






The role of renewables in the Japanese power sector: implications from the EMF35 JMIP

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Abstract

The Japanese power system has unique characteristics with regard to variable renewable energies (VREs), such as higher costs, lower potentials, and less flexibility with the grid connection compared to other major greenhouse-gas-emitting countries. We analyzed the role of renewable energies (REs) in the future Japanese power sector using the results from the model intercomparison project Energy Modeling Forum (EMF) 35 Japan Model Intercomparison Project (JMIP) using varying emission reduction targets and key technological conditions across scenarios. We considered the uncertainties for future capital costs of solar photovoltaics, wind turbines, and batteries in addition to the availability of nuclear and carbon dioxide capture and storage. The results show that REs supply more than 40% of electricity in most of the technology sensitivity scenarios (median 51.0%) when assuming an 80% emission reduction in 2050. The results (excluding scenarios that assume the continuous growth of nuclear power and/or the abundant availability of domestic biomass and carbon-free hydrogen) show that the median VRE shares reach 52.2% in 2050 in the 80% emission reduction scenario. On the contrary, the availability of newly constructed nuclear power, affordable biomass, and carbon-free hydrogen can reduce dependence on VREs to less than 20%. The policy costs were much more sensitive to the capital costs and resource potential of VREs than the battery cost uncertainties. Specifically, while the doubled capital costs of VRE resulted in a 13.0% (inter-model median) increase in the policy cost, the halved capital costs of VREs reduced 8.7% (inter-model median) of the total policy cost. These results imply that lowering the capital costs of VREs would be effective in achieving a long-term emission reduction target considering the current high Japanese VRE costs.

Keywords Variable renewable energy · Resource potential · Capital cost · Battery storage · Renewable energy policy

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Introduction

The large-scale development of renewables is essential to achieve the long-term climate goal stated in the Paris Agreement, the 2-degree and 1.5-degree targets. Luderer et al.

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(2014) analyzed the role of renewable energy in climate change mitigation using the results from a model intercomparison project (MIP) called the Energy Modeling Forum (EMF) 27 and showed that the contribution of renewable energies (REs) to the energy supply strongly increases with climate policy stringency. Another MIP, called the ADVANCE (Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies) project, focusing on the role of variable renewable energies (VREs) for power sector decarbonization, showed that carbon pricing has a substantial impact on VRE deployment (Luderer et al. 2017). In the special report on 1.5 °C, the global REs share in electricity in 2050 will reach more than 60% based on the analyses of four illustrative 1.5 °C consistent pathways (IPCC 2018). This may be true on a global scale, but what about on a national scale? Although Luderer et al. (2017) partially assessed national-scale data, since the participating models in these existing MIPs are global models and developed by researchers from all over the world, the unique characteristics of each country (e.g., capital costs, potentials, local policies, etc.) may not have been appropriately reflected. Indeed, the existing regional- and/or national-scale MIPs, such as EMF24 (Clarke et al. 2014) and EMF32 (Murray et al. 2018) for the US, EMF28 (Knopf et al. 2013) for Europe, and a pilot study of EMF35 (Sugiyama et al. 2019) for Japan, provide implications for regional and/or national climate and energy strategies.

The Japanese power system has unique characteristics in the area of VREs in terms of its relatively higher costs, lower potentials, and less flexibility with the grid connections than other major greenhouse gas (GHG)-emitting countries. A global database of renewable energy from the International Renewable Energy Agency (2019) shows that the global-levelized costs of electricity (LCOEs) from bioenergy, geothermal power, hydropower, and onshore and offshore wind have fallen to the fossil fuel cost range in 2010, and the costs from solar photovoltaics (PVs) reached the fossil fuel cost range in 2014. While the total installed cost of utility-scale solar PVs in Japan decreased by 74% from 2011 to 2018, their absolute installed cost of around 2000 USD₂₀₁₈/kW is still two times higher than in the other major GHG-emitting countries. Kimura and Zissler (2016) compared the price and cost of solar PVs in Japan and Germany, and found that construction costs and module costs are the major factors generating the significant cost differences between the two countries. They point out that the difference in construction costs is based on the installation time in Japan, while the difference in the module costs is due to the import cost of foreign products and the price gap between domestic and foreign products. The capital cost for onshore wind in Japan shows a similar trend as solar PVs, i.e., about 1.5-to-3 times higher than the cost range globally. Mizuno (2014) concluded that the high cost of wind in Japan is due to a lack

of economies of scale, among other reasons. Kimura (2018) analyzed the cost structure of onshore wind in Japan from actual data provided by 38 wind-power plants and revealed that construction work-related costs are increasing rapidly.

As for the resource potentials, Luderer et al. (2017) compared those of solar PVs, concentrating solar power (CSP), and onshore wind for selected regions, and found that the potentials of solar PVs and offshore wind in Japan would comprise less than 20% and 70% of electricity demand in 2100 in the baseline scenario of the ADVANCE project, respectively. Since the resource potentials of these energy sources in all the analyzed regions, except for India and Japan, would comprise more than 100% of the electricity demand in 2100 in the baseline scenario of the ADVANCE project (with a high-capacity factor), the efficient use of resource potential is more necessary in Japan than in other countries.

