The Feasibility of "Complete Decarbonization" of Japan's Power Sector in 2050 – a preliminary study

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This study focuses on the power sector in Japan in 2050 and investigates the possibility of achieving "zero emissions" using an optimal power generation mix (OPGM) model with a 10-min resolution through a year, fully taking into account the grid integration costs with high penetration of intermittent renewable energy. Although the potentials of renewable energies such as wind and solar PV are estimated to be large in Japan, as well as in other countries, the grid integration costs, such as the costs for batteries, curtailment of renewable power output, grid extension and reinforcement, etc., become significant in cases with very high shares of intermittent renewables. In this regard, it would be indispensable to introduce a certain amount of electricity generated by "zero-emission thermal power" technologies, including fossil-fuel fired power generation with carbon capture and sequestration (CCS) or CO_2-free imported hydrogen. Nuclear power is also estimated as effective to reduce the cost hike associated with achieving zero emissions.

Keywords: Renewables, Cost, Power generation, Nuclear, Decarbonization, Hydrogen

1. Background for the study

At the 21st Conference of Parties to the United Nations Framework Convention on Climate Change in late 2015, 196 participating countries adopted the Paris Agreement calling for limiting the temperature rise from the pre-industrial levels to well below 2°C. In advance of the conference, the Japanese government has come up with a target of cutting greenhouse gas (GHG) emissions by 26% from FY2013 by FY2030. In May 2016, the Cabinet also decided on the Plan for Global Warming Countermeasures seeking to reduce GHG emissions by 80% by FY2050.

The GHG emission reduction target for FY2030 was based on the Long-term Energy Supply and Demand Outlook published in 2015. The outlook envisages that Japan would improve energy efficiency by 35% by FY2030 through thorough energy conservation and reduce fossil fuels' share of the power generation mix from 84% in FY2015 to 56% by FY2030 while expanding the nuclear share to 20-22% and the renewables share to 22-24%.

In contrast, no quantitative base has been published for the FY2050 target. This is partly because the target is very ambitious. To achieve this target, Japan would have to make maximum energy conservation efforts, promote the electrification of energy use and supply all power from "zero-emission" sources that emit little CO_2, including nuclear, renewable and zero-emission fossil fuel-fired thermal power generation.

One possible option for zero-emission thermal power generation would be a combination of conventional power generation and the carbon capture and sequestration (CCS) technology. In Japan, however, the possibility of large-scale CCS implementation is uncertain due to relatively high costs and little potential except for aquifers.

Another option is CO_2-free hydrogen-fired thermal power generation. Power generation using hydrogen produced with little CO_2 emissions could contribute much to reducing national GHG emissions. Hydrogen could be produced from fossil fuels in resource-rich countries such as Australia and be transported to Japan. CO_2 emitted during the process of hydrogen production could be stored locally with CCS technology. From the viewpoint of global GHG emissions, this amounts to the effective utilization of unevenly distributed CCS potential.

Renewable energy is expected to expand in line with rapid cost reduction in the future. However, solar photovoltaics and wind power generation, which are particularly expected to grow rapidly in the future, features intermittency, with fluctuating output depending on weather conditions. With high penetration of such intermittent renewables, the reinforcement of electric grids and the adoption of storage systems will be required to maintain grid stability, resulting in considerable

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integration costs which could greatly affect the economics of the power generation sector. As constraints are expected on the realistic potential of nuclear and zero-emission thermal power generation, the main focus of the study on the zero-emission power sector will be on how far renewables could be expanded without intolerable cost hikes.

Against such background, this paper uses a detailed optimal power generation mix (OPGM) model to estimate the possibility of achieving zero or near-zero CO_2 emissions in Japan's power generation sector in 2050. Although it assumes power generation using imported CO_2-free hydrogen as zero-emission thermal power generation, it could also give implications to the use of thermal power generation with CCS, in case the technology is free from geographical or economic constraints.

