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RESEARCH ARTICLE

Practical Generation Resource Planning Based on Screening Curve Method Considering Must-Run Constraints: The Case of Jeju Island's Power Grids

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ABSTRACT The increasing integration of renewable energy sources in the power system necessitates a reassessment of the optimal generation resource mix in long-term planning. To derive a practical solution for the generation mix in response to renewable energy integration, it is necessary to consider additional practical constraints taken into account in real operations. This study introduces an enhanced screening curve method (SCM) incorporating must-run constraints for practical determination of the generation resource mix and estimation of renewable energy curtailment. The inclusion of must-run impact in the SCM contributes to a more practical and accurate estimation of the generation resource mix and expected renewable energy curtailment in long-term planning. A case study was conducted by assuming three different wind penetration scenarios using empirical data from the Jeju power gird. The results suggest indicates that the increasing integration of wind power is likely to decrease mid-load and peak-load generators during high-demand periods and reduce base-load generators during low-demand periods in the generation resource mix results. Additionally, the expected future expansion of wind penetration is projected to elevate both the amount and frequency of renewable energy curtailment at both high and low demand levels. The findings highlight the importance of flexibility resources and measures, such as reducing must-run generation, to address the anticipated increase in renewable energy curtailment. Moreover, the study provides insights for exploring practical solutions in long-term generation planning amid the growing integration of renewable energy.

INDEX TERMS Generation resource plan, must-run generator impact, renewable energy curtailment, screening curve method.

I. INTRODUCTION

According to the national carbon neutrality policy, generating resources are converted from thermal power to renewable energy, leading to an increasing proportion of variable resources in the total generation capacity. In South Korea, Jeju Island has set a target to become a carbon-free island by 2030 (CFI 2030), which aims to supply 100% of its electricity demand through renewable energy sources by 2030. With the enforcement of CFI 2030, the province plans to introduce 4,085 MW of new and renewable energy generation facilities, allowing renewable resources to produce electricity in response to electricity demand. Among these, the largest share of this supply goal is attributed to wind power facilities, accounting for 2,345 MW [1].

With the increasing integration of renewable energy sources into the power system, changes in the optimal generation resource mix are expected in long-term generation planning. To prepare for expected energy resource transition trend, it is necessary to determine new optimal combinations of future power plants that include the impact of renewable energy expansion. Various previous studies have

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aimed to reflect the changes caused by renewable energy into long-term generation resource planning. Several models have been proposed to additionally incorporate short-term operational flexibility in long-term capacity expansion planning. These models consider factors such as unit commitment, maintenance constraints and demand response, due to the uncertainty of renewable energy [2], [3], [4]. Moreover, approaches that encompass newly emerging factors resulting from the introduction of renewable energy, such as environmental costs, carbon reduction, and curtailment costs, have also been discussed in determining the optimal electricity mix [5], [6], [7].

Furthermore, under the uncertainty of renewable energy, long-term generation planning should align with actual power system operation. To achieve this, operational constraints to ensure system stability in response to uncertainties in renewable energy can be incorporated into long-term power generation plans. Due to the significant variability and uncertainty in power generation output from renewable energy sources, a high penetration of renewables in future power systems can significantly affect the stability of the power grid [8]. One notable constraint applied in actual system operations involves restricting some of the thermal power generator output as 'must-run generation' to secure grid stability. Operational constraints, such as must-run constraints, directly related to grid stability have a significant impact on the variation of the generation mix in actual operation. However, there have been few attempts to include them in generation mix decisions in long-term planning. Neglecting practical constraints related to grid stability in generation planning can lead to operationally infeasible results of the generation mix. Hence, to obtain a practical generation mix solution for future years, it can be further considered to take into account the presence of must-run constraints when defining the optimal combination and share of generators.

In addition, the curtailment of renewable energy in power systems due to power grid flexibility issues has also become a significant concern in long-term perspective. When the amount of generated renewable energy is excessive, curtailment can be performed to stabilize the power system instead of accommodating it within the grid [9]. On Jeju Island, curtailment has increased, occurring 77 times (19,449 MWh) in 2020, compared to its initial occurrence three times in 2015 [10]. With the anticipated expansion of renewable energy in long-term planning, both the amount and frequency of curtailment are expected to rise. Therefore, to assess the amount of renewable energy utilized in actual power supply over the long term, it is necessary not only to estimate the energy mix but also to project the expected renewable energy curtailment in the future.

In this study, long-term generation resource planning and the corresponding curtailment estimation are conducted with a focus on considering the impact of must-run constraints. The screening curve method (SCM) was used in this paper to estimate future energy mix for long-term generating resource planning. SCM can provide an initial stack of generators in a fast and cost-effective manner to determine the optimal generation mix for long-term planning [11]. This is also an appropriate model that considers the deployment of renewable energy without involving complicated computations in the long-term investment or generation expansion model. The ultimate objective of the screening curve is to identify the cost-minimizing energy-generation mix for a given set of energy-generating technologies [12]. SCM has an advantage in long-term planning by excluding less economical alternatives and estimating the initial scope of the generation resource mix. However, it had its limitations as it does not address the detailed short-term factors influencing generation costs, making it challenging to apply when high accuracy is required. Nevertheless, recent research has proposed sophisticated SCMs that can partially consider various short-term operational impacts, enabling the provision of more precise approximations. For instance, several SCMs have been proposed to account for the short-term operational constraints of thermal units due to the impact of renewable energy. These SCMs consider factors like start-up costs, unit commitment, and thermal unit cycling within the generation cost function [3], [13]. In addition, an SCM that includes the wind curtailment cost in the model has also been developed to enhance grid flexibility [6]. Therefore, in this paper, SCM was adopted to preserve the benefits of its low computational cost and to produce an operationally feasible generation mix for the target year with minimal data, incorporating must-run constraints that were not considered in the previous study.

The objective of this paper is to establish a practical generation resource mix and evaluate the expected utilization of renewable energy in future years. To achieve this, an SCM incorporating must-run constraints is proposed, allowing the derivation of a practical cost-minimizing generation mix suitable for a power grid with increased renewable energy integration. The proposed method was applied to a case study of the practical power system in Jeju, assuming large-scale wind scenarios. Three different wind penetration level scenarios were considered in this study to estimate the optimal generation mix solutions based on the SCM and annual renewable curtailment capacities in each scenario. This case study presents the expected situation in Jeju from the perspective of long-term supply and demand using real-system data from Jeju. The main contributions of this paper can be summarized as follows:

- The proposed SCM method, which incorporates the must-run constraint, contributes to providing feasible generation mix results in large-scale renewable energy-integrated systems by maintaining the low computational cost of SCM while considering practical constraints encountered in actual operations.
- By utilizing the generation mix results of the proposed SCM, the annual expected curtailment amount for renewable energy can be estimated. This allows for anticipating the amount of curtailment in power systems with high renewable energy integration in

long-term generation planning and developing corresponding strategies.

