Model calculation for Japan's energy mix in 2040 and 2050

The Institute of Energy Economics, Japan

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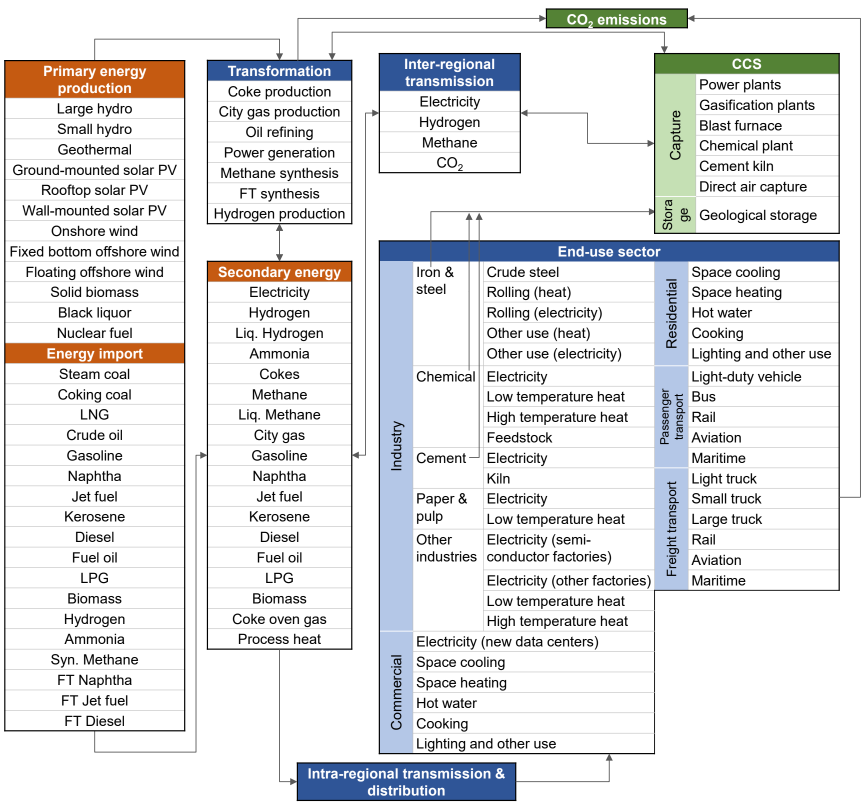
Cost-optimization energy system model: IEEJ-NE_Japan

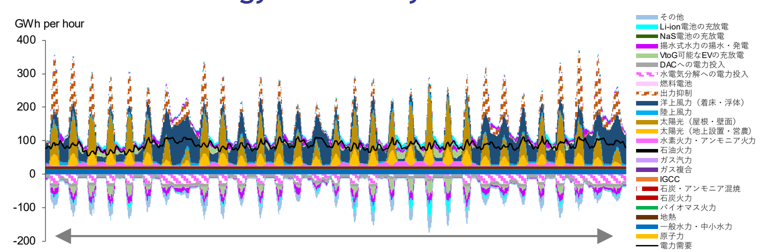
- A linear programming model developed jointly by the Institute of Energy Economics, Japan, the Otsuki Laboratory (Yokohama National University), and Professor Matsuo of Ritsumeikan Asia Pacific University, based on the NE_Japan model developed by the Otsuki Laboratory [1][2][3].
- Calculates an economically rational energy mix for 2050 under CO_2 emission constraints. Electricity supply and demand are calculated in an hourly basis, considering the time variability of renewable energy and grid integration costs.

The entire energy system is covered.



Electricity and hydrogen supply and demand is calculated 24 hours a day x 365 days a year.

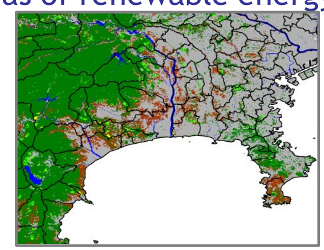
Explicitly take into account the cost of addressing renewable energy variability.



Hourly operation in a month

Estimates renewable energy resources based on geographic information systems (GIS) [4].

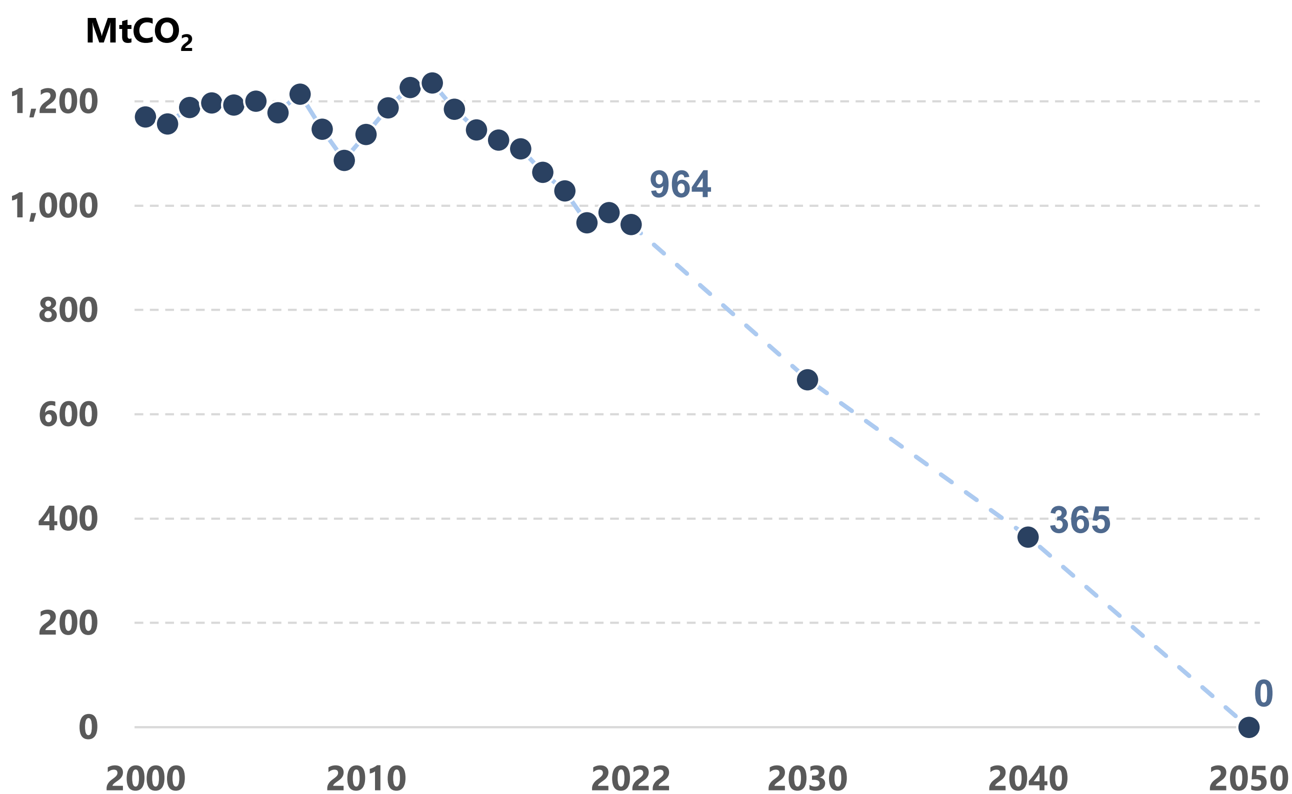
Based on GIS data of land and sea use, as well as 60 million buildings data, the technical potential, and cost depending areas of renewable energy resources are considered.



[1] Otsuki et al, Electrochemistry B, 142(7), pp. 334-346, 2022; [2] Otsuki et al, INT J GREENH GAS CON, 132, 104065, 2024; [3] Otsuki et al, Energy and Climate Change, 4, 100108 2023

Energy-related CO_2 emissions

- The calculations are based on the assumption that energy-related CO_2 emissions will be reduced from the current level (964 million tons in FY2022) to 365 million tons in 2040 and to zero net emissions in 2050.
- The purchase of credits from overseas is not explicitly treated. However, if technologies such as Direct Air Capture (DAC) of CO_2, are implemented overseas, they may be treated as credits, depending on the system design.



(Source of actual data) National Institute for Environmental Studies

Macroeconomic framework

- GDP growth rate is from the Cabinet Office (2024) and population from the National Institute of Population and Social Security Research (2023).
- Based on these, indicators such as material production and transport demands are estimated and used as assumptions for the calculations.

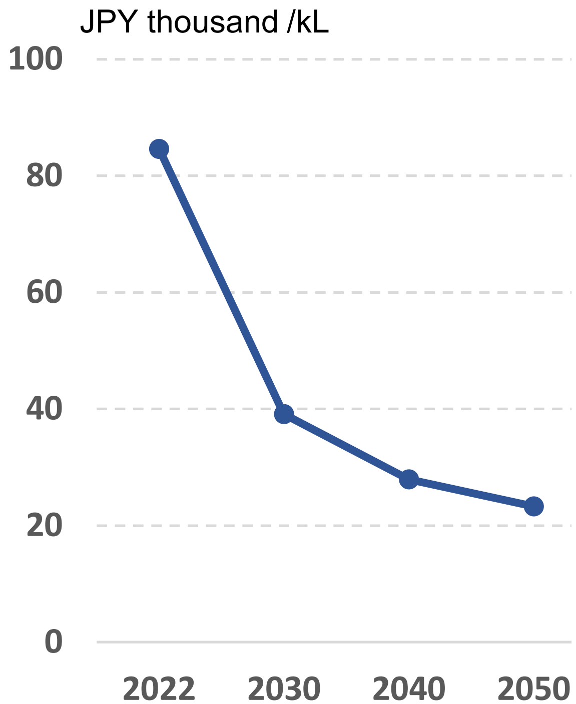
Variable	unit	Actual results for FY2023	Assumption for FY2040	Source and estimation method
GDP Real, 2015 basis	Trillion yen	559	737	Assumes the high growth case of the Cabinet Office (2024) until 2033, and the single-year growth rate in 2033 continues until 2040.
[Growth rate]	[%/year]	[1.0%] (FY2023)	[1.6%] (2023-2040)	
Population	Thousands	124,350	116,270	National Institute of Population and Social Security Research Institute (2023).
Number of households	Thousands	60,770	60,550	Estimated based on population assumptions.
Crude steel production	Million tons	87	78	Estimated based on actual data and future economic and social conditions.
Cement production	Million tons	47	49	
Passenger transport	Billion person - km	1,323	1,269	
Freight transport	Billion ton-km	403	401	

(Sources) Cabinet Office (2024), National Institute of Population and Social Security Research (2023)

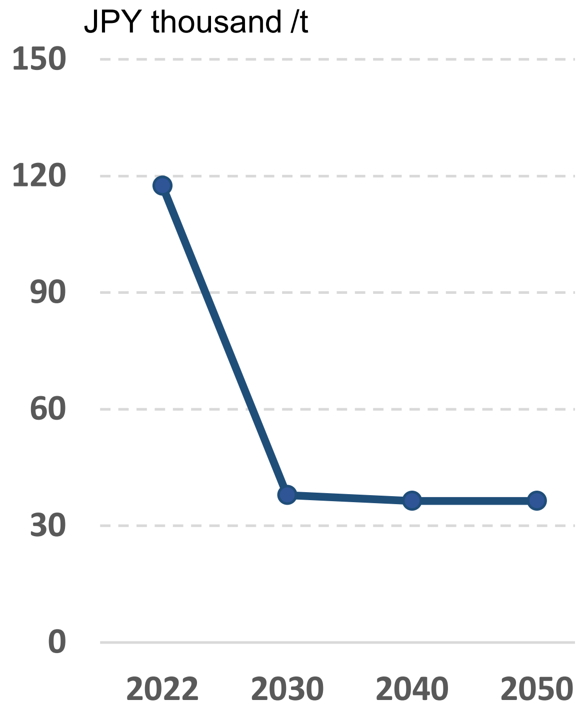
Fossil fuel import prices

- The model considers imports of crude oil, petroleum products (7 types), LNG, steam coal, and coking coal as fossil fuels.
- Import prices are assumed using current CIF prices and the growth rates of price forecasts under the "Net Zero Emissions by 2050" scenario in the IEA "World Energy Outlook 2024."

