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Long-term Electrical Power Transmission Network Expansion Plan for Achieving Carbon Neutrality Goals Toward 2050 and Its Implementation

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SUMMARY

Climate change is an urgent global challenge. Japan is addressing it by striving for carbon neutrality and has formulated the Sixth Strategic Energy Plan, according to which renewable energy sources (RES) will be utilized as major power sources. RES are located in northern and western Japan and will be unevenly developed between these areas according to these areas potentials. Therefore, electricity must be transmitted from RES to demand centers. However, the existing grids were constructed by Japanese transmission operators according to the characteristics of their installation locations, and the capacity of interconnection lines between areas is a bottleneck in cross-regional transmission operation. In such circumstances, nationwide transmission reinforcement is indispensable. Therefore, the Long-term Transmission Expansion Plan was formulated to guide the reinforcement of existing grids.

In this plan, scenarios containing assumptions and presuppositions toward 2050 were generated to clarify uncertainties. Power flow simulations were conducted using nodal models containing approximately 1200 nodes to determine future transmission constraints, and several reinforcement options were devised. These options were then assessed via cost–benefit analysis, and promising ones were selected. According to the results of the baseline scenario, reinforcement of Japan's bulk power systems involving new 6–8 GW high-voltage direct-current lines costs JPY 6–7 trillion (approximately EUR 37–44 billion).

This paper introduces the Long-Term Transmission Network Expansion Plan in Japan and its planning and execution processes. It will help grid planners worldwide plan their power systems to respond to the increasing use of RES.

KEYWORDS

Carbon Neutrality - Cost–Benefit Analysis - HDVC - Renewable Energy - System Planning - Transmission Development

1. INTRODUCTION

To address global climate change, in 2021, the Japanese government announced a new Strategic Energy Plan to achieve carbon neutrality by 2050 by prioritizing energy transition[1]. Specifically, the use of renewable energy sources (RES) as main power sources and the reinforcement of electrical power transmission systems are considered important issues.

Conversely, the future power demand and the development of power plans are highly uncertain[2]. Furthermore, the expansion of electrical power transmission systems requires large investments and long lead times. Therefore, a system that is robust to these uncertainties in the long term should be built.

In the past, Japanese transmission operators constructed grids according to the regional characteristics of their installation locations[3]. These areas are interconnected, but the transmission capacity of interconnection lines is a bottleneck in cross-regional transmission system operation. In such circumstances, the nationwide reinforcement of transmission systems is indispensable.

In this study, power system constraints were identified by simulating power flows based on various scenarios of energy supply sources and power demand toward 2050. Then, plans for reinforcing transmission systems to improve these constraints were evaluated through cost–benefit analysis (CBA). Finally, a long-term outlook on the ideal electrical power transmission system toward 2050 was presented on the basis of the obtained results.

This paper presents a methodology for implementing the Long-Term Transmission Network Expansion Plan, which introduces the maximum use of RES.

2. FUTURE SCENARIOS OF POWER DEMAND AND ENERGY SUPPLY SOURCES

Figure 1 shows the targets set by the Strategic Energy Plan regarding the mixture of energy supply sources. For instance, the RES ratio of a mix, which is calculated by dividing the total amount of RES generation by the total amount of generation of all units, should increase from 18% in 2019 to 36%–38% in 2030 and 50%–60% in 2050. The development of RES in northern and western Japan should be promoted to achieve these targets. These regions have potential for operating large-scale RES, especially offshore wind. Figure 2 shows targets for offshore wind in Japan from 2030 to 2040, as developed by a public-private council. RES can provide power exceeding the demand in these regions, so the power flow from RES regions to central Japan is expected to increase. This requires the reinforcement of electrical power transmission systems.

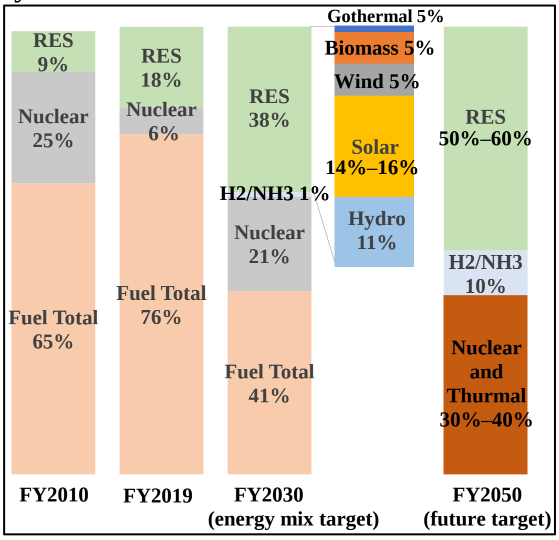

Figure 1 ″Mixture″ of future energy supply sources[6]

