Japan's pathways to achieve carbon neutrality by 2050 – Scenario analysis using an energy modeling methodology

Ozawa, A.[1,*], Tsani, T.[2], Kudoh, Y.[1]

[1] Global Zero Emission Research Center, National Institute of Advanced Industrial Science and Technology (AIST), 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, Japan

[2] Institute of Energy and Climate Research – Techno-Economic Systems Analysis (IEK-3), Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Str., 52428 Jülich, Germany

Abstract

Innovative energy and environmental technologies have an important role in achieving carbon neutrality. However, uncertainties regarding the potential of these technologies still remain. For this reason, possible scenarios for such technologies must be developed to facilitate forward-looking decision-making on national energy strategies. This study investigated multiple scenarios of future energy systems in Japan to achieve net-zero CO_2 emissions by 2050 using a MARKAL (MARKet ALlocation) energy model. Six cases were configured based on different assumptions of renewable and nuclear power, carbon capture and storage, and hydrogen import, and the CO_2 emissions, primary energy supply, final energy consumption, and electricity generation were compared for the different cases. The scenario analysis results suggest that electric power systems in Japan should be fully decarbonized by 2040 in order to achieve carbon neutrality by 2050, implying that renewable power generation should be dominant in the decarbonized electricity sector in Japan. The results also indicate that total energy supply and consumption in 2050 will be between 14.9–15.7 and 9.6–10.2 EJ, respectively, and that 211–256 Mt of CO_2 will need to be removed using advanced CO_2 removal technologies. The results further imply that CO_2 removal technologies will become necessary when industrial decarbonization is difficult.

Highlights

1. We built six scenarios of future energy systems in Japan toward carbon neutrality
2. We used a MARKet ALlocation (MARKAL) energy model
3. Power sector must reduce CO_2 to ~0 by 2040 to achieve carbon neutrality by 2050
4. Total energy supply and consumption in 2050 will be 14.9–15.7 and 9.6–10.2 EJ
5. Using advanced CO_2 removal technologies, 211–256 Mt of CO_2 must be removed

Keywords

energy system; carbon neutrality; multiple scenarios; energy model; MARKAL

Word Count: 5359

List of abbreviations

AIST: National Institute of Advanced Industrial Science and Technology

[*] corresponding author details, akito.ozawa@aist.go.jp

AR6 WG3: Working Group III part of the Sixth Assessment Report

BECCS: biomass energy with carbon capture and storage

$CaCO_3$: calcium carbonate

CCS: carbon capture and storage

CDR: carbon dioxide removal

CIF: cost, insurance, and freight

CO_2: carbon dioxide

DAC: direct air capture

DACCS: direct air capture with carbon storage

EFOM: Energy-Flow-Optimization-Model

EU: European Union

FY: fiscal year

GDP: gross domestic product

GHG: greenhouse gas

H_2: hydrogen

IEA: International Energy Agency

IGCC: integrated gasification combined cycle

IGFC: integrated gasification fuel cell cycle

IPCC: Intergovernmental Panel on Climate Change

IRENA: International Renewable Energy Agency

JPEA: Japan Photovoltaic Energy Association

JPY: Japanese yen

kg: kilogram

kW: kilowatt

KOH: potassium hydroxide

LNG: liquified natural gas

MARKAL: MARKet ALlocation

NDCs: Nationally Determined Contributions

O&M: operation and maintenance

PRIMES: Price-Induced Market Equilibrium System

PV: photovoltaic

TIMES: The Integrated MARKAL EFOM System

USD: United States dollar

%pt.: percent-point

1. Introduction

As the global warming indicators are worsening, movements toward carbon neutrality are taking shape globally. The Intergovernmental Panel on Climate Change (IPCC) reported in the Working Group III part of the Sixth

Assessment Report (AR6 WG3) [1] that global greenhouse gas (GHG) emissions have continued to rise during the period 2010–2019 and stated that the emissions need to peak between 2020 and at the latest before 2025 in order to limit global warming to 1.5°C. The IPCC's AR6 WG3 also reported that limiting warming to 1.5°C would require reaching global net-zero carbon dioxide (CO_2) emissions in the early 2050s. Carbon neutrality has become the most urgent global mission, and over 150 countries have declared carbon neutrality as a long-term environmental target.

In October 2020, Japan declared its long-term goal of reducing GHG emissions to net-zero by 2050. In April 2021, Japan announced a new mid-term GHG reduction target for the fiscal year (FY) 2030, aiming to reduce GHG emissions by 46% from FY2013 levels [2]. Achieving Japan's ambitious GHG reduction targets requires discontinuous innovations in energy and environmental technologies. To accelerate innovation and social implementation of these technologies, in June 2021, the Japanese government formulated a new "Green Growth Strategy," which aims to realize the virtuous cycle of the environment and economy [3]. As part of this strategy, the government selected 14 promising fields expected to grow by 2050 (e.g., renewables, hydrogen energy, and nuclear energy), set high goals, and has steadily implemented action plans according to the phase of technology. The strategy covers key policy measures, including the "Green Innovation Fund," which is a 2 trillion Japanese yen (JPY) (18.2 billion United States dollar (USD)) fund to assist ambitious green projects over the next decade [4] (the exchange rate of 109.75 JPY per USD in 2021 was used for currency conversion [5]).

To execute strategies toward carbon neutrality by 2050, policymakers should manage uncertainties associated with technological development and implementation. Given these uncertainties, many countries have applied a multiple-scenario approach to make flexible decisions on energy transition. The Japanese government applied this approach to explore Japan's pathways toward carbon neutrality by 2050 in the Strategic Energy Plan [6]. The European Commission assessed eight pathways on energy transition in the European Union (EU) by 2050 in its vision for a climate-neutral EU [7]. The government of the United Kingdom conducted an electricity system analysis that modeled approximately 7000 electricity mixes in 2050 for two levels of demand and flexibility and 27 technology–cost combinations to identify standard features of low emissions and low-cost electricity systems [8,9].

As an example of energy transition scenarios toward global carbon neutrality, the International Energy Agency (IEA) published a report on a global pathway to net-zero CO_2 emissions in 2050 [10]. According to this report, global CO_2 emissions from energy use and industrial processes decrease from 31.5 Gt in 2020 to 21.1 Gt in 2030 to reach net-zero in 2050. The global primary energy supply in 2050 will be 543 EJ, 9% lower than in 2020, due to a reduction in energy intensity (the amount of energy used to produce a unit of gross domestic product (GDP)) despite a significant increase in the world population and economy. Electrification contributes significantly to the reduction in energy intensity, and global electricity generation will increase to 71,000 TWh in 2050, 2.7 times more than the value in 2020. Renewable energies contribute the most to the decarbonization of electricity and account for 88% of total electricity generation in 2050. The International Renewable Energy Agency (IRENA) presented another global carbon neutral scenario that is consistent with limiting global warming to 1.5°C [11]. According to the IRENA's 1.5°C scenario, the global primary energy supply will be 612 EJ in 2050, which is 2% higher than in 2020. This scenario also shows that global electricity generation will reach 78,000 TWh in 2050, a three-fold increase from 2020, and the share of renewables will grow to 92% in 2050. These two scenarios suggest that pathways to carbon neutrality should depend on various assumptions.

Energy modeling is a well-known approach for simulating energy transitions, thus providing information on energy and environmental strateies for policymakers. Scenario analyses using various energy modeling methodologies, such as MARKet ALlocation (MARKAL) [12–15], The Integrated MARKAL Energy-Flow-Optimization-Model (or EFOM) System (collectively, TIMES) [16–21], and the Price-Induced Market Equilibrium System (PRIMES) [22–24], have been conducted to evaluate the effect of uncertainties regarding the breakthrough in energy and environmental technologies on future energy systems. Ozawa et al. [12] employed a MARKAL model developed by the National Institute of Advanced Industrial Science and Technology (AIST), known as the AIST-MARKAL model (with subsequent versions), to evaluate the role of hydrogen in future energy systems in Japan to reduce CO_2 emissions from energy use by 80% by 2050 from the 2013 level. Fu and Hobbs [13] studied the uncertainties in electricity demand growth, natural gas prices, and GHG regulations in the power sector. They analyzed the effect of these uncertainties on electric power sector investment decisions and costs in the United States using a MARKAL model. Tsai and Chang [14] analyzed Taiwan's energy systems under different assumptions about technological development and CO_2 mitigation targets by 2050 using Taiwan's MARKAL model. Chiodi et al. [16] and Sgobbi et al. [18] applied the TIMES model to assess the impact of climate mitigation targets in Europe on Irish and European energy systems, respectively. The PRIMES model has been also applied to energy system analysis in European countries; for example, Capros et al. [22] evaluated the impact of energy policy package on EU energy transition and Siskos et al. [23] conducted scenario analysis for transport decarbonisation in the EU.

