Net Zero Japan 2050
—Summary for Business Leaders—

Interim Report on Decarbonization Scenarios for 2050

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June 2023

This report was sponsored by ETI-CGC (an industry-academia collaborative platform established by the University of Tokyo and Japanese business leaders to discuss pathways for Net Zero in Japan) and is intended to stimulate active climate change discussions by publishing the interim results of research activities conducted by Center for Global Commons at the University of Tokyo. The analysis results and views expressed here will be updated in light of future research activities. This report is published under the responsibility of Center for Global Commons and the authors, and does not represent the views of sponsors of ETI-CGC.
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1. Significance of developing Net Zero Japan 2050 Scenarios

In order to keep global temperature rise below 1.5°C from pre-industrial levels, the world must work together and overcome numerous daunting challenges to achieve Net Zero. In close collaboration with Japanese business leaders, the University of Tokyo's Center for Global Commons (CGC) established the Energy Transition Initiative – Center for Global Commons (ETI-CGC). The initiative aims to develop pathways, from a scientific perspective, not only for transforming Japan's energy system but also for creating the economic and social systems that can lead to a prosperous future.

As the first step in this process, the CGC has developed the Net Zero Japan 2050 Scenarios, quantitative scenarios of energy systems that can achieve Net Zero by 2050, and presents them in this interim report, called Summary for Business Leaders While the Basic Policy for the Realization of GX prepared by the Japanese government adopt a forecasting approach for the next 10 years, and are not necessarily explicit on how Net Zero will be achieved by 2050 through the integration of efforts in each sector, this report aims to quantitatively present an overall picture of an energy system for Japan that can achieve Net Zero by 2050. It serves as a foundation for realizing future efforts for Net Zero through a backcasting approach. Considering Japan has relatively difficult geographical conditions that do not make it easy to apply a large scale of renewable energy at low cost and has heavy industries that require the development of innovative technologies beyond clean electricity for decarbonization, the scenarios demonstrates that it is possible to achieve Net Zero in Japan by 2050 through a combination of scientifically recognized approaches: promoting electrification to shift from consumption of fossil fuels to electricity; massive introduction of renewable energy; large-scale introduction of hydrogen, ammonia, and other CO2-free fuels; utilization of nuclear power; and deployment of CO2 capture and storage within the feasible extent. On the other hand, the scenarios clearly highlight the necessity for drastic transitions that are technically feasible but cannot be realized without exceptional levels of policy and investment. These include large-scale electrification in the building and transportation sectors, the introduction of several- to ten-times the current amount of renewable energy (solar and wind), and the procurement of CO2-free hydrogen, with an estimated annual demand of approximately 20 to 40 million tons for both for power generation and direct use.

These scenarios present some of the possible scenarios that could achieve Net Zero for Japan by 2050, and it is important to continue exploring desirable ones among diverse possibilities. In addition, the analysis of each sector involves various assumptions and should be updated with future technological developments. The scenarios do not aim to accurately predict the energy system of the future, but rather to clarify the scale and pace of transitions toward Net Zero in the future by backcasting from the energy system in 2050 through scientific and quantitative discussions and to identify bottlenecks and priority targets for action. The overall picture of the quantitative energy system presented by the Net Zero Japan 2050 Scenarios identifies the technologies that should be drastically accelerated for social implementation and the industrial sectors in which new technological development is required for decarbonization. The ETI-CGC hopes that the development of these scenarios will stimulate a broad discussion on the most effective and practical economic pathways to achieve Net Zero and lead to recommendations for priority targets for technology development and social implementation in each industrial sector, as well as policies and investments to realize the transition.

2. Key messages from the Net Zero Japan 2050 Scenarios

This Summary for Business Leaders gives an overview of the interim results of the Net Zero Japan 2050 Scenario analysis. The key implications that emerged through the analysis are as follows.

- Even under Japan's constraints such as limited renewable energy generation potential capacity and heavy industries that are considered technically difficult to decarbonize, Japan's energy system can technically and economically achieve Net Zero. By promoting globally-acknowledged decarbonization measures such as electrification and conversion to carbon-free fuels in all sectors, it is possible to keep energy costs at a reasonable level without discontinuous changes from the current industrial structure.
- Supply of CO2-free energy to achieve Net Zero will rely on a well-balanced energy mix that combines (1) renewable electricity (mainly solar and wind power), (2) CO2-free fuels (primarily from hydrogen and ammonia), and (3) nuclear power. There are various possible approaches to this combination, and it will be necessary to further explore the optimal mix for Japan, taking into consideration the potential of each energy supply source, social acceptance, etc.
- Diversity and resilience of energy sources will be further enhanced if a sufficient supply of carbon-neutral fuels (biofuels, synfuels derived from captured CO2, and other life-cycle carbon-neutral fuels; hereafter “CN fuels”) can be secured through technological progress that does not compete with food production or damage biodiversity. These energy sources should primarily be used for high-priority applications, taking into account the difficulty of energy conversion and their contribution to resilience.
- To realize CO2-free energy supply, the current energy system, which relies heavily on the direct use of fossil fuels, must be transformed to a new system that uses an optimal combination of electricity, hydrogen/ammonia, and CN fuels. This requires a fundamental transformation of social infrastructure, which in turn urgently requires the advancement of technological development, policy, and investment. It is necessary to further clarify the specifics of these recommendations through future analysis and put them into prompt actions.
- Even if the use of fossil resources can be minimized by 2050, the consumption of fossil fuels will not be eliminated. When using fossil resources, combination with carbon capture and storage (CCS) and carbon capture and utilization (CCU), whereby the conversion of CO2 captured using renewable energy into hydrocarbons, to a limited extent will play an important role.

3. Overview of the Net Zero Japan 2050 Scenarios

a. CO2-free energy supply

There are four main energy sources that can both supply energy to meet the demands of Japanese society and achieve Net Zero in 2050.

(1) Renewable energy from solar, wind, etc.

(2) Nuclear power
(3) CO2-free hydrogen and ammonia
(4) Biofuels and synfuels (Carbon Neutral (CN) fuels)

How to balance these sources in accordance with Japan's situation will be determined based on technological progress and social acceptability, including cost, available supply, safety, etc. On the other hand, in order to support truly sustainable economic activity, regenerative energy sources that can be used in perpetuity without placing a burden on the earth over the long term are essential. Continued use of fossil resources combined with CCS is partly inevitable, especially in the industrial sector, as a realistic option to achieve Net Zero by 2050. However, there is a limit to the amount of CO2 that can be treated by CCS due to geographical restrictions and other factors, so it is necessary to limit the use of CCS to a reasonable and effective extent in the scenarios, giving priority to sectors where CO2 emission reductions are technically difficult.

As summarized in Table **1** below, each of the four main CO2-free energy sources assumed in the 2050 Net Zero scenarios has various challenges (technical, economic, and social acceptability) as well as advantages. Depending on the form of energy use in each sector (e.g., electrification, viability of fuel conversion to hydrogen, etc.), it is necessary to consider the optimal energy mix while taking into account the advantages and disadvantages of each energy source. With regard to matters such as offshore wind power and the cost of CO2-free hydrogen, it is expected that focused investment will further reduce costs by stimulating technological development and mass implementation. On the other hand, social acceptability may be a limiting factor with respect to the introduction of large solar power facilities on land or the massive construction of new nuclear power plants, and such constraints need to be considered in the scenarios.

Table 1 Energy sources that can achieve Net Zero

CO2-free energy source	Advantages	Challenges to overcome
Solar and wind power generation	Large-scale introduction possible	Power generation fluctuations (inevitable in principle) Location constraints (including control of rights) High cost of offshore wind
Nuclear power generation	Large volume and stable supply	Not expected to be a balancing power Location constraints and disposal of nuclear fuel Social acceptability
CO2-free hydrogen and ammonia	Necessary for fuel applications Power generation with balancing power	Low-cost, high-volume procurement (imported from overseas) Difficult to stockpile for long periods (except for organic hydride)
Biofuels and synfuels (CN fuel)	Liquid fuel that is easy to transport and stockpile	Limited supply available More energy required to produce synfuel than hydrogen

b. Scenarios combining CO2-free energy sources

There can be multiple energy scenarios that use a combination of the four CO2-free energy sources to achieve Net Zero. In this analysis, these scenarios were classified based on the energy source maximally utilized, and four typical cases of scenario were analyzed: (1) maximum utilization of renewable energy, (2) maximum utilization of hydrogen, (3) maximum utilization of nuclear power in addition to renewable energy and hydrogen, and (4) maximum utilization of CN fuel.

