A Quantitative Analysis of Japan's Optimal Power Generation Mix towards 2050 - Considering macroeconomic effects of nuclear power generation and hydrogen price -

Hideaki Okabayashi Keisuke Ota* Yuji Matsuo**

Abstract

In this study, assuming the power supply portfolio in Japan in 2050, we conducted a model analysis to achieve carbon neutrality while supplying the required amount of power. The energy model developed in this paper is an integrated model which combines an optimal power generation mix model and an econometric model.

As a result, we show the superiority of nuclear power generation, and at the same time, if the sole purpose is to minimize the costs of power generation and transmission, depending on the preconditions, economic growth is restrained by the ripple effect of the decrease in capital investment related to power plants and the increase in fuel import value, etc. We hope that this study will be a beneficial starting point for both policy makers and electric utilities.

***Key words**:* Hydrogen price, Nuclear power generation, Macro economy, Power generation mix

1. Preface

The sense of impending crisis with regard to climate change is rapidly increasing worldwide. The Sixth Assessment Report[1) released by the Intergovernmental Panel on Climate Change (IPCC) in August 2021 stated for the first time that human impacts on atmospheric, oceanic and terrestrial warming are "unequivocal," removing all uncertainty. In addition, the fact that Shukuro Manabe and others, who developed a climate model to predict global warming and revealed the relationship between carbon dioxide (CO_2) concentration and temperature in the atmosphere for the first time in the world, received the first Nobel Prize in Physics (2021)[2) in climate research in October 2021 symbolizes the growing interest in climate change. Starting with the United Kingdom's passage of a law[3) in June 2019 calling for net zero greenhouse gas (GHG) emissions by 2050, a number of other countries have stated their commitment toward "carbon neutrality" by 2050, and as of October 26, 2021, this number totaled 136 countries and one region (European Union)[4).

In an October 2020 policy speech prior to the special Diet session former Prime Minister Yoshihide Suga declared that "Japan will aim to achieve zero greenhouse gas emissions as a whole, that is, to realize carbon neutrality, and a decarbonized society by 2050."[5) Thereafter, following discussions at the Basic Policy Subcommittee, the "Sixth Strategic Energy Plan"[6) was approved by the Cabinet in October 2021 and included the "Green Growth Strategy"[7) formulated by the Ministry of Economy, Trade and Industry. This strategy is an industrial policy to link the challenge of carbon neutrality in 2050 to a positive cycle involving the economy and environment.

In addition, analysis of the impacts on the economy and the public burden caused by a country's energy selection for carbon neutrality is being actively carried out both domestically and internationally, and there are several works which carried out the same evaluation for Japan. For example, Ram et al. (2017)[8) and WWF Japan (2017)[9) say that even if all Japanese power is supplied with variable renewable energy (VRE) in 2050, the total cost of the power system including the integrated cost will decrease compared to the current situation. On the other hand, if thermal power generation is not available, Matsuo et al. (2018)[10) and Matsuo et al. (2020)[11) state that the power system cost will rise significantly, and if not only VRE but also nuclear power can be used to suppress the cost increase, while Ogimoto et al. (2018)[12) indicates that if power is supplied only by VRE, the unit price of the electric power system will be much higher than the present state.

Since Japan's carbon neutrality declaration, as a similar analysis including new technologies such as hydrogen, at the 43rd meeting (2021)[13) of METI's Basic Policy Subcommittee, the Research Institute of Innovative Technology for the Earth (RITE) and at the 44th meeting (2021)[14), the National Institute for Environmental Studies, the Renewable Energy Foundation, RITE, Deloitte Tohmatsu Consulting, and the Japan Institute of Energy Economics used their own models to evaluate economic rationality mainly on electric power systems, with each recommending a different power generation mix.

However, a common denominator of works 8) to 14) is that they each find that "the lower the total cost of energy system development and upkeep, the more economical." For this reason, the authors are not aware of any research that has quantitatively or simultaneously examined ripple effects on the macro economy caused by changes in the cost of new technologies such as hydrogen and capital investment from the selection of energy systems. Furthermore, the above-mentioned "Green Growth Strategy"[7) is arranged as an action plan for establishing a positive

This report was written by authors for the 38th Energy Systems, Economy and Environment Conference and reproduced and uploaded on IEEJ's website with the permission of Japan Society of Energy and Resources.

cycle and growth of the economy based on a plan aiming to maximize the curtailing of total costs of the energy system, and thus, it can be said that the strategy does not examine these simultaneously.

In this study, the authors assume that carbon neutrality will be achieved by new technologies such as hydrogen thermal power and gas-fired thermal power with carbon dioxide capture and storage (CCS), nuclear power, renewable energy, and storage batteries in the power generation sector in Japan in 2050, which currently accounts for about 46%[15] of Japan's domestic supply of primary energy and is important for achieving carbon neutrality. On top of that, this study will use the Integrated Energy-Economy Model created by the authors by combining optimal power generation mix model and the econometric model using the linear planning method to simultaneously analyze how "macroeconomics such as total cost of power generation and transmission" and "gross domestic product (GDP)" change when the social tolerance of nuclear power and the hydrogen price changes.

Below, this paper consists of the following. Chapter 2 outlines of the model used and the main preconditions are described. Chapter 3 describes the results of the model analysis. After considering the relationship between power generation mix and economic growth, Chapter 4 describes the conclusions and policy implications from this study.