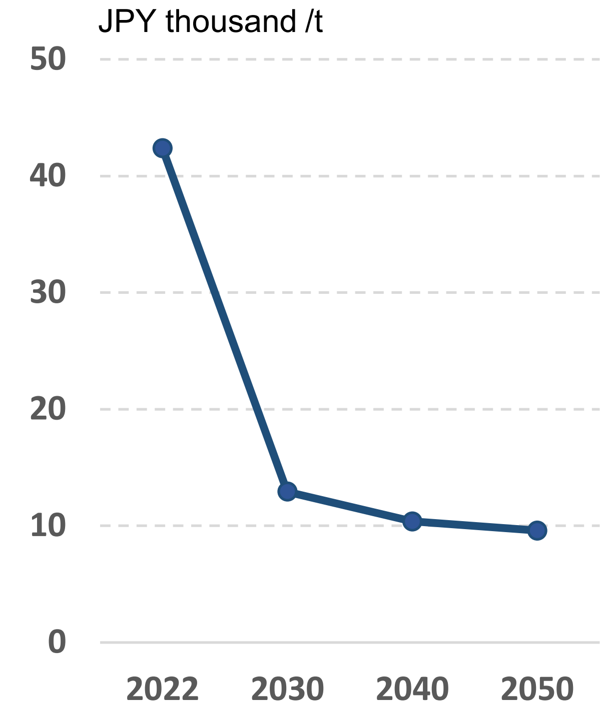
Crude oil



LNG



Coal



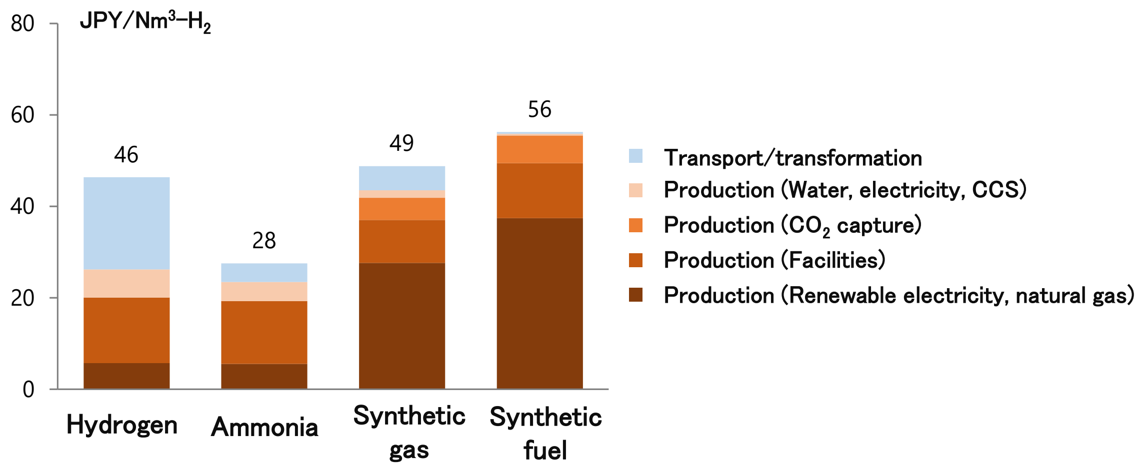
Note: All prices are in 2022 Japanese yen.

Hydrogen energy carrier imports

- Liquid hydrogen, methylcyclohexane (MCH), ammonia, synthetic methane, and synthetic liquid fuels are considered.
- No cap on import volume has been set for any of the hydrogen energy carriers.

Reference scenario

Estimated by building up the cost of the international supply chain based on IEA's "The Future of Hydrogen," Ohtsuki and Shibata (2022), and other sources. The figure below shows the assumption for 2050.



Low hydrogen prices scenario

Further cost reductions are assumed for the costs of overseas renewable power generation, carrier manufacturing facilities, and storage facilities at ports.

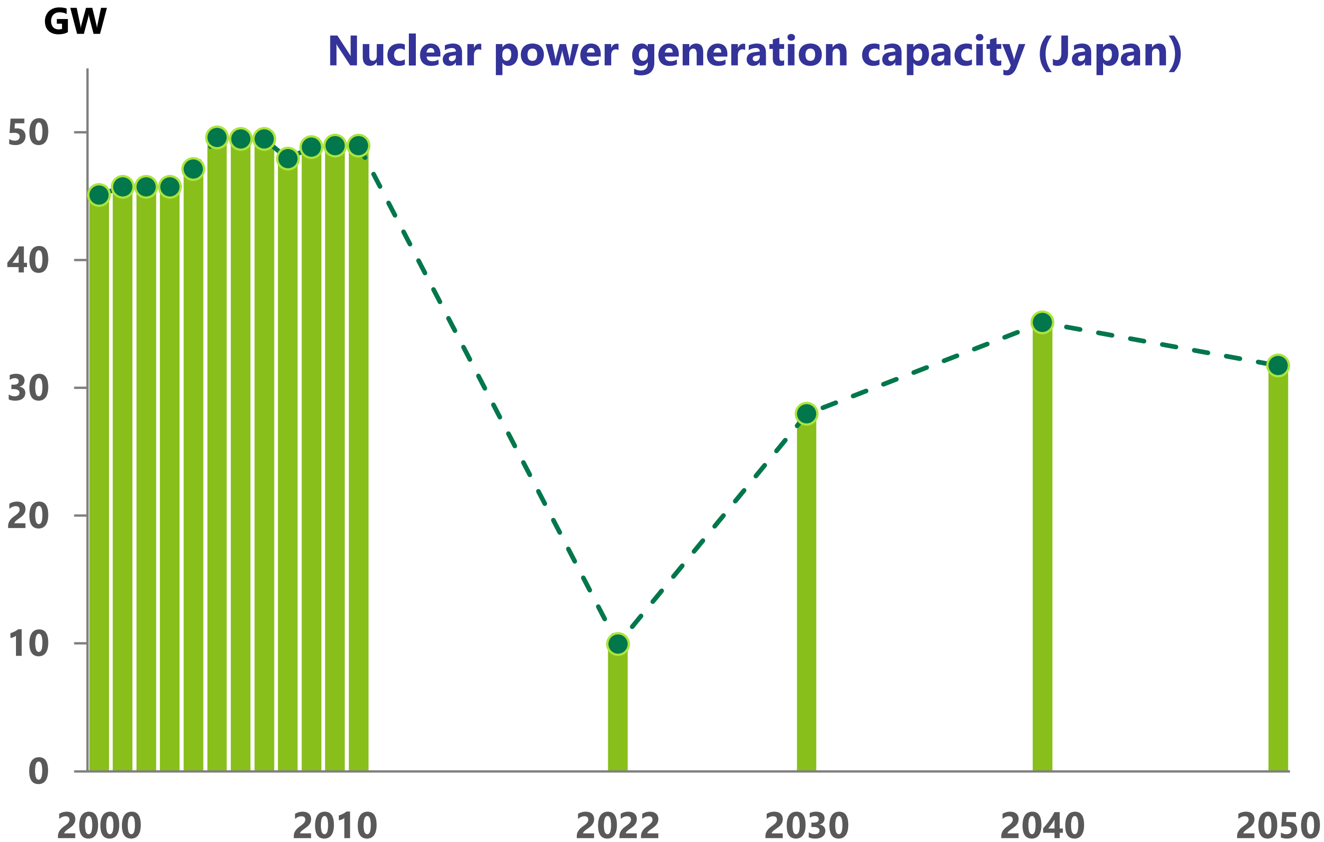
	Assumed prices (2050)
Hydrogen	JPY42/Nm^3-H_2
Ammonia	JPY25/Nm^3-H_2
Synthetic methane	JPY42/Nm^3-H_2
Synthetic liquid fuel	JPY48/Nm^3-H_2

- Prices are in 2022 Japanese yen. Assumes an exchange rate of 130.7 yen/USD.
- For hydrogen (liquefied hydrogen and MCH), reconversion costs after unloading are included
- Hydrogen and ammonia are assumed to be produced from natural gas reforming with CCS, and synthetic methane and synthetic liquid fuels are assumed to be produced from electrolytic hydrogen and atmospheric CO_2. For natural gas reforming with CCS, a carbon tax of 250 USD/tCO_2 is added for CO_2 released to the atmosphere, based on IEA WEO (2023).
- The range of cost reductions from the reference assumption to the hydrogen technology progress assumption varies depending on the differences in the cost structure of each carrier.

(Source) Otsuki and Shibata (2022), Estimation of Production and Supply Cost of Synthetic Methane, 9th Public-Private Conference on Methanation Promotion, Document 3-4,

Nuclear power generation capacity

- It is assumed that the three reactors under construction will be put into operation, while several existing reactors will be decommissioned.
- The reactors that were not decommissioned will be restarted by around 2030, with the lifetime being extended to 60 years.
- “Outages due to external factors” were excluded from the calculation of operating years.
- Total nuclear capacity in 2040 and 2050 will be 35 GW and 32 GW, respectively.

