

Article

Evaluation Method for Penetration Limit of Renewable Energy Sources in Korean Power System

Han Na Gwon, Woo Yeong Choi  and Kyung Soo Kook *

Department of Electrical Engineering, Jeonbuk National University, Deokjin-gu, Jeonju 54896, Korea; canna08@jbnu.ac.kr (H.N.G.); ventus666@jbnu.ac.kr (W.Y.C.)

* Correspondence: kskook@jbnu.ac.kr; Tel.: +82-63-270-2368

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Abstract: As Korea aims to increase the extent to which renewable energy sources (RES) account for up to 20% of the total power generated in the country by 2030, the feasibility of this target is a major concern. This concern largely results from the Korean power system possessing unique characteristics, such as its electrical isolation and high density. To achieve the RES target, the reliable operation of the power system must coexist with an increased share of RES power generation. This study proposes a method to evaluate the penetration limit of RES in the Korean power system considering the existing plans for the long-term electricity supply and demand, as well as its operational requirements. The Korea electric power corporation (KEPCO) planning database of the Korean power system for the next 15 years was employed to determine the penetration limit of RES considering the reliability criteria, including the minimum power generation of conventional sources, primary frequency control requirement, 10-min reserve requirement, and frequency stability.

Keywords: renewable energy sources; penetration limit; Korean power system; criteria

1. Introduction

Korean power systems operate to supply an ever-increasing demand for electricity considering the economic priority of the country to generate resources. Nuclear and coal power plants have supplied about 71% of the required demand in Korea as of 2017 [1]. However, since Korea joined the Paris Agreement in 2015 [2] to globally reduce greenhouse gas emissions [3–5], concerns have been raised in regard to increasing the use of renewable energy resources in these power systems. The Korean government has recently announced that it will increase the proportion of renewable energy sources (RES) to 20% by 2030 through the Basic Plan for Long-term Electricity Supply and Demand (BPE) [5].

RES is dependent on weather conditions, and the performance of these sources is currently poorer than that of conventional sources due to the absence of inherent inertia and frequency response in their operations [6]. Therefore, the additional resources are required as ancillary power sources to considerably increase the share of RES in power systems [7–10]. Moreover, the availability of these additional resources is often limited, which in turn limits the extent to which RES can be accepted by power systems that meet the performance criteria.

Therefore, it is necessary to evaluate the penetration limit of RES into Korean power systems considering their unique characteristics so that appropriate national targets for increasing the use of RES can be analyzed and efficient methods to achieve these targets can be determined. In Korean power systems, not only geographical but also political factors affect the integration of RES because the Korean peninsula is divided by the demilitarized zone. As illustrated in Figure 1 [11], large-scale power plants are mostly located on the south-western and eastern shores while the electric loads are concentrated in the capital area in the north-west of Korea. This requires a long range of transmission from the

generators on the shores to the capital area, thereby adding various constraints to the operations of these power systems, as well as serving as a limiting factor for increasing RES in Korean power systems.

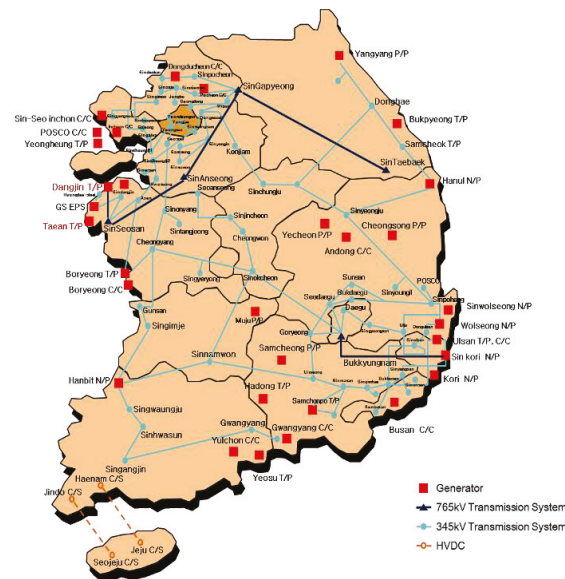


Figure 1. Overview of Korean power systems.

For these reasons, this study proposes an evaluation of the penetration limit of RES considering that the required performance of the Korean power system is maintained despite the high penetration of RES.