2. Methodology

Following previous studies [1)], we made assessment by the linear programming (LP) cost minimization using a detailed OPGM model. As indicated in Figure 1, Japan other than Okinawa is divided into nine regions according to service areas for former general power utilities. These regions are connected with direct or alternate current interconnection lines.

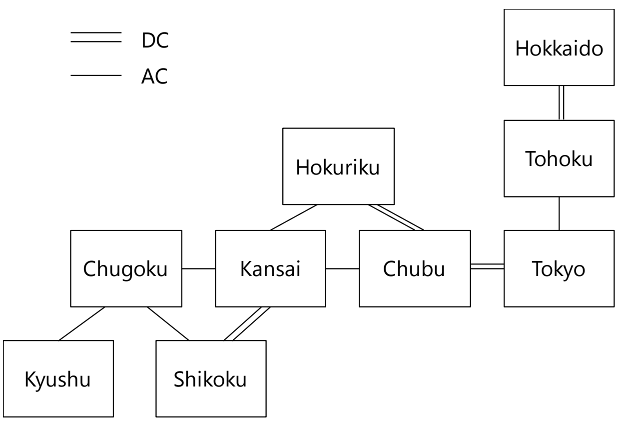


Figure 1 Geographical resolution

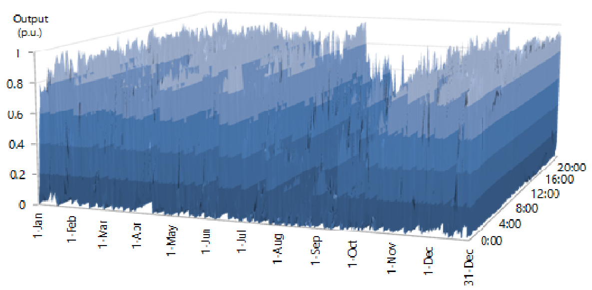


Figure 2 Wind power output profile (Tohoku region)

For each region, actual power demand figures in 2012 were multiplied by a number so that the annual demand equals 1,044 TWh in 2050 according to Reference 2). Solar PV and wind power output profiles were calculated on a 10-minute basis, based on sunlight hours, precipitation, wind velocity and other actual data in 2012 collected by the automated meteorological data acquisition system (AMeDAS). Figure 2 shows the wind power output profile for the Tohoku region.

Table 1 Solar PV and wind power capacity assumptions

Unit: GW	Solar PV	Onshore wind	Offshore wind
Hokkaido	15	146	177
Tohoku	25	67	34
Tokyo	54	5	39
Hokuriku	9	4	0
Chubu	35	9	23
Kansai	26	11	0
Chugoku	24	9	0
Shikoku	13	5	2
Kyushu	37	16	2
Total	239	271	277

Maximum capacities for solar PV and wind power generation were set as seen in Table 1 according to assessments by the Ministry of the Environment (MOE)[3)]. It should be mentioned that realizing these maximum values may not be easy, because it would require power facilities accounting for nearly 4% of Japan's land area. Other renewable power generation is assumed at 212 TWh, including 107 TWh for hydro, 38 TWh for geothermal energy, 35 TWh for biomass, and 33 TWh for others, according to estimates by MOE[4)]. Maximum nuclear power generation capacity is projected at 25 GW covering plants that started operation after 1990s and are now under construction, under an assumption that the nuclear power plant lifetime would have been extended to 60 years in 2050.