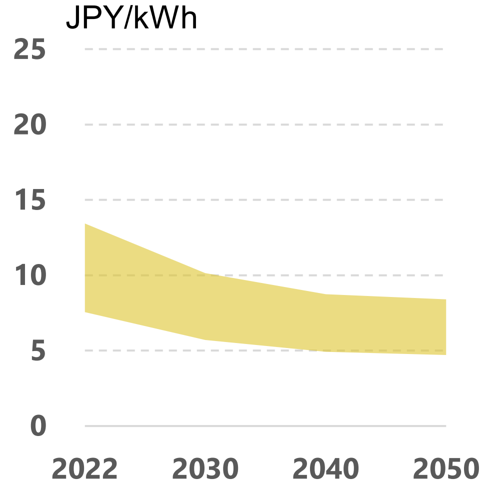


(Sources) Estimated by the IEEJ. Actual figures are from Japan Nuclear Energy Industries Association

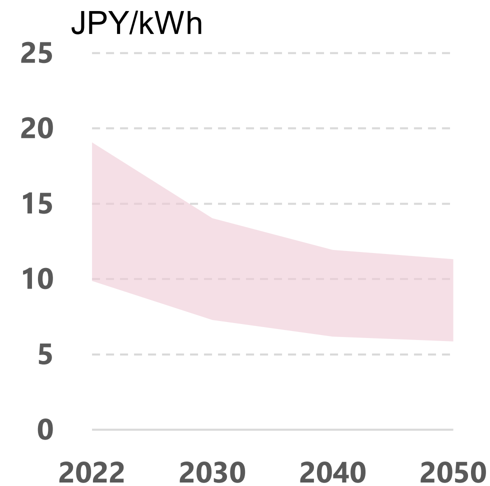
Solar and wind power generation costs (LCOE)

- The generation cost of each power source is assumed by the estimation of the Power Generation Costs Analysis WG. The levelized costs of electricity (LCOE), converted at the real discount rate of 3%, are shown in this slide.
- The LCOE are set in a range based on location conditions and capacity factors, and increase as the installation progresses. (For details, see slide 22)

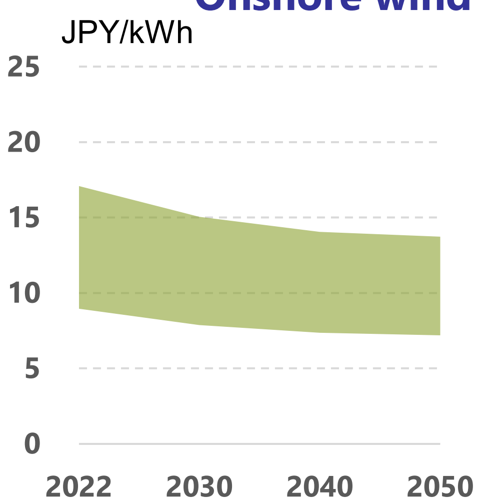
Solar PV (Ground-mounted)



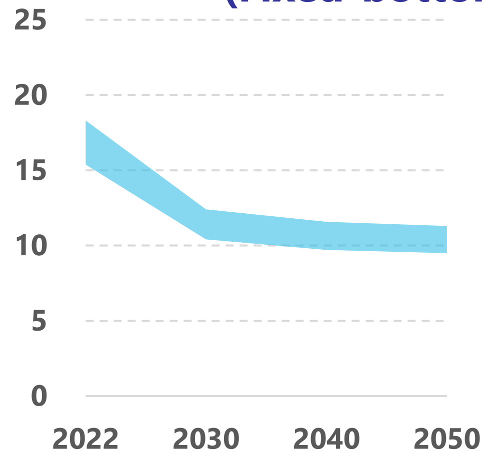
Solar PV (Rooftop)



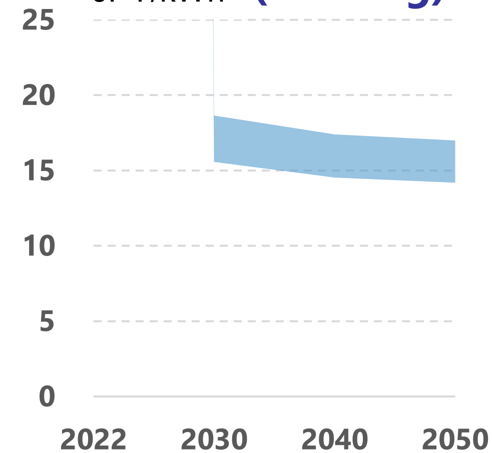
Onshore wind



Offshore wind (Fixed-bottom)



Offshore wind (Floating)



Solar and wind potentials

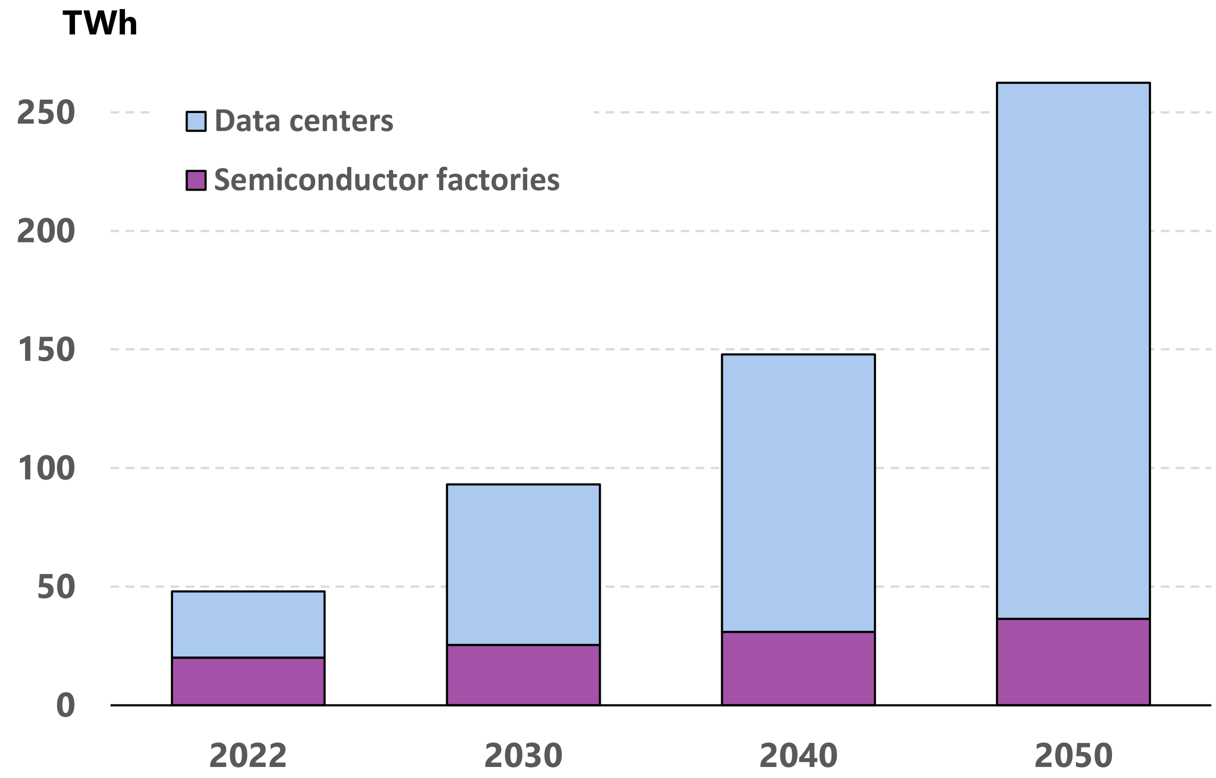
- Solar and wind potentials are assumed for two cases ("Reference" and "High") based on Obane et al. [4].

	Assumptions
PV (Rooftop) (Households)	**Reference** Installed on south, east, and west-facing roofs [4]. **High** Installed on south, east, west, and north-facing roofs [4].
PV (Rooftop) (Buildings)	**Reference** Installed on 7.9%-38.8% of all roof area (based on actual PV installation) depending on building type [4]. **High** Installed on 49.9% of the total roof area [4][5].
PV (Ground-mounted) **Onshore wind**	**Reference** Excludes all types of areas regulated by ordinances [4]. **High** Excludes some of the areas regulated by ordinance [4]. In all cases, it is assumed that all existing facilities, including those in forests, and facilities undergoing environmental assessment will remain in place in 2050.
PV (Farm)	**Reference** Assumes that all of the 840,000 agricultural enterprises (as of 2023) will install 50 kW of solar power generation, which is the range in which the appointment of a chief electricity engineer is not required. (Asano et al. [6]) **High** Installed on all farmland (Ministry of Environment [5]).
Offshore wind	**Reference** Installed in waters with offshore distances of 10-100 km. **High** Installed in the sea area of 0-370.4km (EEZ) away from shore.

*In Europe, China, and other countries where offshore wind facilities have massively been introduced, they can only be installed a few kilometers away from land due to landscape impact and other considerations. ([7], [8])

Power demand of data centers and semiconductor plants

- Increased power demands by future semiconductor factories are estimated based on existing plans and global semiconductor market forecasts.
- The increase in power demands by data centers is assumed based on the estimates by the Central Research Institute of Electric Power Industry [9].
- The power demand increase from current levels will reach 100 TWh by 2040 and 214 TWh by 2050.



