A Quantitative Analysis of Japan's Optimal Power Generation Mix towards 2050

- Analysis Considering Economic Percussion by Investment in Power Resources -

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Abstract

This study performs model analyses assuming the Japanese power supply portfolio in 2050 to evaluate the optimal generation portfolios that contribute to both economic growth and low-cost power supply by 2050. The energy model developed in this paper is an integrated model which combines an optimal power generation mix model and an evaluating econometric model.

Considering the economic ripple effect, portfolios that include zero emission power generation do not necessarily decelerate economic growth, even if the portfolios raise the electric price due to higher system costs. A balanced energy mix using not only zero-emission power generation but also an optimal amount of gas power generation can realize harmonization between the environment and economic growth.

Key words : Nuclear power, Unit cost, Linear programming, Econometrics, Energy mix

1. Introduction

In response to internationally growing interests in global warming prevention, a large number of countries have set national targets regarding greenhouse gas emission cuts.

In June 2019, for instance, the United Kingdom passed a law to reduce GHG emissions to net zero in 2050[1]. In November 2019, France enacted a law to upgrade its national target from a 75% cut in GHG emissions from 1990 by 2050 to carbon neutrality by 2050[2].

Japan as well has enhanced its initiatives to reduce future GHG emissions. In June 2019, the Japanese government made a cabinet decision on the Long-term Strategy under the Paris Agreement[3], proclaiming a “decarbonized society” as the ultimate goal and aiming ambitiously to accomplish it as early as possible in the second half of this century, while boldly taking measures towards the reduction of GHG emissions by 80% by 2050. Japan then became the first country among the Group of Seven industrial democracies to make a decision to proclaim net-zero GHG emissions. In his policy speech[4] in October 2020, Japanese Prime Minister Yoshihide Suga stated, “We hereby declare that by 2050 Japan will aim to reduce greenhouse gas emissions to net-zero, that is, to realize a carbon-neutral, decarbonized society.”

While major countries have set ambitious targets of cutting GHG emissions to net-zero, some countries see growing concerns about an increase in costs for global warming countermeasures.

In France, more than 10 citizens were killed with more than 1,000 citizens and police officers injured in citizens’ anti-government protest called the “Yellow Vest Movement” which grew from the second half of 2018 to the first half of 2019. One of the factors behind the movement was citizens’ discontent with a carbon tax.

In Japan as well, business leaders have expressed concerns about the economic impacts of some GHG emission reduction measures including a carbon tax. In November 2017, the Japan Business Federation known as Keidanren published an opinion on carbon pricing[5], indicating concern that explicit carbon pricing could affect Japan’s international competitiveness.

These cases demonstrate a dilemma between the ideal of net-zero GHG emissions and economic cost hikes accompanying the achievement of the ideal, indicating how important it is to prepare a specific strategy for ambitious GHG emission cuts while minimizing economic impacts.

Given the above, initiatives to analyze the impacts of national energy choices for net-zero emissions on the economy and national burdens have been vigorously implemented at home and abroad.

For instance, many researchers mainly in European countries and the United States have assessed costs for integrating renewable energy and other power sources into electric power systems.

According to a report[6] by the Organization for Economic Cooperation and Development and the Nuclear Energy Agency in 2012, the average cost for integrating variable renewable energy for covering 30% of total power generation differs by country within a 2-8 cents/kWh range. The OECD/NEA estimated the average cost at 2.5-4.0 cents/kWh in a review in a report[7] released in 2018 and at 2 cents/kWh in a model analysis[8] for Europe released in 2019. Cost estimates thus range wide. Many similar estimates have been made mainly in Europe (e.g., Van Zuijlen et al. (2019)[9]) and the United States (e.g., Noel et al. (2017)[10]). Some groups including Jacobson et al. (2015)[11] and a Lappeenranta University group (e.g., Ram et al. (2017) [12]) estimated and published such integration costs for most countries and regions in the world.

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Multiple reports exist about VRE integration cost estimates in Japan. For instance, the abovementioned Lappeenranta University group (e.g., Ram et al. (2017) 12)) and WWF Japan (2017)13) indicated that even if renewable energy covers all power generation in Japan in 2050, total electric system costs including the VRE integration cost would be lower than at present. In contrast, reports by Matsuo et al. (2018)14) and Matsuo et al. (2020)15) estimated that electric system costs would increase substantially if fossil-fired power generation is unavailable in 2050 and that a combination of renewable energy and nuclear power would contribute to holding down cost hikes. Ogimoto et al. (2018) 16) estimated that if VRE alone is used for power generation, the unit electric system cost would be far higher than at present.