Although there have been several studies on the calculation of the penetration limit of RES [12–14], those studies have only been quantitative and restricted to small-scale system models. In the study of Reference [12], the instantaneous penetration limit of the wind power was evaluated only considering quantitative aspects of minimum output, spinning reserve of the conventional generating units and ramp rate capability employing the Mongolia power system. In the case of Reference [13], the penetration level of the wind power in Jeju island was evaluated and it considered the same constraints as Reference [12] and voltage constraints in terms of quantitative aspect. In Reference [12], the penetration limit of the wind power was evaluated only quantitatively, considering the same constraints as [12], and the result was specific to a small test system. However, as the increased penetration of RES in the power system would deteriorate the frequency stability due to the lack of inherent inertia and the limited control capability of RES, the penetration level of RES should be limited by the performance requirements to the frequency control of the power system. Since those previous studies [12–14] did not consider such a qualitative aspect, this study instead aims to identify the RES penetration limit of real power systems in Korea considering both quantitative and qualitative aspects related to the unique characteristics of the Korean power system. In addition, eight real power system models taken from the Korea electric power corporation (KEPCO) planning database for the next 15 years are to be used respectively for each year to evaluate the penetration limit of RES in the Korean power system.

2. Expansion Plan and Penetration Limit of RES in the Korean Power System

2.1. RES Expansion Plan in Korea

This section analyzes the RES expansion plan for the Korean power system. To achieve the goal set by the Korean RES expansion plan, the 8th BPE was announced by the Ministry of Trade, Industry, and Energy [5]. Figure 2 depicts the load forecast and planned sources of power generation over the next 15 years in the Korean BPE.

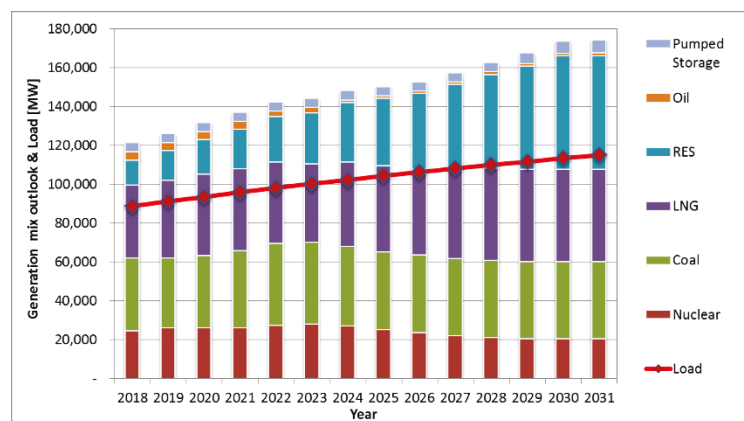


Figure 2. Summary of the Korean Basic Plan for Long-term Electricity Supply and Demand (BPE).

As illustrated in Figure 2, the share accounted for by RES is expected to significantly increase while those of nuclear and oil power plants are expected to decrease over the next 15 years. Among the various types of RES, power generation by both PVs and wind turbine generators is expected to sharply increase. Figure 3 depicts a detailed capacity expansion plan for various RES systems based on the Korean BPE.

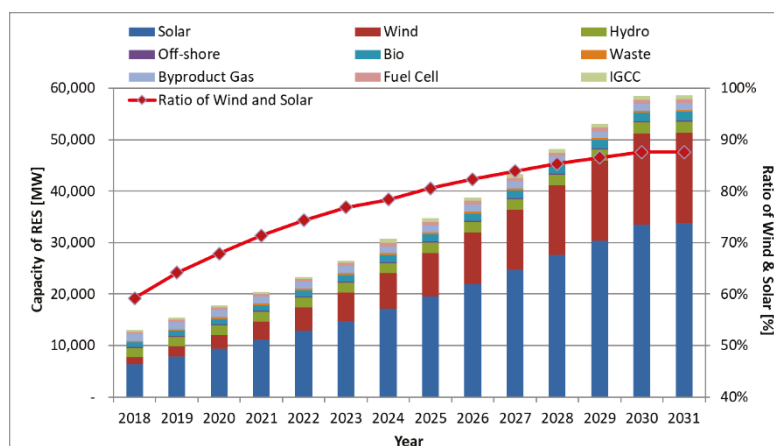


Figure 3. Capacity expansion plan for renewable energy sources (RES) in Korea.