In all scenarios, electrification is promoted in buildings and all other sectors. In Scenario (1) and (3) in particular, thorough electrification is essential to maximize the use of renewable and nuclear power generation. Also, in Scenario (2), a considerable amount of energy demand must be supplied by renewable electricity, and large-scale promotion of electrification will be essential because it is difficult to replace all current fossil fuel use with hydrogen. Therefore, this analysis makes the following assumptions: Scenario (1), (2), and (3) assume the maximum possible electrification; Scenario (1) assumes that solar and wind power generation are introduced in large quantities without any constraint on the amount of electricity available (the maximum amount that can be introduced in the vicinity of Japan) and that the discrepancy with electricity demand is managed through active use of storage batteries. Scenario (2) assumes that CO2-free hydrogen and ammonia procured from overseas is used in large quantities for thermal power generation as balancing power because the introduction of solar/wind power generation and storage batteries is subject to the limitations of potential capacity and high cost. Scenario (1) and (2) assume that nuclear power generation capacity has a 60-year lifespan and no new construction to take place, while Scenario (3) assumes that nuclear power generation is actively utilized while considering life extension, replacement, and new construction of generation facilities. In Scenario (4), it would be relatively easy to replace most of the current fossil fuel use with CN fuels, but it would be difficult to supply CN fuels in as large a quantity as the current fossil fuels, so a considerable push in electrification would still be necessary, although not as great as in Scenario (1) through (3).

The level of difficulty in promoting such electrification varies by sector. There are clear prospects for the technology required for electrification of the building sector, and the task will be to promote its implementation in society. With respect to mobility, the electrification of light passenger vehicles is almost within reach, but there are significant technical hurdles for the electrification of heavy commercial vehicles, especially ships and aircraft, making the use of hydrogen and CN fuels likely necessary for these. In heavy industry, there are several processes that makes substantial electrification very difficult. Therefore, in sectors such as steel, chemical, and cement manufacturing, it will be necessary to continue to use fossil resources in conjunction with CCS, while waiting for innovative technological developments to enable electrification, and attempting maximum conversion to hydrogen and ammonia.

The most desirable scenario among Scenario (1) through (4) for Japan should be determined by considering various socioeconomic criteria. Additionally, another essential factor is whether a viable pathway can be drawn to realize the scenario. Taking the above into consideration, the vision of society that we should target for 2050 may lie somewhere between these Scenarios.

Table 2 Four energy scenarios classified based on the energy source maximally utilized

<table>
<tr><th colspan="2">Scenario classification</th><th>(1) Renewable energy[1] utilization</th><th>(2) Hydrogen[2] utilization</th><th>(3) Renewable energy or hydrogen & nuclear power utilization</th><th>(4) CN fuel[3] utilization</th></tr>
<tr><td rowspan="3">Energy conversion policy by sector</td><td>Buildings</td><td colspan="3">Maximum electrification</td><td>Electrification + CN fuel</td></tr>
<tr><td>Mobility</td><td colspan="3">BEVs, hydrogen for heavy vehicles, CN fuel for aircrafts, etc.</td><td>PHEV using CN fuel
Hydrogen for heavy vehicles
CN fuel for aircraft, etc.</td></tr>
<tr><td>Industry</td><td colspan="4">Fossil resources for use together with electrification, conversion to hydrogen, and CCS (limited use)</td></tr>
<tr><td rowspan="3">Power supply[4]</td><td>Renewable energy</td><td>High potential capacity, low cost</td><td>Low potential capacity, high cost</td><td>Low/high potential capacity, low/high cost</td><td>Low potential capacity, high cost</td></tr>
<tr><td>Nuclear power</td><td colspan="2">60-year lifespan, no new construction</td><td>Lifespan extension, replacement, and new construction[5]</td><td>60-year lifespan, no new construction</td></tr>
<tr><td>Hydrogen-fired thermal power</td><td colspan="4">Provide the balancing power and that renewable energy and nuclear power cannot and compensating for shortfalls</td></tr>
<tr><td colspan="2">Considered scenario # (see below)</td><td>Scenario 7-a</td><td>Scenario 1-a</td><td>Scenario 1-c/7-c</td><td>(Further investigation planned)</td></tr>
</table>

BEV: Battery Electric Vehicle, PHEV: Plug in Hybrid Electric Vehicle

c. Energy demand in 2050

In order to envision an energy system for 2050, it is first necessary to quantify energy demand. The starting point for scenario development is to quantify energy demand for each sector, building assumptions of the scale of activity, product demand, and technological innovation in that sector. This analysis did not consider abrupt socioeconomic system shifts. Instead, it estimated energy demand by assuming the utilization of decarbonization technologies expected in 2050 for each sector. The analysis hypothesized a business-as-usual case in which the current foundation of economic activity and industrial structure continues. It considered a decrease in demand proportional to population decline (about 20%), increase in energy efficiency associated with electrification (especially mobility), progress in recycling (chemical industry and steel), and a mild decline in exports (steel).

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[1] Electricity generated mainly from solar and wind power

[2] CO2-free hydrogen and ammonia procured mainly from overseas

[3] Synfuels produced from biofuels and recovered CO2 (utilized within the constraints of production potential)

[4] Obtained by optimal calculation minimizing power system cost (equipment) with the power supply-demand balance (hourly) within the nine regions of Japan as a condition

[5] Assumed generation capacity to be examined in more detail

Key assumptions for each sector in the decarbonization scenarios are summarized below.

(1) Buildings — heating

Heating-related energy demand is assumed to decrease by 30% from 2019 as a result of a decrease in energy demand due to population decline, improved insulation, increased energy efficiency through electrification (use of heat pumps), and an increase in demand due to improved living standards. It is assumed that hydrogen fuel cells will be used in some environments where use of heat pumps is difficult.

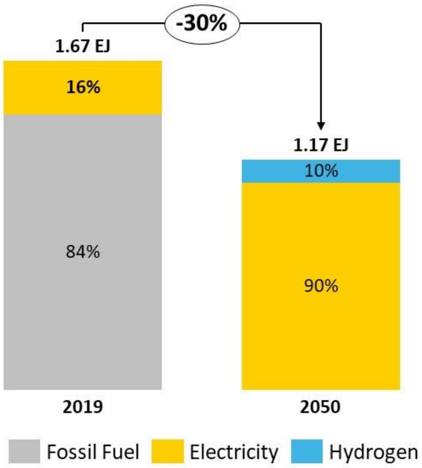


Figure 1 Final energy demand (EJ) — buildings (heating)

(2) Buildings — non-heating

Energy demand is assumed to decrease by 19% due to population decline and by 10% due to improved energy efficiency, and 100% electrification is assumed to be achieved through thorough promotion of electrification.

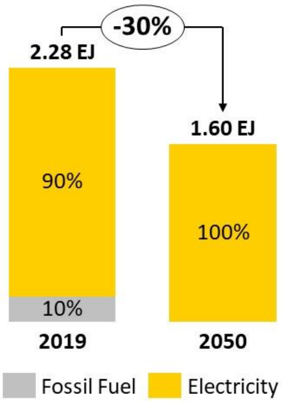


Figure 2 Final energy demand (EJ) — buildings (non-heating)

(3) Ground transport

Transportation demand was assumed to be accordance with the forecast of volume and mileage by the Japan Automobile Manufacturers Association (Figure 1). Transportation energy efficiency is assumed to remain unchanged from the current level, except for an improvement of energy efficiency of passenger electric vehicles (16%).

With the progress of electrification of the drive train, it is assumed that battery-driven electric vehicles (BEVs) and hydrogen-driven vehicles (FCVs) will account for 90% and 10%, respectively, of passenger vehicles (light-duty vehicles; LDVs) on a volume basis, while BEVs and FCVs will account for 60% and 40%, respectively, of commercial vehicles (heavy-duty vehicles; HDVs). The energy demand in 2050 as a result of these assumptions is projected as shown in Figure 2.

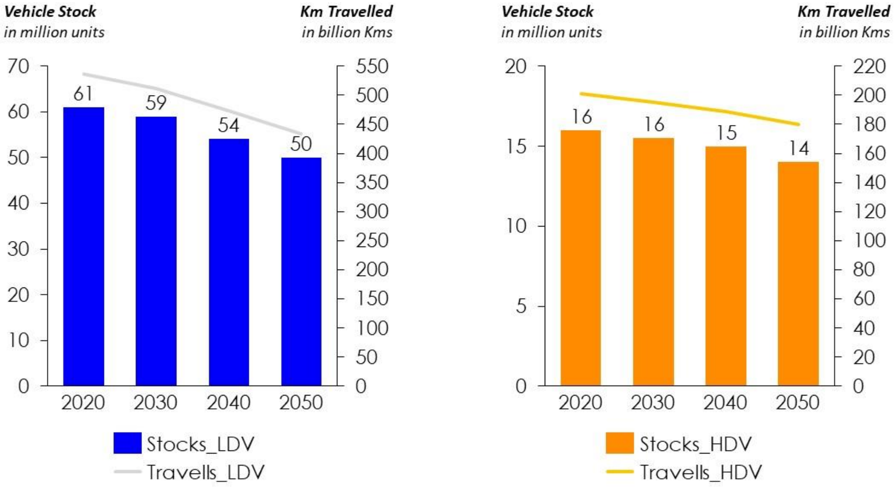


Figure 1 LDV/HDV volume and travel distance forecasts

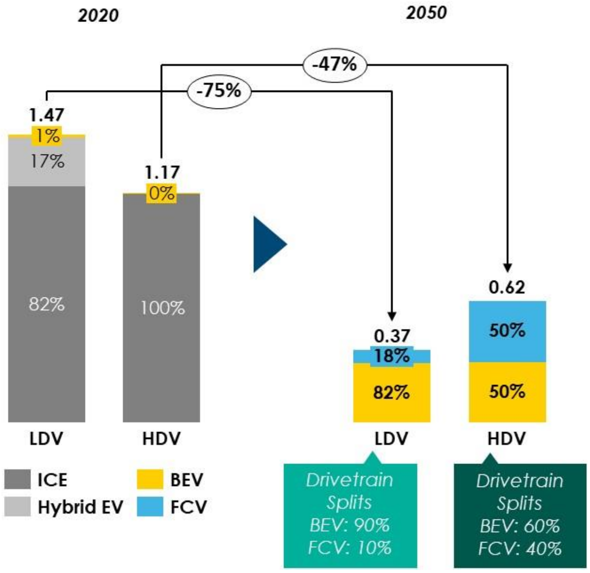


Figure 2 Final energy demand (EJ) — ground transport

(4) Shipping (domestic Japan)

It is assumed that transportation demand will remain constant due to population decline offset with increased demand for cargo transport, and that there will be a 20% improvement in the energy efficiency of vessels. Electric power from storage batteries and fuel cells is assumed to be the mainstream for short-distance marine transportation, with a portion using ammonia internal combustion engines. Energy demand for international transportation is not included in the energy consumption of Japan.