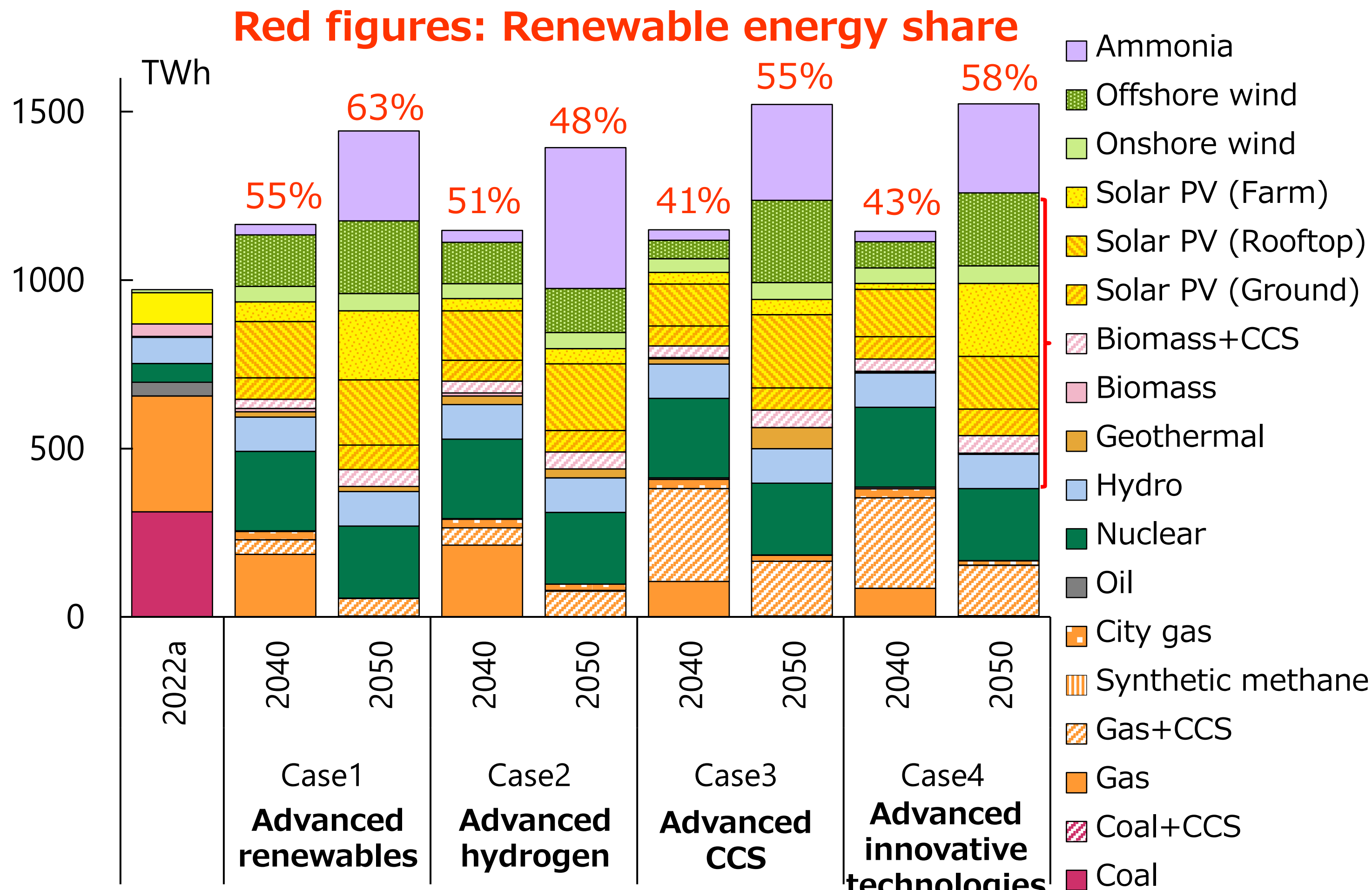
Scenario setting

- Four scenarios are analyzed with the constraint of net zero CO_2 emissions in 2050.
- The electricity sector uses a subjective discount rate of 8%, except for solar PV and wind, for which a discount rate of 5% is assumed.

Case	Renewables	Hydrogen	CCS
Case1 **Advanced renewables**	High	Reference	120 million tons/year in 2050
Case2 **Advanced hydrogen**	Reference	Low prices	120 million tons/year in 2050
Case 3 **Advanced CCS**	Reference	Reference	240 million tons/year in 2050
Case4 **Advanced Innovative Technologies**	High	Low prices	240 million tons/year in 2050

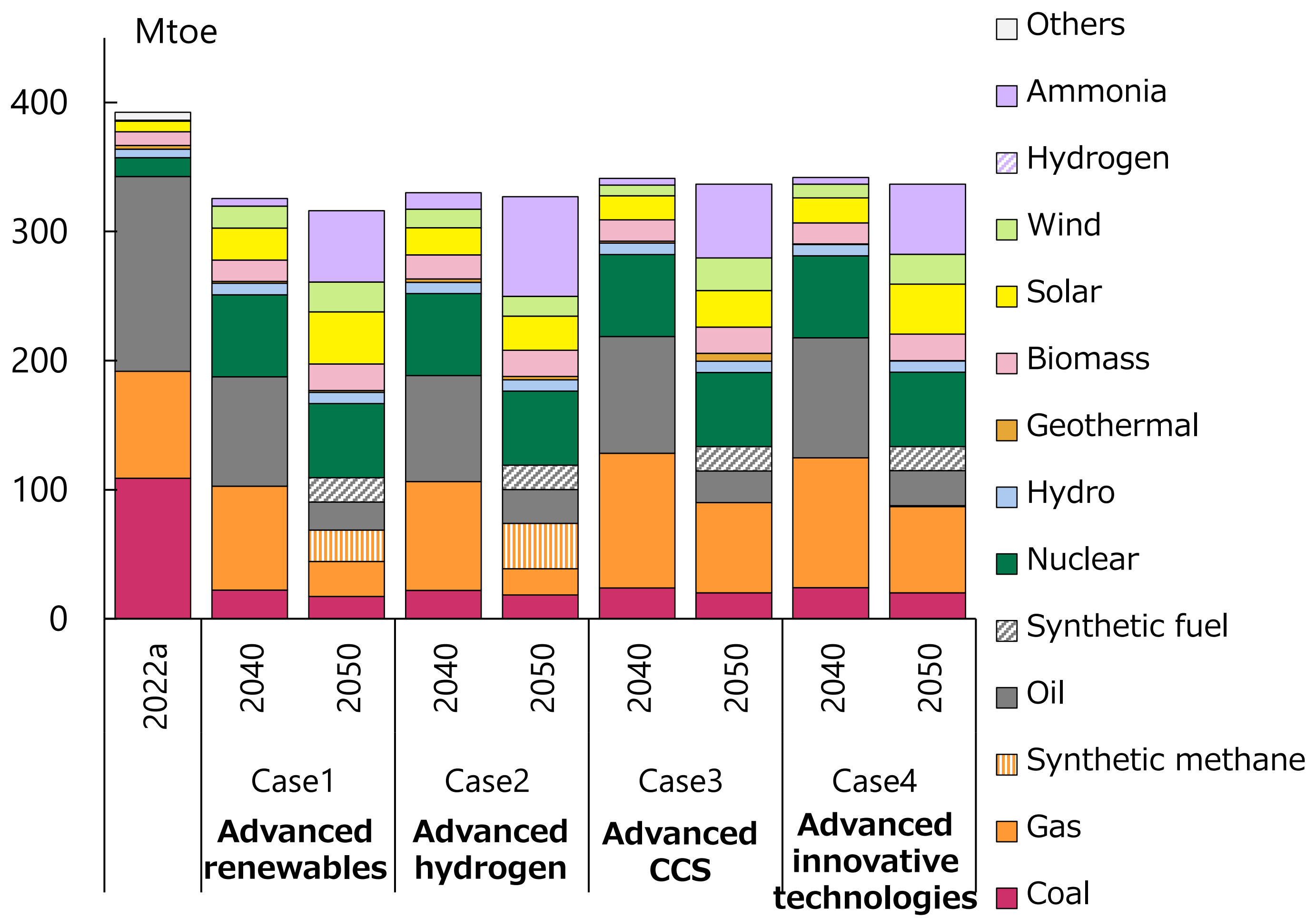
Power generation mix

- The renewable shares in the optimal (i.e., minimum cost) energy mix in 2040 and 2050 are 41%-63%, varying widely depending on assumptions.
- The share may not always increase from 2040 to 2050, since it is assumed that electricity consumption will increase and the cost of hydrogen carriers will decrease.



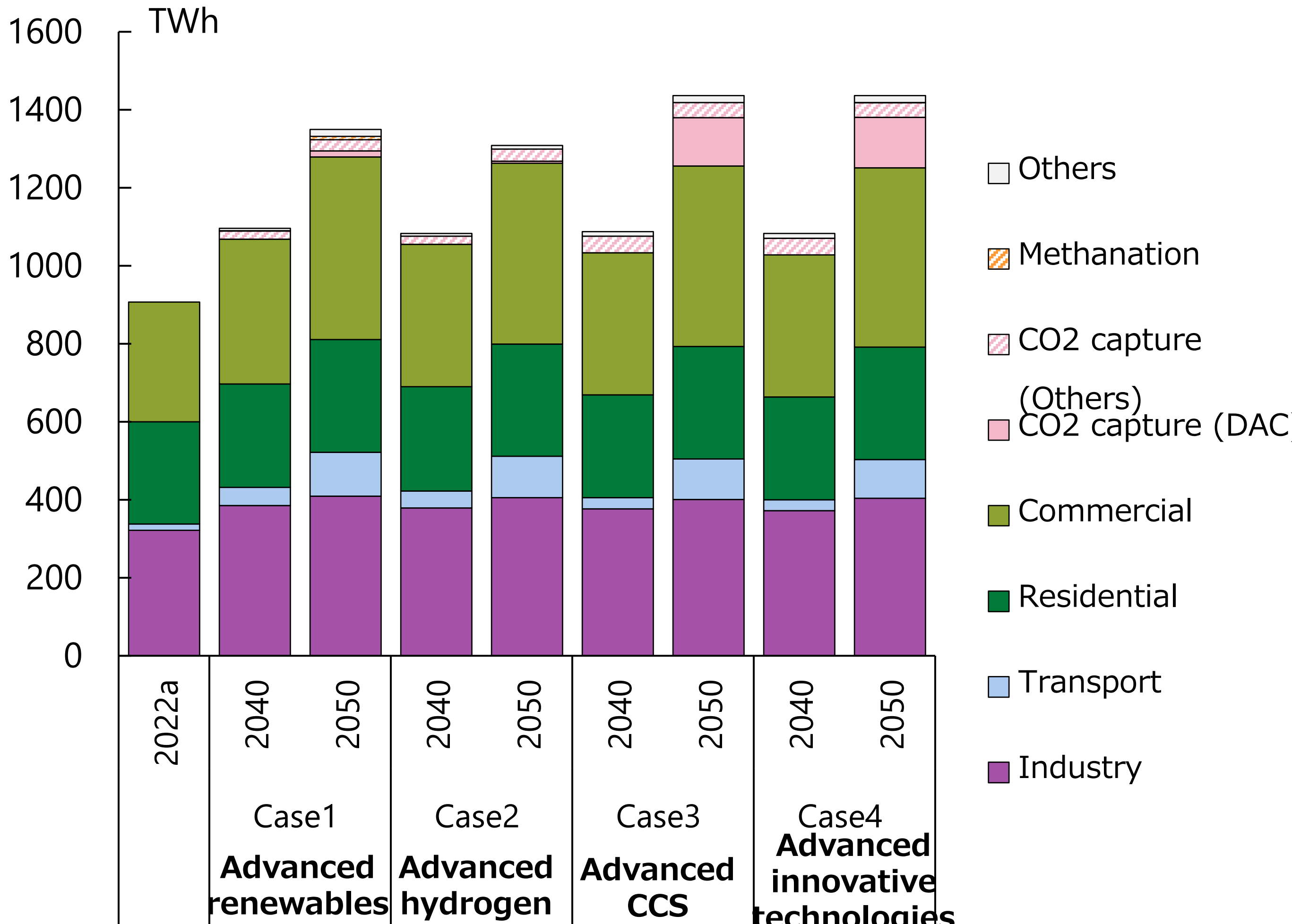
Primary energy supply

- Primary energy supply will decrease from 392 Mtoe in 2022 to 320-340 Mtoe in 2040.
- The share of fossil fuels will be greatly reduced from 87% in 2022 to 57%-64% in 2040 and 20%-34% in 2050. In contrast, the share of renewables and hydrogen energy carriers will increase, and the latter will be around 20% in 2050.