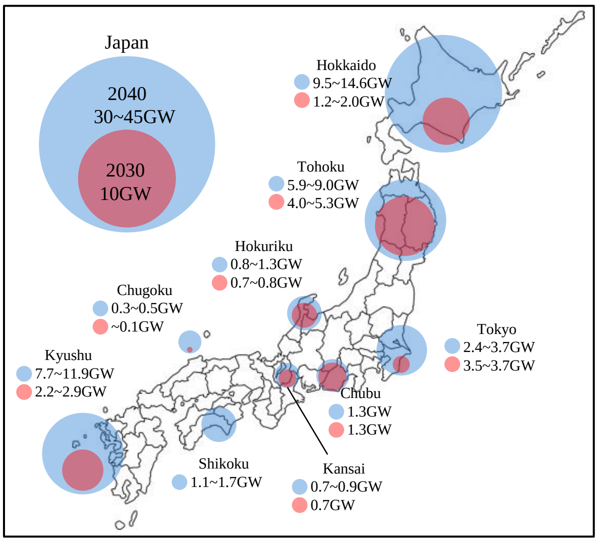

Figure 2 Targets for offshore wind in Japan for 2030 and 2040

Furthermore, future uncertainties need to be considered when formulating long-term policies. Therefore, multiple scenarios of power sources and demand for 2050 were set by the Strategic Energy Plan to respond to changes within the scope of national policy discussions. Table I shows the scenarios of power sources and demand, and Figure 3 shows the expected power demand in future scenarios.
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. Toward 2050, electricity demand is expected to increase to 1.25 PWh, which is 1.4 times that in 2019. Regarding the location of increased electricity demand due to energy transition, the base scenario is that 20% of hydrogen production and direct air capture (DAC) will be allocated near RES, and 20% of heat pumps and electric vehicles (EVs) will be controllably peak-shift. The demand location–controlled scenario states that these will increase to 80%, whereas the demand location–uncontrolled scenario states that energy transition will not be specifically guided in terms of location.

Table I Demand in future scenarios

	Demand location–uncontrolled scenario	Baseline scenario	Demand location–controlled scenario
Demand	•1.25 PWh •Hydrogen production and DAC will be allocated near demand areas. •Heat pumps and EVs will be kept constant.	•1.25 PWh •20% of hydrogen production and DAC will be allocated near RES •20% of heat pumps and EVs will be controllably peak-shift	•1.25 PWh •80% of hydrogen production and DAC will be allocated near RES. •80% of heat pumps and EVs will be controllably peak-shift.

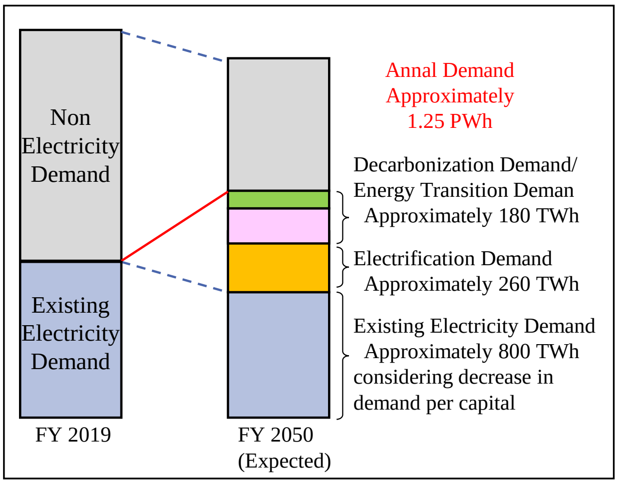

Figure 3 Expected power demand in future scenarios

The assumptions of the Long-term Transmission Expansion Plan regarding power supply resources were based on realizing the supply composition in the Sixth Strategic Energy Plan, especially the RES ratio. The RES potential of sites for developing RES was considered. Many offshore wind farms in northern and western Japan expect large-scale increases and were thus assumed to be developed intensively[4]. Furthermore, the assumption of thermal power stations was based on existing or under-construction plants or those in the planning stage and expecting 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, 5% of all vehicles should have vehicle-to-grid technology[5]. Table II shows cases where the capacities of supply power sources increase or decrease by 20% from the baseline scenario. Figure 4 shows the RES and demand of each region in the baseline scenario.