Another unique characteristic of Japanese power system is the relatively low flexibility in the grid connections. Particularly, the Japanese power grid is a longitudinal structure with few detours and different frequencies in Eastern (50 Hz) and Western (60 Hz) Japan. These conditions reduce the flexibility of power systems supplied by the interregional power transmission. The International Energy Agency (2011) analyzed the VRE penetration potentials of electricity demand and showed that Japan has the lowest VRE penetration potential (19%) among the selected eight power areas due to its low grid strength, low coordination of flexible resource use, and the VRE forecasted use at the time of the analysis. Mizuno (2014) pointed out that the development of wind has not increased to date due to this limited grid capacity, the current electricity market structure, and grid operating practices by the existing electricity power companies.

We have developed the following three research questions and sought to answer them to provide policy implications for decarbonizing the Japanese power system based on its unique characteristics in VRE development. First, how much RE or VRE will be introduced in the future Japanese power sector under Japan's mid-century strategy? Second, how much does the uncertainty of the RE and VRE variables (i.e., the cost and resource potential) affect future RE and VRE shares and the policy cost of emission reduction? Third, how much does the varying emission reduction target affect the share of RE and VRE in the power supply?

There are several existing studies that approach these research questions using power dispatch models. The research group of the University of Tokyo developed a high time-resolution optimal power generation mix model and revealed that integrating high VRE penetrations brings about a decrease in the capacity factor of the liquefied natural gas (LNG) combined cycle (Komiya and Fujii 2014), increases the importance of electricity conservations (Komiya and Fujii 2015), and makes necessary the capacity

expansion of inter- or intra-regional power transmission lines (Komiya and Fujii 2017). Matsuo et al. (2020) analyzed the possibility of the power system in Japan achieving zero emissions by 2050, and found that the required storage capacity is determined mainly by the duration of windless and sunless periods. Shiraki et al. (2016) estimated the future siting and scale of power plants under CO₂ emission reduction targets using a dynamic multiregional optimal-generation planning model. Along with the above studies using power dispatch models, studies using energy system models and integrated assessment models (IAMs) also provided the impact of emission reduction targets on the power sector (Silva Herran et al. 2019; Kato and Kurosawa 2019; Fujimori et al. 2019). However, all of these studies implemented by a single model or a single-model framework. In addition, scenario protocols vary by study, and thus, it is difficult to provide an intercomparison of the results. A robust conclusion can be drawn by comparing the results of multiple model analyses under a unified scenario framework.

In this study, we analyzed the role of renewables in the future Japanese power sector using the scenario results from the model intercomparison project EMF35 JMIP by varying the key climate policy and technological conditions across the scenarios. The remainder of this paper is structured as follows: the *policy environment* section reviews the current policy environment surrounding REs in Japan; the *model intercomparison of the parameter settings and modeling* section reviews the parameter settings and modeling of REs in the participating models; the *model intercomparison of results from the EMF35 JMIP scenario* section compares the results of the scenario analysis in EMF35 JMIP, and the *conclusion* section summarizes the findings from this study and their policy implications.

Policy environment

To provide policy implications based on the results from the model intercomparison study, it is important to understand the actual policy trends surrounding RE development in Japan. Thus, in this section, we briefly overview the current policy environment surrounding RE development in Japan. Reflecting the unique characteristics of Japanese REs, policies surrounding REs are described in terms of cost, resource potential, and grid flexibility. In addition, the current conditions of non-RE low-carbon generators, such as nuclear power, thermal power with carbon capture and storage (CCS), and hydrogen power, are summarized. A comparison of electricity system transitions, focusing on solar PVs, nuclear power, and wind power, between Germany and Japan is found in Cherp et al. (2017). Readers can also refer to Yu et al. (2016) for the development of Japanese solar

PVs compared to those in China and Germany. For Japanese wind policy and development, see Mizuno (2014).

Policies accelerating cost reduction (FIT, auctions, and price targets)

In 2012, a feed-in-tariff (FIT) scheme was initiated by replacing the existing excess electricity purchasing scheme of solar PVs and the renewable portfolio standard (RPS) law. Like other countries, the FIT has accelerated the introduction of renewable energy in Japan. Over the 5 years since 2012, RE rates in electricity demand increased from 10 to 16%, with most of the increases coming from solar PVs (Agency for Natural Resources and Energy Japan 2019). From the introduction of the FIT scheme until March 2020, more than 70% of cumulative purchased electricity comes from solar PV (275 TWh), followed by biomass (58 TWh, 14.8%), wind (44 TWh, 11.3%), small hydropower (14 TWh, 3.6%), and geothermal power (0.9 TWh, 0.2%) (Agency for Natural Resources and Energy 2020).

The capital cost of solar PVs has been steadily decreasing from 465 JPY/W in 2012 to 364 JPY/W in 2017 due to technological development and the introduction of solar PVs in Japan. While the purchase price of FIT has fallen to less than half from 40 JPY/kWh in 2012 to 18 JPY/kWh in 2018 due to capital cost reductions, the FIT levy reached 2.2 trillion JPY/year (= 2.6 JPY/kWh) in 2017 (the currencies are as reported from the original reference and have not been converted to a value for a specific year, since there is almost no inflation in Japan).

To control the ever-increasing FIT levy, an auction system was started to decide purchase prices for large-scale solar PVs (from 2017) and biomass power generation (from 2018) (International Energy Agency 2019). While 39.8 MW of solar PVs has been contracted at 10.99–13.00 JPY/kWh of the purchase price in the fifth auction round in 2020, biomass power generation has never been successfully bid until its second auction round. In 2020, the decision process for the purchase price of bottom-mounted-type offshore wind power will transition toward an auction scheme.

