IRENA Forum

June 8th, 2021

Scenario Analyses for 2050 Carbon Neutrality in Japan

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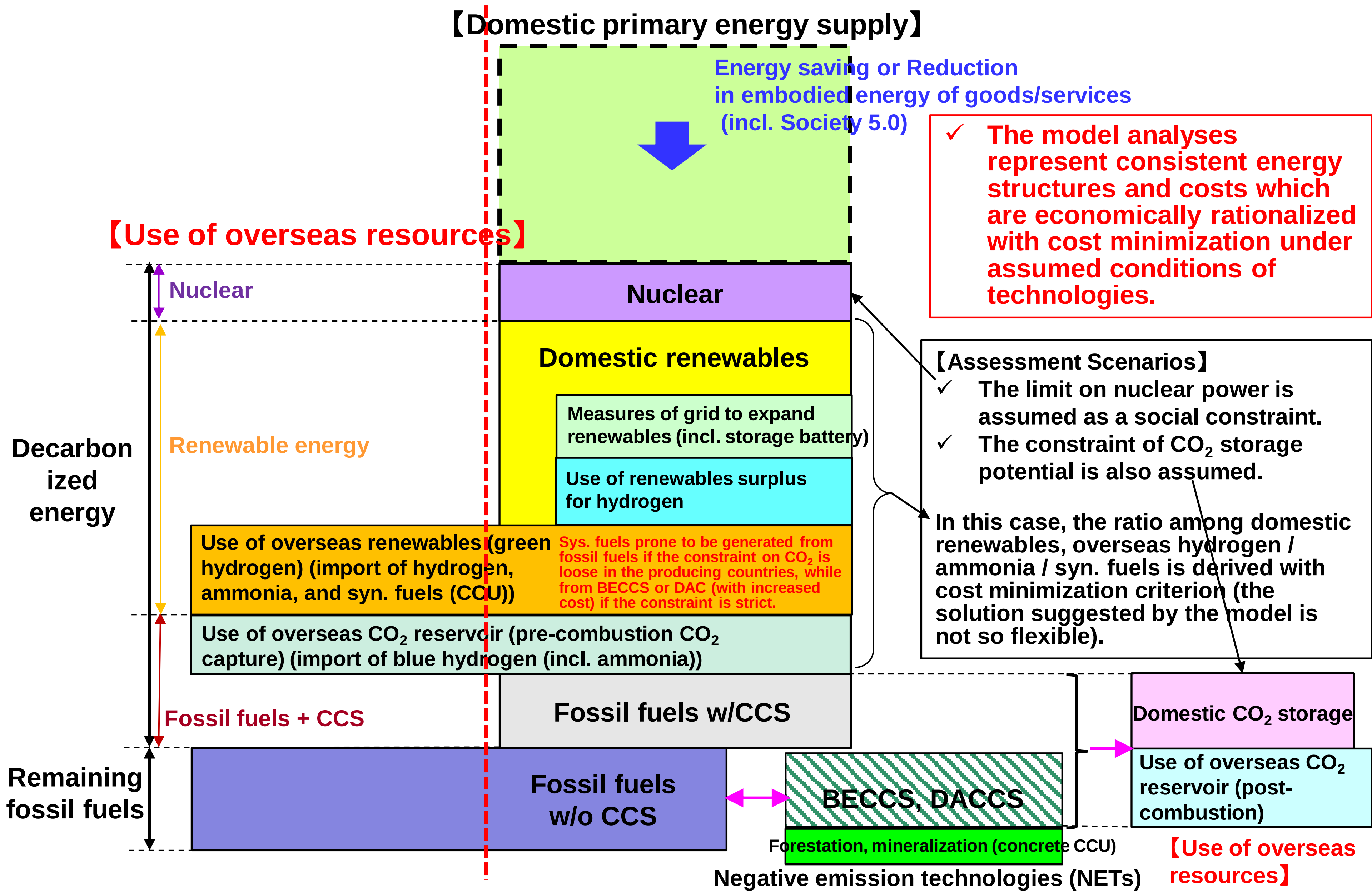
Image of Primary Energy in Japan for Net Zero Emissions

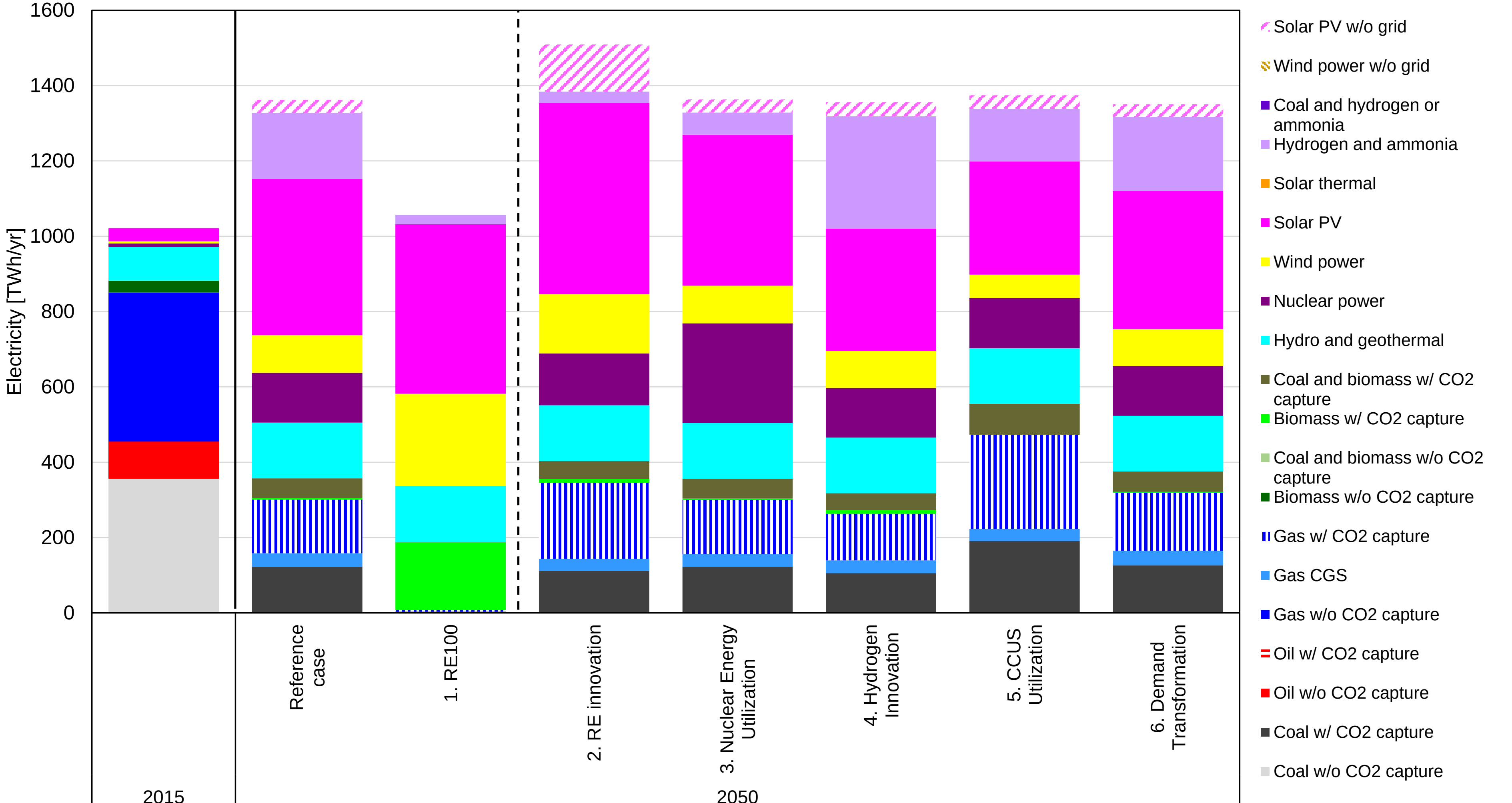


Scenario Assumption for GHG Net Zero Emissions in Japan and Share of Renewables in Total Electricity Supply in 2050