Power generation costs were set for each power source according to Reference 5). Solar PV and wind power generation costs are assumed to continue declining through 2050, achieving a substantial fall from the present level. Other assumptions were set according to References 1), 6) and 7) and other past studies. Assumptions used for the calculation in this paper are given in Tables 2-5. As for pumped-hydro power generation, the maximum kW capacity was set according to the

Table 2 Power generation cost assumptions (nuclear and hydrogen thermal power generation)

	Nuclear	Hydrogen
Initial cost [1,000 yen/kW]	420	120
Lifetime	40	40
Annual expense ratio	0.057	0.024
Thermal efficiency	-	0.57
Self-consumption rate	0.04	0.02
Fuel cost	1.8 yen/kWh	(Table 5)
Maximum output growth rate	0.02	0.44
Maximum output reduction rate	0.02	0.31
Maximum seasonal capacity factor	0.90	0.85
Maximum annual capacity factor	0.80	0.80
Daily start & stop operation frequency	0.0	0.50
Minimum output level	0.30	0.30

Table 3 Power generation cost assumptions (solar PV and wind)

		High	Low
Solar PV	Initial cost [1,000 yen/kW]	188	169
	Lifetime	30	30
	Annual expense ratio	0.008	0.008
Onshore wind	Initial cost [1,000 yen/kW]	284	212
	Lifetime	20	20
	Annual expense ratio	0.017	0.017
Offshore wind	Initial cost [1,000 yen/kW]	446	360
	Lifetime	20	20
	Annual expense ratio	0.040	0.040

Table 4 Power storage capacity assumptions

	Pumped hydro	NaS battery	Li-ion battery
Initial cost ［1,000 yen/kW］	200	-	-
Annual expense ratio	0.01	-	-
Initial cost ［1,000 yen/kWh］	1	(See Table 5)	
Annual expense ratio	0.01	0.01	0.01
Lifetime	60	15	15
Maximum charge and discharge frequency	-	4,500	3,500
Cycle efficiency	0.70	0.85	0.85
Self-discharge rate [1/hour]	1E-4	5E-4	5E-4
C-rate	-	0.14	2.0

Table 5 Other assumptions

	High	Low
Imported hydrogen [yen/Nm^3]	30	20
NaS battery [USD/kWh]	200	100
Li-ion battery [USD/kWh]	739	100
Water electrolysis system [USD/kW]	793	462
Hydrogen tank [euro/kg]	600	500

literature, which was multiplied by six to calculate the maximum kWh capacity. For more details of the model used for this paper, see Reference 1). It should be noted that the costs are always underestimated by this model because it does not take into account the costs for grid reinforcement within regions.

We set high and low cost assumptions. The higher renewable energy and storage costs are and the lower imported hydrogen costs are, the smaller renewable power generation in the optimal generation mix is. Therefore, we set four cost cases, with high and low cost assumptions for "renewables and storage", as well as high and low cost assumptions for imported hydrogen.

3. Results and discussion

3.1 Optimal results

Figure 3 indicates the cost optimal energy mix for the four cost cases. In each case, nuclear power generation is used up to the maximum, with wind and solar PV generation expanding depending on the assumed costs. In the low hydrogen and low renewables cost case, the share for intermittent renewables (wind and solar PV) stands at 13%. In the high hydrogen and low renewables cost case in which renewable energy expands most among the four cases, intermittent renewables' share rises to 33%. In these optimal cases, offshore wind power generation is not introduced because of the high costs.

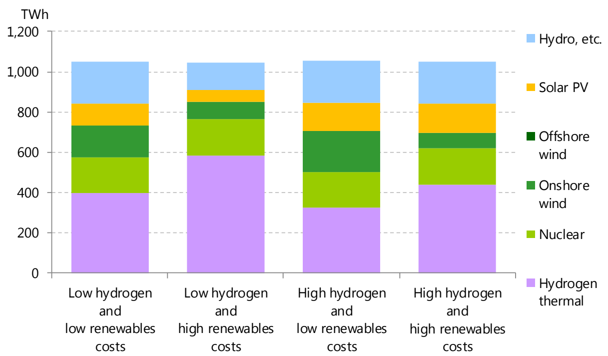


Figure 3 Cost optimal results

3.2 Electricity generation mix with different levels of zero-emission thermal power generation

Figures 4 and 5 indicate the power generation mix and the unit system cost for the low hydrogen and low renewables cost case with hydrogen power generation fixed at 0-600 TWh. The less hydrogen power generation is, the more renewable energy power generation is required. Due to the upper limits for solar

PV and onshore wind power generation, offshore wind is required with hydrogen power generation at 25 TWh or less in the cases with nuclear power, and at 100 TWh or less without nuclear power. Without nuclear and hydrogen power generation, the share of offshore wind rises to 26%. In the cases without hydrogen, total power generation increases due to the power losses resulting from massive battery requirements.