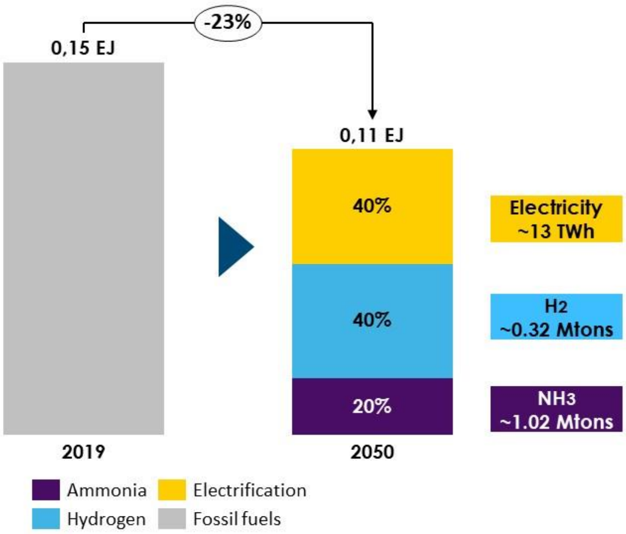


Figure 3 Final energy demand (EJ) — shipping

(5) Aviation

The amount of freight ton-kilometers for both domestic and international freight transportation is assumed to be unchanged from 2019 levels, with the impact of population decline and logistics growth offsetting each other. A 19% decrease commensurate with population decline is assumed for passenger transportation. Meanwhile, energy efficiency is assumed to improve by 40% in both freight and passenger transportation. Electrification is assumed to be limited to short distances, and the main energy sources to be artificial fuels synthesized from CO2 (40%) and biofuels (40%).

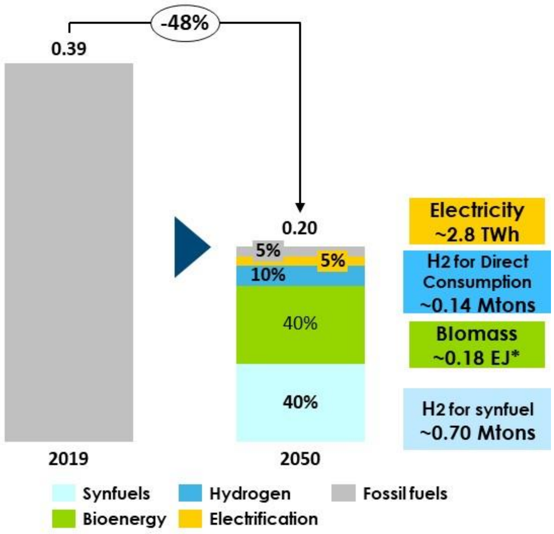


Figure 4 Final energy demand (EJ) — aviation

(6) Iron making

Domestic demand is assumed to decrease by 19% in proportion to population. The ratio of exports to domestic steel supply is assumed to decrease from 33% to 20% due to increased production capacity in Southeast Asia and other foreign countries. Progress in recycling is assumed to increase the share of steel scrap in steel raw materials from 35% in 2019 to 70%. Two thirds of the remaining pig iron production is assumed to be converted from blast furnaces using coal to direct reduction of iron (DRI) using hydrogen. Furthermore, the ratio of electric arc furnaces in steel production is assumed to increase from 25% in 2019 to 50%. Under these assumptions, the energy demand decreases by 53% shown in Figure 7 is derived assuming the energy efficiency of each process (Figure 6).

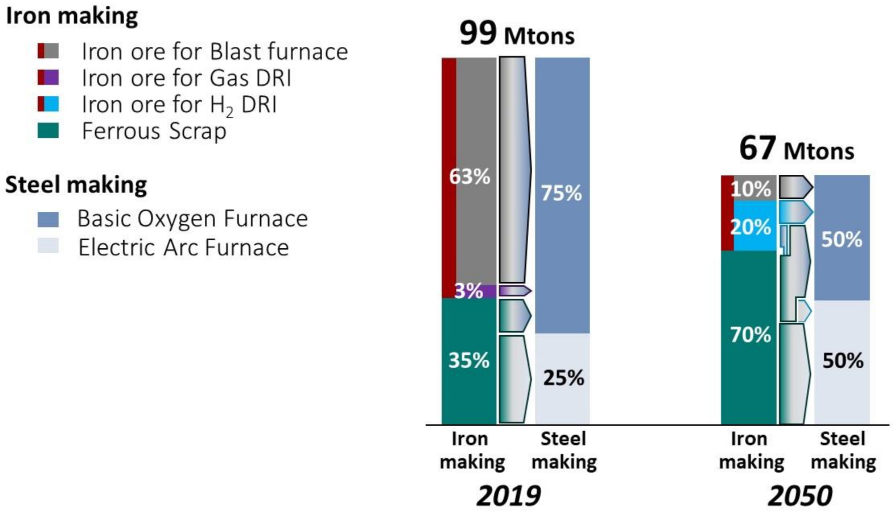
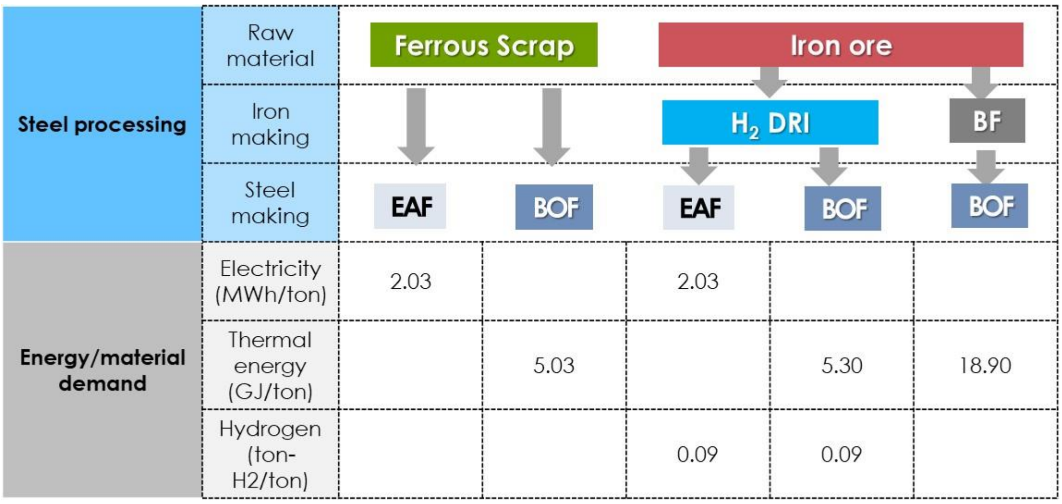


Figure 5 Hypothesized steel production volume and manufacturing process ratios



Steel processing	Raw material	Ferrous Scrap		Iron ore		
	Iron making			H_2 DRI		BF
	Steel making	EAF	BOF	EAF	BOF	BOF
Energy/material demand	Electricity (MWh/ton)	2.03		2.03		
	Thermal energy (GJ/ton)		5.03		5.30	18.90
	Hydrogen (ton-H2/ton)			0.09	0.09	

BF: Blast Furnace, BOF: Basic Oxygen Furnace, DRI: Direct Reduction of Iron, EAF: Electric Arc Furnace

Figure 6 Energy efficiency of each process in iron making

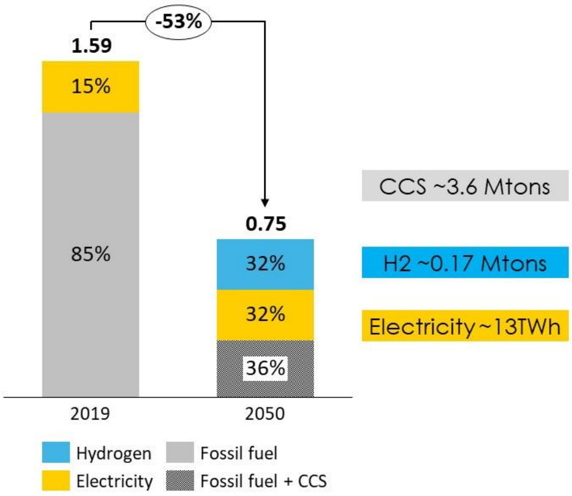


Figure 7 Final energy demand (EJ) — steel

(7) Chemicals

In terms of demand, a 47% per capita decrease in the use of plastics and a 10% per capita decrease in the use of chemicals other than plastics (except for 19% per capita decrease in fertilizers) is assumed. By way of chemical feedstocks to meet these demands, the primary method of plastics recycling, which is currently heat recovery, is assumed to be converted mainly to mechanical recycling and chemical recycling, and the shortfall in demand to be met by bio-feedstocks (Figure 9). The energy intensity of the chemical process is assumed to remain unchanged from 2019 at 49.5 GJ/t. The energy for production is assumed to be sourced from 35% electricity, 30% hydrogen, and 35% fossil fuels + CCS.