<table>
<tr><th>Scenario</th><th>Cost of renewable energy</th><th>Ratio of nuclear power</th><th>Cost of hydrogen</th><th>CCUS (Storage potential)</th><th>Fully autonomous driving (Car ride sharing)</th><th>Share of RE in total electricity</th></tr>
<tr><td>Reference Case*1</td><td rowspan="2">Standard cost</td><td>10%</td><td rowspan="4">Standard cost</td><td rowspan="2">Domestic storage:91MtCO2/yr, Overseas transportation: 235MtCO2/yr</td><td rowspan="6">Standard assumption (no fully autonomous cars)</td><td>54% (Optimization results)</td></tr>
<tr><td>1. Renewable Energy 100% (RE 100)</td><td>0%</td><td>Almost 100% (Assumption)</td></tr>
<tr><td>2. Renewable Energy Innovation</td><td>Low cost</td><td>10%</td><td rowspan="3">Domestic storage: 91MtCO2/yr, Overseas transportation: 235MtCO2/yr</td><td>63% (Optimization results)</td></tr>
<tr><td>3. Nuclear Power Utilization*2</td><td rowspan="4">Standard cost</td><td>20%</td><td>53% (Optimization results)</td></tr>
<tr><td>4. Hydrogen Innovation</td><td rowspan="3">10%</td><td>Hydrogen production such as water electrolysis, hydrogen liquefaction facility cost: Halved</td><td>47% (Optimization results)</td></tr>
<tr><td>5. CCUS Utilization</td><td rowspan="2">Standard cost</td><td>Domestic: 273MtCO2/yr、Overseas: 282MtCO2/yr</td><td>44% (Optimization results)</td></tr>
<tr><td>6. Demand Transformation</td><td>Domestic: 91Mt, Overseas: 235Mt</td><td>Realization and diffusion of fully autonomous driving and expansion of car ride sharing after 2030, and decrease in material production due to reduction of the number of automobiles</td><td>51% (Optimization results)</td></tr>
</table>

*1: There is no feasible solution without DAC, and DAC is assumed to be available in all scenarios for carbon neutrality by 2050 in Japan.
*2: Nuclear power utilization scenarios up to the share of 50% are also examined.

Electricity Supply in Japan in 2050



✓ **Increases in integration costs are observed in the case where renewable energy share is higher than that in the Reference case. Especially for the RE100 case, a surge in integration costs significantly raises marginal cost of electricity supply, causing considerable decrease in electricity demand. An increase in BECCS instead of fossil fuel with CCS is observed for supply-demand balance.**

Marginal electricity supply costs for carbon neutrality in 2050 : Japan and other developed countries

	Marginal cost of electricity [US$/MWh]
Reference Case*1	221
1. Renewable Energy 100% (RE 100)	485
2. Renewable Energy Innovation	198
3. Nuclear Power Utilization*2	215～177
4. Hydrogen Innovation	213
5. CCUS Utilization	207
6. Demand Transformation	221

	Model estimation for 2020	Reference Case*1	2. Renewable Energy Innovation
Japan	123	221	198
US	57	99	87
UK	99	201	176
France	110	160	147
Germany	115	188	164
North Europe	79	127	111

[US$/MWh]

Note: The costs exclude power transmission and distribution costs excluding grid integration costs of VRE.

✓ **For all the countries, marginal electricity costs increase for achieving carbon neutrality. In Japan larger increases of the costs are estimated due to higher costs of renewables and the grid integration costs, and CO2 storage potentials.**

Appendix

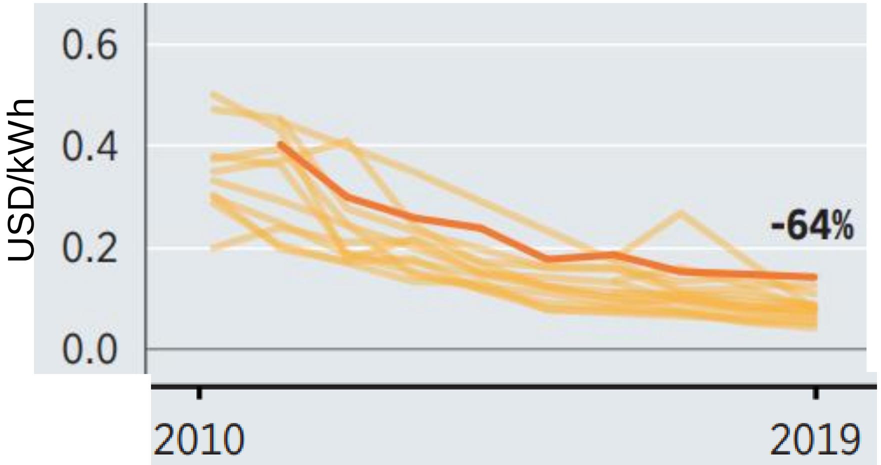
Energy Assessment Model: DNE21+
(Dynamic New Earth 21+)

- Systemic cost evaluation on energy and CO_2 reduction technologies is possible.
- Linear programming model (minimizing world energy system cost; with 10mil. variables and 10mil. constrained conditions)
- Evaluation time period: 2000-2100
  Representative time points: 2005, 2010, 2015, 2020, 2025, 2030, 2040, 2050, 2070 and 2100
- World divided into 54 regions
  Large area countries, e.g., US and China, are further disaggregated, totaling 77 world regions.
- Interregional trade: coal, crude oil/oil products, natural gas/syn. methane, electricity, ethanol, hydrogen, CO_2 (provided that external transfer of CO_2 is not assumed in the baseline)
- Bottom-up modeling for technologies on energy supply side (e.g., power sector) and CCUS
- For energy demand side, bottom-up modeling conducted for the industry sector including steel, cement, paper, chemicals and aluminum, the transport sector, and a part of the residential & commercial sector, considering CGS for other industry and residential & commercial sectors.
- Bottom-up modeling for international marine bunker and aviation.
- Around 500 specific technologies are modeled, with lifetime of equipment considered.
- Top-down modeling for others (energy saving effect is estimated using log-term price elasticity.

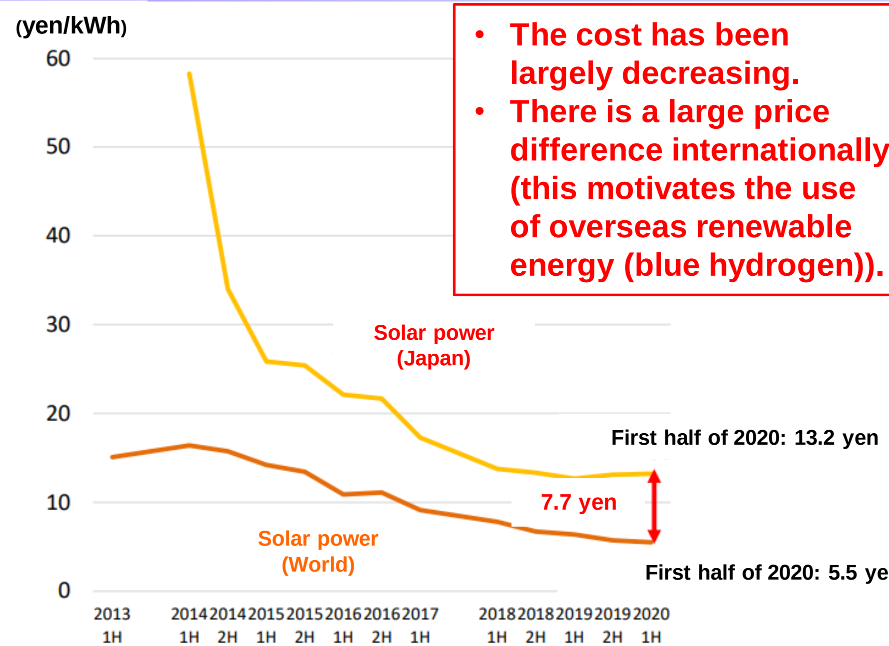
- **Regional and sectoral technological information provided in detail enough to analyze consistently.**
- **For analyzing the 2050 carbon neutrality in Japan, the integration costs of VRE are estimated by using a generation mix model having five regions within Japan and interregional grid connections developed by the University of Tokyo and IEEJ, and they are integrated into the DNE21+.**
- **Analyses on non-CO_2 GHG possible with another model RITE has developed based on US EPA's assumptions.**