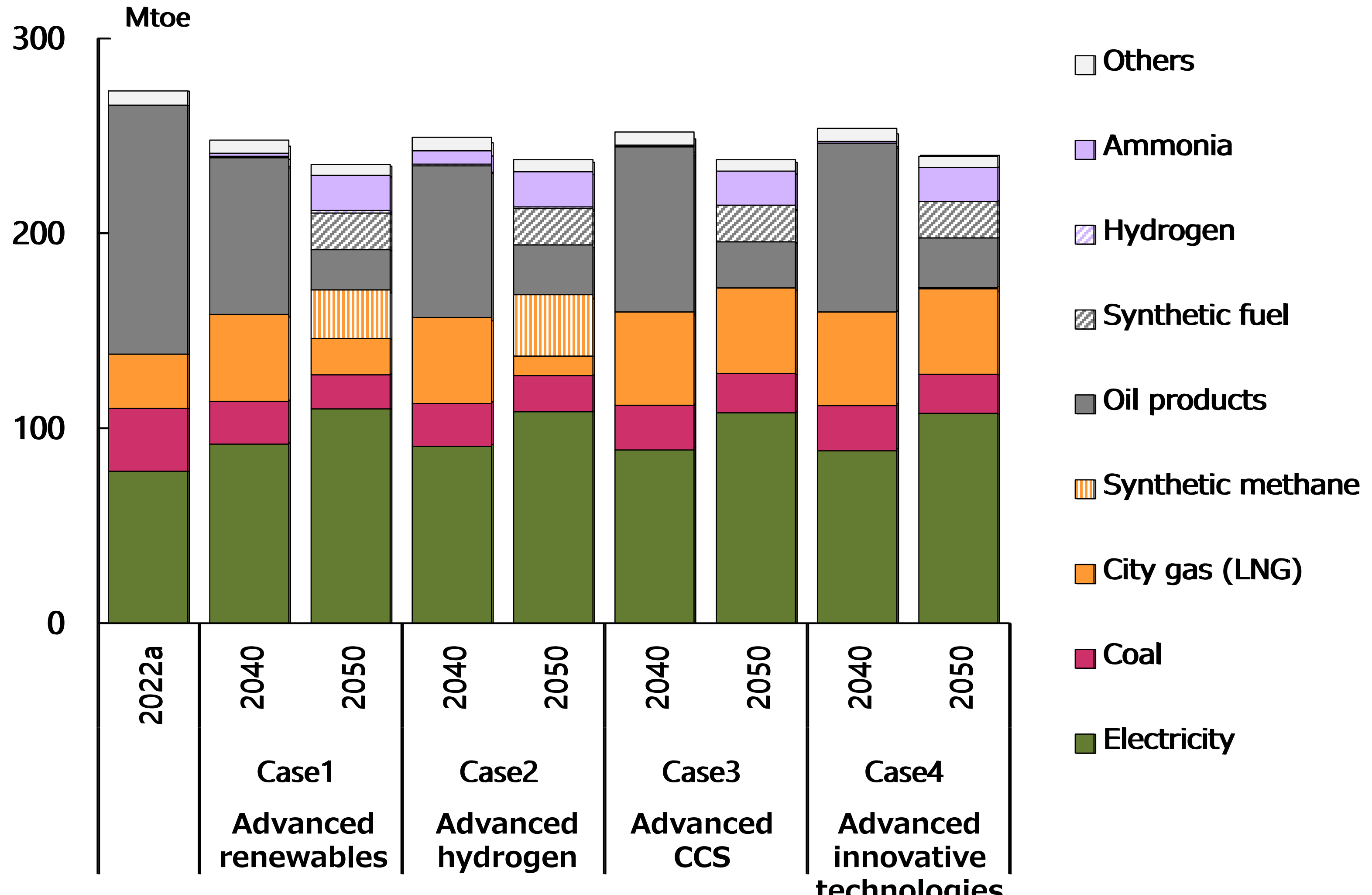
Electricity demand

- Electricity demand will rise significantly, not only due to increased demand for power from data centers and semiconductor factories, but also due to the need to decarbonize the energy demand sector, from 907 TWh in 2022 to 1,080-1,100 TWh in 2040 and 1,310-1,440 TWh in 2050.
- In Cases 3 and 4, where the CCS storage capacity is high, more than 100 TWh of electricity is used for direct air capture (DAC) of carbon dioxide.



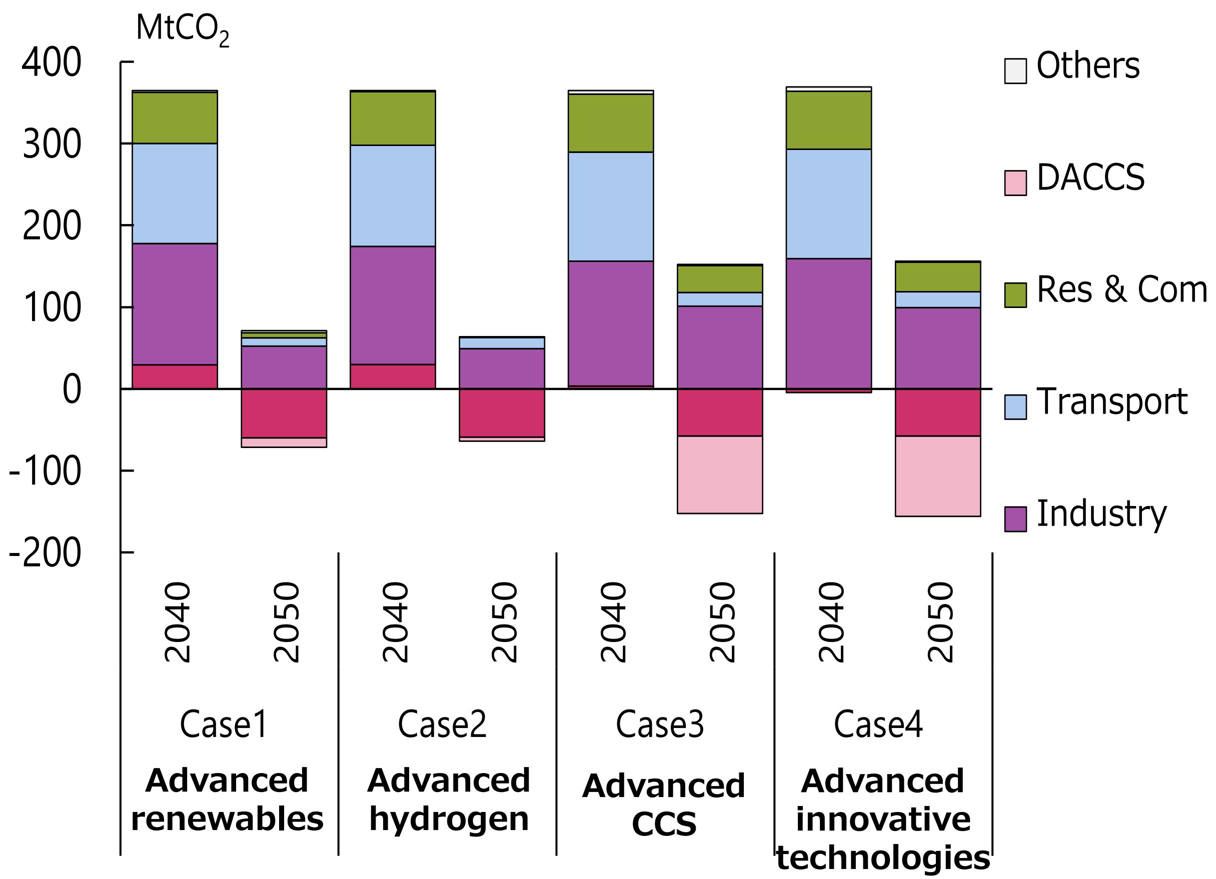
Final energy consumption

- Total final energy consumption will decline, falling from 2022 by 7%-9% by 2040 and 12%-14% by 2050.
- The share of electricity will increase from 30% in 2022 to 35%-37% in 2040 and 45%-47% in 2050. Still, other energy demands account for more than half of total final energy consumption.



