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Scenario Analysis Towards 2050 Using an Optimisation Model: Exploring Japan's Energy Future through a Supply–Demand Outlook

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60th Anniversary

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Developments in Japan's Energy Landscape

<Developments in Japan's energy landscape since IEEJ's founding>

- ✓ **Post-WWII:** Building the energy infrastructure to support post-war economic growth
- ✓ **1970s:** Promoting energy diversification triggered by the oil crises
- ✓ **1990s:** Growing debate on global warming
- ✓ **2010s:** Advances in decarbonisation technologies → Early 2020s: Strengthening decarbonisation momentum
- ✓ **February 2022:** Russia's invasion of Ukraine ⇔ rising security uncertainty and a global return to the 3E balance
- ✓ **February 2025:** Formulation of the 7th Strategic Energy Plan

<Recent issues>

- ✓ Rise of 'country-first' policies, and shifts in national power and geopolitics among countries
- ✓ Intensifying global industrial competition and rising energy prices ≥ climate policy concerns
- ✓ New challenges and concerns over supply chains and decarbonisation technologies
- ✓ The invasion of Ukraine and the blockade of the Strait of Hormuz ⇒ a reminder of risks to stable energy supply

⇒ Reviewing Japan's energy security is an urgent priority, and there is a growing need for a transition towards a more balanced energy supply–demand structure.

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For Energy Supply–Demand Scenario Analysis

✓ Key points for the energy supply–demand scenario analysis

- Rethinking the nature of energy security
- Presenting responses to continued rises in energy supply costs
- Presenting options beyond analyses premised on the NDC (greenhouse gas reduction target)
- Developing a long-term outlook that reflects changes since the 7th Strategic Energy Plan

	Fundamental perspectives		Perspectives requiring deeper analysis
Energy security	Promoting energy conservation Diversifying energy sources Diversifying supply sources	×	Chokepoints Supply chains (e.g. dependence on specific countries)
Economic efficiency	Reducing costs Securing international competitiveness	×	Hidden system costs (e.g. integration costs) Changes in cost structure (e.g. inflation)
Environmental sustainability	Reducing greenhouse gases Reducing environmental burden International contribution	×	Options for other scenarios with a view to achieving carbon neutrality Local acceptance and coexistence with host communities

✓ What this analysis aims to achieve

- Technology-neutral approach
- Focus on cost analysis reflecting ongoing discussions on integration costs

⇒ Using an analytical model that explicitly accounts for costs ⇒ applying the IEEJ-NE model*

Note: IEEJ is the English abbreviation of The Institute of Energy Economics, Japan; NE stands for New Earth.

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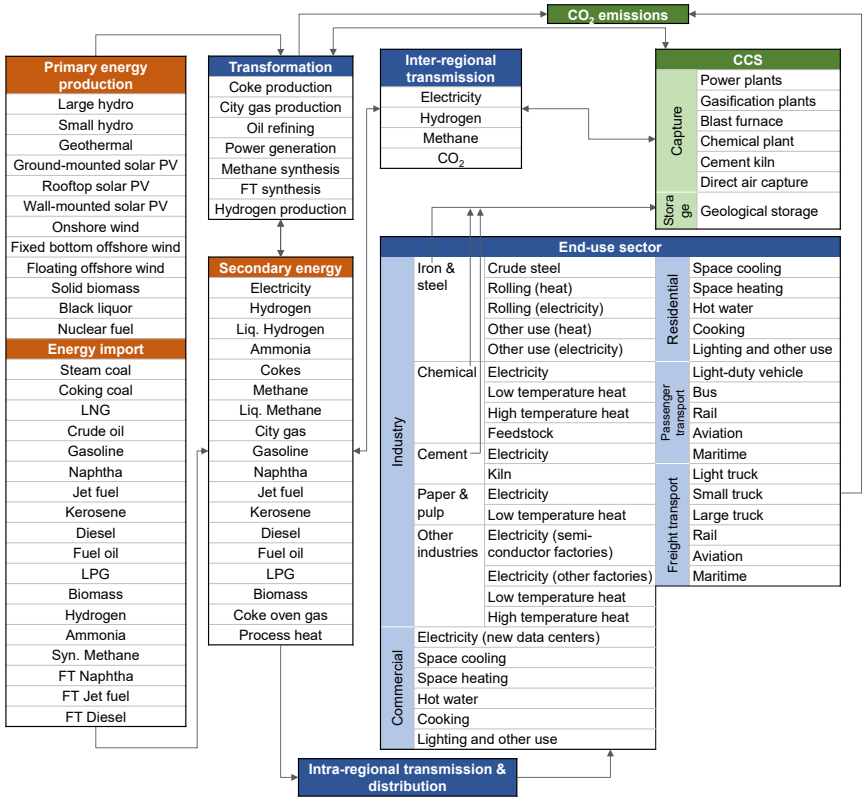
Overview of the IEEJ-NE model

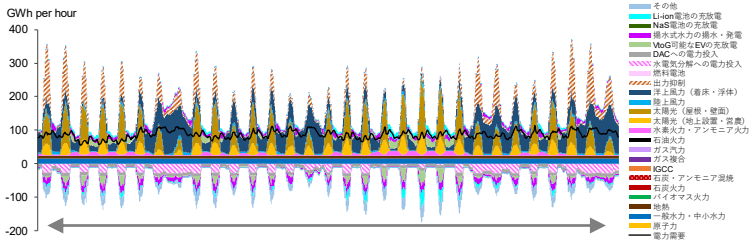
- ✓ A linear programming model jointly developed by IEEJ, the Otsuki Laboratory of Waseda University, and Prof. Matsuo at Ritsumeikan Asia Pacific University, based on the NE_Japan model built at the Otsuki Laboratory.
- ✓ The model identifies the cost-minimising combination of energy technologies under a given set of constraints.