In 2019, the Japanese government set a price target for commercial-scale solar PVs of 7 JPY/kWh by 2025, which is 5 years ahead of its previous target (Calculation Committee for Procurement Price 2019). In addition, the price committee also mentioned the need to accelerate the cost reduction effort to achieve a price target for wind of 8–9 JPY/kWh by 2030. There is also an increasing interest in offshore sources due to a new law that allows for the long-time use of an ocean area for offshore wind-power generation. The purchase price of the FIT for offshore wind was set to 36 JPY/kWh in 2019 compared to the several cents per kWh achieved in other jurisdictions, although the transition to an

auction scheme is expected to drastically reduce the cost. See Komiyama and Fujii (2021) for more detail.

Policies to properly use resource potential (zoning and promoting act)

In response to concerns about the effect on living and natural environments surrounding wind turbines, zoning methodology has been developed in Japan. In 2018, the Japanese government formulated the first manual of zoning methodology related to wind-power generators for local governments (Ministry of the Environment Japan 2018). This manual recommends local governments set areas that can be used to promote the introduction of both onshore and offshore wind-power generation as well as areas that prioritize environmental conservation in coordination with local stakeholders.

At the beginning of the enforcement of the Act of Promoting the Utilization of Sea Areas in the Development of Power Generation Facilities Using Maritime Renewable Energy Resources in April 2019 (Ministry of Economy Trade and Industry Japan 2019), offshore wind in Japan moved to the early stages of deployment. The objective of the act was to promote the utilization of specific maritime areas related to the development of power generation facilities while making efforts to harmonize with other measures related to the ocean. While all the offshore wind generators, which had been built by the end of 2018, were originally in demonstration projects, two of them have begun commercial operation, and there are 13 additional offshore wind projects (for a total output of about 4.4 GW) that are in the environmental impact assessment process (Ministry of Land Infrastructure Transport and Tourism Japan 2019). The act designates four promising maritime areas as targets of the promotion projects and 11 candidates as promising maritime areas. However, most of them are in the Tohoku area, like resource potential for onshore winds, and, thus, inter-regional transmission is necessary to maximize the utilization of resource potential. See Komiyama and Fujii (2021) for more detail.

Policies toward a flexible power grid (strengthening the transmission grid and flexible resource management)

As mentioned in the *Introduction* section, the Japanese power grid is a longitudinal structure and has different frequencies in Eastern and Western Japan. Furthermore, since RE resources are unevenly distributed, strengthening transmission lines is essential for utilizing RE potential. The transmission capacity between Hokkaido and Honshu increased 1.5-fold in 2019, and there is a plan to enforce the frequency converters connecting Eastern and Western Japan to 3 GW. Along with these infrastructure investments, the

existing transmission facilities are planned for full utilization via changes in the policies and operations of Japanese power transmission system. This is a Japanese version of the “connect and manage” principle, and is composed of the rationalization of the anticipated current, the application of the N-1 power control (instantaneous power limit at the time of failure on a single transmission line or a transformer, a so-called N-1 contingency), and the non-firm connection (power source connection on the condition of limiting the output at normal times) (Federation of Electric Power Companies of Japan 2018).

As for flexible resources, energy resource aggregation businesses have been providing adjustment services to transmission and distribution system operators (TDSO) using demand responses (DR), battery storages, and private generators after 2016. For the cross-regional procurement of adjustment services, the Japanese government plans to start a balancing market for adjusting RE fluctuations in 2021 as well as for all balancing services in 2024.

Current situation of non-RE low-carbon generators (nuclear, CCS, and hydrogen)

The fifth edition of the strategic energy plan decided upon by the Japanese Cabinet in 2018 shows that existing nuclear power plants should be restarted operation if the Nuclear Regulatory Commission judges that a nuclear power plant fulfills the regulatory standards. The additional costs of putting nuclear plants into compliance with regulatory standards are expected to be 100 billion JPY per unit (Power Generation Cost Verification Working Group of Advisory Committee for Natural Resources and Energy 2020). As of April 2020, 6 nuclear power plants out of 33 were in operation (Japan Nuclear Safety Institute 2020). In addition, the plan also mentioned that dependence on nuclear power plants should be reduced as much as possible through the introduction of REs, energy conservations, and improving the efficiency of thermal power plants.

In 2019, the Japan Atomic Energy Relations Organization (JAERO) released the latest results of a public opinion survey on nuclear energy that has been conducted annually since 2006 (Japan Atomic Energy Relations Organization 2019). Regarding the preferred methods of power generation in Japan, the number of respondents selecting nuclear power dropped from 36.9 to 16.7% after the Fukushima Daiichi accident in 2011 and stayed at the same level through 2019. Regarding the future use of nuclear power, almost half of the respondents (49.4%) chose “continue it, but gradually reduce it to zero”, and this fraction has not changed since 2014. The second largest group chose “do not know” (22.7%) followed by “stop it immediately” (11.2%), “maintain the pre-earthquake level” (9.3%), and “increase it” (2.0%).

In Japan, a demonstration of carbon capture and storage (CCS) has been conducted using off-gas from a hydrogen production facility in Hokkaido. About 300kt-CO₂ in total was injected for 4 years until the end of 2019 (Japan CCS 2020). Although the strategic energy plan mentions the consideration of rendering coal power plants as CCS-ready, the equipment at a commercial power plant has just been installed for demonstration experiments (Ministry of Economy Trade and Industry Japan 2017; Osaki CoolGen Corporation and New Energy and Industrial Technology Development Organization 2019; Toshiba Energy Systems & Solutions Corporation 2019), and it has not been introduced in other power plants in 2020.