There are thus numerous studies assessing the economy of the power sector by energy choice. However, most of them focus on the economy of total costs for overall electric system development, maintenance and management. Studies are scarce on a wider range of quantitative macroeconomic impacts including the economic effects of investment in power generation equipment, the economic burden of a carbon tax and the multiplier effects of fiscal spending expansion based on carbon tax revenue.

Some studies including the Asia-Pacific Integrated Model (2009) 17) by the Japanese National Institute for Environmental Studies have used applied general equipment models to analyze overall macroeconomic impacts. They base estimation on economic growth assumptions and can express the macroeconomic impacts of carbon tax and other policies as distortions from the equilibrium for a case in which these policies are not introduced. As far as they depend on an assumption that each economic entity would conduct rational behavior based on price information under complete information, however, they fail to indicate recession, market disequilibrium and other gaps. If carbon tax and other constraints are imposed, GDP would decrease under these models. There are some constraints on their applications.

For instance, full employment is assumed for the labor market under the applied general equipment models. Even if the government implements a green new deal to stimulate the economy during a recession, such deal's impacts on GDP would be difficult for these models to analyze.

Given such a situation, this study uses an energy economy model into which we integrated an optimal power generation mix model using linear programming and a macro econometric model to analyze the impacts of energy choices for Japan's electric system on total electric system costs and macroeconomic indicators such as GDP.

Here is the composition of this paper: Chapter 2 describes an overview of the model used in this study and major assumptions. Chapter 3 outlines model analysis results. Based on the results, Chapter 4 considers an optimal power generation mix to balance decarbonization with economic growth and describes this study's policy implications.

2. Assessment method

2.1 Integrated energy economy model

This study developed an integrated energy economy model for estimation to assess the impacts of Japan's energy choices on total electric system costs and macroeconomic indicators through 2050.

The model developed for this study is an integrated energy economy model combining a top-down econometric model and a bottom-up cost-minimizing optimal power generation mix model. The top-down econometric model was developed by Murota et al. (2005)18) and improved in Yanagisawa (2008)19) and Komiyama et al. (2012)20). The bottom-up cost-minimizing optimal power generation mix model is a Japanese optimal power generation mix model that was developed by Fujii and Komiyama (2017)21) and improved in Matsuo et al. (2019)22) and Matsuo et al. (2020)15).

2.2 Econometric model

The econometric model estimates economic indicators based on assumptions for overseas factors such as global trade, economic policies such as public investment, demographics, and fossil fuel and other energy prices.

As shown in Figure 1, the econometric model focuses on gross domestic product and its components such as investment, imports and exports and calculates fund flows in the national economy.

The model consists mainly of the real expenditure module, the wage-price module, the income distribution module and the labor module and can estimate the impacts of changes in exogenous variables on the economy. See Komiyama et al. (2012) 20) for details of the model.

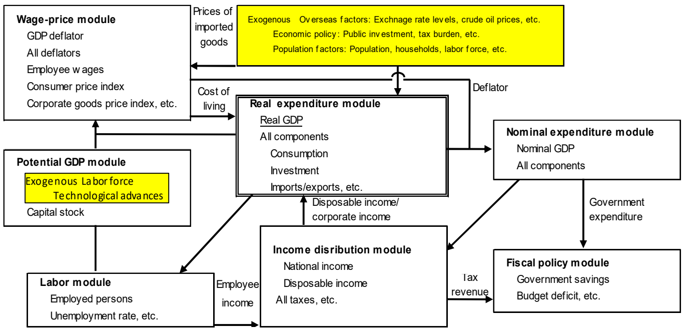

Figure 1 Econometric model

2.3 Optimal power generation mix model

This study used the optimal power generation mix model to simulate and analyze cost-minimizing electricity supply under multilateral constraints for Japan’s power sector in 2050.

The optimal power generation mix model uses linear programming to simulate a country’s energy system to determine energy supply and demand and the economically rational size of energy technologies. The target function is discounted total system costs during the computation period. The constraint equation covers constraints on resources, energy supply and demand, etc.