The analysis covers the entire energy system



Electricity and hydrogen supply and demand are calculated for 24 hours × 365 days

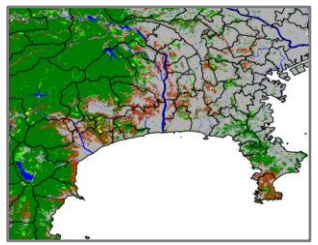
Explicitly accounts for measures to manage the variability of renewable energy, including their associated costs.



Hourly operation in a month

Renewable energy technical potential estimated using a geographic information system (GIS)

Renewable resource potential, capacity factors and capital costs are considered using gridded land- and sea-use data and information on around 60 million buildings.



Source: Otsuki et al., IEEJ Trans. Power and Energy, 142(7), pp. 334–346, 2022; Otsuki et al., INT J GREENH GAS CON, 132, 104065, 2024; Otsuki et al., Energy and Climate Change, 4, 100108, 2023; IEEJ, 'Model estimates of the 2040 and 2050 energy mix', 66th Meeting of the Subcommittee on Basic Policy, Advisory Committee for Natural Resources and Energy, 2024

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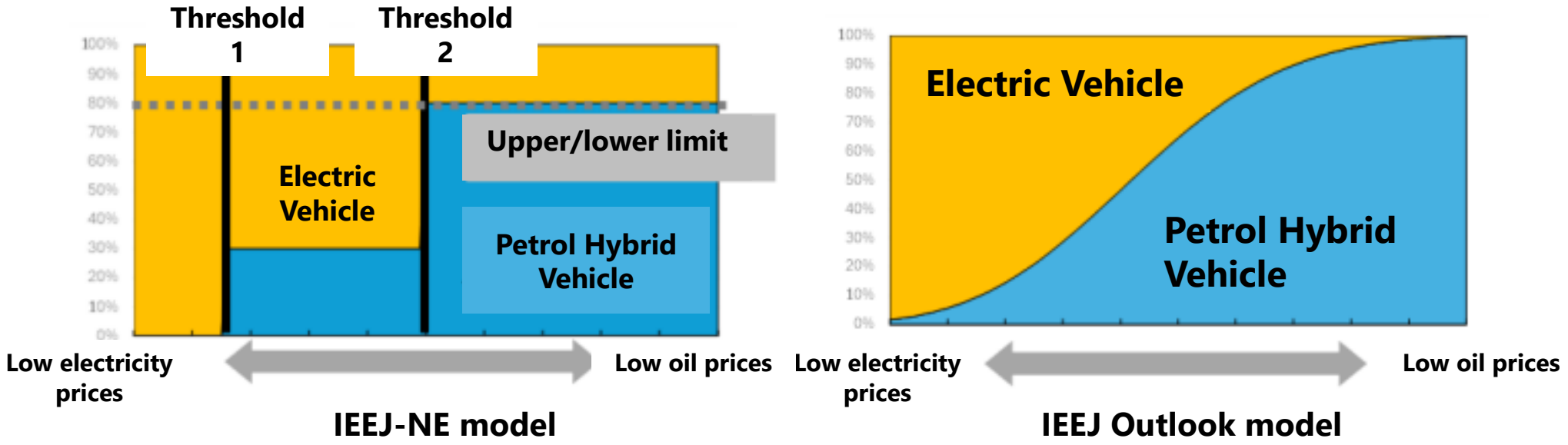
Reference: Comparison of the IEEJ-NE model and the IEEJ Outlook model

- ✓ **IEEJ-NE model:**
  - Analyses the combination of technologies subject to constraints such as upper and lower limits on technology deployment ⇒ the selected technologies can change substantially at certain thresholds.
- ✓ **IEEJ Outlook model:**
  - Analyses the energy mix that emerges when realistic levels and the pace of technology deployment are taken into account ⇒ it depicts a structure in which the share of a given technology rises gradually.

Schematic of the determinants of energy technology selection



Source: Prepared by the author based on Endo (2025), Energy Trend Topics, 'IEEJ Outlook and the technology-selection model: differences and implications of the two model analyses', IEEJ website.

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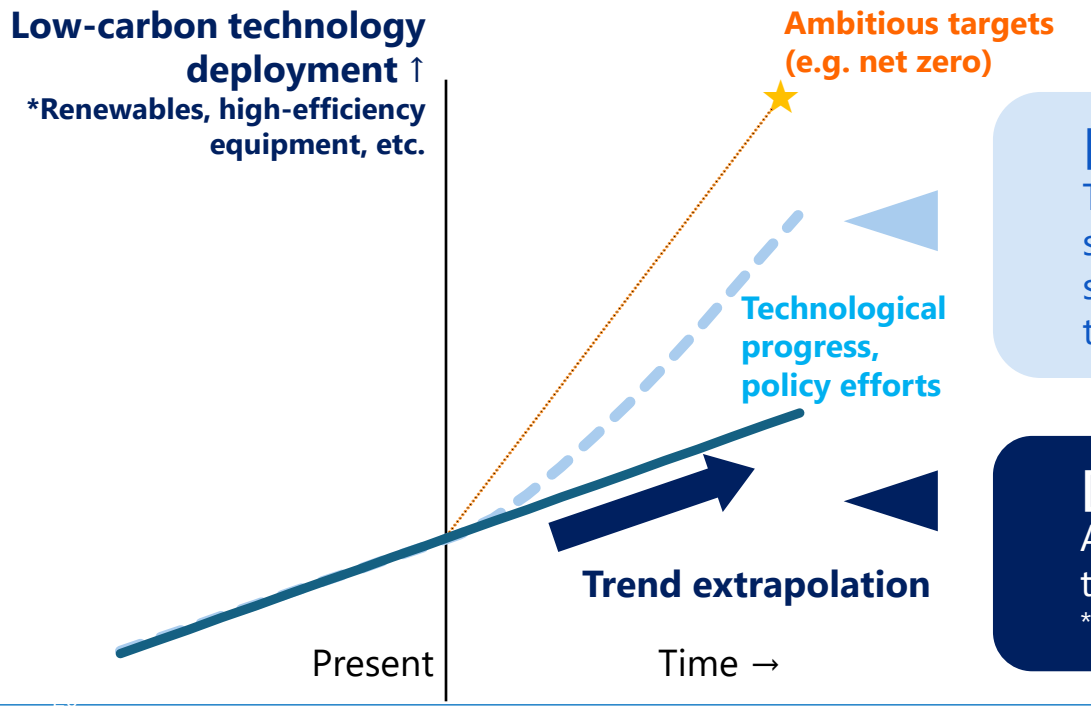
Aim of the Analysis and Scenario Setting