As for the public perception of CCS in Japan, the results of the survey conducted by Saito et al. (2019) showed that the general Japanese public did not know much about CCS and hold a Not in My Backyard (NIMBY) perception regarding CCS implementation.

In 2017, a basic hydrogen strategy was formulated to accomplish a world-leading hydrogen-based society (Ministerial Council on Renewable Energy Hydrogen and Related Issues 2017). In this strategy, the price target for imported hydrogen by around 2030 was set at 30 JPY/Nm³, which is one-third of the current level. The strategy also plans to try lowering the hydrogen price in the future to 20 JPY/Nm³ as well as to start using imported hydrogen for hydrogen-fired power plants around 2030. As for domestic hydrogen development, the Fukushima Hydrogen Energy Research Field (FH2R), which is equipped with a 10 MW hydrogen production system using electricity from 20 MW of solar PVs, came online in March 2020 (New Energy and Industrial Technology Development Organization et al. 2020).

Itaoka et al. (2017) conducted a public survey regarding hydrogen, hydrogen infrastructure, and fuel cell vehicles, although it did not target the hydrogen power plant itself. Due to the diffusion of household fuel cell systems and exposure about the hydrogen society in the media, awareness of hydrogen energy, hydrogen infrastructure, and fuel cell vehicles in 2015 increased when compared to that in 2008. However, the percentage of respondents who knew about hydrogen was only 32%, which was much lower than for nuclear power, solar PV, and wind power, which had an overall awareness of more than 80%.

Model intercomparison of the parameter settings and modeling

Before the presentation of the analysis of the results from the MIPs, it is necessary to organize the preconditions of each model. This study focused on four preconditions that would affect the results of the future RE share in the power sector: the generation costs, resource potentials of REs, modeling of

VRE integration challenges, and non-renewable low-carbon generators in the participating models.

Brief summary of the participating models

Five models participated in EMF35 JMIP: AIM/Enduse-Japan, AIM/Hub-Japan, DNE21, IEEJ_Japan 2017, and TIMES-Japan. Except for AIM/Hub-Japan, which is the only general equilibrium model, the other models are partial equilibrium models. As for a detailed description of the participating models, see Sugiyama et al. (2021) as well as Supplementary Table S1.

Levelized cost of electricity

Although several factors affect the determination of the generation mix in the model, the generation cost is one of the most important factors, since models are basically driven by the cost-effectiveness paradigm. Thus, comparing cost parameters among and within the model helps in understanding the results of each model. The simplest approach is to compare the technoeconomic parameters (i.e., capital cost, operation and maintenance cost, conversion efficiency, etc.) separately. Another approach is to use the levelized cost of electricity (LCOE). The former promotes understanding of the variation in each input parameter in the models, but makes it difficult to compare unit generation costs within the model. The latter is helpful in identifying the order and range of unit generation costs and thus provides insight into the preferable (i.e., less-expensive) generator for each model. Moreover, a comparison of the LCOE among the models reveals the variation in the future expectations for the LCOE among the modeling teams. In this study, we adopt an LCOE approach to understand the precondition of the cost parameters in the participating models (for the simple comparisons of the capital costs for the selected generators and fuel prices among the participating models, see Supplementary Figs. S1 and S2).

The LCOE is calculated based on the two equations:

$$\text{LCOE} = \frac{\text{Capital}}{h \times cf} + \frac{\text{Fixed O\&M}}{h \times cf} + \text{Variable O \&M} + \frac{\text{Fuel}}{eff} \quad (1)$$

$$\text{Capital} = \text{Initial} \times \frac{r}{1 - \frac{1}{(1+r)^{life}}}, \quad (2)$$

where the different variables indicate: *Capital* = annualized capital cost [JPY/kW]; *FixedO&M* = fixed operations and maintenance (O&M) cost [JPY/kW]; *VariableO&M* = variable O&M cost [JPY/kWh]; *Fuel* = fuel price [JPY/kWh]; *h* = annual hours (8760 = 365 days * 24 h); *cf* = capacity factor of each generator [-]; *eff* = conversion efficiency of each

generator [-]; *Initial* =initial cost [JPY/kW];*r* =discount rate (0.05) [-]; *life* =lifetime of each generator [year].

Note that the LCOE calculated by Eqs. (1) and (2) does not include the carbon price and system integration cost. This is because the objective of the LCOE comparison here is to approximately understand the input parameter setting. Although generation cost is one of the major determinants of generation mix, other factors, including the preconditions described in the following sections, also affect the generation mix. Thus, we treated the LCOE analysis as the starting point for the discussion and tried to calculate the LCOE using a minimum number of parameters.

To calculate the LCOE, while the variables used as the input parameters of each model are directly adopted, the variables as the output parameters (i.e., *cf* of all the models and *Fuel* of AIM/Hub-Japan and DNE21) are exogenously assumed. The capacity factors used for the LCOE calculation are shown in Supplementary Table S3. The values 50% and 85% are used for the fired power plant, which operates as mid-load and baseload, respectively. Two capacity factor cases are assumed for the non-biomass renewables to consider different types of resource conditions. The fuel prices of AIM/Hub-Japan are adopted from the output of the baseline scenario.