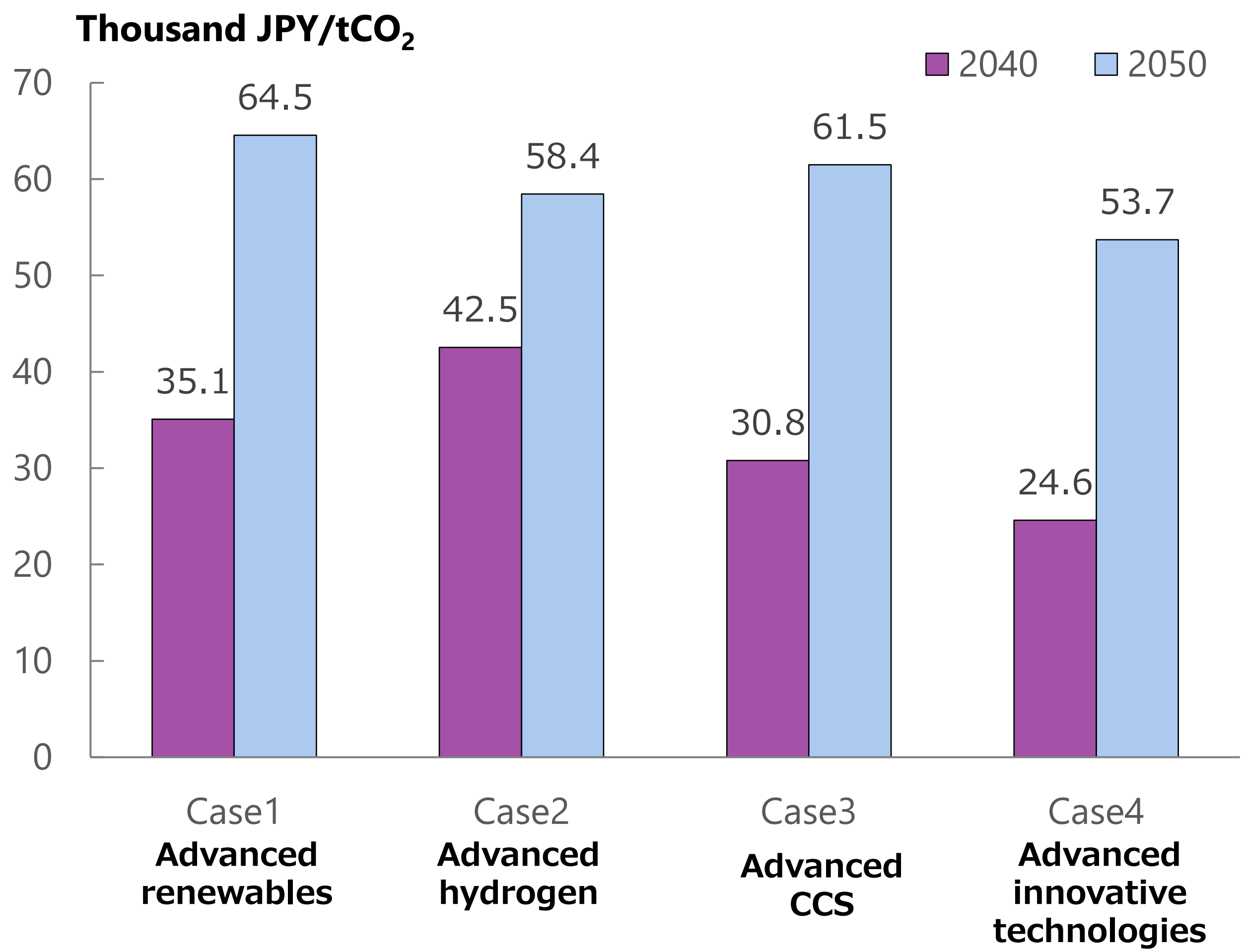
CO_2 emissions by sector

- In 2040, large CO_2 emissions will remain in industry, transportation and other sectors.
- In 2050, CO_2 emissions will remain especially in the industrial sector, and will be offset by negative emission technologies (NETs) such as BECCS (biomass power generation + CCS) and DACCS (direct air capture of CO2 and CCS).
- The amount of NETs is particularly large in Cases 3 and 4.



Marginal abatement cost of CO_2

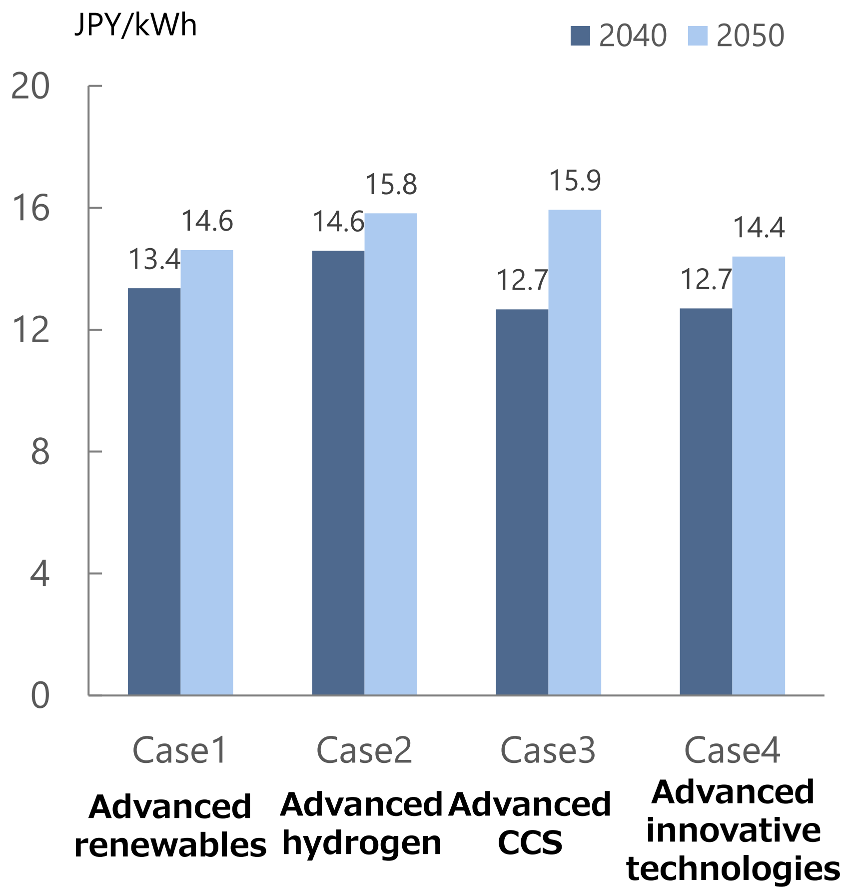
- The marginal abatement costs of CO_2 will rise significantly in all cases:
  JPY 25-43 thousand/tCO_2 in 2040 and JPY 54-65 thousand/tCO_2 in 2050.
- The figure in the innovative technology expansion case (Case 4) is lower than in the other cases, suggesting the impact of technological innovation to achieve carbon neutrality.



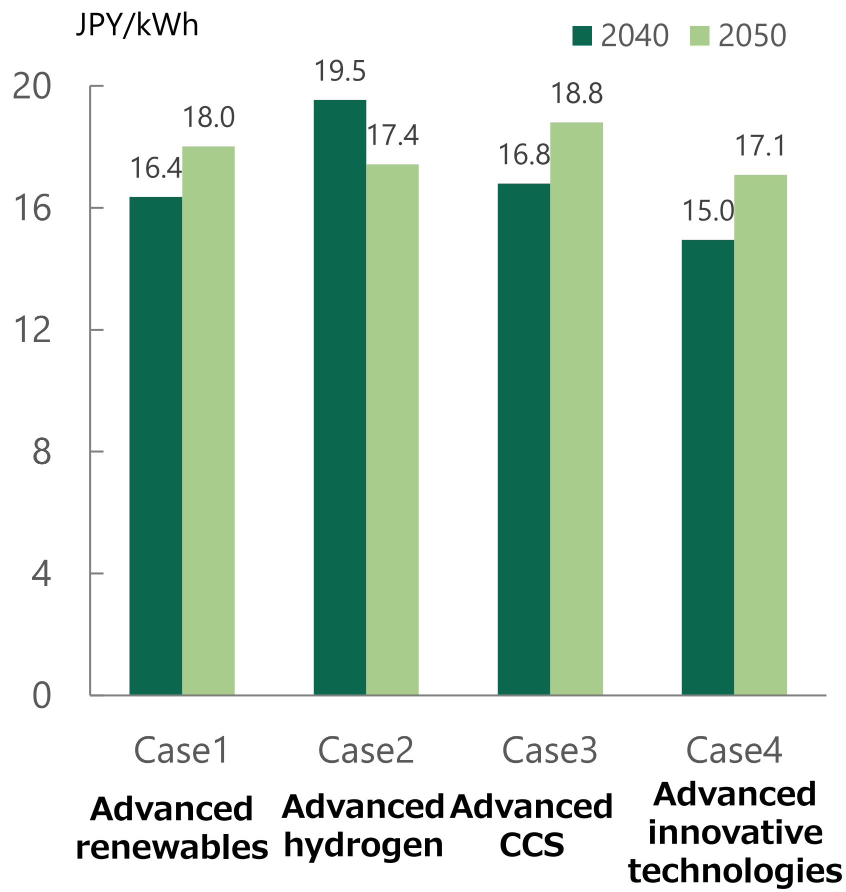
Average and marginal costs of electricity

- The average electricity cost will rise to JPY 12.7-14.6/kWh in 2040 and JPY 14.4-15.9/kWh in 2050, while the marginal electricity cost will rise to JPY 15.0-19.5/kWh in 2040 and JPY 17.1-18.8/kWh in 2050.
- They are the lowest in the innovative technology expansion case.

Average electricity cost



Marginal electricity cost



Conclusion

- In order to decarbonize the energy system for the long-term future, the power generation sector must be decarbonized, and energy demands must be converted to electricity with improved energy efficiency.
- Electricity demand is expected to increase over the long term, and this will need to be met by low-carbon generation technologies. The “optimal” power generation mix is determined by the total system cost of the energy system as a whole, not just the technology alone, which can vary widely depending on various assumptions.
- Electricity will still account for less than 50% of final energy consumption, and it is highly likely that a certain amount of fuels other than electricity will remain in energy demand sectors. Thus, it will be necessary to decarbonize fuels or reduce or offset CO_2 emissions through CCS or negative emission technologies (NETs).
- Importing decarbonized energy from abroad is considered essential, including hydrogen energy carriers (hydrogen, ammonia, synthetic methane, synthetic liquid fuels) and the transport of CO_2 abroad. Which of these options will actually be used depends on future cost assumptions; the results of this analysis are only an example.
- The hurdles to achieving carbon neutrality in 2050 are high, with marginal abatement costs of CO_2 rising to around JPY 60,000/tCO_2 under any scenario. To achieve this goal without a significant impact on people ‘s lives, efforts to reduce the cost of innovative technologies will be essential, along with appropriate policy support for them.
- Given the uncertainties in the model estimates, it would be desirable to pursue a variety of technology options and a balanced energy mix.

Reference materials

Low-carbon technologies considered in the model

The model calculates the optimal configuration of over 500 technologies.

Low-carbon technologies considered in the model (excerpts)

Highly efficient technology		High-efficiency equipment on the energy supply and demand side
Nuclear power		Light-water reactors
Renew-able energy	Solar PV	Ground-mounted, rooftop (south, east, west, and north), farms
	Wind	Onshore wind, offshore wind (fixed-bottom and floating)
	Others	Large hydro, small and medium hydro, geothermal, biomass
CCUS	Capture	Power generation, hydrogen production, blast furnaces, chemical industry, direct air capture
	Utilization and storage	Methane synthesis, liquid fuel synthesis, domestic geological storage, overseas geological storage
Hydro-gen carrier	Import	Liquid hydrogen, methylcyclohexane, ammonia, synthetic methane, FT synthetic fuel
	Hydrogen utilization	Mono-fired power generation, direct hydrogen reduction steelmaking, boilers and industrial furnaces for the chemical industry, automobiles, ships, fuel synthesis
	Ammonia use	Mono-fired power generation, coal/ammonia co-firing, ships, boilers and industrial furnaces for the chemical industry
Energy storage		Pumped hydro, Li-ion batteries, NaS batteries, redox flow batteries, hydrogen storage
Demand response		Electricity demand shift by charging electric vehicles, VtoG for passenger electric vehicles, and heat pump water heaters
Negative emission technology		Direct air capture + CO_2 storage, biomass-fired power generation + CO_2 capture and storage

Model input/output data

- Input data includes energy service demand through 2075, costs and efficiencies of technologies, and upper/lower limits of the introduction of facilities.
- The results of the analyses will provide information on the optimal combination of energy-related technologies, as well as economic indices.