- ✓ Japan's energy supply–demand outlook to 2050 is developed using a technology-selection model*.
  - Outcome: Future energy supply and demand and CO_2 emissions
- ✓ We define two scenarios, with different assumptions about the degree of progress in technology and policy.
  - **Reference Scenario (REF):** a scenario assuming that current trends continue
  - **Advanced Technologies Scenario (ATS):** a scenario that promotes reform of the energy supply–demand structure, assuming improvements in the cost of individual technologies, technology deployment, policy support, etc.



[Advanced Technologies Scenario]
The ATS assumes an accelerated transition in Japan's energy supply–demand by pursuing CO_2 reductions while ensuring stable energy supply. Deployment of advanced technologies and supporting policies is expected.

[Reference Scenario]
Against the backdrop of energy and environmental policies to date, past trend-based changes continue.
*This does not mean that policies, technologies, etc. are fixed at current levels.

Note: The base year for the model analysis is FY2022.

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Scope of Costs Covered by the IEEJ-NE model

- ✓ The energy system cost is defined as the objective for cost minimisation
- ✓ The energy system cost includes not only generation-related costs but also the costs of demand technologies and energy infrastructure.

Scope of costs covered by the IEEJ-NE model

Examples of items	Capital cost	O&M cost	Fuel cost	External cost* (e.g. CO_2 cost)	Economic security (mainly economic impacts)
Demand technologies	**Energy system cost (demand technologies + energy infrastructure + generation technologies)**				**Costs of maintaining supply chains and related risks, and economic impacts ⇒ details in Topic 2**
Energy infrastructure (e.g. grids, charging stations, CCS-related infrastructure, etc.)					
of which: fuel supply					
of which: T&D	**Power system cost (LCOE + integration cost (partial)) ⇒ details in Topic 1**				
Generation technologies	Generation cost (LCOE: Levelised Cost of Electricity)				

Note: Power system cost, integration cost and the cost of economic security are covered in detail in Topics 1 and 2. External costs are assumed to be internalised, for example the external cost of CO_2 emissions via a carbon price; this CO_2 cost is included in the energy system cost in this estimate.

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Assumptions for the Macroeconomy and Preconditions

- ✓ GDP growth is assumed by reference to the IMF World Economic Outlook (April 2026) and other sources.
- ✓ Fossil fuel prices follow the assumptions of IEEJ Outlook 2026.
- ✓ CO_2 prices are assumed with reference to the IEA World Energy Outlook and other sources.
  - REF assumes about JPY 5,000–8,000/tCO_2 over 2030–2050, referring to IEA and trends both at home and abroad.
  - ATS assumes JPY 30,000/tCO_2 in 2050, higher than REF with reference to the IEA Net Zero scenario.

Item	Unit	FY2022 actual	FY2050 assumption	Notes
GDP (real, 2020 base)	JPY trillion	584	709	Assumed with reference to the IMF World Economic Outlook (published April 2026) and IEEJ Outlook 2026
[Growth rate]	[%/year]	[0.7%] (2000–2022)	[0.7%] (2022–2050)	
Population	Million persons	125	105	Assumed with reference to the National Institute of Population and Social Security Research (2023)
Number of households	Million households	60	58	IEEJ estimates based on the population assumption.
Crude steel production	million tonnes	88	76	IEEJ estimates based on actual data, economic growth assumptions and IEEJ Outlook 2026.
Passenger transport	billion passenger-km	1,262	1,232	
Freight transport	billion tonne-km	410	400	

Note: For the macroeconomy, a more conservative growth rate is assumed than the economic assumptions discussed for the 7th Strategic Energy Plan.

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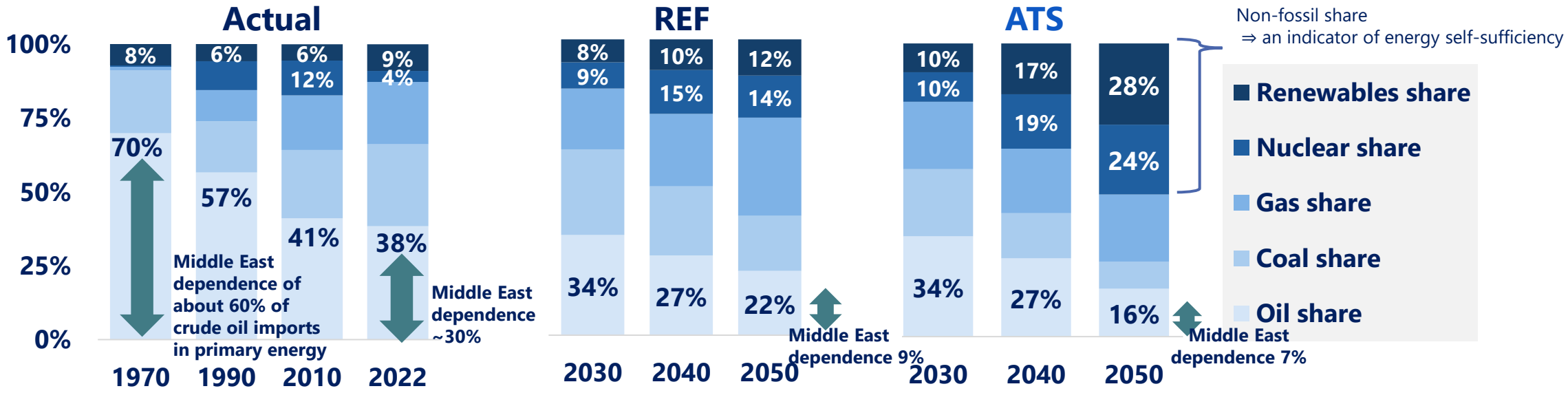
Diversifying Energy Sources Underpins Energy Security