As illustrated in Figure 3, the PVs and wind turbine generators are expected to account for more than 85% of the RES capacity in 2031.

2.2. Penetration Limit of RES

Although the capacity of RES is expected to increase to achieve the national target for RES by 2030 in Korea, the feasibility of this projection must be reviewed in terms of power system operations. In principle, because RES, such as PVs and wind turbine generators, have no inherent inertia and lack the facility for frequency control via a governor (as are found in conventional generators) [7,15], the replacement of conventional sources with RES is likely to negatively affect the performance of the Korean power system. The unique characteristics of the Korean power system, including its electric isolation, would amplify these negative effects of RES. If frequency disturbances caused by contingencies, such as the sudden loss of a large-scale generator occurs when the penetration level of RES is high, it would be more difficult to maintain the frequency of the power system within the operating limits due to the inherent insufficiency of RES to provide frequency control. Therefore, the share of RES in the Korean power system may be limited to maintain the performance of the power system as is required. The maximum extent to which RES may be used in power generation while

maintaining the required amount of power generation is defined as the penetration limit of RES in the power system. Moreover, the Korea Power Exchange (KPX) operates the Korean power system to meet certain operation criteria [16–18] via frequency control reserves, and 10-min reserves are provided by online generators scheduled in a day-ahead market. Thus, the penetration limit of RES needs to be identified in the planning stage considering the capability of the Korean power system to maintain its performance with the available resources.

3. Evaluation Method of the Penetration Limit of RES

3.1. Penetration Limit Determined by the Minimum Power Generation of Conventional Sources

To maintain the performance and optimize the operating cost of the power system, a certain number of conventional sources are required to provide power reserves and supply the base loads. Because conventional sources need to be operated at a level greater than their minimum generation level to keep those availabilities, the portion of power generated by RES may be limited by the minimum generation levels of the required conventional sources. Thus, the penetration limit of RES, i.e., P_{RES} , needs to be determined by Equation (1):

$$P_{RES} \leq P_{Load} - \sum_{i=1}^n P_{min, i} \quad (1)$$

Here, P_{Load} is the total load in the power system, $P_{min, i}$ is the minimum generation of the i -th generator, and n is the total number of in-service generators in the power system.

3.2. Penetration Limit Determined by the Primary Frequency Control Requirement

As RES integration increases the variability of the power system [9], the power system needs an additional frequency response service to maintain its frequency within the operating ranges of the power system while incorporating a high penetration level of RES. This system should be able to support the variability resulting from both the load and RES even in the event of a generator trip in the power system. Thus, the penetration level of RES must also be limited to the extent to which the integrated RES power system can compensate for the experienced variability in terms of the primary frequency control. This limit can be expressed by Equation (2):

$$P_{RES} \leq \frac{1}{VR_{RES}} \sqrt{\sum_{i=1}^m \{ \min(PFC_i, (P_{max, i} - P_{gen, i})) \}^2} \quad (2)$$

Here, VR_{RES} represents the variation rate of the RES outputs in contrast to the total capacity of the RES, PFC_i is the expected amount of the primary frequency control from the i -th generator based on their droop, and $P_{max, i}$ and $P_{gen, i}$ are the maximum and dispatched power output from the i -th generator, respectively.

3.3. Penetration Limit Determined by the 10-Min Reserve Requirement

RES integrated power systems should be able to manage the uncertainty added by RES systems as a result of their dependence on weather conditions. The Korean power system maintains a 10-min reserve service provided by the ramping of generators over 10 min to serve as a backup for the contingency of the largest unit. Therefore, the penetration level of RES may be limited by the extent to which the integrated RES systems can compensate for this 10-min reserve service. This limit can be represented by Equation (3):

$$P_{RES} \leq \frac{1}{\alpha} \left[\min \left\{ 10 \times \sum_{i=1}^n P_{rr, i}, \sum_{i=1}^n (P_{max, i} - P_{gen, i}) \right\} - P_{SR} \right] \quad (3)$$

Here, α is an uncertainty index of the RES, which can be calculated as a portion of the largest plant of RES over the total generation capacity, $P_{rr, i}$ is the ramping capability of the i -th conventional sources in terms of the ramp rate, and $P_{max, i}$ and $P_{gen, i}$ are the maximum and dispatched power outputs from the i -th conventional sources, respectively. P_{SR} is the existing spinning reserve in the power system without the use of integrated RES.