The remainder of this paper is organized as follows: Section II introduces the simplest version of SCM and must-run constraints; Section III describes the procedure for obtaining the optimal generation mix considering must-run constraints and the method of curtailment estimation; Section IV presents the results of the energy mix and estimated renewable energy curtailment assuming different cases for wind penetration using real-system data from Jeju; Section V then concludes.

II. SCREENING CURVE METHOD

A. BASIC DESCRIPTION

SCM can be used to determine the most economical energy mix that minimizes the total sum of the generation costs for given sets of units [3]. This model presents long-term generation planning results by estimating the energy mix based on a combination of generator cost information and load profiles.

First, the total annual generation cost was calculated for each generating unit to derive a generation-cost curve. Depending on the constraints included in the total generation-cost equation, several types of SCMs can be established. In this section, we introduce the simplest form of the SCM, which considers only fixed and variable costs when calculating the total generation cost and not considering additional operational constraints. Equation (1) represents the annual total generation cost for each generator with a 1-MW capacity [14].

$$\text{Total cost} = \text{Fixed cost} + \text{Variable cost} \cdot T(l) \tag{1}$$

Here, $T(l)$ is the annual operating time at a specific load level l, the units of the total cost and fixed cost are \$/MW/year, and the unit of variable cost is \$/MWh. As indicated in (1), when calculating the total cost, the fixed cost is independent of the amount of power generated, whereas the variable cost depends on the amount of power generated by each unit. The fixed and variable costs can be expressed in detail as shown in (2) and (3), respectively. The fixed and variable costs include the investment cost of the generator and the cost of operation, such as fuel cost, respectively.

$$\text{Fixed cost} = \text{Annualized capital cost} + \text{Fixed O\&M cost} \tag{2}$$

$$\text{Variable cost} = \text{Fuel cost} + \text{Variable O\&M cost} \tag{3}$$

By using (1) as the generation cost function for each generator, the annual generation cost curves for all generators can subsequently be obtained. Fig. 1 shows the annual generation cost curves for synchronous generators operating within the Jeju power system in 2021, and the relevant generator information is detailed in Table 1. The fixed and variable costs are expressed through the y-intercept and slope of the graph, respectively. In the case of Jeju, as it depicts the cost curves of existing generators that are already in operation, the y-intercepts for all generators appear to be at zero (Fig. 1). This implies that the fixed cost of the generator is zero since it is assumed that the existing generator has no fixed costs, such as construction investment [15]. Therefore, in this case, only the second term in (1), which includes the variable cost, is considered as the total generation cost. From Fig. 1, it can be interpreted that HVDC1 and HVDC2 have the lowest generation costs (here, the variable cost), while TP3 has the highest generation cost in the Jeju power system.

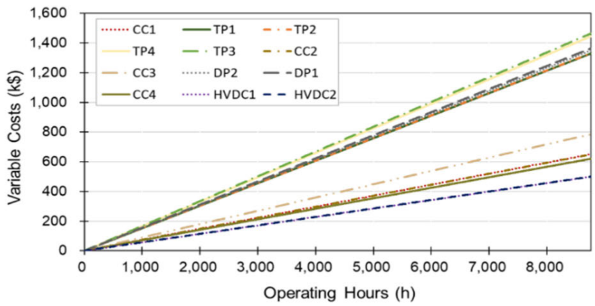

FIGURE 1. Annual generation cost curves for existing generators in the Jeju power system.

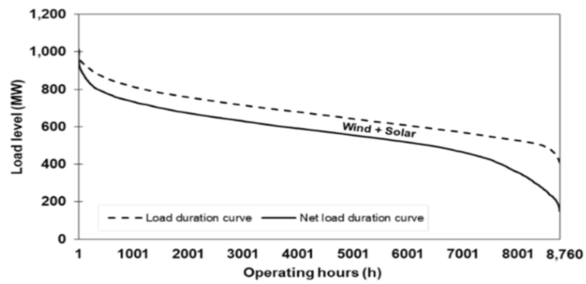

FIGURE 2. Annual load duration curve (LDC) and net load duration curve (NLDC) of the Jeju power system. The dotted and solid lines are examples of the load and net load duration curves, respectively.

Second, in the SCM, a load duration curve (LDC) is required in terms of demand to determine the annual operating time and energy mix of a given generation unit. The LDC is a curve sorted hourly by the load level over a period (usually a year, 8760 h). It reflects the arrangement of the real-time electricity demand in the order of the load level while also showing the operating time of the generator corresponding to each load level.

Economically, it is reasonable to deploy renewable energy on grid whenever it is available due to its lower variable costs compared to traditional fuel-based generators [16]. In this context, within the SCM aimed at finding the most cost-effective generation mix, the power output from wind and solar energy can be considered as a negative load, allowing for the inclusion of renewable energy's impact in the SCM [17]. At a specific time point, t, the net load was calculated by subtracting the solar and wind power from the load, as shown in (4). Similar to LDC, net loads can also be sorted in the order of load levels, and this is known as the net load duration curve (NLDC). Fig. 2 shows the LDC and NLDC using the actual load profile of the Jeju power system for 2021.

$$\text{Net load}_t = \text{Load}_t - \text{Solar}_t - \text{Wind}_t \tag{4}$$

Finally, the SCM finds a solution that can minimize the sum of the total generation costs of all generators to satisfy the load demand, which determines the optimal annual operating time and amount of generation for each unit. Using the previously obtained generation cost curve and load duration curve (Figs. 1 and 2), a cost-effective generation mix can be obtained by matching generation cost information and load profile at each load level based on operating hours. Fig. 3 shows the results of combining the annual generation cost curve (Fig. 1) and NLDC (Fig. 2) over the operating time using the Jeju data from 2021. In addition, the SCM-based optimal generation mix result for Jeju is presented at the right side of Fig. 3. The optimal capacity and operating time for each generator can typically be determined from the intersections between the graphs that combine generation costs and load levels. However, in the example shown in Fig. 3, no intersections are observed between the curves due to the absence of fixed costs, as only existing generators are considered. Consequently, traditional generators are dispatched for power supply based on their variable costs, following the order of lowest to highest variable cost. This implies that the sequence of participation in dispatch is directly associated with the ranking of variable costs. In Fig. 3, HVDC1 and HVDC2, which exhibit low total generation costs in Jeju, serve as base loads. In contrast, TP1 and TP2, with relatively higher total generation costs, operate as peak loads with fewer annual operating hours. Additionally, the energy mix in Fig. 3 consists of only traditional power sources, excluding renewable energy sources. This is because, as discussed in Section II-A, the effect of renewable generation has already been accounted for as negative load through the NLDC.

