



THE 2035 JAPAN REPORT

**PLUMMETING COSTS OF SOLAR, WIND,
AND BATTERIES CAN ACCELERATE JAPAN'S CLEAN
AND INDEPENDENT ELECTRICITY FUTURE**

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A photograph of a bamboo forest. The bamboo stalks are tall and thin, with a light green color. The leaves are yellowish-green. A path is visible in the foreground, and a person is walking away from the camera. The path is bordered by a low wall made of dry grass or straw. The sky is visible through the trees, and the overall atmosphere is peaceful and natural.

ABSTRACT

Japan faces a significant energy security risk as it imports nearly all of the fuel used in its power sector, with clean electricity accounting for only 24% of the total. This study shows that, due to the decreasing costs of solar, wind (especially offshore), and battery technology, Japan can achieve a 90% clean electricity share by 2035. This would also result in a 6% reduction in electricity costs, nearly eliminate dependence on imported LNG and coal, as well as dramatically reduce power sector emissions. Additionally, the study finds that Japan's power grid will remain dependable without the need for new gas capacity or coal generation. To take advantage of these significant economic, environmental, and energy security benefits, strong policies such as a 90% clean electricity target by 2035 and corresponding renewable deployment goals are required.



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ACKNOWLEDGEMENTS

Funding for this report was provided by Climate Imperative Foundation.

The following people provided invaluable technical support, input, review, and assistance in making this report possible:

Kimiko Hirata and Chisaki Watanabe of Climate Integrate

James Hyungkwan Kim of Lawrence Berkeley National Laboratory

Yoh Yasuda of Kyoto University

Anya Breitenbach of Forge & Foundry Strategic

Jin Kato of Japan Wind Power Association

Takeaki Masukawa and Kanzo Sugimoto of Japan Photovoltaic Energy Association

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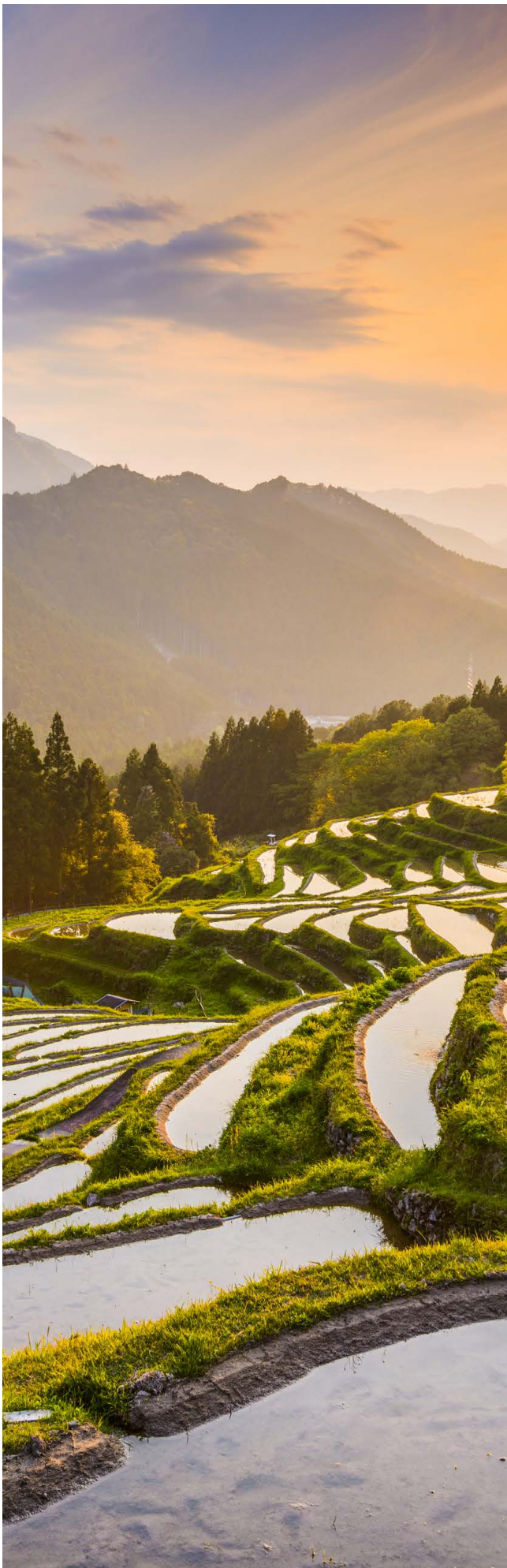


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EXECUTIVE SUMMARY

The global energy crisis poses critical challenges for the Japanese people and their economy. The country depends on foreign fossil fuel imports for about 90% of its primary energy consumption. At the same time, technological advancements and dramatic reductions in solar, wind, and battery storage costs present new opportunities to make clean electricity generation more affordable, while reducing emissions and better positioning the country to meet its 2050 goal of carbon neutrality.

The most important strategy for decarbonization is establishing clean energy sources to feed the grid and substantially increase its supply Japan's electricity without using fossil fuels. These clean energy options include primarily solar- and wind-based renewable energy (RE), as well as smaller amounts of power generated by nuclear and natural gas plants. Generation from any resource that does not produce direct carbon dioxide (CO₂) emissions is considered clean energy in this analysis, including generation from solar, wind, hydropower, biomass, geothermal, hydrogen, and nuclear sources.

Japan's near-term goal is to transition 59% of electricity generation to clean energy sources by Fiscal Year (FY) 2030, compared to the 24% of electricity supplied by these sources in FY 2019. This study examines the factors involved in hitting cost, dependability, and emissions targets, while making even greater cuts in fossil fuel used for electricity generation by 2035.

The study addresses three vital questions:

What effect will recent declines in wind, solar, and battery storage costs have on the pace and scale of renewable resource development?

What clean energy goals are technically and economically feasible, given the inherent uncertainties such as electricity demand growth, fossil fuel prices, and RE and energy storage costs?

How can a faster transition to clean energy deliver not only environmental and economic benefits, but also reduce security risks related to dependence on imported fossil fuels?

Using detailed state-of-the-art capacity expansion and hourly dispatch models to explore one core Clean Energy policy scenario (referred to throughout this report as the “Clean Energy” scenario), researchers examined its potential impact on Japan in the 2020 through 2035 time frame. This core Clean Energy Scenario evaluates transition from Japan’s non-fossil electricity generation goal for 2030 to a 90% clean generation electric system by 2035. The study also applied multiple sensitivity analyses to this Clean Energy Scenario, including high and low renewable energy and storage costs; high fossil fuel prices (2022 levels); high levels of electrification; and the extended lifetime of nuclear generators.

The Clean Energy Scenario limits annual deployment of clean energy generation to that needed to exceed Japanese government goal of non-fossil energy commanding a 59% share of electricity generation by 2030, and a 90% share by 2035. Research findings show that this share of clean energy deployment can be achievable, dependable, and cost effective. Rapid increases in renewable energy generation, in tandem with growth in electrification of technologies, show promise to accelerate progress toward Japan’s carbon neutrality goals and combat climate change.



KEY FINDINGS

Table ES-1 shows the report's findings at a glance, and the following discussion expands on these findings.

TABLE ES1. *Japan's Power System Characteristics by Case Modeled in the Report*

| | CURRENT GRID (2023) | 90% CLEAN (2035) |
|-----------------------------|---------------------|------------------|
| Highly Decarbonized Grid | | ○ |
| Dependable Grid | ○ | ○ |
| Electricity Cost Reductions | | ○ |
| Feasible Scale-Up | | ○ |
| Environmental Savings | | ○ |
| Energy Independence | | ○ |

STRONG POLICIES ARE REQUIRED TO CREATE A 90% CLEAN GRID BY 2035

The 90% Clean Grid (Clean Energy Scenario) assumes strong policies drive 90% clean electricity by 2035. Institutional, market, and regulatory changes needed to facilitate the rapid transformation to a 90% clean power sector in Japan.



JAPAN'S 90% CLEAN GRID IS DEPENDABLE WITHOUT COAL GENERATION OR NEW NATURAL GAS PLANTS

There has been longstanding debate about whether Japan could dependably operate electricity systems with high shares of variable RE (VRE). The study finds that a 90% clean energy grid that features accelerated solar and wind capacity additions, new battery storage, and new interregional transmission infrastructure can be combined with a small percentage of the existing fossil fuel-based generation capacity to dependably meet Japan's electricity demand, while maintaining planning reserve margin and operating reserves. An addition of 116 gigawatt hours (GWh; 29 gigawatts for 4 hours) of battery storage and 11.8 gigawatts (GW) of new interregional transmission lines, coupled with existing flexible methods of generation (dispatchable hydropower, pumped hydropower, and natural gas), can cost-effectively balance operation of a 90% clean energy grid, even during periods of low RE generation and/or high demand.

In the Clean Energy Scenario, RE generated mainly from solar photovoltaic (PV) and wind sources totals 70% of annual electricity generation by 2035. Nuclear power and natural gas-fired power account for 20% and 10% of electricity generated, respectively. All existing coal plants, which generated 32% of the total electricity supply in FY 2019, are phased out by 2035, and no new fossil fuel-powered plants are built.

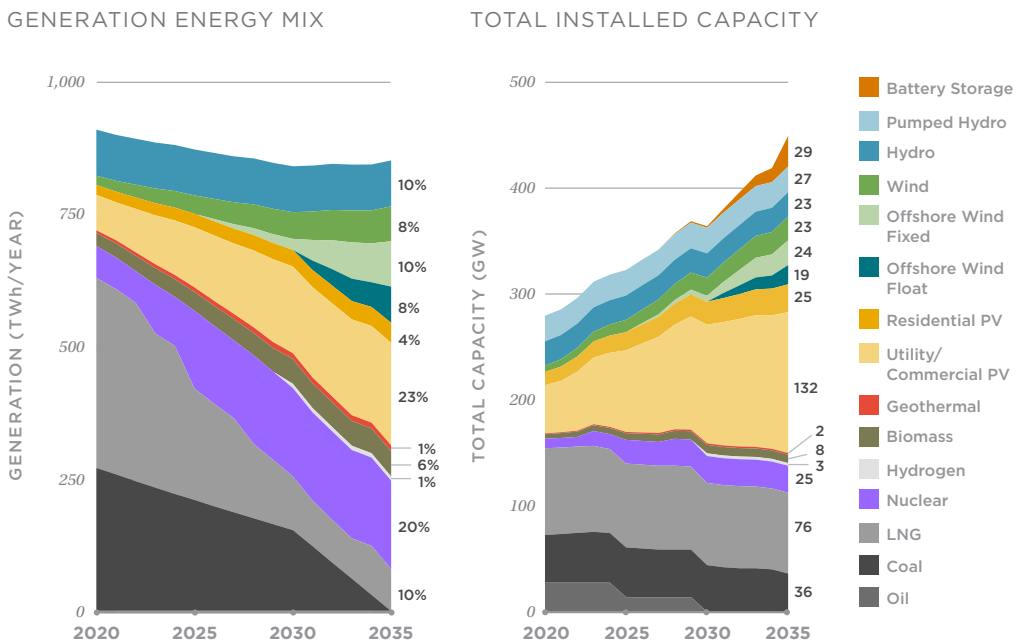


FIGURE ES1. *Generation Energy Mix and Total Installed Capacity between 2020 and 2035, Clean Energy Scenario*



ELECTRICITY COSTS FROM THE 90% CLEAN GRID ARE LOWER THAN TODAY'S COSTS

In the Clean Energy Scenario, RE coupled with enhanced energy storage and interregional transmission lines make it possible to displace a significant amount of generation from existing coal and natural gas plants, while maintaining grid dependability and decreasing wholesale electricity costs. The incremental cost of developing new solar and wind plants, battery storage, and transmission infrastructure in the Clean Energy Scenario is smaller than the fossil fuel, operation and maintenance (O&M), and fixed costs found in running today's typical fossil fuel-fired plants (Figure ES2).

This suggests that more rapid deployment of renewable generation, increasing by an average of 10 GW per year between 2020 and 2035, would actually reduce average wholesale electricity costs by 6% from the 2020 level. Wholesale electricity costs include the cost of generation and storage, plus incremental transmission investments. If social costs of carbon (SCC) is included, wholesale electricity costs are about 36% lower in 2035 under the Clean Energy Scenario than they are in 2020, assuming 12,980 JPY/ton of CO₂ (\$118/t-CO₂) at 2.5% discount rate from the latest study (Rennert et al., 2022). All scenarios in this study include the current level of Global Warming Countermeasure Tax, 289 JPY/t-CO₂ (\$2.6/t-CO₂), not the SCC presented here.

Retaining natural gas-fired power plants helps balancing seasonal and cross-day load variation against solar and wind generation, reducing the necessity of long-duration energy storage and further renewable plant buildout.

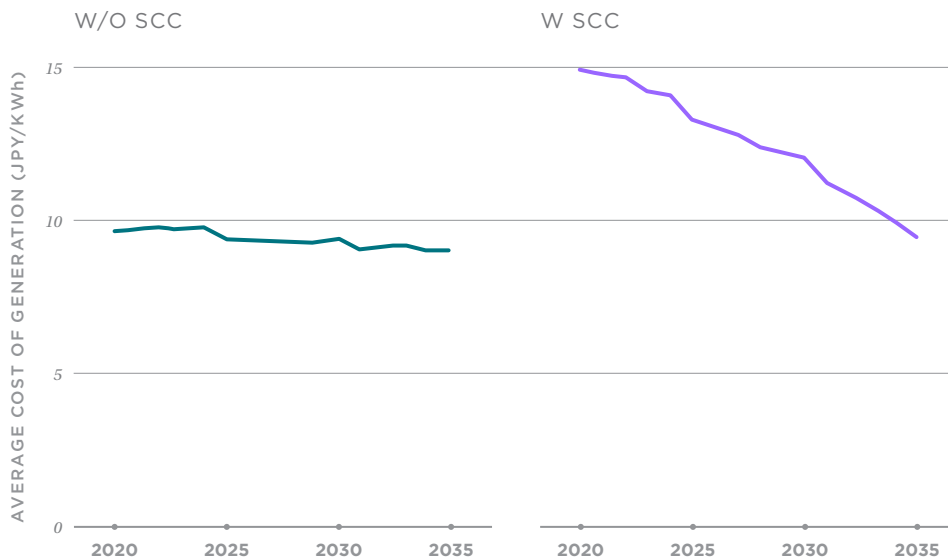


FIGURE ES2. Wholesale Electricity Costs with and without Social Costs of Carbon (SCC) for the Clean Energy Scenario, between 2020 and 2035 (2020 JPY)

85% REDUCED FOSSIL FUEL IMPORTS AND A 90% CLEAN ENERGY GRID CAN SIGNIFICANTLY BOLSTER JAPAN’S ENERGY SECURITY

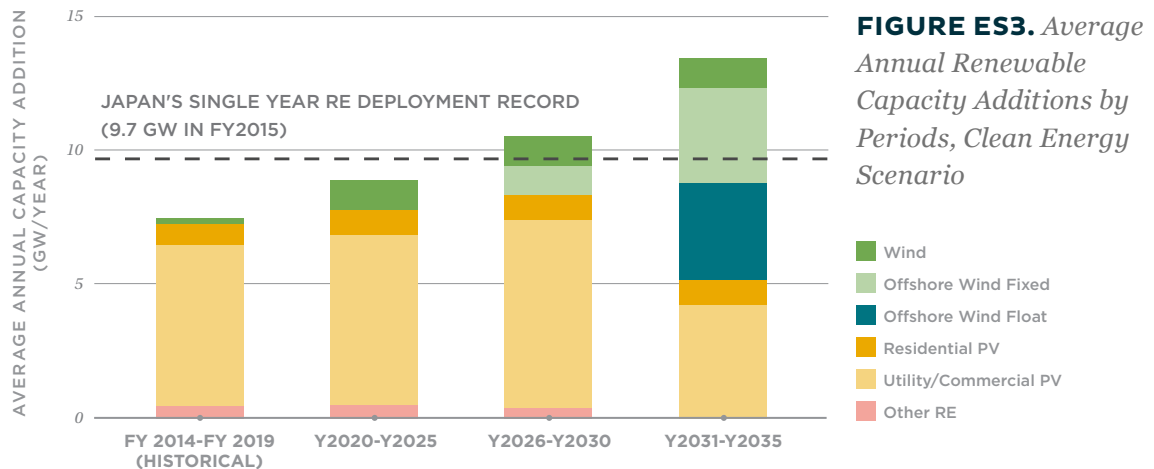
Under the Clean Energy scenario, imported coal and natural gas costs would decrease by 85%, from 3.9 trillion JPY in 2020 to 0.59 trillion JPY in 2035. The decline in imported coal and natural gas costs would be even greater over time under the high fuel cost sensitivity scenario (set at the 2022 cost levels), compared to the base fuel costs used in the Clean Energy Scenario. Not only would the 90% clean energy grid translate into lower electric bills. By maximizing Japan’s use of domestic renewable resources, it would significantly decrease the nation’s heavy dependence on imported fossil fuels. In turn, this would bolster Japan’s energy security, insulating consumers and the economy from skyrocketing international fossil fuel prices.

SCALING-UP RENEWABLES TO ACHIEVE THE 90% CLEAN ENERGY GRID IS FEASIBLE

Under the 90% Clean Energy Scenario, the combined capacity of all RE sources rise from 90 GW in 2020 to 188 GW in 2030 and 254 GW in 2035 (Figure ES1). In particular, accelerated wind and solar capacity growth makes the 90% clean energy grid feasible.

On average, an additional 10 GW of RE need to be brought on-line each year (from 2020 to 2035). This annual increase, comparable to Japan’s single-year renewable buildout record of 9.7 GW (FY 2015), is challenging but feasible (Figure ES3).

Solar power additions are dominant in 2020s, while offshore wind’s continued technology cost declines and high capacity factors make it the dominant growth area in the 2030s. This shift to clean energy will require attention to rapidly break down institutional, market, and regulatory barriers, along with swift advancements in battery storage and interregional transmission lines to balance VRE generation against loads.



CLEAN ENERGY CAN CUT ELECTRICITY SECTOR CO₂ EMISSIONS BY 92%

Generating 90% of electricity from clean energy by 2035 would significantly cut carbon dioxide (CO₂) emissions, resulting in important environmental benefits. By 2035, the Clean Energy Scenario was shown to potentially reduce total electricity sector CO₂ emissions by 92% compared to 2020 levels. The reductions of 345 million tons of CO₂ emissions in 2035 is equal to nearly 30% of Japan’s total CO₂ emissions in FY 2019. As a result, the emission intensity of electricity generation drops by 91% from 404 kilograms (kg)-CO₂/kilowatt hour (kWh) in 2020 to 36 kg-CO₂/kWh in 2035. The extremely low emission intensity supports deeper decarbonization of other sectors, such as electrified transportation, heating, and more.

It also reduces exposure to fine particulate matter (PM_{2.5}), sulfur dioxide (SO₂), nitrogen oxide (NO_x), and heavy metals (e.g., mercury, cadmium, arsenic, chromium, and beryllium) emitted by fossil fuel-burning power plants. This could deliver significant health benefits, potentially extending lifespan and reducing the societal costs of medical care.

REACHING COST-EFFECTIVE LEVELS OF CLEAN ENERGY GENERATION WILL REQUIRE OVERCOMING POLICY, MARKET, AND LAND-USE BARRIERS

A rapid and cost-effective transition to the 90% clean energy grid will require integrated, sustained policy support to overcome institutional, market, and regulatory barriers. The share of electricity generated from RE sources in the Clean Energy Scenario begins to accelerate in the 2020-2035 time period, suggesting that policy and regulatory changes to speed up deployment should begin sooner rather than later.

The recommendations outlined below are intended to inform debate on public and corporate policies to address the pressing energy and climate crisis with stable business models, low integration costs, dependable systems, and minimal land-use impacts.

