showed little variation in its share.

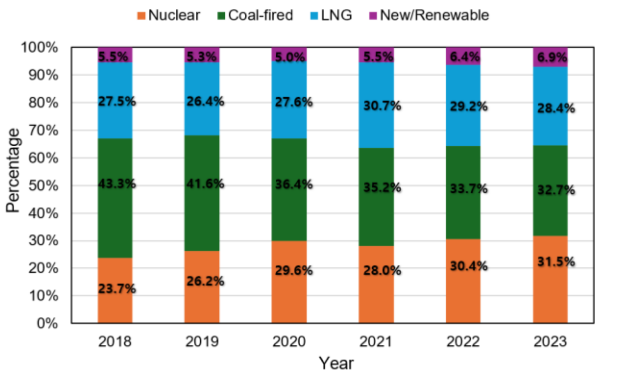

Fig. 1. Each power source’s share in power trading volume from 2018 to 2023.

2.3 Each Power Source’s Contribution to Load-following

Fig. 2 shows the contribution ratios to load-following. It is found that although the share of power trading volume from new and renewable energy increased, its overall contribution to load-following did not change significantly. Conversely, despite a gradual decrease in the share of coal-fired power in the trading volume, its contribution to the overall load-following ratio increased from 10% to 19.4%. Considering that the power generation from renewable energy sources cannot be flexibly adjusted, it can be inferred that the load-following capability of coal-fired power generation plays a significant role in mitigating the instability of the power supply caused by the intermittency of renewable energy as for now.

Table I shows the average load-following ratio during the top 5% of coal-fired power generation load-following periods from 2018 to 2023 and it reveals a significant increase in both the fluctuations of renewable energy and the corresponding adjustments by coal-fired power plants. In 2023, there is a clear trend of the proportion of renewable energy increasingly running counter to power demand, with coal-fired power plants progressively offsetting this imbalance. Eq (1) shows how average load-following was calculated.

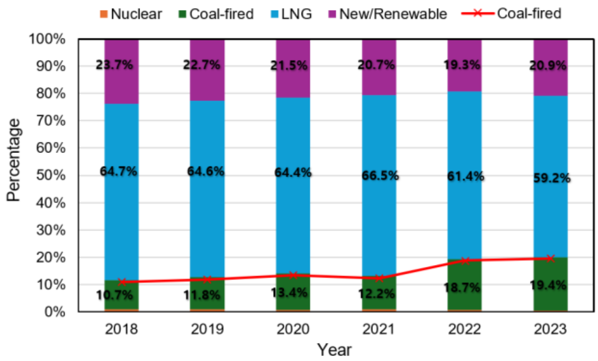

Fig. 2. Each power source's contribution to load-following from 2018 to 2023.

$$\text{Average load following} = \frac{\sum_{01/01\ 00:00}^{12/31\ 24:00}\left(\frac{hourly\ changed\ MW\ \ energy\ source}{hourly\ changed\ MW\ from\ total\ energy\ source}\right)}{24h \times 365 days} \quad (1)$$

Table I: Average load-following operation

	Nuclear [%]	Coal-fired [%]	LNG [%]	New/ Renewable [%]
2018	0.29	41.1	39.9	18.7
2019	2.1	6.7	66.0	25.2
2020	0.06	38.0	49.9	12.0
2021	-0.21	57.5	38.5	4.2
2022	-0.10	89.0	36.0	-24.9
2023	-0.31	96.3	35.1	-31.1

2.4 Load-Following trend of Coal-fired power plants

Meanwhile, Fig. 3 illustrates that the average load-following capacity of coal-fired power plants increased steadily from 163.8 MW/h in 2018 to 391.9 MW/h in 2023. If this trend continues, it is projected to exceed 1 GW/h by 2036, more than 2.5 times the current level. Considering that the maximum load-following volume in 2023 is approximately 10 times the average load-following volume, the maximum load-following volume of coal-fired power generation in 2036 could approach 10 GW/h.

Based on the demand forecast of 136 GW and the target generation ratio of 15%(20GW) set in the 10th Basic Plan for Electricity Supply and Demand, the load-following rate in 2036 would be 0.84%P_r/min. Previous studies have shown from numerical analysis that, considering the CO_2 emission, stability and economic feasibility of a coal-fired power plant system, the load-following rate should not exceed 0.8–1.2%P_r/min. Maintaining a load-following rate of 0.5%P_r/min or lower being optimal for economic performance and stability [3]. Considering that larger plants generally exhibit lower rate of load-following, the target values proposed in this study should be adjusted downward for larger capacity units. Therefore, enhancing the load-following capability of nuclear power plants, which currently experience minimal load-following rate, is essential.