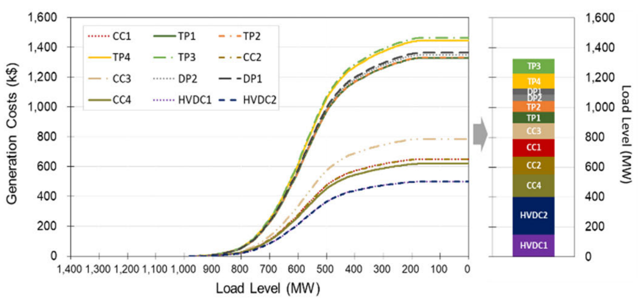

FIGURE 3. Results of optimal generation mix based on screening curve method (SCM) of the Jeju power system in 2021. This can be obtained by plotting the generation cost curves in Fig. 1 with the net load duration curve in Fig. 2.

B. CONSIDERATION OF MUST-RUN GENERATOR IMPACT

1) ADDITION OF MUST-RUN CONSTRAINTS

The simplest form of SCM, discussed in Section II-A, does not consider any operational constraints when determining the generation mix. To ensure system stability in response to the output variability of renewable energy, various operational constraints can be introduced into the SCM. In this study, to derive practical generation resource planning considering real-system constraints, an SCM has been proposed that incorporates the effects of must-run generation as an additional constraint on power generation. The addition of a must-run constraint to the generators' operating conditions can result in changes to the optimal generation-mix solution.

The concept of must-run units was established to enable system operators to maintain security and reliability during system operation [18]. To prepare for the rapidly changing power output of renewables and maintain the stability of the power system, some units can be selected that must continue to operate; these are called must-run generators [12]. For instance, wind and solar, nuclear, and the minimum levels of thermal generation required for system stability are all regarded as must-run units [19]. For simplicity, only the minimum levels of thermal generation required for grid stability were regarded as must-run units in this study. Under the given grid conditions, generators designated as must-run have to remain online (that is, in service) and must participate in the power supply for at least the minimum stable generation of the thermal units. Therefore, $P_{i,t}$, which denotes the power output of the must-run unit i at time t, must satisfy the constraints described in (5).

$$P_{\min,i} \leq P_{i,t} \leq CAP_i \quad \forall i \in I \tag{5}$$

CAP_i is the installed capacity of unit i and $P_{\min,i}$ is the minimum stable generation of unit i. Here, the minimum stable generation is the output level at which the generator can be stably operated for a long time and stably ramped up to the maximum output [20]. Furthermore, I denotes the set of all possible must-run generators, defined as $I = \{\text{MRG}_1, \text{MRG}_2, \cdots, \text{MRG}_n$, where i represents an index within set I. Subsequently, $\text{MR}_{t,\min}$, which denotes the minimum must-run level at time t, can be described by (6).

$$MR_{t,\min} = \sum\nolimits_{i}^{N(l)} P_{\min,i} \tag{6}$$

Here, $N(l)$ represents the number of operating must-run generators for the load level at time t. $\text{MR}_{t,\min}$ can be expressed as the sum of the minimum stable generations of the must-run units for the load level at time t.

2) VARIATION IN LOAD DURATION CURVE

In this study, a new type of LDC is applied within the SCM to incorporate the impact of must-run generation. For a must-run generation, both the generating unit and its minimum power generation have already been determined and contribute to power supply. As a result, it can be assumed that a specific portion of the energy mix is considered fixed. Therefore, similarly to how wind and solar generation were previously regarded as negative loads (see Section II-A), the minimum must-run generation can also be represented as a negative load. Consequently, when the must-run constraints are additionally considered in SCM, the NLDC defined in (4) can be transformed as (7):

$$\text{Residual load}_t = \text{Load}_t - \text{MR}_{t,\min} - \text{Solar}_t - \text{Wind}_t \tag{7}$$

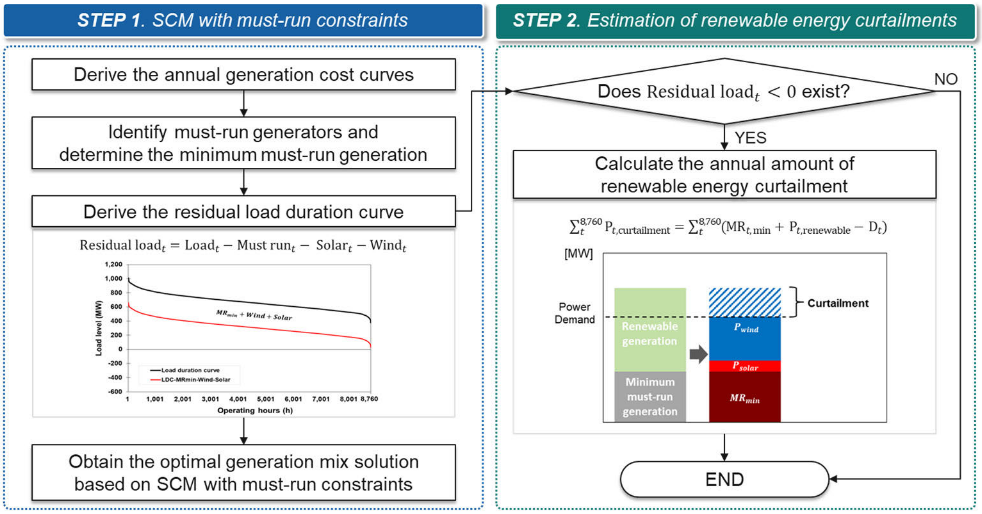

FIGURE 4. The proposed practical generation resource planning approach based on screening curve method (SCM) including must-run constraints.

The residual load at time t was obtained by subtracting the generation of the minimum must-run, solar, and wind energy from the load. When configuring the generation mix in SCM considering the must-run, we only need to determine the mix for the remaining loads, except for the minimum must-run generation.

III. PRACTICAL GENERATION RESOURCE PLANNING APPROACH BASED ON PROPOSED SCREENING CURVE METHOD

This section outlines a procedure for establishing the optimal generation mix through SCM incorporating must-run constraints and estimating renewable energy curtailment, as illustrated in Fig. 4.

A. PROCEDURE FOR OBTAINING THE OPTIMAL GENERATION MIX CONSIDERING MUST-RUN CONSTRAINTS

The procedure for determining the optimal generation mix by adding must-run generation constraints to the SCM is depicted in the left figure of Fig. 4. First, annual generation cost curves for each generator are derived based on the generation cost information of the generators. Subsequently, the must-run generators are identified based on the load level, and the minimum must-run generation is determined. For instance, the number of operating must-run units varies depending on the load level in Jeju. In this case, the minimum must-run generation is determined by identifying the level of power demand at a specific time point. The number of must-run units is small at low loads and increases at high loads. Detailed information on the must-run operation for the Jeju power system is provided in Table 2. The determined minimum must-run generation is considered as a fixed component of the generation mix for stable system operation. Therefore, within the SCM, it is treated as a negative load. As a result, the residual load at each time step must be met only by the remaining synchronous generators, excluding the already considered minimum must-run generation as a negative load and renewable energy generation.