- ✓ **Energy security ⇒ Changes in the primary energy supply mix**
  - Some 50 years after the oil crises, oil's share of primary energy supply has halved.
    - ➢ The share of primary energy supply linked to Middle Eastern crude oil declines to 9% in REF and 7% in ATS by 2050.*
  - Coal declines, mainly in power generation, partly owing to the expansion of non-fossil energy.
  - Gas is supported by lower coal use and fuel switching in industry, and its relative importance is increasing.
  - As a result, the diversity of primary energy increases.
    - ➢ Change in the HHI diversity index: 5,399 in 1970 → 2,788 in 2022 → 2,274 (REF) / 2,212 (ATS) in 2050.

Trends in the primary energy supply mix



Note: Estimated assuming the Middle East dependence of crude oil falls from about 95% today to 80%.
HHI = Herfindahl–Hirschman Index; smaller values indicate greater diversification.

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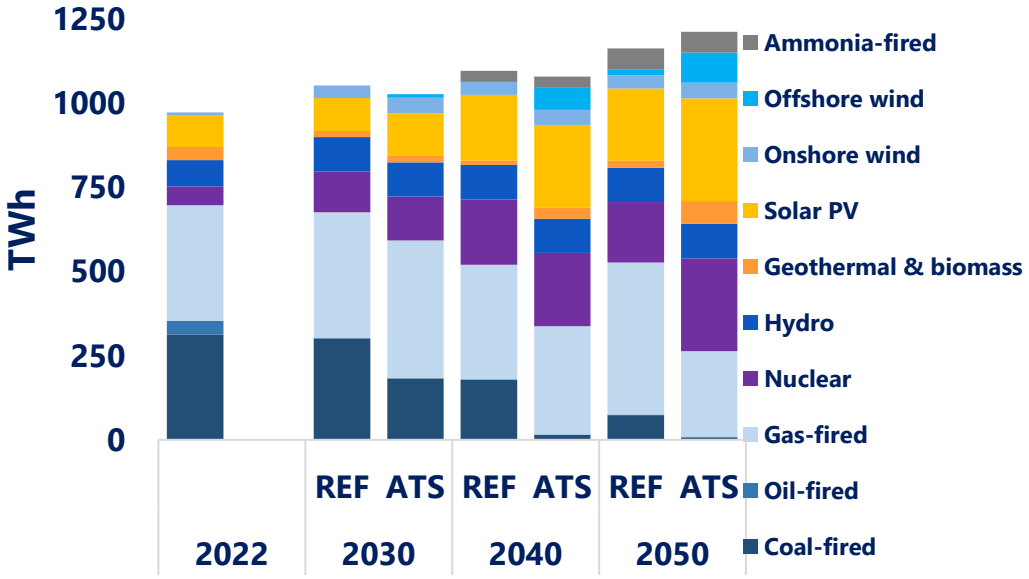
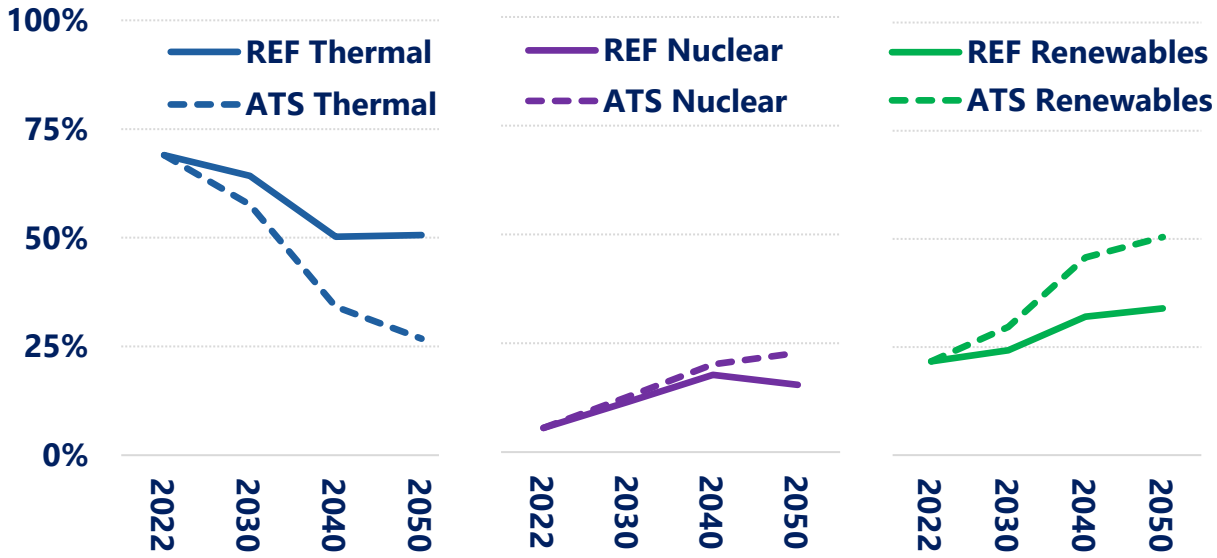
Coal-fired Power Shrinks and the Generation Mix Diversifies

- ✓ **Energy security ⇒ Changes in the power generation mix**
  - In REF, coal-fired generation declines substantially over time, although thermal power continues to play a role.
  - In ATS, the coal-to-gas switch advances further towards 2050, renewables and nuclear expand and decarbonised thermal power (CCS, ammonia, etc.) is deployed.
  - In both the REF and ATS scenarios, thermal power provides flexibility and backup capacity, nuclear power serves as a stable baseload source, and variable renewables supply low-cost electricity.

