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Summary

Climate change is an urgent global challenge. Japan decided to address it by trying to achieve carbon neutrality and formulated the Sixth Strategic Energy Plan. The Sixth Strategic Energy Plan stated renewable energy resources (RES) would be utilized as the major power sources. RES will be unevenly developed between areas according to their potentials with which northern and western regions of Japan are abundant. So, it is necessary to transmit electricity from RES to demand centers from these regions. But in the past, Japanese transmission operators have constructed grids according to their regional characteristics, and capacities of interconnection lines between areas are bottlenecks for cross-regional transmission operation. In such circumstances, nationwide transmission reinforcement is indispensable. Therefore, the Long-term Transmission Network Expansion Plan was formulated as guidance for reinforcements of existing grids.

In its planning, scenarios containing assumptions and presuppositions towards 2050 were generated to clarify uncertainties. Power flow simulations, in which the simulation model contains approximately 1200 nodes, were conducted to determine transmission constraints in the future. From their results, reinforcement options were devised. Then, proposed options were assessed by cost-benefit analysis to select promising ones. According to the results of the baseline scenario, reinforcement of the bulk power systems which includes new 6 GW and 8 GW High Voltage Direct Current (HVDC) lines costs six to seven trillion yen. Yearly benefits were calculated at 730 billion yen and CO_2 reduction reached 24.3 million tons.

This paper presents a description of the Long-term Transmission Network Expansion Plan and its planning process. It will help grid planners globally plan their power systems to respond to the increasing RES.

Keywords

Transmission Development, Carbon Neutrality, Renewable Energy, System Planning, Cost-Benefit Analysis, HVDC

Introduction

Climate change is an urgent global challenge; Japan has decided to address it by trying to achieve carbon neutrality and formulating the Sixth Strategic Energy Plan[1]. The plan stated renewable energy resources (RES) would be utilized as the major power sources. RES are expected to be developed unevenly between areas according to their potential; therefore, it will be necessary to transmit electricity from RES development regions to demand centers.

However, there are deep uncertainties regarding demand prediction, development of power supply sources, long lead times, and large-scale investments necessary for transmission expansions[1]. Therefore, from a long-term perspective, it is needed to consider a transmission system that is sufficiently flexible to respond to these uncertainties.

In the past, Japanese transmission operators in each area have constructed grids according to their regional characteristics[3]. These areas are interconnected, but the transmission capacity of the interconnection lines are bottlenecks for cross-regional transmission system operation. In such circumstances, the nationwide reinforcement of transmission systems is indispensable. Therefore, the future of the transmission system towards 2050 lies in the Long-term Transmission Network Expansion Plan, and based on it, the reinforcement of existing grids is promoted.

In the Long-term Transmission Network Expansion Plan, scenarios containing assumptions of demand and power supply resources towards 2050 were generated according to the Sixth Strategic Energy Plan. The future power flow was simulated based on these scenarios, and transmission constraints were identified. Reinforcement options to mitigate these constraints were evaluated by cost-benefit analysis (CBA).

This paper introduces a long-term plan that realizes the mass introduction of RES and its planning process. The first section explains future scenarios employed in this perspective. The following section discusses methodologies, including power flow simulations, which determine the transmission constraints, and CBA for transmission expansions. Finally, the Long-term Transmission Network Expansion Plan and its implications are described.

Scenarios Towards 2050

Japan formulated the Sixth Strategic Energy Plan in 2021 to realize carbon neutrality by 2050. Figure 1 shows the future target of supply composition in this plan. For instance, In the mix, the RES ratio, which is calculated by dividing the total amount of RES generation by the total amount of generation of all units, should increase to 36%–38% in 2030 and 50%–60% in 2050 from 18% in 2019.

Therefore, promoting RES developments in Japan’s northern and western parts with abundant RES potential is indispensable. However, these regions, especially the northern region, have a small demand compared with their RES potentials. Therefore, Figure 2 shows that it should reinforce the transmission systems to transmit electricity from RES to the demand centers.