In a geographical division, Japan excluding Okinawa is divided into nine according to the service areas of nine former general power utilities. These areas are assumed as connected through direct or alternating current interconnection cables.

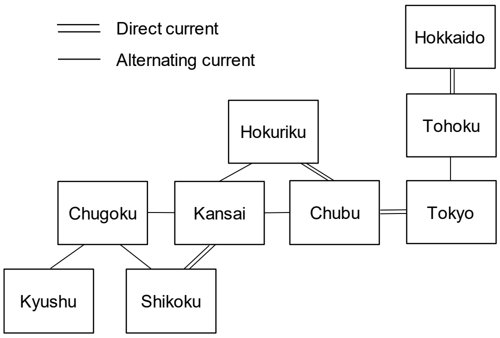

Figure 2 Geographical division

This study computed and assessed annual electricity supply and demand on an hour-to-hour basis (dividing a year into 8,760 hours by multiplying 24 hours by 365 days).

2.4 Integrated energy economy model structure

The abovementioned optimal power generation mix model can estimate the most efficient cost-minimizing power generation mix under constraints by using linear programming. While a country’s energy demand is required to be given exogenously as an assumption, the demand itself is influenced by power source choices.

While heavy dependence on cheap fossil fuels for power generation is likely to be an optimum solution to minimize power supply costs under the optimal power generation mix model, for instance, national wealth outflow through massive fuel oil imports may exert downward pressure on GDP and domestic electricity demand.

While a power generation mix using massive nuclear and renewable energy capacity requires higher total electricity system costs than that depending heavily on fossil fuels under the optimal power generation mix model, a curb on national wealth outflow through fossil fuel imports and an increase in private capital investment in domestic power generation equipment may exert upward pressure on GDP and electricity demand.

To conduct an analysis considering mutual relations between the impacts of changes in the power generation mix on electricity supply costs and macroeconomic indicators, this study developed an integrated energy economy model in which the econometric and optimal power generation mix models share exogenous variables as assumptions and analyzed how energy choices for the electricity system would impact total electricity supply costs and the whole of the Japanese economy.

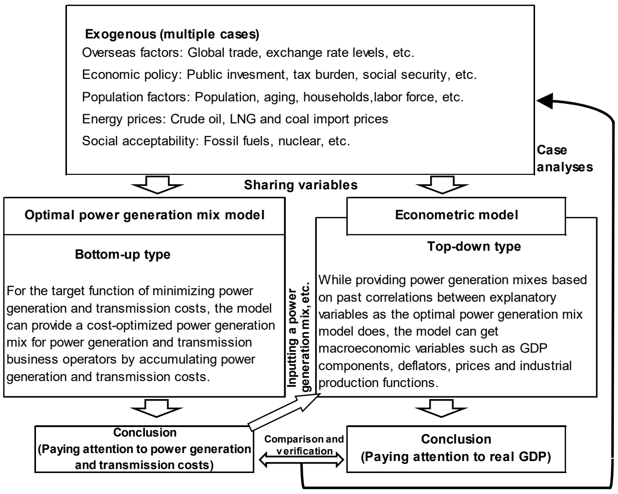

Figure 3 Integrated energy economy model

The integrated energy economy model used the optimal power generation mix model to estimate cost-minimizing power generation mixes and total system costs under multiple assumptions set for constraints on power source choices.

Then, the model computed variables including total power generation and transmission costs covering capital investment, fuel, carbon tax and other costs for the optimal power generation mix estimated by the optimal power generation mix model and exogenously put the variables into the econometric model to estimate real GDP and other macroeconomic variables. We compared and verified the two models’ conclusions and conducted additional case analyses regarding variables, as necessary.

The amount of capital investment refers to NEDO (2014) [23], Ishii (2014) [24], TEPCO (2020) [25], the government’s Procurement Price Calculation Committee (2020) [26] and Mitsubishi Research Institute (2020) [27]. As a result, the domestic production rate for the total investment of equipment costs and construction costs will be 95% for nuclear power, 50% for coal / gas-fired power, 40% for batteries, 27% for solar PV, 23% for onshore wind, and 22% for offshore wind. In addition, all carbon tax revenues shall be returned to the domestic economy as government consumption expenditures such as environmental measures. When a large amount of carbon tax is introduced in Japan, changes in the international competitiveness of imports and exports due to differences in environmental policies with other countries are not taken into consideration.