Trends in the power generation mix



Trends in shares by generation source



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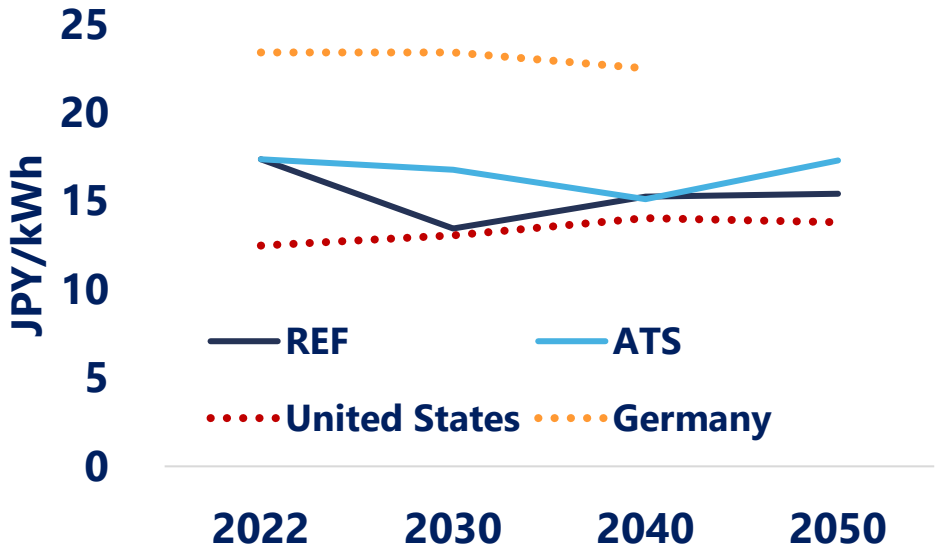
Managing Energy Costs Is Critical for Competitiveness

✓ **Economic efficiency ⇒ Changes in electricity supply cost and energy system cost**

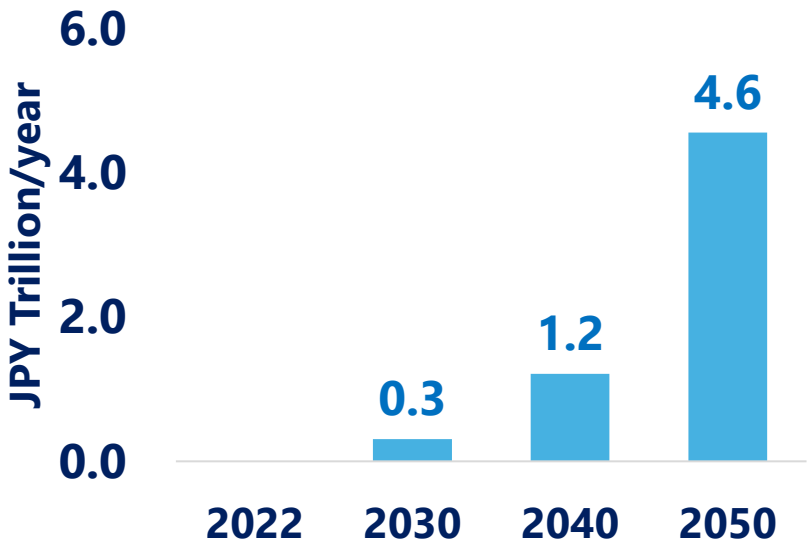
- In both REF and ATS, further cost reductions are expected. However, costs rise gradually as suitable sites for renewables become scarcer in ATS.
  (Expanding the restart of NPPs contributes about JPY 0.7 trillion/year in cost savings in REF in 2050.)
- The gap with US power supply costs may also narrow.
- The total energy system cost relative to the REF scenario begins to rise around 2040.

Comparison of electricity supply cost outlooks



Note: For REF and ATS, 3 JPY/kWh is added to the average generation cost as the cost of power supply.
Source: United States, prepared by IEEJ from USDOE/EIA, AEO 2026 (industrial electricity cost of the Counterfactual Baseline case; 2025 real prices, converted at 150 JPY/USD). Germany, prepared by IEEJ from Kopernikus-Projekt Ariadne, 'Die Energiewende kosteneffizient gestalten – Szenarien zur Klimaneutralität 2045' (industrial electricity cost of the NEP; presumed real prices, though not specified in detail; converted at 180 JPY/EUR).

Change in energy system cost from REF (ATS)



Note: All costs are in 2022 real prices.