Changes in Solar & Wind Power Generation Costs

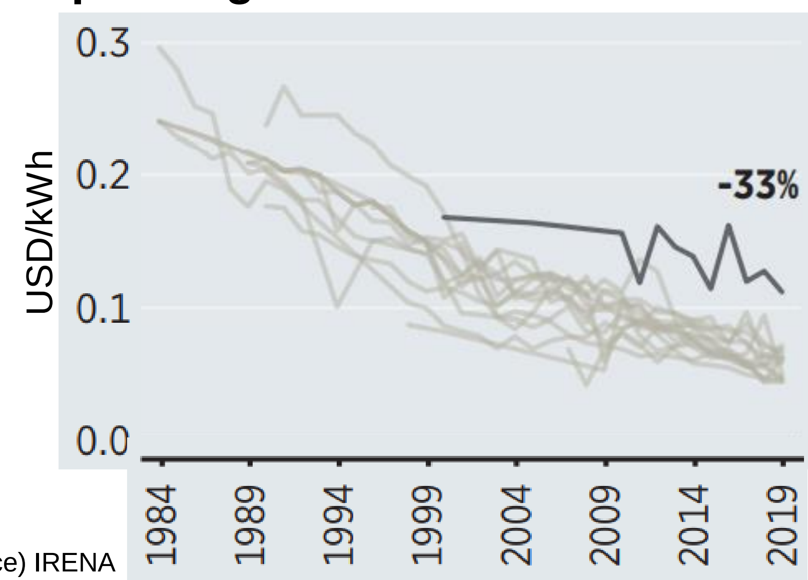
Solar power generation



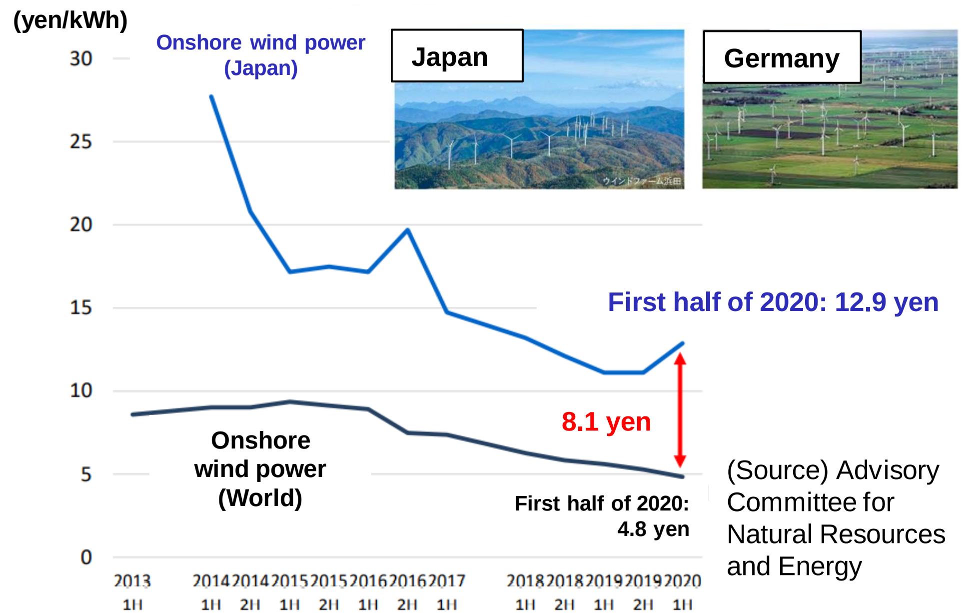
- The cost has been largely decreasing.
- There is a large price difference internationally (this motivates the use of overseas renewable energy (blue hydrogen)).



Wind power generation



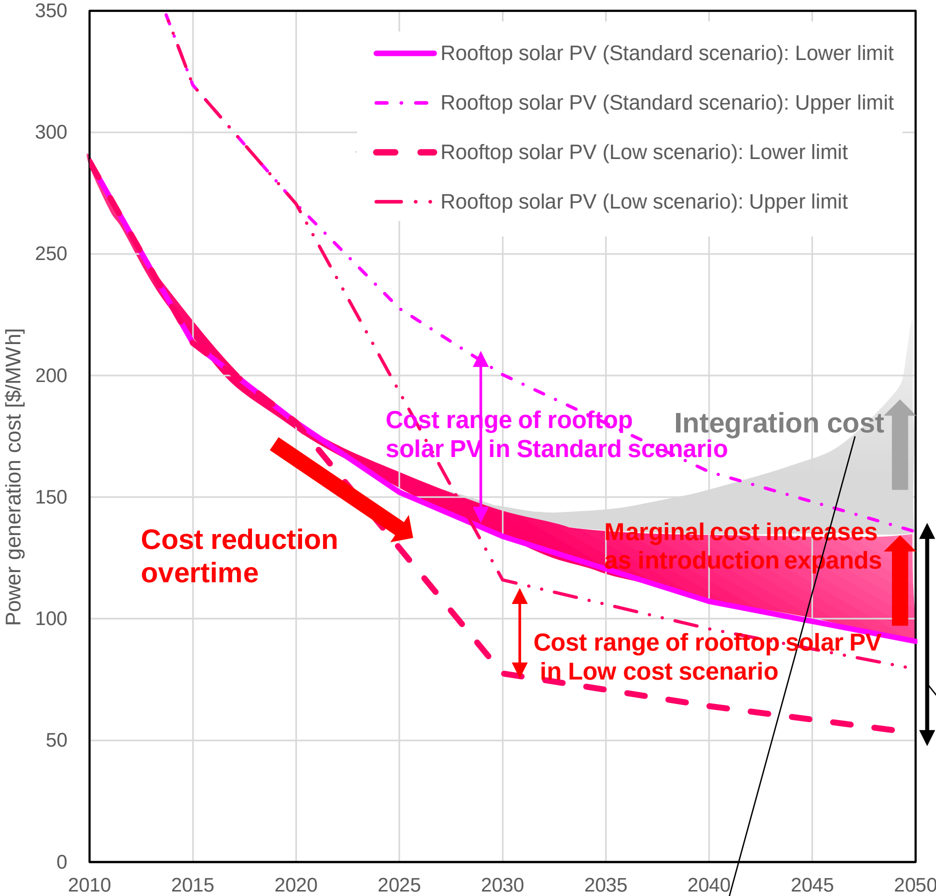
(Source) IRENA



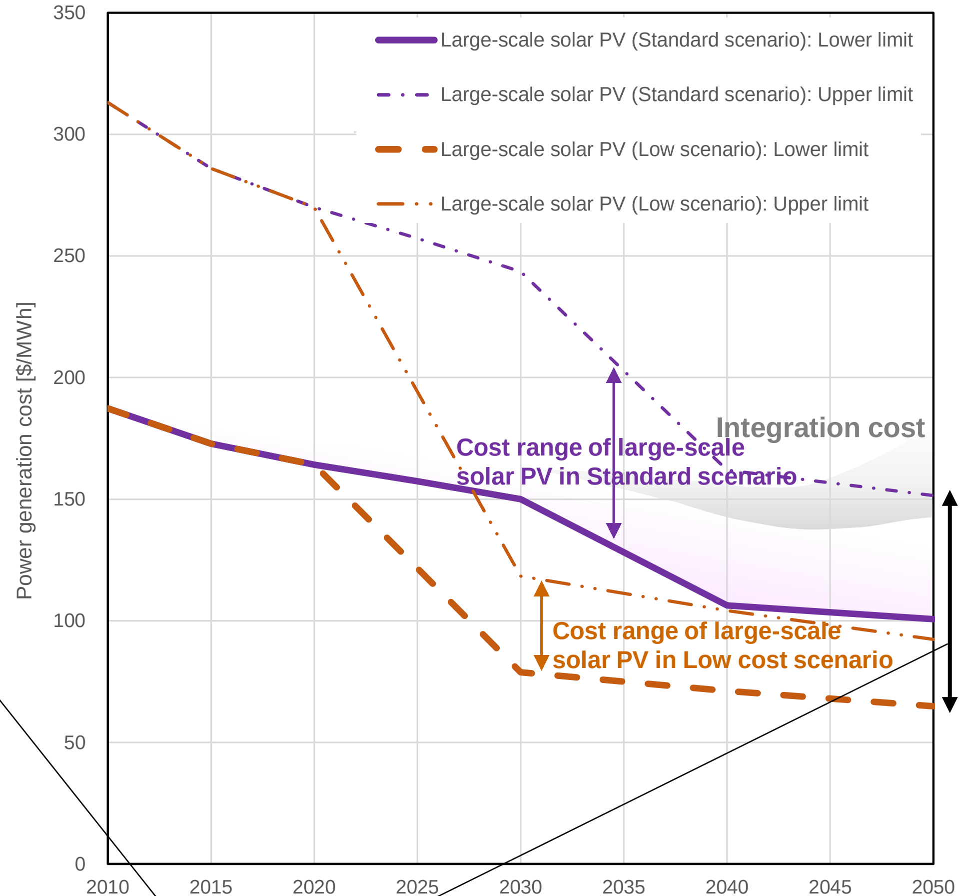
(Source) Advisory Committee for Natural Resources and Energy