Recent studies have employed energy models to investigate energy transition scenarios toward establishing carbon-neutral energy systems in a particular country, such as the United Kingdom [15], China [17], and Portugal [19]. Capros et al. [24] used the PRIMES model to investigate pathways toward climate neutrality in the EU by 2050 and 2070 and analyze impacts on energy demand, supply, and costs. In Japan, Pambudi et al. [20] developed a hydrogen scenario for decarbonizing electricty sector using the TIMES-Japan model. They found that hydrogen supply would reach 1,600 PJ in 2050, which accounted for 11% of total primary energy supply. They also determined that CO_2 emissions in the hydrogen scenario would be 338 Mt in 2050, 43% lower than those in the base scenario without hydrogen. Pambudi et al. [21] also employed the same model to evaluate the impact of carbon capture and storage (CCS) for reducing CO_2 emissions in the industry sector in Japan. Kato et al. [25] conducted a multi-scenario analysis of energy transition in Japan under various assumptions on CO_2 emissions reduction target (70%, 80%, and 90% in 2050 with relative to 2013) and the availability of low-carbon technologies (CCS and nuclear power). Their scenario analysis results suggested that a 90% CO_2 emissions reduction in 2050 from the 2013 level could be achieved if biomass energy with carbon capture and storage (BECCS) was available, and if up to 150 Mt of anual CCS capacity could be secured by 2050. Chaube et al. [26] evaluated the role of current and emerging technologies in Japan's energy systems up to 2100 using a TIMES model. Even though these previous studies have provided some important implications for decarbonizing energy systems in Japan, Japan's pathways to achieve net-zero CO_2 emissions in 2050 have not yet been fully investigated.

Even though innovative energy and environmental technologies should have important roles in carbon-neutral energy systems, uncertainties associated with breakthrough of the technologies still remain, which may affect the energy transition. Although many studies have analyzed energy transition in Japan using energy models [12,20,21,25,26], they have not yet reflected the Japanese GHG reduction targets and goals, which aim to reduce emissions by 46% by FY2030 and achieve carbon neutrality by 2050. Although we previously attempted to evaluate Japan's pathways to achieve carbon neutrality using the AIST-MARKAL model and its datasets to achieve 80% CO_2 reduction in 2050 [12], we could obtain no feasible solutions. Sugiyama et al. conducted an intercomparison study using five energy models to evaluate Japan's long-term climate and energy policy [27] and showed that achieving net-zero emissions by 2050 was only feasible in two models that incorporate carbon dioxide removal (CDR) technologies.

Given these situations, we aimed to analyze energy transition toward establishing carbon-neutral energy systems in Japan under different assumptions of technological development and implementation which have not yet been fully investigated. In this study, we incorporated CDR technologies into the AIST-MARKAL model to analyze Japan's future carbon-neutral energy system. The transition of Japan's energy system toward achieving net-zero CO_2 emissions by 2050 was simulated under various settings of renewable and nuclear power, CCS, and hydrogen import. Using the MARKAL simulation results, we compared CO_2 emissions, primary energy supply, electricity generation, and final energy consumption by 2050 in different cases. This study will help policymakers discuss energy and environmental strategies in Japan.

2. Methodology and assumptions

2.1. AIST-MARKAL model

MARKAL is a well-known operations research model for energy system analysis which was originally proposed by the Energy Technology Systems Analysis Program of the IEA [28]. MARKAL aims to identify optimal energy mix and technology combination using linear programming. The objective function Z of MARKAL is minimized, as it represents the net present value of whole system (Eq. (1)).

$$Z = \sum_{r=1}^{R} \sum_{t=1}^{NPER} ANNCOST(r,t) \cdot \left((1+d)^{-NYRS\cdot(t-1)} + (1+d)^{-NYRS\cdot(t-1)-1} + (1+d)^{-NYRS\cdot(t-1)-2} + \cdots + (1+d)^{-NYRS\cdot t+1} \right), \quad (1)$$

where $ANNCOST(r,t)$ is the annual cost in region r for period t which includes capital and operating costs for technologies, mining and import costs and export revenues for primary energy sources, and delivery and distribution costs for secondary energy carriers; d is the discount rate; $NPER$ is the number of periods; and $NYRS$ is the number of years in each period.

The MARKAL model also requires that the constraints regarding energy systems, such as capacity transfer of technologies, supply-demand balance of energy sources and carriers, and CO_2 mitigation target, be satisfied. Further descriptions of the MARKAL model are provided in Loulou et al. [29].

Various MARKAL models have been developed by AIST, in order to evaluate the contribution of new energy technologies and environmental policies on future energy systems in Japan [12,30–35]. This study was established using the latest version of the AIST-MARKAL model, which considers Japan as one region. This model considers the period between 2010 and 2050 and uses a reference energy system (Fig. 1) consisting of primary energy sources, conversion and process technologies, secondary energy carriers, end-use technologies, and energy service demands.

Over 350 types of technologies and 110 kinds of energy sources and carriers are incorporated into this version of the AIST-MARKAL model.

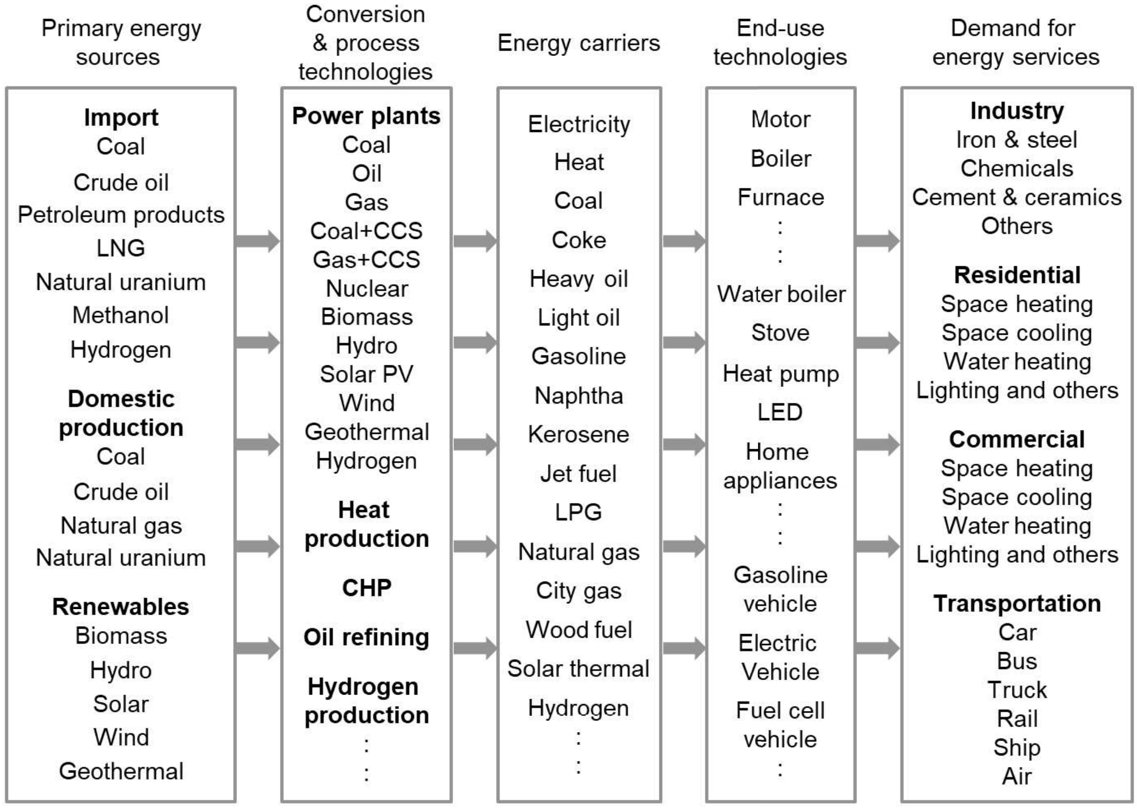

Fig. 1. Reference energy system assumed in the AIST-MARKAL model. Reprinted from Int. J. Hydrogen Energy, 43/39, Ozawa, A., Kudoh, Y., Murata, A., Honda, T., Saita, I., Takagi, H., Hydrogen in low-carbon energy systems in Japan by 2050: The uncertainties of technology development and implementation, 18083-94, Copyright (2018), with permission from Elsevier.

MARKAL requires exogenous parameters for (1) CO_2 mitigation targets, (2) energy service demands in each sector, (3) cost of the primary energy sources, and (4) attributes of the technologies, such as cost, efficiency, and lifespan. The parameters assumed in this analysis are explained in the following subsections.

2.2. Assumption on CO_2 mitigation target

Table 1 shows Japan's net CO_2 emissions constraints assumed in this study. According to the draft revision of Nationally Determined Contributions (commonly known as NDCs) of Japan, to mitigate total GHG emissions by 46% by 2030 from the 2013 level, CO_2 emissions from energy use must be mitigated by 45% over the same period [36]. This reduction was set as a CO_2 emission constraint by 2030. As Japan's long-term climate mitigation target, we assumed that net-zero emissions would be achieved by 2050 [2].