Table II Consideration of power supply uncertainties

			Common between scenarios	Dealing with future uncertainties
Energy source	RES	Photovoltaics	260 GW	Change the amount of introduction (±20%).
		Onshore wind	41 GW	
		Offshore wind	45 GW	
		H_2, biomass, and geothermal	60 GW	–
	Thermal		125 GW	Change the total capacity (±20%).
	Nuclear		25 GW	Change the availability (±20%).
	H_2 and NH_3		20 GW	Change the amount of introduction (±20%).

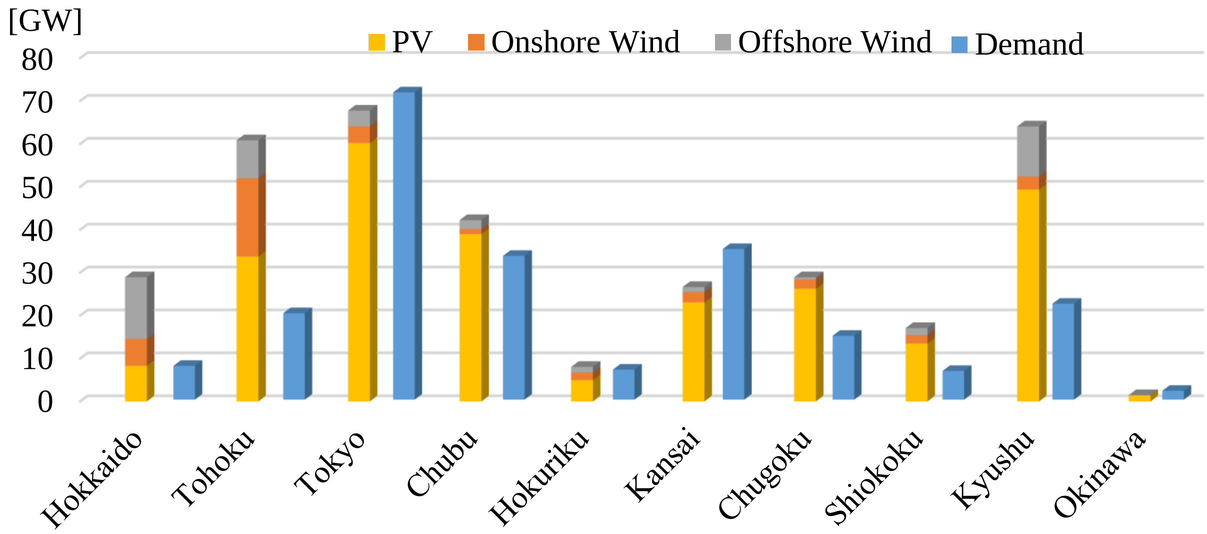

Figure 4 RES and demand of each region in baseline scenario

3. METHODS OF FORMULATING LONG-TERM PLANS

The future power flow in each scenario was simulated, and the transmission constraints of the electrical power system were identified. Then, reinforcement measures for overcoming these constraints were evaluated through CBA.

(1) System Reinforcement Policy Based on Power Flow Simulation

A nodal model consisting of approximately 1200 nodes was constructed to simulate the future nationwide power flow. This model was based on a bulk electrical power system in Japan comprising 500, 275, and, partially, 154 kV buses and branches with the highest and second-highest voltage in each area. In the simulation, the electricity generation cost associated with each unit was set according to its station type, and the total electricity generation cost was minimized through the merit order. This cost included the start-up, fuel, and emission costs of each station. Regarding RES, the necessary constraints, such as adjustability, were considered for each region. Power flow simulations based on these conditions were performed hourly for 8760 h, and the transmission constraints were highlighted. Then, several options for reinforcing the electrical power transmission system can be proposed. Figure 5 shows the simulation results before reinforcement (baseline scenario).