Establishing Medium-Term Policy Targets (Beyond 2030)

- Set medium-term targets for renewable generation and coal phaseout in 2035 and beyond to reduce policy and market uncertainties
- Create coherent policy packages to enable the medium-term policy targets including research, development, and demonstration (RD&D) and carbon pricing

Accelerating RE Deployment and Coal-Fired Power Phaseout By Mitigating Environmental Externalities

- Consolidate feed-in tariffs, including feed-in premiums, and auctions, to accelerate renewable deployment
- Increase the price of carbon to accelerate coal-fired power phaseout
- Invest part of the carbon revenues in RD&D related to innovations needed to create a zero-carbon grid

Lowering Institutional and Societal Barriers to Rapid RE Deployment

- Establish qualified renewable energy zones (REZs) with suitable topography and land-use designations to avoid delays in permitting and deployment

- Integrate the zoning process in transmission planning
- Involve stakeholders at early stages of planning to cultivate public input and acceptance

Pursuing a Just Energy Transition through Targeted Assistance Policies

- Mitigate the societal and economic impacts of coal phaseout with transition assistance programs for communities and businesses
- Use carbon revenues to reimburse households and businesses for part of their utility expenditures, reducing the tax burden

Ensuring System Dependability, Enhancing Operational Flexibility, and Boosting Energy Efficiency

- Create markets and profitable business models for flexible resources including energy storage, demand-side management and measures, and flexible generation
- Drive investments in cost-effective energy efficiency improvement through standard setting or adoption of fiscal incentives

Through the support of these policies, swift decarbonization of Japan's electricity system would make it possible to more quickly cut emissions related to faster and more widespread electrification of other sectors, reducing CO₂ emissions and smoothing the country's path to a carbon-neutral economy by 2050.

1

INTRODUCTION

Japan, the world's third-largest economy, is facing a pressing series of related energy-related dilemmas in the wake of the Russian invasion of Ukraine: simultaneously ensuring energy affordability and energy security, while making the deep cuts in greenhouse gas (GHG) emissions needed to meet the nation's climate change goals. These targets include shifting electricity generation to 59% clean energy sources by 2035 and achieving carbon neutrality by 2050 in support of Japan's commitment to the global goal of limiting the average temperature increase to 1.5°C.

As of 2020, only 11.2% of Japan's primary energy was supplied by domestic resources (GoJ, 2021b), exposing the nation's people and economy to the high volatility of international fuel prices (Figure 1). Liquefied natural gas (LNG) and coal power plants (typically fueled with coal N.E.S., a common type of coal used in Japan) still account for roughly 80% of the nation's electricity generation. Spikes in international energy prices led to Japan's 2022 wholesale electricity price of 22.6 Yen (JPY)/kWh being double that of the average in the preceding 10 years (11.5 JPY/kWh from 2012-2021).



Japan recently established a national target of net-zero GHG emissions by 2050 (GoJ, 2021a). This builds on the government's earlier nationally determined commitment (NDC) to reduce GHG emission levels from 26% to 46% between 2013 and 2030, which was made as part of the Paris Agreement (GoJ, 2021d; GoJ, 2021e). Meeting these ambitious 2030 and 2050 national and international climate change commitments will require accelerated deployment of renewable energy (RE) and early phaseout of coal-powered electricity generation plants.

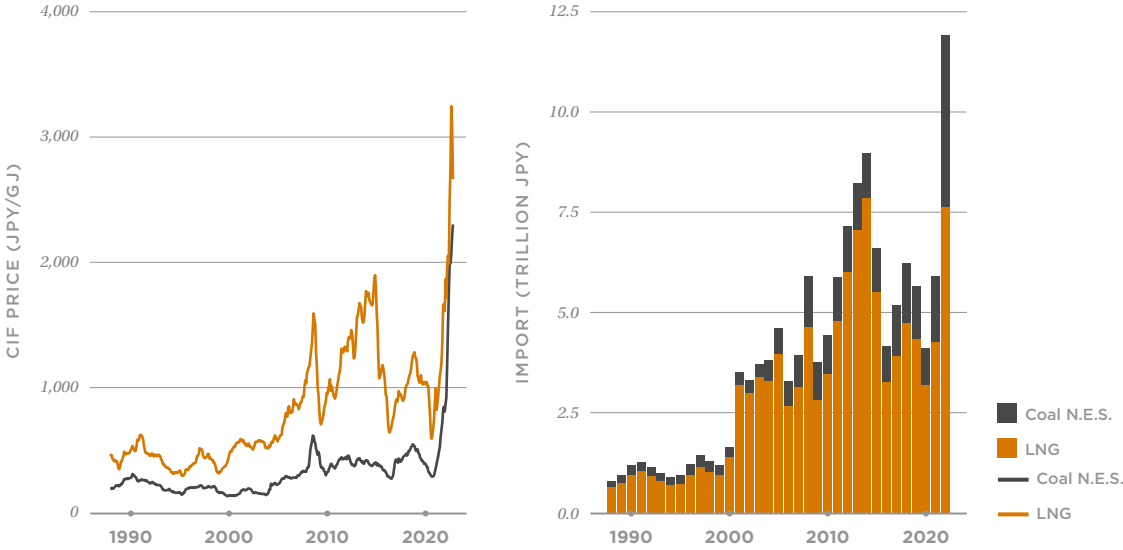


FIGURE 1. *CIF (Cost, Insurance, and Freight) Price and Annual Import of Coal N.E.S. and LNG in Japan (nominal)*

Note: N.E.S. is a common type of coal for electricity generation

Skyrocketing fossil fuel prices, global constraints on fossil fuel supplies, and ambitious climate change targets create strong motivation for shifting to clean energy. As seen in U.S., Indian, and Chinese analyses, recent advancements and dramatic cost reductions in solar, wind, and battery storage technologies create new opportunities to improve energy security, maximizing the use of domestic energy resources while reducing emissions and costs related to electricity generation (Bistline et al., 2022; Abhyankar et al., 2021, 2022; Phadke et al., 2020). The economic case to tackle energy challenges with accelerated deployment of clean energy is particularly strong in fuel-resource-poor countries such as Japan. Given that global carbon emissions must be halved by 2030 to limit warming to 1.5°C and avoid catastrophic climate impacts (IPCC, 2018), it is imperative that Japan accelerates its transition to a clean energy grid.

This report examines the technical feasibility, costs, and implications of Japan increasing the share of electricity generated from clean (non-fossil) energy to 90% by 2035. The report aims to answer three key questions:

What effect will recent declines in wind, solar, and battery storage costs have on the pace and scale of renewable resource development?

What clean energy goals are technically and economically feasible, given the inherent uncertainties including in electricity demand growth, fossil fuel prices, and RE and energy storage costs?

How can a faster transition to clean energy deliver not only environmental and economic benefits, but also reduce security risks related to dependence on imported fossil fuels?

The electricity sector will play a pivotal role in meeting Japan's environmental goals. Generation of a larger share of electricity from non-fossil sources, combined with electrification of the transportation, industrial, and building sectors, can result in significant emissions reductions.

This report draws from and expands upon a growing body of literature and analysis that explore high-renewable and low-carbon power systems around the world. Several recent studies assessed the operational and economic impacts of a high share of VRE on Japan's power grid in the near term (e.g. Komiyama and Fujii, 2014, Komiyama and Fujii, 2017, Komiyama and Fujii, 2019, Komiyama and Fujii, 2021) and in 2050 (e.g. Matsuo et al., 2018; Matsuo et al., 2020). However, most of the recent studies did not consider the recent dramatic decline in renewable energy and battery storage costs, allowed interregional transmission expansions, or explored the detailed pathways for deep decarbonization of power systems to a targeted year, which is often 2050. Our study attempts to build on the existing literature and address some of these gaps by (a) developing a spatially and temporally resolved capacity expansion and economic dispatch model using an industry standard platform, PLEXOS, that assesses the least cost resource mix at the national level, with interregional transmission requirement, and power plant level hourly economic dispatch, (b) using the latest renewable energy and storage cost estimates and trends, informed by prices observed in the market and expert consultations, and (c) explore the opportunities for large CO₂ reductions to happen more rapidly while bolstering Japan's energy security.

The report is organized into the following sections:

- Section 2 provides an overview of methods used in the electricity and emissions analyses.
- Section 3 describes results.
- Section 4 summarizes key conclusions, provides policy recommendations, and outlines priority areas for future research.

2

METHODS AND DATA SUMMARY

This study is based on intensive scenario building, cost data development, and power system modeling using detailed, best-available data inputs, and state-of-the-art modeling tools. The analysis combines detailed load, wind, and solar profiles with projections for RE, and energy storage costs. Generation from any resource that does not produce direct CO₂ emissions is considered to be clean energy in this analysis, including generation from solar, wind, hydropower, biomass, hydrogen, and nuclear sources.

Models are based on a detailed representation of Japan's electricity system, including hourly transmission constraints, region-specific wind and solar profiles, and recent RE and energy storage cost projections.

Analyses found in this report use capacity expansion and hourly dispatch models developed in PLEXOS (an industry standard capacity expansion and production cost modeling platform) to analyze the least-cost (optimal) combination of generation, storage, and interregional transmission strategies on an annual basis. Electricity demand projections are based on government projections and scenarios described in the 6th Strategic Energy Plan of Japan (GoJ, 2021e)

This section provides a brief overview of the study's core policy scenario, key inputs and assumptions, modeling tools and approaches, and sensitivity analyses. The study appendices include detailed descriptions of methods and inputs used for modeling and the development of hourly load, wind, and solar profiles.

2.1 POLICY SCENARIO

The analysis used in this study examines one core scenario. The Clean Energy Scenario is consistent with current Japanese policy goals for 2030 and G7's

commitment to fully or predominantly decarbonizing electricity by 2035, and explores whether further expansion of clean energy deployment through 2035 is achievable, dependable, and cost-effective. This scenario is based on clean (non-fossil) energy resources being used to generate a 90% share of Japan's electricity by 2035. Sensitivity analyses explore variations on the Clean Energy Scenario.

Table 1 benchmarks the Clean Energy Scenario assumptions against national 2030 and 2035 goals. This study's assumptions related to coal generation, RE generation and capacity, and the share of electricity generated from non-fossil energy (including RE) sources include:

- Coal generation is forced to phase out by 2035.
- The amount of new RE generation that can be added in any given year must exceed the amount needed to meet current policy targets for 2030.
- After 2030, annual targets for generation of electricity from clean energy sources must be met.
- The total amount of electricity generated is calculated through least-cost optimization, subject to limits such as 2030 and 2035 clean energy generation targets, and nuclear power regulatory policy targets.



TABLE 1. Policy Scenario Assumptions Benchmarked Against National Goals

| | NATIONAL GOALS | CLEAN ENERGY SCENARIO ASSUMPTIONS |
|---|---|---|
| Reference policies or plans | <ul style="list-style-type: none"> • New 2030 U.N. NDC Target • 6th Strategic Energy Plan • Japan 2050 Carbon Neutrality Goal • G7 pledge to achieve “fully or predominantly decarbonized” electricity by 2035 | |
| Coal generation | <ul style="list-style-type: none"> • G7 pledge to phase out unabated coal by 2035 | <ul style="list-style-type: none"> • 19% by 2030 (6th Strategic Energy Plan) • All plants phased out by 2035 |
| RE generation capacity additions | <ul style="list-style-type: none"> • 36%-38% by 2030 <ul style="list-style-type: none"> - PV: 103.5 GW - 117.6 GW - Wind: 23.6 GW <ul style="list-style-type: none"> • Onshore 17.9 GW • Offshore 5.7 GW | <ul style="list-style-type: none"> • At least 36% by 2030 |
| Clean (non-fossil) energy generation share | <ul style="list-style-type: none"> • 59% by 2030 <ul style="list-style-type: none"> - RE 36-38% - Nuclear 20%-22% - Hydrogen/Ammonia 1% | <ul style="list-style-type: none"> • 59% in 2030 • 90% in 2035 • Linear increase between 2030 and 2035 |
| Nuclear restart | <ul style="list-style-type: none"> • All operatable plants restart | <ul style="list-style-type: none"> • 20-year extension of lifetime • 25 GW restart (restart year depends on individual plants) • No addition of new nuclear plants |
| Hydrogen or ammonia | 1% in 2030 | 1% in 2030 |

GW = gigawatts; PV = photovoltaic

2.2 MODELING TOOLS AND APPROACH

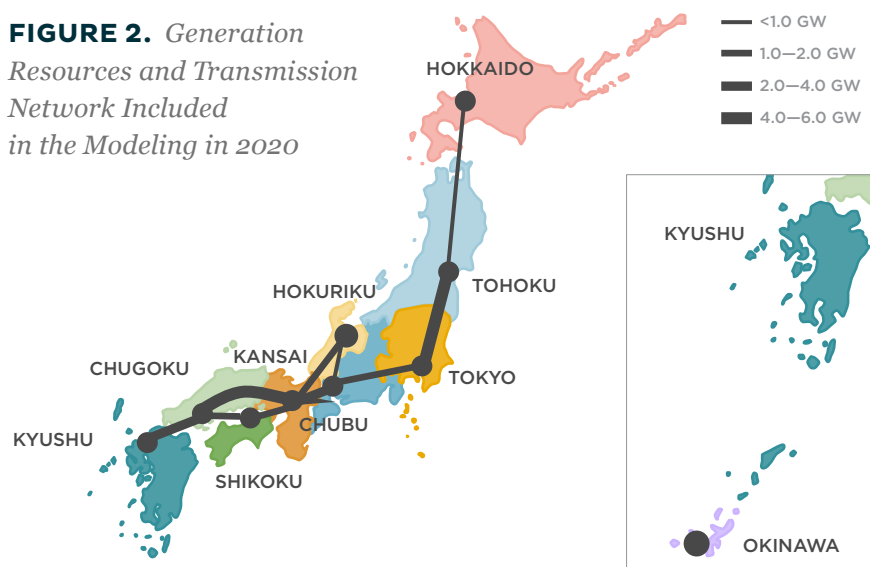
The electricity system analysis was conducted using PLEXOS, a modeling platform widely used for industry-standard power systems analysis. Researchers used a two-stage modeling approach.

First, a capacity expansion model was used to develop least-cost generation, storage, and interregional transmission portfolios each year from 2020 to 2035 for core and sensitivity scenario. Then, a production cost model was used to examine 2035 operating costs, emissions, and dependability for 8,760 hours based on

DC power flows; it does not consider the more complex dynamics of AC power systems. Generation, transmission, and storage investments and operations are optimized to achieve the 2030 generation mix based on the *6th Strategic Energy Plan of Japan* and 90% clean energy generation with the phaseout of coal-fired plants by 2035.

Models included generation resources, generation constraints, unit commitments, and transmission constraints (available transfer capacity) for 10 nodes connected by 23 gigawatts (GW) of interregional transmission corridors in 2020 (Figure 2). The model excludes generators that are not dispatched by the transmission & distribution companies (i.e., off-grid generators are excluded). Analysis assumed that the electricity system was balanced in every hour, and the 10% planning reserve margin in the capacity expansion model and three types of operational reserves in the production cost model were managed at a regional grid scale (for details, see Appendix B), enabling efficient resource sharing among regions.

FIGURE 2. *Generation Resources and Transmission Network Included in the Modeling in 2020*



2.3 KEY MODELING INPUT

Electricity Demand

Growth in Japan's electricity demand between now and 2035 is highly uncertain. It will depend on the structure and pace of growth or decline in the economy, the population, and the level of electrification in the transportation, industry, and buildings sectors.

Electricity demand is projected to decline by 0.8% every year through 2030 in line with the sixth Strategic Energy Plan based on anticipated energy efficiency improvements and population decline (GoJ, 2021d). Japan's expected population drop is significant, from 125.3 million people in 2020 to 112.2 million in 2035 (GoJ, 2022b). Based on these projections, researchers assume electricity demand will decrease between 2020 and 2030, and then remain stable from 2030 through 2035 (see Figure 3). This study excludes generators that are not dispatched by the transmission & distribution companies (i.e., off-grid generators are excluded). This study also considers increased electrification of the transportation, industry, and buildings sectors as part of the sensitivity analysis, where electricity demand is assumed to stay constant rather than decline after 2020.

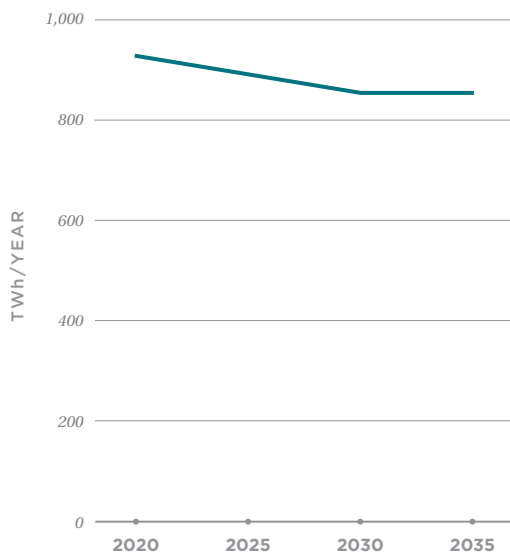


FIGURE 3. *National Electricity Demand Projection Used in Clean Energy Scenario*

TWh = terawatt hours.
Transmission and distribution loss: 4%



Technology and Fuel Costs

Extensive resource cost inputs included those for wind, solar, and battery storage technology, as well as coal and natural gas. The United States National Renewable Energy Laboratory (NREL) Annual Technology Base (ATB) provides projections of installed and fixed operation and maintenance (O&M) costs for onshore wind, offshore wind, solar photovoltaic (PV), and battery storage in the United States (NREL, 2022). Plummeting costs for wind and solar energy have dramatically improved the prospects for rapid, cost-effective decarbonization, leading to levelized cost of electricity (LCOE) projections for the ATB scenarios being revised downwards in almost every year between 2015 and 2019 (Phadke et al., 2020). Projections of installed costs and fixed operations and maintenance (O&M) costs for generation, energy storage, and interregional transmission lines in Japan are primarily based on Japan’s cost data. For solar, wind, and battery cost projection, we combined Japan’s cost data, the 2022 ATB forecasts and industry consultations with necessary adjustment to reflect Japan’s country-specific factors.

Given simultaneous technological advancements and future cost uncertainties, offshore wind and battery storage technology costs (low, base, and high price inputs for the core and sensitivity scenarios) in this study are based on 2020 Japanese costs (Advisory Committee, 2021) and are assumed to converge with the U.S. costs projected in NREL’s advanced (“Low” in this report), moderate (“Base”), and conservative (“High”) ATB scenarios. Utility and commercial-scale solar uses ATB’s commercial-scale solar projection due to the relatively small scale of non-residential solar PV projects in Japan. Onshore wind costs are based on the assumption that the capital costs converge to those of ATB estimates, while non-capital costs are held constant across the study period. Figure 4 summarizes the capital cost projections of solar, wind, and battery technologies. Grid connection costs of offshore wind are adjusted according to the proximity between the offshore wind clusters and high voltage transmission lines. The technology costs of other technologies are summarized in Appendix B.