The LCOE calculation reveals that some of variable renewable options do not become competitive, even in 2050, without a climate policy as opposed to the predictions of global trends by market analyst firms (e.g., Bloomberg New

Energy Finance 2019). Figure 1 shows the LCOEs in 2020 and 2050 in the participating models. The technologies are sorted by the lower range of LCOEs in 2050. The LCOEs of DNE21 are not depicted due to a lack of data availability (for more detail, see Supplementary Information). In AIM/Hub-Japan and IEEJ_Japan 2017, onshore wind and solar PVs become cost-competitive in 2050 due to the capital cost reduction. In TIMES-Japan, while the LCOE of solar PVs becomes less-expensive than a gas generator, the LCOE of wind remains a relatively expensive option.

Resource potentials of REs

The resource potentials of solar PVs in the participating models are mostly near the estimates of the Ministry of the Environment, Japan (MOEJ) (2017), while those of wind vary greatly because of different grid constraint considerations and localized resource endowments (Fig. 2). AIM/Hub-Japan uses their own estimation of VRE potentials (Silva Herran et al. 2016). TIMES-Japan uses data that explicitly includes the effects of technology improvements until 2050 (Matsukawa et al. 2017; Saito et al. 2017). Since DNE21 has constraints that substantially decide the upper limit of the VRE share (see the *modeling of VRE integration* section), the model does not assume the resource potentials for solar PVs. The coverage of the wind potential varies by the technology representation and the definition of potential in each model. The wind potential of AIM/Enduse-Japan is

Fig. 1 LCOEs in 2020 and 2050 in the participating models. The technologies are sorted based on the lower LCOEs in 2050 in each model. The LCOE does not include carbon price and system integration cost. The range represents different conditions of capacity factors. ^aOther in IEEJ_Japan 2017 and TIMES-Japan represent an ammonia generation plant and a top-pressure recovery turbine plant, respectively

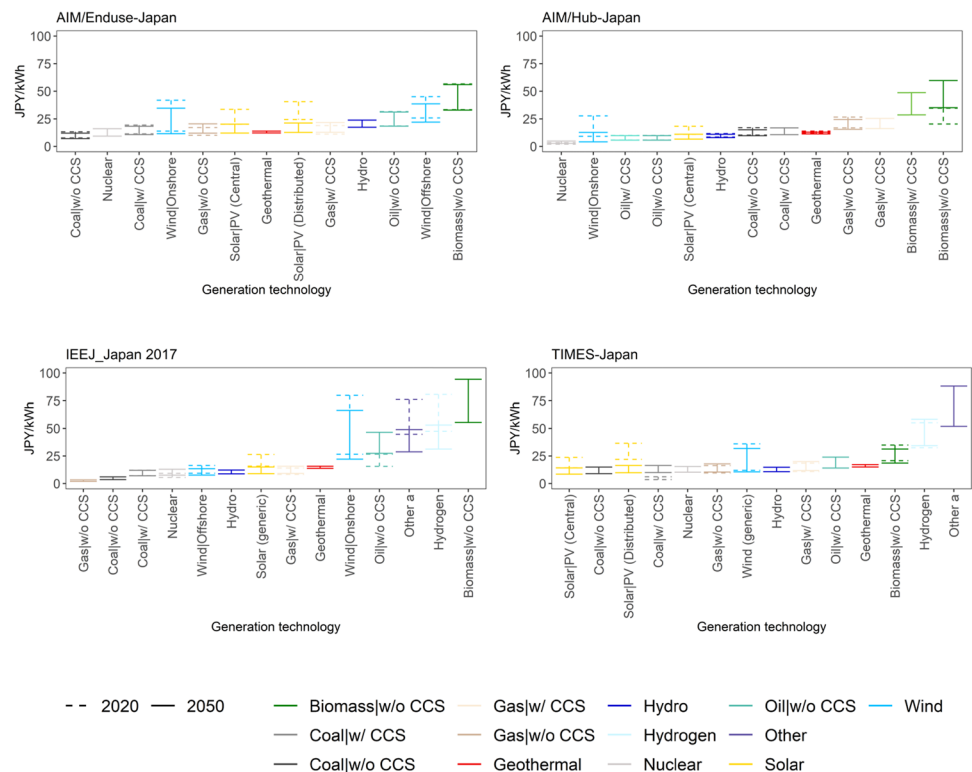
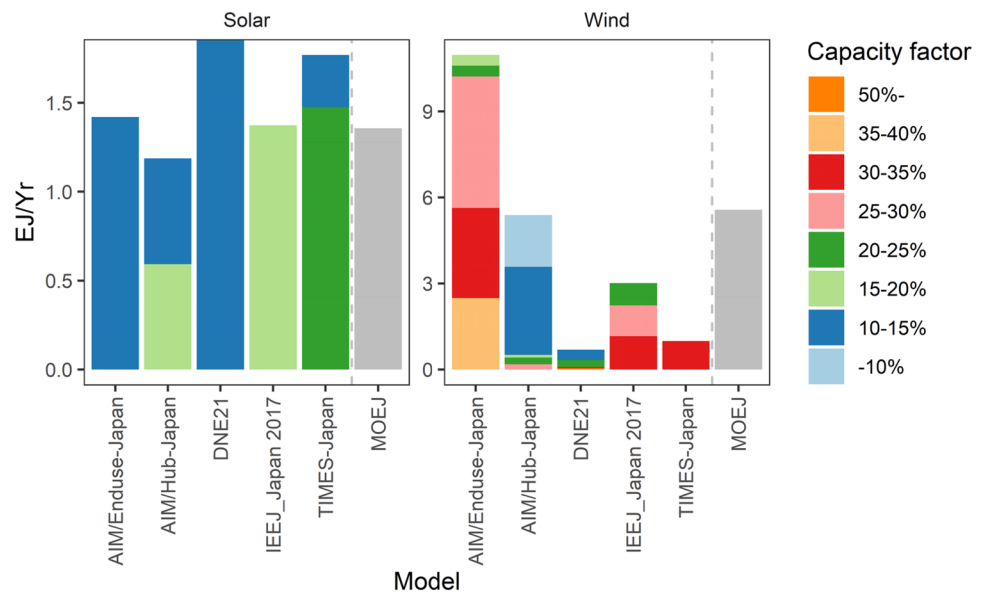