The unit system cost rises as hydrogen power generation declines. It stands at 11 yen/kWh with hydrogen power generation at 600 TWh, at 20.0 yen/kWh without hydrogen power generation but with nuclear power generation, and at 24.9 yen/kWh without hydrogen and nuclear power generation. The largest contributor to the cost rise is the storage cost. It stands at 5.5 yen/kWh without nuclear and at 7.3 yen/kWh with nuclear. The power transmission cost also expands with high wind penetration, since wind power is endowed almost exclusively in the northern part of the country.

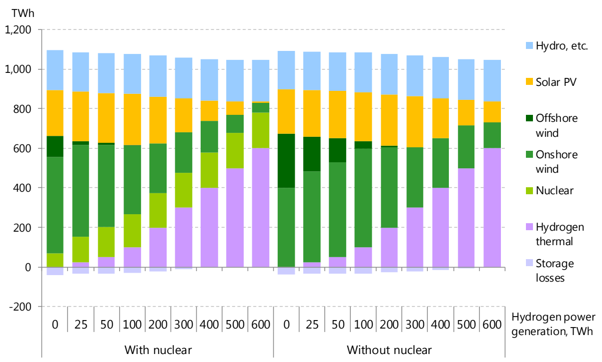


Figure 4 Power generation mix with different levels of thermal power generation

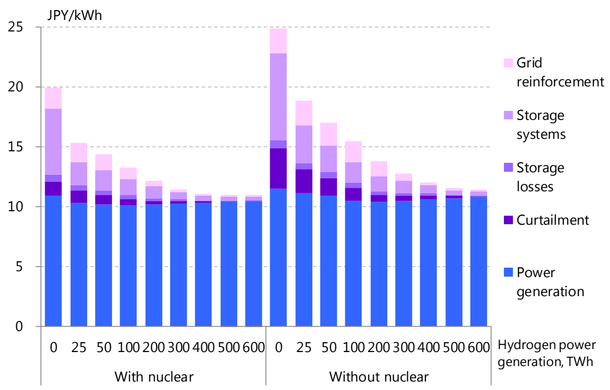


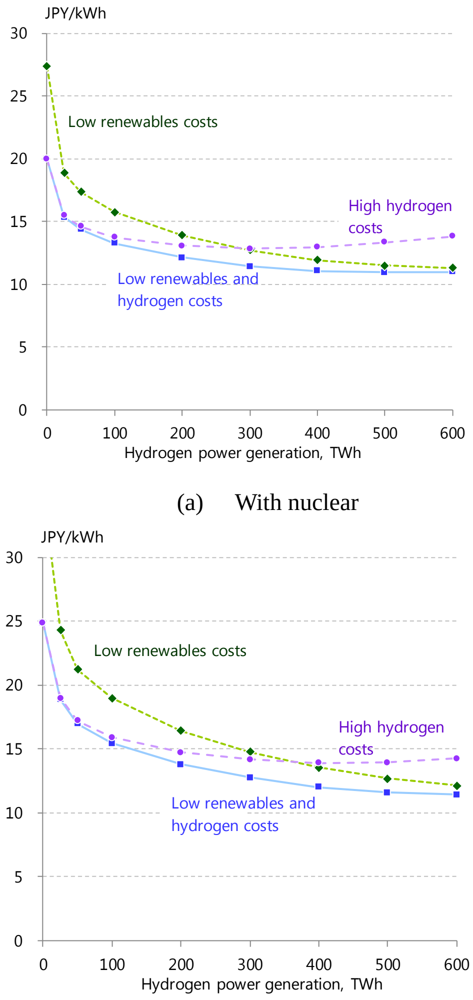
Figure 5 Unit system cost with different levels of thermal power generation

As the costs for wind and solar PV are assumed to rapidly decline through 2050, the average "power generation" cost does not rise significantly even without hydrogen power generation. However, as the effective capacity factor declines on the curtailment of surplus electricity that is not used or stored, the unit cost can be expected to rise as indicated by "curtailment" in Figure 5.