2. Evaluation Method

2.1 Integrated Economy-Energy Model

In order to simultaneously evaluate the effect of changes in the preconditions related to nuclear power generation and hydrogen price on the high and low costs of power generation and transmission and high and low economic growth (scale) in the case of restrictions for the power production sector to achieve carbon neutrality, this study adopts an "Integrated Energy-Economy Model" that combines a cost minimization optimal power generation mix model and an econometric model.

The cost-minimization optimal power generation mix model models Japan's power generation mix by a linear planning method. This model was based on Fuji and Komiyama (2017)[16] and improved by Matsuo et al. (2019)[17], Matsuo et al. (2020)[11] Okabayashi et al. (2021)[18] . It determines the introduction scale of equipment and technology that is the minimum cost according to the supply and demand of power. The objective function is the total cost of the system after discounting over a calculation period, and as a constraint formula, resource quantity constraints and power supply and demand balance constraints are considered. The regional division is nine regions that integrate Kyushu and Okinawa in the supply area of the former general electric utility, and the integrated region is connected by DC or AC interconnected power lines. The annual supply and demand of power is calculated by the granularity of 1 hour (365×24 = 8,760 divisions).

The econometric model was developed by Murota et al. (2005)[19] and improved by Yangagisawa (2008)[20], Komiyama et al. (2012)[21], Okabayashi et al. (2021)[18]. Based on the preconditions of overseas factors such as global trade, economic policies such as public investment, demographics, and energy prices such as fossil fuel prices, the model estimates various economic indicators, and sensitivity analysis of the national economy is also possible, focusing on GDP, investments constituting it, and imports and exports. It consists mainly of real expenditure module, wage price module, income distribution module, labor module, and can estimate the effect of changes in various exogenic variables on the economy as a whole. For details of the model, see Komiyama et al. (2012)[21], Okabayashi et al. (2021)[18].

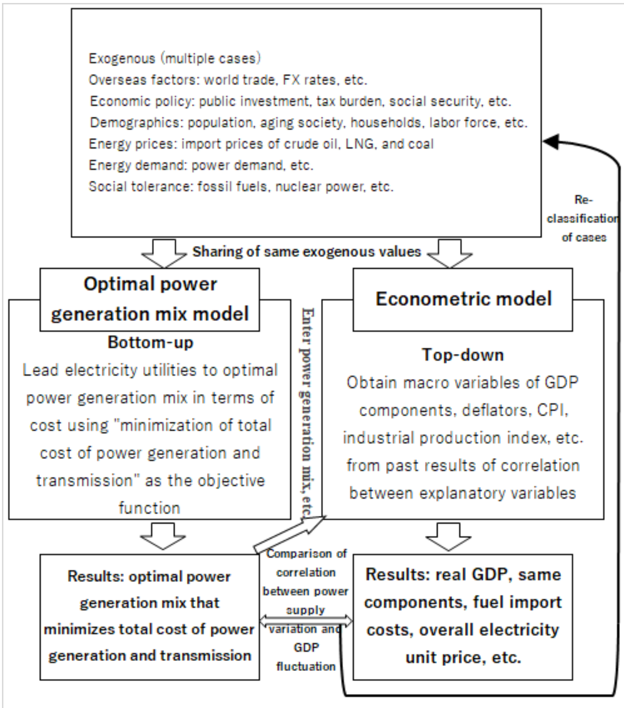

Figure 1 Integrated Energy-Economy Model

2.2 Trial Calculation Case

This study does not cover conventional thermal power generation such as coal-, gas-, and oil-fired power generation based on the assumption of atmospheric emission of combustion CO_2 from fossil fuels; instead it covers carbon neutrality-compatible gas-fired power with CCS. As the assumption for 2050, Table 1 indicates a total of 12 cases, consisting of 4 cases each of (a) decommissioning case, (b) existing facility tolerance cases, and (c) new facility tolerance case as divided into groups according to the level of tolerance in the society of nuclear power plants, and hydrogen thermal fuel costs are 12 yen to 40 yen / Nm^3 using real prices in 2018. The following prices are all real 2018 prices.

Additionally, these 12 cases exemplified the characteristic case division that ultimately led to the significant conclusion presented, and in actual estimation, more than 150 cases were examined, with most of these introduced into the Integrated Energy-Economy Model, confirming the results.

Table 1 Comparison of Each Trial Calculation by Case Number

Group	Case no.	Nuclear power		Hydrogen price (yen/Nm^3)
		Existing	New	
(a) Nuclear power decommissioning case	①	×	×	12
	②	×	×	20
	③	×	×	30
	④	×	×	40
(b) Nuclear power existing facility tolerance case	⑤	○	×	12
	⑥	○	×	20
	⑦	○	×	30
	⑧	○	×	40
(c) Nuclear power new facility tolerance case	⑨	○	○	12
	⑩	○	○	20
	⑪	○	○	30
	⑫	○	○	40

2.3 Conditions

In all cases, in accordance with Matsuo et others (2019)[17], the preconditions were set assuming the energy mix of a carbon neutral state in Japan in 2050. However, some conditions were set independently according to the purpose of this study as follows.

(1) Amount of power generated

The amount of power generated was assumed to be about the technical progress scenario (1,003 TWh/year in 2050) in IEEJ Outlook 2021 (2020)[22], but since the amount of power generated including that not supplied to the electric power market increases or decreases due to the occurrence of output suppression of renewable energy, it is shown in the results (**Table 8**) described later.