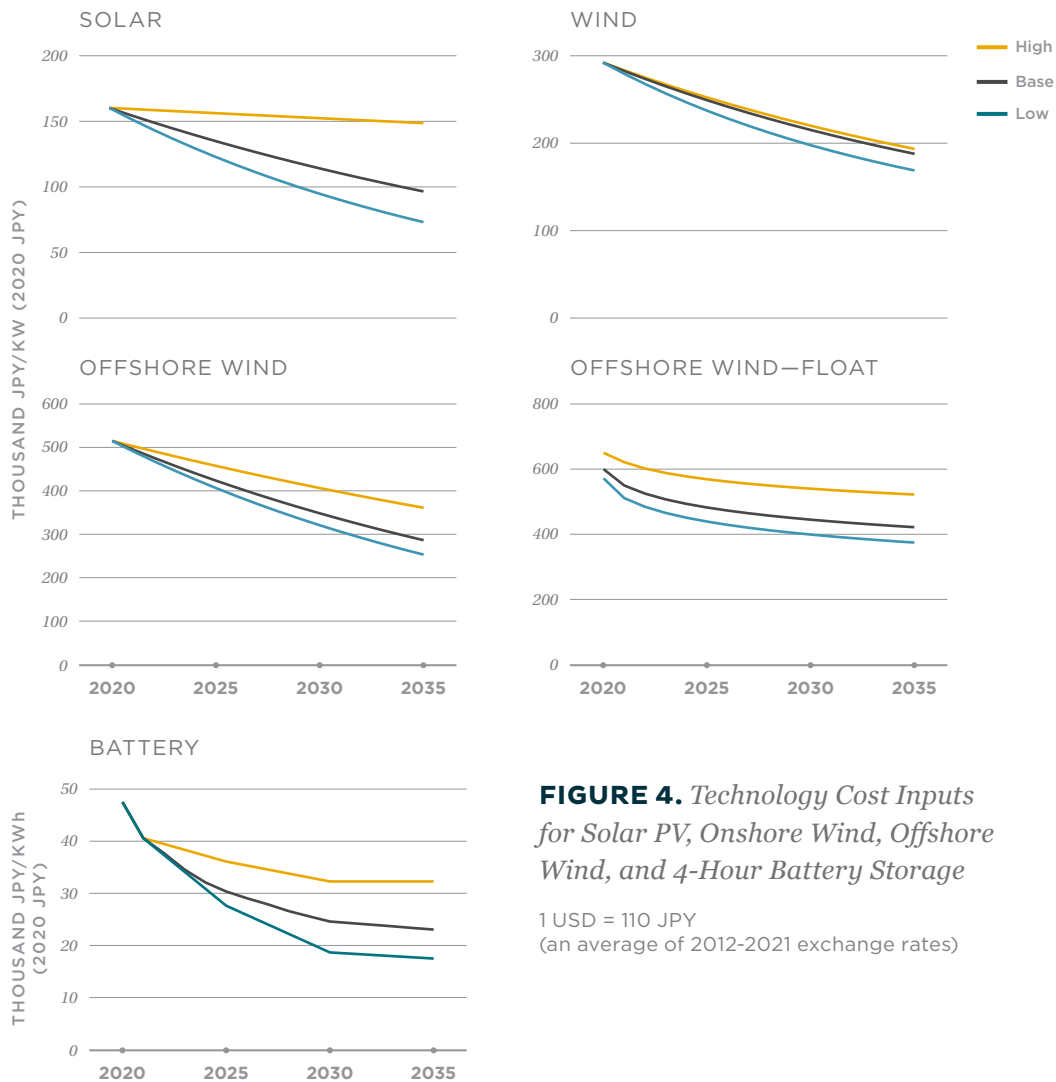


FIGURE 4. *Technology Cost Inputs for Solar PV, Onshore Wind, Offshore Wind, and 4-Hour Battery Storage*

Longer-term fuel price trends in Japan are highly uncertain. Coal and gas prices rose to record levels in 2011 and 2022 (GoJ, 2022b). The study's high fuel price sensitivity scenario bases Japanese fuel prices on the average from January to September 2022 (GoJ, 2022b). The base fuel price used for the core and additional sensitivity scenarios is based on the average between July 2012 and December 2021 (Figure 5). This study does not consider a low fuel price scenario, because future prices will not likely be lower than historical trends given global supply constraints.

Because the study did not model intraregional transmission, the model, distribution-connected, and transmission-connected resources look the same from an operational perspective. Data on land, incremental distribution, and transmission

costs was not detailed enough to more meaningfully assess the tradeoffs between utility-scale and distributed resources.

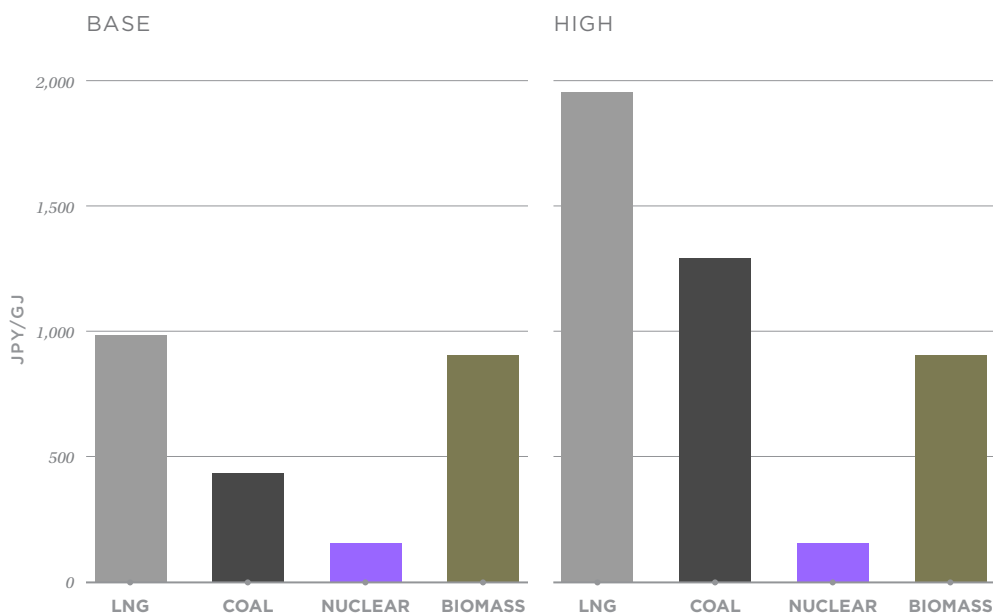


FIGURE 5. Fuel Price Inputs for Coal and Gas

1 USD = 110 JPY (an average of 2012-2021 exchange rates). GJ = gigajoules.

Solar and Wind Profiles

For this study, we estimated wind and solar resource potential and developed detailed solar and wind profiles for each region in Japan. The methodology can be divided into two parts. First part involves estimating the resource potential, i.e., the maximum solar and wind capacity that can be installed in a region. We use average annual capacity factors from Global Wind and Solar Atlas and multiple exclusion criteria to estimate the potential. Exclusion criteria include elevation, slope, landcover, natural parks, defense areas, fishery zones and ocean depth. The second part involves developing detailed hourly generation profiles. We use meteorological data from reanalysis datasets and simulate site level wind and solar generation using NREL’s System Advisor Model (SAM) Typical wind and solar farms are designed in SAM and hourly generation is estimated by passing meteorological data through it. We then use an aggregation algorithm to combine hourly generation from multiple sites in a region and create a representative regional wind

and solar resource profile. For offshore wind we develop multiple clusters for fixed and floating wind using the spatially constrained multivariate clustering algorithm. We then develop profiles for each of those clusters. Complete methodology and data sources are discussed in detail in Appendix C.

Nuclear Generation

Because factors other than economics often motivate operation and expansion of nuclear power facilities, this study bases nuclear generation capacity projections on policy targets, rather than on cost. As of 2022, 10 nuclear power plants already restarted, while 7 and 10 nuclear power plants are approved for and under review for restart, respectively. It was assumed that all of the existing nuclear power plants that already applied for approval would resume operation by 2023 (for already approved plants) and 2025 (for plants under review) under the current aggressive nuclear restart policy. The base case also assumes every nuclear plant is granted 20-year operating permit extension. As a sensitivity, this study also included a scenario that conservatively assumes no 20-year extension is granted for any nuclear power plants, except for those already granted extension.



Other Assumptions

Table 2 summarizes other assumptions used in this study.

TABLE 2. *Other Assumptions*

| PARAMETER | ASSUMPTIONS |
|--|---|
| Coal retirements | The retirement of existing coal-fired plants at the end of each of their 50-year lifetimes, decreasing the amount of coal generation each year, until coal generation is completely phased out in 2035. |
| Gas retirements | The retirement of existing gas-fired plants at the end of each of their 50-year lifetimes. |
| Nuclear extensions | The retirement of existing nuclear plants at the end of each of their 60-year lifetimes including 20-year extension in the base cases. |
| Transmission expansions | A maximum 100% increase in existing individual transmission line capacity. |
| Solar PV retirements and capacities | The retirement of solar PV plants at the end of each of their 30-year lifetimes and an average capacity factor (CF) of 17%. |
| Wind turbine retirements and capacities | The retirement of wind turbines at the end of each of their 30-year lifetimes and average CFs of 31% (onshore) and 44% (offshore). |
| Maximum annual capacity expansion | Solar PV and onshore wind capacity limited to the historical maximum for solar PV installations and twice as much as the historical maximum for onshore wind turbine installations (based on 2012-2020 data). |

2.4 SENSITIVITY ANALYSIS

The analysis considered five sensitivities: “High RE and Storage Cost scenario”, “Low RE and Storage Cost scenario”, “High Fuel Cost scenario”, “Low Nuclear scenario”, and “High Electrification scenario”. These sensitivity cases differ only from the core Clean Energy Scenario by changing the assumptions for one key input parameter. Low RE and Storage Cost scenario and High RE and Storage Cost scenario use our cost projections based on the NREL ATB 2022 advanced and conservative cases, respectively. The High Fuel Cost scenario applies the 2022 level fuel costs across the entire study period. The Low Nuclear scenario assumes no 20-year lifetime extension is granted, except for those that have already been granted the extension as of 2022. The High Electrification scenario assumes electricity demand stays constant during the study period.

For dependability, we conducted two types of sensitivity analyses. First, to test the system dependability during very high system stress, we simulated the hourly dispatch in the net peak load weeks with an unanticipated demand shock (10% increase in demand in the highest 2035 summer and winter net load periods). Second, to examine the system dependability impact of the inter-annual variability in wind, solar, and hydropower generation, we also simulated the hourly operation of the Japan's power system over 35,040 hours (each hour in 4 weather years).

3

KEY FINDINGS

This section highlights the key findings from this analysis. Results for the sensitivity analyses are integrated with these key findings. Additional details are provided in the appendices.

3.1 JAPAN'S 90% CLEAN ENERGY GRID CAN DEPENDABLY MEET ELECTRICITY DEMAND WITH LARGE ADDITIONS OF RE AND ENERGY STORAGE

There has been longstanding debate about whether Japan could dependably operate electricity systems with high shares of VRE. The study finds that a 90% clean energy grid that features accelerated solar and wind capacity additions, new battery storage, and augmented interregional transmission infrastructure can be combined with a small percentage of the existing fossil fuel-based generation and pumped hydro storage capacity to dependably meet Japan's electricity demand without coal generation, while maintaining necessary planning reserve margin and operating reserves.

In the Clean Energy with base fuel price scenario, clean energy generation increases from 24% of total generation in 2020 to 59% in 2030. This mix will make it possible to meet 2030 NDC goals and eventually attain a clean energy generation share of 90% in 2035.

The significant increase in clean energy is mainly supplied by expanding the shares of energy generated by offshore and onshore wind (26%) and solar PV (27%) (Figure 6). Battery storage capacity grows to 1.5 GW in 2030 and 29 GW in 2035, to integrate more solar and wind generation. The steep increase in the battery storage deployment rate in 2030 is dependent on two factors:

- Abundant existing pumped hydro storage provide sufficient energy storage in the 2020s
- Solar and wind generation accounting for a relatively small percentage of total generation in the 2020s (20% in 2025 and 30% in 2029)

Natural gas-fired power, generating the largest share of electricity (37%) in FY 2019, accounts for 10% of total generation in 2035. Retirement of each coal-fired plant as it reaches 50 years in service reduces the total capacity of these plants by about 45 GW from 2020 to 36 GW in 2035. All existing coal plants, generating 32% of total electricity supply in FY 2019, are forced to phased out by 2035, and no new fossil fuel-powered plants are built.

Although not in regular operation, prior to their 50-year retirement, the remaining coal-fired power plants provide planning reserve margin and operating reserves. Reservoir hydropower, natural gas, and energy storage also compensate for capacity shortfalls in extreme climate events such as historic heat wave.

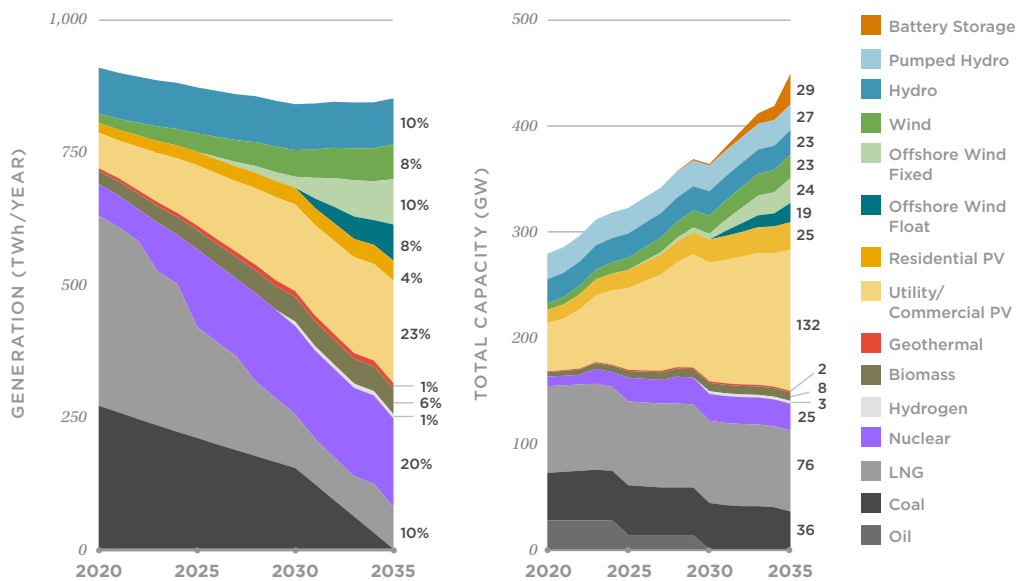


FIGURE 6. Generation Energy Mix and Total Installed Capacity between 2020 and 2035, Clean Energy Scenario

Researchers also conducted sensitivity analyses with different inputs and assumptions. The difference in generation mix and installed capacity of all scenarios from the Clean Energy Scenario is summarized in Figure 7.

First, under the High Fuel Cost Scenario, solar and wind technologies deliver electricity at a price far cheaper than that produced with coal and LNG. This results in an additional 35 GW of solar and wind capacity, 19 GW of battery storage

capacity, and 7 GW of interregional transmission lines by 2035 (compared to the Clean Energy Scenario), leading to 94% clean energy in 2035.

Second, the High RE and Storage Cost sensitivity scenario, with more transmission facilities and offshore wind plants and fewer solar and energy storage resources, deploys proportions of resources opposite those of the Low RE and Storage Cost sensitivity scenario. This trend is due to the relationship between battery storage and transmission prices. When transmission is cheaper than battery storage, transmission is built to utilize wind resources in distant areas in northern part of Japan. On the other hand, when battery storage is cheaper than transmission construction, battery storage enables the deployment of solar PV near load centers such as Tokyo, Nagoya, and Osaka.

Third, the High Electrification scenario requires additional solar, wind, battery storage, and transmission capacity, as well as more frequent natural gas plant operation.

Fourth, the Low Nuclear scenario suggests that the addition of 9 GW of solar, 14 GW of offshore wind, 17 GW of battery storage, and 11 GW of interregional transmission lines can complement retirement of 8 GW of nuclear capacity when plants reach 40 years of service by 2035.



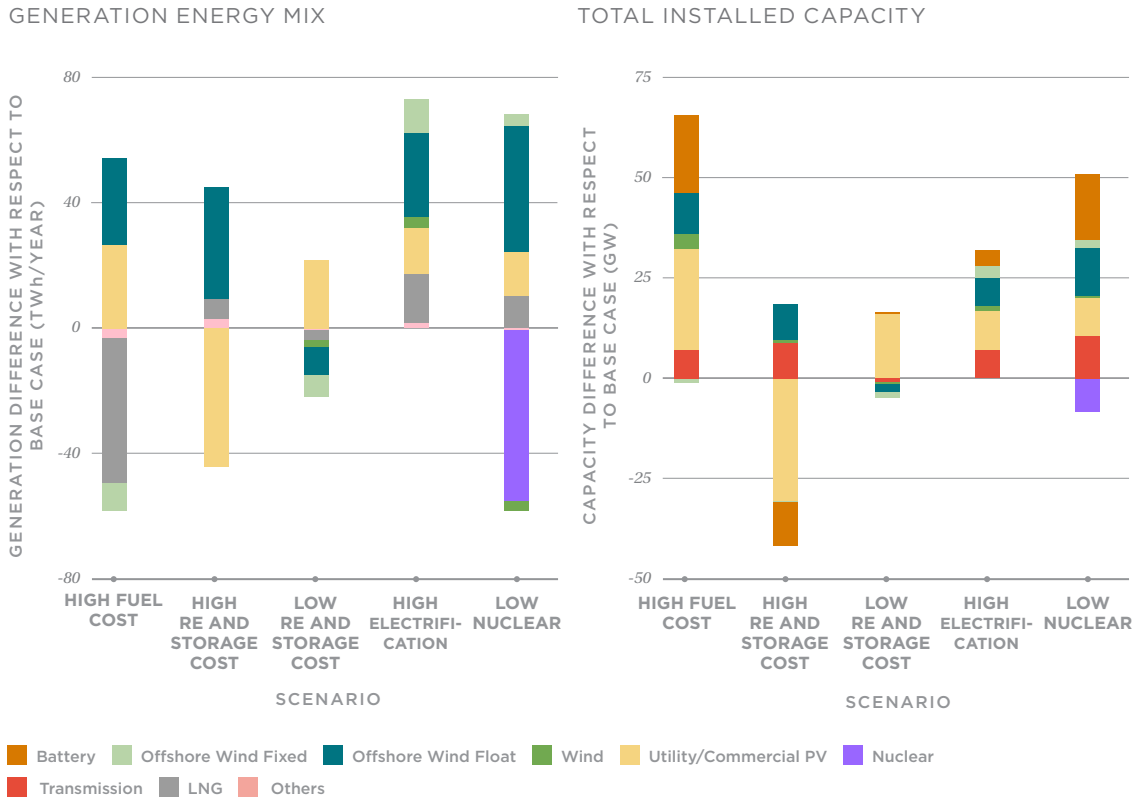


FIGURE 7. *Difference in Generation Mix and Total Installed Capacity in 2035 for All Sensitivity Scenarios When Compared to Clean Energy Scenario*

The study’s dispatch results show that the optimal capacity mix can meet demand every hour of the year without loss of load in 10 regions, while abiding by technical constraints including operating reserves, ramp rates, and minimum generation levels. Figure 8 shows the average hourly system dispatch for all 12 months of 2035 in the Clean Energy Scenario. Throughout the year, energy storage (including new battery storage and existing pumped hydro) charges during the day and discharges at the times in the evening and morning, when solar PV does not generate electricity to balance the load and variable generation. Despite the addition of battery storage, about 9% of available renewable energy must be curtailed annually, as shown in Figure 8.

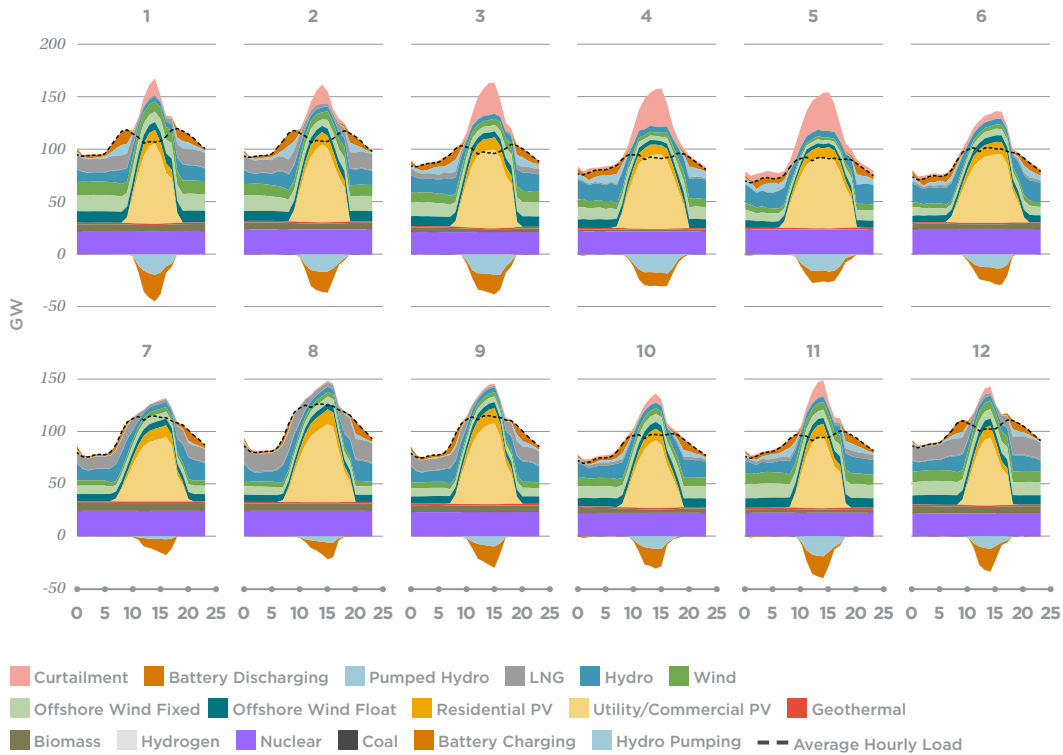


FIGURE 8. National System Average Hourly Dispatch in 2035 for 12 Months

On the other hand, natural gas plants that operate mostly in high net load (load minus the output from variable solar and wind RE sources, also known as “residual load”) winter and summer seasons are critical for balancing the grid. Figures 9 and 10 show net loads in the peak weeks of summer and winter, respectively. The summer net load peaks on August 7 at 8 p.m., when solar generation quickly drops to zero after sunset, and the system load is still high. The winter net load peaks on January 30 at 8 a.m., when wind generation decreases, and solar generation does not yet start.