Fig. 2 Resource potentials of solar PV (left) and wind (right) in 2050 in the participating models based on capacity factor and estimation by the Ministry of the Environment, Japan (MOEJ). Since MOE does not provide resource potentials by capacity factor, the values are depicted in gray. Potentials in TIMES-Japan include the effect of technology improvement. DNE21 assumes infinite resource potentials for solar PVs, because there is another upper limit of the total VRE penetration. The definition of resource potential for wind varies by model (see main text)



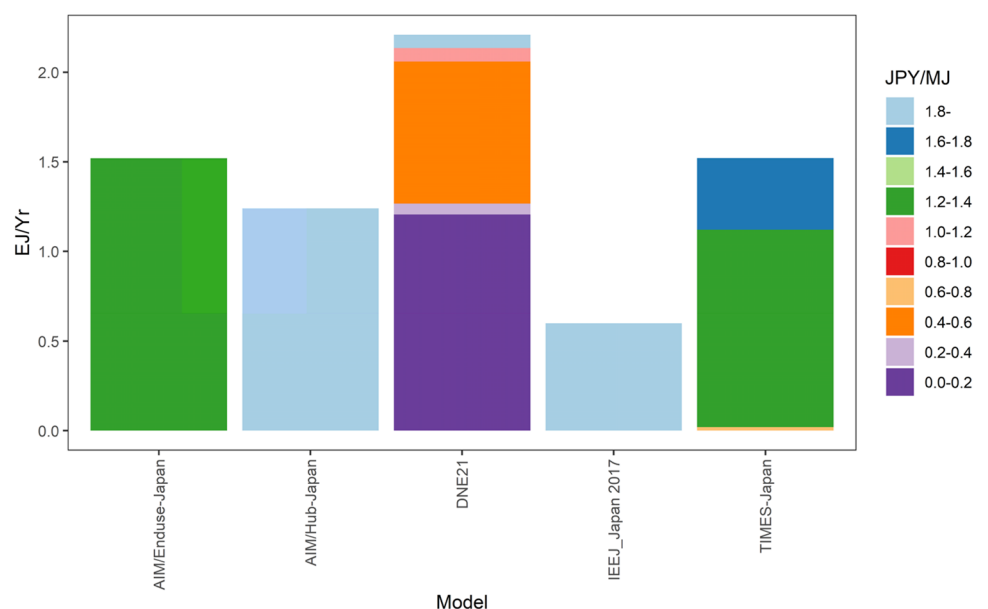
relatively large, since the model explicitly deals with offshore wind. The wind potential of AIM/Hub-Japan includes only onshore resources. The wind potentials in DNE21 and TIMES-Japan are relatively small, since they adjust resource potentials to consider the constraint of inter-regional transmission lines. Specifically, they discount wind potential by considering the capacity of inter-regional transmission lines between high-demand regions, such as the Greater Tokyo Area, and regions that have high wind potentials, such as the Hokkaido and Tohoku areas.

The potentials of biomass are less varied than those for solar and wind among the models (Fig. 3). Except for DNE21, most of the biomass resources less than 1.6 EJ/year can be extracted with the price more than 1.4 JPY/MJ. DNE21 assumes abundant and affordable biomass potentials based on the estimation of the global land-use and energy model (GLUE) (Yamamoto and Yamaji 1996).

Modeling of VRE integration

Table 1 shows the modeling of the VRE integration in the participating models. The modeling of the VRE integration in IAMs can be categorized into two elements: (a) how

Fig. 3 Resource potential of biomass. As resource potential of TIMES-Japan varies by scenario, maximum value is depicted



to model the additional cost of the grid flexibility options and (b) how many time resolutions and regions which they explicitly consider.

We classified the modeling of the grid flexibility options into three levels. The simplest representation is to include the upper/lower limits of the penetration rate and growth rate of the VREs. Since AIM/Hub-Japan is myopic and a computational general equilibrium model, a maximum/minimum growth rate can help to avoid an unrealistic energy transition in the power sector. While DNE21 explicitly models some specific integration options, such as storage and curtailment, it includes a maximum share of VREs to be 15% of the total electricity supply to consider the difficulty of the VRE integration, which is not explicitly considered in the model.

The second level of modeling the VRE integration is implicit representation as an additional cost. In general, increasing VRE requires battery storage and curtailment

and thus increases the generation costs. In this modeling, the integration costs for the flexibility options are modeled as a function of the VRE share, which is calculated by other specific models. With this modeling of VRE integration, the model can consider integration cost even without the explicit modeling of the specific technology options for VRE integration. Among the participating models, AIM/Hub-Japan and IEEJ_Japan 2017 have such functions (for AIM/Hub-Japan, see Dai et al. 2017; for IEEJ_Japan 2017, see Matsuo et al. 2020). For more information on system integration cost, see Matsuo and Komiyama (2021).