2.5 Estimation cases

To consider a wide range of constraints on the electricity system in 2050, this study first developed, compared and developed six basic cases as shown in Figure 4. Numbers in Table 1 indicate case numbers. The six cases indicate whether the use of fossil fuels for power generation, a carbon tax or new nuclear power plant construction would be socially accepted.

After comparing and verifying the six cases, this study input five more cases into the two models to clarify gaps between the optimal power generation mix model and econometric model assessment results. A total of 11 cases were thus compared and verified, as discussed in Chapter 3.

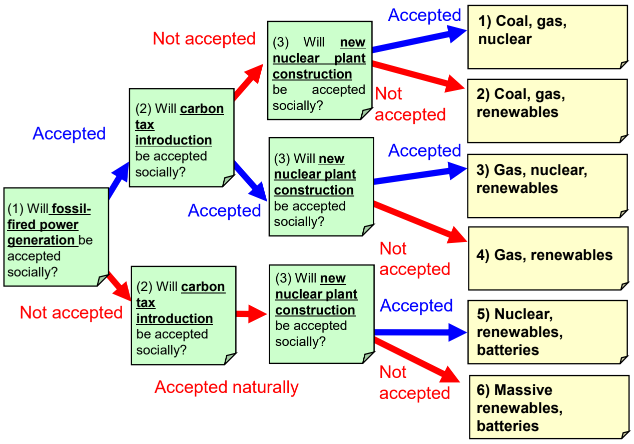

Figure 4 Estimated cases

Table 1 Presence or absence of basic power sources in estimated cases

Case number	1)	2)	3)	4)	5)	6)
Carbon tax	Present level		$120/t-CO$_2$ ※			
Existing coal	○	○	×	×	×	×
Gas	○	○	○	○	×	×
New nuclear	○	×	○	×	○	×

※ World Bank "State and Trends of Carbon Pricing 2020" 12p. Japan's carbon tax is assumed to reach the Swedish level of $119/5-CO$_2$, the highest in the world as of April 1, 2020. Under the optimal power generation mix model, coal-fired power plants will disappear completely at this carbon tax level. The exchange rate is 110 yen/dollar.

2.6 Assumptions

In each case, we set assumptions for Japan's energy mix for 2050 according to IEEJ (2018)$^{21)}$ and IEEJ (2019)$^{22)}$. In line with the objective of this study, however, we set some exclusive assumptions for this study as follows:

(1) Nuclear power generation

The power generation costs and performances of existing large nuclear reactors are used for the estimation. The maximum available nuclear power generation capacity for 2050 covers existing reactors other than those to be decommissioned and under-construction reactors as of October 2020, totaling 42.5 GW. Given a service life of 60 years, 17.0 GW out of the existing capacity will be subjected to decommissioning by 2050. If new reactors are profitable and accepted socially, however, reactors subject to decommissioning will be replaced with new ones with the same or less capacity. Construction costs for existing and under-construction reactors (hereinafter referred to as existing reactors) within 60 years from the launch of operation were deducted as sunk costs for nuclear plant operators from capital costs at the time of estimation.

Table 2 Power generation cost and performance assumptions (large existing and new reactors)

Unit construction cost [1,000 yen/kW]	420
Years of operation	40
Full cost rate	1.00
Captive consumption rate	0.04
Fuel cost [yen/kWh]	1.8
Maximum output growth rate	0.02
Maximum output decrease rate	0.02
Maximum annual capacity factor	0.80
Minimum output level	0.80

(2) Renewable energy power generation

Renewable energy power generation cost reduction targets given by the government's Procurement Price Calculation Committee in February 2020$^{26)}$ call for cutting the unit power generation cost to 7.0 yen/kWh for solar PV and 8-9 yen/kWh for wind by 2025 or 2030. Since these targets deviate far from the past cost reduction trend in Japan. Therefore, we assumed the unit cost in 2050 at 7.0 yen/kWh for solar PV and at 8.5 yen/kWh for onshore wind. The offshore wind power generation cost is assumed to decline as much as the onshore wind cost. (as shown in Table 3.)