In both cases, natural gas plants, hydro, and energy storage help balance the peaks. Even during the highest net load weeks in 2035, the RE share of overall generation is ~59% in the summer and ~72% in the winter, while the annual average share is 90%.

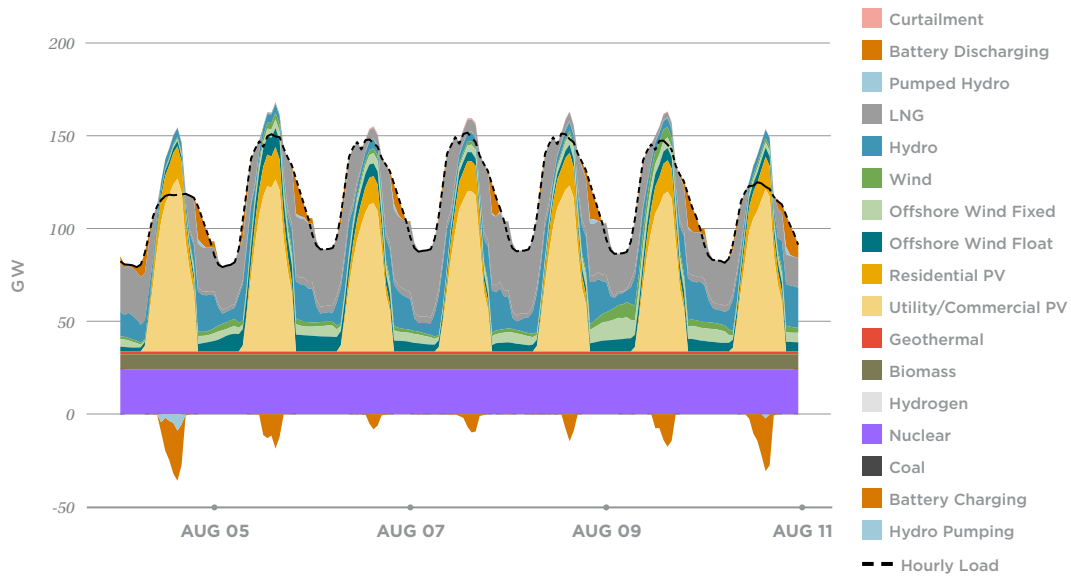


FIGURE 9. National System Dispatch in the Highest Net Load Week of Summer 2035

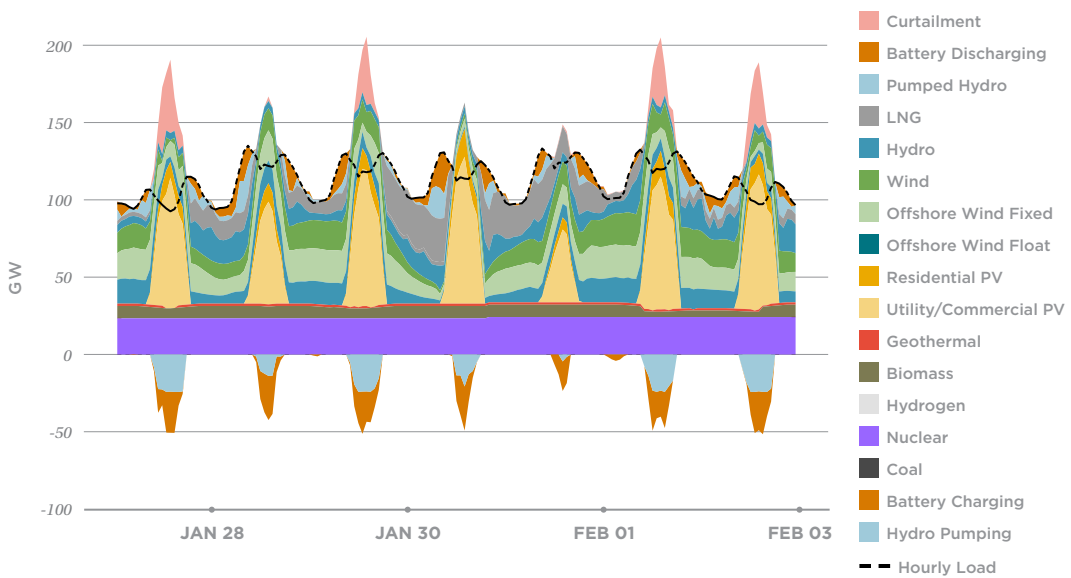


FIGURE 10. National System Dispatch in the Highest Net Load Week of Winter 2035

In addition, to further validate the optimal generation capacity needed to meet system demand every hour, even during periods of low RE generation and/or high demand, researchers conducted two sensitivity analyses that simulate hourly operation of Japan's power system:

- With extreme demand bumps in summer and winter
- For four weather years (35,040 hours, using the time-synchronized load data and solar and wind generation data from 2017–2020)

The first sensitivity analysis showed that with a 10% demand shock (extreme increase due to a historic heat wave or deep freeze), in which peak demand increases to from 153 GW to nearly 168 GW, the system still has adequate resources to meet electricity needs during the highest summer and winter net load weeks (Figures 11 and Figure 12). Coal power plants that have been reserved for such events briefly operate to support the unusual demand peak during this period.

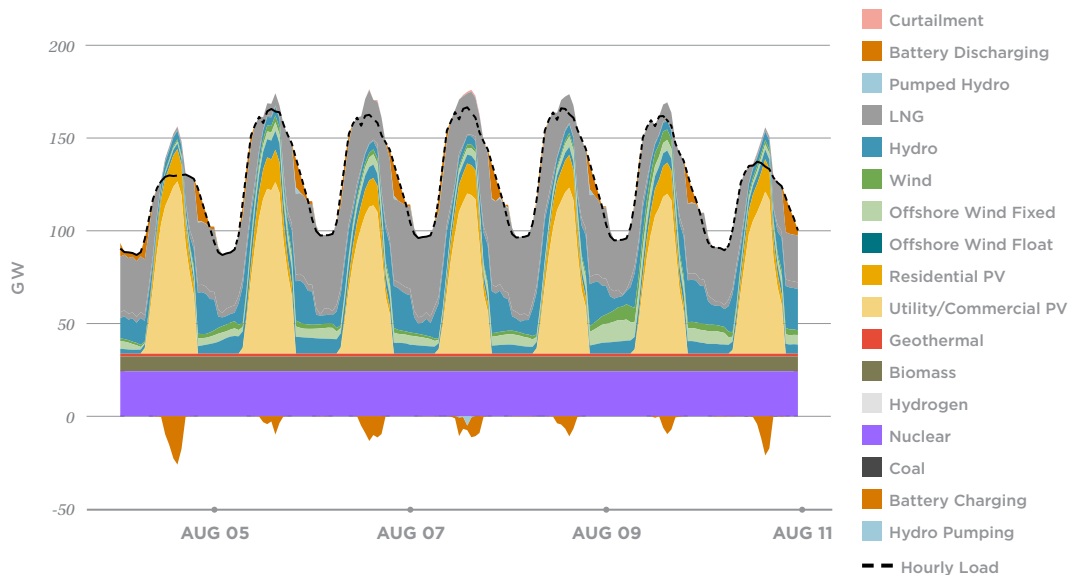


FIGURE 11. National System Dispatch in the Highest Net Load Week in Summer 2035, with a 10% Demand Shock

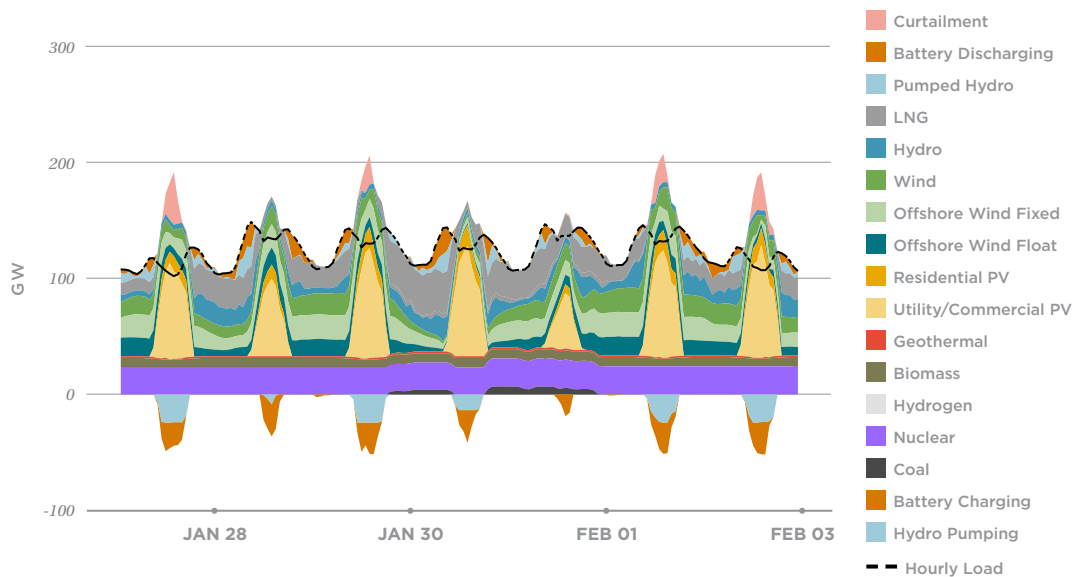


FIGURE 12. National System Dispatch in the Highest Net Load Week in Winter 2035, with a 10% Demand Shock

The second sensitivity analysis with dispatch simulation showed that the optimal capacity mix could meet the electricity load of 10 regions for each hour across a span of four weather years (35,040 hours in all), while still abiding by technical constraints (see Appendix B for details). During the four weather years, the study finds significant seasonal (intra-year) variation in load and solar and wind generation, as shown in Figure 13.

Daily loads peak twice in summer (August) and winter (January) months at 2,979–3,195 GWh/day. (This and future metrics are based on a seven-day moving average.) Solar generation peaks in late May–July at 768–818 GWh/day. Onshore and offshore wind generation peaks in the winter at 678–766 GWh/day in January.

The load hits the bottom in late April or early May at 1,751–1,918 GWh/day (59%–63% of its peak). Solar and wind generation decline the most in fall and winter (October through January) at 213–316 GWh/day (26%–41% of its peak). The next-lowest generation period for RE is in the summer (June through September), with solar at 41–55 GWh/day (11%–15% of its peak) and wind at 110–177 GWh/day (14%–26% of its peak).

Natural gas plants play a critical role in balancing loads with the seasonal variability of RE at multiple timescales. Battery storage, pumped hydro, and natural gas plants play critical roles in daily and hourly balancing.

While the annual capacity factor of natural gas plants is 21%–26%, the monthly summer capacity factor is as high as 51%. In the 2050-time horizon, long-duration energy storage such as hydrogen plus RE can replace the seasonal balancing function of natural gas plants (Mahmud et al., 2023) but existing natural gas plants can play a pivotal role in the short- and mid-term period, maintaining power system dependability at a relatively low cost.

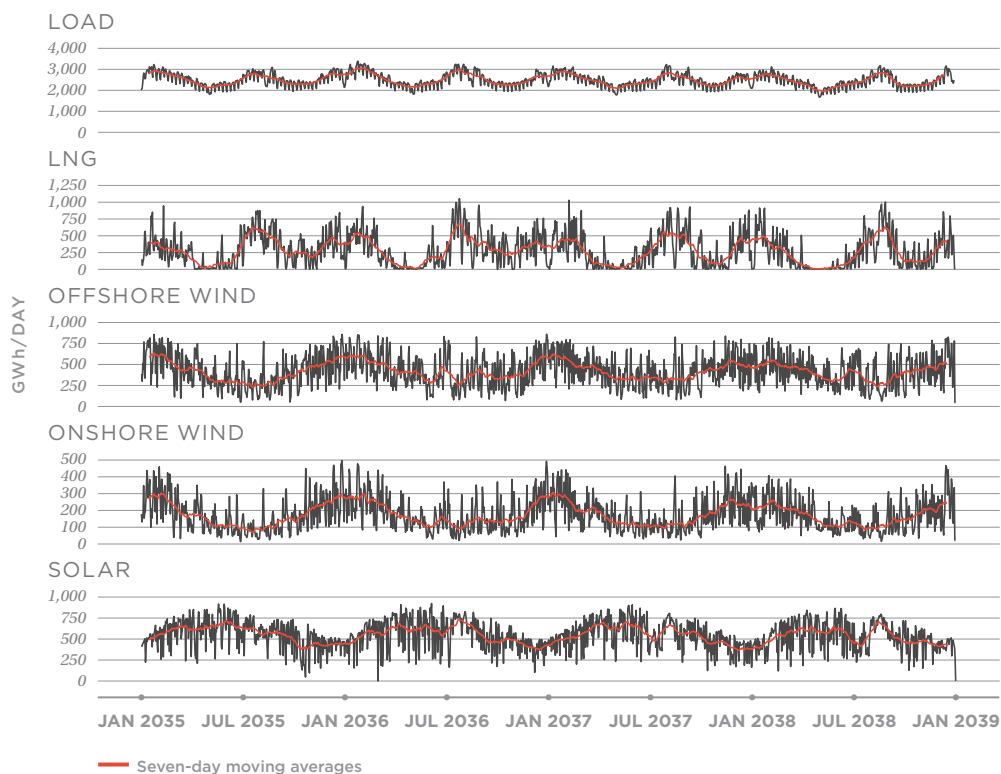


FIGURE 13. Daily Load and Power System Dispatch of Natural Gas and Variable Renewable Generation Over 4 Weather Years in the 90% Clean Case

3.2 CLEAN ENERGY DEPLOYMENT CAN REDUCE WHOLESALE ELECTRICITY COSTS BY 6%

The Clean Energy Scenario’s average wholesale electricity costs suggest that the 2035 policy goals for additions to renewable generation capacity can be cost-effective. Average wholesale electricity costs are lower in 2035 under the 90% Clean Energy Scenario than they are in 2020 (Figure 14). In the Clean Energy Scenario, the average 2035 wholesale electricity cost (9.03 JPY/kWh) is 6% lower

than the average 2020 average wholesale cost (9.67 JPY/kWh) (Figure 15) under conservative fuel price assumptions based on 2012–2021 averages. If social costs of carbon (SCC) is included, wholesale electricity costs are about 36% lower in 2035 under the Clean Energy Scenario than they are in 2020, assuming 12,980 JPY/t-CO₂ (\$118/t-CO₂) at 2.5% discount rate from the latest study (Rennert et al., 2022). All scenarios in this study include the current level of Global Warming Countermeasure Tax, 289 JPY/t-CO₂ (\$2.6/t-CO₂), not the SCC presented here.

Average wholesale electricity costs are total wholesale electricity costs divided by total generation. Here, wholesale electricity costs include costs for installed capacity, fixed O&M, fuel for generation, energy storage, and incremental interregional transmission investments. Distribution costs and existing transmission costs are not included.

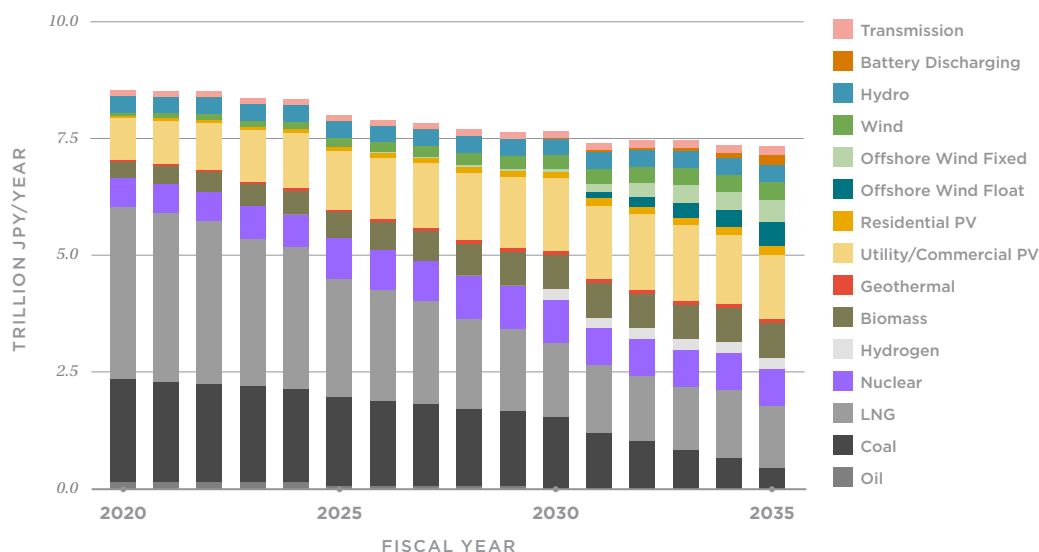


FIGURE 14. Annual Wholesale Electricity Costs in 2020 JPY, Clean Energy Scenario

The cost of electricity generated by RE sources depends less on volatile fossil fuel prices and more on the capital costs (Figure 14). Given the lead time required for construction of power plants and transmission lines, proactive planning is essential to expedite the process.

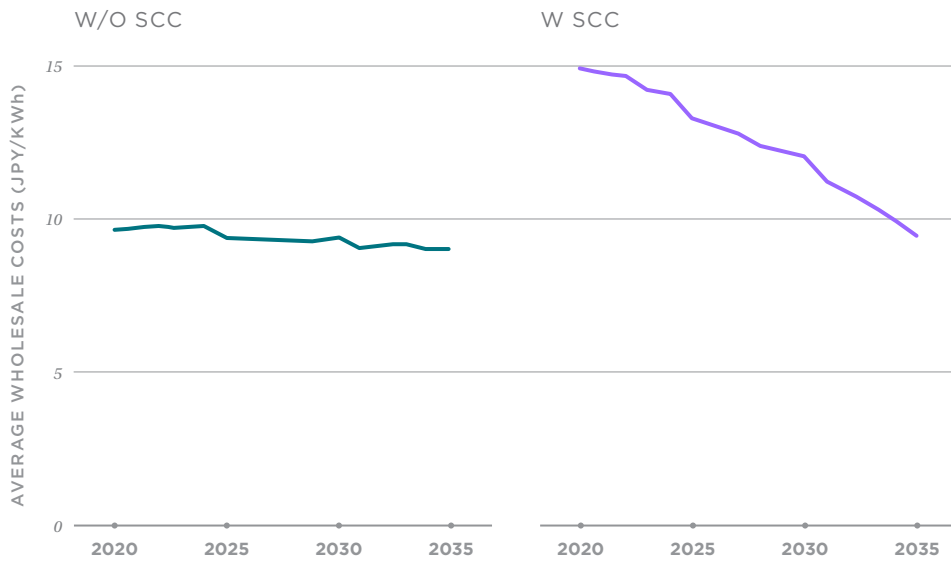


FIGURE 15. Average Wholesale Electricity Costs with and without Social Costs of Carbon (SCC) for the Clean Energy Scenario

In the Clean Energy Scenario, RE coupled with enhanced energy storage and interregional transmission lines make it possible to displace a significant amount of generation from existing coal and natural gas plants, while maintaining grid dependability and decreasing wholesale electricity costs. The incremental cost of developing new solar and wind plants, battery storage, and transmission infrastructure in the Clean Energy Scenario is smaller than the fossil fuel, operation and maintenance (O&M), and fixed costs found in running today’s typical fossil fuel-fired plants (Figure 16).