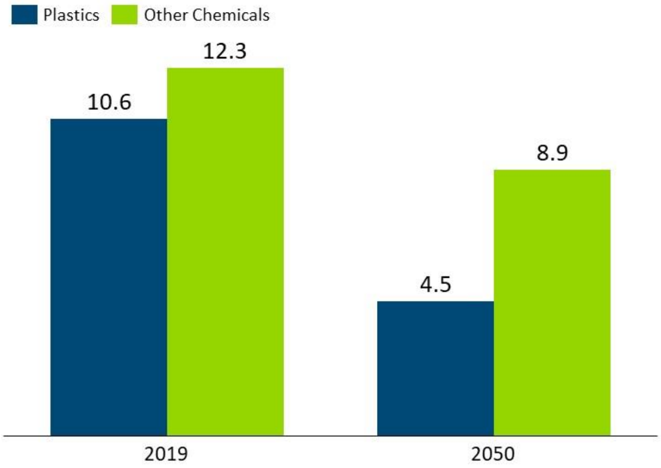


Figure 8 Chemical product demand (million tons) — chemicals

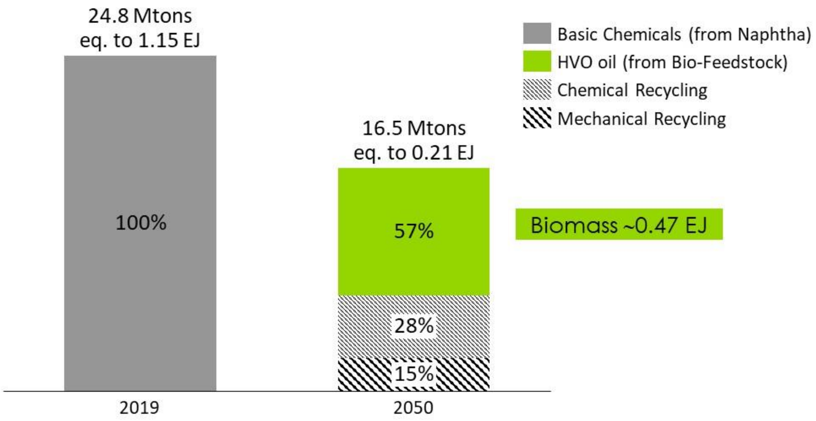


Figure 9 Chemical feedstock

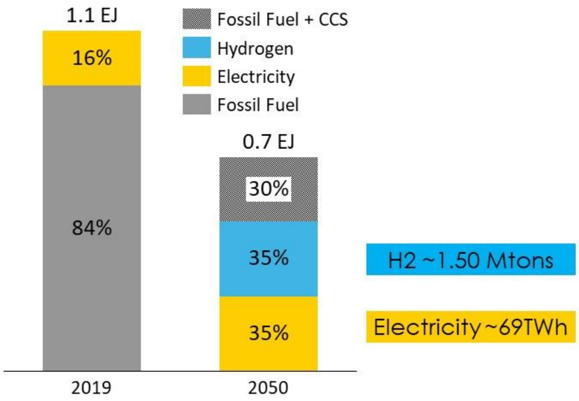


Figure 10 Final energy demand (EJ) — chemicals

(8) Cement

Energy demand is expected to decrease by 19% due to population decline and by 10% due to improved manufacturing efficiency. Technically, energy-savings in the firing process, electrification of heating, and use of biofuels and hydrogen are assumed while CCS is considered to be essential for the inevitable CO2 emissions.

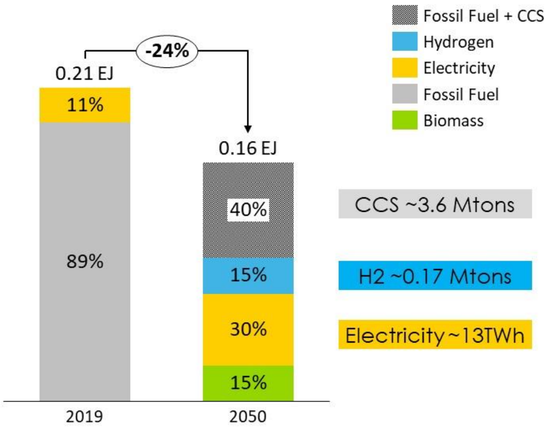


Figure 11 Final energy demand (EJ) — cement

エラー! 参照元が見つかりません。 shows the main decarbonization technologies and changes in energy demand in each of the sectors described above (2019 values are actual values and 2050 values are the result of this scenario analysis). Energy demand is expected to decrease by 43%, from 13.2 EJ to 7.5 EJ.

Figure 14 presents the results with energy demand in each sector on the vertical axis and the percentage of supply of each energy source on the horizontal axis. The area occupied by each color represents the total supply of each energy source in 2019 and 2050, respectively. In all of the Scenarios (1) through (4) described in the previous section, the promotion of electrification is essential under the constraints of achieving Net Zero. For this reason, the energy demand estimates presented here for each sector assume the maximum possible promotion of electrification. (In the case of maximum utilization of CN fuel in Scenario (4), it is possible that CN fuels could directly replace current fossil fuel use. However, since the supply potential of CN fuels needs to be further examined in future study, this study only presents scenarios assuming maximum electrification.) Correspondingly, fossil fuels represented in black (without CCS in 2019) account for the majority of the area in 2019, while electricity represented in blue accounts for about 69% of final energy demand in the 2050 scenarios.

Table 3 Overview of final energy demand in Japan in 2019 and 2050

Sector	Primary decarbonization technology		Final energy demand (EJ)	
			2019	2050
Buildings — heating	Thorough electrification of heat supply (use of energy-efficient heat pumps, etc.)		1.67	1.17
Buildings — non-heating	Reduction of power consumption of existing appliances, computer equipment, etc. by improvement of energy efficiency		2.28	1.60
Passenger vehicles (LDV)	Nearly all electrified		1.47	0.38
Commercial vehicles (HDV)	Combination of electrification and hydrogen-powered depending on application		1.16	0.62
Shipping	Combination of electric-powered for short distance travel	Use of clean ammonia for long-distance domestic navigation	0.15	0.11
Aviation		Utilization of biofuels or synfuels (SAF)	0.39	0.20
Cement	Decrease in energy demand due to improved manufacturing efficiency, and energy saving and electrification of the firing process. CCS utilized for residual emissions.		0.21	0.16
Steel	Use of recycled steel. Use of hydrogen in crude steel production. Approx. half of steel production electrified. CCS utilized for residual emissions.		1.59	0.75
Chemicals	Increase of recycling rate (especially chemical recycling), reduction of plastic consumption, and electrification of chemical processes. CCS utilized for residual emissions.		2.28	0.92
Other	Progress in clean electrification made in railroads, agriculture, and other industries		1.92	1.55
Total			13.2	7.52

Note: Decreased demand due to population decline in 2050 (approximately 20% decrease from 2019) is taken into account in all sectors.

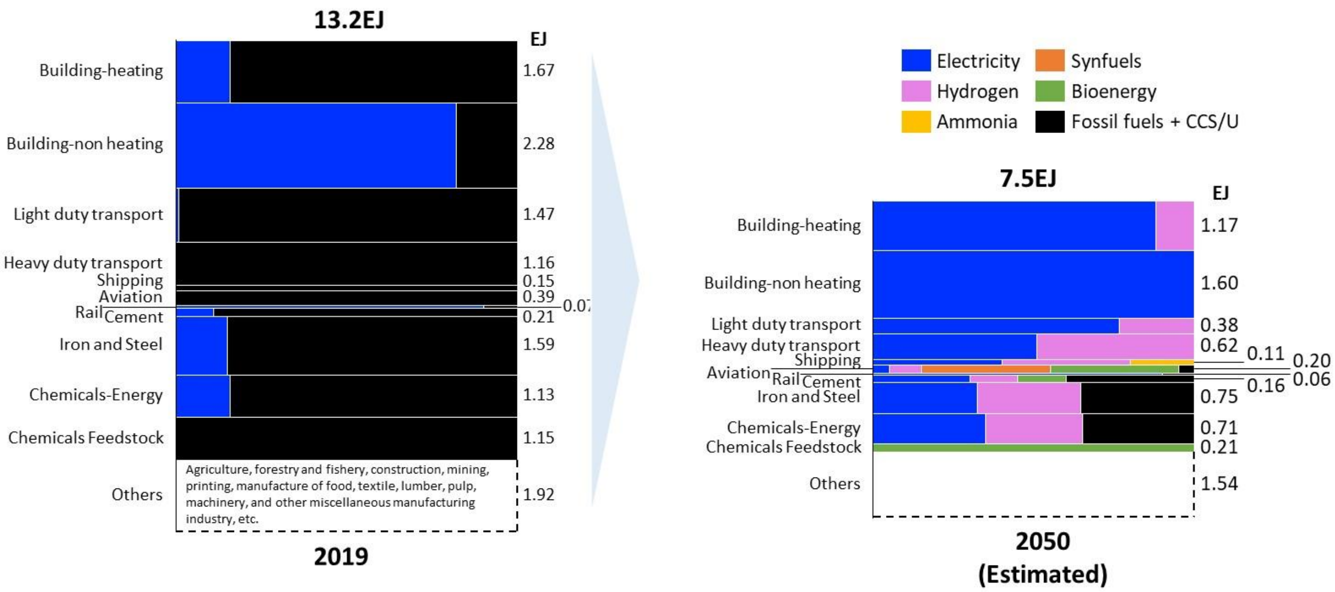


Figure 12 Energy demand (EJ) in 2019 (actual) and 2050 (estimated)