(2) Nuclear power generation

As shown in **Table 2**, the power generation cost and performance of existing large reactors as at the current level were assumed. In 2050, the maximum installable amount of nuclear power generation capacity in 2050 was assumed to be 42.5 GW combining the total capacity of new reactors under construction and existing reactors, which had not been decommissioned as of October 2021. Assuming 60-year operation, by 2050, 17 GW of existing reactors will be decommissioned, but when the profitability of a new reactor is obtained and new expansion is socially acceptable, replacement is performed up to the interconnected capacity of the abolished power plant, and if it is not accepted, it is assumed that it will be decommissioned. Furthermore, the construction cost of reactors under construction or already in operation (collectively referred to as “existing reactors”) that do not reach 60 years by 2050 after the start of operation in 2050 is assumed to be a sunk cost of the electric utility and deducted from the capital cost at the time of calculation.

Table 2 Power Generation Cost/Performance Assumption (Nuclear Power)

Construction cost (1,000 yen/kW)	420
Service life (existing) (years)	60
Service life (new) (years)	40
Annual expense ratio (%)	4.5
In-house consumption rate (%)	4
Fuel cost (yen/kWh)	1.8
Upper limit of output increase (%)	2
Lower limit of output increase (%)	2
Upper limit of annual utilization rate (%)	80
Minimal output level (%)	80

(3) Renewable energy power generation

Referencing the cost reduction target for renewable energy by the Government's procurement price calculation committee (2021)[23] and the cost assumption for 2030 of the power generation cost verification working group report (2021)[24], this study assumed that the lower limit of the expected unit price range will be reached in the 2050 cross-section, and further assumed that solar power is 7.0 yen/kWh, onshore wind power is 8.5 yen/kWh, and offshore wind power is 10.0 yen/kWh, while construction cost and service life were assumed to be as shown in Table 3.

Table 3 Power Generation Cost Assumption （PV and Wind Power Generation）

		Standard
PV	Construction cost (1,000 yen/kW) Service life (years) Annual expense ratio (%)	102 30 1.4
Onshore wind	Construction cost (1,000 yen/kW) Service life (years) Annual expense ratio (%)	190 30 2.1
Offshore wind	Construction cost (1,000 yen/kW) Service life (years) Annual expense ratio (%)	286 30 4.4

The maximum installable amount of PV and wind power was set as shown in **Table 4**. Although the latest version (2021)[25)] of the potential evaluation values by the Ministry of the Environment is used for both PV and wind power, the figures of Obane et al. (2019)[26)] are used only for onshore wind power from the viewpoint of realistic land use constraints.

Table 4 Maximum Installable PV and Wind Power Precondition

Unit: GW	PV	Onshore wind	Offshore wind
Hokkaido	14.6	16.4	207.2
Tohoku	32.0	2.8	88.3
Tokyo	60.1	0.6	45.4
Hokuriku	7.8	0.2	3.5
Chubu	33.2	0.5	35.5
Kansai	28.8	0.6	7.4
Chugoku	17.2	0.8	4.2
Shikoku	10.7	0.5	14.7
Kyushu/Okinawa	31.0	2.2	54.0
Total	235.1	24.6	460.3

(4) Storage batteries

The storage battery cost was set at US$150/kWh in the middle case of Cole and Frazier (2019)[27)] for lithium-ion batteries (Table 5). Furthermore, according to the above-mentioned past study[17)], it is assumed that pumped-storage power generation (163 GWh) equivalent to existing facilities is used separately.

Table 5 Storage Battery Cost Assumption

Storage batteries (USD/kWh)*	150

*Each model was configured using 1 US dollar equals 110 Japanese yen.

(5) Thermal Power Generation in Response to Carbon Neutrality

This study assumed that all coal-, gas- and oil-fired power plants based on the assumption of atmospheric dissipation of combustion CO_2 will be decommissioned in a manner corresponding to carbon neutrality, and thermal power generation, which will continue to be an important adjustment power source, was examined on the assumption that only hydrogen power generation and gas thermal power with CCS can be used. The study also assumes that the entire amount of hydrogen and gas for thermal power will be imported, and the CCS method includes not only deep subterranean injection in Japan but also the case of transferring the collected CO_2 liquid overseas, including looping back with LNG, and injecting it underground, and both hydrogen-fired and gas-fired with CCS do not have an upper limit on the installation capacity of the power plant. In addition, gas thermal power with CCS incorporates the efficiency deterioration from the conventional gas thermal power plant based on IEA (2020)[28)]. The assumptions of the power generation facilities are as shown in **Table 6.**

Table 6 Power Generation Cost Assumption (Hydrogen Thermal and Gas Thermal with CCS)

	Hydrogen thermal	Gas thermal with CCS
Construction cost (1,000 yen/kW)	128	159.5
Service life (years)	40	40
Annual expense ratio (%)	2.4	2.4
Heat efficiency (%)	57	47*
In-house consumption rate (%)	2	2
Fuel cost	(Table 7)	(Table 7)
Upper limit of output increase (%)	26	44
Lower limit of output increase (%)	31	31
Upper limit of seasonal utilization rate (%)	95	95
Upper limit of annual utilization rate (%)	80	80
DSS operating ratio (%)	50	50
Minimal output level (%)	30	30

*After deducting energy consumption for CCS.