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

		Standard
Solar PV	Unit construction cost [1,000 yen/kW]	102
	Years of operation	30
	Full cost rate	0.014
Onshore wind	Unit construction cost [1,000 yen/kW]	190
	Years of operation	30
	Full cost rate	0.021
Offshore wind	Unit construction cost [1,000 yen/kW]	286
	Years of operation	30
	Full cost rate	0.044

Maximum available solar PV and wind power generation capacity was assumed as shown in Table 4. Although Matsuo et al. (2019)[22] as cited above used potential assessment data by the Ministry of the Environment, this study used estimates in Obane, et al. (2019)[28] from the viewpoint of realistic constraints.

Table 4 Maximum available solar PV and wind power generation capacity assumptions

Unit: GW	Solar PV	Onshore wind	Offshore wind
Hokkaido	14.7	16.4	177.1
Tohoku	24.8	2.8	33.9
Tokyo	54.4	0.6	38.8
Hokuriku	9.3	0.2	0.1
Chubu	35.5	0.5	23.3
Kansai	26.0	0.6	0.04
Chugoku	24.2	0.8	0.1
Shikoku	13.1	0.5	1.9
Kyushu	37.5	2.2	2.0
Total	239.3	24.6	277.2

(3) Batteries

Lithium-ion batteries were adopted for a battery cost assumption. The median case of US$150kWh of Cole and Frazier (2019)[29] is assumed as a standard case (Table 5). In line with Matsuo et al. (2019)[22] as cited above, pump-up power generation capacity is separately assumed at the existing level of 163 GWh.

Table 5 Battery cost assumption

	Standard
Battery［US$/kWh］※	150

※Calculated at 110 yen/dollar and input to all models.

(4) Fossil-fired power generation

This study assumed the use of existing coal- and gas-fired power plants without giving consideration to hydrogen or CCS-fitted thermal power plants. Table 6 shows assumptions for fossil-fired power plants.

Table 6 Power generation cost assumptions (coal- and gas-fired plants)

	Coal	Gas
Unit construction cost [1,000 yen/kW]	250	120
Years of operation	40	40
Full cost rate	0.037	0.024
Thermal efficiency	0.48	0.57
Captive consumption rate	0.06	0.02
Fuel cost [yen/kWh]	(Table 7)	(Table 7)
Maximum output growth rate	0.26	0.44
Maximum output decrease rate	0.31	0.31
Maximum seasonal capacity factor	0.90	0.95
Maximum annual capacity factor	0.80	0.80
DSS (daily start-stop) operation rate	0.00	0.50
Minimum output level	0.30	0.30

Fuel cost assumptions in IEEJ (2019)[30] were used as shown in Table 7.

Table 7 Fuel cost assumptions

	Standard
Coal［US$/t］※	123
LNG［US$/MMBtu］※	10.5

※Calculated at 110 yen/dollar and input to all models.

3. Assessment results

3.1 Power generation mix minimizing power generation and transmission costs under optimal power generation mix model

The optimal power generation mix and its power generation and transmission costs under the optimal power generation mix model are shown in Table 8.

Carbon tax levels will exert great influence on coal-fired power generation. In cases in which the current petroleum and coal tax level will be maintained (see Cases 1) and 2)), the existing coal-fired power generation capacity will be maintained to the maximum extent. Meanwhile, renewable energy power generation capacity in these cases will be far less than in the other cases, losing to cost-competitive coal-fired capacity.

In cases in which the carbon tax will increase substantially (to \$120/t-CO_2 in Cases 3) to 6)), optimal power generation mixes will differ far from the above ones. Coal-fired capacity affected by the carbon tax will disappear completely. In its place, gas-fired, solar PV and wind (onshore and offshore) capacity will increase substantially.

Nuclear power generation capacity will be close to the maximum available level in all cases in principle because of its cost competitiveness. In Case 1) in which the carbon tax will remain at the present level, new nuclear capacity will be 2 GW lower because of coal-fired plants' even higher cost competitiveness.

Under the optimal power generation mix model of which a target function is the minimized power generation and transmission cost level, Case 1) represents the optimal (cost-minimizing) power generation mix. Power generation and transmission costs will rise in cases of curbs on new nuclear plants, higher carbon tax levels and greater restrictions on fossil fuels or any other power source. In Case 6) which represents the toughest restrictions, the costs will be the highest at 18.96 trillion yen (assessed as the worst from the viewpoint of lower costs).