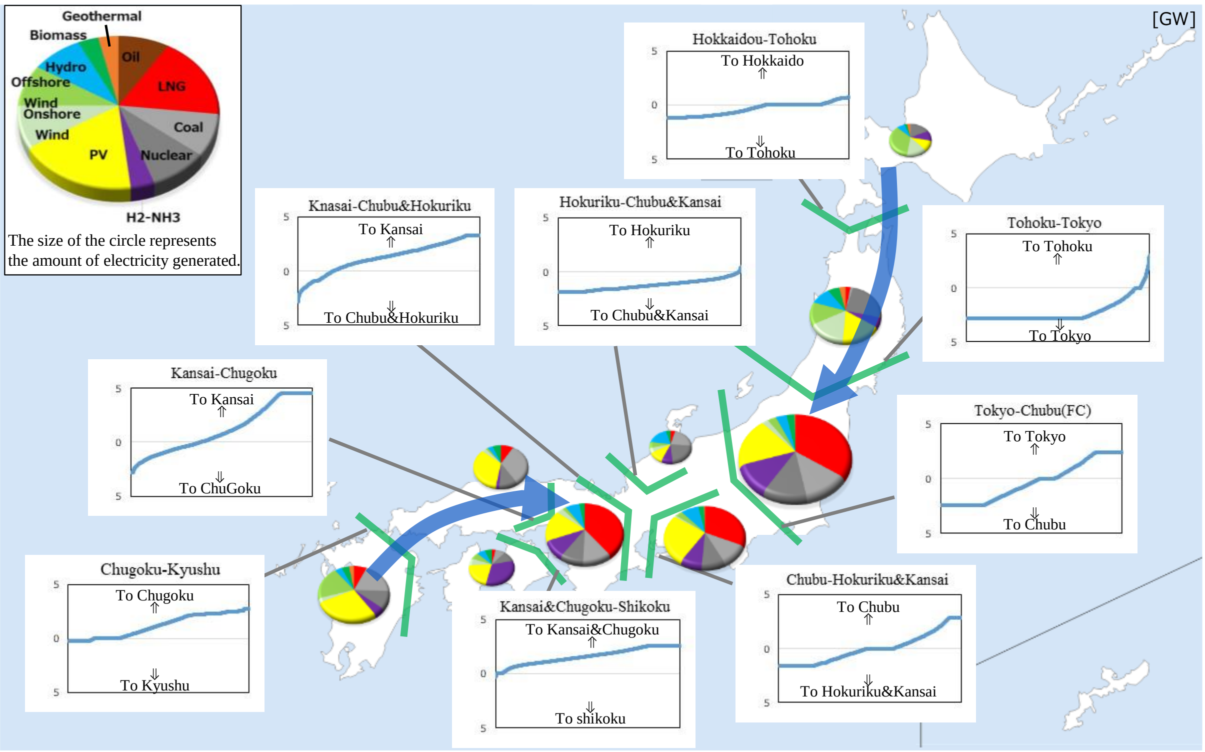

Figure 5 Results of power flow simulation before reinforcement (baseline scenario)

(2) CBA

CBA was performed to determine an optimized overall electrical power transmission system, including energy supply sources, by selecting the most effective, efficient expansion option . Figure 6 shows the CBA method, which was used to calculate the benefit–cost ratio (BCR), or the cost-effectiveness of system reinforcement. Simultaneously, the outcome of decreasing the RES curtailment caused by transmission capacity or ancillary service constraints was assessed. The results of reducing the RES curtailment ratio, the amount required for power adjustment, inertia force, etc. were also evaluated. The optimal combination of system reinforcement as a whole was evaluated using this analysis.

In CBA, total costs and benefits over 30 years were calculated. These costs comprised additional operational costs due to reinforcements, generation costs (including the start-up costs of units and fuel costs), and grid expansion costs. The benefits were reductions in operating costs (including emission and fuel costs) and transmission losses and improvement in adequacy. A discount factor of 4% per year was used to convert future costs and benefits into present values.

Regarding fuel costs, fuel market price fluctuations were uncertain. Therefore, a fuel price band based on the price history was set. A BCR of over 1 for an expansion option was considered reasonable because the benefits in such a case exceeded the costs. In this process, the expansion options were broadly considered for a flexible response to future uncertainties. For example, an expansion option with a BCR band of 0.8–1.3 was included in the options. However, an expansion option with a BCR band of 0.5–0.9 or a BCR of below 1 was excluded from the options.

The optimal nationwide reinforcement package was formed by assessing multiple reinforcement options according to their BCRs and reductions in the RES curtailment ratio. 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, the RES curtailment ratio of 0% indicated that all RES units could operate at their full potential. Therefore, the 400 MW option in the figure was excluded from the reinforcement options because its BCR was below 1. For the rest, the 300 MW option was considered optimal because the effect of reducing the RES curtailment ratio was saturated.