Finally, in the SCM with must-run constraints, the optimal generation mix solution is derived by utilizing the generation cost curves and residual load duration curve. The detailed process is as follows: First, for the generators that are currently online (i.e., must-run units), they are dispatched in order of their low generation cost. If all the online must-run units generate at their maximum power output and the generation still cannot meet the demand, the offline generators (i.e., generators in the off state, non-must-run units) are started, beginning with the generator with the lowest generation cost. Their generation output is gradually increased. This process is repeated until the generation meets the demand of the residual load. When the generation fulfills the demand, the process of deriving the generation mix is terminated. Ultimately, the final generation mix results are obtained by combining the minimum must-run generation for each load level and the dispatch results of the synchronous generators for each time step.

B. ESTIMATION OF RENEWABLE ENERGY CURTAILMENT

In an energy system, curtailment (that is, limiting the power output of renewable energy) is a simple way to deal with excessive renewable energy output [21]. Meanwhile, in power systems where wind and solar penetration has increased significantly, renewable energy curtailment can be caused by various factors, such as an imbalance in supply and demand or the limited capacity of transmission lines [19]. This study focused on the amount of curtailment in terms of power balancing caused by overgeneration during low demand. Overgeneration in the power grid can occur when the sum of wind and solar power and the must-run generation (that is, the minimum thermal power output levels for grid stability) are higher than the load demand [19].

TABLE 1. Generator information of jeju power system in 2021.

Name	Type of generator	Installed capacity (MW)	Minimum power output (MW)	Maximum power output (MW)	Variable cost ($/MWh)
TP1	Thermal power plant	75	46	75	151
TP2	Thermal power plant	75	46	75	152
TP3	Thermal power plant	100	55	100	167
TP4	Thermal power plant	100	55	100	165
DP1	Internal combustion by diesel	40	27	40	155
DP2	Internal combustion by diesel	40	27	40	154
CC1	Combined cycle	120	78	120	75
CC2	Combined cycle	120	78	120	74
CC3	Combined cycle	105	43	105	89
CC4	Combined cycle	150	54	150	70
HVDC1	HVDC from mainland	300	50	150	57 [a]
HVDC2	HVDC from mainland	400	40	250	57 [a]
Wind	Wind turbines	295	0	295	-
PV	Photovoltaic	525	0	525	-

[a]The variable cost of HVDC is assumed to be based on the system marginal price of the mainland.

TABLE 2. Must-run information by load level of jeju power system.

Load Level (MW)	Number of units in must-run status	Minimum must-run level (MW)
0 to 500	6	315
501 to 600	7	370
601 to 900	8	448
901 to 1040	9	491

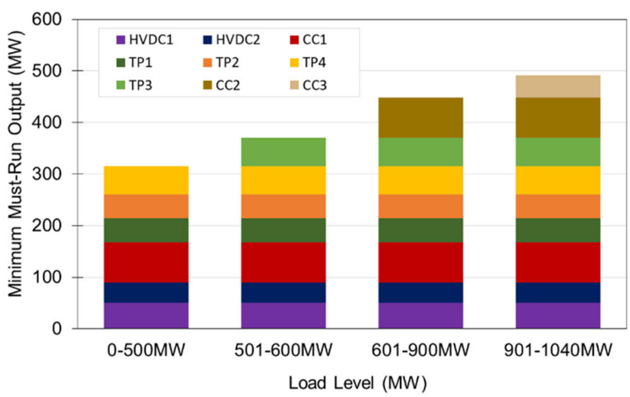

FIGURE 5. The operating conditions of must-run generators for different load levels in the Jeju system. The number of must-run units depends on the demand level.

With the additional consideration of must-run constraints, renewable energy curtailment may occur if the sum of the minimum must-run level and the power output of renewable energy exceeds the electricity demand at a specific time. Consequently, in accordance with the optimal generation resource mix results derived in this paper, the expected annual curtailment can be estimated following the procedure illustrated in the right of Fig. 4. As discussed in Section II-A, variable-generating resources, such as wind and solar, are regarded as negative loads in the SCM. This means that any available renewable energy must be unconditionally integrated into the network [22]. However, even when there is ample renewable generation to meet demand, it might not be used for power supply due to the operating conditions of other generators and power system stability. If the criteria outlined in (8) are met, renewable energy is curtailed. The amount of curtailed renewable energy is calculated using (9):

TABLE 3. Base case (2021) and three scenarios with different wind penetration levels.

	Annual electricity demand (MWh)	Installed capacity of wind (MW)	Annual wind power generation (MWh)	Wind Penetration (%)
Base Case (Real data in 2021)	5,870,631	295	524,929	9
Scenario 1		589	1,049,858	18
Scenario 2		884	1,574,787	27
Scenario 3		1,178	2,099,716	36

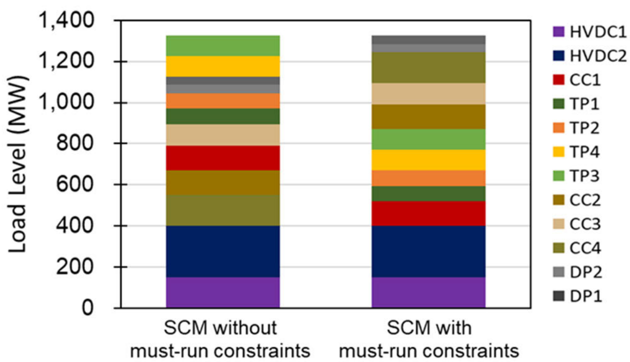

FIGURE 6. Comparison of practical generation mix results for synchronous generators based on screening curve method (SCM) with and without must-run constraints.

$$\mathrm{MR}_{t,\min} + P_{t,\text{renewable}} > D_t \tag{8}$$

$$P_{t,\text{curtailment}} = \mathrm{MR}_{t,\min} + P_{t,\text{renewable}} - D_t \tag{9}$$

Here, D_t is the electric power demand at time t, and $\mathrm{MR}_{t,\min}$ is the minimum power output of the must-run generators. $P_{t,\text{renewable}}$ and $P_{t,\text{curtailment}}$ represent the amounts of renewable generation and curtailment at time t, respectively. Using the above equations, the annual wind curtailment capacity for different wind penetration levels can be estimated in Section IV-C.