Table 8 Optimal power generation mixes and ranking of power generation and transmission costs

Optimal power generation mix model (Unit: GW)

Case No.	1)	2)	3)	4)	5)	6)
Existing coal	40	40	-	-	-	-
Gas	82	97	120	137	-	-
Fossil total	122	137	120	137	-	-
Existing nuclear	26	26	26	26	26	26
New nuclear	15	-	17	-	17	-
Nuclear total	41	26	43	26	43	26
Solar PV	-	171	171	188	239	231
Onshore wind	2.5	11	11	12	25	25
Offshore wind	-	-	-	-	155	250
Geothermal/biomass	16	16	16	16	16	16
Renewables total	18	197	197	215	435	521
Hydro	20	20	20	20	20	20
Generation capacity	201	380	380	398	497	567
Batteries (GWh)	0.2	0.1	0.2	0.3	173	150
Generation (GWh)	1,010	1,009	1,017	1,016	1,043	1,043
Carbon tax	Present level		\$120/t-CO_2			
Power generation and transmission costs (1 trillion yen)	8.68	8.74	10.30	10.78	16.07	18.96
Same as above (yen/kWh)	8.59	8.66	10.13	10.61	15.41	18.18
Cost ranking	1	2	3	4	5	6

3.2 Power generation mix to maximize real GDP under econometric model

Table 9 shows the results of inputting each case's power generation mix into the top-down econometric model developed by the IEEJ. Case 3) represents the optimal power generation mix model to maximize Japan's real GDP. Cases 1) and 2) that posted the first and second lowest costs are ranked fifth and sixth under the econometric model.

Table 9 Real GDP ranking for same cases as in Table 8

Econometric model (Unit: 1 trillion yen)

Case No.	1)	2)	3)	4)	5)	6)
Real GDP	812.6	810.5	814.0	813.7	813.9	812.9
GDP ranking	5	6	1	3	2	4
Private consumption expenditure	413.6	413.8	415.8	415.4	414.9	413.9
Government consumption expenditure	99.7	99.7	100.8	101.1	99.7	99.7
Private nonresidential investment	104.8	107.5	108.5	108.2	114.9	117.0
Fossil fuel imports	35.1	31.7	30.7	31.7	27.6	27.6
Overall unit electricity price (yen/kWh)	24.72	37.60	37.96	38.28	44.43	47.59

3.3 Comparison between optimal power generation mix model and econometric models

Table 10 extracted and compared the power generation and transmission cost ranking under the optimal power generation mix model in Table 8 and the GDP ranking under the econometric model in Table 9, indicating clear differences between the results under the two models.

Table 10 Power generation and transmission cost ranking vs. real GDP ranking

Optimal power generation mix model

Case No.	1)	2)	3)	4)	5)	6)
Carbon tax	Present level		\$120/t-CO_2			
Power generation/ transmission costs (1 trillion yen)	8.68	8.74	10.30	10.78	16.07	18.96
Same as above (yen/kWh)	8.59	8.66	10.13	10.61	15.41	18.18
Cost ranking	1	2	3	4	5	6

Econometric model

Real GDP	812.6	810.5	814.0	813.7	813.9	812.9
GDP ranking	5	6	1	3	2	4

(Reference) CO_2 emissions (As coal-fired 0.80kg-CO_2/kWh, gas-fired 0.43kg-CO_2/kWh)

CO_2 emissions (Mt-CO_2)	320.9	366.5	128.3	169.7	-	-
CO_2 saving ranking	4	5	2	3	1	1

(1) Comparing Cases 1) and 2) with Cases 3) to 6)

Under the optimal power generation mix model, coal-fired power generation will be highly competitive as far as the carbon tax level remains at the present level. In Case 1), it will appear to be a promising power source, with solar PV limited to zero and with new nuclear plant construction restricted. Under the econometric model, however, GDP will fail to grow due to carbon tax revenue's failure to be used for government consumption expenditure, private nonresidential investment's failure to increase amid low unit investment cost and massive existing capacity for coal-fired power generation and massive fossil fuel imports representing national wealth outflow in Cases 1) and 2). Eventually, coal-fired power generation will be given low ratings under the econometric model and run counter to climate change countermeasures.