Fuel costs were set based on the fuel cost assumptions of RITE in the Hydrogen and Fuel Cell Strategy Roadmap (2019)[29)] and the 43rd meeting of the Basic Policy Subcommittee 43rd (2021)[14)], as shown in **Table 1** and **Table 7** below**.** In particular, the concept of case classification of hydrogen price (unit price) is as described at the beginning of **2.2 Trial Calculation Case.**

Table 7 Fuel Cost Assumption and Hydrogen Price Case Classification

Gas power generation with CCS (LCOE) (yen/kWh)	16
CCS price (1,000 yen/t-CO_2)	10
Hydrogen price (yen/Nm^3)	12, 20, 30, 40

LCOE: Levelized cost of electricity

(6) Other Preconditions

As for the domestic rate of capital investment in power generation and transmission, the domestic rate of total investment in facilities and construction was assumed to be 95% for nuclear power, 80% for hydrogen thermal and gas thermal with CCS, 40% for storage batteries, 27% for PV, 23% for onshore wind power, and 22% for offshore wind power, referencing NEDO (2014) [30)], Ishii (2014) [31)], TEPCO (2020) [32)], Mitsubishi Research Institute (2020)[33)], Procurement Price Calculation Committee (2021)[23)], and the 43rd meeting of the Basic Policy Subcommittee 43rd Meeting (2021) (RITE) [14)]. In addition, carbon tax is not considered because it does not affect the power supply selection under carbon neutrality. Changes in the international competitiveness of imports and exports due to differences in environmental policies with other countries are not taken into account.

3. Evaluation Results

3.1 Evaluation Results using the Integrated Energy-Economy Model

The impact of the power generation mix on macroeconomic indicators is arranged and compared in **Table 8** below, after using the Integrated Energy-Economy Model to derive the power generation mix in which the total cost of power generation and transmission is minimized.

Table 8 Power Generation Mix for Minimizing Total Cost of Power Generation and Transmission and Macro Economy

Group	(a) Nuclear power decommissioning case			
Case Number Hydrogen (yen/Nm^3)	① 12	② 20	③ 30	④ 40
Existing nuclear power (GW)	―	―	―	―
New nuclear power (GW)	―	―	―	―
Nuclear total (GW)	―	―	―	―
Hydrogen thermal (GW)	162	161	121	―
Gas thermal with CCS (GW)	―	―	―	99
Thermal total (GW)	162	161	121	99
PV (GW)	79	194	165	182
Onshore wind (GW)	12	17	25	25
Offshore wind (GW)	―	―	156	186
Geothermal/biomass (GW)	16	16	16	16
Hydroelectric (GW)	20	20	20	20
Renewables total (GW)	127	246	382	428
Installed capacity (GW)	289	407	503	528
Storage batteries (GWh)	0.2	0.5	58	93
Power generation amount (TWh)	1,009	1,013	1,026	1,031
Total cost of power generation and transmission (Tn yen)	**10.65**	**12.39**	**14.34**	**15.00**
Same as above (yen/kWh)	**10.55**	**12.22**	**13.98**	**14.55**
Same as above rank ( ) is overall rank	**1 (4)**	**2 (8)**	**3 (11)**	**4 (12)**
Real GDP (Tn yen)	**628.0**	**628.8**	**629.2**	**628.4**
Same as above rank ( ) is overall rank	**4 (12)**	**2 (10)**	**1 (8)**	**3 (11)**
Private consumption expenditure (Tn yen)	318.9	319.2	319.3	319.1
Government consumption expenditure (Tn yen)	76.7	76.7	76.7	76.7
Private sector capital investment (Tn yen)	84.7	86.1	89.1	88.9
Fuel imports (Tn yen)	28.9	27.2	24.0	23.2
Overall rates for electricity and lighting (yen/kWh)	23.64	25.67	30.21	30.75

Group	(b) Nuclear power existing facility tolerance case			
Case Number Hydrogen (yen/Nm^3)	⑤ 12	⑥ 20	⑦ 30	⑧ 40
Existing nuclear power (GW)	26	26	26	26
New nuclear power (GW)	―	―	―	―
Nuclear total (GW)	26	26	26	26
Hydrogen thermal (GW)	137	137	101	―
Gas thermal with CCS (GW)	―	―	―	83
Thermal total (GW)	137	137	101	83
PV (GW)	67	168	145	161
Onshore wind (GW)	10	12	25	25
Offshore wind (GW)	―	―	120	135
Geothermal/biomass (GW)	16	16	16	16
Hydroelectric (GW)	20	20	20	20
Renewables total (GW)	112	216	326	357
Installed capacity (GW)	275	379	452	466
Storage batteries (GWh)	0.2	0.3	56	84
Power generation amount (TWh)	1,009	1,014	1,026	1,029
Total cost of power generation and transmission (Tn yen)	**9.84**	**11.15**	**12.55**	**12.99**
Same as above (yen/kWh)	**9.75**	**11.00**	**12.23**	**12.62**
Same as above rank ( ) is overall rank	**1 (2)**	**2 (5)**	**3 (9)**	**4 (10)**
Real GDP (Tn yen)	**629.1**	**630.0**	**630.2**	**629.6**
Same as above rank ( ) is overall rank	**4 (9)**	**2 (6)**	**1 (4)**	**3 (7)**
Private consumption expenditure (Tn yen)	319.8	320.2	320.3	320.1
Government consumption expenditure (Tn yen)	76.7	76.7	76.7	76.7
Private sector capital investment (Tn yen)	84.9	86.2	88.5	88.0
Fuel imports (Tn yen)	27.5	25.8	23.3	22.8
Overall rates for electricity and lighting (yen/kWh)	23.60	25.06	28.47	28.49