The third level of modeling the VRE integration is the explicit modeling of specific integration options. This modeling can include not only economic conditions but also technological conditions, such as conversion efficiency and capacity requirement. AIM/Enduse-Japan, DNE21, and TIMES-Japan explicitly model multiple integration options.

Table 1 Representation of VRE integration in the participating IAMs

Level of representation	Modeling	AIM/ Enduse- Japan	AIM/Hub-Japan	DNE 21	IEEJ_ Japan 2017	TIMES-Japan
Simple representation as share or growth rate	Max./min. share	No	No	Yes	No	No
	Max./min. growth rate	No	Yes	No	No	No
Implicit representation as additional cost	Backup capacity ^a	Yes	No	No	No	No
	Integration costs (and/or cost penalty) ^b	No	Yes ^c	No	Yes ^d	No
Explicit modeling of specific integration options	Storage	Yes	No ^c	Yes	No ^d	Yes
	Curtailment	Yes	No ^c	Yes	No ^d	No
	Demand response	Yes	No	No	No	No
	Interregional transmission	Yes	No	No ^e	No ^d	No ^e
	Electrolysis (hydrogen storage)	Yes	No	Yes	Yes	Yes
	Intraregional transmission	No	No ^f	No	No	No
	Spinning reserve	No	No	Yes	No	No
Single time-resolution ^g	Annual load balance	No	Yes (1)	No	No	No
Simple time-resolution	Load duration curve	No	No	No	No	No
Detailed time-resolution ^g	Chronological load curve	Yes (96)	No	Yes (24)	Yes (6) (8760) ^d	Yes (6)
	Chronological VRE output profiles	Yes (96)	No	Yes (24)	Yes (6) (8760) ^d	Yes (6)
Spatial resolution	# of spatial resolutions	10	1	2	1 9 ^d	1

^aThe term “backup capacity” means setting a backup capacity or cost for the penetration of variable renewables as a dedicated parameter

^bThe term “integration cost and cost penalty” means additional costs for the penetration of variable renewables that are NOT explicitly represented in the model

^cConsidered as the function of VRE share (see Dai et al. 2017)

^dConsidered in the optimal power generation mix model (OPGM), in which supply cost is a function of VRE integration in IEEJ_Japan 2017

^eConstraint of inter-regional transmission is considered when VRE potentials are estimated

^fConstraint of intra-regional transmission is considered when VRE potentials are estimated

^gNumbers in brackets represent the number of time steps per year

Although most of the models considered storage and curtailment, demand responses and the constraint of spinning reserve are rarely modeled. While AIM/Enduse-Japan includes the expansion of inter-regional transmissions lines under the cost minimization process, other models consider it when the resource potentials of VREs are estimated.

Another element of the VRE integration modeling is time and spatial resolution. AIM/Hub-Japan, the only general equilibrium model, considers the demand–supply balance of electricity yearly. The other partial equilibrium models assume multiple and chronological load curves for both electricity demand and VRE outputs. While IEEJ_Japan 2017 itself has a time-resolution of six slices, it is soft-linked to a power dispatch model with an hourly resolution. Among the single-model frameworks (AIM/Enduse-Japan, DNE21, and TIMES-Japan), AIM/Enduse-Japan has the most detailed time-resolution of 96 slices (1-h steps for 4 representative days = three seasons + peak day). Detailed special resolutions are found in AIM/Enduse-Japan and a power dispatch model used in the IEEJ_Japan 2017 framework, which was set based on the Japanese TDSO areas. DNE21 sets two regions representing areas with different frequencies.

Non-renewable low-carbon generators and negative emissions

Table 2 shows the list of low-emission generators—except for the REs—in the models. The availability of the negative emissions is also listed. Imported hydrogen and negative emission by biomass CCS are considered in three out of the five models. Nuclear power is included in all the participating models, but four models assume the upper limit of electricity supply from nuclear power due to the public perception of nuclear in Japan.

Model intercomparison of results from the EMF35 JMIP scenarios

Scenarios used for the REs analysis

The scenarios used in this study are shown in Table 3. To analyze the impact of the emission reduction targets, we adopted six policy sensitivity scenarios with the reduction targets for CO₂ emissions from the energy and industrial processes. The main policy scenario, 26by30+80by50_Def, requests each model to impose Japan’s Nationally Determined Contribution (NDC, 26% emissions reduction by FY2030 relative to the FY2013 levels) and mid-century strategy (80% emissions reduction by 2050). Note that the base year for the 2050 emission target is left to the modeling team, since there is no base year in the official stated Japan’s mid-century strategy (as for the base year set by each modeling team, see Supplementary Table S2). In addition to the baseline scenario and policy sensitivity scenarios with a default parameter setting, 10 technology sensitivity scenarios with the officially stated emission reduction target (26by30+80by50_xx) were used to capture the uncertainty of the technological conditions, such as the capital cost of VREs, resource potentials of VREs, and capital cost of battery storages. Parameter settings not stated in the scenario protocol are left to the modeling team.

Apart from the technology and policy conditions, two key drivers of socio-economic conditions, i.e., population and gross domestic product (GDP), were harmonized among the models (Supplementary Fig. S3). For a detailed description of the scenarios used for the REs analysis, see Sugiyama et al. (2021) and Supplementary Information.