IV. CASE STUDIES FOR JEJU ISLAND

A. DATA DESCRIPTION

Generator and load data collected from the Jeju real system in 2021 were used for the case studies [23], [24]. In this case study, the optimal generation mix solution was determined considering only the existing generators, and Table 1 provides a summary of the type and operational details of each

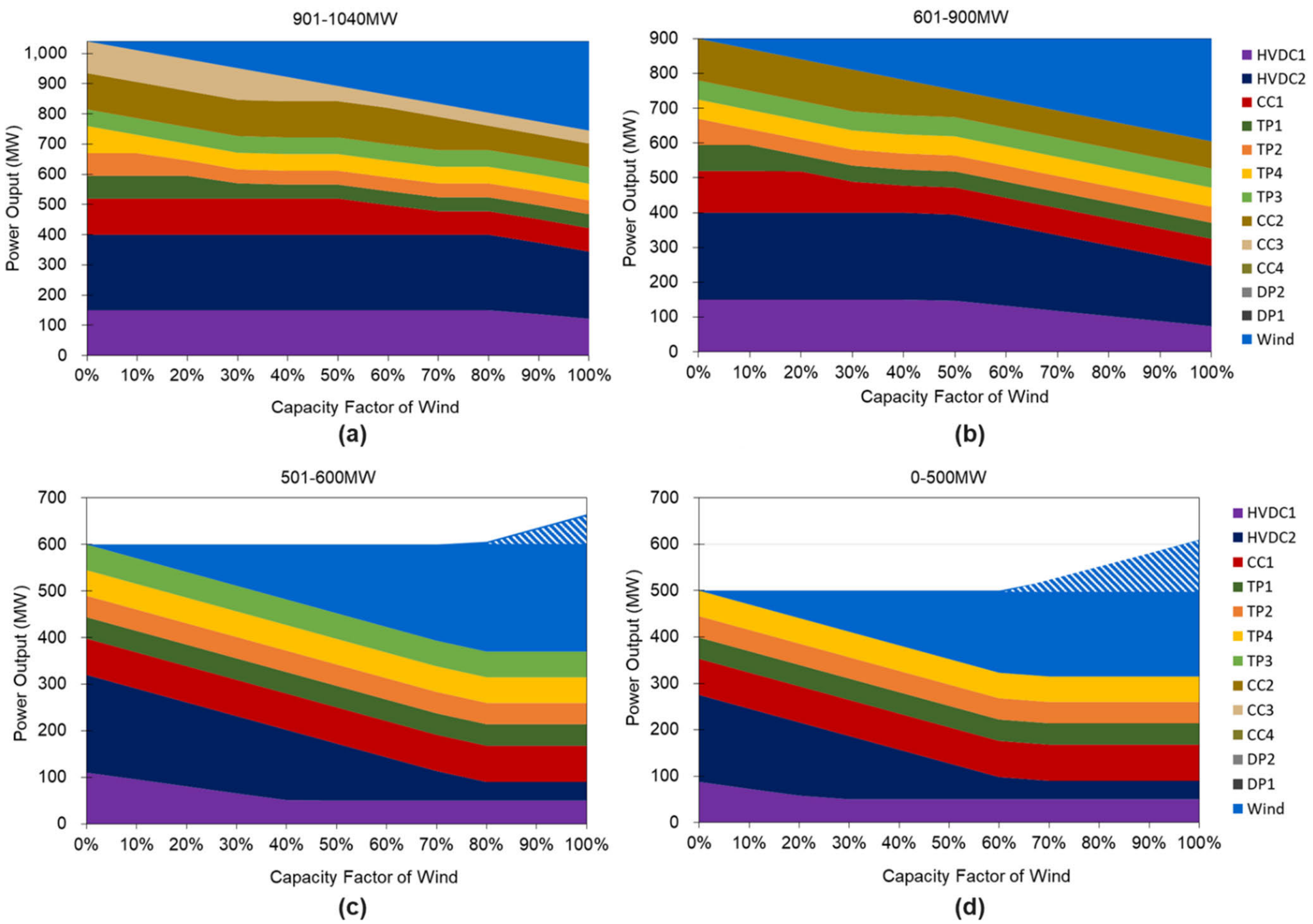

FIGURE 7. Results of optimal generation resource mix for base case according to wind capacity factor. The capacity factor here represents the ratio of wind power output to installed wind capacity and this was simulated based on SCM with considering must-run constraints for each load level: (a) 901–1040MW; (b) 601–900MW; (c) 501–600MW; and (d) 0–500MW. Blue hatched area means wind curtailment.

generator used in all case studies. Generator cost data for the Jeju system in 2020 were applied in the SCM. In 2021, the total installed electricity generation capacity in Jeju was 1,764 MW, of which 295 MW was wind and 525 MW was solar. TP-, DP-, and CC-type generators represent thermal power plants located on Jeju Island, and high-voltage direct currents (HVDCs) represent electricity transmitted from mainland to Jeju Island. HVDC transmission lines function as synchronous generators in the Jeju power system, and the amount of power received is adjusted according to the system situation. HVDC contributes significantly to the total power generation on Jeju Island and serves as a valuable source for intermittent backup. The 2021 annual (8,760 h) hourly load profile is illustrated in Fig. 2, with an annual peak demand of 1,012 MW [23].

In this paper, empirical must-run operational data from the Jeju system were employed to derive practical generation-mix solutions while accounting for the impact of must-run units. Table 2 provides an overview of the operational conditions of the must-run units in the Jeju power system, which were used in the simulations. As illustrated in Table 2, the number of generators operating as must-run units increases as the load level increases. The minimum must-run level in Table 2 represents the cumulative minimum power outputs of generators identified as must-run units at various load levels. Detailed information is visualized in Fig. 5.

B. THREE SCENARIOS WITH DIFFERENT WIND PENETRATION LEVELS

In this study, three different wind penetration scenarios with increased installed wind capacity were established to estimate the generation mix results and amount of curtailment in renewable energy-dominant power systems. To create the scenarios, 2021 power generation and load data for Jeju Island were regarded as the base case. According to the empirical data for Jeju in 2021, the proportion of wind power to the annual electricity demand was 8.94%, and the installed capacity was 295 MW. Furthermore, according to the 10th Basic Plan in South Korea [25], Jeju Island plans to expand its wind capacity to a total of 2,345 MW by 2030. This expansion indicates a significant increase in wind power facilities over the coming years. To analyze the effect of this rapid increase in wind power facilities on the practical generation mix of Jeju, our simulation focused solely on wind power, excluding