As a result of this promotion of electrification, electricity demand is expected to increase by 56% over 2019, reaching 1,448 TWh per year, as shown in Figure 13. Note that all hydrogen is assumed to be imported, and the electricity used in each sector to produce hydrogen is not included in the electricity demand here.

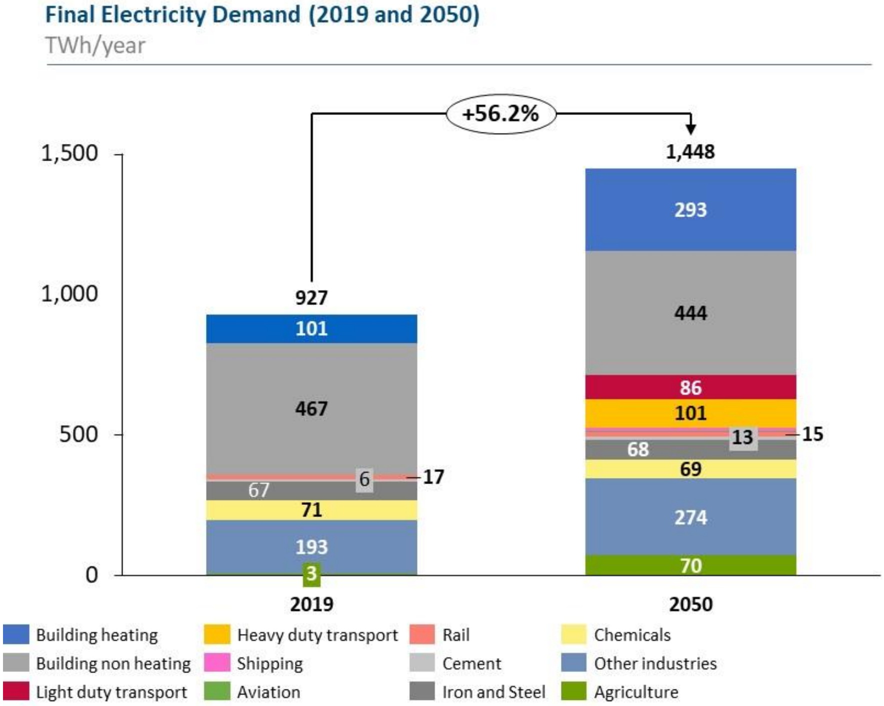


Figure 13 Electricity demand (TWh) in 2019 (actual) and 2050 (estimated)

If future progress of this study indicates that more desirable changes in the social and economic structure can be hypothesized, the assumptions for estimating energy demand will be revised accordingly, and energy demand in 2050 will be reexamined.

d. Power mix modeling

Optimization calculations were performed to identify the optimal power mix that meets the assumed annual power demand of 1,448 TWh in 2050 as described in the previous section, such that the power system cost is minimized while maintaining the balance between supply and demand of electricity. In conducting this simulation, analysis was conducted using an optimal power generation mix (OPGM) model[6] with the cooperation of Professor Ryoichi Komiyama, the Fujii-Komiyama Laboratory at the University of Tokyo.

The power mix was derived by optimization calculations for the 11 cases shown in エラー! 参照元が見つかりません。, including Scenario (1) through (4) shown in エラー! 参照元が見つかりません。. The three assumptions that were varied in each case were (i) the cost of solar/wind power and storage batteries, (ii) the

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[6] OPGM is an analytical model of electricity supply and demand for a power system based on linear programming, where the objective function is to minimize the power system cost (generation cost + fuel cost + power storage cost). Analysis was conducted with zero CO2 emissions as a constraint within a geographic and temporal resolution of the hourly electricity supply-demand balance in the nine regions of Japan.

potential capacity of solar and wind power installed, and (iii) the installed capacity of nuclear power. Regarding power generation costs, Bloomberg NEF's 2050 cost outlook (high and low) was used for solar/wind power and storage batteries[7], and the 2030 values from METI data[8] were referred for other power generation costs. All fossil fuel-based power generation was assumed to be combined with CCS, and the same METI data were used for the cost of this[9]. Thermal power generation using CO2-free hydrogen and ammonia is assumed to be exclusively fired and not to require CCS. Hydrogen cost was assumed to be 20 JPY/Nm^3 (approximately 2 USD/kg), in line with the government target for 2050. It was also assumed that there would be no quantity constraints on the hydrogen through imports.

Table 4 Eleven cases of power mix derived by the OPGM model

Case	1-c	1-b	1-a	2	3	4	5	6	7-a	7-b	7-c
RE cost	High					Low					
Storage battery cost	Japan – high					Japan – low			USA & Germany – medium		
RE potential capacity limit[10]	Low			High	No limit	Low	High	No limit			
Nuclear power generation installed capacity[11] (GW)	46	37	24							37	46

Hydrogen + nuclear power utilization scenario

Hydrogen utilization scenario

Renewable energy utilization scenario

Renewable energy + nuclear power utilization

The case numbers correspond to the ease of introducing renewable energy and storage batteries. In Case 1, the cost of renewable energy generation and storage batteries is assumed to be high, and the potential capacity of renewable energy to be small, making it a case where renewable energy generation is difficult to introduce. Conversely, in Case 7, the cost of renewable energy generation and storage batteries is low, and renewable energy generation is introduced without any limits on the potential capacity, making it a case where renewable energy generation is introduced to the maximum extent possible, including the contribution of storage batteries

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[7] Bloomberg NEF(2022), *1H 2022 LCOE Update*

[8] Set based on the Ministry of Economy, Trade and Industry's "List of various types of power source (Document 3, Working Group on Power Generation Cost Verification (8th Meeting) of the Advisory Committee for Natural Resources and Energy)" [in Japanese].

[9] Set based on the Ministry of Economy, Trade and Industry's "List of various types of power source (Document 3, Working Group on Power Generation Cost Verification (8th Meeting) of the Advisory Committee for Natural Resources and Energy)" [in Japanese].

[10] Low: PV 259 GW, onshore wind 41 GW, offshore wind 47 GW. Ministry of the Environment, "Entrusted Work Concerning the Development and Disclosure of Basic Zoning Information Concerning Renewable Energies (FY 2019) (March 2020)". High: PV 699 GW, onshore wind 285 GW, offshore wind 1,120 GW. Central Research Institute of Electric Power Industry, "Examination of Mass Introduction Scenarios for Wind and Solar Power Generation Toward Realization of Net Zero" [in Japanese] (Strategic Policy Committee of the Advisory Committee for Natural Resources and Energy, 34th Session, December 14, 2020).

[11] 24 GW capacity assumes 60-years operation of existing nuclear power plants and 37 GW capacity assumes 80-years operation of existing nuclear power plants. Data from "31st Session of the Nuclear Energy Subcommittee, Electricity and Gas Industry Committee, Advisory Committee for Natural Resources and Energy" [in Japanese]. 46 GW is the sum of the existing nuclear power plant capacity assuming 80-years operation and the capacity of nuclear power plants for which there are plans for new construction. Current Status of Nuclear Power Plants in Japan, Japan Atomic Industrial Forum, Inc.(https://www. jaif. or. jp/cms_admin/wp-content/uploads/2023/01/jp-npps-operation20230110. pdf, accessed: January 30, 2023).

to the adjustment of electricity supply and demand. Cases 2 through 6 assume situations intermediate between the two.

Concerning the installed capacity of nuclear power plants, the following cases were assumed: existing nuclear power plants are phased out, based on a lifespan of 60 years (24 GW installed capacity in 2050; subcase “-a” or none); the upper limit of operation period is tentatively extended to 80 years, based on the basic policy on the shift from nuclear power phase-out as presented in the government's GX Implementation Council (37 GW; subcase “-b”); all nuclear power generation from ongoing new construction projects is operational (46 GW; subcase “-c”).

The correspondence with Scenarios (1) through (4) shown in エラー! 参照元が見つかりません。 is also noted in エラー! 参照元が見つかりません。.