Assumption for Solar PV Power Generation Costs in Japan：Time Series

Rooftop solar PV power generation



Large-scale solar PV power generation



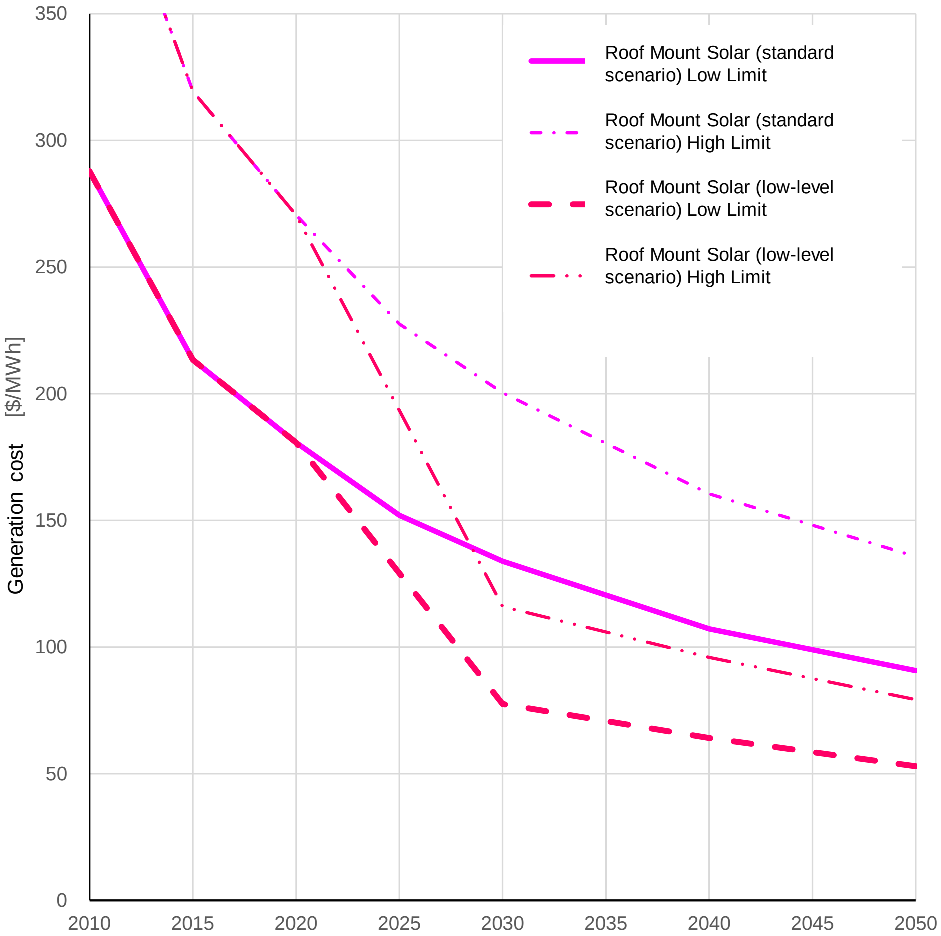
Assumption on integration cost is given on page 30.

Cost and potential curve in 2050 is given on page 28.

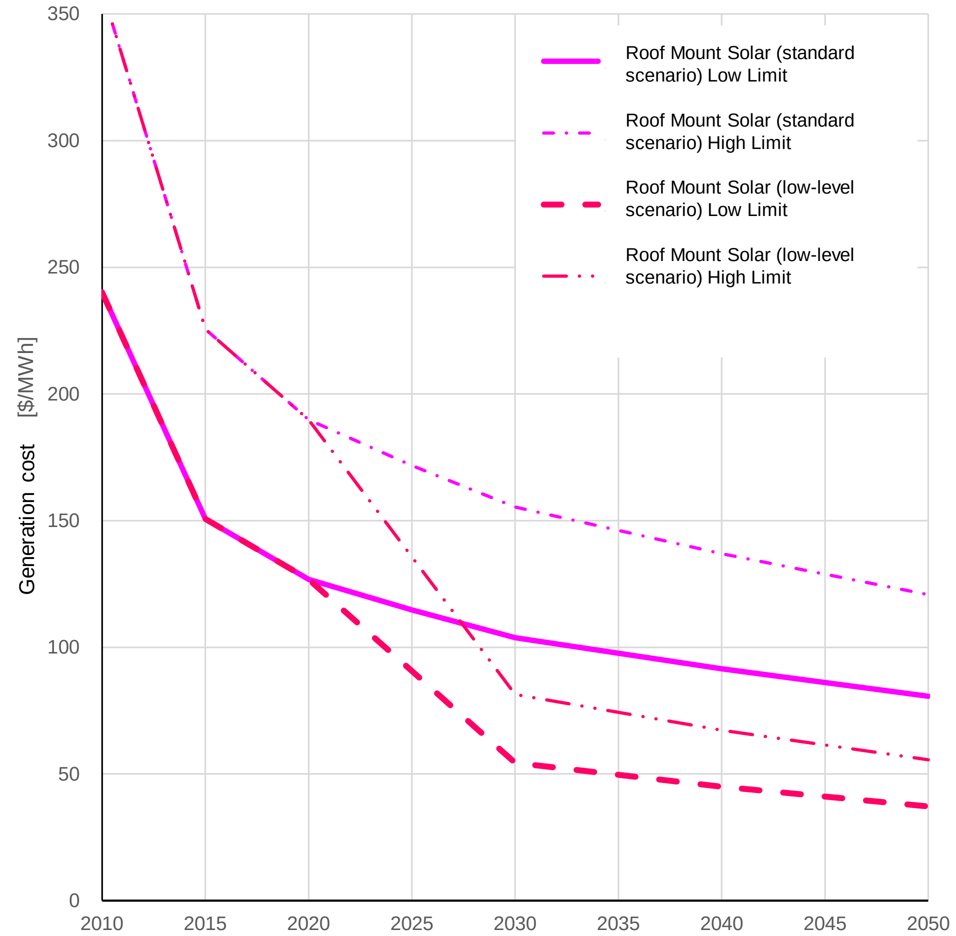
*It should be noted that this is the average cost of the facility stock installed at each point in time, and is not the cost limited to new facility installed at that point in time.
(Note) The gradation part is just an image of model calculation.