Group	(c) Nuclear power new facility tolerance case			
Case Number Hydrogen (yen/Nm^3)	⑨ 12	⑩ 20	⑪ 30	⑫ 40
Existing nuclear power (GW)	26	26	26	26
New nuclear power (GW)	16	17	17	17
Nuclear total (GW)	42	43	43	43
Hydrogen thermal (GW)	120	120	88	―
Gas thermal with CCS (GW)	―	―	―	69
Thermal total (GW)	120	120	88	69
PV (GW)	53	147	168	194
Onshore wind (GW)	9	12	25	25
Offshore wind (GW)	―	―	66	76
Geothermal/biomass (GW)	16	16	16	16
Hydroelectric (GW)	20	20	20	20

Renewables total (GW)	99	194	290	330
Installed capacity (GW)	261	357	421	441
Storage batteries (GWh)	0.1	0.2	51	84
Power generation amount (TWh)	1,009	1,014	1,025	1,030
Total cost of power generation and transmission (Tn yen)	**9.60**	**10.63**	**11.79**	**12.23**
Same as above (yen/kWh)	**9.51**	**10.48**	**11.51**	**11.88**
Same as above rank ( ) is overall rank	**1 (1)**	**2 (3)**	**3 (6)**	**4 (7)**
Real GDP (Tn yen)	**630.0**	**631.2**	**631.0**	**630.3**
Same as above rank ( ) is overall rank	**4 (5)**	**1 (1)**	**2 (2)**	**3 (3)**
Private consumption expenditure (Tn yen)	320.4	321.0	320.9	320.7
Government consumption expenditure (Tn yen)	76.7	76.7	76.7	76.7
Private sector capital investment (Tn yen)	85.0	86.2	87.7	87.3
Fuel imports (Tn yen)	26.7	25.0	23.1	22.6
Overall rates for electricity and lighting (yen/kWh)	22.91	24.15	26.64	26.80

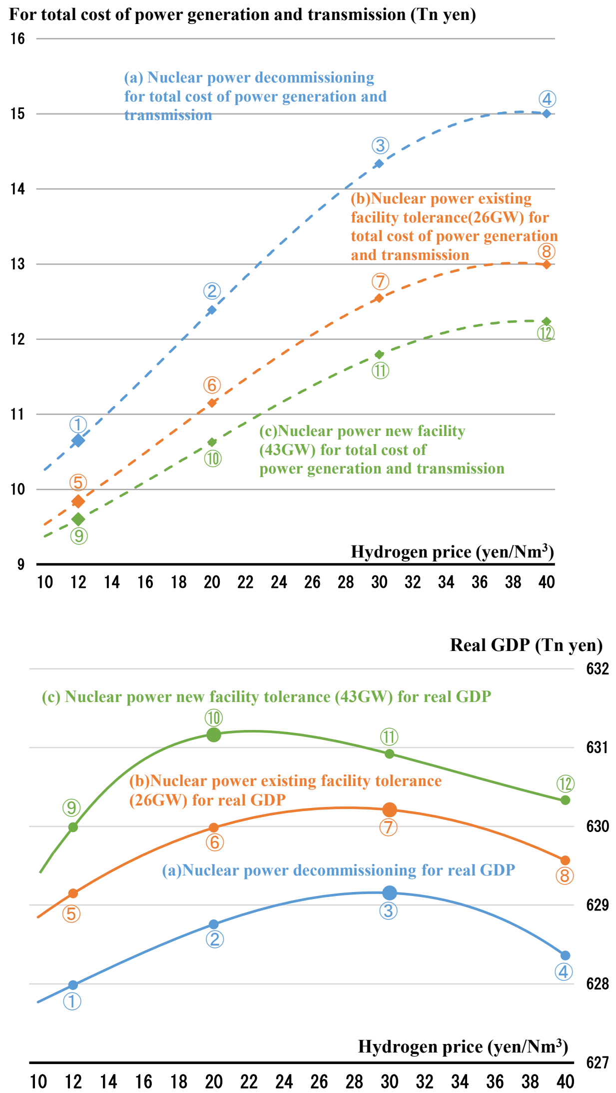

Figure 2 Correlation between Hydrogen Price and Total Cost of Power Generation and Transmission / Real GDP

(1) Nuclear power helps reduce total cost of power generation and transmission and increase real GDP

As shown in **Figure 2,** in the upper graph of the total cost of power generation and transmission, (c) < (b) < (a), and the larger the installed capacity of nuclear power, the lower the cost, resulting in a higher reading (ranking). On the other hand, in the lower graph of real GDP, (a) < (b) < (c), and the larger the installed capacity of nuclear power, the larger the absolute amount, and the higher the reading (ranking). When (a) and (c) are compared, there is a divergence of about 2 to 3 trillion yen in both the total cost of power generation and transmission and real GDP.

This is because, in addition to the lower cost of power generation and transmission considered to be a strength in the past, nuclear power has a high ripple effect on capital investment due to its large-scale construction costs and high domestic production rate of materials and equipment (increase in private capital investment), consumption is stimulated due to an increase in employee income etc. (increase in private consumption expenditure), and the import amount of fuel such as hydrogen is also suppressed (decrease in fuel imports), which is expected to boost GDP.

(2) In terms of hydrogen prices, "less expensive is not always better"

Generally speaking, it is believed that "the lower the price of fuel including hydrogen, the better for both electric utilities and the Japanese economy," but different results were obtained in the Integrated Energy-Economy Model.