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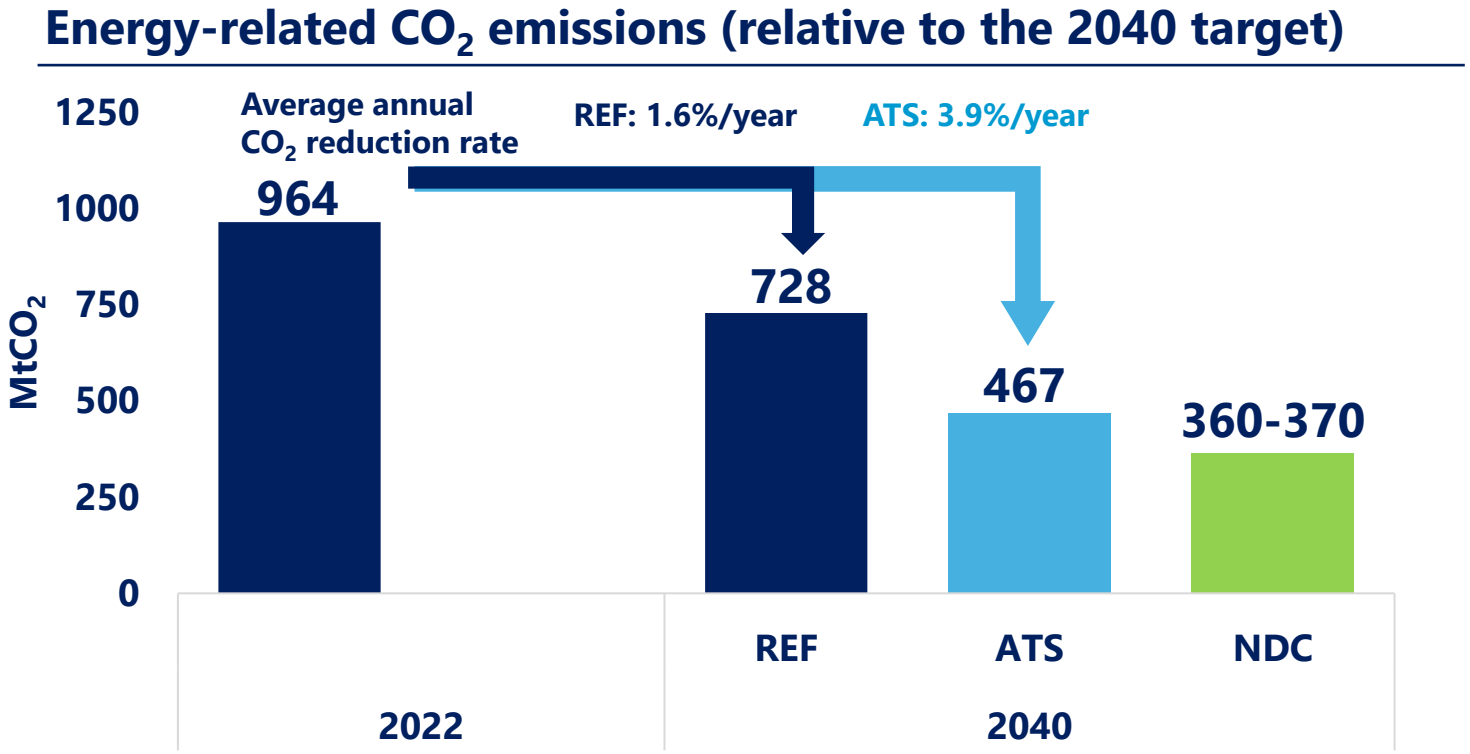
Energy-related CO_2 Emissions Fall Short of the NDC Target

✓ **Environmental sustainability ⇒ The Ambition Level of the 2040 NDC**

- In REF, CO_2 falls owing to lower renewable costs and gradual progress in energy conservation.
- In ATS, CO_2 reductions exceed those in REF, partly because coal demand is substantially reduced.*
- Greater effort will be required to meet the NDC target and to achieve carbon neutrality by 2050.



Note: For 2040, this is below the 'technology progress' scenario (539 $MtCO_2$), which shows the least CO_2 reduction among those presented in materials related to the 7th Strategic Energy Plan. Units are million tonnes of CO_2. For reference, the reduction in energy-related CO_2 in FY2024 was 1.6% year on year (Source: Ministry of the Environment).

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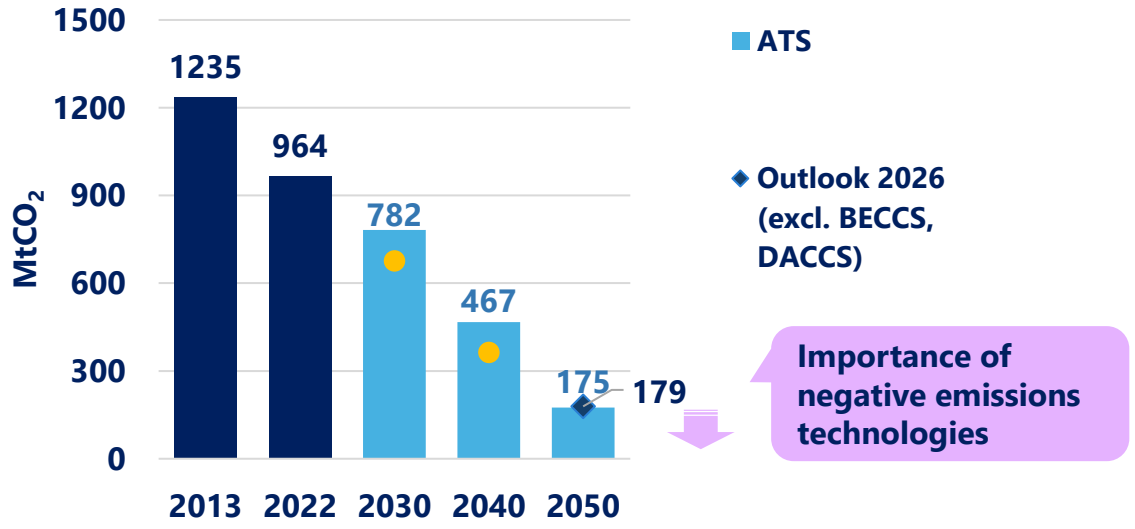
Negative Emissions Are Key to Achieving Carbon Neutrality