Based on the above scenario settings, the power mix in 2050 was calculated by optimization calculations taking into account the hourly power supply-demand balance given by the OPGM model. The power mix for Scenarios (1) through (4) is shown in Figure 14.

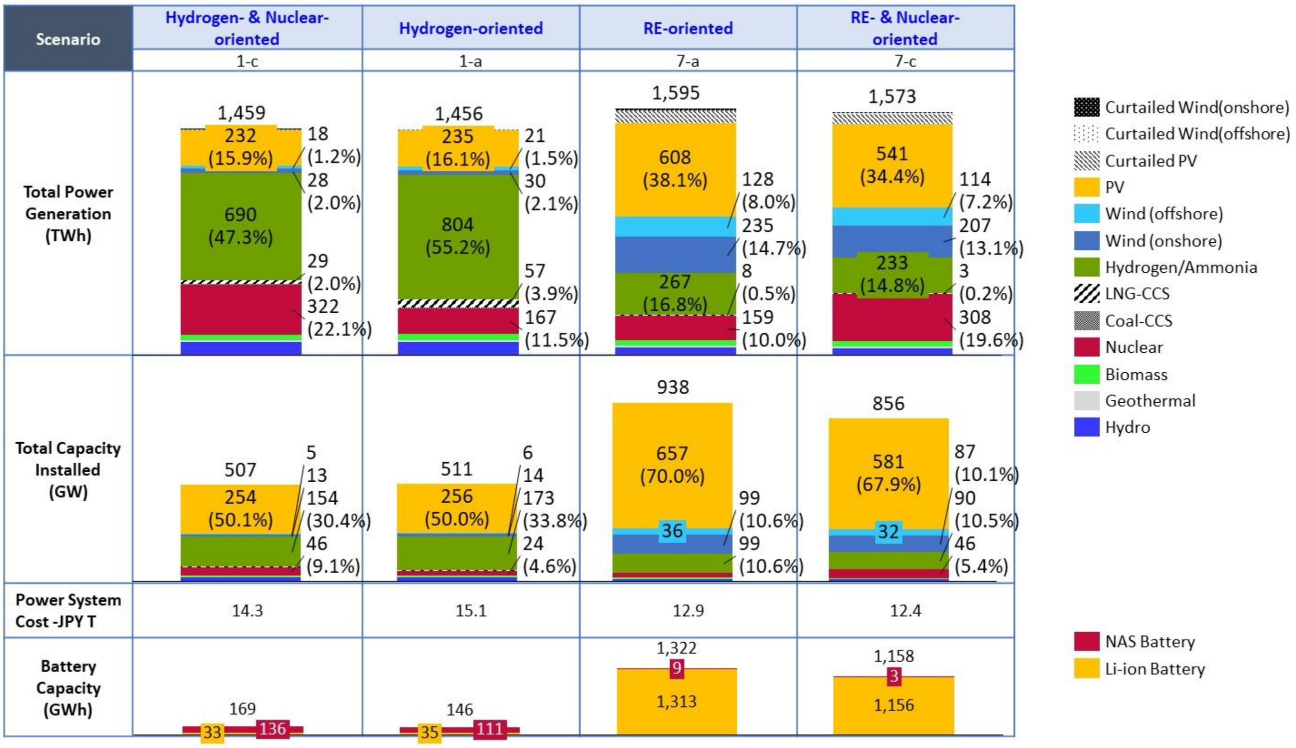

Figure 14 2050 power mix

- Maximum hydrogen + nuclear power utilization scenario (1-c): Limited amount of renewable energy generation and storage batteries installed due to cost and potential capacity limits. The introduction of 46 GW of nuclear capacity reduces the need for hydrogen (ammonia) fired thermal power generation relative to 1-a. The power system cost is also slightly reduced compared to 1-a.
- Maximum hydrogen utilization scenario (1-a): Limited amount of renewable energy generation and

storage batteries installed due to cost and potential capacity limits. Hydrogen (ammonia) fired thermal power generation is the main source of electricity supply, accounting for 55% of total power generation. Power system costs are the highest of the four scenarios.

- Maximum renewable energy utilization scenario (7-a): Largest amount of renewable energy generation installed, and a large number of storage batteries installed to fill the gap between the amount of electricity generated each hour and electricity demand. Due to the low renewable energy operation rate and frequent output curtailment, the power generation installed capacity is the highest. The installed capacity of solar power generation is 657 GW, about 10 times the current capacity.
- Maximum renewable energy & nuclear power utilization scenario (7-c): Although much of the electricity supply depends on renewable energy generation, the introduction of 46 GW of nuclear power reduces the amount of renewable energy generation compared to 7-a. Power system costs are also reduced slightly from 7-a.

In all cases, the use of thermal power generation combining fossil fuels and CCS is extremely limited. This is because fossil fuel-based thermal power generation is slightly more expensive than hydrogen-based thermal power generation, based on the assumption that hydrogen can be imported at the government's target cost of 20 JPY/Nm^3 (about 2 USD/kg) in 2050 without quantity constraints.

Regarding storage battery demand in the mobility sector, it is calculated that 5.8 TWh (3.2 TWh for passenger vehicles and 2.6 TWh for commercial vehicles) of storage batteries are required. The storage battery demand in the renewable energy utilization scenario (1.322 TWh) corresponds to 19% of the total storage battery demand taking into account demand in mobility, while storage battery demand in the hydrogen + nuclear power utilization scenario, which makes the least use of storage batteries (0.169 TWh), corresponds to 3%.

In the OPGM simulation, in nine regions that are currently used as a unit for power supply and demand adjustment in Japan, considering the hourly power supply and demand balance (“same amount at the same time”), the combination of power sources that minimizes power system costs is calculated. In the hydrogen + nuclear power utilization scenario (1-c), nuclear power is operated as the base power source, while hydrogen (ammonia) power generation is introduced in large quantities and functions as a balancing power for renewable energy sources (solar and wind power). On the other hand, in the renewable energy utilization scenario (7-a), a large amount of renewable energy generation is introduced, and storage batteries play an important role in balancing the hourly electricity supply-demand balance. Solar power output is curtailed frequently and in large quantities.