Input	
Demand	• Energy Service Demand • Hourly power load curve
Cost efficiency	• Energy import prices • Costs and efficiencyies
Upper limits for intro-duction	• Renewable energies • CO_2 Storage • Nuclear power
Other	• CO_2 Constraints • Hourly VRE output • Distance between regions (land and sea) • Existing capacity, etc.

Minimize the cumulative total system cost until 2075 under CO_2 restrictions

*The total system cost includes the cost of imported fuels and equipments, as well as those for operation and maintenance

Output	
Energy mix	• Primary energy mix • Power generation mix • Hydrogen supply • Final energy consumption, etc.
Tech-nology	• Equipment capacity • Operation
Eco-nomc efficiency	• System cost • Marginal costs (Energy prices) • Marginal abatement cost of CO_2 • Shadow prices of facilities, etc.

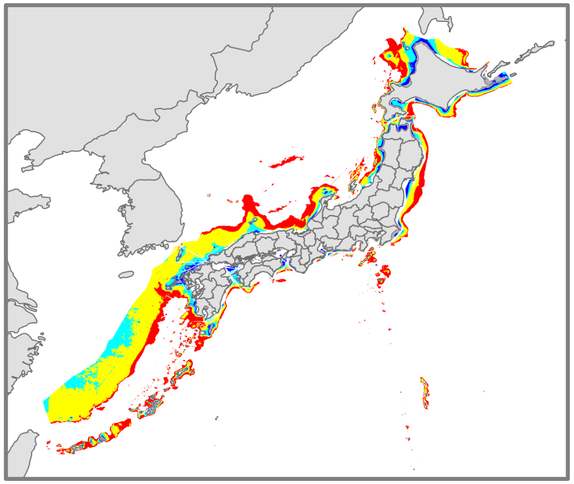
Model details

Formularization	• Linear programming
Analysis period	• Optimization calculations are performed over the entire period from 2022 to 2075, with six representative years.
Regional resolution	• 5 regions (Hokkaido, Tohoku, Kanto, Western Japan, Kyushu&Okinawa)
Time resolution	• Electricity generation and hydrogen: Calculated on an hourly basis for a representative year. Explicitly considers output variability of renewable energy sources, as well as hydrogen storage costs required during hydrogen and synthetic fuel production. • For items other than those above, the yearly supply-demand balance is considered.
Greenhouse gas	• Energy-derived CO_2
Inter-regional transportation	• Electricity, hydrogen, methane, and CO_2
Final consumption sectors	**Energy service demand** • Final consumption is represented as 39 types of energy service demand. • Energy demand for semiconductor factories and data centers. **Energy demand sectors** • Industries: Steel, cement, chemicals, paper and pulp, other industries • Transportation: passenger cars, buses, light trucks, small trucks, heavy trucks, railway, aviation, and navigation • Buildings: Residential and commercial
Number of technologies	• Bottom-up modeling of over 500 supply- and demand-side technologies

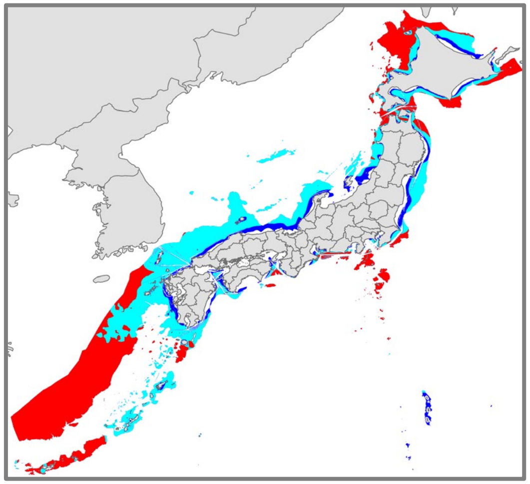
Offshore wind power grading

- Offshore wind power generation is assumed to be installed in the potential promotion areas based on the Japanese zoning rule by referring to Obane et al [7] [8].
- Unlike photovoltaic power generation, capital costs and facility utilization rates for offshore wind power vary greatly depending on the water depth and wind conditions in the sea where it is installed. Therefore, the model was divided into a total of 60 grades by model node, water depth, and average annual wind speed,
- This allows offshore wind power to be introduced in the order of the lowest generating cost, which is determined by the capital cost and facility utilization rate in the optimization model.

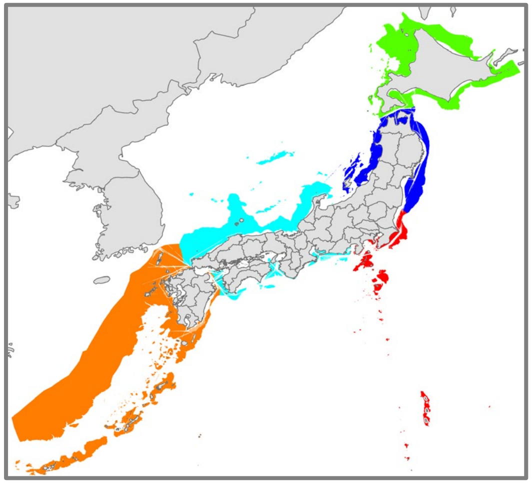
Classification by depth (4 grades)



Classification by wind speed (3 grades)



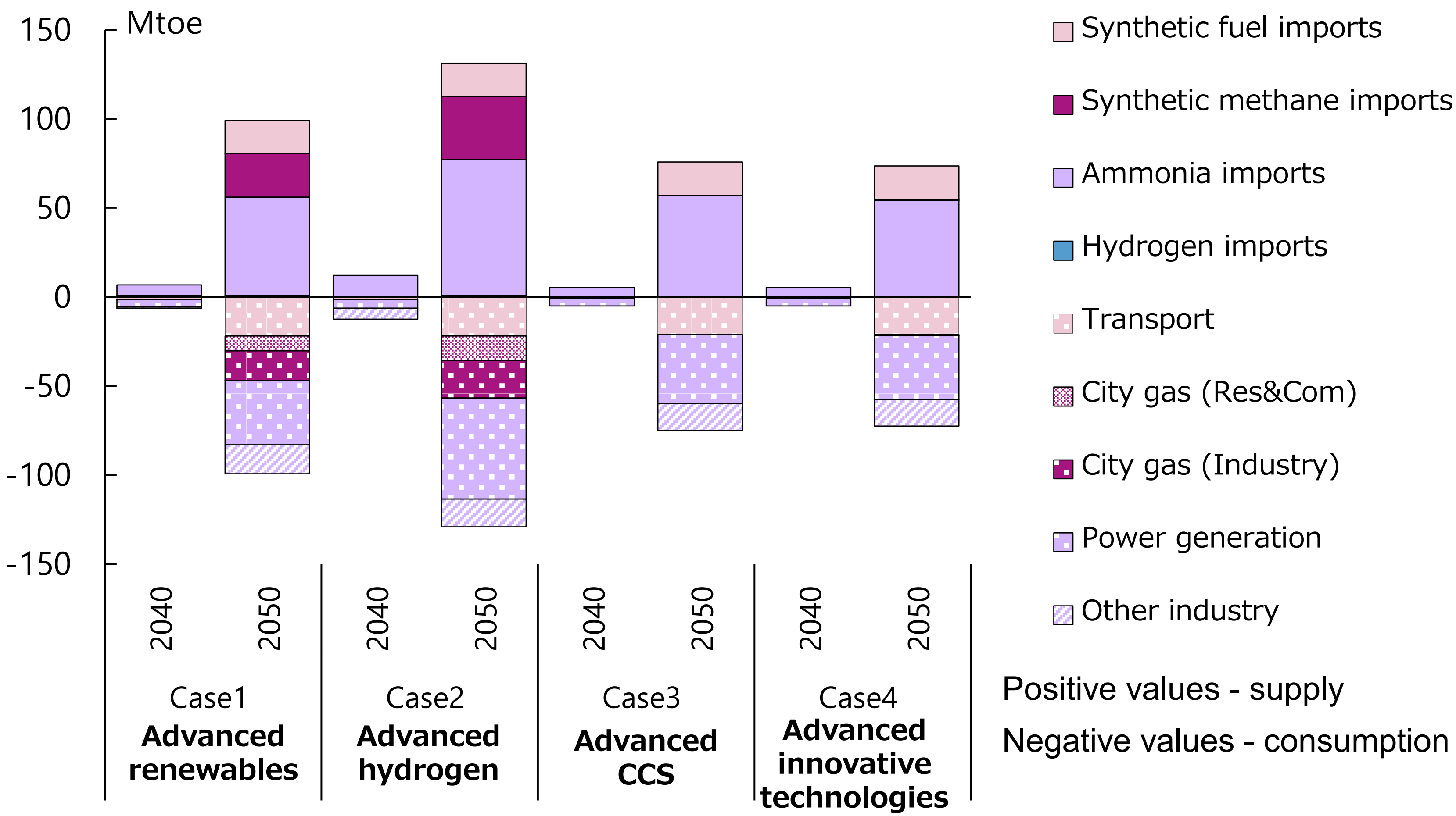
Classification by grid areas (5 grades)



→ By classification in 60 grades, offshore power generations will be installed in locations where the cost of electricity generation is higher as the amount installed increases in the model.

Hydrogen balance

- From 2040 to 2050, hydrogen and other hydrogen energy carriers such as ammonia, synthetic methane, and synthetic liquid fuels will be imported and used for power generation, city gas substitution, transportation, and industry.
- How zero-emission fuels are used (e.g., hydrogen in transportation or synthetic liquid fuels) depends heavily on cost assumptions.