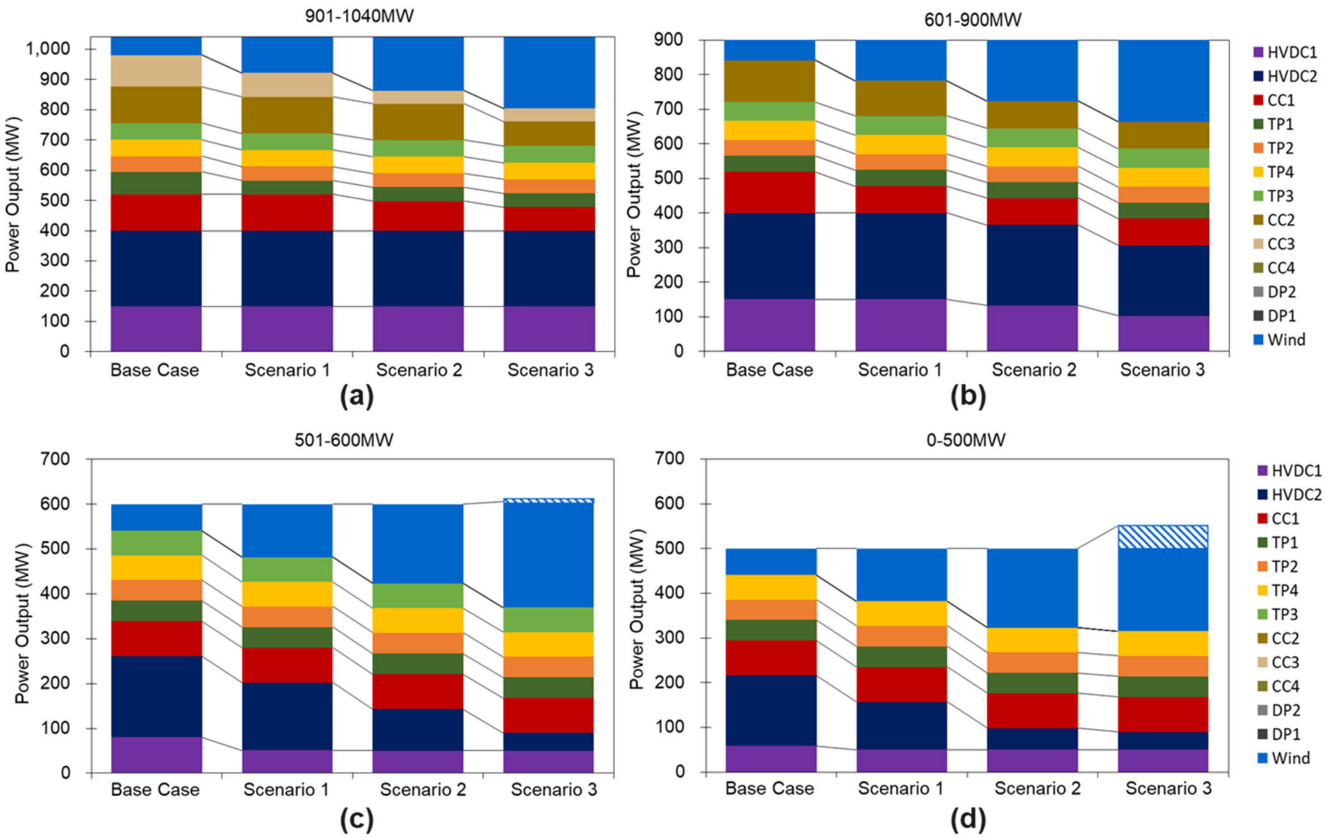

FIGURE 8. **Results of optimal generation resource mix for three scenarios with different wind penetration levels. This was simulated based on the screening curve method (SCM) with considering must-run constraints for each load level: (a) 901–1040MW; (b) 601–900MW; (c) 501–600MW; and (d) 0–500MW. Wind power output is assumed by applying a capacity factor of 20.3%. Blue hatched area means wind curtailment.**

solar energy from the renewable energy sources. For the simulation, scenarios of doubling, tripling, and quadrupling the installed wind capacity compared with 2021 were all assumed and presented in Table 3. For all scenarios, the annual power demand was fixed to be the same as that of the actual data for 2021, and only the chronological wind power generation data were scaled up based on the base case. The wind penetration in Table 3 is the ratio of wind power to annual electricity demand, calculated as the annual wind power generation divided by the annual electricity demand.

C. RESULTS AND DISCUSSION

1) OPTIMAL GENERATION MIX BASED ON SCREENING CURVE METHOD CONSIDERING MUST-RUN CONSTRAINTS

To obtain the optimal generation mix for the Jeju case, we can first generate annual generation cost curves and a load duration curve, as shown in Fig. 1 and Fig. 2, respectively. Then, by applying the proposed method, Fig. 6 illustrates the generation resource mix results for the Jeju power system in cases both with and without must-run constraints. The results in Fig. 6 demonstrate significant changes in the composition of mid-load and peak-load generation units when considering must-run constraints compared to not considering them. In the SCM result without must-run constraints, technologies with lower cost were positioned at the bottom of the optimal energy generation mix, according to the power generation cost ranking. The traditional generators listed in Table 1 can be arranged in ascending order of variable costs as follows: HVDC1 = HVDC2 < CC4 < CC2 < CC1 < CC3 < TP1 < TP2 < DP2 < DP1 < TP4 < TP3, and the results without considering must-run constraints follow this order of dispatch. In contrast, in the SCM result with must-run constraints, higher-cost generators like TP-type generators have moved up in dispatch priority as they are now operating as must-run units, leading to a change in dispatch order.

Based on the SCM results with must-run constraints for the traditional generators in Fig. 6, Fig. 7 illustrates how the generation resource mix changes in response to variations in the wind capacity factor for the base case. The optimal generation mix outcomes are separately displayed for different demand levels, considering distinct must-run unit constraints for each load level. As shown in Fig. 7, with increasing wind capacity factors at all load levels, the generator with the highest generation cost was gradually replaced by wind generation. At relatively high load levels (Figs. 7 (a) and (b)), even when the wind capacity factor reached 100%, the output of the other synchronous generators could be reduced to accommodate all wind generation. However, at relatively low load levels (Figs. 7 (c) and (d)), wind curtailment was observed. This is because that must-run generators, even if not the most