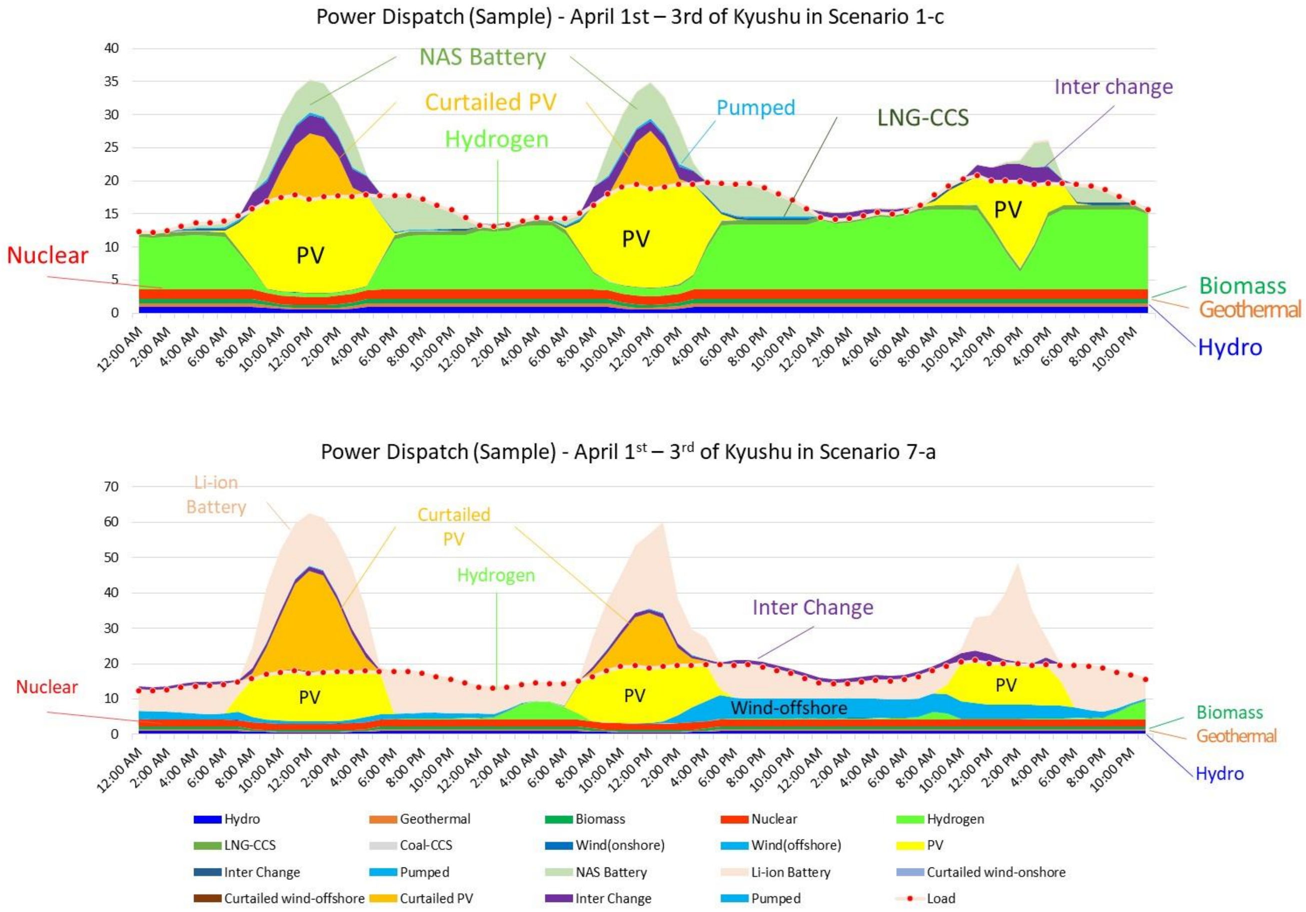

Figure 15 Example of electricity supply and demand management

Of the four scenarios, the scenario that requires the most hydrogen is the hydrogen utilization scenario at 43 million tons, while the scenario that requires the least is the renewable energy + nuclear power utilization scenario at 18 million tons. In the latter scenario, if green hydrogen were produced by water electrolysis using the entire amount of output-curtailed electricity from renewable energy generation, 1.8 million tons of hydrogen could be produced. This is equivalent to about 1/5 of the 7.9 million tons of non-power generation hydrogen demand in 2050, most of which will need to be produced by means other than electricity from the Japan power grid. In other words, it is necessary to rely on imports or hydrogen production from off-grid renewable energy sources, such as deep offshore wind power.

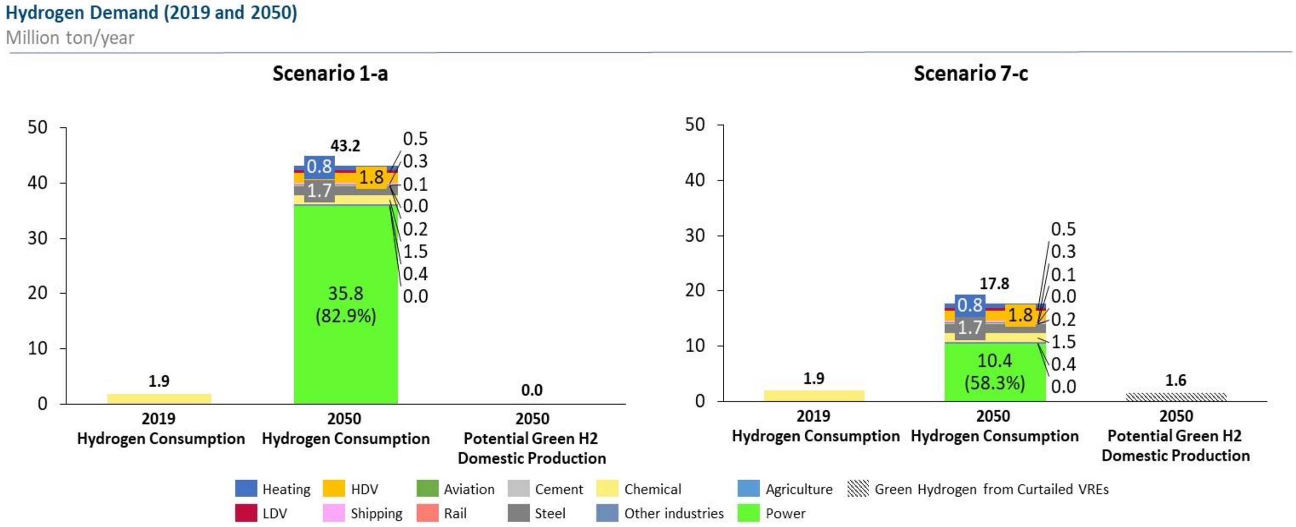

Figure 16 2050 hydrogen demand

Of the four scenarios, the scenario that requires the most CCS is the hydrogen utilization scenario (1-a), which is estimated to require 67 million tons of CCS. The scenario with the lowest CCS demand is the renewable energy + nuclear power utilization scenario (7-c), which requires 49 million tons of CCS. Although there are many uncertainties, the amount of CCS processing within Japan is expected to be 100 million tons per year, and the amount of CCS required in this scenario is within the range of the amount of CCS that can be processed.

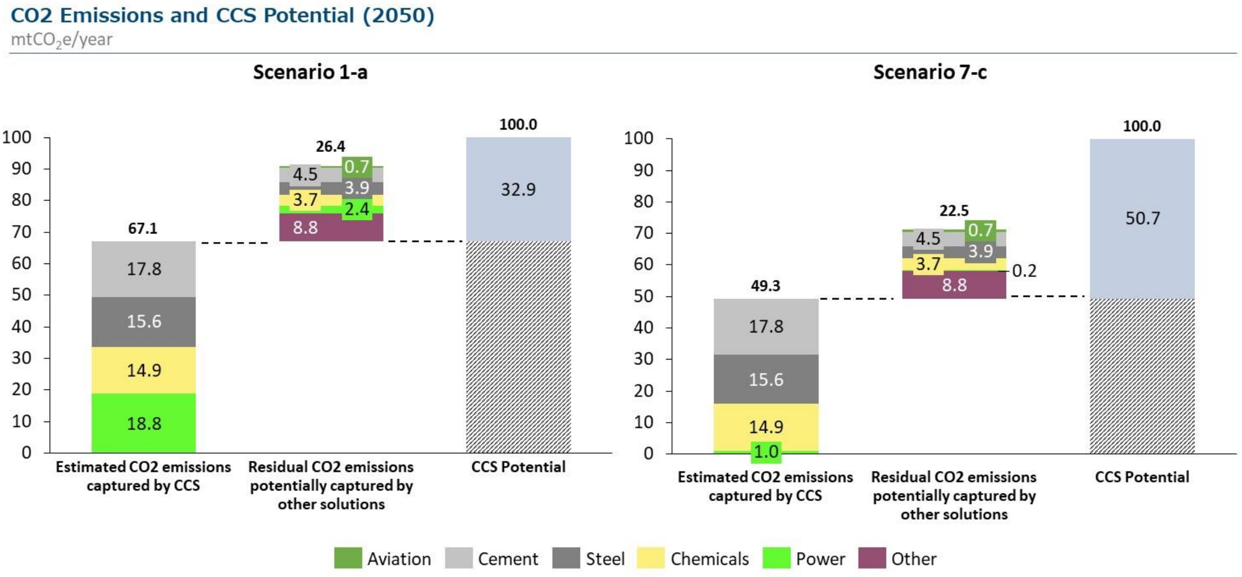

Figure 17 Required CCS in 2050

4. Issues and actions to utilize each energy source

This scenario analysis showed that even under the characteristic conditions of Japan such as a limited renewable energy generation potential capacity and a heavy industry that is considered technically difficult to decarbonize, Japan has the potential to achieve Net Zero while keeping energy costs at a reasonable level without abrupt changes from the current industrial structure. This can be achieved by promoting globally-accepted decarbonization measures such as electrification and conversion to carbon-free fuels in all sectors. A number of issues must be resolved in order to realize the energy system picture presented in these scenarios. The most important of these are as follows.

a. Solar and wind power generation

- For the mass introduction of renewable energy (especially solar power), it is essential to lower the cost of storage batteries, which are necessary for balancing power. A maximum of 1.3 TWh of storage batteries is required (for Scenario 7-a). Storage batteries for power system balancing require a much longer cycle life and higher reliability than storage batteries for vehicles because they are subjected to repetitive near-maximum charge-discharge cycles at a higher frequency.
- A maximum of 657 GW of solar cells needs to be installed (Scenario 7-a). This is almost equal to the 699 GW of potential capacity estimated by the Ministry of the Environment, and will require a drastic change in land use, including the conversion of the agricultural land that accounts for much of that potential capacity. Needless to say, the introduction of such a large number of solar cells should avoid causing environmental damage or vulnerability to disasters.
- The maximum wind power capacity indicated by the simulation is 159 GW (Scenario 6), which is more than the potential capacity estimated by the Central Research Institute of Electric Power Industry, but much less than the amount estimated by the Ministry of the Environment. A shift to offshore wind power in particular is expected in the case where the aforementioned large-scale installation of solar cells is difficult. Currently, cost and many other factors are obstacles to the introduction of offshore wind power, especially in remote locations. In order to encourage the large-scale introduction of offshore wind power, it is essential to lower the cost of innovative technologies such as floating offshore wind power, while concurrently ensuring the predictability of the business opportunities through government leadership.
- Although this analysis takes into account hourly balancing constraints, it does not consider stability of frequency in the AC power grid. Frequency stabilization is a challenge when large amounts of solar and wind power are introduced into the power system via inverters and the ratio of power generation by rotating machinery, which has a frequency stabilizing effect due to inertial forces, is greatly reduced.

b. Hydrogen and ammonia

- It is estimated that an annual amount of approximately 19.3 million tons (Case 7-a) to 43.2

million tons (Case 1-a) of CO2-free hydrogen and ammonia is necessary. Of this, 11.9 million tons (Case 7-a) to 35.8 million tons (Case 1-a) is for power generation. The higher case exceeds the government's goal of 23.5 million tons (hydrogen + ammonia) by 2050.