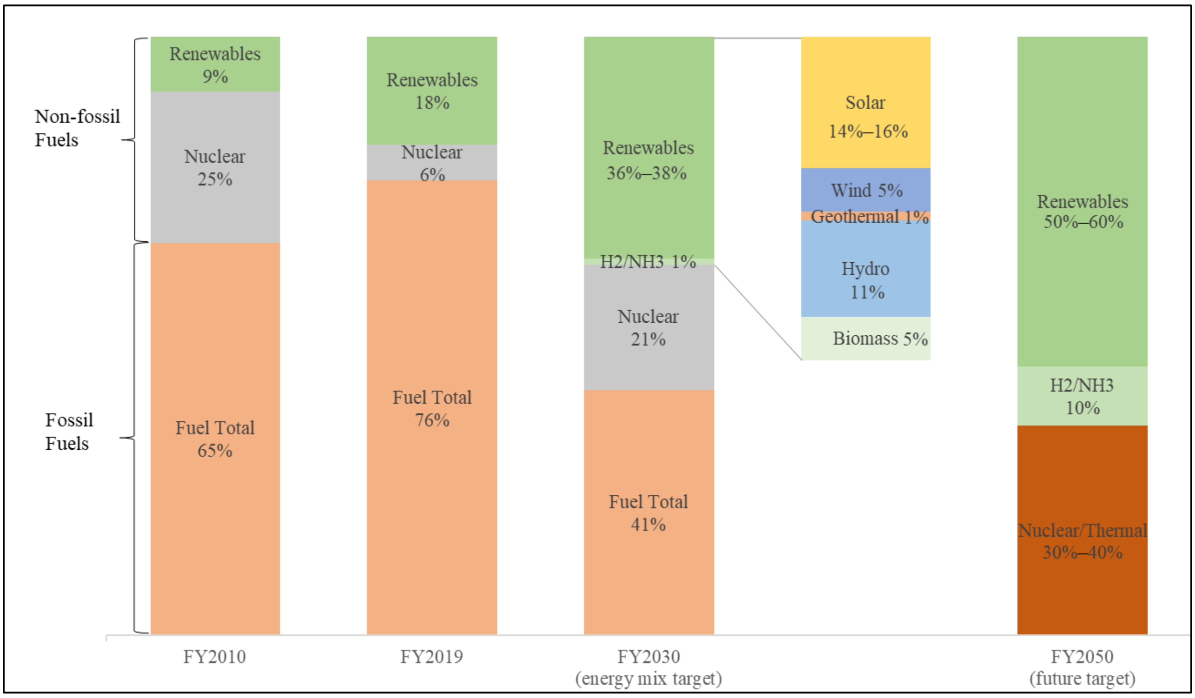

Figure 1 Supply Composition in the Future[4]