Figure 6 shows the unit system cost for the low cost case, as well as those for the high hydrogen cost case and the high renewables cost case. In the case with zero hydrogen power generation with nuclear power, the unit system cost stands at 20.0 yen/kWh and 27.3 yen/kWh for the low and high renewables cost cases, respectively. Of the unit system cost, the grid integration cost (the costs other than "power generation" in Figure 5) comes to 9.1 yen/kWh and 13.8 yen/kWh for the low and high renewables cost cases, respectively. Without nuclear and hydrogen power generation, the unit system cost stands at 24.9 yen/kWh (including 13.4 yen/kWh for grid integration) for the low renewables cost case and 35.2 yen/kWh (including 21.2 yen/kWh for grid integration) for the high renewables cost case.

Without hydrogen power generation, the unit system cost is the same for the high and low hydrogen cost cases. As hydrogen power generation increases, however, the unit system cost rises, following a convex curve, of which the minimal point represents the optimal power mix shown in Figure 3. With hydrogen power generation at 600 TWh with nuclear power generation, the unit system cost comes to 11.0 yen/kWh and 13.8 yen/kWh for the low and high hydrogen cost cases, respectively.

These results indicate that the unit system cost rises rapidly as zero-emission thermal power generation slips below 100 TWh. This suggests that it is very difficult to depend only on nuclear and renewable energy with little flexibility and that at least a certain level of thermal power generation would be indispensable for holding down cost hikes. At the same time, in the cases with nuclear power generation, for example, the unit system cost rises rather moderately with hydrogen power generation larger than 200 TWh. As far as renewable energy costs will decline substantially by 2050 as assumed in this paper, we can say that renewable energy power generation could be considerably expanded at least from the viewpoint of economic efficiency.



(a) With nuclear

(b) Without nuclear

Figure 6 Unit system cost

The unit system cost gap between the cases with and without nuclear stands at 4.9 yen/kWh and 7.0 yen/kWh for the low and high renewables cost cases, respectively, with zero hydrogen power generation. This indicates that nuclear power would be useful for holding down cost spikes with very small levels of thermal power generation.

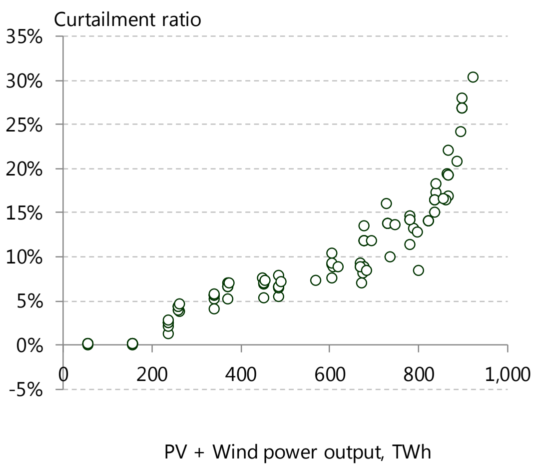


Figure 7 Wind and solar PV curtailment rate

In the cases with high penetration of intermittent renewables, even with storage systems installed for grid operation, massive curtailment of surplus power is required. Figure 7 indicates wind and solar PV power generation on the horizontal scale and the average curtailment rate on the vertical scale. Electricity generated by intermittent renewables is cut by 35% at the maximum.