Table 1 Japan's net CO_2 emissions assumed in this study

Year	2010	2020	2030	2040	2050
CO_2 emissions [Mt-CO_2/yr.]	1223	994	680	340	0

2.3. Assumptions on the energy service demands and energy prices

To estimate the energy service demands, the projections of GDP, population, and households were assumed as shown in Table 2 following the assumptions of the New Energy and Industrial Technology Development Organization and the Institute of Energy Economics, Japan [37].

Table 2 GDP, population, and households assumed in this study

Year	2010	2020	2030	2040	2050
GDP (constant 2005 price) [JPY/T (USD/T)]	512 (4.65)	607 (5.51)	711 (6.45)	780 (7.08)	827 (7.50)
Population [million]	128	124	117	108	97
Households [million]	53.4	56.5	54.7	51.2	47.2

The fossil fuels prices follow the assumptions of the New Energy and Industrial Technology Development Organization and the Institute of Energy Economics, Japan [37]. The cost, insurance, and freight (CIF) prices of crude oil, coal, and liquified natural gas (LNG) were assumed to increase from 2010 to 2050 by 67%, 27%, and 34%, respectively. As for hydrogen import, we assumed that international hydrogen transport from overseas to Japan would become available by 2030. Two cases were configured for the hydrogen's CIF prices as shown in Table 3; the low-price case corresponds to Japan's basic hydrogen strategy [38].

Table 3 CIF prices of hydrogen (unit: [JPY/kg (USD/kg)])

Year	2030	2040	2050
High-price case	450 (4.1)	390 (3.6)	330 (3.0)
Low-price case	330 (3.0)	280 (2.5)	220 (2.0)

2.4. Assumptions on technologies

Most technological parameters for this analysis follow the assumptions of previous studies [12,34]. The following parameters were modified to reflect the recent progress in energy and environmental technologies. Technological parameters and cost assumptions are shown in Appendix (Tables A1 and A2).

2.4.1 Power generation costs

The current cost of power generation technologies was obtained from a cost analysis performed using a model plant method [39,40]. The future cost was estimated using Japan's cost targets [41,42] or the assumptions of the IEA World Energy Outlook 2016 [43].

2.4.2 Dispatchable power generation

Dispatchable power plants can be turned on/off, or their power output can be adjusted according to the electricity demand. These power plants can contribute to power system flexibility by filling the gap between power demand and power supply from non-dispatchable energy sources, such as variable renewable energy. To account for the need for power system flexibility in the AIST-MARKAL model, we added a constraint to the minimum share of power output by dispatchable power plants based on the results of a power-generation mix analysis [44]. We assumed that at least 30% of annual electricity generation should be obtained from thermal power plants fueled by fossil fuels, biomass, or hydrogen, according to the grid constraints in Japan.

2.4.3 Renewable power-generation capacity

The AIST-MARKAL model considers five types of renewable energy sources: solar photovoltaic (PV), wind, hydro, geothermal, and biomass energy. We configured three cases of maximum renewable power-generation capacity in Table 4 based on references [45–47].

Table 4 Maximum of renewable power-generation capacity (unit: [GW])

Year	2030			2050		
Case	Low	Middle	High	Low	Middle	High
Solar PV	77.8	102.0	150.0	221.3	248.4	300.0
Wind	21.6	28.8	32.5	21.6	50.0	70.0
Hydro	22.0	23.8	25.7	24.1	27.7	31.4
Geothermal	2.2	2.3	2.4	4.9	5.3	7.9
Biomass	5.1	6.0	6.8	5.8	6.2	7.4

2.4.4 Nuclear power-generation capacity

Because of the accident at the Fukushima Daiichi Nuclear Power Plant in 2011, Japan's Nuclear Regulation Authority reviewed the safety guidelines and regulatory requirements for commercial nuclear power reactors. The new regulatory requirements were enforced beginning on July 8, 2013, and all nuclear power plants in Japan had to stop their operation and adapt to the new regulatory requirements in order to restart the reactors. Out of the existing nuclear power plants in Japan with a combined capacity of 33.1 GW, plants with a combined capacity of 9.1 GW were in operation as of 2020. Presently, additional plants with a total capacity of 15.7 GW are at the planning stage or under construction. Considering these circumstances, we configured two cases with maximum nuclear power-generation capacity (Table 5). The low-capacity case assumes that existing plants will adopt new regulatory requirements and become available by 2025, while new plant projects would be canceled. In the high-capacity case, we assumed that both existing and newly constructed nuclear power plants would become available by 2025. In both cases, the lifespan of the nuclear power generation was set to 60 years.

Table 5 Maximum nuclear power-generation capacity (unit: [GW])

Year	2010	2020	2030	2040	2050
Low-capacity case	49.0	9.1	33.1	29.5	19.0
High-capacity case	49.0	9.1	48.8	45.2	34.7

2.4.5 CCS

Based on energy system analysis of the New Energy and Industrial Technology Development Organization and the Institute of Energy Economics, Japan [37], we assumed that process of CO_2 capture from power plants and industrial facilities (iron, steel, and cement) would be available by 2030. For each process, the CO_2 capture efficiency was set to 90%, and the cost of CO_2 transport and storage was set to 5,000 JPY/t-CO_2 (45.6 USD/t-CO_2) [37]. We also configured two cases of the upper limit of CO_2 storage (per year) from the scenario analysis conducted by the Research Institute of Innovative Technology for the Earth [48], where the upper limit was assumed to be 300 Mt-CO_2/yr. in the low-capacity case and 400 Mt-CO_2/yr. in the high-capacity case.

2.4.6 CDR technologies

We assumed that the processes of direct air capture with carbon storage (DACCS) and BECCS would be available by 2030. The properties of the direct air capture (DAC) process shown in Table 6 were set based on the cost evaluation of the DAC technology by the Center for Low-Carbon Society Strategy [49]. This process comprises two connected chemical loops that use potassium hydroxide (KOH) and calcium carbonate ($CaCO_3$), and natural gas is consumed as fuel to supply electricity and heat to the process.

Table 6 Properties of the DAC process

Property [Unit]	Value
Investment cost [JPY/t-CO_2 (USD/t-CO_2)]	20,600 (188)
Labor cost [JPY/t-CO_2 (USD/t-CO_2)]	100 (0.9)
Fuel cost [JPY/t-CO_2 (USD/t-CO_2)]	13,300 (121)
Utility cost [JPY/t-CO_2 (USD/t-CO_2)]	1,400 (13)
Fuel consumption [MJ/t-CO_2]	5966
$CaCO_3$ consumption [kg/t-CO_2]	20.5
Water consumption [kg/t-CO_2]	3199

For BECCS, we assume CO_2 capture from biomass power plants and additional costs and efficiency loss to install and operate CO_2 capture facilities (Table 7) are based on the techno-economic evaluation by the IEA Greenhouse Gas Research and Development Program [50]. This process entails post-combustion CO_2 capture technologies using monoethanolamine, and energy consumption by this process can be regarded as the efficiency loss of power plants.

Table 7 Properties of CO_2 capture process from biomass power plants

Property [Unit]	Value
Additional investment cost [JPY/MW (USD/MW)]	108 (0.98)
Additional fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	4 (0.04)
Additional variable O&M cost [JPY/MWh (USD/MWh)]	554 (4.95)
Efficiency loss [%pt.]	15.9

Note: O&M: operation and maintenance

2.5. Case settings

In this study, we configured six simulation cases (Table 8) with different combinations of maximum renewable and nuclear power-generation capacities, the upper limit of annual CO_2 storage, and CIF prices of hydrogen.

Table 8 Simulation case configurations

Case name	Maximum	Maximum	Upper	CIF prices of hydrogen

	renewable power-generation capacity (Table 4)	nuclear power-generation capacity (Table 5)	limit of annual CO_2 storage	(Table 3)
Base case	Middle	Low (19.0 GW in 2050)	Low (300 Mt-CO_2/yr.)	High (330 JPY/kg-H_2 (3.0 USD/kg-H_2) in 2050)
REN_high case	***High***	Low (19.0 GW in 2050)	Low (300 Mt-CO_2/yr.)	High (330 JPY/kg-H_2 (3.0 USD/kg-H_2) in 2050)
REN_low case	***Low***	Low (19.0 GW in 2050)	Low (300 Mt-CO_2/yr.)	High (330 JPY/kg-H_2 (3.0 USD/kg-H_2) in 2050)
NUC_high case	Middle	***High (34.7 GW in 2050)***	Low (300 Mt-CO_2/yr.)	High (330 JPY/kg-H_2 (3.0 USD/kg-H_2) in 2050)
CCS_high case	Middle	Low (19.0 GW in 2050)	***High (400 Mt-CO_2/yr.)***	High (330 JPY/kg-H_2 (3.0 USD/kg-H_2) in 2050)
H2P_low case	Middle	Low (19.0 GW in 2050)	Low (300 Mt-CO_2/yr.)	***Low (220 JPY/kg-H_2 (2.0 USD/kg-H_2) in 2050)***

3. Results

3.1. Base case results

Fig. 2 shows the transition of CO_2 emissions from energy use between 2010 and 2050 in the base case scenario. The total CO_2 emissions decrease approximately linearly after 2015 and reach zero in 2050. The breakdown of emissions indicates that the electricity sector should make a large contribution to the mitigation of CO_2 emissions in Japan. Carbon dioxide emissions from the power sector drop to nearly zero in 2040 and become negative afterward. The commercial, residential, and transportation sectors also show high reduction rates of 99.5% and 89.1%, respectively, between 2010 and 2050. On the other hand, the industrial CO_2 emissions show a low reduction rate of

29.6% in 2050 from the 2010 level. CDR technologies are required to offset the residual emissions, and 215 Mt of CO_2 will be removed by 2050 through DACCS and BECCS processes.