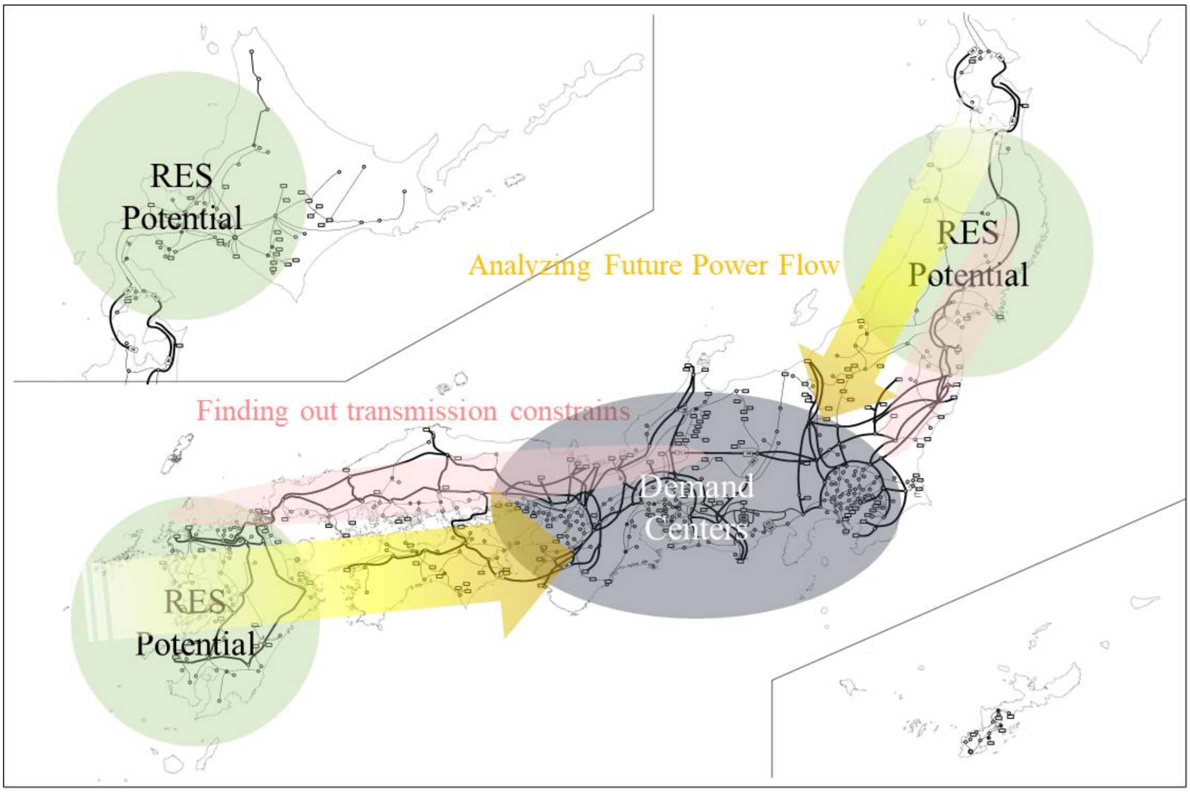

Figure 2 Distribution of RES Potentials and Demand Centers

With these expectations, scenarios containing assumptions of demand and supply power sources were generated to study from a long-term perspective the use of transmission networks to realize the mass introduction of RES. Scenario assumptions are based on the targets presented by the Sixth Strategic Energy Plan, and some presuppositions are included. Table 1 shows an example.

Table 1 Baseline Scenario Assumptions

			Baseline Scenario
Annual Demand			1.26 PWh
Supply	RES	PV	260 GW
		Onshore Wind	41 GW
		Offshore Wind	45 GW
		Hydro, Biomass, and Geothermal	60 GW
	Other	Thermal	125 GW
		Nuclear	25 GW
		H_2, NH_3	20 GW

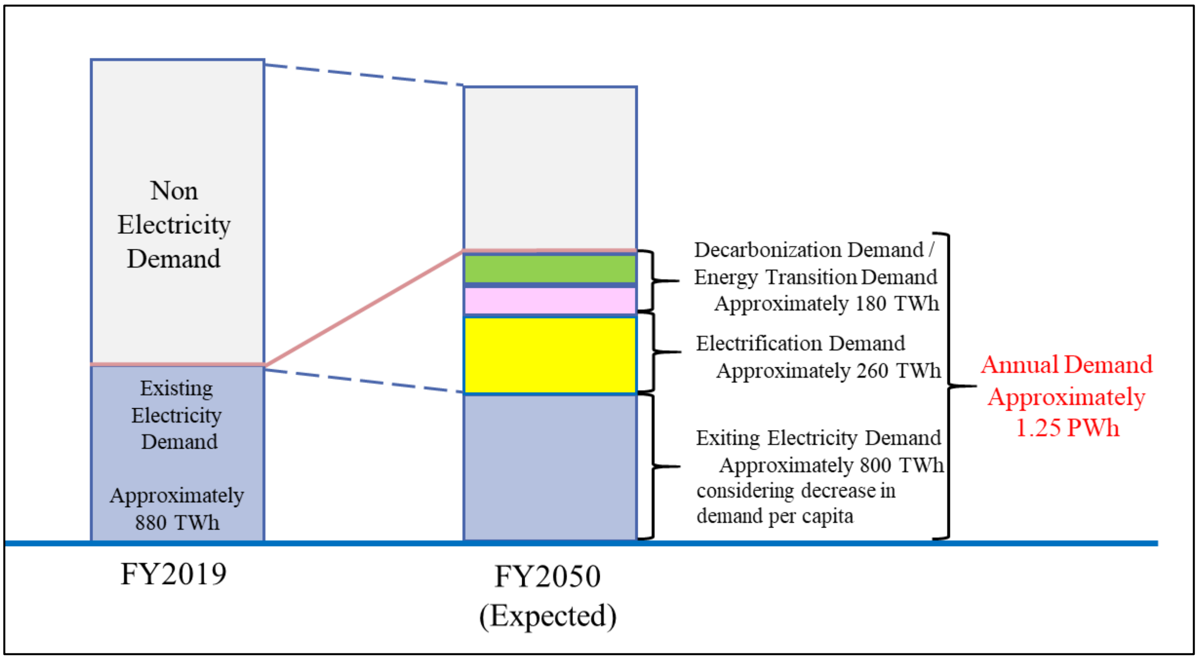

Figure 3 Energy Demand

Electricity demand was calculated based on Japan's demographic characteristics and economic expectations, including an increase in demand caused by promoting electrification and energy transition. Figure 3 represents its overview. In the baseline scenario towards 2050, electricity demand was expected to increase to 1.25 PWh, 1.4 times that in 2019. Further, to clarify uncertainties, scenarios in which demand increased or decreased by 20% from the baseline scenario or other scenarios which contain different distributions of demand from the baseline scenario were assessed.