Assumption for Rooftop Solar PV Power Generation Cost in Japan: Time Series

Stock

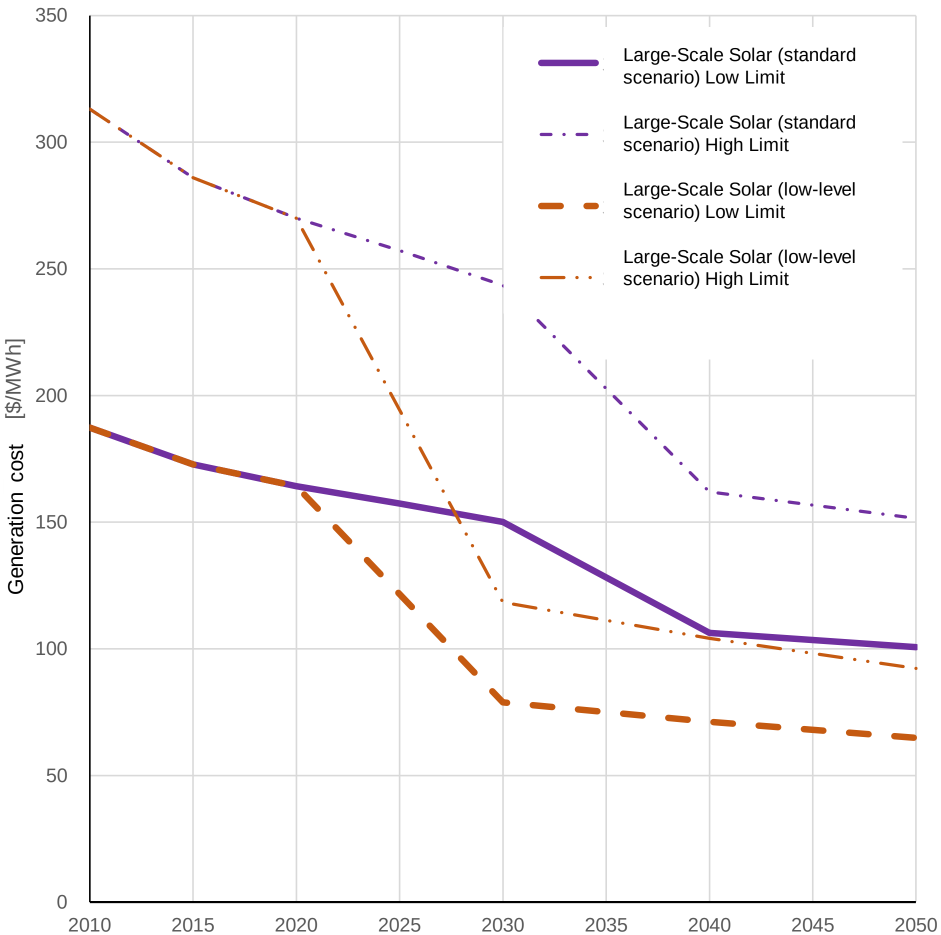


Flow

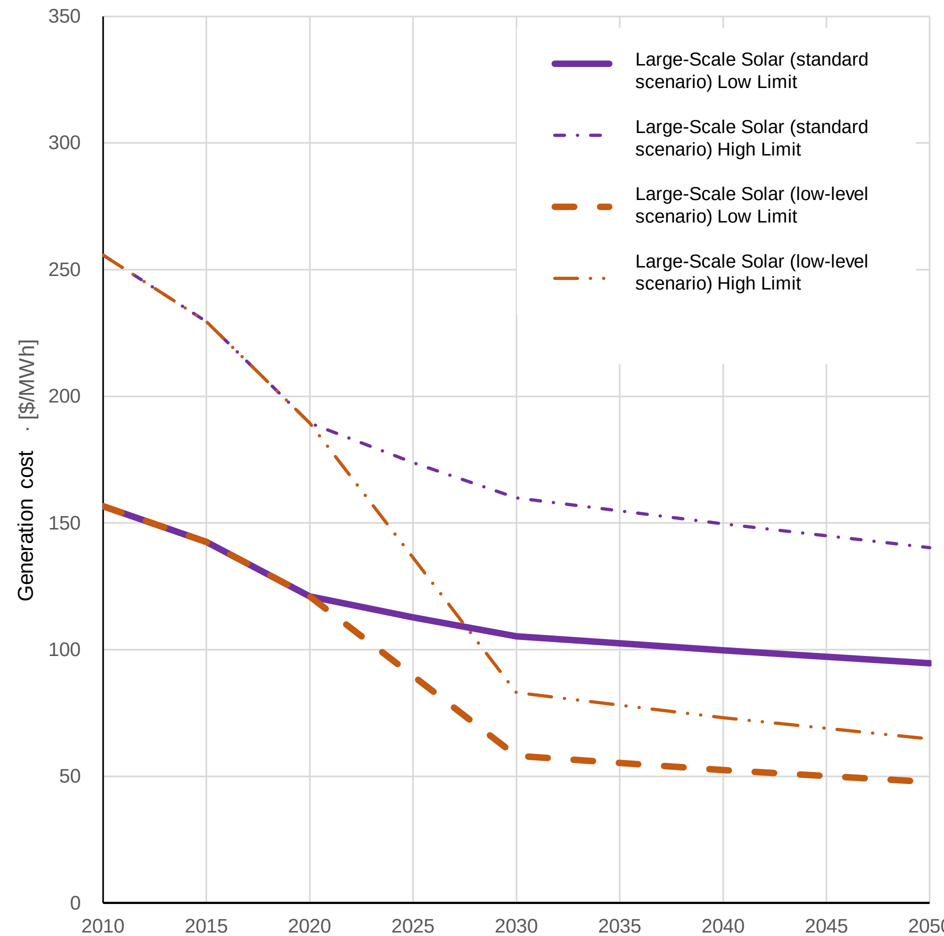


Assumption for Large-Scale Solar PV Power Generation Cost in Japan: Time Series

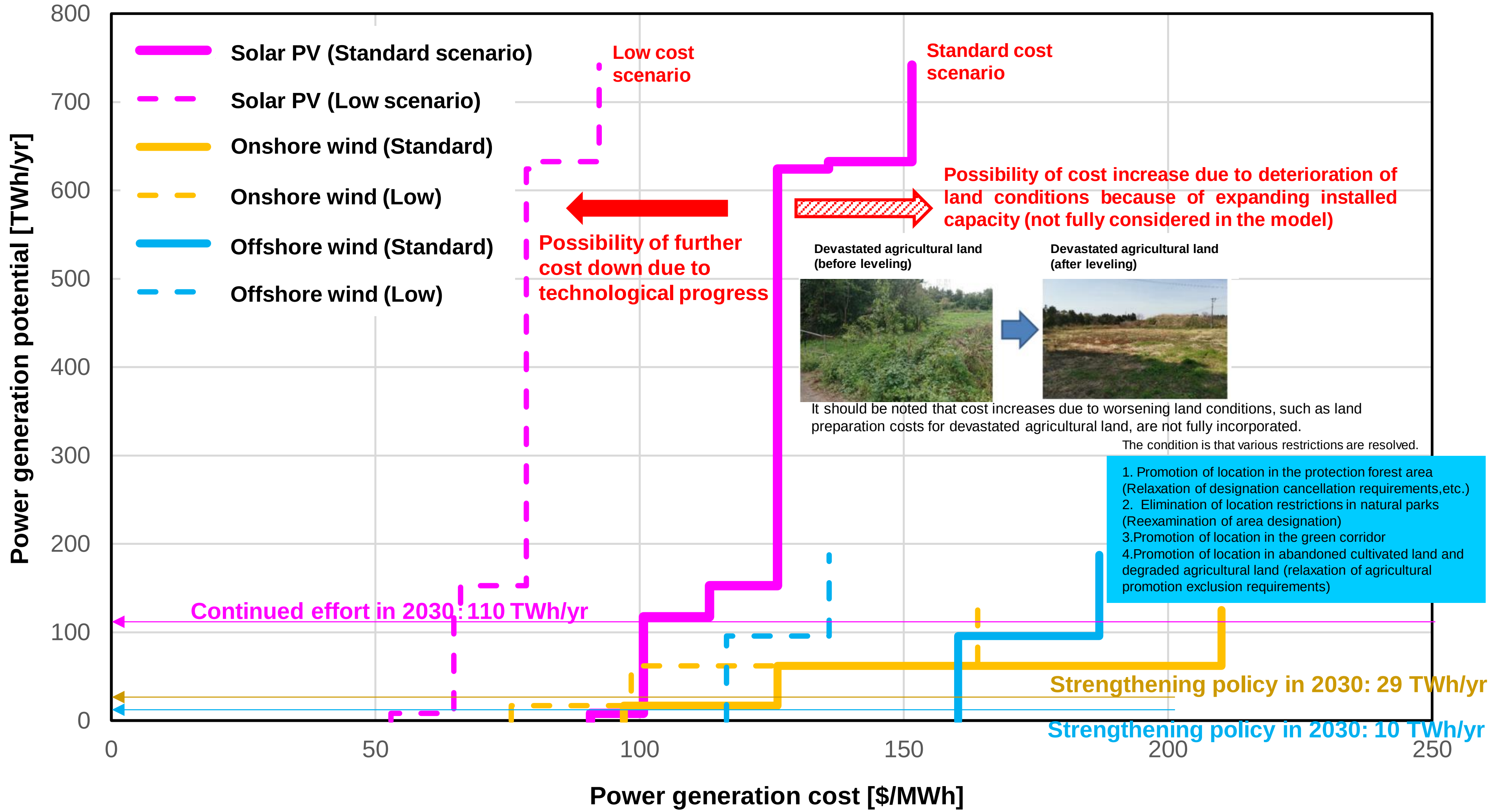
Stock



Flow



Assumption for Japan’s Variable Renewable Energy Cost and Potential in 2050

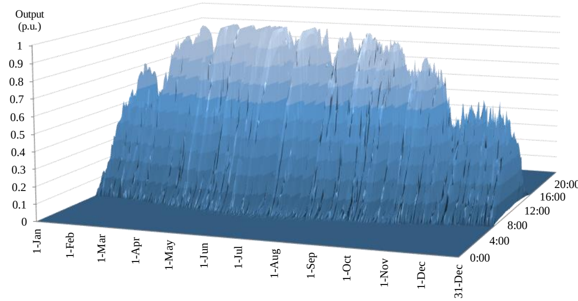


*Cost and potential of solar PV power generation is estimated by RITE based on the GIS data for the amount of solar radiation and land use, and facility costs, etc. Both rooftop and large-scale solar power generation are included in this Figure. Cost and potential of onshore wind power generation is estimated by RITE based on the GIS data for wind conditions and land use, and facility costs, etc.

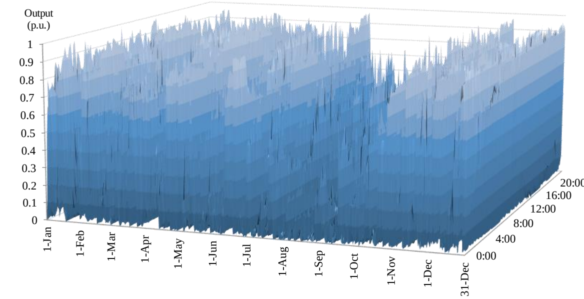
Assumptions for Estimating Integration Cost in the Univ. Tokyo - IEEJ Model

Regional aggregation

Divide Japan into 5 regions: [1] Hokkaido, [2] Northeastern area, [3] Tokyo, [4] Western area other than Kyushu, [5] Kyushu



Output example of PV



Output example of wind power

Considered in modeling ・・・ Output control, power storage system (pumped hydro, lithium-ion battery and hydrogen storage), reduction of power generation facility utilization, inter-regional power transmission lines, electricity loss in storage and transmission

Not considered in modeling ・・・ Intra-regional power transmission lines, power grid, influence of decrease of rotational inertia, grid power storage by EV, prediction error of VRE output, supply disruption risk during dark doldrums