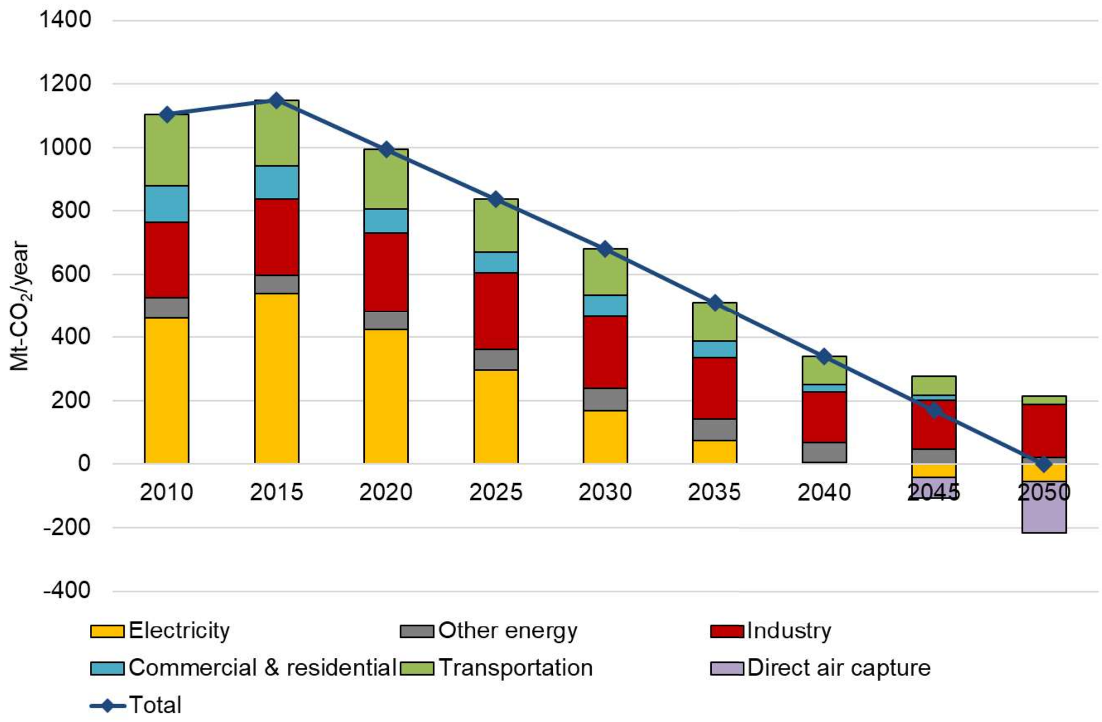

Fig. 2. Transition of energy-related CO_2 emissions in the base case scenario.

Fig. 3 shows the transition of the primary energy supply in the base case between 2010 and 2050. The total energy supply falls to 14.9 EJ in 2050, which is 27.0% lower than that in 2010, due to population decline and improvement in technical efficiency in Japan. The results indicate that the energy shift from fossil fuels to renewables and hydrogen is essential for carbon neutrality. Coal and oil show a high reduction rate of 84.8% and 71.1%, respectively, between 2010 and 2050, whereas energy supply from renewables rises to approximately 3.5 times during the same period. Hydrogen imports increase rapidly after 2040 and rise to 3.0 EJ in 2050, accounting for 20% of total energy supply.

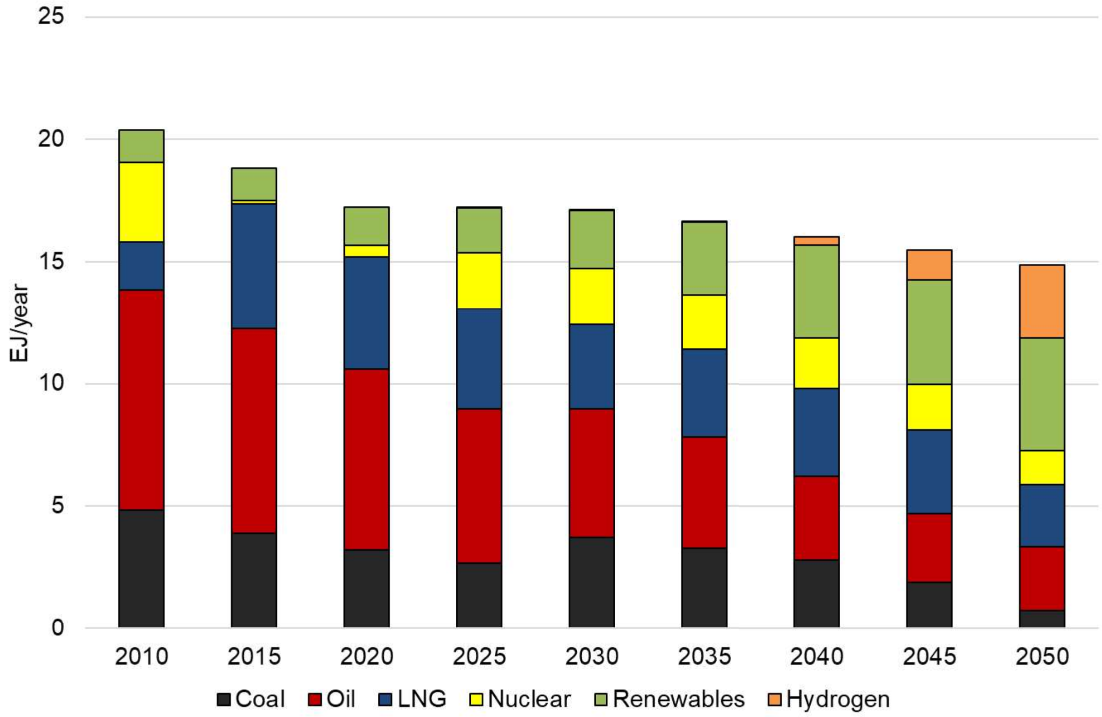

Fig. 3. Transition of primary energy supply in the base case scenario.

Fig. 4 shows the power-generation transition by source in the base case scenario between 2010 and 2050. The annual electricity demand changes from 1112 TWh in 2010 to 1047 TWh in 2050. This occurs despite advances in electrification because of a decrease in energy demand due to population decline and improvement in technical efficiency. Renewables contribute the most to decarbonizing electricity generation. Power generation from renewables grows to 2.4 times by 2030 and 3.9 times by 2050 from the 2010 levels. This raises the share of renewables in total power generation from 15% (180 TWh) in 2010 to 38% (344 TWh) in 2030 and 62% (654 TWh) in 2050. This simulation result is consistent with Japan's new Strategic Energy Plan, which was approved by the Cabinet in October 2021 [6]. Among various renewable power generation systems, the contribution of solar PV and wind power increases drastically; the installed capacities of solar PV and wind power in 2050 are 248.4 and 46.9 GW, respectively. Biomass power with CCS plays an essential role as a CDR technology in the electricity sector and generates 35 TWh of electricity in 2050. Hydrogen power generation also contributes to the decarbonization of the electricity sector. The hydrogen share of power generation increases to 25% in 2050, corresponding to an increase in hydrogen imports (Fig. 3). The results also suggest that, in this case, coal power plants without CCS should be phased out by 2035.