3.4. Dynamic Penetration Limit Determined by the Frequency Stability

When the penetration of RES in the power system increases, its performance in terms of frequency response is diminished by the lack of inherent inertia and the limited control capability of RES. As the power system operator sets a minimum standard level for the nadir frequency during a transient period to avoid any unscheduled load shedding, the penetration level of RES in the power system should be limited to the level where the nadir frequency can reach the minimum standard during a transient period. This penetration level can be defined as the dynamic penetration limit. The procedure proposed to determine the dynamic penetration limit of the RES is illustrated in Figure 4.

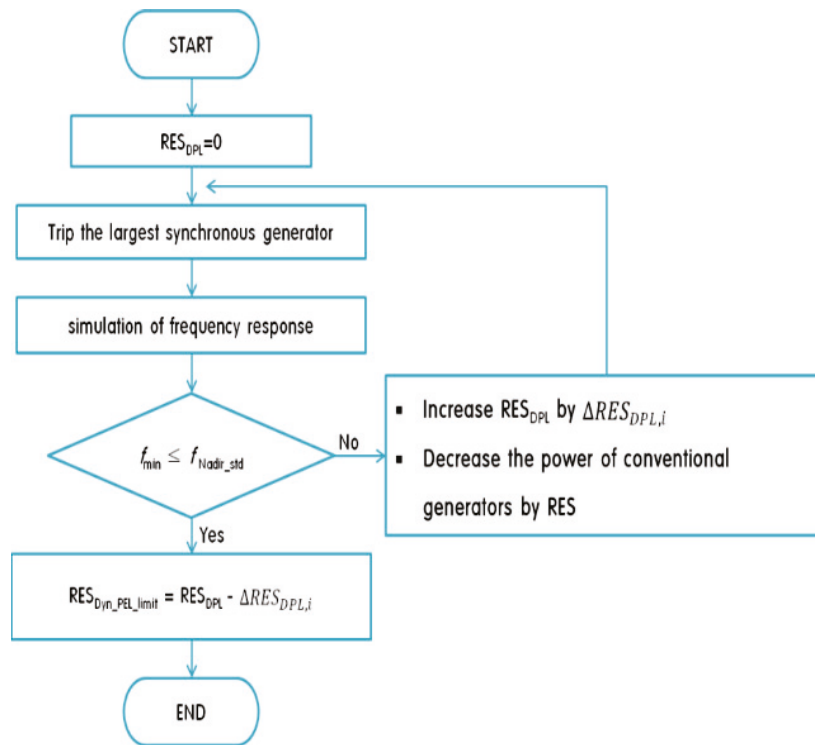


Figure 4. Evaluation procedure for the dynamic penetration limit of RES.

In Figure 4, the penetration level of RES integrated into the power system is increased by replacing the synchronous generation source with the increased use of RES, ΔRES_{DPL_i} [19]. When the simulation of the frequency response indicates that f_{min} is less than or equal to the predefined nadir frequency standard (f_{Nadir_std}), the process stops and the dynamic penetration limit of the RES is determined by the penetration level of the previous step in the process.

4. Case Study

4.1. Test System

In this study, the proposed method was applied to identify the penetration limit of RES in the Korean power system. As KEPCO has established a planning database for the Korean power system for the next 15 years based on BPE, 8 power system models taken from the KEPCO database were adapted to determine the penetration limit of RES in the Korean power system for each year. In addition,

the dynamic parameters of the employed models were adjusted considering the frequency regulation supply of 1500 MW that is maintained by the KPX [16–18,20].

4.2. Penetration Limit Determined by the Minimum Power Generation of Conventional Generators

Based on an 8-year database of the Korean power system, the penetration limit of RES was calculated by Equation (1) using the minimum power generated by conventional sources and the load forecasts. Figure 5 depicts the calculated penetration limit of RES in the Korean power system for each year.