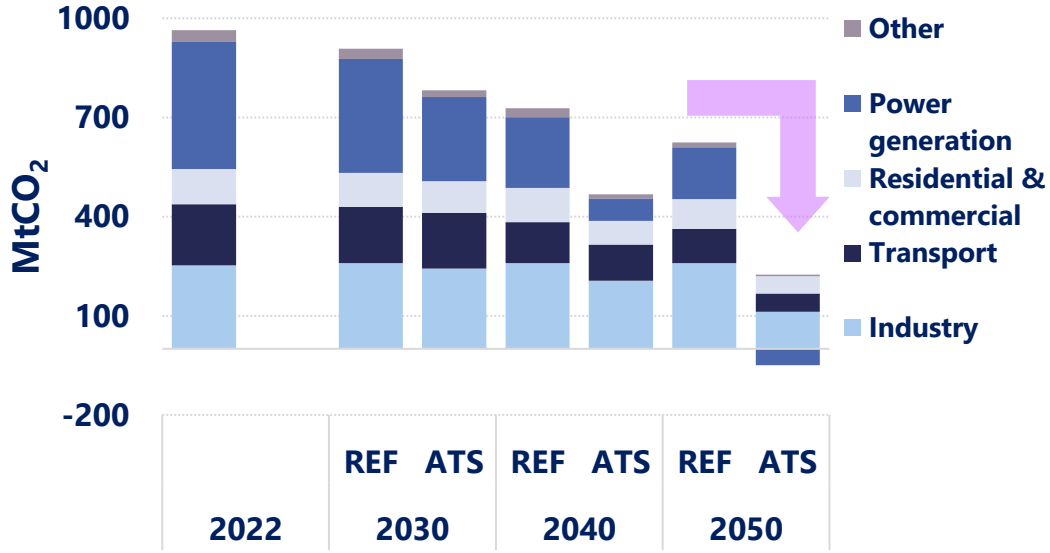
✓ Environmental sustainability ⇒ Trends in energy-related CO_2 emissions

- CO_2 falls continuously but does not reach the NDC or carbon neutrality (CN).
- Negative emissions technologies (NETs) are key to meeting the NDC and achieving CN.
- In ATS, emissions fall in the industrial sector towards 2050 and, in the power sector in particular, become net negative once BECCS is included.

Comparison of energy-related CO_2 emissions (ATS) with the NDC and IEEJ Outlook 2026 (Advanced Technologies Scenario)



Energy-related CO_2 emissions by sector



Note: The Advanced Technologies Scenario of IEEJ Outlook depicts an emissions-reduction path consistent with the 2°C target worldwide. In Outlook 2026, Japan's energy-related CO_2 emissions in 2050, including BECCS and DACCS, are estimated at 99 $MtCO_2$.

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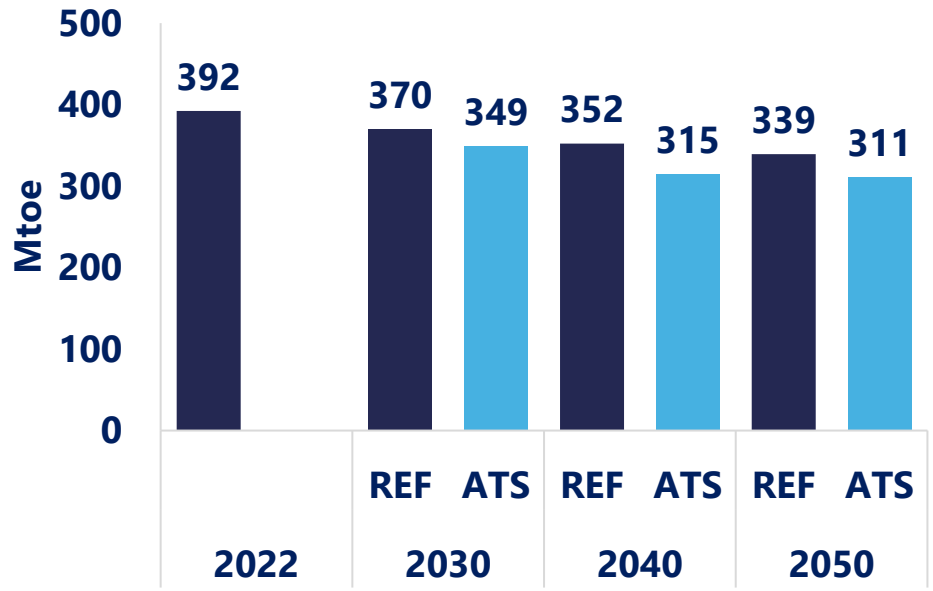
Energy Conservation Advances Continuously through Technology Turnover and Efficiency Gains