(2) Comparing Case 1) with Case 2), Case 3) with Case 4), Case 5) with Case 6)

Under the optimal power generation mix model, power generation and transmission costs for nuclear energy will decline (with higher ratings given) in all cases if existing capacity (26 GW) is combined with capacity addition and replacement (17 GW). Even under the econometric model, nuclear capacity addition and replacement will surely push up GDP through massive construction investment, high domestic contents for nuclear equipment and curbs on fossil fuel imports. Therefore, nuclear capacity addition and replacement will be given high ratings under both models.

(3) Comparing Cases 3) to 6)

If the carbon tax assumption is the same for all cases under the optimal power generation mix model, gas-fired power generation will achieve the lowest power generation and transmission costs in Case 3) (massive gas-fired power generation capacity around 120 GW) in which gas-fired capacity will be increased beyond the existing capacity of 83 GW in the Survey of Electric Power Statistics (2020) [31)] by the Agency for Natural Resources and Energy. Case 3) will indicate the greatest significance of gas-fired capacity as a power supply-demand balancer among the cases. Under the carbon tax imposition, Case 3) may achieve both the lowest costs for power utilities under the optimal power generation mix model and the highest GDP under the econometric model.

By the way, CO_2 emissions are added as reference information, but Case 3) is superior to Cases 1) and 2), which have many coal-fired power plants, in terms of CO_2 saving, and is inferior to Cases 5) and 6), which do not emit CO_2. The purpose of this study is to compare power generation cost and GDP, and three comparative verifications including decarbonization will be the subject of future study.

3.4 Deriving final results through additional case studies

Under the econometric model, however, gas-fired capacity features low construction investment and fossil fuel imports and is expected to produce a relatively smaller GDP-boosting effect than other power sources. Therefore, we thought that additional case studies would be required to verify whether Case 3) may maximize GDP. Then, we set up five gas-fired capacity cases with 20 GW increments between Case 3) (gas-fired capacity at 120 GW) and Case 5) (no gas-fired capacity) that indicated the first and second largest GDP in Table 11 and put the five new cases into the optimal power generation mix and econometric models for additional estimation. Table 12 indicates additional estimation results.

The comparison of the seven cases between Cases 3) and 5) found that Case 3)-2 may maximize GDP while holding down an increase in power generation and transmission costs for power utilities by mixing gas-fired capacity around 80 GW (close to the existing level of 83 GW) with renewable energy and batteries in a balanced manner. The finding indicates that gas-fired, renewable and battery capacity shares in the power generation mix may differ between Case 3) for the lowest costs for power utilities and Case 3)-2 for the largest GDP.

Case 3)-2 for gas-fired capacity at 80 GW will maximize GDP mainly because this gas-fired capacity level will be more useful for maintaining power supply in the absence of wind and sunshine than lower gas-fired capacity cases. If gas-fired capacity is cut to 40 GW or less, renewable energy and battery capacity levels will be far higher, resulting in frequent renewable energy output suppression that would boost costs for power utilities to affect their business performance. In the cases of higher gas-fired capacity, GDP may fail to rise due to low gas-fired capacity construction costs and fossil fuel import expansion, as noted above. Therefore, Case 3)-2 in which renewable energy and batteries will diffuse while refraining from triggering frequent output suppression that could lead to unnecessary power cost hikes would be one of the optimal solutions regarding the best power generation mix for the Japanese economy.

Table 11 Final results

Case No.	Cited again 3)	New 3)-1	New 3)-2	New 3)-3	New 3)-4	New 3)-5	Cited again 5)
Existing coal	-	-	-	-	-	-	-
Gas	120	100	80	60	40	20	-
Fossil total	120	100	80	60	40	20	-
Existing nuclear	26	26	26	26	26	26	26
New nuclear	17	17	17	17	17	17	17
Nuclear total	43	43	43	43	43	43	43
Solar PV	171	189	197	209	208	239	239
Onshore wind	11	11	12	14	19	25	25
Offshore wind	-	-	-	21	60	103	155
Geothermal/ biomass	16	16	16	16	16	16	16
Renewables total	197	215	224	260	303	382	435
Hydro	20	20	20	20	20	20	20
Generation capacity	380	378	367	383	406	465	497
Batteries (GWh)	0.2	24	44	72	110	160	173
Generation (GWh)	1,017	1,018	1,020	1,024	1,030	1,039	1,043
Power generation/ transmission costs (1 trillion yen)	10.30	10.37	10.48	10.68	11.27	12.83	16.07
Same as above (yen/kWh)	10.13	10.18	10.27	10.43	10.95	12.35	15.41
Cost ranking	1	2	3	4	5	6	7
Real GDP	814.0	814.4	814.6	814.2	813.7	813.6	813.9
GDP ranking	4	2	1	3	6	7	5
Private consumption expenditure	415.8	416.0	416.1	415.9	415.4	415.2	414.9
Government consumption expenditure	100.8	100.7	100.7	100.5	100.1	99.8	99.7
Private non residential investment	108.5	108.7	108.8	109.7	111.1	113.1	114.9
Fossil fuel imports	30.7	30.3	30.2	29.3	28.2	27.8	27.6
Overall unit electricity price (yen/kWh)	37.96	38.10	38.03	39.50	41.36	43.19	44.43