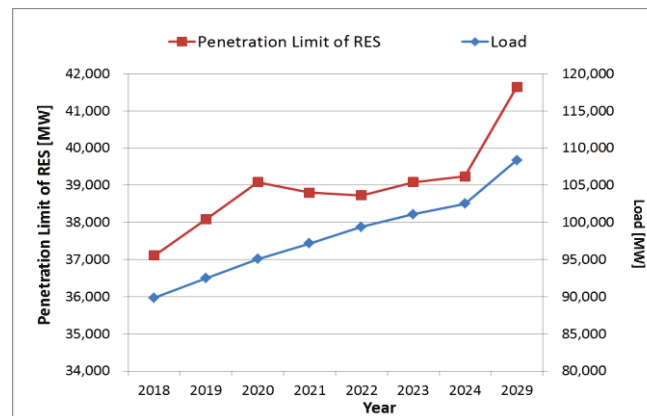


Figure 5. Penetration limit of RES calculated using the minimum generation of conventional sources.

As depicted in Figure 5, the penetration limit of RES considering the minimum generation of conventional source increases in overall as the loads level increases by year. This is because the number of conventional sources increases to meet the increased loads and those increased conventional sources are the potential amount of RES to replace. In the case of between 2020 and 2021, the penetration limit of RES decreases since many small-scale conventional sources are replaced with new large-scale conventional source according to the Korean basic plan for Long-term Electricity Supply and Demand.

4.3. Penetration Limit Determined by the Primary Frequency Control Requirement

To evaluate the penetration limit of RES considering the primary frequency control requirement, VR_{RES} was adopted as 14.7%, which is derived from the results of an existing study [8]. Figure 6 depicts the calculated penetration limit of the RES for each year.

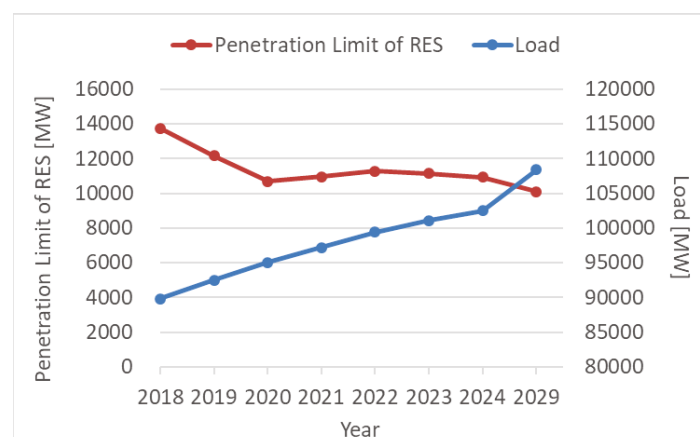


Figure 6. Penetration limit of RES calculated using the primary frequency control.

As depicted in Figure 6, the penetration limits of RES calculated using the primary frequency control requirement for each year was similar across all years except for the first three years. This could be because the planning database of the Korean power system is developed assuming that the primary frequency control requirement is maintained as a standard value over each year. However, in case of between 2018 and 2020, the penetration limit of RES is higher than other case because they have more amount of primary frequency control reserve in the planning database of Korean power system.

4.4. Penetration Limit Determined by the 10-Min Reserve Requirement

To evaluate the penetration limit of RES considering the 10-min reserve requirement, α was applied as 4.69%, which is derived from an existing study [8]. Figure 7 depicts the calculated penetration limit of the RES for each year.

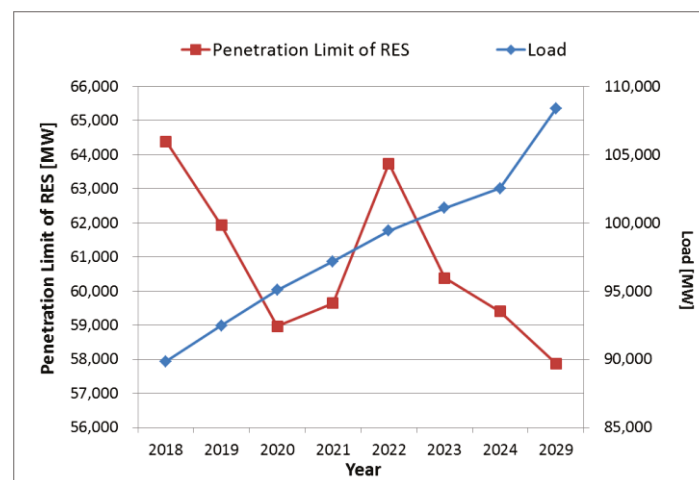


Figure 7. Penetration limit of RES calculated using the 10-min reserve.