In the cases with high penetration of wind power, interconnection lines from Hokkaido and Tohoku to Tokyo must be expanded significantly. For the Hokkaido-Tohoku interconnection lines, for example, the capacity must be increased from the present level at 0.6 GW, with a plan to expand by 0.3 GW, to 60 GW by 2050, in a case without nuclear and hydrogen power generation.

Figure 8 shows power demand and generation mix in May (total for the nine utilities) for the optimal case and the zero thermal and nuclear power case (low costs). In the optimal case, nuclear (green) and hydro (aqua) are used as baseload power sources, with hydrogen (purple) meeting fluctuations in wind and solar PV output. As mentioned above, the share of intermittent renewables is 12% in this case. In May when demand is lowest with large solar PV outputs, hydrogen power generation declines to zero temporarily. In the zero thermal and nuclear power generation case, solar PV output largely exceeds demand with large-scale curtailment, showing quite inefficient system operation.

In this study, an upper limit is set on nuclear capacity for the cases with nuclear power generation. Figure 9 shows the shadow price for this constraint (a median value for the nine regions) shown as the cost per installed capacity (yen/kW). This can be interpreted as the maximum unit cost escalation from the assumed level at 420,000 yen/kW, with which nuclear power can still contribute to the decarbonization of the power sector. As thermal power generation declines, it rises to 2 to 3 million yen/kW, indicating a growing potential role of nuclear power.

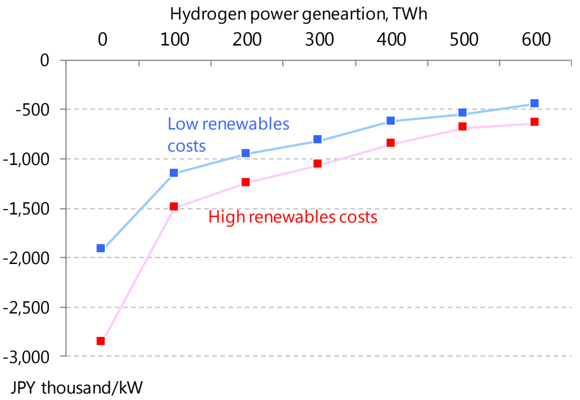
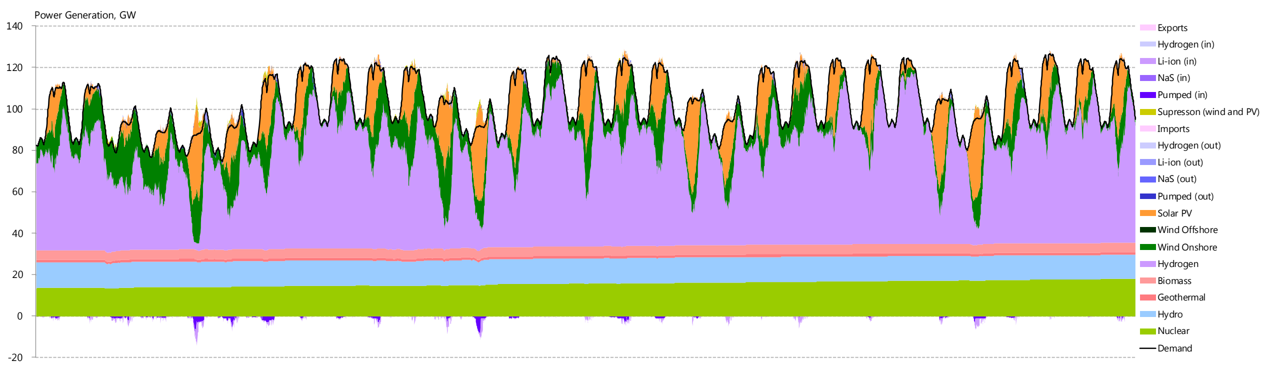