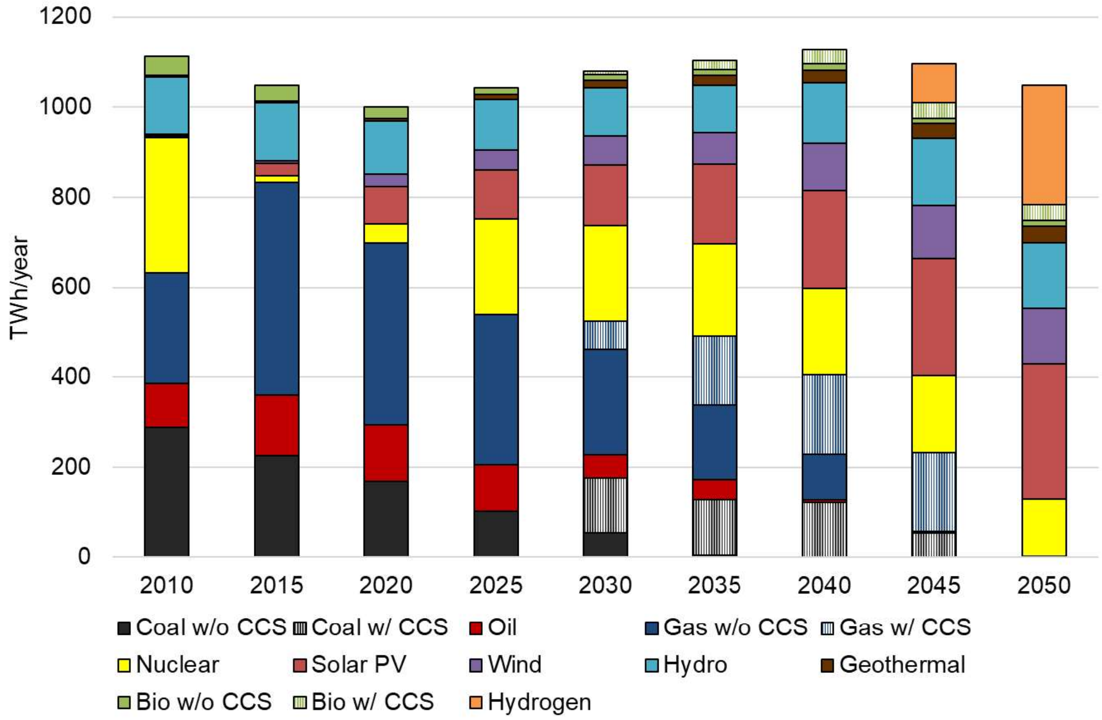

Fig. 4. Transition of power generation by sources in the base case scenario.

Fig. 5 shows the transition of the final energy consumption in the base case scenario between 2010 and 2050. The total final energy consumption trend is similar to total energy supply and falls from 14.0 EJ in 2010 to 9.7 EJ in 2050. The energy shift from fossil fuels to decarbonized electricity and hydrogen can be observed in the results. In terms of final energy consumption, the share of electricity and hydrogen increases from 27% (3.8 EJ) in 2010 to 59% (5.7 EJ) in 2050, whereas fossil fuel consumption falls drastically, and the reduction rates of coal, oil, and gas products from 2010 to 2050 are 63.5%, 63.7%, and 55.4%, respectively.

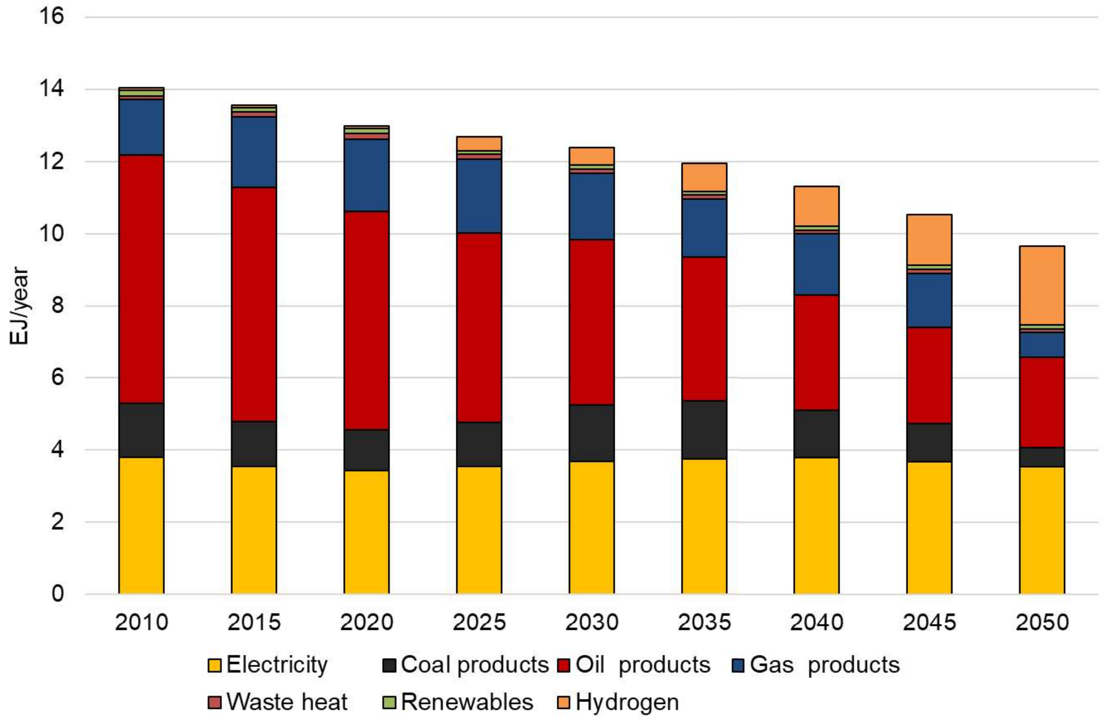

Fig. 5. Transition of final energy consumption in the base case scenario.

3.2. Comparison among different cases

Fig. 6 illustrates the CO_2 emissions in 2050 for all six cases. In the CCS_high case, the residual CO_2 emissions in 2050 are 256 Mt, which is 19% more than those in the base case. Increased emissions mainly come from the transportation sector and are offset by the DACCS process. In the CCS_high case, 7.3 Gt of CO_2 is captured from industrial facilities, power plants, or directly from the atmosphere by 2050. This accounts for ~85% of the estimated CO_2 storage capacity in Japan [51]. The results also show that the CO_2 emissions in the other four cases are similar to those in the base case.

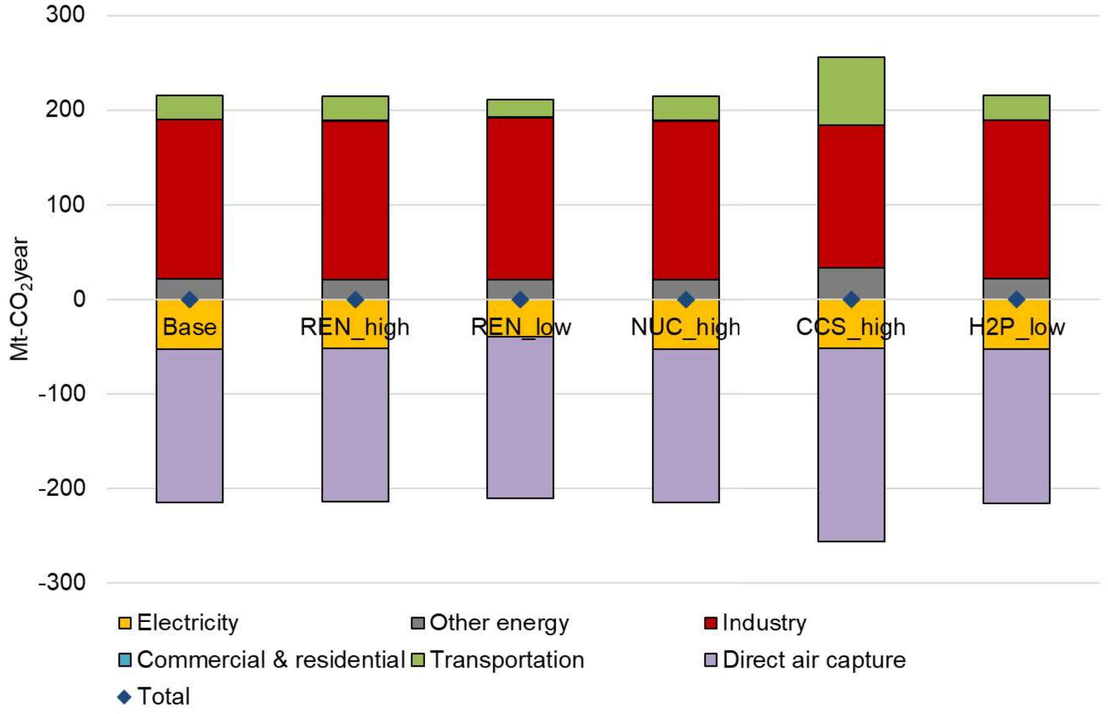

Fig. 6. Energy-related CO_2 emissions in 2050 for all six cases of this study.

The primary energy supply in 2050 for all six cases is shown in Fig. 7. The total energy supply in 2050 ranges from 14.9 to 15.7 EJ, depending on the parameter settings in each case. The results in the REN_high and REN_low cases indicate that the energy supply from renewables ranges between 3.9 and 5.2 EJ, depending on the assumptions of the maximum renewable power-generation capacity (Table 4). In the NUC_high case, 2.4 EJ of nuclear fuel is supplied in 2050, which is 79% higher than that in the base case. In the CCS_high case, the share of fossil fuels in the total energy supply is 47% in 2050, and 1.1 EJ of coal and 2.6 EJ of LNG are supplied in that year. In the H2P_low case, hydrogen imports increases to 3.8 EJ in 2050, accounting for 25% of the total energy supply.