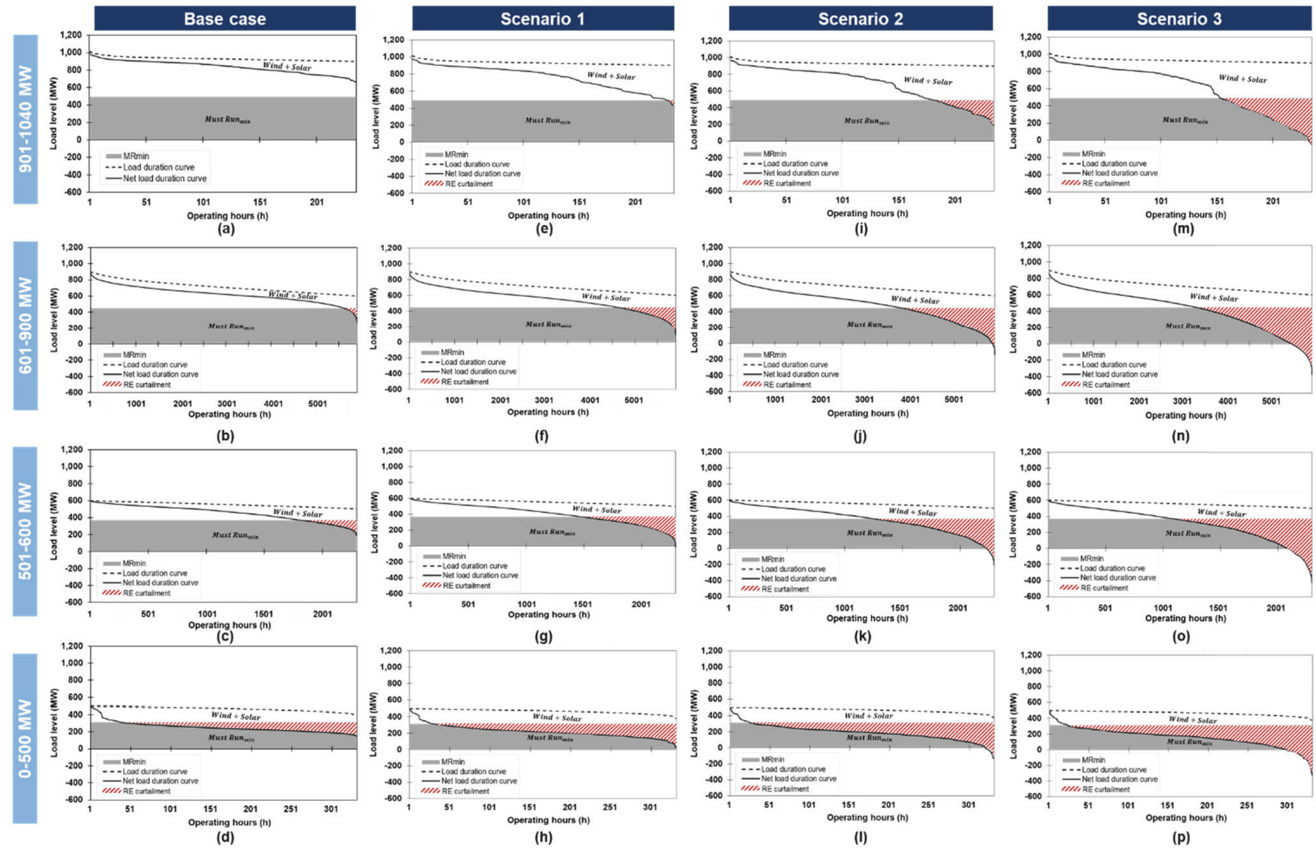

FIGURE 9. The expected amount of renewable energy curtailment for base case and three scenarios based on the screening curve method (SCM) considering must-run constraints for each load level: (a) 901–1040MW (Base case); (b) 601–900MW (Base case); (c) 501–600MW (Base case); (d) 0–500MW (Base case); (e) 901–1040MW (Scenario 1); (f) 601–900MW (Scenario 1); (g) 501–600MW (Scenario 1); (h) 0–500MW (Scenario 1); (i) 901–1040MW (Scenario 2); (j) 601–900MW (Scenario 2); (k) 501–600MW (Scenario 2); (l) 0–500MW (Scenario 2); (m) 901–1040MW (Scenario 3); (n) 601–900MW (Scenario 3); (o) 501–600MW (Scenario 3); (p) 0–500MW (Scenario 3). The actual electricity demand data from the Jeju system in 2021 was applied in the simulation. The red hatched area overlapping the gray area represents the renewable curtailment resulting from must-run constraints.

cost-effective, cannot be taken offline and must be maintained at or above their minimum stable output levels. Consequently, there comes a point where it is no longer feasible to reduce the output of synchronous generators to ensure grid stability. Specifically, curtailment started to occur at 70% of the wind capacity factor for a demand level of 501–600 MW and at 60% for 0–500 MW. This curtailed energy represents the excess renewable output that cannot be accommodated in the grid, even after adjusting the must-run units to their minimum output levels. In other words, based on the simulation results for the base case, it can be confirmed that wind curtailment occurs when wind power is heavily injected at low loads.

Next, in order to estimate optimal energy-mix planning for the future wind capacity expansion system, case studies were conducted for three scenarios with different wind penetration levels. Fig. 8 presents a comparison of the generator operating strategies, applying a capacity factor of 20.3% (the annual average wind capacity factor in 2021) to each wind-installed capacity scenario listed in Table 3. In Fig. 8, as wind penetration increases from the base case to Scenario 3, the power output of traditional generators decreases sequentially, starting with the generator having the lowest economic priority (the last dispatch order). If the generator is a must-run unit and reaches its minimum output level during the reduction process, the power output of the next less economic generator is decreased.

When demand was high, ranging from 901–1,040 MW (Fig. 8(a)), with increasing wind penetration, a capacity transition primarily occurred from the TP-type generators, which correspond to relatively less economic must-run units, to wind generators. Subsequently, there was a capacity transition from the CC-type generators, the next less economic (higher generation cost) must-run units, to wind generators. At this high load level, adjustments at mid-load and peak-load were sufficient to accommodate wind power, resulting in no changes in the resource mix share for HVDC1 and HVDC2, which correspond to the base-load generators.

When the demand was in the range of 601–900 MW (Fig. 8(b)), TP-type generators, which have relatively high generation cost, were already operating at the minimum must-run levels. Therefore, there was no change in the share of TP-type generators. Instead, as wind capacity expanded, the share of CC-type generators, which represent the next less economic generators, decreased, affecting the mid-load and peak-load shares. In Scenario 2 and 3, the share of base load also decreased to meet supply-demand balance.

TABLE 4. Annual renewable energy curtailment for different wind penetration scenarios.

	Consideration of must-run constraints	Load Level (MW)								Annual Total	
		901 to 1040		601 to 900		501 to 600		0 to 500			
		Amount of curtailment (MWh)	Curtailment occurrence time (h)	Amount of curtailment (MWh)	Curtailment occurrence time (h)	Amount of curtailment (MWh)	Curtailment occurrence time (h)	Amount of curtailment (MWh)	Curtailment occurrence time (h)	Amount of curtailment (MWh)	Curtailment occurrence time (h)
Base case	Not considered	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	Considered	0 (0%)	0 (0%)	12,585 (2%)	276 (5%)	26,629 (12%)	482 (21%)	23,119 (32%)	294 (89%)	62,333 (7%)	1,052 (12%)
Scenario 1	Not considered	0 (0%)	0 (0%)	0 (0%)	0 (0%)	12 (0%)	1 (0%)	0 (0%)	0 (0%)	12 (0%)	1 (0%)
	Considered	175 (0%)	6 (3%)	123,169 (13%)	1,275 (22%)	80,889 (24%)	818 (36%)	32,806 (40%)	302 (91%)	237,039 (17%)	2,401 (27%)
Scenario 2	Not considered	0 (0%)	0 (0%)	1,945 (0%)	58 (1%)	4,171 (1%)	67 (3%)	586 (1%)	11 (3%)	6,702 (0%)	136 (2%)
	Considered	6,353 (11%)	53 (23%)	362,025 (27%)	2,081 (35%)	157,949 (35%)	1,047 (46%)	42,658 (47%)	306 (92%)	568,986 (29%)	3,487 (40%)
Scenario 3	Not considered	87 (0%)	3 (1%)	46,192 (3%)	467 (8%)	26,050 (5%)	206 (9%)	2,807 (3%)	32 (10%)	75,136 (3%)	708 (8%)
	Considered	18,082 (24%)	82 (35%)	657,806 (38%)	2,585 (44%)	245,108 (44%)	1,204 (52%)	52,607 (52%)	308 (93%)	973,603 (40%)	4,179 (48%)