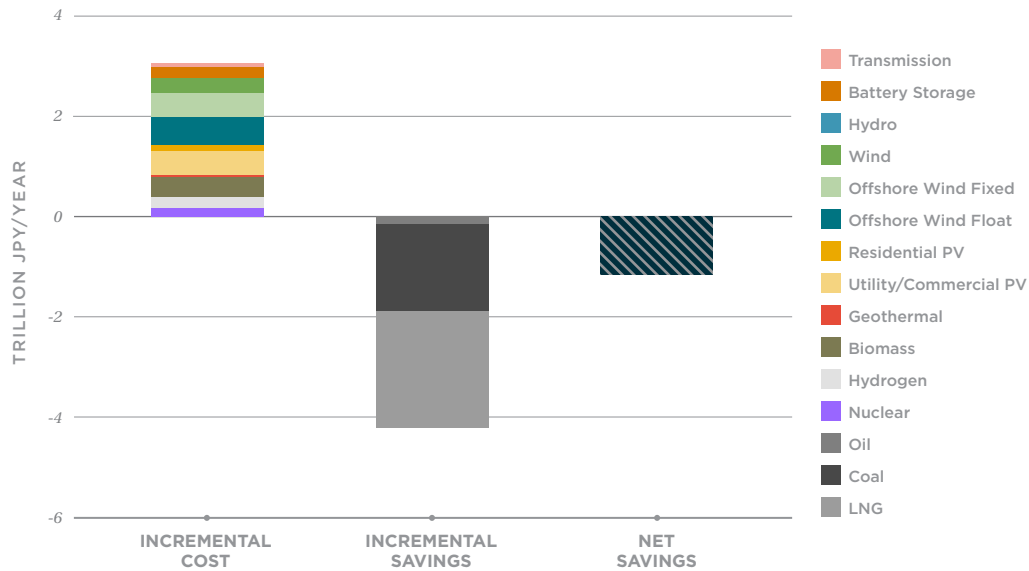
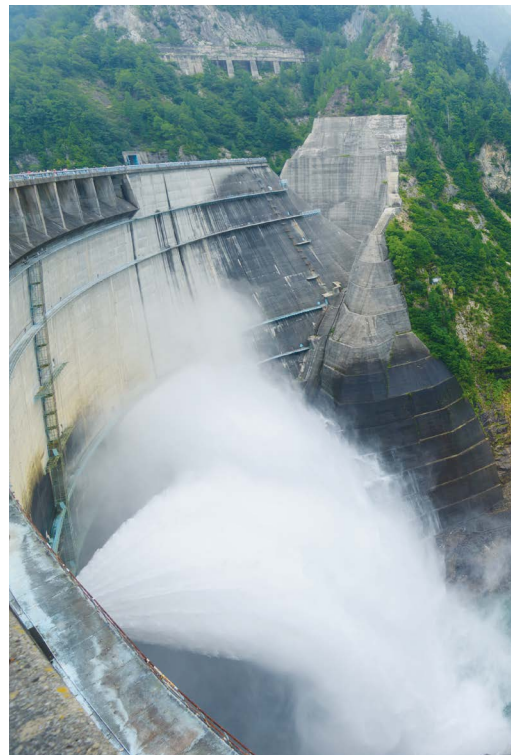


FIGURE 16. Incremental Costs, Incremental Cost Savings, and Incremental Net Costs in the Clean Energy Scenario, between 2020 and 2035 (in 2020 JPY)

The sensitivity analysis shows that the 90% clean energy grid is affordable based on a number of assumptions as shown in Figure 17. With 2022-level fuel costs (High Fuel Costs Scenario) and replacement of most of current natural gas and all of coal plants with new renewables, the average wholesale costs can be significantly reduced by 31% between 2020 and 2035. In all the other scenarios with the base fuel costs, the average wholesale costs of the 90% clean energy grid are stable within a range of -10% (Low RE and Storage Costs) and +0.6% (Low Nuclear). The sensitivity analyses show that average 2035 generation costs could increase by as much as 0.4% with high RE and storage costs, or decrease by as much as 10% as a result of low RE and storage costs.



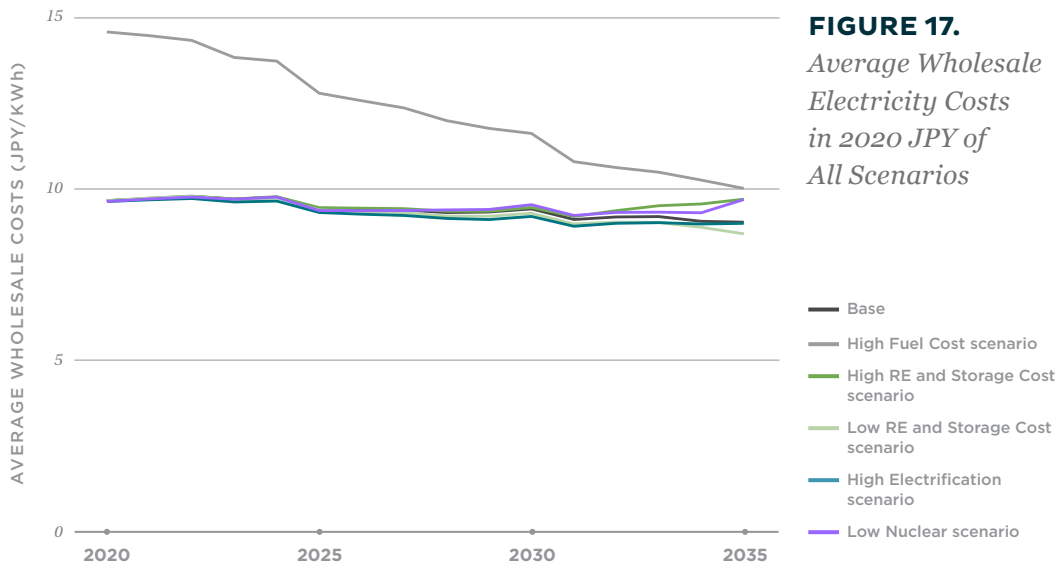


FIGURE 17.
Average Wholesale Electricity Costs in 2020 JPY of All Scenarios

3.3 90% CLEAN ENERGY DEPLOYMENT CAN REDUCE FOSSIL FUEL IMPORT COSTS BY 85%, BOLSTERING JAPAN'S ENERGY SECURITY

Under the 90% Clean Energy Scenario with base fuel prices, imported coal and natural gas costs would decrease by 85%, from 3.9 trillion JPY in 2020 to 0.59 trillion JPY in 2035 (Figure 18). The scenario's base fuel prices offer even greater savings when compared with 2022 levels.

The study estimates final average 2022 imported coal and natural gas costs, based on the current high fuel prices, at 7.3 trillion JPY. In 2022, in a single year, the LNG prices doubled and coal prices more than tripled in comparison the averages across the previous 10 years (2012–2021).

Not only would the 90% clean energy grid translate into lower electric bills. Maximizing Japan's use of domestic renewable resources would significantly decrease the nation's heavy dependence on imported fossil fuels. In turn, this would bolster Japan's energy security, and insulating the economy from skyrocketing international fossil fuel prices.

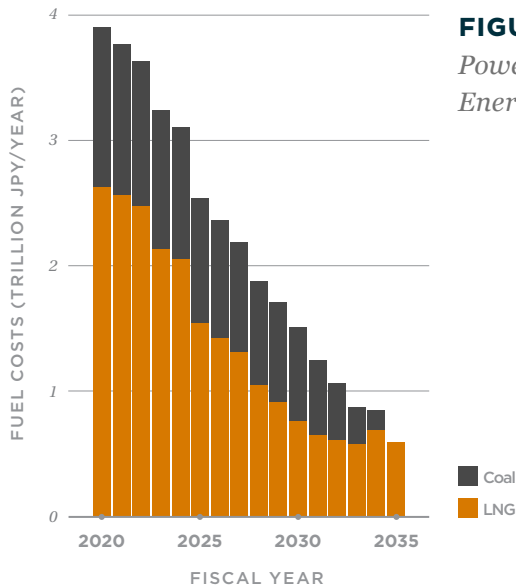


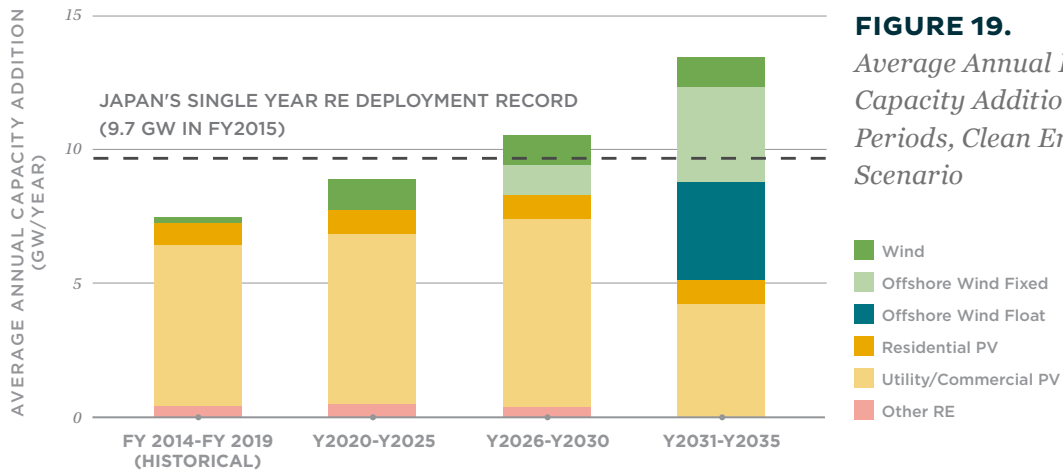
FIGURE 18. Imported Fuel Costs for Power Generation Under the Clean Energy Scenario in 2020 JPY

3.4 SCALING-UP RENEWABLES TO ACHIEVE A 90% CLEAN ENERGY GRID IS FEASIBLE

Under the 90% Clean Energy Scenario, the combined capacity of all RE sources rises from 90 GW in 2020 to 188 GW in 2030 and 254 GW in 2035 (Figure 19). In particular, accelerated wind and solar capacity growth makes the 90% clean energy grid feasible.

On average, an additional 10 GW of renewable energy need to be brought online each year (from 2020 to 2035). This annual increase, comparable to Japan’s single-year renewable buildout record of 9.7 GW (FY 2015), is challenging but feasible.

Solar power additions are dominant in 2020s, while offshore wind’s continued technology cost declines and high capacity factors make it the dominant growth area in the 2030s. This shift to clean energy will require attention to rapidly break down institutional, market, and regulatory barriers.



It will also call for swift advancements in battery storage and interregional transmission lines to balance VRE generation against loads. Battery storage capacity grows to 1.5 GW in 2030 and 29 GW in 2035, at the rate of 6 GW/year in 2030s. While 5.5 GW in transmission capacity additions have already been approved between now and 2028, an additional 6.3 GW of expansion is needed to support 90% clean energy deployment (Figure 20). These outcomes rely on the following aspects of the Clean Energy Scenario:

- Deep reductions in installed costs for solar PV and wind power make it possible to cost-effectively build these systems.
- Low-cost grid-scale battery storage allows for development closer to load centers, reducing requirements for expensive long-distance transmission lines and investments in grid balancing.
- Electricity demand is not expected to grow between 2020 and 2035, minimizing incremental increases transmission investment.

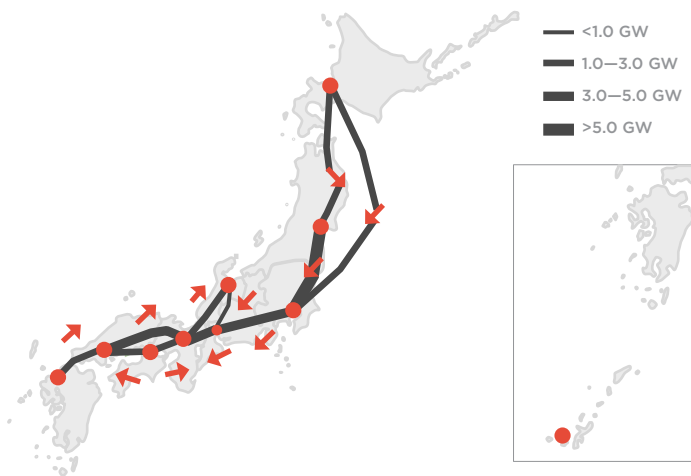
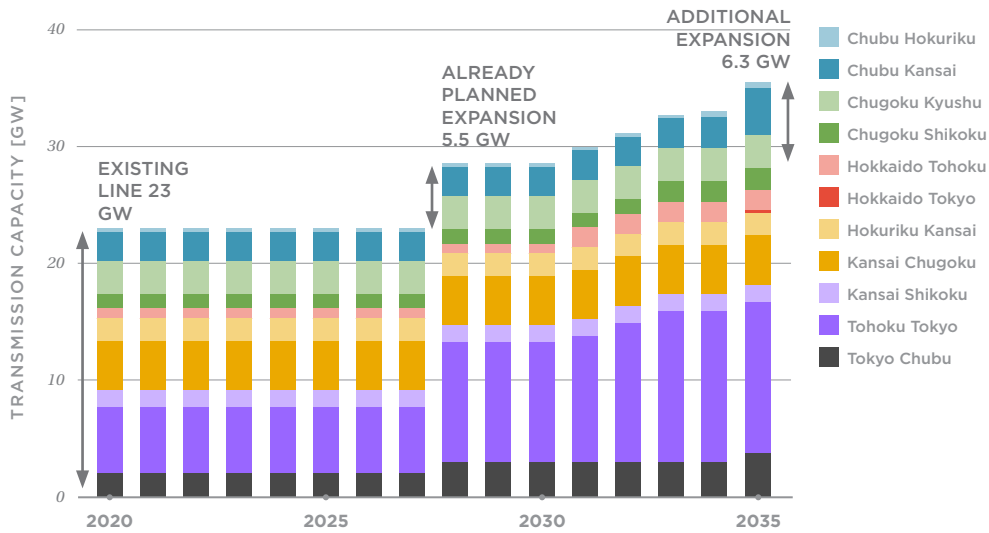


FIGURE 20.
Transmission Capacity Expansion by 2035 in Clean Energy Scenario

Under the Clean Energy Scenario, the 90% clean energy grid requires 38 trillion JPY (real 2020 JPY) of cumulative investment from 2020 to 2035 (Fig 21). This capital investment in predominantly RE generation, battery storage, and interregional transmission is essentially financed with fossil fuel cost savings. This represents 27% of the Japanese government’s goal of public and private “green transformation (GX)” investments totaling 150 trillion JPY over the next decade (GoJ, 2022a). Japanese Government defines GX as “structural transition from fossil-fuel centered industry and society to clean energy centered industry and society (ibid).

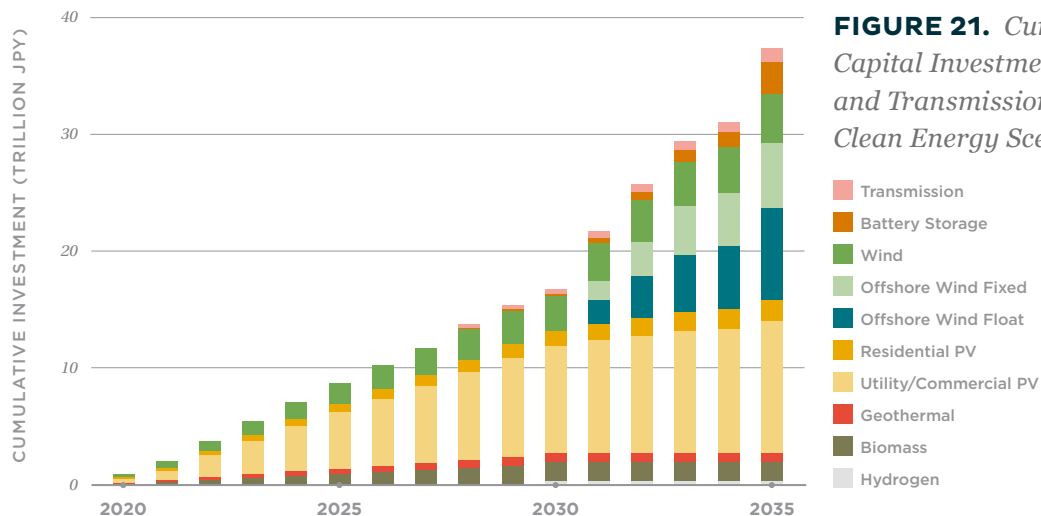


FIGURE 21. Cumulative New Capital Investment for Generation and Transmission, 2020–2035, Clean Energy Scenario

3.5 CLEAN ENERGY CAN CUT CO₂ EMISSIONS BY 92%, PROVIDING SIGNIFICANT ENVIRONMENTAL BENEFITS

Generating 90% of electricity from clean energy by 2035 would significantly cut CO₂ emissions, resulting in important environmental benefits. As shown in Figure 22, By 2035, the Clean Energy Scenario was shown to potentially reduce electricity sector CO₂ emissions by 92% (345 million tons of CO₂, approximately equivalent to 30% of Japan’s total CO₂ emissions in FY 2019) compared to 2020 levels. According to simulation results, this is possible as the emission intensity of electric generation drops by 91% from 404 kilograms (kg)-CO₂/kilowatt hour (kWh) in 2020 to 36 kg-CO₂/kWh in 2035. The extremely low emission intensity supports deeper decarbonization of other sectors, such as electrified transportation, heating, and more.

It also reduces exposure to fine particulate matter (PM_{2.5}), sulfur dioxide (SO₂), nitrogen oxide (NO_x), and heavy metals (e.g., mercury, cadmium, arsenic, chromium, and beryllium) emitted by fossil fuel-burning power plants (J. Lelieveld et al., 2015; Ito, 2010). This could deliver significant health benefits, potentially extending lifespan.

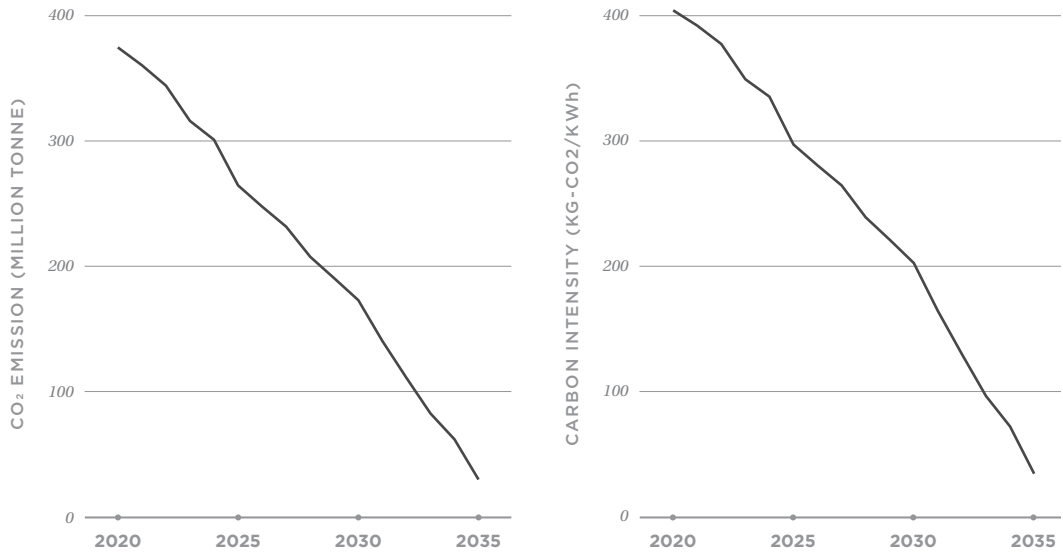


FIGURE 22. CO₂ Emissions and Carbon Intensity, Clean Energy Scenario

4

CAVEATS AND FUTURE WORK

Although we assessed an operationally feasible least-cost pathway of Japan's power system using weather-synchronized load and generation data, further work is needed to advance our understanding of other facets of a 90% clean power system. First, this report primarily focuses on renewable-specific technology pathways rather than explore the full portfolio of clean energy technologies. The technologies and approaches examined in this report could contribute to deep decarbonization of the future electricity supply, lowering system costs while accelerating emission reductions. Additionally, issues such as loss of load probability, system inertia, alternating-current (AC) transmission flow of both intra- and inter- regional transmission lines, and issues in AC power system such as reactive power compensation need further assessment. Options to address these issues have been identified elsewhere (for example, Denholm, 2020).