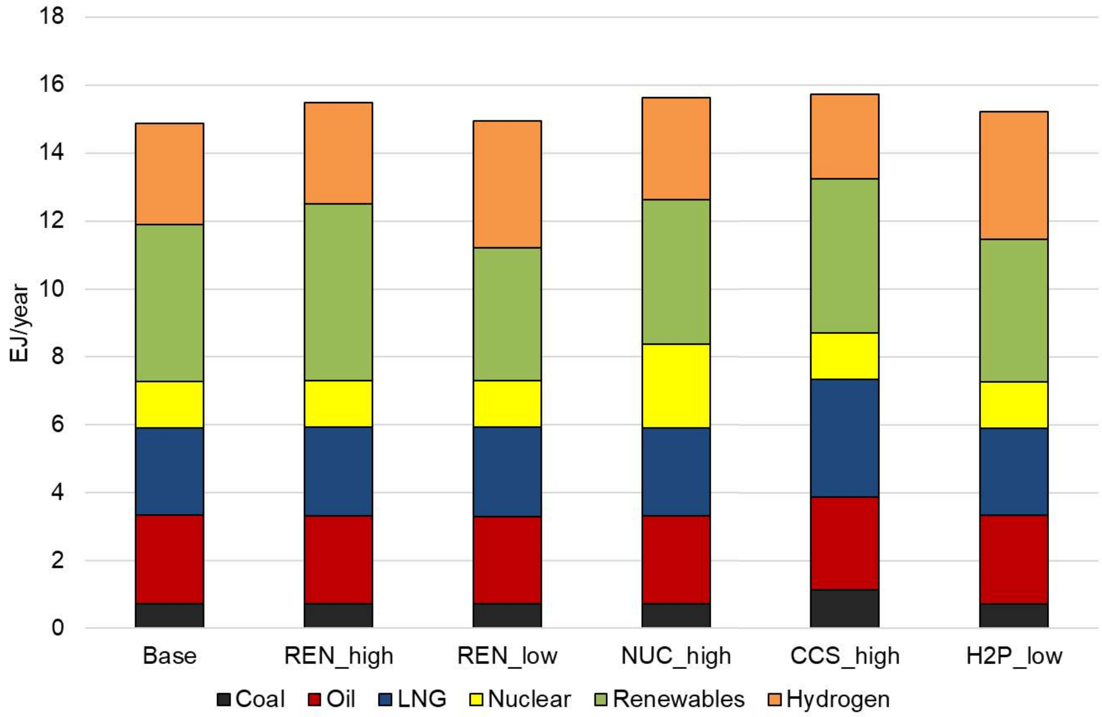

Fig. 7. Primary energy supply in 2050 for all six cases of this study.

Fig. 8 shows the power generation by source in 2050 for all six cases. The total amount of power generation ranges between 993 and 1047 TWh, and the share of renewables in total power generation ranges between 49% and 62% (510–654 TWh). The share of renewables in the REN_high case is the same as that in the base case, even though a higher maximum renewable power-generation capacity is assumed in the REN_high case. This occurs because of the constraint on the minimum share of dispatchable power generation; thermal power plants fueled by fossil fuels, biomass, or hydrogen must supply at least 30% of annual electricity generation to guarantee power system flexibility. In the NUC_high case, nuclear power supplies 22% (227 TWh) of the total amount of power generation in 2050, which affects the increase in nuclear fuel supply (Fig. 7). Hydrogen power generation acts as a dispatchable power source in the decarbonized electricity sector, and its share ranges between 23% and 38% in 2050.

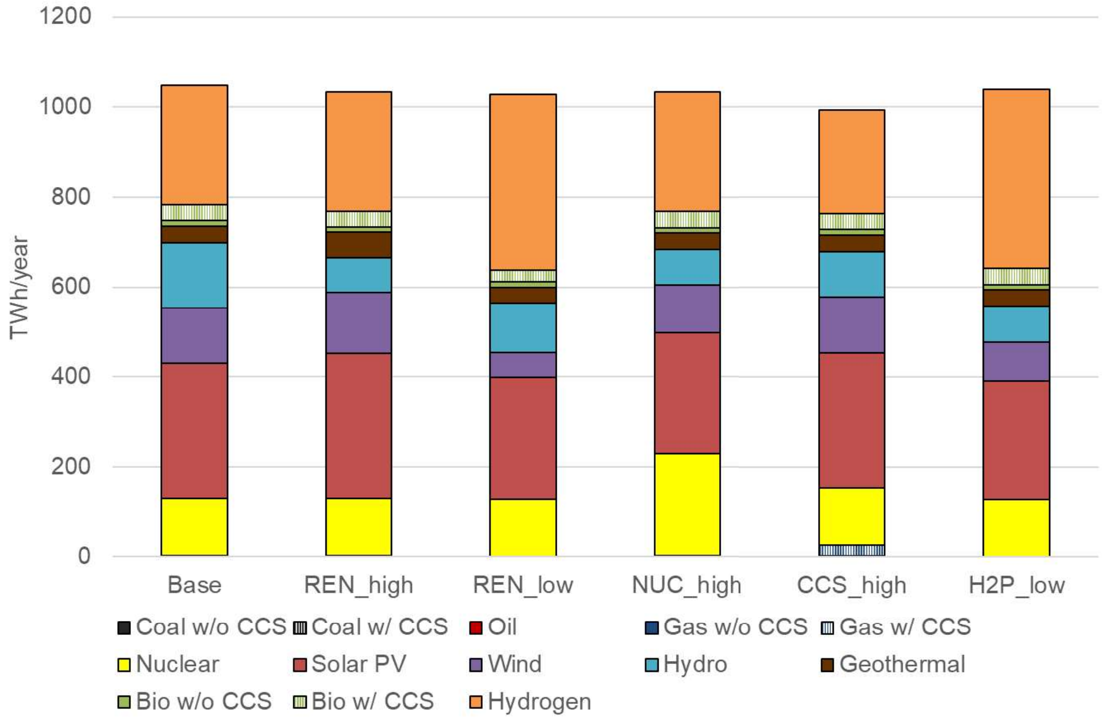

Fig. 8. Power generation by source in 2050 for all six cases of this study.

Fig. 9 shows final energy consumption in 2050 in six cases. The total final energy consumption in 2050 is 10.2 EJ in the CCS_high case and 9.6–9.7 EJ in the other five cases. Consumption of coal and gas products in the CCS_high case is 55% and 48% larger than that in the base case due to increased consumption in transportation and industry sectors.

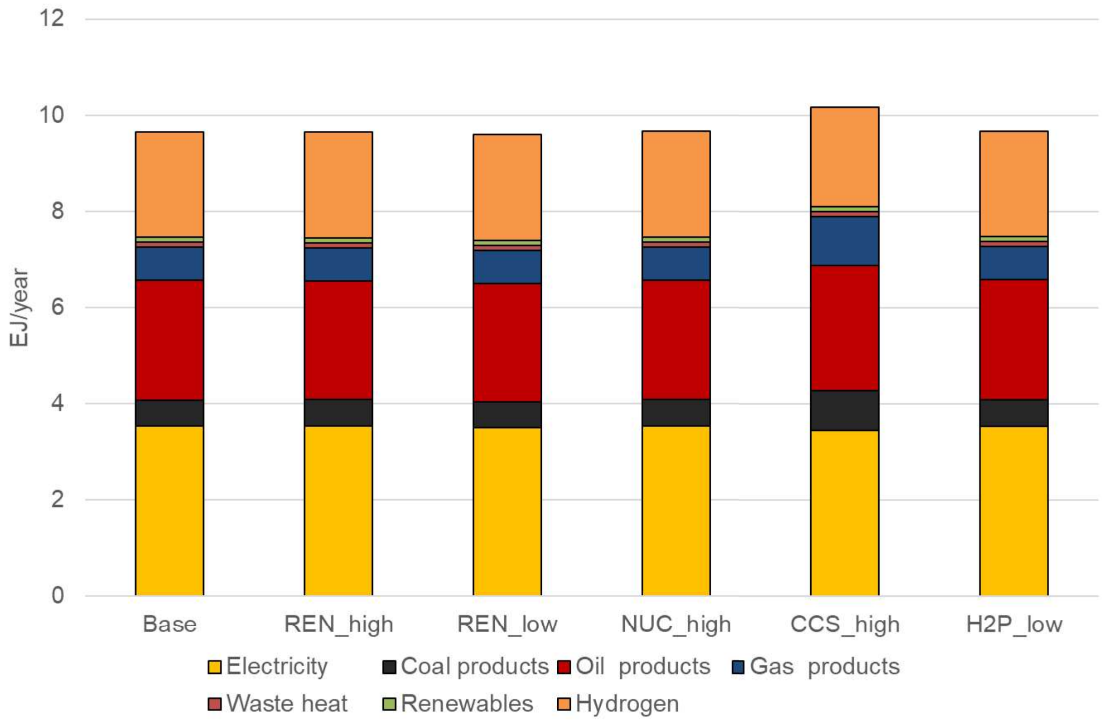

Fig. 9. Final energy consumption in 2050 for all six cases of this study.