Assumptions regarding power supply resources were based on realizing the supply composition, especially the RES ratio, as shown in the Sixth Strategic Energy Plan. The RES potential was considered in sites for developing RES. Many offshore wind farms expected a large-scale increase and were assumed to be developed intensively in Japan's northern and western parts[5]. Furthermore, the assumption of thermal power stations was based on existing or under-construction plants or those in the planning stage and expected retirement. H_2/NH_3 generation plants should replace them after 45 years of operation. Nuclear power plants, including existing and under-construction plants or those in the planning stage, should operate for up to 60 years. Moreover, it was supposed to use 5% of all vehicles for batteries as vehicle-to-grid (V2G)[6]. The cases that the capacity of supply power sources increased or decreased by 20% from the baseline scenario and sites for developing RES changed from the scenario were also considered.

Methodology

The power flow in the future was simulated based on the scenarios from the previous section and transmission constraints were identified. The methods used to assess reinforcement options to address these constraints are described in the following sections.

Supply–Demand and Power Flow Simulations

The Nodal simulation model was built to simulate the nationwide power flow in the future. It represents the bulk power system in Japan comprising 500 kV, 275 kV, and partially 154 kV buses and transmission lines with the highest and second-highest voltage in each area. This model consists of approximately 1200 nodes; some have supply power sources and demand. Transmission lines between two nodes have operational capacities in long-used current transmission system operations.

In simulation settings, each unit was assigned a generation cost based on its station type, which included start-up, fuel, and emission costs. Constraints of thermal units, storage hydro units, and batteries, such as ramp-rate or minimum capacity, were also considered. The objective function of simulations was to minimize the total generation cost by merit order.

Power flow simulations were conducted for 8760 hours based on these conditions. Transmission constraints were identified by them. Then, several reinforcement options for them were devised to mitigate these constraints.

CBA

CBA was conducted to determine the overall optimized transmission system, including power supply sources, by selecting effective and efficient combinations. Figure 4 shows an example of the CBA process. CBA calculates the benefit–cost ratio (BCR). Simultaneously, the effect of decreasing RES curtailment caused by the transmission capacity constraints or the ancillary service constraints was assessed. Grid stability and the increase in the required inertia and balancing capacity were also assessed.

In CBA, total costs and benefits over 30 years were calculated. Costs comprise additional operational costs due to reinforcements, generation costs consisting of start-up costs of units and fuel costs, and grid expansion costs. Benefits comprise reducing operating costs, including emission and fuel costs, transmission losses, and improvement in adequacy. The discount factor was set to 4% per year to convert future costs and benefits into present values.

Regarding fuel costs, uncertainties exist about the fuel market price fluctuations. Therefore, fuel prices were considered a band based on the price history. Therefore, BCR was also a band. If the upper side of the BCR band is over 1, it is considered reasonable because the benefits could exceed the costs. In this process, the expansion options were broadly considered for a flexible response to future uncertainties. For example, if a BCR band is 0.8–1.3, that expansion is included in the options. However, if a BCR band is 0.5–0.9, or the BCR is below 1, that reinforcement is excluded from the options.

The optimal nationwide reinforcement package was formed by assessing multiple reinforcement options according to their BCRs and reduction in the RES curtailment ratio, and Figure 4 provides an example. The RES curtailment ratio was calculated by dividing the actual amount of RES generation in a simulation by the ideal amount of RES generation. For example, if RES curtailment ratio reaches

100%, all RES units can operate at their full potential. Therefore, the 400 MW option in the figure is excluded from reinforcement options because BCR is below 1. For the rest, the 300 MW option is considered optimal because the effect of the reducing RES curtailment ratio is saturated.