Second, our assessment does not explicitly address the operational impacts of day-ahead / intra-day forecast errors in RE and load, while we included operating (spinning) reserves in our production cost model to ensure the least-cost system has a certain capability to address such forecast errors. However, several studies have shown that with state-of-the-art forecasting techniques and the shorter gate closure time, the impact of such forecast errors appears to be small (for example, Hodge, 2015; Martinz-Anido, 2016; IEA Wind TCP Task 25, 2021).

Although this analysis does not attempt a full power-system dependability assessment, we perform scenario and sensitivity analysis to ensure that demand is met in all periods, including during extreme weather events and periods of low renewable energy generation. This modeling approach provides confidence that a 90% clean electricity grid is operationally feasible.

5

CONCLUSIONS AND POLICY INSIGHTS

Sustained declines in costs for wind, solar, and energy storage technologies create new opportunities to lower Japan's wholesale electricity costs and reduce related emissions. The results of this study suggest that expanding Japan's share of electricity generated from clean energy sources to around 59% by 2030, and then to 90% by 2035, would deliver the needed reductions in electricity costs, while making it possible to meet carbon neutrality and air quality improvement goals.

Transitioning to a system with 90% of electricity generated from clean energy sources would require overcoming barriers to the development and integration of wind generation, solar generation, and energy storage technologies. This final section summarizes the study's key conclusions, provides recommendations for changes in policy and regulation based on the results, and outlines possible priorities for future research to meet those challenges.

5.1 KEY CONCLUSIONS

Declining wind, solar, and energy storage costs are changing the economics of Japan's electricity sector. This analysis illustrates emerging changes in the economics of Japan's electricity sector. In the selected scenarios, the lowest-cost resources for meeting electricity demand growth combine wind, solar, and energy storage.

Japan's electricity system can be dependably operated with high levels of clean energy generation. The base fuel price case analysis shows that a highly dependable system is possible with 90% of Japan's electricity provided by clean energy sources, without any coal generation. This 2035 generation model is shown

to operate dependably with a mix of 59% (in summer) to 72% (in winter) wind and solar energy—even during unanticipated load increases.

Increasing clean energy generation would deliver additional emission reduction and health benefits. Increasing the share of clean energy generation to 90% or more by 2035 would significantly cut CO₂ emissions. Additional reductions in air pollutant emissions can be delivered by widespread electrification of the greater economy, offering environmental and health benefits beyond the scope of this study.

For instance, an accelerated shift to electric vehicles and batteries charged with power from clean energy plants will reduce both vehicle tailpipe and power plant emissions. The combination of electrification and clean energy generation would be a powerful force in hastening progress toward Japan’s environmental goals.

Reaching cost-effective levels of clean energy generation will require overcoming barriers to wind, solar, and energy storage development and integration. The Clean Energy Scenario involves an unprecedented scale of wind, solar, and energy storage development. From 2030 to 2035 in the Clean Energy Scenario, RE generation grows from nearly 188 GW to 254 GW in 2035. Battery storage grows to 29 GW by 2035. Successfully adding clean energy systems to the grid at this scale and in this time frame requires significant changes in regulations, markets, operations, and land use.

Meeting 2035 goals will rely on a shift to a low-cost RE pathway that begins now. For the share of electricity generated from RE sources to begin its acceleration in the 2020–2035 time period (as in the Clean Energy Scenario), policy and regulatory changes to support this deployment need to be immediately implemented. While there already may be momentum behind the accelerated growth of wind and solar energy development, lowering remaining barriers to rapid expansion of battery storage has yet to be made a near-term priority.

5.2 POSSIBLE FUTURE ACTIONS

The enabling conditions needed to deliver benefits in five key areas are:

Establishing Medium-Term Policy Targets (Beyond 2030)

This study has shown that the clean energy transition will require massive investments in generation, storage, and transmission, and significant technological innovation. Possible technological and policy options to support the transition are

diverse. To avoid technology lock-in and investment in future stranded assets that lead to high costs in the power system, Japan needs medium-term policy targets to guide technology development and capital investment (Hidalgo-Gonzalez et al., 2021).

While a 2030 short-term target for the generation mix and a long-term 2050 carbon neutrality goal have been set (GoJ, 2021d), Japan has not established intermediate RE and emissions targets to bridge between those 2030 and 2050 objectives. Specific policy schemes to support these targets, such as carbon pricing, have yet to be presented. Given that energy projects typically require more than a decade of planning and capital investment, the need to set medium-term policy targets beyond 2030 is urgent.

The Japanese government plans to invest trillions of dollars in decarbonization technologies through the Green Innovation Fund (GoJ, 2021c) and Green Transformation (GX) Bonds (GoJ, 2022a) to achieve carbon neutrality by 2050. In allocating these massive amounts of public funds, it is essential to align plans with medium- and long-term policy targets to maximize cost-effectiveness.

Accelerating RE Deployment and Coal-Fired Power Phaseout

Carbon emissions are the representative environmental externalities. In principle, internalizing the societal cost of carbon (SCC) with carbon pricing is vital to efficiently reduce carbon emissions (Rode et al., 2021).

Estimates of the SCC vary widely. For example, the U.S. Environmental Protection Agency proposed increasing their estimate of the SCC from the current standard of 51 USD /t-CO₂ to 190 USD /t-CO₂ (Interagency Working Group, 2021). Currently, Japan's carbon price is 289 JPY /t-CO₂ (2.6 USD /t-CO₂). The Japanese government is currently planning to introduce a new emissions trading scheme, which will include the electric power sector starting in 2026 (GoJ, 2022a).

Increasing the carbon price closer to the level of the estimated SCC should accelerate the clean energy transition. Carbon taxes and emissions trading have been introduced in many countries worldwide and across industries including the electric power sector (e.g., RGGI in the U.S., California, EU-ETS, Canada, and China).

However, an immediate, significant increase in carbon price to match the SCC is often politically or economically infeasible. In those instances, a combination of other policy measures is called for to achieve a clean energy transition.

Japan has supported various types of RE through feed-in tariffs (FIT), including the newly introduced Feed-in Premium (FIP). Unlike the typical renewable portfolio standard (RPS), which encourages competition among RE technologies, a FIT controls the deployment rate of different RE technologies through tailored financial incentives (Lesser & Su, 2008). This makes mass deployment practical and could result in cost reductions for offshore wind power in Japan.

Carbon pricing and FIT are both needed for an economically feasible phaseout of coal-fired power generation, the largest source of CO₂ emissions in Japan's electric power system. Based on this study's analysis, 99% of coal can be phased out by 2035 by linearly increasing the carbon price from 289 JPY /t-CO₂ (2.6 USD /t-CO₂) in 2020 to 6,000 JPY /t-CO₂ (55 USD /t-CO₂) in 2035, assuming the base fuel prices used in this paper (see Appendix D).

This price is low compared to existing or planned carbon prices in other developed countries (approximate JPY equivalents):

- European Union: About 90 Euros (EUR) /t-CO₂ in 2022 (12,600 JPY/t-CO₂, 1 EUR = 140 JPY)
- Canada: 65 Canadian Dollars (CAD) /t-CO₂ in 2023 and 170 CAD /t-CO₂ in 2035 (6,500 JPY/t-CO₂ in 2023 and 17,000 JPY/t-CO₂ in 2035, 1 CAD = 100 JPY)
- Singapore: 25 Singapore Dollars (SGD) /t-CO₂ in 2024, 45 SGD /t-CO₂ in 2026, and 50–80 SGD/t-CO₂ in 2030 (2,500 JPY/t-CO₂ in 2024, 4,500 JPY/t-CO₂ in 2026, 5,000-8,000 JPY/t-CO₂ in 2030, 1 SGD = 100 JPY)

Furthermore, the revenue from carbon pricing can be used as a financial resource for public and private investment in decarbonizing technologies. In addition, as shown in below, the tax burden of carbon pricing can be mitigated by partial reimbursement.

Reducing Institutional and Societal Barriers to Rapid RE Deployment

In addition to economic barriers, there are institutional and societal barriers to the large-scale, rapid deployment of RE, including potential community and environmental impacts of RE projects, delays in the administrative process such as permits and approvals, and investment risks. Some RE projects have reportedly led to societal and environmental debates that span entire countries (Segreto et al., 2020), including in Japan. For the large-scale, rapid deployment of RE, it is necessary to eliminate not only economic barriers presented by carbon pricing and FIT, but also these institutional and societal barriers.

To properly weigh societal and environmental considerations and to expedite the permitting process for construction and connection to the grid, multi-stakeholder processes have proven effective in the selection and zoning of suitable sites (USAID and NREL, 2017). Lack of social acceptance can be a significant obstacle to RE development in countries worldwide, including Japan.

Renewable energy zones (REZs) are geographic areas with high-quality RE resources that have been pre-qualified as socially and environmentally suitable for development. Early involvement of relevant stakeholders in selecting REZs can effectively avert development issues, helping expedite the permitting and approval process. Texas and California have selected REZs for wind energy, solar power, and transmission line projects since the late 2000s to streamline development and permitting, reduce economic costs, and minimize environmental impacts.

In addition, inexpensive RE and cost-effective RE deployment need to be made national priorities. Because the benefits of enhanced energy security and reduced emissions are enjoyed by the nation as a whole, power transmission investments should be allocated nationwide, (Andrade & Baldick, 2017). A transmission line master plan is currently being developed by the Organization for Cross-regional Coordination of Transmission Operators, Japan (OCCTO) to integrate high share of renewable electricity.

Pursuing a Just Energy Transition through Targeted Assistance Policies

Economic pain inflicted on the few will never result in a just energy transition (Wang & Lo, 2021). This can be addressed in part by refunding a portion of the revenue from carbon pricing to individual households with programs such as California's climate credits and Canada's climate action incentives. Allocating the revenues from carbon pricing to benefit disadvantaged/low-income communities is another effective strategy to ensure a just transition. For example, at least 35% of California's cap-and-trade auction revenue is allocated for the use of disadvantaged/low-income communities in dealing with environmental justice issues.

The socioeconomic impacts of coal-fired power phaseout on local communities and businesses also require mitigation. Carbon price revenues can soften the economic and workforce impacts of plant closures by funding training for local workers in new skills, financial compensation, and accelerated depreciation to local communities and company employees. For example, under the American Rescue Plan Act of 2021 and the Inflation Reduction Act of 2022, the U.S. government is facilitating the transition from coal to renewable energy. These efforts include establishing financial and technical assistance through the Just Transition Fund and the National Economic Transition Platform.

Ensuring Power System Dependability, Enhancing Operational Flexibility, and Boosting Energy Efficiency

As presented in this study, it is especially vital to ensure flexibility and dependability in a grid dominated by solar and wind power, with their inherent variability and uncertainty. When transitioning from a fossil fuel-based power system to a RE-based power system, there is a risk of jeopardizing the dependability of energy systems without adequate coordination (Grubert & Hastings-Simon, 2022). Flexibility can be supported by flexible gas-fired and hydropower plants, energy storage systems, and demand side management and measures (e.g., demand response and vehicle-to-grid) (Degefa et al., 2021). Appropriate design of capacity and ancillary service markets and profitable business models are necessary to encourage sufficient investments in these and other flexibility resources.

Battery storage significantly contributes to the dependability of the electric power system, as this analysis has shown. Policy targets can encourage commercialization of battery storage and help secure revenue in the various capacity and ancillary service markets.

In addition, subsidies or a mandate to deploy a certain level of battery storage can be effective at the early stages of battery storage deployment, when the technology and markets are still relatively immature. The U.S. federal government provides an investment tax credit (ITC) for battery storage installed with solar power under the Inflation Reduction Act of 2022 (Inflation Reduction Act of 2022, 2022). In addition, nine U.S. state governments mandate electric utilities to procure or install battery storage.

Demand response measures also have great potential to ensure the dependability of the electricity system, especially in response to the record heat and cold waves expected to become more frequent as climate change progresses. Similarly, the capacity and ancillary markets enable natural gas-fired, flexible thermal power generation to play a role in ensuring the system's dependability on summer and winter peak load days.

This proposed investment in the transmission and distribution network will also improve the system's dependability by sharing planning reserve margin and operating reserves among regions and smoothing the fluctuation of loads and variable renewable energy generation. Constructing a transmission and distribution network requires a long lead time of about 5 to 10 years, which makes early planning all the more crucial.

Energy efficiency measures are effective in improving dependability and lowering power system costs (Relf et al., 2018). Record heat and cold waves associated

with climate change are expected to cause future increase in peak loads. Building insulation will lower these peak loads and strengthen the dependability of the power system. Since the economic payback time of insulation is typically short, mandatory measures such as strengthening insulation requirements in building codes are often most effective for new buildings. On the other hand, financial incentives can be more effective for retrofitting existing building stock.

Through these possible actions, the swift decarbonization of Japan's electricity system would make it possible to more quickly electrify other demand sectors, reducing CO₂ emissions and smoothing the country's path to a carbon-neutral economy by 2050.

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APPENDIX A | MODELING APPROACH

The state-of-the-art methodology for studies that assess the impacts of high renewable energy (RE) share on electric power systems is to use capacity expansion and production cost models. For this study, we use a combination of a capacity expansion model and a production cost model using PLEXOS, an industry-standard model that is used by grid operators and utilities worldwide (Abhyankar et al.; 2022, IRENA, 2017). First, we use a capacity expansion model to identify the least-cost (“optimal”) generation, storage, and interregional transmission investments from 2020 to 2035 that meet regional electric power demand requirements, grid dependability (reserve) requirements, technology resource constraints, and policy constraints. Second, we use the production cost model to assess the operational feasibility of the least-cost portfolio by simulating hourly dispatch of generators, storage, and transmission ties in the year 2035. For each year, we simulate hourly economic dispatch using the production cost model to ensure that the grid can run dependably for all 8,760 hours in the year, including the hours when the system is most constrained.

PLEXOS uses deterministic, mixed-integer optimization to minimize the cost of meeting load given physical (e.g., generator capacities, ramp rates, transmission limits) and economic (e.g., fuel prices, start-up costs, import/export limits) grid parameters. Moreover, PLEXOS simulates unit commitment and actual energy dispatch for each hour (at 1-minute intervals) of a given period. As a transparent model, PLEXOS makes available to the user the entire mathematical problem formulation. The model minimizes total generation cost (fixed plus variable costs) for the entire system, including existing and new generation capacity and transmission networks (Abhyankar et al., 2022). We assess the optimal resource mix under a range of scenarios examining deployment rates, coal plant retirements, demand growth, electricity market design, demand response, and supply chain challenges.

We represent the Japanese electricity grid using 9 interconnected nodes connected by 23 GW of interregional transmission corridors and 1 isolated node (Okinawa) in 2020 (Figure 2). The transfer capacity of each inter-provincial interface is assumed to be half the sum of transmission line capacities between the two regions in order to capture the operating constraints in an AC power transmission network.

Figure A1 depicts our overall method and the various data components.

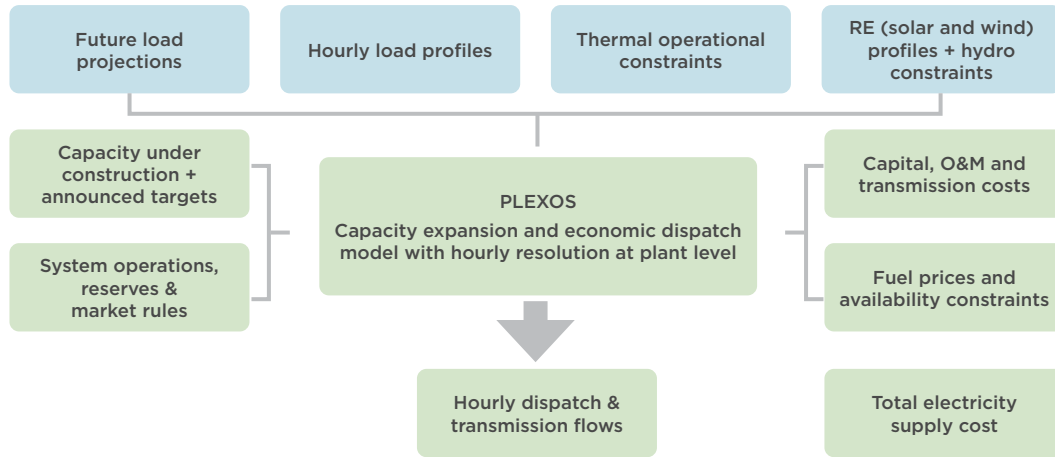


FIGURE A1. Overall modeling approach

APPENDIX B | MODELING INPUTS

Projections of installed costs and fixed operations and maintenance (O&M) costs for onshore wind, offshore wind, solar PV, and battery storage in Japan are based on Japan's cost data; the 2022 United States National Renewable Energy Laboratory (NREL) Annual Technology Base (ATB) forecasts; and industry consultations (Committee on Procurement Prices, 2022; GoJ 2021f; NREL 2022). Table B1 shows the assumptions on capital costs of wind, solar, and battery storage. Roundtrip efficiency of battery storage and pumped hydro storage are assumed to be 90% and 80%, respectively.

TABLE B1. Solar, wind, and battery storage capital cost assumptions

| YEAR | LOW | BASE | HIGH | LOW | BASE | HIGH |
|------|---|----------------|----------------|---|----------------|----------------|
| | SOLAR PV COST/KW: THOUSAND JPY/KW (USD/KW) | | | BATTERY STORAGE (4-HR) COST/KW: THOUSAND JPY/KW (USD/KW) | | |
| 2020 | 198 (1,800) | 198 (1,800) | 198 (1,800) | 48 (433) | 48 (433) | 48 (433) |
| 2030 | 81 (736) | 102 (927) | 166 (1,510) | 16 (141) | 25 (225) | 30 (273) |
| 2035 | 76 (691) | 96 (873) | 150 (1,360) | 14 (127) | 23 (229) | 27 (246) |
| | Onshore wind Cost/kW: thousand JPY/kW (USD/kW) | | | Offshore wind (fixed-bottom) Cost/kW: thousand JPY/kW (USD/kW) | | |
| 2020 | 280 (2,550) | 280 (2,550) | 280 (2,550) | 515 (4,681) | 515 (4,681) | 515 (4,681) |
| 2030 | 204 (1,850) | 222 (2,020) | 226 (2,050) | 321 (2,915) | 348 (3,614) | 406 (3,691) |
| 2035 | 188 (1,710) | 207 (1,880) | 212 (1,930) | 253 (2,301) | 286 (2,602) | 361 (3,278) |
| | Offshore wind (floating) Cost/kW: thousand JPY/kW (USD/kW) | | | | | |
| 2020 | 572 (5,200) | 600 (5,455) | 650 (5,908) | | | |
| 2030 | 399 (3,629) | 445 (4,042) | 539 (4,901) | | | |
| 2035 | 374 (3,406) | 421 (3,832) | 521 (4,738) | | | |

1 USD = 110 JPY (Average exchange rate from 09/2013 to 08/2022)

Other clean energy costs and operational parameters have been taken from Japanese Government estimates (GoJ 2021f, Committee on the Procurement Prices of Renewable Electricity, 2022) and industry consultations. Table B2 summarizes the assumptions.