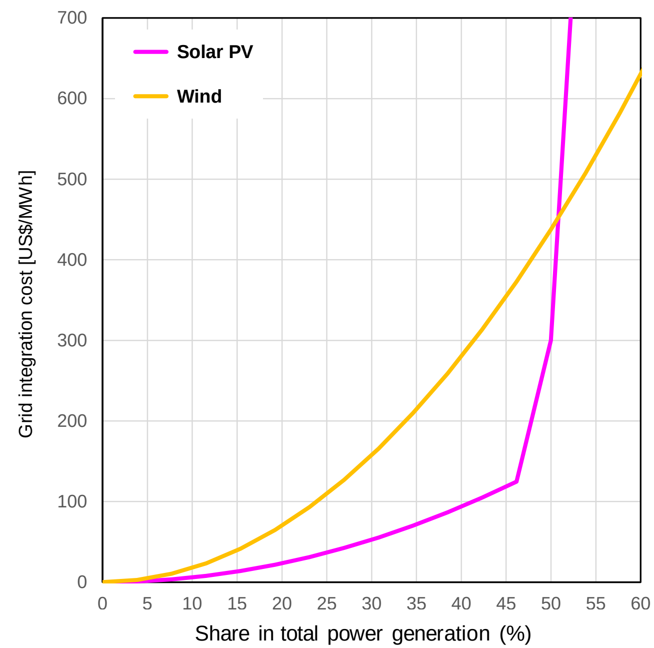
Power storage system

Mainly with Lithium-ion battery (setting 150$/kWh in 2050 based on estimation by the National Renewable Energy Laboratory (NREL)), it is assumed that existing pumped-storage hydropower and hydrogen storage will be used together.

Cost of interconnection lines

With reference to the plan by the Organization for Cross-regional Coordination of Transmission Operators, costs of interconnection lines are assumed to be 200,000 yen/kW between areas [1] [2] and [3][4], and 30,000 yen/kW in other areas, with an annual expense ratio of 8%. Underground transmission lines and submarine cables between Hokkaido and Tokyo are not considered.

Marginal cost of grid integration for VRE in Japan



Assumption for Nuclear Power Generation Cost

Year	Facility cost ($/kW)		Power generation unit price ($/MWh)	
	Year 2000 price	Year 2018 price	Year 2000 price	Year 2018 price
2020	2763	4029	75	110
2030	2779	4053	76	111
2050	2794	4075	78	114
2100	2824	4117	79	115

***1 The figures in the table are assumed values for Japan. For the rest of the world, location factors are multiplied, resulting in slightly different assumptions.**

***2 Since the base year of the model is 2000, the 2000 price is also shown; the conversion from the 2000 price to the 2018 price is multiplied by 1.46 (based on CPI of U.S.).**

***3 The conversion to cost per unit of electricity generated is based on a capacity factor of 85%.**

Assumption for CO_2 Capture Technology

	Capital costs (price in 2000) ($/kW)	Generating efficiency (LHV%)	CO_2 recovery rate (%)
IGCC/IGFC with CO_2 Capture*1	2800 – 2050	34.0 – 58.2	90 – 99
Natural gas oxy-fuel power*1	1900 – 1400	40.7 – 53.3	90 - 99
	Capital costs (price in 2000) (1000$/(tCO2/hr))	Required power (MWh/tCO2)	CO_2 recovery rate (%)
Post-combustion CO_2 capture from coal-fired power plants*1	851 – 749	0.308 – 0.154	90
Post-combustion CO_2 capture from natural gas-fired power plants*1	1309 – 1164	0.396 – 0.333	90
Post-combustion CO_2 capture from biomass-fired power plant*1	1964 – 1728	0.809 – 0.415	90
CO_2 capture from gasification*1	62	0.218	90 – 95
CO_2 capture from steelworks blast furnace gas*1	386 - 319	0.171 – 0.150	90
	Capital costs (price in 2000) (1000$/(tCO2/hr))	Required fuel (GJ/tCO2) Recovered power (MWh/tCO2)	CO_2 recovery rate (%)
CO_2 capture from clinker manufacturing*2	2485 - 2246	4.87 – 3.66 0.199 – 0.150	90

*1 The range of values in the table indicates improvement from 2015 to 2100.

*2 It is assumed that the assumed values have a range shown in the table depending on the fuel type used in the kiln body, CO2 capture, and compression equipment.

Note) It is 2000 price. The US consumer price index (CPI) in 2018 is 1.46 when the CPI in 2000 is 1.

Not only the CO_2 capture technologies in the power sector, but also CO_2 capture from gasification (during hydrogen production) and CO_2 capture from steelworks blast furnace gas and from clinker manufacturing are explicitly modeled.

Assumption for CO_2 Transportation and Storage

	CO_2 storage potentials ($GtCO_2$)		【References】 IPCC SRCCS (2005) ($GtCO_2$)	Storage costs ($\$/tCO_2$)*1
	Japan	World		
Depl. oil well (EOR)	0.0	112.4	675–900	92 – 227*2
Depl. gas well	0.0	147.3 – 241.5		10 – 32
Deep saline aquifer	11.3	3140.1	10^3–10^4	5 – 85
Coalbed (ECBMR)	0.0	148.2	3–200	47 – 274*2

Note 1: It is assumed that the CO_2 storage potentials of depl. gas well could be expanded to the upper limit in the table with the increase of future mining volume.

Note 2: It is assumed that the storage costs could rise within the range in the table with the increase of accumulated storage amount.

*1 The costs for CO_2 capture are not included. They are assumed separately.

*2 Oil and gas profits from enhanced oil recovery and enhanced methane recovery are not included in this figure, but they are assumed separately.

- **The constraint on CO_2 storage expansion is assumed considering the difficulties of its rapid expansion, e.g. limited number of drilling rigs; storage can be expanded by 0.02%/yr until 2030 and afterwards by 0.04%/yr for domestic/regional total storage implementation in the baseline scenario. (The maximum storage potential in 2050 is 91$MtCO_2$/yr in Japan's case, where CCS is assumed to be available after 2030.)**
- **It can be expanded up to 3 times (273 $MtCO_2$/yr) that in CCUS innovation scenario. (Total storage potential is fixed.)**

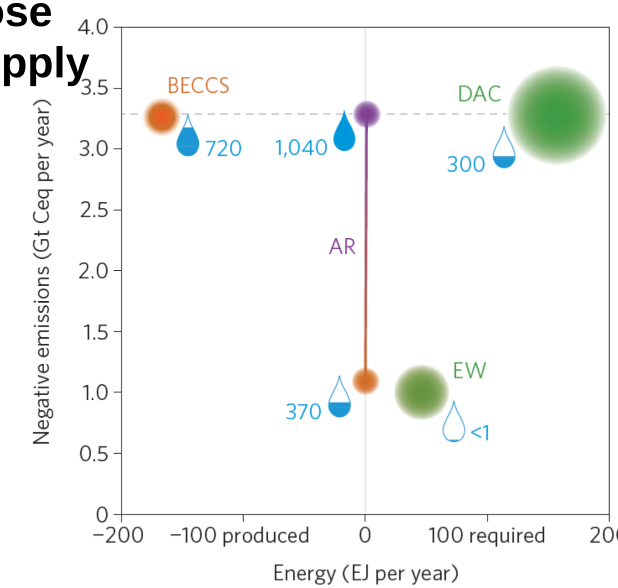
CO_2 transportation cost

- **CO_2 transportation costs from the sources to the reservoirs are assumed separately as 1.36$\$/tCO_2$ (per 100km) and 300km for average transport distance in Japan's case.**
- **For large area countries which are disaggregated in the models (US, Russia, China and Australia), the interregional CO_2 transportation costs are estimated according to the transportation distance.**
- **Cross-border CO_2 transportation is also assumed. In Reference scenario, the upper limit of export from Japan is 235 $MtCO_2$ (equivalent to one-sixth of 2013 GHG emissions). (In CCUS utilization scenario, it is 282 $MtCO_2$ (equivalent to one-fifth of 2013 emissions)).**

Assumption for Direct Air Capture (DAC)

- DAC is a technology to capture atmospheric CO_2 at low level of about 400ppm, requiring more amounts of energy than capturing exhaust gas emissions from fossil fuels combustion.
- On the other hand, DACCS (up to storage) can achieve negative emissions.
- It is economical to deploy in area close to CO2 storage and where energy supply is available at low cost such as low cost PV.

Climeworks



Required energy (horizontal axis), Land areas (color), Investments (circle size) etc.

Land requirements (Mha per yr)
1000
800
600
400
200
0

EW: Enhanced weathering
AR : Afforestation and reforestation

Smith et al. (2015)

Assumed energy consumption and facility costs of DAC in 2020 based on M. Fasihi et al., (2019):

This analyses adopt "Conservative" among 2 scenarios, "Base" and "Conservative", by Fasihi et al.