(Reference) CO_2 emissions (As coal-fired 0.80kg-CO_2/kWh, gas-fired 0.43kg-CO_2/kWh)

CO_2 emissions (Mt-CO_2)	128.3	119.2	114.0	84.4	43.3	12.0	-
CO_2 saving ranking	7	6	5	4	3	2	1

4. Conclusion

This study finally put 11 scenarios for Japan's power sector in 2050 into the integrated energy economic model combining the optimal power generation mix model adopted by power utilities for considering the best mix of coal-fired, gas-fired, nuclear and renewable energy power generation and batteries with the econometric model used widely for considering energy policies, quantitatively indicating that an optimal solution for minimizing power utilities' power generation and transmission costs differs from that for maximizing Japan's GDP.

Comparison between data within the two thick frames in the lower part of Table 11 indicates that a transition from Case 3) to Case 3)-2 boosts Japan's real GDP by about 600 billion yen and power utilities' power generation and transmission costs by about 200 billion yen. On the contrary, a transition from Case 3)-2 to Case 3) reduces power utilities' costs by 200 billion yen and real GDP by about 600 billion yen. This means that policymakers and power utilities have different optimal solutions regarding the best power generation mix and can cooperate in handling energy and economic policies adequately to produce Japan's virtuous economic cycle.

This study is designed to provide recommendations about power sources that Japan should focus on from now towards 2050 based on feasible technologies and costs at present. In addition to power generation technologies covered by this study, hydrogen and ammonia power generation, and CCS (carbon capture and storage) and CCUS (carbon capture, utilization and storage) technologies are conceivable for the future. However, we have intentionally refrained from considering these new technologies. This is because these new technologies are in the demonstration phase rather than in the commercialization phase, leaving great uncertainties about their commercialization before 2050, their costs and capacity levels for power utilities and their spillover effects on the Japanese economy. The uncertainties could destabilize estimation. If these new technologies' costs conceivable in the demonstration phase are assumed, these technologies, like coal-fired power generation under a high carbon tax, could disappear from a power generation mix through model computation. Given that Japan has shifted the target from a low-carbon society to a decarbonized society as indicated by the prime minister's latest policy address4), however, these new technologies will become key factors for considering the future power generation mix. As soon as capacity levels, costs and targets for these technologies' commercialization are clarified, we would like to subject them to consideration and comparison.

As for the effect of boosting GDP, if the price of fossil fuels rises, the superiority of gas-fired power generation will decrease. And if renewable energy and batteries become cheaper, their superiority will increase. In these cases, GDP will be maximized to the right of Case 3) -2, that is, to Case 3) -3. The same is true in the opposite direction, and the evaluation results may change.

In addition, the domestic production rate of capital investment is set with reference to the current rate. For this reason, if the rates of various power generations and batteries become higher than expected in the future, private capital investment will increase and GDP will increase according to the amount of their composition ratio, and if the rate decreases, GDP will decrease.

Furthermore, although we assume that a large amount of carbon tax will be levied, we do not currently assume international competitiveness adjustment of products called "border adjustment measures", but we will consider it in the future.

As far as we know, no earlier study has used specific figures to comprehensively discuss correlations between power utilities' cost-based optimization of a power generation mix and economic indicators including real GDP. Therefore, we hope that this study would help provide a useful direction for both power utilities and the Japanese economy. We will continue to consider the relationship between the power generation mix and economic activities from different angles.

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