Item	
Fuel cost	Monetize the benefits and factor them into the BCR
Emission cost	
Adequacy	
Transmission losses	
Security	Considered as non-monetary value in evaluating system reinforcement plan
RES curtailment ratio	
CO2 emissions	
Adjustment	
Inertia force	

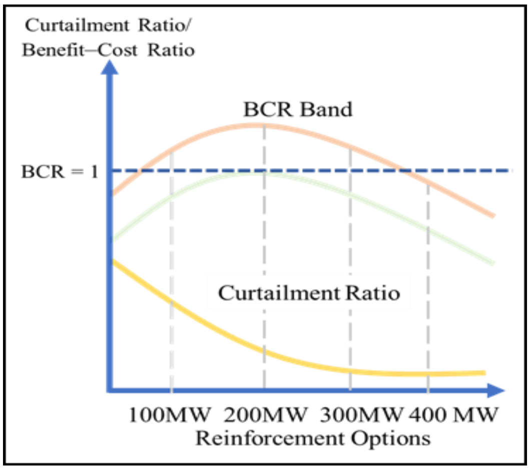

Figure 6 Cost–Benefit Analysis method for system reinforcement

4. LONG-TERM EXPANSION PLAN OF POWER TRANSMISSION NETWORK

Figure 7 shows the long-term baseline scenario of a wide-area grid system in Japan based on the above analysis. Figure 8 shows a comparison of the CBA results for each scenario, and Figure 9 shows a comparison of the effects of increasing the RES. In the baseline scenario, the amount of investment required for future system reinforcement is JPY 6.0–7.0 trillion (approximately EUR 37–44 billion). A distinctive feature of this reinforcement is that a new 6–8 GW high-voltage direct-current (HVDC) system will be required for the efficient transmission of the energy produced by the RES in the Hokkaido and Tohoku regions to the Tokyo area, which is the center of power demand. The following summarizes the areas where grid reinforcement will be required.

Eastern region: New HVDC lines are needed for the efficient transmission of the 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 in the baseline and demand location–controlled scenarios. In the demand location–uncontrolled scenario, each of these capacities will increase by 2 GW.

Central-western region: The 2.8 GW reinforcement of the Chugoku–Kyushu interconnection line is a promising option for the efficient transmission of the electricity generated by the RES in the western region, Kyushu, to the demand centers, Kansai and Chubu. Furthermore, reinforcements in the central region (Chubu, Hokuriku, and Kansai) improve the BCR. In this region, the reinforcement scale is similar in all scenarios.

These results suggest that realizing the mass introduction of RES toward 2050 requires an investment of JPY 6–8 trillion (approximately EUR 37–50 billion) for system reinforcement.

However, the achieved benefits for the entire power system may exceed this investment. In addition, the scale of grid reinforcement is smaller in other scenarios than in the demand location–uncontrolled scenario. Hence, optimizing the locations of power demand and energy sources can reduce the total investment amount required for system reinforcement. This study shows the importance of identifying the locations of power demand and energy sources to promote system reinforcement based on these trends comprehensively. Furthermore, existing power system facilities are aging and should be upgraded. For efficient grid construction, these grids should be expanded in coordination with the upgrading of existing facilities. This plan provides guidance for the reinforcement of systems and the replacement of obsolete facilities. Several reinforcements are currently being considered for realization, including a plan to install a 2 GW HVDC in the eastern region.