		Energy consumption（/tCO2）		Facility costs（Euro/(tCO2/yr)）	
		2020	2050	2020	2050
High temperature (electrification) system (HT DAC)	Elec. (kWh)	1535	1316	815	222
Low temperature systems （LT DAC）: use of hydrogen or gas for heat	Heat (GJ)	6.3 (=1750 kWh)	4.0	730	199
	Elec. (kWh)	250	182		

Assumption for Hydrogen Production and Transport-Related Technologies

Hydrogen production technologies

	Facility cost (US$/(toe/yr))	Conversion efficiency (%)
Coal gasification	1188 - 752	60%
Gas reforming	963 - 733	70%
Biomass gasification	1188 - 752	60%
Water electrolysis	2050 - 667	64 - 84%

Liquefaction technology

	Facility cost (US$/(toe/yr))	Electricity consumption (MWh/toe)
Natural gas/Synthetic methane	226	0.36
Hydrogen	1563	1.98

Transport cost

		Facility cost	Variable cost*1
		Electricity: $/kW Other energy: US$/(toe/yr) CO_2: US$/($tCO_2$/yr)	Energy: US$/toe CO_2: US$/tCO_2
Electricity*2		283.3+1066.7L	-
Hydrogen	Pipeline*3	210.0L	5.0L
	Tanker	69.5L	7.26+0.60L
CO_2	Pipeline*3	99.4L	2.35L
	Tanker	47.5L	1.77L
Natural gas (The same applies to synthetic methane.)	Pipeline*2	128.3L	3.5L
	Tanker	35.1L	8.09+0.39L

L: Distance between regions (1000km)

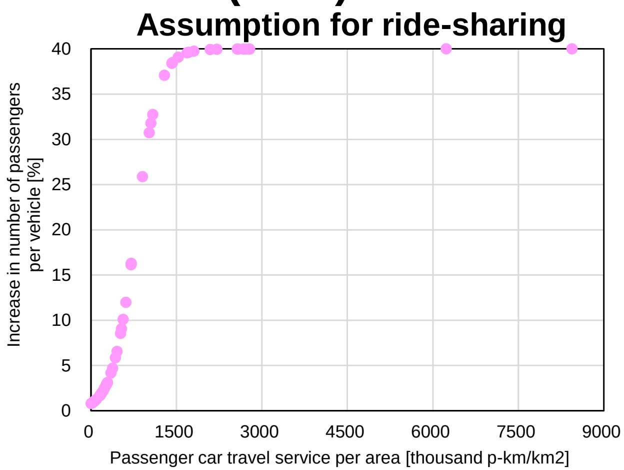
*1 For ships, the distance-independent term assumes fuel costs. For pipelines, the distance-dependent terms assume fuel costs and compression power costs, respectively.

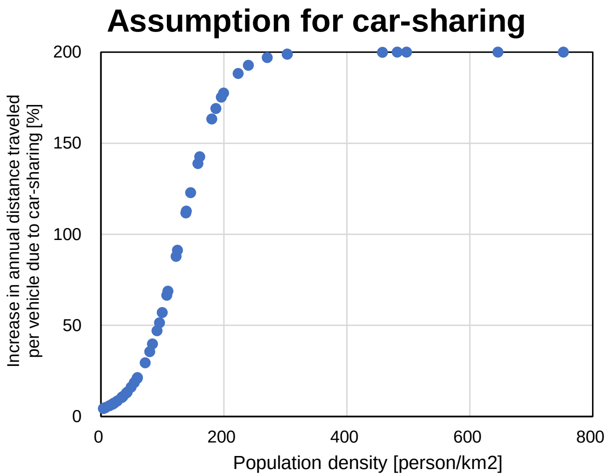
*2 For submarine transmission lines, fixed costs are assumed to be 10 times higher than the above.

*3 For submarine pipelines, fixed costs are assumed to be three times higher than above.

Assumption for Shared Mobility Induced by Fully Autonomous Cars

- In the case where demand decreases through car-sharing, fully autonomous shared cars can be available after 2030, and key parameters are assumed as below, mainly following Fulton et al. (2017).



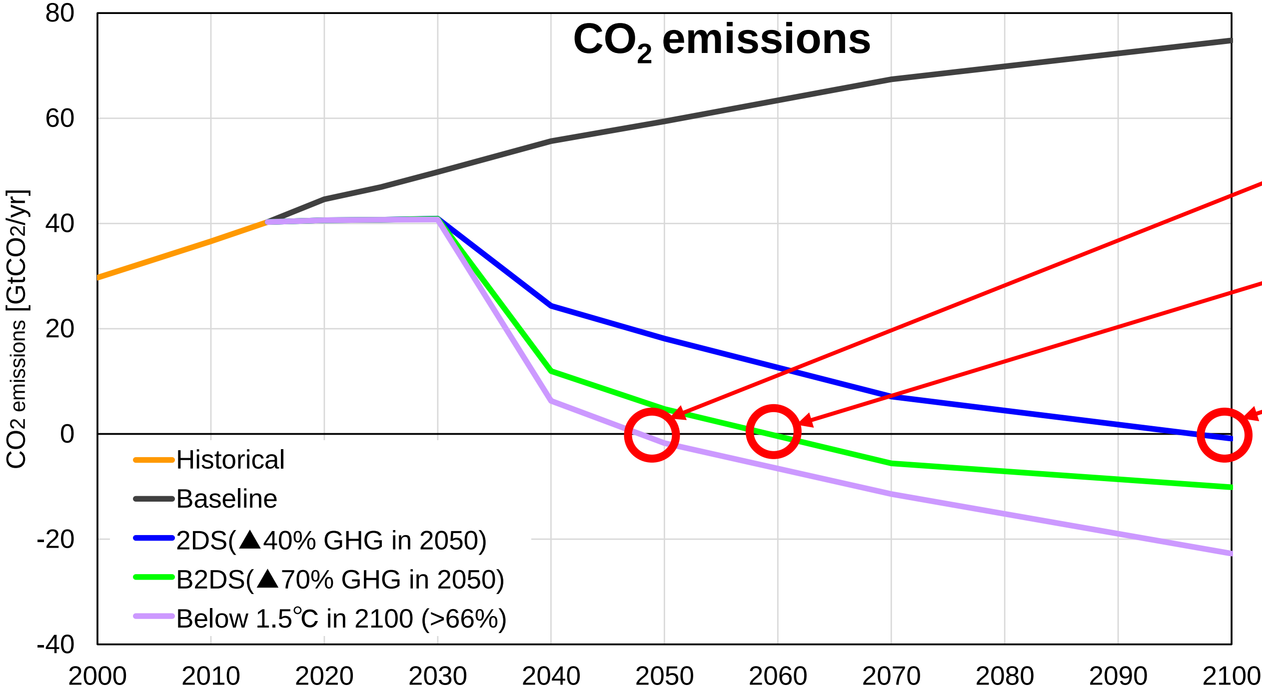


	Traditional car (private car)	Fully autonomous car (shared car)
Car body price	Assumed precisely depending on car types	2030: +10000$ 2050: +5000$ 2100: +2800$ (compared to traditional cars)
Lifespan of car	13-20 years	4-19 years
Number of passengers per vehicle	2050: 1.1-1.5 passengers 2100: 1.1-1.3 passengers	2050: 1.17-2.06 passengers 2100: 1.11-1.89 passengers

- Opportunity costs of time required for driving and costs related to safety are considered.
- Impacts of the reduction in the number of cars induced by car- & ride-sharing are considered.

Following impacts driven by decrease in the number of cars are considered: 1. decrease in steel products and plastic products, 2. decrease in concrete and steel products due to the decrease in multi-storey car park space.

Global Baseline Emissions and Assumed Emissions Scenarios under 2°C and 1.5°C



Net zero CO_2 emissions around 2050

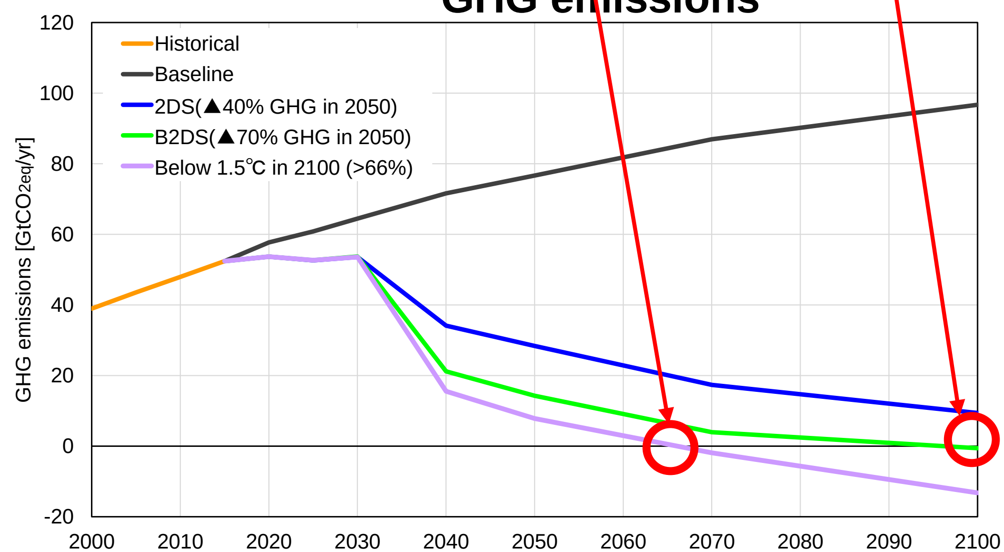
Net zero CO_2 emissions around 2060

Net zero CO_2 emissions around 2100

Net zero GHG emissions around 2065

Net zero GHG emissions around 2100

GHG emissions



Note) Emissions for baseline shows model estimates results under SSP2, not assumed scenario

※ 2DS, B2DS, B1.5OS scenarios assume emission constraints equivalent to NDCs of each nation up to 2030

In the scenario analyses of Japan’s 2050 carbon neutrality, 1.5°C global scenarios are assumed in addition to Japan’s emissions reduction scenarios, for the global competition for carbon neutral resources to be considered.