- The only possible way to produce such a large amount of hydrogen in Japan through renewable energy generation and water electrolysis is to introduce a large amount of offshore wind power. Domestic production of blue hydrogen using fossil resources imported from abroad is unrealistic given CCS throughput constraints.
- Domestically produced CO2-free hydrogen and ammonia is important for energy security, but it is uncertain whether it will be able to meet all of Japan's hydrogen demand in 2050, and it is necessary to secure a large volume and stable procurement route for CO2-free hydrogen and ammonia produced overseas.
- Thermal power generation technology based exclusively on hydrogen and ammonia, rather than co-firing with fossil fuels, is a requirement in order to decarbonize the power supply by 2050. Technology development and social implementation for this needs to be accelerated.

c. Nuclear power

- Nuclear power is expected to function as a base load for the steady supply of electricity, but it cannot cover the majority of power supply.
- In Case 1, where the constraint on renewable energy generation is significant, the increase in nuclear power installed capacity results in a reduction in installed capacity and operation rate of hydrogen-fired thermal power generation. In Case 7, where the constraint on renewable energy generation is minor, the increase in the installed capacity of nuclear power generation results in a reduction in installed capacity of renewable energy generation, storage batteries, and hydrogen generation. These trends suggest that nuclear power may be the only solution to decarbonize the power supply in a situation where the mass introduction of renewable energy and hydrogen-fired thermal power generation is difficult.
- The share of electricity supplied by nuclear power (independent of the cost of renewable energy generation, storage batteries, and hydrogen-fired thermal power generation) is limited to the installed capacity of nuclear power generation. For 24 GW of installed capacity (Cases 1-a through 7-a), this is 10 to 11%, and 19 to 22% for 46 GW of installed capacity (Cases 1-c and 7-c).
- In order for nuclear power to become a major power source, the installed capacity of 46 GW or less assumed in this analysis is not sufficient. To introduce nuclear power generation of larger capacity, it is essential to build public consensus on the renewal of facilities and the construction of new nuclear power plants, as well as to establish a sustainable nuclear fuel cycle. Additional social costs are not considered in this simulation (safety costs, etc.) and the time required to build new facilities must also be taken into account.

d. Storage batteries

- The mass introduction of solar and wind power generation (Case 7) requires the mass introduction of storage batteries to balance the mismatch between electricity supply and demand.
- It is estimated that 0.15 to 1.32 TWh of storage battery capacity is needed for power balancing and 5.8 TWh for mobility.
- It is necessary to resolve lithium supply concerns (refining country risk reduction and recycling) and develop new technologies that do not rely on lithium.
- A significant extension of cycle life and improved reliability are required for power balancing in particular.
- It is also necessary to develop technologies to reduce CO2 emissions in the manufacturing, recycling, and disposal processes.

e. Buildings

- Policies and investment are needed to promote the upgrading of building facilities in order to make heat pumps as the primary heat source.
- To convert water heating in housing complexes to heat pumps, it is essential to radically downsize heat pump water heaters in accordance with the limited space available.
- When the energy supply for buildings is almost entirely electrified, its resilience becomes a concern. It is necessary to introduce an integrated energy system that manages energy demand and supply, in which solar cells and storage batteries are installed in close proximity to buildings as far as geographical conditions allow. This energy management system will enable independent power supply during disasters.
- To improve the energy efficiency of building air conditioning, it is essential to control the flow of heat in and out of the building, and it is extremely important to strengthen insulation and make windows and other openings more sophisticated.

f. Ground transport

- It is assumed that 90% of passenger and other LDVs will be storage battery-driven electric vehicles, but the utilization rate of storage batteries for vehicles is very low, and there is significant concern that this will be waste of storage battery resources.
- It is expected to minimize the total capacity of storage battery for passenger vehicles by the increased use of shared vehicles and the proliferation of rapid charging facilities.
- The utilization rate of storage batteries for vehicles can be increased by the expansion of vehicle-to-grid systems, which allow electric vehicle batteries to serve for the matching between demand and supply in the power grid.
- Once sufficient quantities of CN fuel become available, plug-in hybrid vehicles utilizing CN fuel are expected to reduce the use of storage batteries in passenger vehicles (Figure 18).

- Technological innovations are needed to decarbonize commercial, maintenance and other HDVs. Electrification is a common issue for both storage battery-driven and hydrogen-driven systems. Conversion to hydrogen will require high-capacity fuel cells for vehicles and advances in hydrogen storage technology.

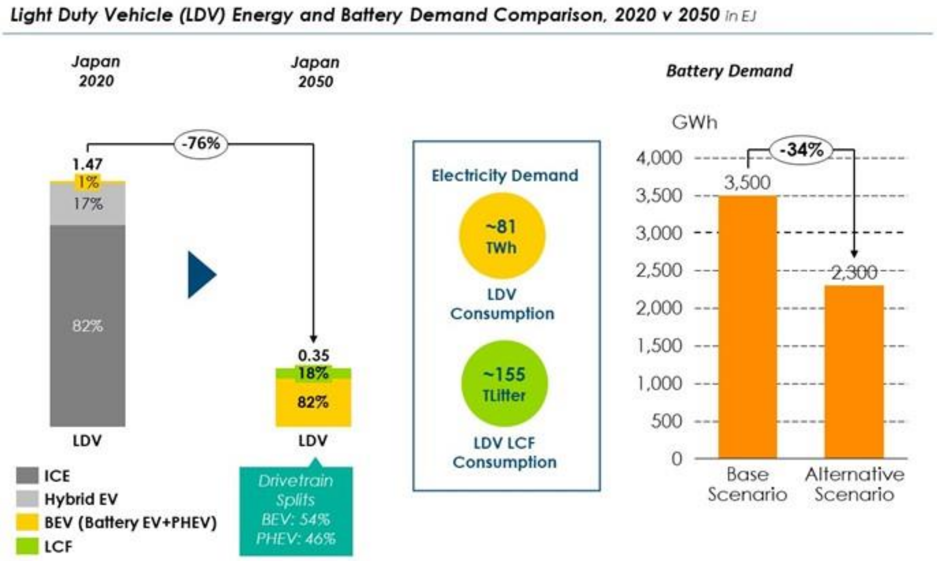

Figure 18 Passenger vehicle energy and battery demand

(in the case a large supply of CN fuel is available)

g. Steel

- Institutional development is necessary to encourage greater use of scrap materials and the establishment of supply chains.
- It is necessary to promote the conversion from blast furnaces to direct hydrogen reduction in the iron making process and to electric arc furnaces in the steel making process.
- Technological development and promotion of introduction of technologies that further reduce CO2 emissions and direct hydrogen reduction, etc., beyond the CO2 Ultimate Reduction System for Cool Earth 50 (COURSE 50) currently under consideration, are required.

h. Chemicals

- It is necessary to convert to recyclable plastic products through processes that minimize energy input and CO2 emissions, and to develop institutions to promote recycling.
- The development of innovative chemical recycling technologies is expected to significantly improve the recycling rate.
- Electrification and conversion to hydrogen of the material conversion process will be important.
- In order to replace conventional processes that use fossil resources, there is a need to develop technologies and promote the introduction of chemical synthesis processes that use bio-resources as feedstock.

5. Future research efforts

Based on the assumption that current industrial structure, population, and other macroeconomic trends will continue, this scenario analysis has highlighted the scale of efforts required for Japan to achieve Net Zero by 2050 as well as the sectors that will need to undergo major transformation from 2019 to 2050, that is, the sectors that are highly critical to the success of achieving Net Zero.

Sectors which require investigation of decarbonization scenarios in detail and intensive discussion on transition strategies can be categorized as follows.

- Sectors which have some prospect for decarbonization technologies and accordingly strategies for social implementation should be discussed:
  Buildings and mobility
- Sectors which further progress in decarbonization technologies is needed:
  Steel and chemicals
- Sectors which, although not included in detail in this analysis, have the potential to increase explosively in energy demand toward 2050:
  IT (networks, information processing, sensing, etc.)

Another important consideration concerning power supply common to all sectors is the strategy to introduce 400 to 700 GW of solar power or at least 200 GW of offshore wind power in Japan by 2050. Furthermore, investigation of CN utilization scenarios is a task for the future, and it is necessary to study CN fuel supply potential and CN utilization energy scenarios in each sector.

Regarding future transition strategies, we will clarify the necessary technologies and development direction, focusing on the sectors mentioned above, and quantitatively discuss the transitions required in each sector in the pathway to 2050. In doing so, we would like to identify bottlenecks to early adoption of decarbonizing technologies, such as institutional deficiencies and lack of investment that hinder transitions, and to identify specific policies needed to resolve these bottlenecks. We would like to study not only the actions necessary regarding technologies and institutions related to individual sectors, but also cross-sectoral economic measures, such as carbon pricing and methods of finance. By quantitatively estimating the scale of investment necessary for transitions in each sector and aggregating these estimates to present the scale of investment required to achieve Net Zero in Japan, we would like to discuss and propose the appropriate scale and measures for required investment and additional policies, and if needed to discuss proposed means such as GX transition bonds.

Furthermore, we would like to develop our research to envisage a bright and prosperous Japan in 2050, a society that maximizes well-being, and a future vision that reflects changes in industrial structures and lifestyles.