Figure 9 Shadow price related to the nuclear capacity constraint

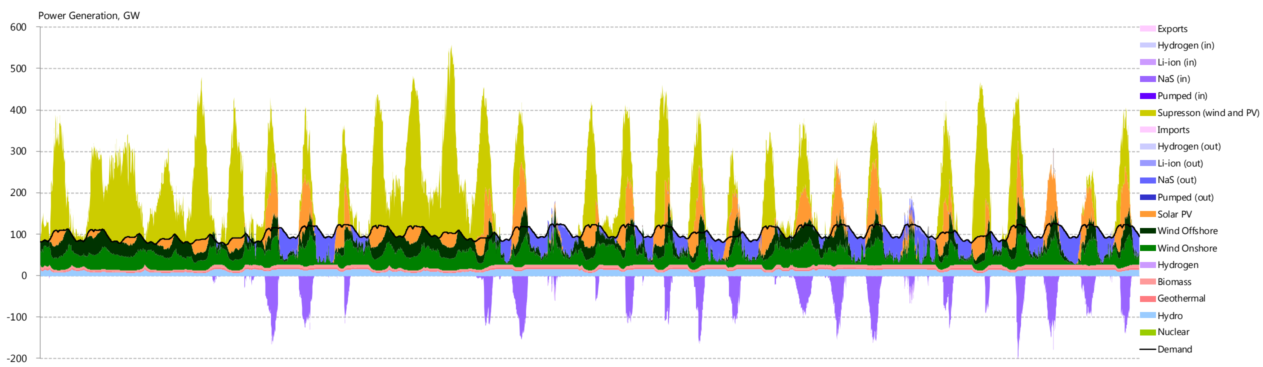
4. Conclusion

In this paper, we used a detailed power generation mix model for assessing the economics of Japan's complete decarbonization of the power sector in 2050. While fossil fuels are dominant in the present power mix, intermittent renewables are expected to play a great role in decarbonizing the power sector. Realistically, however, land utilization constraints may be expected to arise on the expansion of renewable power generation. Even without such restrictions, not only the high penetration of onshore wind and solar PV power generation but also that of costlier offshore wind power generation will be required to raise intermittent renewables penetration beyond 60%. As the penetration increases, additional grid integration costs will present greater and greater challenges. If it rises beyond 70%, some areas may have renewable power generation capacity that far exceeds electricity demand and may have to be largely curtailed, resulting in inefficient grid operations. Therefore, pursuing the best balance between renewable energy and zero-emission thermal power generation will become a particularly important issue.

If massive zero-emission thermal power generation, either imported hydrogen power generation or CCS-equipped thermal power generation, is made available cheaply, the complete decarbonization of the power sector will be economically feasible. If not, however, additional grid integration costs may increase to intolerable levels. In these cases, not only the curtailment of surplus power generation with intermittent renewables but also massive power storage systems will be required to maintain grid stability. In this regard, technology research and development to reduce power storage system costs



(a) Optimal case (low costs)



(b) Zero nuclear and thermal power generation case (low costs)

Figure 8 Power supply and demand in May (total for the nine utilities)

will become one of the important issues. At the same time, even if the costs for renewable power generation and power storage systems are reduced dramatically, the unit system cost may rise significantly as thermal power generation slips below 100 TWh, amounting to some 10% of total power generation. Therefore, at least a certain level of thermal power generation will be indispensable even in 2050.

In the wake of the Fukushima Daiichi nuclear power plant accident, it may be difficult to build new nuclear power plants in Japan in the near future. If constraints arise on the expansion of zero-emission thermal power generation, however, nuclear power generation can play a great role in holding down the total system cost. Given this, an option to maintain nuclear energy as a proven zero-emission power source is apparently important from the viewpoint of long-term energy policies.

When considering future energy policies, it is always important to pursue a balanced energy mix. Depending on a limited range of power sources is not desirable from the viewpoint of risk management. In this regard, it would be necessary to proceed with technology development not only for renewable energies but also for other technologies including storage systems and zero-emission thermal power generation, to promote the decarbonization of the power systems to meet the long-term GHG reduction targets.

Acknowledgements

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