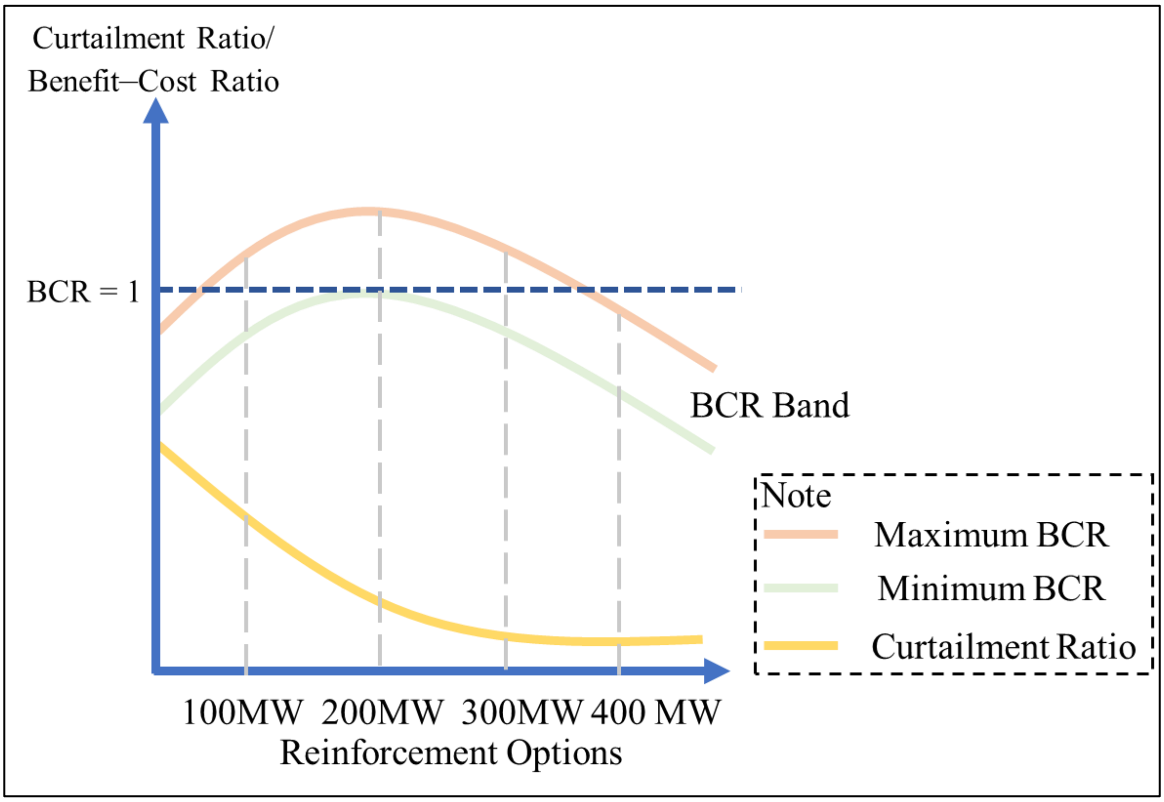

Figure 4 Example of Selecting Options

Long-term Transmission Network Expansion Plan

Figure 5 represents the long-term perspective of the above studies. Figure 5 and Table 2 are an example of reinforcements in the baseline scenario, showing that it will cost six to seven trillion yen to reinforce Japan's bulk power system. The following summarizes the areas where grid reinforcements will be required.

Eastern region: New high-voltage direct current (HVDC) lines are needed to efficiently transmit electricity generated by RES in Japan's northern parts to the demand center, Tokyo. A promising option is 6 GW HVDC lines from Hokkaido to Tohoku and 8 GW HVDC lines from Tohoku to Tokyo.

Central-western region: The 2.8 GW reinforcement of the Chugoku–Kyushu interconnection line is a promising option to efficiently transmit electricity generated by RES in the western region, Kyushu, to the demand centers, Kansai and Chubu. Furthermore, reinforcements in the central region, comprising Chubu, Hokuriku, and Kansai, were confirmed to improve the BCR.

Frequency converters (FCs): Japan's nationwide transmission system divides into 50 Hz in the Eastern region and 60 Hz in the Central-western region, interconnected by FCs. The FC transmission capacity should be reinforced from 2.1 GW to 3.3 GW by the end of FY2027. This study confirmed that another 2.7 GW of reinforcement could exceed BCR 1.