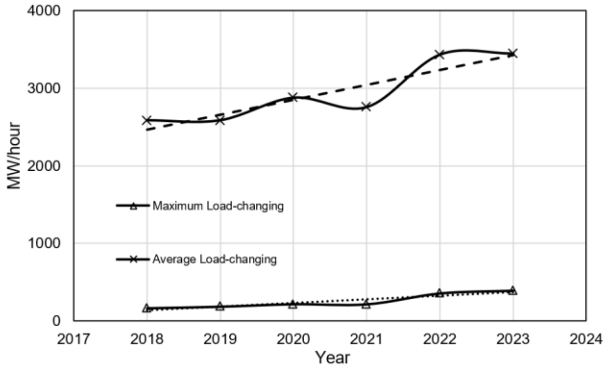

Fig. 3. Trend of coal-fire power plants' annual average and maximum load-following from 2018 to 2023.

2.5 Impact of Increased Load-following capability of NPP

To reduce the load-following burden of coal-fired power plants expected in 2036, it is feasible to implement load-following operations in the currently operating APR1400 nuclear power plants and to utilize the load-following capability of next-generation nuclear power plants.

If the six currently operating APR1400 nuclear power plants achieve a load-following rate of 0.7%P_r/min, they could potentially replace most of the load-following capacity that coal-fired power plants are expected to handle in the future.

If the 170MW i-SMR under development in South Korea achieves a load-following rate of 5%P_r/min, the construction of eight additional units could offset the almost all load-following burden currently managed by coal-fired power plants.

According to European Utility Requirements (EUR), generation III or higher nuclear power plants must be designed to operate within a range of 50%P_r to 100%P_r can accommodate an output change rate of 3-5%P_r/min[4]. Since all the nuclear power plants mentioned above are Generation III or higher, the proposed strategy is technically feasible.

However, since coal-fired power plants can also follow load within the 50%P_r to 100%P_r range, they are unable to fully accommodate the maximum range of load-following of 10 GW as described in the previous scenarios. The APR 1400 utilization scenario accounts for the maximum range of load-following of 4.2GW, the i-SMR construction scenario for 0.68 GW Table II presents the load-following performance of coal-fired power plants under an extreme scenario, assuming a load variation of 10 GW/h, transitioning from 50%P_r to 100%P_r.

Table II: The rate of Load-following of coal-fired power plants in an extreme scenario

	Load-following capability [P_r/min]	number of units	Extreme scenario		
			maximum range of load-following [GW]		Coal-fired, rate of load-following [P_r/min]
			Nuclear	Coal-fired	
APR1400	0.7	6	4.2	5.8	0.48
i-SMR	5	8	0.68	9.32	0.78

Reducing the coal power load-following required capability means that the margin to respond to the unexpected load increase or decrease can be further enhanced. Thus, this will improve the stability of the electricity supply in future Korea.

3. Conclusions

To increase the power generation ratio of new and renewable energy and reduce the share of coal-fired power generation to 15% by 2036, as outlined in the government's 10th Basic Plan for Electricity Supply and Demand, enhancing the load-following capability of nuclear power plants is essential for the stable and economical operation of coal-fired power plants.

Given the current trend, in order to maintain the maximum rate of load-following of coal-fired power generation below 0.5%P_r/min, if all currently operating APR1400 nuclear power plants can have 0.7%Pr/min load following capability. Considering the current trends, enhancing the load-following capabilities of nuclear power plants is essential for the stable and economical operation of coal-fired power plants. Leveraging the existing APR1400 reactors or constructing new i-SMR could significantly reduce the load-following burden on coal-fired power plants.

It is noteworthy that this result is not to suggest that nuclear power plant load following is important to simply reduce coal power load following burden. In contrast, it is instead to illustrate that all thermal power generators have to have load following capability to respond to the future electricity market where deep intermittent renewable energy penetration is expected.

Furthermore, these estimates are based on the assumption that the load variability of new and renewable energy remains at current levels, without accounting for the expansion of energy storage. Therefore, research is needed on an effective target value for the load following capability of nuclear power plants that reflects the effects of the continued increase in the proportion of renewable energy.

Acknowledgements

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government MOTIE (No. RS-2024-00400615).

REFERENCES

[1] Ministry of Trade, Industry and Energy, 10th Basic Plan for Long-Term Electricity Supply and Demand, 2023.

[2] Korea Power Exchange, Hourly Facility Capacity and Power Trading Volumes by Fuel Sources (2018-2023), 2024.

[3] C. Yang, X. Hao, Q. Zhang, H. Chen, Z. Yin, F. Jin, Performance Analysis of a 300MW Coal-Fired Power Unit during the Transient Process for Peak Shaving, Energies, 16, 3727, 2023

[4] EPRI, Utility Requirements Document, Revision 10, Revision 10, United States, 2008.