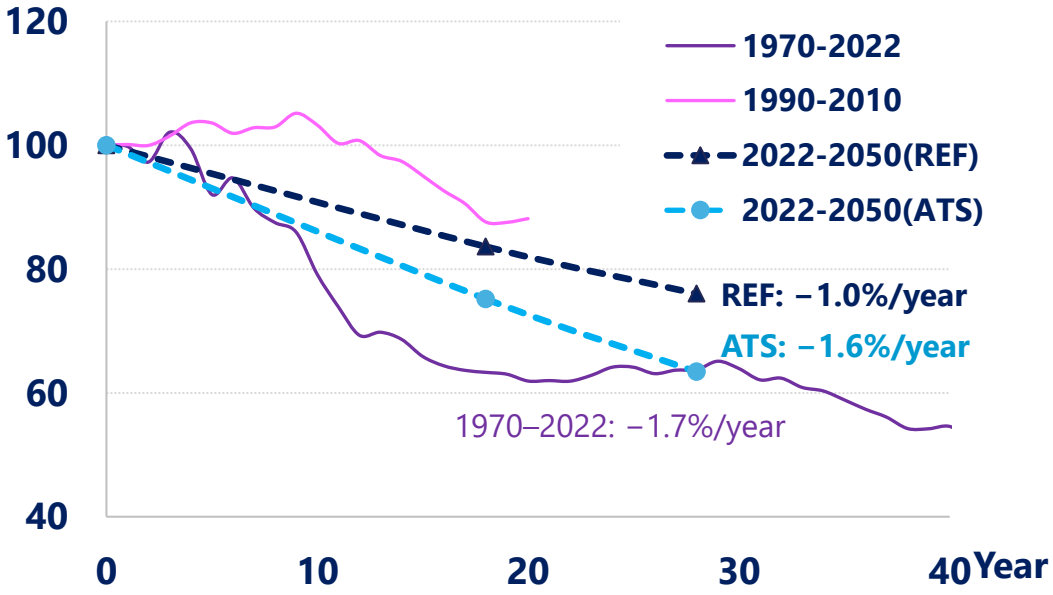
- ✓ In REF, primary energy declines gradually owing to higher fossil fuel prices and improved efficiency.
- ✓ In ATS, energy conservation advances further through the deployment of high-efficiency technologies and contributions from AI applications (left figure).
- ✓ The model results show that the pace of improvement in final energy intensity (final energy consumption / GDP), in ATS, is comparable to the long-term pace over the 30 years following the oil crises (right figure).

Trends in primary energy supply



Note: The unit Mtoe in the left figure is million tonnes of oil equivalent.

Final energy intensity indexed to the base year (start year = 100)



Note: REF and ATS are model results reflecting the deployment of energy-conservation technologies. 1970–2022 and 1990–2010 are actual values.

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Challenges for Reforming the Energy Supply–Demand Structure Suggested by the Model Analysis

- ✓ The result suggests that energy security and decarbonisation can be mutually reinforcing, but cost and technology constraints remain critical.
- ✓ The design of policies and regulations that encourage technology development, initiatives and behavioural change also becomes important.

1. Securing future energy resources and the use of technology

- Diversifying energy sources, including nuclear as a stable baseload source, and diversifying energy supply sources
- Securing supply chains for resources and technologies (e.g. decarbonisation technologies and AI)

2. Securing international competitiveness and containing energy costs

- Measures to reduce energy costs amid rising fuel-price volatility and shrinking availability of suitable renewable sites
- Addressing hidden costs such as integration costs associated with variable renewables
- Mechanisms to secure the funding needed for capital investment (development of related systems, including GX)
- Efforts to raise Japan's presence in international markets through low- and zero-carbon technologies

3. Seeking realistic solutions for global warming and environmental measures

- Reaching the NDC remains challenging, but greenhouse gas reductions do progress
- Realistic actions that also keep the 2°C target in mind
- Efforts to secure technology options that contribute to achieving CN in the future (e.g. negative emissions technologies)

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Reference: Assumptions on Technology Deployment by Scenario

- ✓ Preconditions and constraints, such as upper limits on technology deployment, are assumed as follows.
- ✓ For the power sector, technologies such as CCS and hydrogen, which are expected to be deployed through the Long-Term Decarbonisation Power Source Auction, etc., are assumed as lower limits.

Assumptions on technology deployment by scenario

Item	REF	ATS	Notes
Nuclear	26.7 GW	41.0 GW	Assumes lifetime extensions of existing reactors and operation of planned new builds, giving the capacities shown as of 2050. REF: reactors that started operating in the 1970s remain until 2040 and those from the 1980s until 2050; new builds are those currently 'under construction'. ATS: assumes maximum use of existing reactors, including 'count stop', so all restarted reactors remain in 2050; new builds cover those currently under construction or planned.
Renewable cost	Based on Working Group on Verification of Generation Costs	4–25% lower CAPEX than REF	In ATS, cost reductions from REF are assumed as technology advances.
Upper limit on renewable deployment	PV 378 GW, onshore wind 25 GW, hydropower (large-scale) 23 GW		Upper limits on variable renewable capacity are assumed with reference to Obane (2024), etc. For offshore wind, capital costs, capacity factors and capacity limits are assumed by water depth (in 15-metre increments). Hydropower limits are assumed from supply plans, etc.
Battery storage cost	33,800 JPY/kWh	12,900 JPY/kWh	Assumes cost reductions from promoting battery technology development, etc. (The figures are example cost assumptions for lithium-ion batteries as of 2050.)
Upper limit on DR participation rate	11% (Electric Vehicle (EV)), 25% (Heat pump (HP))	26% (Electric Vehicle (EV)), 50% (Heat pump (HP))	EV demand response is assumed with reference to ENTSO-E's Distributed Energy scenario, with vehicle-to-grid (V2G) in mind. ENTSO-E. (2025) ENTSO-E and ENTSOG public consultation on the TYNDP 2026 Scenarios' input assumptions, data, parameters and methodologies.
Efficiency gains from digital tech (e.g. AI)	Not included	Included	In ATS, efficiency gains in the demand sectors (industry, transport, residential and commercial) from process improvements using digital technologies such as AI are considered.
Upper limit on CCS	120 million tonnes CO2/year	240 million tonnes CO_2/year	Assumed as a value including domestic and overseas volumes, with reference to the final summary of the Study Group on the Long-Term CCS Roadmap.

Note: All figures in the table are assumed values as of 2050. For the nuclear 'count stop', under the GX Decarbonisation Power Supply Act (in force from June 2025), periods of suspension due to external factors may be added to the prescribed operating period (40 or 60 years from initial start-up); this effect is taken into account.

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