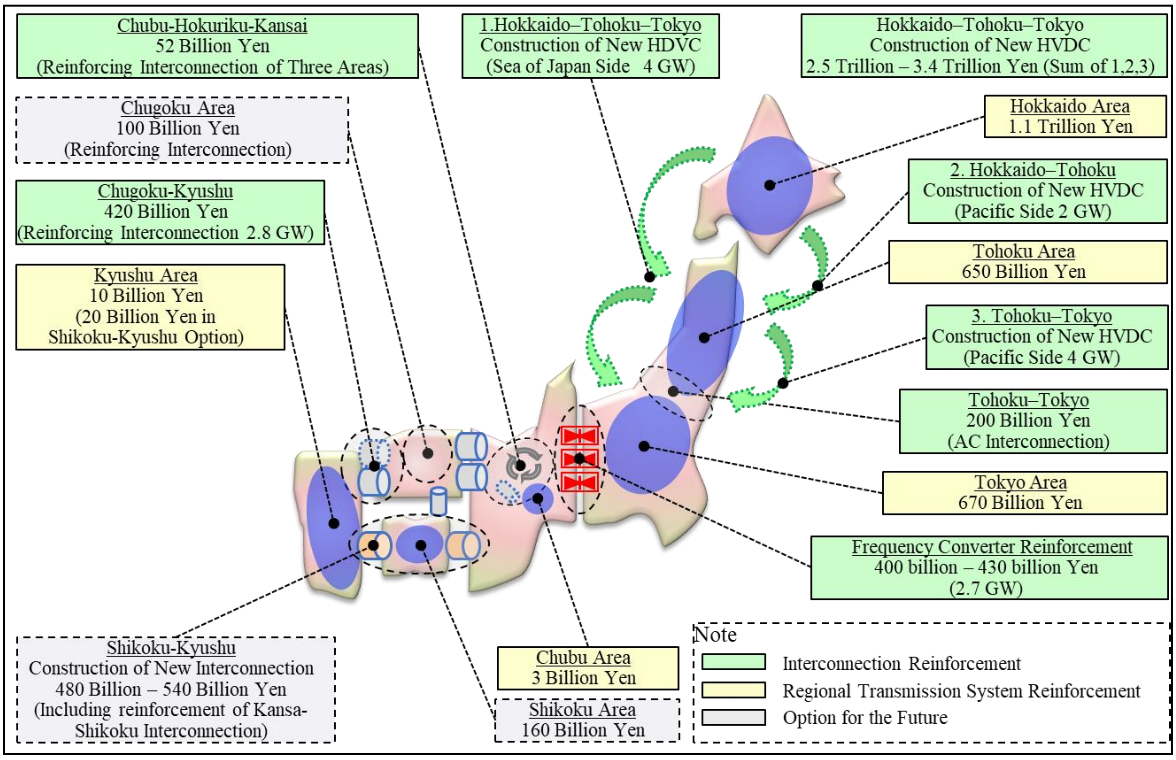

Figure 5 Example of the Expansion Plan

Table 2 Results of the Baseline Scenario

	Baseline Scenario
Investment Costs	6 Trillion Yen–7 Trillion Yen
Yearly Benefit	420 Billion Yen–730 Billion Yen
CO_2 Reduction	24.3 Million Ton
BCR Band	0.72–1.46
RES Curtailment Ratio “Without” → “With”	21.9% → 12.3% (7%*)
RES Ratio “Without” → “With”	42.8% → 47.2% (50%*)
*** this is a reference value if policies, such as intervention in the distribution of demand and supply, are implemented with grid expansions.**	

Although there are some differences in reinforcement recommendations between scenarios, the recommendation for the baseline scenario correlates with other scenarios. This study shows the necessary reinforcements of Japan’s bulk power system to realize the mass introduction of RES towards 2050. While a seven trillion scale investment is needed to implement the reinforcements in the recommendation, benefits from the nationwide transmission network would exceed the cost. Multiple scenarios were employed and sensitivity analyses by redistributing the demand and power supply sources were conducted. The results confirmed that the investment could be cut off by optimizing the distribution of demand and power supply sources. Therefore, comprehensively promoting grid expansions are recommended while considering policies such as intervention in the distribution of demand and power supply sources. Furthermore, the existing power system facilities are aging and should be upgraded. For efficient grid construction, expanding grids in coordination with the upgrades in existing facilities is crucial. This plan is guidance for the process of reinforcing the system and replacing obsolete facilities.

Conclusion

This paper summarized the long-term plan for reinforcements to Japan's bulk power system. This plan is the grand design of the Japanese electricity system for the future. This plan reasonably guides grid expansions when it is necessary to use RES as major power sources to realize carbon neutrality in 2050.

This paper presents a long-term and integrated grid planning method for introducing RES into large-scale electricity systems. It will assist grid planners worldwide in designing their power systems to accommodate the growing use of RES.

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