As illustrated in Figure 7, the penetration limit of RES decreases in the trend of overall years. This calculation was made assuming that the 10-min reserve requirement remains unchanged over the years with increasing loads and this can be a reason why the penetration limit of RES in percent decrease by year. In case of 2022, as the conventional sources with good ramping capability have been added to the system, the penetration limit of RES is higher than others.

4.5. Penetration Limit Determined by the Frequency Stability

To evaluate the dynamic penetration limit of RES using the frequency stability, a Power System Simulation for Engineering (PSS/E) is used to simulate the frequency response of Korean power systems integrated with RES and the calculation method in Section 3.4 is applied. Figure 8 depicts the diminishing frequency response to the trip of a 1500 MW generator in the Korean power system according to an increasing penetration level of RES.

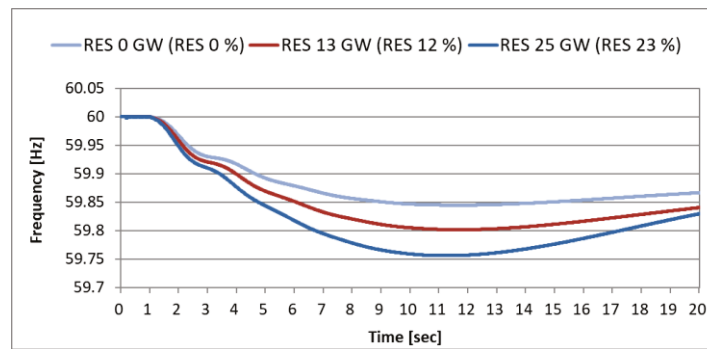


Figure 8. Frequency response simulation of the Korean power system with increasing RES penetration.

In the simulation, the Korean power system models described in Section 4.1 were adopted and the predefined nadir frequency standard was applied as 59.8 Hz, which is the lower frequency limit in the frequency operating range of the KPX [11]. The results show that performance of frequency control is deteriorated by increasing penetration of RES in the power system. Therefore, the dynamic penetration limit of RES determines to 12,484 MW in Figure 8. Figure 9 depicts the dynamic penetration limit of RES in the Korean power system.

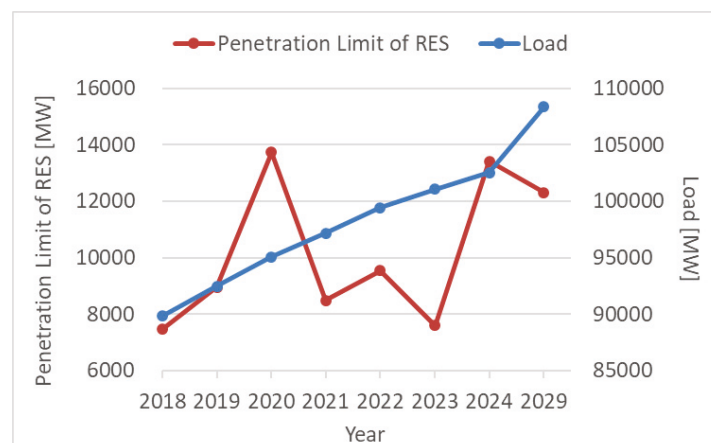


Figure 9. Penetration limit of RES calculated by the frequency stability.

As illustrated in Figure 9, the dynamic penetration limit of RES calculated using the frequency stability for each year was similar across all years except for a few years. This is because the amount of primary frequency control reserve is maintained standard value over each year as Figure 6. In case of between 2020 and 2021, the dynamic penetration decreases due to lack of inertia caused by the replacement of small-scale conventional sources with new large-scale conventional source.

4.6. Penetration Limit of RES in the Korean Power System

In previous sections, the limits of RES penetration in the Korean power system were evaluated as constrained by the minimum generation of conventional sources, primary frequency control requirement, 10-min reserve requirement, and frequency stability. Figure 10 depicts the comparison of the calculated penetration limits of RES.