TABLE B2. *Other Clean Technology Costs and Operational Parameters*

| | CAPITAL COST* | FIXED O&M COST* | HEAT RATE (GJ/MWh) | FORCED OUTAGE RATE (%) | MAINTENANCE OUTAGE RATE (%) | RAMPING (% OF INSTALLED CAPACITY PER MINUTE) | AUXILIARY CONSUMPTION (%) |
|--------------------------|----------------|-----------------|--------------------|------------------------|-----------------------------|--|---------------------------|
| Biomass | 398 (3,620) | 27 (245) | 8.3 | 5 | 10 | N/A | 6 |
| Geothermal | 790 (7,180) | 33 (300) | N/A | 5 | 10 | N/A | 11 |
| Hydropower | 620 (5,640) | 16 (145) | N/A | 5 | 5 | 100% | 1 |
| Hydrogen; Ammonia | 161 (1,460) | 6.4 (58) | 6.6 | 5 | 5 | 2% | 2.3 |

* Capital and fixed O&M costs are in 1,000 JPY/kW (2020 JPY/2020 USD) / 1 USD = 110 JPY (Average exchange rate from 09/2013 to 08/2022)

TABLE B3. *Conventional Technology Costs and Operational Parameters*

| | CAPITAL COST* | FIXED O&M COST* | HEAT RATE (GJ/MWh) | FORCED OUTAGE RATE (%) | MAINTENANCE OUTAGE RATE (%) | COLD-START TIME (HOURS) | MINIMUM UP-TIME (HOURS) | MINIMUM DOWN-TIME (HOURS) | TECHNICAL MINIMUM LEVEL (%) | RAMPING (% OF INSTALLED CAPACITY PER MINUTE) | AUXILIARY CONSUMPTION (%) |
|-----------------|----------------|-----------------|--------------------|------------------------|-----------------------------|-------------------------|-------------------------|---------------------------|-----------------------------|--|---------------------------|
| Coal | 244 (2,220) | 11.9 (108) | 8.3 | 5 | 10 | 24 | 12 | 6 | 40 | 1 | 5.5 |
| Gas CCGT | 161 (1,460) | 6.4 (58) | 6.6 | 5 | 5 | 12 | 6 | 3 | 30 | 2 | 2.3 |
| Gas GT | 101 (922) | 2.3 (21) | 9.7 | 5 | 5 | 1 | 1 | 1 | 20 | 10 | 2.3 |
| Nuclear | 516 (4,690) | 17.3 (157) | 10.3 | 5 | 20 | 96 | 96 | 96 | 90 | N/A | 4.0 |

* Capital and fixed O&M costs are in thousand JPY/kW (2020 thousand JPY [2020 USD]); 1 USD = 110 JPY (Average exchange rate from 09/2013 to 08/2022)

Conventional technology (coal, nuclear, natural gas) capital and fixed O&M costs have been taken from previous Japan and U.S. estimates (GoJ, 2021f; NREL, 2022). Operational parameters such as ramp rates, technical minimum levels, auxiliary consumption, minimum up and down times, etc., have been taken from the data used in previous Japan and U.S. studies, regulatory norms, and expert/industry consultations. They are summarized in Table B3. Capacity and commission year of existing power plants are taken from multiple sources including Japan Electricity Power Exchange database (JEPX, 2022), Feed-in Tariff Statistics (METI, 2022), generation companies' websites, and Electric Utility Businesses Handbook (METI, 2021).

TABLE B4. *Summary of Key Assumptions and Variables*

| PARAMETER | ASSUMPTION | SOURCE |
|--|---|---|
| Geographic Scope | 10 regions (nodes) | |
| Solar, Wind, and Battery Storage Technology Costs | NREL ATB 2022 projections with adjustments | NREL ATB 2022, GoJ 2021f, Advisory Committee 2021, Expert consultations |
| Other RE and Conventional Technology Costs | Geothermal, biomass, hydro, hydrogen, natural gas, coal, and nuclear costs are based on Japanese Government estimations. | GoJ 2021f, Expert consultations |
| Operations & Maintenance (O&M) | Fixed and variable O&M costs of all non-retired plants are included | |
| Weighted Average Cost of Capital (WACC) | 2.5 % (real) | OCCTO 2021, Expert consultations |
| Electricity Demand | Annual and monthly amounts, along with daily and hourly load profiles, all by region. | GoJ 2021e, 10 Regional T&D companies' website, Expert consultations |
| Extreme Events Analysis | Use weather data and energy load for four weather-years (2017-2020). Weather affects both demand and wind and solar supply. | |
| Nuclear Retirements | Nuclear plants that are not granted 20-year extension as of 2022 assumed to retire in 40 years in the nuclear retirement sensitivity. | Expert consultations |

| PARAMETER | ASSUMPTION | SOURCE |
|---|--|---|
| Technical Lifespan | <p>Wind: 30 years</p> <p>Solar PV: 30 years</p> <p>Hydropower: 100 years</p> <p>Battery: 15 years</p> <p>Nuclear: 60 years</p> <p>Gas: 50 years</p> <p>Coal: 50 years</p> | GoJ 2021f, JEPX 2022, NREL 2022, Expert consultations |
| Economic Lifespan | Standard amortization is 30 years, batteries are 15 years. | Expert consultations |
| Residential Solar, Geothermal, Hydrogen, and Biomass | Their 2030 targets are met at least, while more deployment is allowed when economical. | GoJ 2021e |
| Carbon Price | The CO ₂ price is 289 JPY/t-CO ₂ for all cases from 2020 to 2035. In the carbon price analysis (appendix D), the CO ₂ price linearly ramps up from 2026, reaching the final CO ₂ price by 2035. | |
| Planning Reserve Margin | 10% in each region | Expert Consultation |
| Operating Reserves | Regulation reserves, spinning reserves (contingency reserves), and flexibility reserves (ramping reserves) are included as a function of load and solar and wind share. The reserve requirement levels are calculated based on Lew et al. (2013) | Lew et al. (2013), ReEDs (2021), Expert consultation |
| Firm capacity of renewable energy | In estimating planning reserve margin, we used firm capacity estimates of renewable energy (i.e., solar, wind, and hydro) in each region from Japanese authority (OCCTO 2021). | OCCTO (2021), Expert consultation |

APPENDIX C | SOLAR AND WIND PROFILES

We estimated the solar and wind (offshore and onshore) resource potential and profiles from the ground up. This section explains the methodology used, which can be divided into two parts. The first part involves estimating the total resource potential of solar and wind available in each region. This forms an upper limit on the amount of new capacity that can be built in PLEXOS for each region. To estimate resource potential, we use the capacity factor data along with multiple exclusion datasets, including land cover, elevation, slope of terrain, natural parks, fishery zones and defense areas. The second part involves estimating the representative hourly solar and wind profiles for each region. Profiles are estimated at site level using meteorological data from re-analysis datasets, and then an aggregation algorithm is used to create a provincial/cluster level representative profile. The potential and profiles are estimated at the regional level for onshore wind and solar and at a cluster level for floating and fix bottom offshore wind.

RESOURCE POTENTIAL

Solar

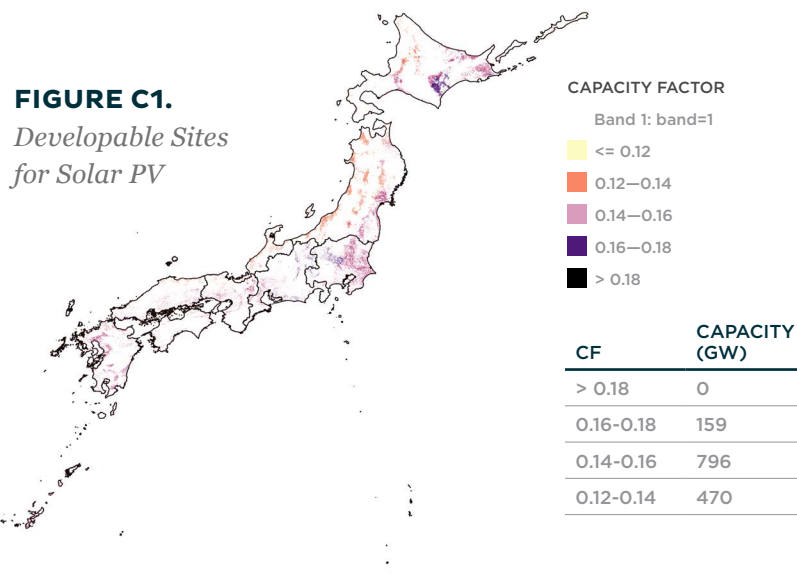
To estimate the solar resource potential in each region, we start with the complete area of that region and remove the areas which are not suitable for solar development. We use four exclusion criteria for estimating the solar resource potential: land cover, slope, elevation and natural parks.

The land cover dataset comes from the European Space Agency's Copernicus programme. We use the Moderate Dynamic Land Cover Dataset, which has a spatial resolution of 100m and divides land cover into 23 classes. We exclude dense forest (i.e., forests with canopy > 70%), wetlands, moss and lichens, urban and builtup areas, areas with snow and ice, permanent water bodies, and open seas.

In addition to land cover, we use elevation and slope to remove areas not suitable for solar development. The elevation data also comes from the European Space Agency's Copernicus programme, the Copernicus GLO-30 Digital Elevation Model. The dataset has a spatial resolution of 30 m and provides elevation of the surface of earth, including man made buildings and infrastructure. We estimate slope from the elevation dataset using the planar method. The method estimates the steepest descent based on the maximum change in elevations between the cell and the 8 neighboring cells (Burrough, et al., 1995).

We exclude areas which have an elevation of more than 4,000 m and slope above 5 degrees. We then remove areas which fall under the territory of natural parks. After exclusions based upon land cover, elevation, slope, and natural parks, the areas that are left in a region are considered suitable for solar development.

To estimate the quality of solar resource potential in each region, we use the resource data from Global Solar Atlas. Solar Atlas provides annual average solar capacity factors at 30 arcsec (~1 km) spatial resolution. This dataset and its wind counterpart, Global Wind Atlas, were developed by the World Bank. The Solar Atlas models solar generation using 10 years of meteorological data and creates an averaged solar capacity factor data. We combine the capacity factor data with the RE suitability data derived, after exclusions, to create a solar resource map of Japan (Figure C1). This map shows the capacity factor at all developable sites in Japan.

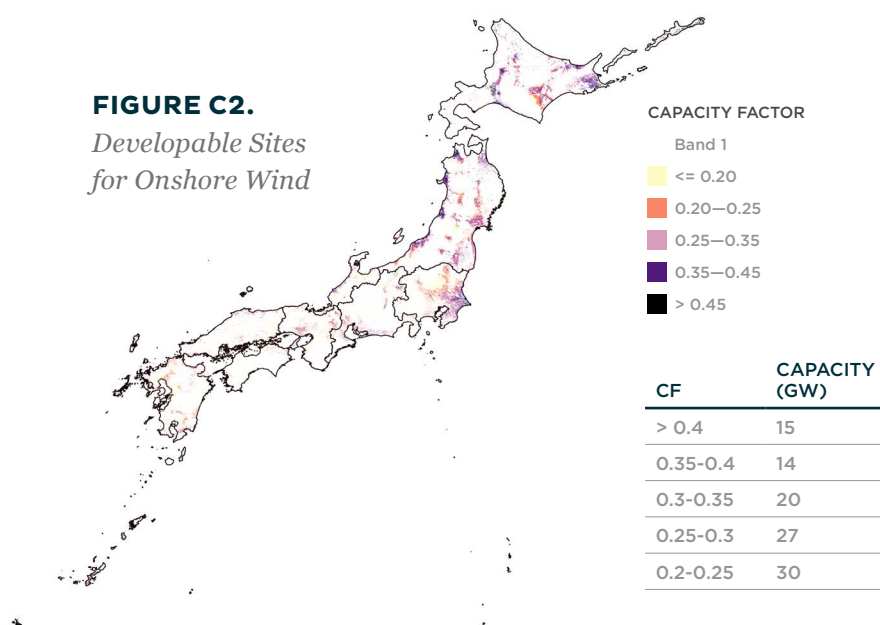


ONSHORE WIND

The methodology for estimating onshore wind resource potential is very similar to the method used for solar. We take the complete area of a region and remove the areas not suitable for wind development to estimate the resource potential. We use the same land cover, elevation, slope, and natural parks datasets as used for solar. However, we use different limits on elevation and slope as solar and wind have different slope and elevation considerations. We exclude areas with elevation greater than 3000m and slope greater than 11.31 degrees for onshore wind.

For land cover, we use the same criteria as solar and remove dense forests (i.e., forest with canopy > 70%), wetlands, moss and lichens, urban and builtup areas, areas with snow and ice, permanent water bodies, and open seas. The Global Wind Atlas provides the annual average wind capacity factors at 1 km spatial resolution. It was created using 10 years of hourly meteorological data, and then averaged to get an annual average capacity factor for a site. We combine the Wind Atlas capacity factor data with our developable sites data to get a wind resource map of Japan (Figure C2). This map shows the onshore wind capacity factors at all developable sites in Japan.

FIGURE C2.
*Developable Sites
for Onshore Wind*



OFFSHORE WIND

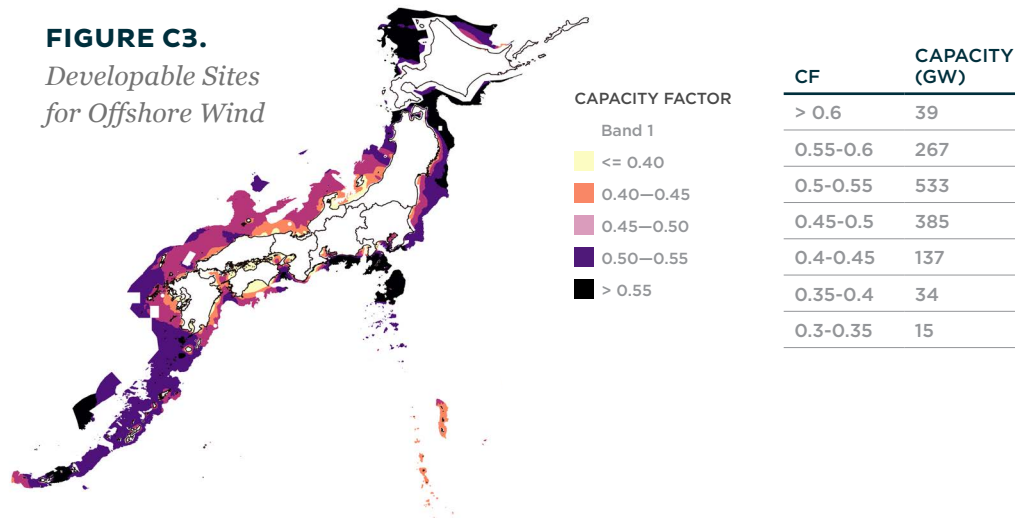
To estimate the offshore wind resource potential, we use the map of the exclusive economic zone (EEZ) of Japan, ocean depth data, GIS datasets of the locations of defense areas and fishery zones. Surprisingly, we know very little about the topography of Earth's oceans, even less than we know about the topography of Mars.

The best global bathymetry dataset available is from the General Bathymetric Chart of the Oceans (GEBCO). GEBCO dataset has global coverage and has a spatial resolution of 500 m. We start with a map of the EEZ of Japan and remove sites with ocean depth greater than 1,000 m. We assume that sites with depth greater

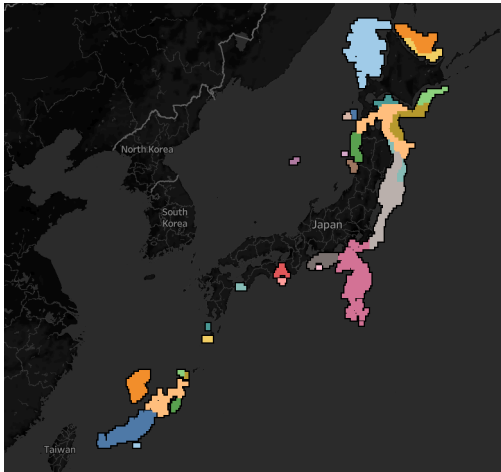
than 1,000 m are currently not economically developable for offshore wind. The sites with ocean depth less than 60m are suitable for fixed bottom technology, and the sites with ocean depth between 60 and 1,000m are assumed to be suitable for floating wind technology.

These limits on technology suitability are derived from NREL which uses the same limits for the United States. We then removed areas which fall in the territory of defense areas and fishery zones. As we did for solar and wind, we combined this dataset with the capacity factor data from the Global Wind Atlas to create an offshore wind resource map for Japan, showing the capacity factor at all developable offshore locations (Figure C3). We then developed cluster the fixed bottom and floating wind sites using the Multivariate Spatially Constrained Clustering algorithm. The clustering was done so as to keep the spatially contiguous sites which have similar capacity factors in the same clusters. We create 30 clusters for floating wind and 10 clustering for fixed bottom offshore wind. Most of the Japanese offshore wind potential is at a ocean depth more than 60m so more clusters were created for floating offshore wind. The maps of the clusters are shown in Figure C4.

FIGURE C3.
*Developable Sites
for Offshore Wind*



FLOATING



FIXED

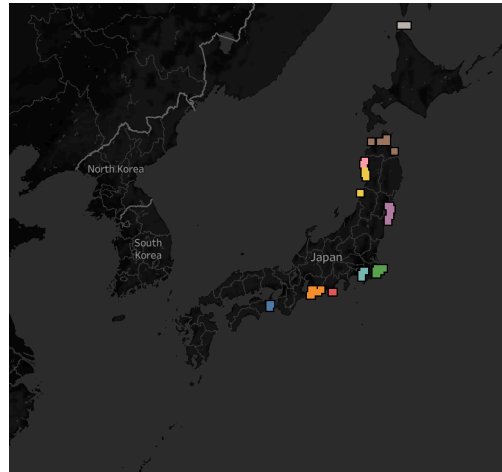


FIGURE C4. *Clusters for floating wind and fixed bottom offshore wind*

MODELING RESOURCE PROFILES

Here we describe the methodology used to create representative solar and wind hourly generation profiles for each region. We use the resource map dataset created in the previous section, i.e., the dataset with capacity factors at developable sites. In addition, we use meteorological data from reanalysis datasets. We extract wind speed, pressure, temperature, solar irradiance, etc., from reanalysis datasets and pass them through a software tool that models wind farms and solar parks to provide hourly solar and wind generation outputs. Several sites in a region are aggregated to create a representative generation profile for each region. The methodologies for solar, onshore wind, and offshore wind are discussed in detail below.

Solar

In the previous section, we created a gridded dataset of developable sites with annual average capacity factors. That gave us a technical resource potential, but not all sites which technically can be developed would actually be developed. The quality of resources drives the economics, and only the best resource sites actually get developed. To get a representative resource profile for each region, we need to find a sample of the best sites and aggregate their individual profiles.

For estimating the solar profile, we filter out the top 25 percentile of the sites with the highest capacity factor. To ensure that we do not select very low-capacity

factor sites, we only keep sites with capacity factors greater than 15%. From this pool of top sites in a region, we randomly select 2,000 sites. We then estimate hourly generation at each of these 2,000 sites and average them to create a representative solar profile for the region. Hourly meteorological data from ERA5 is used to estimate hourly generation at each of the 2,000 sites.

ERA5 is an hourly reanalysis dataset from European Centre for Medium-Range Weather Forecasts (ECMWF, 2020ECMWF, 2020ECMWF, 2020ECMWF, 2020ECMWF, 2020ECMWF, 2020) and has a spatial resolution of 30 km x 30 km. ERA5 provides historical hourly data on wind speed, temperature, pressure, solar radiation, etc., at 137 pressure levels from surface up to a height of 80 km. To estimate solar generation, we extract the surface solar radiation downwards (ssrd), temperature at 2 m and u and v component of wind speed at 10 m height. To model solar generation at a site, we also need Direct Normal Irradiance (DNI) and Direct Horizontal Irradiance (DHI). The ssrd variable from ERA5 gives the Global Horizontal Irradiance (GHI), and we use GHI to estimate DHI and DNI.

NREL's DISC model provides empirical relationships between GHI and DHI, GHI and DNI, based on Maxwell, 1987. NREL's System Advisor Model (NREL, 2017) is used to model solar generation. The SAM software development kit takes GHI, DHI, DNI, temperature, and u and v wind components as inputs, and then outputs solar generation. We use a single axis system to simulate solar generation using SAM. The hourly generation at 2,000 sites is averaged to create a representative profile for the region.

Onshore Wind

The methodology for estimating onshore wind profiles is very similar to solar, and a similar method is used to select sample sites in each region. We filter the top 25 percentile of sites from the annual average capacity factor dataset developed while estimating resource potential. To avoid very low-capacity factor sites, we remove sites with capacity factors of less than 20%.

From this we randomly select 2,000 sites. We simulate hourly generation for a year for each of these 2,000 sites using the SAM model. We model a wind farm with 32 turbines, arranged in an 8 x 4 rectangular shape. SAM takes wind speed at the hub height of the turbine, wind direction, surface pressure, and temperature as inputs, and then gives hourly farm generation as output.