Percent values in parentheses under "Amount of curtailment (MW)" indicate the ratio of renewable energy curtailment to the overall renewable energy generation during the respective period. Percent values in parentheses under "Curtailment occurrence time (h)" indicate the ratio of curtailment occurrence time to the total duration.

When the demand was relatively low, ranging from 501–600 MW (Fig. 8(c)) and 0–500 MW (Fig. 8(d)), all must-run units, except HVDC1 and HVDC2, operated at their minimum stable outputs in all scenarios. Consequently, as wind penetration increased, the share of base load corresponding to HVDC1 and HVDC2 decreased. Moreover, in Scenario 3, wind curtailment occurred because all must-run units had been reduced to their minimum output levels, leaving no further capacity to decrease in the output of the synchronous generators.

In summary, it is expected that as wind penetration increases, the share of generating resource of mid-load and peak-load generators will decrease at high demand levels. Conversely, at low demand levels, the share of generating resource of base-load generators will decrease as wind penetration increases. Moreover, at low load levels, Scenario 3, with the most substantial wind capacity increase, experiences wind curtailment due to the minimum must-run generation. This implies that in future wind expansion scenarios, there could be operational situations where, despite abundant wind resources during periods of low demand, wind integration into the grid may be limited due to must-run constraints.

2) EXPECTED AMOUNT OF RENEWABLE ENERGY CURTAILMENT

Even with the expected expansion of renewable energy capacity in future power system, it is not guaranteed that all generated power from renewable sources will be utilized in the power supply. To evaluate the annual renewable energy generation that can practically be integrated into the grid as wind power increases, we used actual load data in 2021 to estimate the annual renewable energy curtailment from a supply-demand balance perspective in the wind capacity increase scenarios. The simulation results for the expected amount of renewable energy curtailment based on scenario-specific resource mix planning are presented in Fig. 9 and Table 4.

Fig. 9 illustrates the estimated amount of renewable energy curtailment for each scenario at different load levels, considering the must-run constraints in the SCM. At relatively low load levels, curtailed renewable energy occurred in all cases, with a higher occurrence as electricity demand decreased. At high load levels, such as 901-1040 MW, there was no renewable energy curtailment in the base case with low wind penetration, as adjustments in other traditional generators accommodated the abundant wind generation. However, as wind penetration increased, renewable energy curtailment was observed even during peak load situations. This suggests that with the expected growth in wind capacity in the future, curtailment of renewable energy may occur not only during low-demand periods but also frequently during high-demand periods, indicating a substantial increase in annual curtailment.

Table 4 compares the estimated annual renewable energy curtailment results for different wind penetration scenarios when considering must-run constraints (Fig. 9) and when not considering them. It is evident that, in all scenarios, considering must-run constraints leads to an increase in the amount and duration of curtailment compared to the cases without these constraints. The significant differences between the two cases highlight the substantial impact of considering the practical constraints of must-run conditions on generation planning. Particularly at low demand levels, such as 0-500 MW, considering must-run constraints resulted in curtailment for more than 90% of the total duration consistently across Scenario 1 to 3. This implies that at low demand levels below 500 MW, renewable curtailment occurs frequently to maintain a stable supply-demand balance in the grid. Analyzing the annual total renewable curtailment for each scenario, Scenario 3, in particular, has approximately half the duration of curtailment occurrence and an amount equivalent to about 40% of the annual renewable energy generation. Therefore, in long-term generation planning, strategies such as securing flexibility resources and relaxing minimum must-run constraints are essential to mitigate curtailment caused by the expansion of wind installed capacity.

V. CONCLUSION

Considering that a large amount of wind power deployment is expected in the upcoming years, a new energy generation mix that includes high wind penetration should be investigated. To derive a practical solution for the future generation resource mix, it becomes essential to incorporate additional considerations of constraints from real systems when determining the optimal combination of generators.

In this paper, we propose a screening curve method (SCM) augmented with must-run constraints to determine a practical generation resource mix from the perspective of long-term generation planning. Additionally, we introduce an approach for estimating the annual amount of renewable curtailment, taking into account real operational constraints in the decision-making process for long-term supply planning. The proposed SCM method, incorporating must-run constraints, allows for the approximation of the target year's generation mix with minimal data, resulting in low computational costs and maintaining the simplicity of the basic SCM. Furthermore, by advancing the traditional SCM to consider must-run constraints, which are essential in the actual operation of the power system for maintaining system stability, it contributes to long-term practical generation planning by providing feasible estimates of the generation resource mix and annual renewable curtailment for future renewable energy expansion scenarios.

A case study was conducted by applying the proposed method using empirical data from the Jeju power grid. Three scenarios with different wind penetration levels were established for simulation, and their results were compared. The following summarizes the key findings obtained through the case study:

- Based on the obtained practical generation resource mix results, an increase in wind power integration is anticipated to result in a decrease in the proportion of mid-load and peak-load generators at high demand levels. Conversely, at low demand levels, the proportion of base-load generators is expected to decrease, with the possibility of curtailment in certain situations.
- Based on the estimated annual renewable energy curtailment results, the future expansion of wind penetration is expected to increase the frequency of renewable energy curtailment at both high and low demand levels. This curtailment was mainly observed at low demand levels with the current level of wind penetration, but it is anticipated to occur more frequently, even at high demand levels in the future. Therefore, in long-term generation resource planning, it highlights the crucial necessity of formulating strategies to minimize curtailment and optimize the utilization of generated wind power. This includes actions like reducing the minimum output level of must-run units and introducing flexible resources such as energy storage systems.

In the future, there is potential to improve the SCM by incorporating additional operational constraints that frequently arise from the integration of variable renewable energy sources. The inclusion of short-term operational constraints, such as start-up costs and the ramp-up/down rates of generators, holds the promise of producing a more sophisticated and refined practical generation mix solution.

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