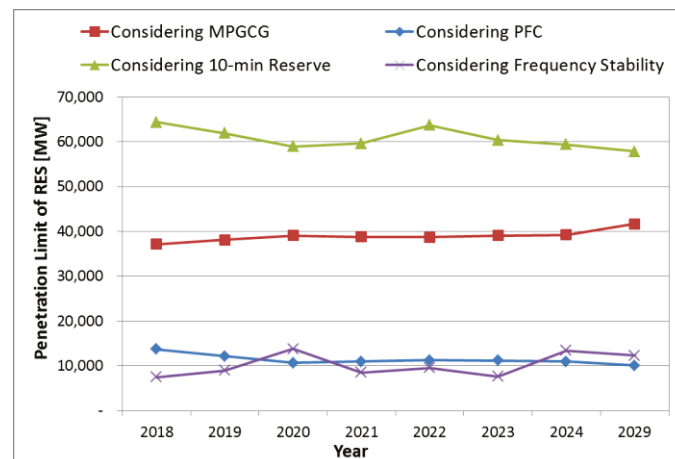


Figure 10. Comparison of the penetration limits of RES.

The most limiting calculated penetration limit determines the overall penetration limit of RES for each year. Therefore, it is found that the penetration level of RES is limited by the frequency stability in the Korean power system for five years, whereas the primary frequency response requirement limits the penetration level of RES for three years. The overall penetration limits of RES are between 7459 MW and 10,915 MW, and these values are between 8.3% and 11.23% of the peak load.

In addition, Figure 11 depicts the comparison of the penetration limits with the capacities of RES planned in the BPE.

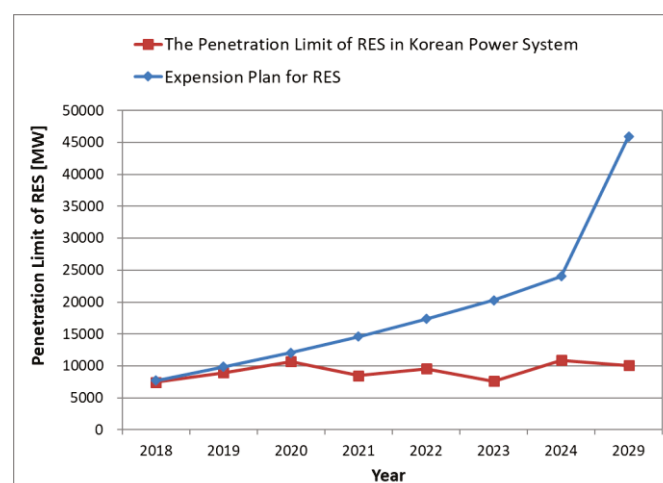


Figure 11. Comparison of the determined penetration limit and planned capacity of RES in Korea.

As illustrated in Figure 11, it is found that the capacities of RES planned in the coming years exceed the calculated penetration limits of RES and the amount by which the prediction exceeds increases in later years. Therefore, the planned power generation by RES could be significantly curtailed to meet the required performance criteria if no other countermeasures to increase the penetration limits of RES are prepared.

5. Conclusions

This study proposed a method to evaluate the penetration limit of RES in the Korean power system and determined the extent of this penetration by employing a simulation model for the Korean power system for the next 15 years. The proposed method considered a minimum amount of power generated using conventional sources, primary frequency control requirement, 10-min reserve requirement,

and frequency stability to confirm the secured operation of the Korean power system with a high penetration of RES.

Through various case studies, it was found that the penetration limits of RES in the Korean power system are between 8.3% and 11.23% of the peak loads for the next 15 years. Additionally, the main limiting factors were found to be the frequency stability criterion and the primary frequency response requirement in the Korean power system. Furthermore, from 2019 onwards, as the calculated penetration limit of RES was found to be exceeded by that planned in the 8th BPE, it is important for appropriate countermeasures to be prepared to achieve this RES penetration target in Korea. Although the evaluation method is proposed for the Korean power system considering its quite unique characteristics, it can be also applied to other power systems by setting those limits of the proposed methods based on their own operation criteria since its evaluation is based on both quantitative and qualitative aspects of the power system.

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