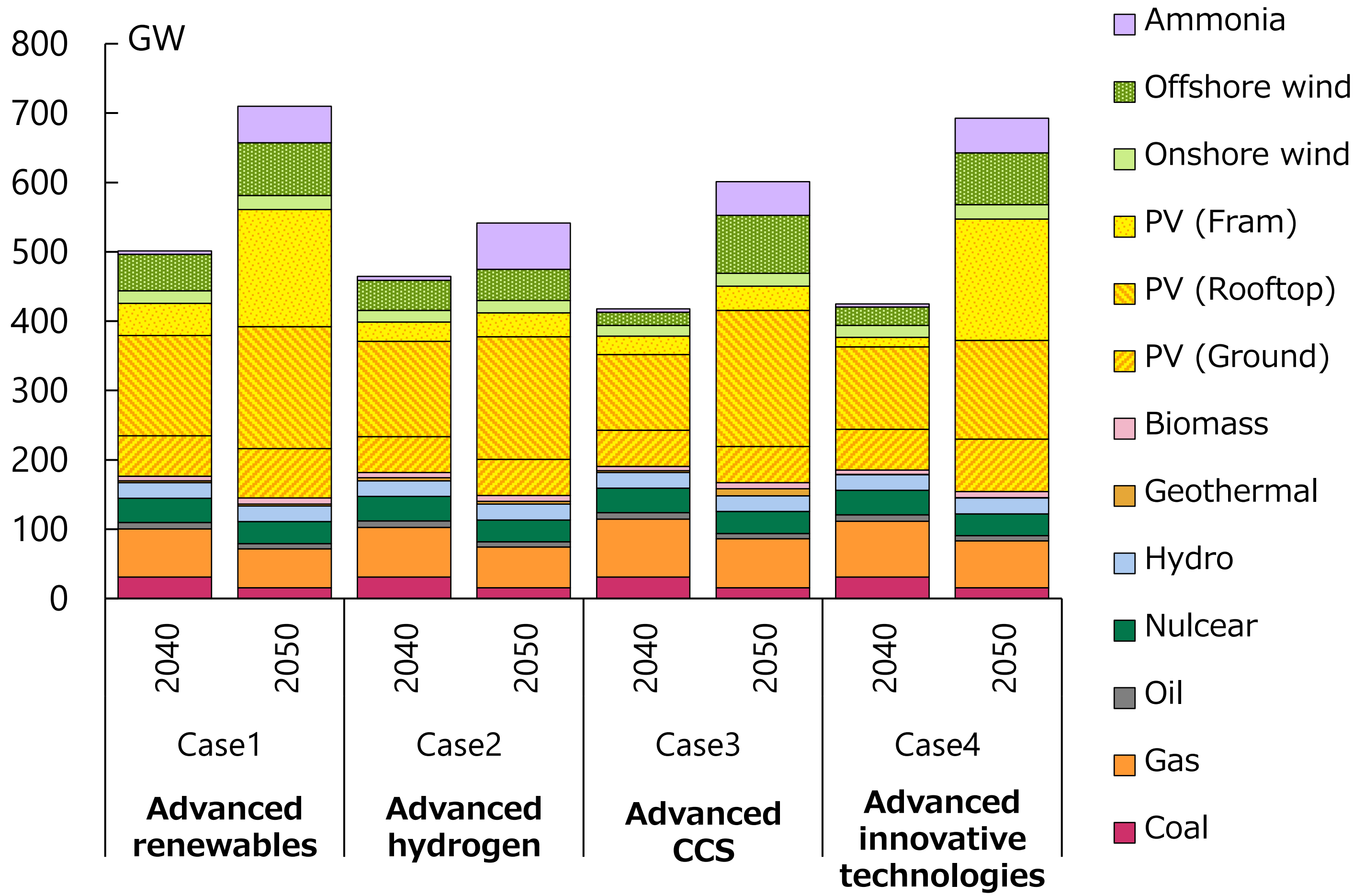


Positive values - supply

Negative values - consumption

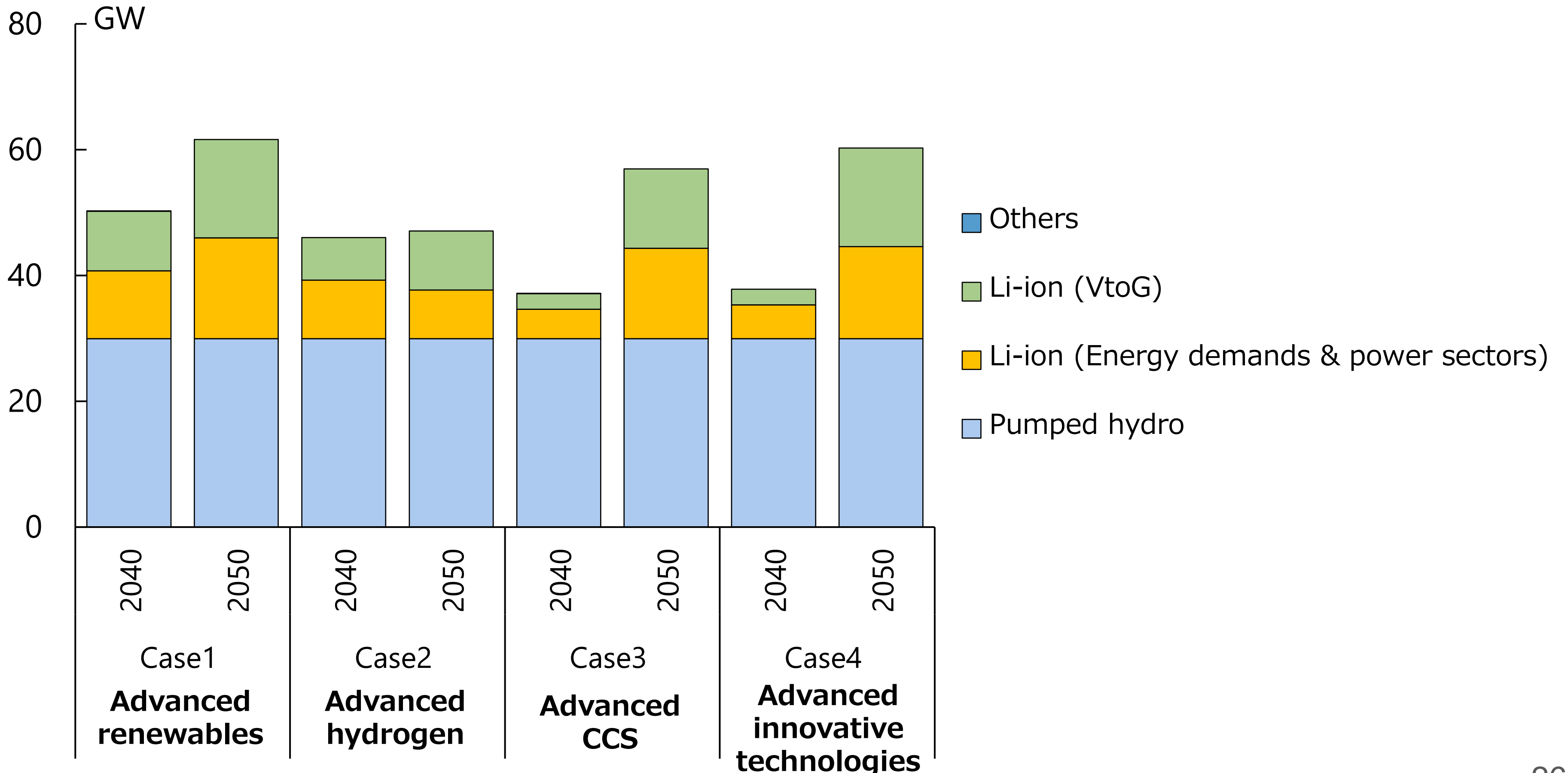
Power generation capacity

- The installed capacity of renewable energy generation will expand rapidly. Solar PV and wind will reach 188-249 GW and 35-71 GW, respectively, by 2040, and reach 263-416 GW and 63-102 GW, respectively, by 2050.



Energy storage facility capacity

- As the introduction of renewable energy generation expands, storage facilities will need to be expanded.
- In the figure below, "VtoG" shows the installed capacity of discharge equipment from electric vehicles. It is assumed that demand response (DR) by shifting the charging time of electric vehicles is possible even when discharge equipment is not installed.



References

[1] Takashi Otsuki, Hideaki Obane, Yasuaki Kawakami, Kei Shimogori, Yuji Mizuno, Soichi Morimoto, Yuhji Matsuo, Energy mix for net zero CO_2 emissions by 2050 in Japan, IEEJ Transactions on Power and Energy, 142(7), pp. 334-346, July 2022 , DOI: 10.1541/ieejpes.142.334

[2] Takashi Otsuki, Yoshiaki Shibata, Yuhji Matsuo, Hideaki Obane, Soichi Morimoto, Role of carbon dioxide capture and storage in energy systems for net- zero emissions in Japan, International Journal of Greenhouse Gas Control, Volume 132, February 2024, 104065, DOI: 10.1016/j.ijggc.2024.104065

[3] Takashi Otsuki, Ryoichi Komiyama, Yasumasa Fujii, Hiroko Nakamura, Temporally Detailed Modeling and Analysis of Global Net Zero Energy Systems Focusing on Variable Renewable Energy, Energy and Climate Change, Volume 4, December 2023, 100108, DOI: 10.1016/j.egycc.2023.100108

[4] Hideaki Obane, Akiko Sasagawa, Soichi Morimoto, Yoshiaki Shibata, Takashi Otsuki, Evaluation of Photovoltaic Potential Considering Local Ordinances and Building Characteristics.JST Social Scenario Research Report No. R6-01, August 2024 DOI: 10.5281/zenodo.13328721
http://www.hondo.ynu.ac.jp/JST/assets/docs/obane_et_al_2024.pdf

[5] Ministry of the Environment, Report on Commissioned Work for Maintenance and Publication of Basic Zoning Information on Renewable Energy in Fiscal Year 2048
https://www.renewable-energy-potential.env.go.jp/RenewableEnergy/report/r01.html

[6] Kenji Asano, Yu Nagai, Hideaki Obane, Study on Mass Introduction Scenario of Wind Power and Photovoltaic Power Generation for Realization of Net Zero, Basic Policy Subcommittee, Advisory Committee on Natural Resources and Energy, Agency for Natural Resources and Energy, METI (34th Meeting).
https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/034/034_007.pdf

[7] Hideaki Obane, Yu Nagai, Shinsuke Toyonaga, Kenji Asano, "A Study on the Potential Promotion Areas for Offshore Wind Power Utilization Considering the Renewable Energy Sea Area Utilization Law," Research Papers Y19502, Institute of Social and Economic Research, 2019.
https://criepi.denken.or.jp/jp/serc/research/publications/view?indexId=46

References

[8] Hideaki Obane, Yu Nagai, Kenji Asano, Assessing the potential areas for developing offshore wind energy in Japanese territorial waters considering national zoning and possible social conflicts, Marine Policy, Vol 129, 2021 zoning and possible social conflicts, Marine Policy, Vol 129, 2021

[9] Takayuki Mase, Kazuyoshi Nakano, Shunichi Hienuki, Shogo Sakamoto, Assumption of Long-Term Electricity Demand in Japan until FY2050 - Tentative Estimation Results of Basic Demand and Additional Factors (Energy Saving and Electrification) -, January 24, 2024, Wide-Area Management Promotion Organization of Electric Power Industry, Study Group on Future Electricity Supply and Demand Scenarios, 3rd Study Group. The 3rd meeting of the study group on future electricity supply and demand scenarios, January 24, 2024. https://www.occto.or.jp/iinkai/shorai_jukyu/2023/files/shoraijukyu_03_02_01.pdf