4. Discussions

In the present study, we investigated Japan's pathways to achieve carbon neutrality by 2050 under various assumptions about future technologies. The simulation results have important implications for Japan's long-term energy transition and environmental mitigation strategies.

First, decarbonization of the electricity sector is essential for achieving net-zero emissions by 2050. The electricity sector has contributed to the highest energy-related CO_2 emissions in Japan. In FY2019, 1029 Mt of energy-related CO_2 was emitted in Japan, and 39% (396 Mt) of the emissions came from the electricity sector [52]. The transition of CO_2 emissions in the base case (Fig. 2) indicates that Japan's electric power systems should be decarbonized by 2040 to achieve net-zero emissions by 2050. In our previous study using the AIST-MARKAL model [12], we clarified that Japan need to reduce CO_2 emissions from the power sector to zero by 2050 to reduce CO_2 emissions from energy use by 80% by 2050 from the 2013 level. A comparison between the simulation results obtained in this study and our previous study implies that the electricity sector should achieve zero emissions 10 years earlier in order to achieve the necessary state of carbon neutrality than aim to reduce CO_2 by 80% by 2050.

Second, decarbonized electricity systems should comprise various low-carbon energy sources (i.e., renewables, nuclear power, fossil fuels with CCS, and hydrogen). As shown in Fig. 4 and Fig. 8, renewables will become the main power source in future electricity systems, accounting for 49–62% of the total power generation in 2050. Renewable power will generate up to 650 TWh in 2050, almost double that of 80% CO_2 reduction scenario. The simulation results also highlight the importance of solar PV and wind power generation. In the base case, the solar PV and wind power capacity in 2050 becomes 4.5 and 11.2 times the current capacities, respectively. "Research, development, and demonstration" for advanced renewable power technologies (e.g., offshore wind farms and innovative solar panels) is necessary to expand renewable power-generation capacity in Japan. Ensuring power system flexibility is also important to enhance renewable energy penetration, and fossil fuels with CCS, biomass, and hydrogen will serve as a dispatchable power source in the decarbonized electricity sector. Among them, hydrogen power will play a dominant part in decarbonized dispatchable power plants, because the share of fossil fuels with CCS and biomass power is limited due to domestic CCS storage capacities and biomass resources, respectively. The results in Fig. 7 show that the hydrogen share in 2050 increased to 38% when the CIF price of hydrogen imported to Japan was low (H2P_low case). This implies that reducing hydrogen import costs is crucial for hydrogen utilization in Japan's electricity sector. In Japan's basic hydrogen strategy [38], establishing an international hydrogen supply chain is considered as an essential component of a hydrogen economy because it can reduce the procurement costs of low-carbon hydrogen produced from overseas. Demonstration projects have been conducted, with the aim of the establishing international hydrogen supply chains economic transport using different hydrogen energy carriers [53–55]. If hydrogen import costs cannot be reduced despite these efforts, the contribution of fossil fuel with CCS and biomass power becomes more important. This will require further efforts including developing CCS overseas and importing biomass resources. Another important finding from the simulation is that coal-fired power plants without CCS will be phased out by 2035.Following the Fukushima Daiichi Nuclear Power Plant accident in 2011, power generation companies began using coal-fired power plants to compensate for the closure of nuclear power reactors.

Hence, in Japan, coal-fired power plants with 3.0 GW capacity have operated since 2012, and new plants with 8.7 GW capacity are currently under construction in Japan. The simulation results further suggest that these newly constructed coal-fired power plants should be "CCS ready" or "ammonia ready"; i.e., they should be designed to apply CCS retrofit [56] or ammonia co-firing [57].

Third, reducing CO_2 emissions in the industry sector is more complicated than in other sectors. Industrial decarbonization is considered a global challenge for achieving carbon neutrality [10,11]. Japan retains a strong presence of heavy industry, which mostly consumes fossil fuels, and 279 Mt of CO_2 is emitted by the industrial sector in FY2019 [52]. In the base case (Fig. 2), industrial CO_2 emissions are 168 Mt in 2050, which accounts for 78% of the residual emissions in that year. This result suggests that over two-thirds of industrial CO_2 emissions will remain until 2050, implying the difficulty of industrial decarbonization. This finding is similar to the simulation results obtained using other energy models [58,59]. Some promising technologies can reduce CO_2 emissions from the industrial sector, such as CCS and hydrogen used in steelmaking processes [60,61], carbon capture and utilization, and biomass use in the chemical industry [62]; however, their costs are considerably higher than those of conventional processes. Technological innovations in manufacturing processes are required to achieve industrial decarbonization economically [63].

Fourth, CDR should work as a backstop technology in carbon-neutral energy systems. As shown in Fig. 6, 211–256 Mt of CO_2 will be removed by 2050 using DACCS and BECCS to offset the residual emissions and achieve net-zero emissions. Because the captured amount of CO_2 from the atmosphere is almost the same as the amount of CO_2 emitted from the industry, CDR technology, especially DAC, becomes necessary when industrial decarbonization is difficult, as was assumed in this study. Dependency on CDR can be decreased if Japan can reduce industrial CO_2 emissions. The results in Fig. 6 also indicate that the total amount of CO_2 to be removed by 2050 will increase when the upper limit of annual CO_2 storage is high (CCS_high case). Here, over 85% of Japan's promising CO_2 storage potential will be occupied by 2050. This implies that Japan cannot rely only on domestic CCS in the long term to achieve carbon neutrality. Therefore, cooperation with foreign countries to explore CCS opportunities or to implement other CDR technologies will be necessary to sustain carbon neutrality in Japan beyond 2050 [64].

The simulation results have highlighted the importance of the breakthrough in energy and environmental technologies, such as low-carbon power generation, industrial decarbonization, and CDR. We have also evaluated the interrelationships between the energy and environmental technologies. The results indicate that the contribution of each technology in carbon-neutral energy systems in Japan may depend on the status of other technologies. These findings can provide useful information for policymakers who must decide the future directions of energy and environmental strategies of Japan. In this study, we have investigated the influence of uncertainties from a technological aspect. However, other factors, such as socioeconomic factors (e.g., future population and GDP) that can affect the final energy demand and energy transition, remain uncertain. In future work, we plan to analyze the energy transition toward establishing carbon-neutral energy systems in Japan under different socioeconomic assumptions. We will also assess carbon-neutral energy systems in Japan based on various criteria including domestic energy prices which can affect Japan's economy.

5. Conclusion

In this study, we investigated Japan's pathways to achieve carbon neutrality in 2050 using an energy system model developed by the AIST. To assess the uncertainties associated with the breakthrough in energy and environmental technologies in the future, energy system analyses were conducted for six cases assuming different parameter settings for renewable and nuclear power, CCS, and hydrogen import.

The simulation results suggest that carbon neutrality by 2050 can be achieved by using all low-carbon technologies; further the electricity sector of Japan should achieve full decarbonization by 2040 if Japan is to achieve carbon neutrality by 2050. From this perspective, renewable energies should be dominant in the decarbonized electricity sector in Japan, along with other low-carbon technologies such as CCS, nuclear power, and hydrogen. The simulation results also indicated that the industry sector would face difficulties in reducing CO_2 emissions, and that CDR will be required in order to have to offset the residual emissions and achieve net-zero emissions. Over 200 Mt of CO_2 should be removed using the DACCS and BECCS processes by 2050.

The results showed multiple potential scenarios for achieving carbon neutrality in Japan by 2050 by focusing on the contribution of technological breakthrough to the long-term energy transition. Our future work will evaluate the effects of other parameters on energy systems. For instance, significant uncertainty remains about the contribution of natural carbon sinks (e.g., afforestation and land-use change) to carbon neutrality, which was not discussed in this study. Further, socioeconomic factors are also important in achieving carbon neutrality; assumptions on population and economic growth rate can significantly affect future energy demand, hence these should be investigated in future studies. We will also assess the effect of energy transition on domestic energy price, which is expected to affect the long-term competitiveness of the Japanese industry.

Author Contributions

Akito Ozawa: Conceptualization, methodology, data curation, software, investigation, visualization, writing–original draft, and funding acquisition. Tsamara Tsani: Data curation software. Yuki Kudoh: Writing - review & editing, and supervision.

Declaration of Competing Interest

None.