First of all, as can be confirmed by looking left to right in the upper graph of **Figure 2**, the total cost of power generation and transmission of electric utilities falls under the belief "the lower the hydrogen price, the better." All dashed lines in the upper graph show that the decrease in hydrogen price leads to a decrease in the total cost of power generation and transmission. Furthermore, this is because at the time it reaches a plateau from (3), (7), and (11) to (4), (8), and (12) on the right, as hydrogen prices increase, they are completely replaced by gas-fired power plants with CCS that demonstrate the same adjusted power supply functions.

However, the real GDP of the lower graph is different from that of the top in that it the curves outward on top. On the right side from the vicinity of (3), (7), and (10), which are the tops of the arc, the decrease in the total cost of power generation and transmission and the increase in real GDP are both realized, resulting in "the lower the fuel price, the better," but on the left side of the top, “the lower the fuel price, the worse,” which is the opposite.

First, on the right side of the apex, hydrogen thermal power (gas thermal power with CCS when hydrogen price is 40 yen / Nm^3 or more) is treated as “adjusted power source”, and it compensates for the insufficient amount of power that cannot be generated by renewable energy and nuclear power introduced in large quantities. The “downward effect” of the increase in fuel imports due to soaring hydrogen prices will act more strongly than the “upward effect” in real GDP due to the large introduction of renewable energy and storage batteries and due to capital investment and consumption stimulus. For this reason, the higher the hydrogen price (the lower), the lower the real GDP, and the lower (the higher) the fuel price, which means “the lower the fuel price, the better.” However, the domestic production rate of renewable energy is set closely to the current state at 27% for solar power generation, 23% for onshore wind power, and 22 % for offshore wind power. By increasing the domestic production rate of renewable energy, there is a possibility that real GDP can be increased in response to the increase in fuel imports under high hydrogen prices.

On the other hand, on the left side of the top of the lower graph of Figure 2, hydrogen thermal power is treated as the “main power source,” most of the renewable energy is withdrawn from the market, and in some cases such as (9) in Table 8, withdrawal of nuclear power is also started. At this time, for real GDP, all of the case (1), (5) and (9) in group (a) to (c) sink to the lowest (4th) of, and (1) nuclear power decommissioning case was naturally the lowest overall (12th). The first reason for this is that renewable energy has a low overall utilization rate, and since there is a need to introduce more installed capacity (kW) than hydrogen thermal power per amount of power generation, when the introduction is suppressed, the total construction investment is rapidly reduced. PV generation (102,000 yen/kW), which sees a significant withdrawal when hydrogen thermal power plants are cheaper, has a lower capital cost than hydrogen thermal power (128,000 yen/kW), has a lower domestic production rate, and the multiplier effect is smaller than hydrogen thermal power, exceeding the reduction effect of the aforementioned investment. The second is that hydrogen thermal power, which is introduced instead of renewable energy without the need for fuel, requires continuous fuel imports.

(3) Substitutability of hydrogen thermal and gas thermal with CCS

In the cases of hydrogen price 40 yen / Nm^3 of (4), (8), and (12), hydrogen thermal power is replaced by gas thermal power with CCS of the same adjusted power source and withdrawal occurs, while in cases of hydrogen price 30 yen / Nm^3 (3) of (7) and (11), conversely, the share of hydrogen thermal power is 100%. At a hydrogen price of upper 30 yen/nm^3, hydrogen thermal power and gas thermal power with CCS competed for a share of 100-0. On the assumption that it is completely substituted depending on the price as the same adjustment power source, such extreme results are derived, but it results in the difficult problem of optimization analysis of equipment and technology selection. In fact, it is difficult to construct hydrogen-fired or gas-fired power plants with CCS in advance after predicting the hydrogen price around 2050 based on price fluctuations. In addition to the difficulty of changing the equipment capacity immediately, it is also expected that the flexibility and stability of the procurement quantity of the fuel contract will be difficult at the same time, suggesting the possibility that both may actually have to be mixed.

(4) Evaluation Results under the Integrated Energy-Economy Model

If only the calculation results of these 12 cases are compared, the minimization of the total cost of power generation and transmission (1st overall) is case (9) (Nuclear Power New Facility Tolerance Case, 5th in real GDP at 12 yen/Nm^3) and the maximization of real GDP due to the spread of the power generation mix to the entire Japanese economy (1st overall) is said to be divided from the case (10) (Nuclear Power New Facility Tolerance Case, 20 yen/Nm^3, total cost of power generation and transmission) and the evaluation was divided.

Fundamentally speaking, however, it is a higher priority to aim at improving Japan's macroeconomic capacity as a whole rather than minimizing the total cost of power generation and transmission, and for the choice to eliminate renewable energy by requesting hydrogen thermal power, a situation (10) in which the baseload nuclear power, peak-compatible hydrogen thermal or gas thermal with CCS, and renewable energy contributing to CO_2 reduction are well balanced, even under carbon neutrality is believed to constitute the optimal power generation mix for 2050.

4. Conclusion

In this study, the authors input the 12 scenario assumptions of targeting Japan’s electric power sector in 2050 repeatedly into the Integrated Energy-Economy Model, which combines two different models, for power generation mix such as nuclear power, hydrogen thermal power, gas-fired thermal power with CCS, renewable energy, and storage batteries, and factually confirmed that the minimized total cost of power generation and transmission by electric utilities even under strict restrictions of carbon neutrality does not necessarily maximize the real GDP of the Japanese economy.

Although this finding is from calculation results, there is a gap of about 200 billion yen between the difference in total cost of power generation and transmission of 1.0 trillion yen and real GDP of 1.2 trillion yen between cases (9) and (10). It is possible that economic rationality as a whole is higher in case (10).