【ref.】Concept of Innovation in Power Supply Ref. Value

- **Each power source must overcome a large hurdle to achieve the reference values for power sources in 2050 as presented at the Strategic Policy Committee.**
- **Under these conditions, for the 30 to 40% of nuclear power and fossil+CCUS, in case the upper limit of nuclear power is 10%, it is necessary to cover 20-30% with fossill+CCUS, thus it is assumed a considerable amount of CO2 is stored at home/abroad including CCUS required amount other than the electric power sector. For hydrogen/ ammonia and carbon recycled fuel, it is assumed that infrastructure development, etc. is expected to execute a large-scale transportation without setting the upper limit of supply on the model.**
- **It should be noted that in this analysis, the conditions were set by mechanically assuming such CCS storage amount based on the above reference values.**

2020/12/21 Strategic Policy Committee Material

In order to aim for carbon neutrality in 2050, stable power supply from decarbonized power sources is indispensable. From the perspective of 3E+S, multiple scenarios will be analyzed without limiting to the following. In deepening the discussion, the positioning of each power source is suggested as follows.

Established decarbonized power source		Renewable Energy	・Continue to aim for maximum introduction as the main power source in 2050. ・Immediately work on issues to promote the maximum introduction such as adjustment amount, transmission capacity, ensuring inertial force, responding to natural conditions and social constraints, maximizing cost control, and increasing social transformation to cost increases. ・How about deepening discussions on covering 50-60%(approx.) of the generated power (* 1) with renewable energy in 2050 as a reference value (* 2)?
Established decarbonized power source		Nuclear power	・As an established decarbonized power source, aim for a certain scale of utilization on the premise of safety. ・In order to restore public trust, make an increased effort to improve safety, gain understanding and cooperation of the location area, solve back-end problems, secure business feasibility, maintain human resources and technical capabilities, etc. How about deepening discussion on covering 30-40% (approx.) with nuclear power which is a carbon-free power source other than renewable energy and hydrogen/ammonia, along with fossil+CCUS/carbon cycle in 2050 as a reference value (* 2)?
Power sources required innovation	Thermal power	Fossil + CCUS	・While having the advantages of supply capacity, adjustment power, and inertial force, decarbonization of fossil-fired power is the disadvantage. ・Aim to utilize on a certain scale iimmediately by developing technology and suitable sites, expanding applications and reducing cost, etc., toward the implementation of CCUS / carbon recycling. How about deepening discussion on covering 30-40% (approx.) together with nuclear power which is a carbon-free power source other than renewable energy and hydrogen/ammonia in 2050 as a reference value (* 2)?
Power sources required innovation	Thermal power	Hydrogen, Ammonia	・While having the advantages of adjusting power and inertial force without emitting carbon during combustion, the challenges are establishing technology for large-scale power generation, reducing costs, and securing supply. Aim to build a stable supply chain immediately by promoting co-firing of gas-/coal-fired power, increasing supply and demand. ・Aim for a certain scale of utilization as a carbon-free power source, taking into account competition with industrial and transportation demand. Based on the fact that procurement required for future power generation is estimated to be 5-10-million ton as basic hydrogen strategy, how about deepening discussion on covering 10% (approx.) of generated power with hydrogen/ammonia in 2050 as a reference value (* 2)?

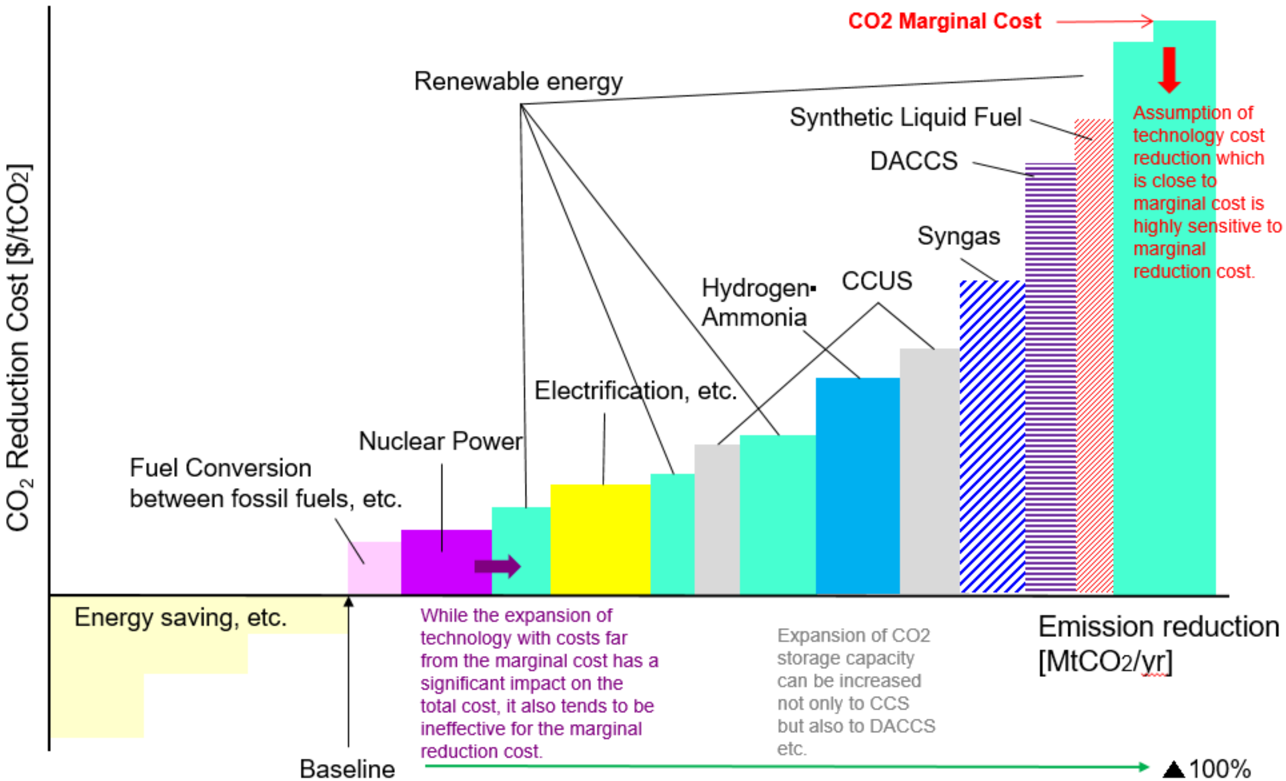
1: The amount of power generated in 2050 will be about 1.3-1.5 trillion kwh as a reference value (2) based on the power generation estimation by RITE presented at "the 33rd Strategic Policy Committee".

*2: This is not as a government goal, this is one guideline / option for future discussions. This will be the one of options to deliberate in considering multiple scenarios in the future.

【ref.】Marginal Abatement Cost & Total Energy System Cost

※ The cost curve is illustrated as an image (in reality, it is complicated due to the correlation between technologies)

[Area cost]：
[▲100%Total Energy System Cost]ー
[Baseline Total Energy System Cost]



（Approx. CO2 103 million tons, GHG 1.15 billion tons in 2050）

	Energy System Cost*1 (billion US$/yr)	
Reference case	1179	—
1.Renewable Energy 100%	1284	(+106)
2.Renewable Energy Innovation	1142	(-37)
3.Nuclear Power Utilization*2	1166～1133	(-13～-45)
4.Hydrogen Innovation	1160	(-19)
5.CCUS Utilization	1150	(-29)
6.Case where demand decreases due to car sharing	909	(-270)

*1：Numbers in parentheses are fluctuations from the reference

*2：Nuclear utilization scenarios represent results from 20% and 50% nuclear ratios

CO_2 Marginal Abatement Costs for carbon neutrality in 2050: Japan and other countries

	Reference Case	2. Renewable Energy Innovation
Japan	525	469
US	167	138
UK	181	141
EU	211	169
Others	162	138

[US$/$tCO_2$]