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Appendix

Table A1 Technological parameters on power generation technologies

Source	Type	Lifespan [year]	Availability factor/ capacity factor	Year available
Coal	Steam turbine	40	70%	< 2010
	Integrated gasification	40	70%	2020

	combined cycle (IGCC)			
	Integrated gasification fuel cell cycle (IGFC)	40	70%	2030
	Steam turbine with CCS	40	70%	2030
	IGCC with CCS	40	70%	2030
	IGFC with CCS	40	70%	2030
Oil	Steam turbine	40	23%	< 2010
Gas	Steam turbine	40	70%	< 2010
	Combined cycle	40	70%	< 2010
	Combined cycle with CCS	40	70%	2030
Nuclear	Light water reactor	60	60-70%	< 2010
Solar PV	Residential (< 10kW)	25	12%	< 2010
	Commercial and utility-scale (> 10kW)	25	16%	< 2010
Wind	Onshore	25	23-30%	< 2010
	Bottom-mounted offshore	25	30%	2020
	Floating offshore	25	30%	2020
Hydro	Mid- to large-scale (> 1MW)	60	55%	< 2010
	Small-scale (< 1MW)	60	55%	< 2010
Geothermal		40	80%	< 2010
Biomass	Waste	40	70-85%	< 2010
	Wood	30	80-87%	< 2010
	Recycled wood	30	80-87%	< 2010
	Wood with CCS	30	80-87%	2030
Hydrogen	Combined cycle	40	70%	2025

Table A2 Cost assumptions on power generation technologies

Source	Type	Property [Unit]	2010	2020	2030	2040	2050
Coal	Steam turbine	Investment cost [JPY/MW (USD/MW)]	230 (2.1)	250 (2.28)	250 (2.28)	250 (2.28)	250 (2.28)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	12 (0.11)	10 (0.09)	10 (0.09)	10 (0.09)	10 (0.09)

		Variable O&M cost [JPY/MWh (USD/MWh)]	565 (5.15)	565 (5.15)	565 (5.15)	565 (5.15)	565 (5.15)
	IGCC	Investment cost [JPY/MW (USD/MW)]		288 (2.62)	288 (2.62)	288 (2.62)	288 (2.62)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]		12 (0.11)	12 (0.11)	12 (0.11)	12 (0.11)
		Variable O&M cost [JPY/MWh (USD/MWh)]		497 (4.53)	497 (4.53)	497 (4.53)	497 (4.53)
	IGFC	Investment cost [JPY/MW (USD/MW)]			320 (2.92)	320 (2.92)	320 (2.92)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]			12 (0.11)	12 (0.11)	12 (0.11)
		Variable O&M cost [JPY/MWh (USD/MWh)]			497 (4.53)	497 (4.53)	497 (4.53)
	Steam turbine with CCS	Investment cost [JPY/MW (USD/MW)]			348 (3.17)	348 (3.17)	348 (3.17)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]			21 (0.19)	21 (0.19)	21 (0.19)
		Variable O&M cost [JPY/MWh (USD/MWh)]			565 (5.15)	565 (5.15)	565 (5.15)
	IGCC with CCS	Investment cost [JPY/MW (USD/MW)]			316 (2.88)	316 (2.88)	316 (2.88)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]			18 (0.16)	18 (0.16)	18 (0.16)
		Variable O&M cost [JPY/MWh (USD/MWh)]			497 (4.53)	497 (4.53)	497 (4.53)
	IGFC with CCS	Investment cost [JPY/MW (USD/MW)]			348 (3.17)	348 (3.17)	348 (3.17)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]			18 (0.16)	18 (0.16)	18 (0.16)
		Variable O&M cost [JPY/MWh (USD/MWh)]			497 (4.53)	497 (4.53)	497 (4.53)
Oil	Steam turbine	Investment cost [JPY/MW	190	200	200	200	200

		(USD/MW)]	(1.73)	(1.82)	(1.82)	(1.82)	(1.82)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	10 (0.09)	6 (0.05)	6 (0.05)	6 (0.05)	6 (0.05)
		Variable O&M cost [JPY/MWh (USD/MWh)]	1854 (16.89)	1854 (16.89)	1854 (16.89)	1854 (16.89)	1854 (16.89)
Gas	Steam turbine	Investment cost [JPY/MW (USD/MW)]	171 (1.56)	171 (1.56)	171 (1.56)	171 (1.56)	171 (1.56)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	9 (0.08)	9 (0.08)	9 (0.08)	9 (0.08)	9 (0.08)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Combined cycle	Investment cost [JPY/MW (USD/MW)]	120 (1.09)	120 (1.09)	120 (1.09)	120 (1.09)	120 (1.09)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	6 (0.05)	4 (0.04)	4 (0.04)	4 (0.04)	4 (0.04)
		Variable O&M cost [JPY/MWh (USD/MWh)]	281 (2.56)	266 (2.43)	252 (2.3)	252 (2.3)	252 (2.3)
	Combined cycle with CCS	Investment cost [JPY/MW (USD/MW)]			164 (1.49)	164 (1.49)	164 (1.49)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]			14 (0.13)	14 (0.13)	14 (0.13)
		Variable O&M cost [JPY/MWh (USD/MWh)]			252 (2.3)	252 (2.3)	252 (2.3)
Nuclear	Light water reactor	Investment cost [JPY/MW (USD/MW)]	350 (3.19)	370 (3.37)	370 (3.37)	370 (3.37)	370 (3.37)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	25 (0.23)	19 (0.17)	19 (0.17)	19 (0.17)	19 (0.17)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Solar PV	Residential (< 10kW)	Investment cost [JPY/MW (USD/MW)]	496 (4.52)	300 (2.73)	200 (1.82)	200 (1.82)	200 (1.82)
		Fixed O&M cost [JPY/MW/yr.	8 (0.07)	3 (0.03)	3 (0.03)	3 (0.03)	3 (0.03)

		(USD/MW/yr.)]					
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Commercial and utility-scale (> 10kW)	Investment cost [JPY/MW (USD/MW)]	450 (4.1)	200 (1.82)	100 (0.91)	100 (0.91)	100 (0.91)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	16 (0.15)	3 (0.03)	3 (0.03)	3 (0.03)	3 (0.03)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Wind	Onshore	Investment cost [JPY/MW (USD/MW)]	275 (2.51)	271 (2.47)	246 (2.24)	246 (2.24)	246 (2.24)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	15 (0.14)	5 (0.05)	4 (0.04)	4 (0.04)	4 (0.04)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Bottom-mounted offshore	Investment cost [JPY/MW (USD/MW)]		425 (3.87)	246 (2.24)	246 (2.24)	246 (2.24)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]		5 (0.05)	4 (0.04)	4 (0.04)	4 (0.04)
		Variable O&M cost [JPY/MWh (USD/MWh)]		0 (0)	0 (0)	0 (0)	0 (0)
	Floating offshore	Investment cost [JPY/MW (USD/MW)]		708 (6.45)	579 (5.28)	579 (5.28)	579 (5.28)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]		26 (0.24)	10 (0.09)	10 (0.09)	10 (0.09)
		Variable O&M cost [JPY/MWh (USD/MWh)]		0 (0)	0 (0)	0 (0)	0 (0)
Hydro	Mid- to large-scale (> 1MW)	Investment cost [JPY/MW (USD/MW)]	850 (7.74)	640 (5.83)	640 (5.83)	640 (5.83)	640 (5.83)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	23 (0.21)	9 (0.08)	9 (0.08)	9 (0.08)	9 (0.08)
		Variable O&M cost	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

		[JPY/MWh (USD/MWh)]					
	Small-scale (< 1MW)	Investment cost [JPY/MW (USD/MW)]	900 (8.2)	881 (8.03)	875 (7.97)	875 (7.97)	875 (7.97)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	82 (0.75)	71 (0.65)	71 (0.65)	71 (0.65)	71 (0.65)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Geothermal		Investment cost [JPY/MW (USD/MW)]	800 (7.29)	790 (7.2)	790 (7.2)	790 (7.2)	790 (7.2)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	46 (0.42)	33 (0.3)	33 (0.3)	33 (0.3)	33 (0.3)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Biomass	Waste	Investment cost [JPY/MW (USD/MW)]	356 (3.24)	304 (2.77)	291 (2.65)	284 (2.59)	284 (2.59)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	19 (0.17)	22 (0.2)	21 (0.19)	19 (0.17)	19 (0.17)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Wood	Investment cost [JPY/MW (USD/MW)]	410 (3.74)	390 (3.55)	373 (3.4)	365 (3.33)	365 (3.33)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	38 (0.35)	25 (0.23)	25 (0.23)	24 (0.22)	24 (0.22)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Recycled wood	Investment cost [JPY/MW (USD/MW)]	350 (3.19)	343 (3.13)	328 (2.99)	321 (2.92)	321 (2.92)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]	34 (0.31)	25 (0.23)	25 (0.23)	24 (0.22)	24 (0.22)
		Variable O&M cost [JPY/MWh (USD/MWh)]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Wood with CCS	Investment cost [JPY/MW (USD/MW)]			481 (4.38)	473 (4.31)	473 (4.31)

		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]			29 (0.27)	28 (0.26)	28 (0.26)
		Variable O&M cost [JPY/MWh (USD/MWh)]			544 (4.95)	544 (4.95)	544 (4.95)
Hydrogen	Combined cycle	Investment cost [JPY/MW (USD/MW)]			120 (1.09)	120 (1.09)	120 (1.09)
		Fixed O&M cost [JPY/MW/yr. (USD/MW/yr.)]			4 (0.04)	4 (0.04)	4 (0.04)
		Variable O&M cost [JPY/MWh (USD/MWh)]			252 (2.3)	252 (2.3)	252 (2.3)

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