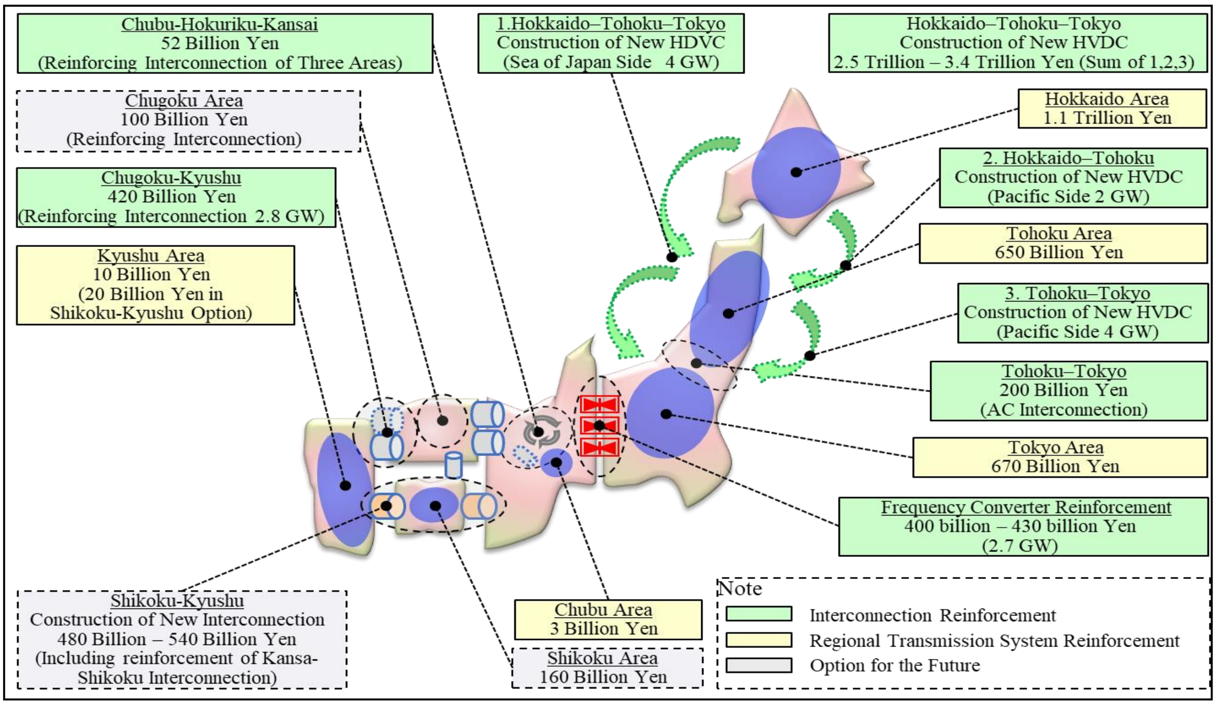

Figure 7 Long-Term Transmission Network Expansion Plan in Japan

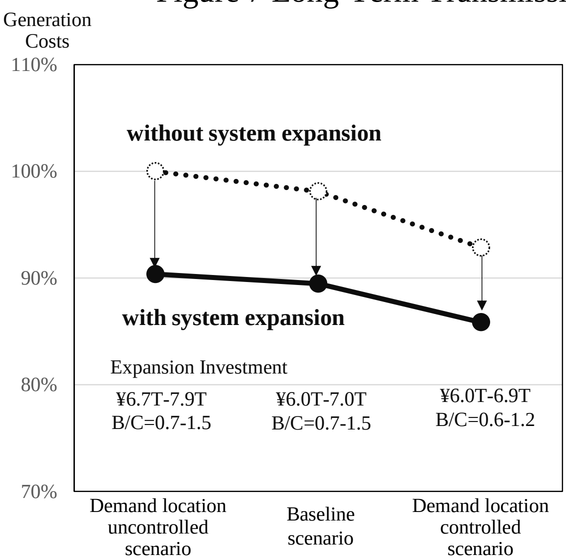

Figure 8 CBA of system reinforcement

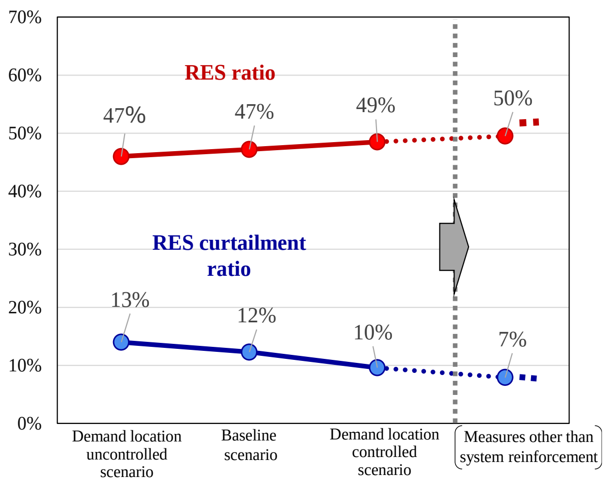

Figure 9 Effect of expanding RES due to system reinforcement

5. CONCLUSION

This paper presents the content and an implementation method of the Long-Term Transmission Network Expansion Plan, which are hitherto the biggest project addressing future electrical power transmission systems in Japan. This long-term plan provides guidelines for the formation of a national grid where RES are the main energy sources and electrical power transmission is reinforced to achieve carbon neutrality by 2050.

This paper also shows a long-term integrated grid planning method for introducing RES into large-scale electricity systems. This study will help grid planners globally in designing power systems capable of addressing the increasing use of RES.

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