Therefore, in Japan's pursuit of carbon neutrality, considering the degree of influence on the macroeconomics to a certain extent, in addition to minimizing the general total cost of power generation and transmission for power generation mix, may provide a new way of thinking on the assumption of energy mix and energy prices. Recently, discussions are taking place in Japan and abroad on the risk of stable supply of electric power when the power generation mix is biased toward LNG thermal power. Although it bears repeating, it must be recognized that the state in which some power supply -- hydrogen thermal power in this study -- culls other power sources in the future may not always be rational from a macroeconomic point of view, and at the same time, narrowing the width of the power generation mix raises the risk of hindering stable supply.

Paradoxically, it can be said that one possibility of growing the Japanese economy while considering power generation and transmission and achieving carbon neutrality by closely coordinating policy makers and electric utilities and appropriately carrying out energy and economic policies has been shown.

In this study, assuming that the technology and cost that can be estimated at present, the authors intended to propose the impact of changes in power generation mix and fuel prices on the macro economy for the cross section of 2050 to achieve carbon neutrality.

In the real economy, the model cannot reflect the situation such as the continuous change in the cost of CO_2 disposal due to market prices and other factors acting on hydrogen and gas prices and CCS prices, the difficulty of foreseeing the future price of fuel at the start of power source construction, and the construction of power sources requires several years of construction and that installed capacity cannot be changed overnight.

Regarding the setting of preconditions, it should be noted that the evaluation results can change due to changes in the preconditions such as soaring or crashing fuel prices such as gas and hydrogen, construction investment amounts of each power source and storage battery, domestic production rate of materials and equipment, changes in equipment efficiency and utilization rate, continuous occurrence of windless and non-sunshine periods, occurrence of inter-border adjustment measures based on energy and CO_2 prices, and changes in international competitiveness.

As far as the authors know, there is no prior study that uses concrete numbers to comprehensively discusses the relationship between the total cost of power generation and transmission and various economic indicators, focusing on the change in fuel prices under carbon neutrality restrictions and the social tolerance of each power source, and it is expected that this research will be a starting point for presenting a useful direction to both policy makers and electric utilities.

Acknowledgements
Part of this study was funded by MEXT's Nuclear Power System Research and Development Project JPMXD0220354480 and the Environmental Restoration and Conservation Agency's environmental research promotion budget (2-2104). The authors extend their appreciation to all relevant parties.

----

* Researcher, Electric Power Group, Electric Power Industry & New and Renewable Energy Unit, Institute of Energy Economics, Japan
**Associate Professor, College of Asia Pacific Studies, Ritsumeikan Asia Pacific University（1-1, Jumonjibaru, Beppu, Oita Prefecture 874-8577 Japan）

Works Cited

1) IPCC; Climate Change 2021: The Physical Science Basis, (2021) https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/ (Accessed on 2021/11/16)
2) The Nobel Prize outreach; The Nobel Prize in Physics 2021, (2021) https://www.nobelprize.org/prizes/physics/2021/summary/ (Accessed on 2021/11/16)
3) Gov.UK; UK becomes first major economy to pass net zero emissions law, (2019) https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law (Accessed on 2021/11/16)
4) The Global Climate Action Portal UNFCCC; Climate

Ambition Alliance
https://climateaction.unfccc.int/views/cooperative-initiative-details.html?id=94 (Accessed on 2021/11/16)

5) Prime Minister's Office; Policy Speech by the Prime Minister (2020). Speech by the Prime Minister to the 203rd Session of the Diet. October 26, 2020
https://www.kantei.go.jp/jp/99_suga/statement/2020/1026shoshinhyomei.html (Accessed on 2021/11/16)

6) Ministry of Economy, Trade and Industry; The Sixth Strategic Energy Plan, March 10, 2021
https://www.meti.go.jp/press/2021/10/20211022005/20211022005-1.pdf (Accessed on 2021/11/16)

7) Ministry of Economy, Trade and Industry; "Green Growth Strategy Through Achieving Carbon Neutrality in 2050," December 25, 2020
https://www.meti.go.jp/press/2020/12/20201225012/20201225012-2.pdf (Accessed on 2021/11/16)

8) M. Ram, D. Bogdanov, A. Aghahosseini, A.S. Oyewo, A. Gulagi, M. Child, H-J. Fell, C. Breyer; Global energy system based on 100% renewable energy – power sector, (2017)
https://www.researchgate.net/publication/320934766_Global_Energy_System_based_on_100_Renewable_Energy_-_Power_Sector (Accessed on 2021/11/16)

9) WWF Japan; Long-term Scenarios for Decarbonizing Japan (2017)
https://www.wwf.or.jp/press/475.html (Accessed on 2021/11/16)

10) Y. Matsuo, S. Endo, Y. Nagatomi, Y. Shibata, R. Komiyama and Y. Fujii; A quantitative analysis of Japan's optimal power generation mix in 2050 and the role of CO_2-free hydrogen, Energy, 165 (2018), pp.1200-1219.

11) Y. Matsuo, S. Endo, Y. Nagatomi, Y. Shibata, R. Komiyama and Y. Fujii; Investigating the economics of the power sector under high penetration of variable renewable energies, Applied Energy, 267 (2020), 113956.

12) K. Ogimoto, C. Urabe, T. Saito; Japan's energy supply and demand study for 2050: Possibility and challenges of 100% renewable energy in the future，Proceedings of the 34th Conference on Energy, Economy, and Environment, 31-5 (2018), pp. 697-702.