Meteorological data is taken from MERRA2. It provides wind speed at 10 m and 50 m, which are then scaled to the hub height of the wind turbine used. Surface pressure and temperature are also available from MERRA2. For simulating wind

generation, we used meteorological data from U.S. National Aeronautics and Space Administration (NASA)'s Modern-Era Retrospective analysis for Research and Applications (MERRA2) dataset which has a spatial resolution of 0.5 deg x 0.625 deg. MERRA2 data is shown to have better accuracy for wind speeds than ERA5, for this reason, we select MERRA2 despite it having much lower spatial resolution compared to ERA5. The spatial resolution of MERRA2 is 0.5 deg x 0.625 deg, quite high for modeling wind speed, as winds can vary significantly by local topography. To account for some of the effects of local topography, we use the average wind speed data from Wind Atlas, which has a much higher spatial resolution of 1 km x 1 km. We create a scaling factor using the average wind speed data from Wind Atlas and average wind speed data from MERRA2. We scale the hourly wind speeds in MERRA2 by this factor to get a more accurate wind speed profile.

Corrected wind speeds are then passed through to SAM to get hourly generation. The hourly generation from 2,000 sites is averaged to get a representative profile for the region.

Offshore Wind

Because there are no predefined regional boundaries for offshore wind, we have to create artificial clusters to get representative profiles. We clustered the offshore wind sites into multiple clusters as discussed in earlier section. For each fixed and floating wind cluster we estimate one representative profile in each of the clusters. For the purpose of estimating profiles, we only keep sites with capacity factor greater than 40% in each of the clusters. We assume that only sites with capacity factor more than 40% are currently economically developable. We simulate hourly generations at each site using SAM. Wind speed and direction at hub height, temperature and pressure data is required for simulating wind generation in SAM. The hourly generation from the all the sites in the cluster is aggregated to create a representative profile for each cluster.

APPENDIX D | CARBON PRICE SENSITIVITY

Carbon pricing is a policy instrument widely used to reduce CO₂ emissions around the world. Japan's current carbon price (as of 2022) is 289 JPY/t-CO₂. The Japanese government is currently planning to introduce a new emissions trading scheme, which includes electric power sector starting in 2026 (GoJ, 2022a).

In this sensitivity analysis, we relax constraints on the clean energy target (i.e., 90% of electricity generation comes from clean energy by 2035) and the coal phaseout (i.e., coal generation is phased out by 2035) in the capacity expansion modeling. We raised carbon price on CO₂ emissions at various rates to examine the effect of carbon price levels on generation mix and CO₂ emissions. Under the original scenarios, carbon price is constant at 289 JPY/t-CO₂. In this sensitivity analysis, we set the target carbon prices in 2035 at 2,000 JPY/t-CO₂, 3,000 JPY/t-CO₂, 4,000 JPY/t-CO₂, 5,000 JPY/t-CO₂, and 6,000 JPY/t-CO₂. We assume that the carbon prices linearly increase from 289 JPY in 2025 to the target carbon price in 2035, as shown in Figure D1.

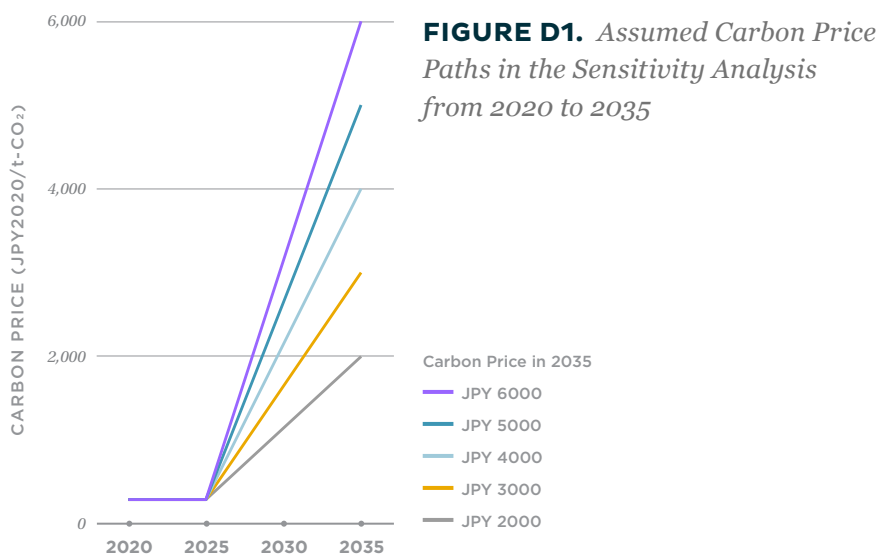


Figure D2 summarizes the generation mix and emissions in 2035 with different carbon prices. Without 90% clean energy target or coal phaseout constraints, coal is competitive with natural gas plants and operates in 2035, unless carbon price is raised to 6,000 JPY/t-CO₂. With the level of carbon price, clean power accounts for 91% of generation, and coal power accounts for less than 0.4% of generation.

Due to high emission coefficient of coal power plants, emission reduction depends on the capacity factor of coal plants. Even if clean energy sources (i.e., renewables and nuclear) account for 80% of electricity supply with 2,000 JPY/t-CO₂ carbon price, its emissions reduction is only 69% from the 2020 level. Increasing carbon price level reduces coal plant operation, resulting in significant decline in CO₂ emissions, up to 7% of the 2020 level. This implies that emissions reduction requires substantially raising carbon prices from the current level; renewable energy deployment is not sufficient in terms of climate change mitigation. This level of carbon price would also enable a 90% clean energy grid, if institutional and societal barriers for clean energy deployment are lifted.

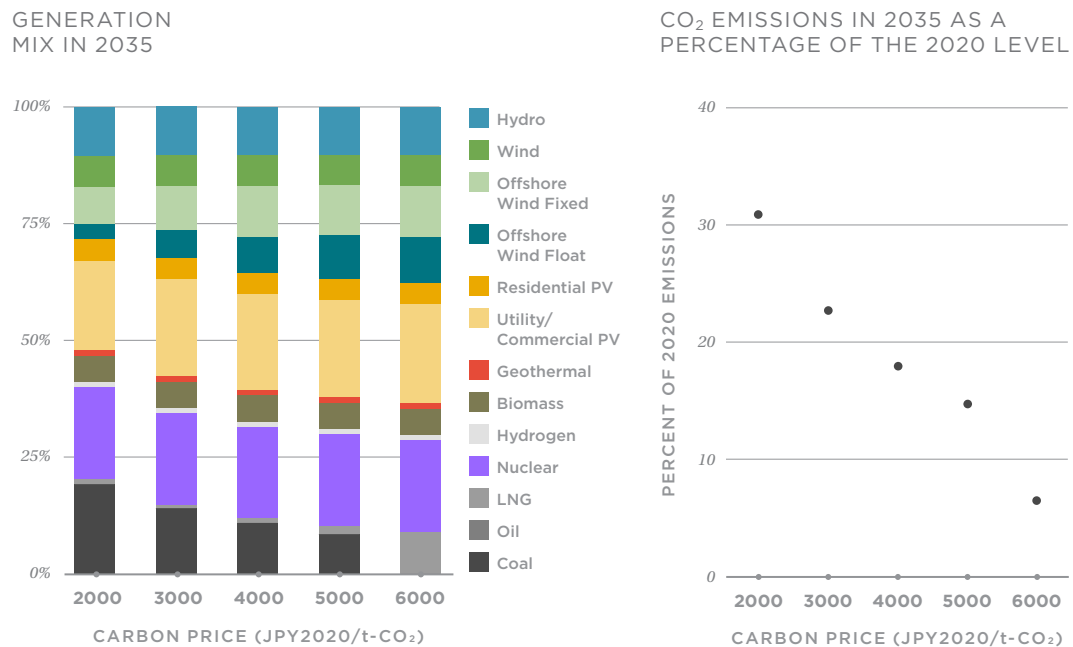


FIGURE D2. Generation Mix and CO₂ emission in 2035 under different carbon price targets

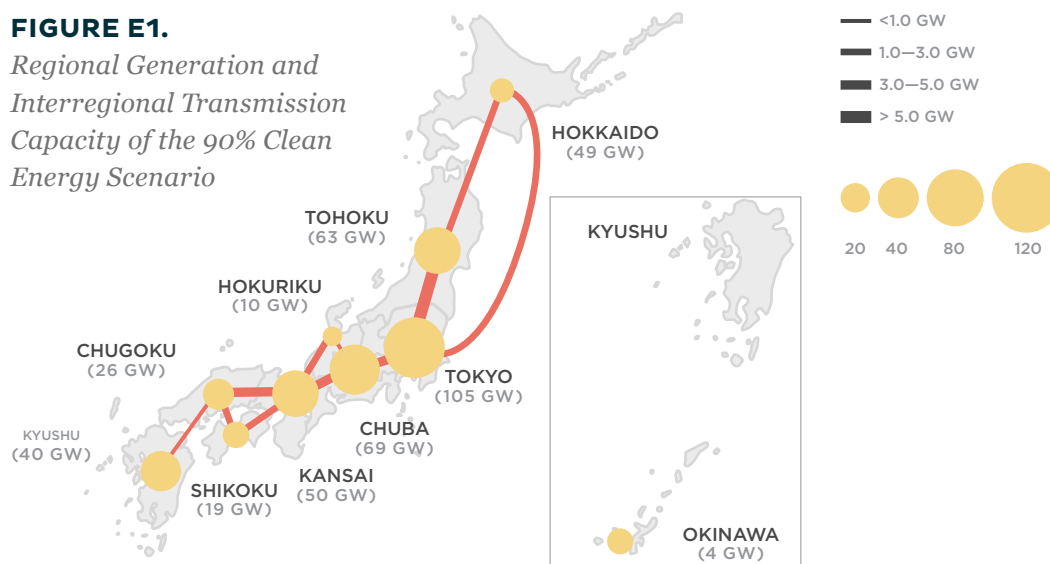
APPENDIX E | REGIONAL RESULTS OF BASE SCENARIO

Figures E1, E2, and E3 summarize the regional distribution of the least-cost capacity mix in 2035 under the 90% Clean Energy Scenario with base fuel costs and the generation mix. The capacity mix and generation mix are significantly different, depending on the existing generation, pumped hydropower storage, and transmission capacity, plus various types of additional renewable energy potential.

While wind resources are geographically concentrated in particular areas, solar PV is widely available across the regions. Abundant, high quality onshore and offshore wind resources located in Tohoku and Hokkaido are utilized with 6 GW of the new transmission lines to send the wind energy to Tokyo. As a result, 100% of the electricity is supplied by clean energy in these northern regions, representing 45% of wind capacity. In Shikoku and Okinawa, about 40% of the electricity is supplied by offshore wind as well. Solar PV provides 38% and 37% of electricity supply in Tokyo and Chugoku regions. The share of solar and wind (VREs) is more than 50% in six regions (Hokkaido, Tohoku, Tokyo, Chubu, Shikoku, and Okinawa). Battery storage, pumped-hydro storage, natural gas plants, hydro plants, and interregional transmission lines collectively provide operational flexibility to integrate such a high VRE share.

FIGURE E1.

Regional Generation and Interregional Transmission Capacity of the 90% Clean Energy Scenario



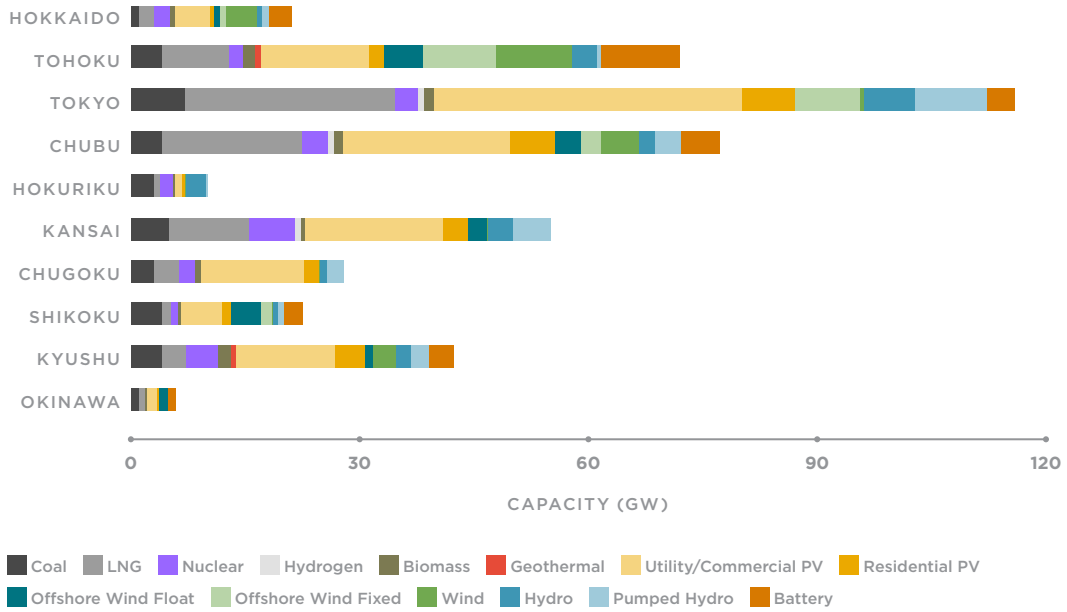


FIGURE E2. 2035 Generation Capacity by Region under the 90% Clean Energy Scenario

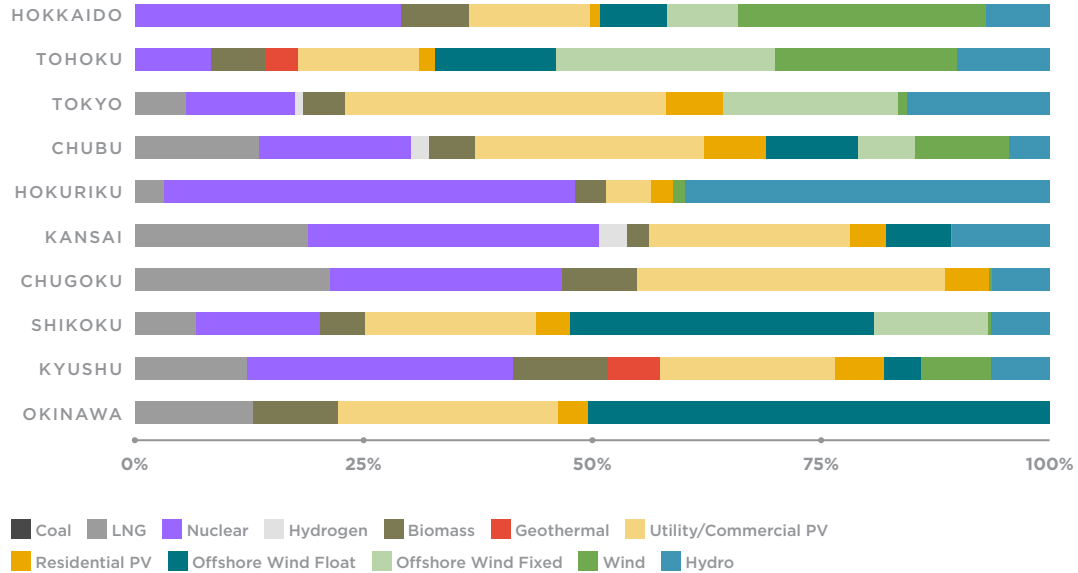


FIGURE E3. 2035 Generation Mix by Region under the 90% Clean Energy Scenario

APPENDIX F | SENSITIVITY ANALYSIS

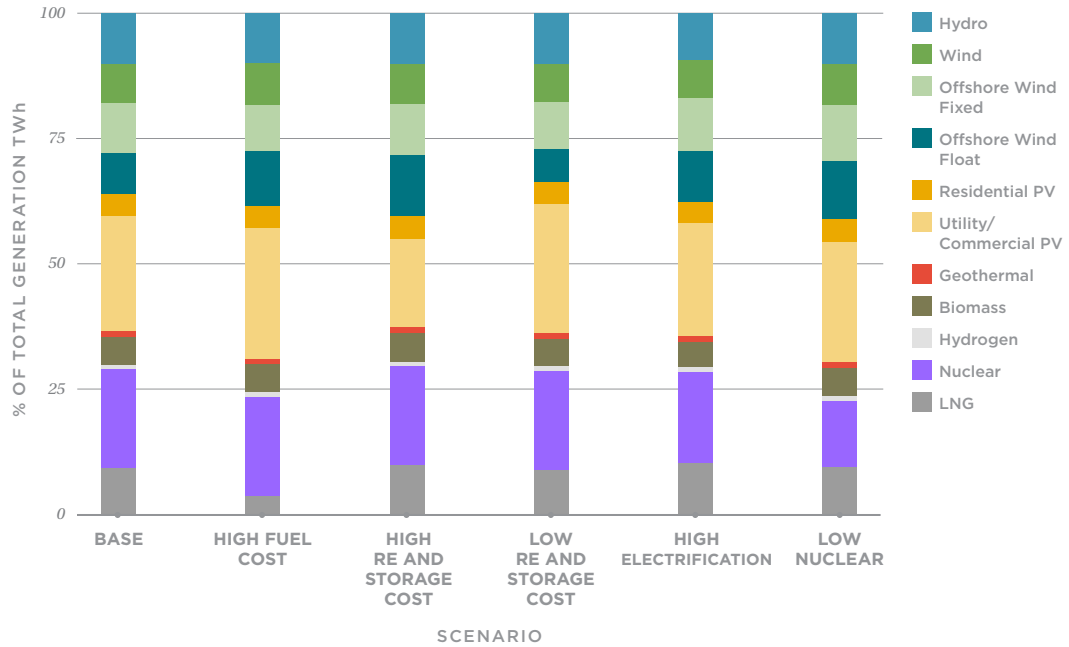


FIGURE F1. 2035 Generation Mix of All Scenarios

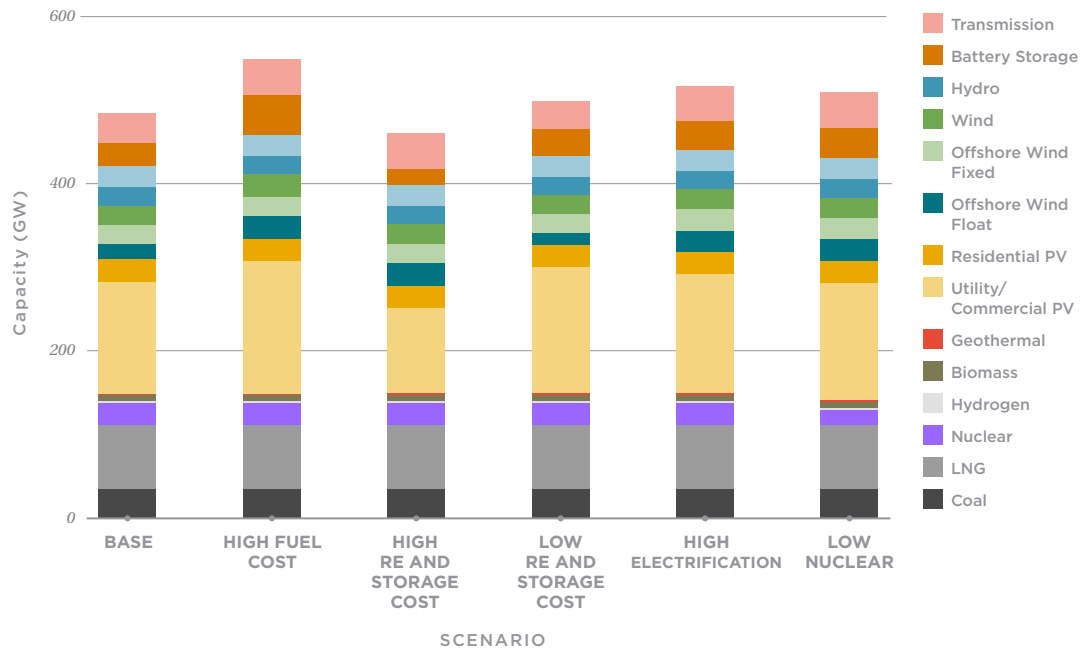


FIGURE F2. 2035 Capacity Mix of All Scenarios