13) Ministry of Economy, Trade, and Industry; Handouts from Strategic Policy Committee (43rd Meeting), Advisory Committee for Natural Resources and Energy
https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/2021/043/ (Accessed on 2021/11/16)

14) Ministry of Economy, Trade, and Industry; Handouts from Strategic Policy Committee (44th Meeting), Advisory Committee for Natural Resources and Energy
https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/2021/044 (Accessed on 2021/11/16)

15) Ministry of Economy, Trade, and Industry; FY2019 Energy Supply and Demand Report (Revised Report), Comprehensive Energy Statistics
https://www.enecho.meti.go.jp/statistics/total_energy/pdf/honbun2019fyr2.pdf (Accessed on 2021/11/16)

16) R. Komiyama and Y. Fujii; Assessment of post-Fukushima renewable energy policy in Japan's nation-wide power grid, Energy Policy, 101, (2017), pp.594-611.

17) Y. Matsuo, S. Endo, Y. Nagatomi, Y. Shibata, R. Komiyama, Y. Fujii; A Study on the Feasibility of "Complete Decarbonization" of Japan's Power Sector in 2050 : The Effect of Changes in Meteorological Conditions, Journal of Japan Society of Energy and Resources, 40-3 (2019), pp.49-58.

18) H. Okabayashi, T. Shibata, Y. Matsuo; Study on the optimal power supply portfolio in 2050—Quantitative analysis considering macroeconomic effects--, Journal of Japan Society of Energy and Resources, 42-4 (2021), pp.215-223.

19) Y. Murota, M. Koshikuni, K. Ito; Guide to Economic Forecast with Personal Computer for Macro Interindsutry Analysis (2005), 275, Toyo Keizai Inc.

20) A. Yanagisawa; Japan's long-term energy supply and demand outlook--environmental constraints and outlook for 2030 under changing energy markets--, (2008). Energy and Resources, 29(6), pp.13-17.

21) R. Komiyama, K. Suzuki, Y. Nagatomi, Y. Matsuo, S. Suehiro; Analysis of Japan's energy supply and demand, Journal of Japan Society of Energy and Resources, 33-2 (2012), pp.34-43
http://www.jser.gr.jp/journal/journal_pdf/2012/journal201203_5.pdf (Accessed on 2021/11/16)

22) The Institute of Energy Economics, Japan; IEEJ Outlook 2021, (2021)
https://eneken.ieej.or.jp/data/9170.pdf (Accessed on 2021/11/16)

23) Procurement Price Calculation Committee, Ministry of Economy, Trade, and Industry; Opinions on Procurement Prices, etc. for 2021 and onward, (2021)
https://www.meti.go.jp/shingikai/santeii/20210127_report.html (Accessed on 2021/11/16)

24) Power Generation Cost Verification Working Group, Ministry of Economy, Trade, and Industry; Report on the Power Generation

Cost Verification to the Strategic Policy Committee, (2021) https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/cost_wg/pdf/cost_wg_20210908_01.pdf (Accessed on 2021/11/16)

25) Ministry of the Environment; Report on consignment work for maintenance and disclosure of zoning basic information on renewable energy 2020 (Revised March 1, 2021) https://www.renewable-energy-potential.env.go.jp/RenewableEnergy/report/r01.html (Accessed on 2021/11/16)

26) H. Obane, Y. Nagai, K. Asano; Evaluating technical potential of ground-mounted solar and on-shore wind energy in Japan, Central Research Institute of Electric Power Industry Report Y18003, (2019) https://criepi.denken.or.jp/jp/kenkikaku/report/detail/Y18003.html (Accessed on 2021/11/16)

27) W. Cole and A.W. Frazier; Cost Projections for Utility-Scale Battery Storage, (2019) https://www.nrel.gov/docs/fy19osti/73222.pdf (Accessed on 2021/11/16)

28) International Energy Agency; Projected Costs of Generating Electricity 2020, (2020) https://www.iea.org/reports/projected-costs-of-generating-electricity-2020 (Accessed on 2021/11/26)

29) Ministry of Economy, Trade, and Industry; New Strategic Roadmap for Hydrogen and Fuel Cells, (20109) https://www.meti.go.jp/press/2018/03/20190312001/20190312001-1.pdf (Accessed on 2021/11/16)

30) NEDO; NEDO Renewable Energy Technology White Paper. 2nd ed., 2014 https://www.nedo.go.jp/library/ne_hakusyo_index.html (Accessed on 2021/11/16)

31) S. Ishii; Efficiency of Nuclear Power Generation and Industrial Policy - Domestic Production and Improved Standardization, 2014. pp. 28 https://www.rieti.go.jp/jp/publications/summary/14050002.html (Accessed on 2021/11/16)

32) Tokyo Electric Power Company Holdings, Incorporated; Look at TEPCO by mathematical table -Overview of each nuclear power plant (2020) https://www.tepco.co.jp/corporateinfo/illustrated/nuclear-power/nuclear-plants-j.html (Accessed on 2021/11/16)

33) Mitsubishi Research Institute; Current understand the power storage systems, Ministry of Economy, Trade and Industry 1st Stationary Power Storage System Promotion Study Group, (2020) https://www.meti.go.jp/shingikai/energy_environment/storage_system/pdf/001_05_00.pdf (Accessed on 2021/11/16)

Contact: report@tky.ieej.or.jp

https://eneken.ieej.or.jp/en/