Impacts of emission reduction on the power sector

Figure 4 shows the electricity supply, CO₂ emissions from the power sector, and the emission factor of electricity in the Baseline_Def and 26by30+80by50_Def scenarios. There is no consensus for the trend in electricity supply among the models, but that within the models are consistent regardless of the scenario. Specifically, AIM/Hub-Japan, DNE21, and

Table 2 Non-renewable low-carbon generators considered in the participating models

	AIM/Enduse-Japan	AIM/Hub-Japan	DNE 21	IEEJ_Japan 2017	TIMES-Japan
Nuclear	Yes, with maximum quantity constraint	Yes, with maximum quantity constraint	Yes, without quantity constraint	Yes, with maximum quantity constraint	Yes, with maximum quantity constraint
Hydrogen-fired	No	No	Yes	Yes	Yes
Fossils w/CCS	Yes	Yes	Yes	Yes	Yes
Biomass w/CCS	Yes	Yes	Yes	No	No

Table 3 List of the EMF 35 JMIP scenarios used in the analysis

Dimension	Scenarios	Notes
Baseline	Baseline_Def	Assumed no emission reduction target with default parameter settings
Policy stringency (emissions constraint)	26by30+80by50_Def	NDC and mid-century strategy
	26by30+70by50_Def	NDC and 70% reduction by 2050
	26by30+90by50_Def	NDC and 90% reduction by 2050
	26by30+100by50_Def	NDC and 100% reduction by 2050
	16by30+80by50_Def	16% reduction by 2030 and mid-century strategy
Technology sensitivity	36by30+80by50_Def	36% reduction by 2030 and mid-century strategy
	26by30+80by50_LoVREcost	The costs of VREs are halved
	26by30+80by50_HiVREcost	The costs of VREs are doubled
	26by30+80by50_LoVREpot	The potentials of VREs are halved
	26by30+80by50_HiVREpot	The potentials of VREs are doubled
	26by30+80by50_NoCCS	No CCS is available
	26by30+80by50_LimNuc	Only limited deployment of nuclear power is allowed
	26by30+80by50_NoNuc	Nuclear power is not available
	26by30+80by50_HighInt	High challenges with renewable system integration
	26by30+80by50_LoInt	Low challenges with renewable system integration
	26by30+80by50_LoStorageCost	The cost of battery storage is greatly reduced

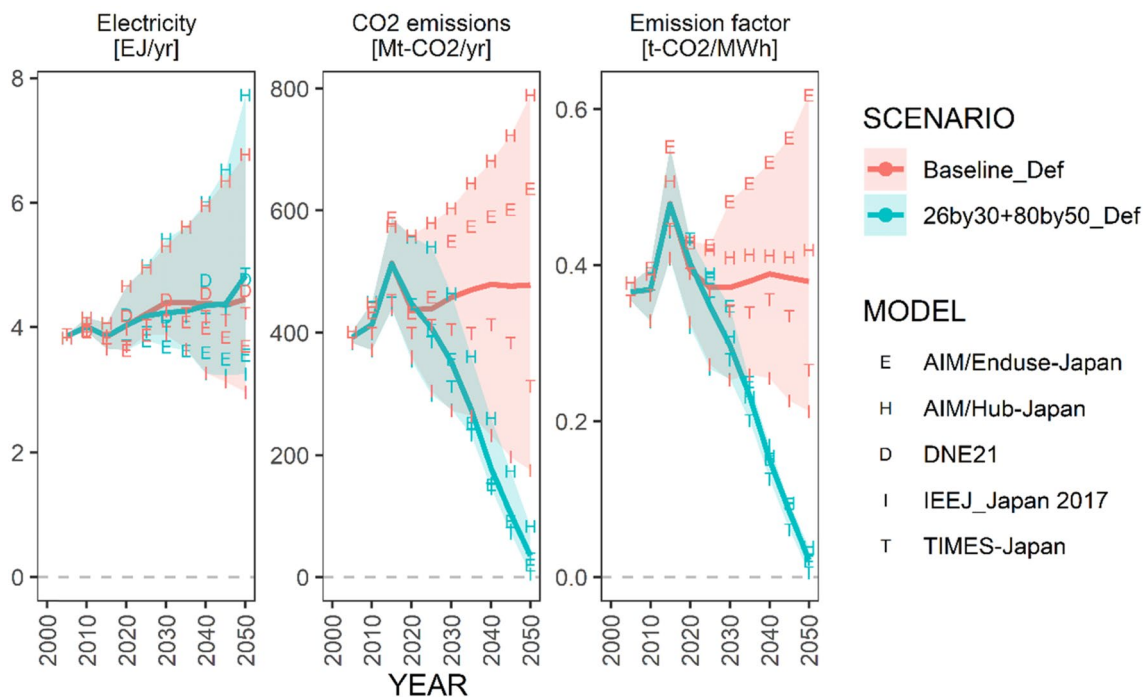


Fig. 4 Electricity supply, CO₂ emissions from the power sector, and the emission factors of electricity in the Baseline_Def and 26by30+80by50_Def scenarios. Solid lines represent the mean values of each variable. The shaded regions represent the range of the models

TIMES-Japan estimate an increase in electricity consumption and AIM/Enduse-Japan and IEEJ_Japan 2017 project a decrease. A relative change in electricity supply between 2010 and 2050 ranges $\pm 20\%$ in the models except for AIM/Hub-Japan, which estimates an increase of 1.8–2.2 times the 2010 levels. A doubling of the power supply of AIM/

Hub-Japan may be due to the high electrification rate of the final energy consumption (Sakamoto et al. 2021).

All participating models estimated that the CO₂ emission from the power sector in the 26by30+80by50_Def scenario decreases by more than 90% of the 2010 levels, but the preferred low-emission power options differ. The inter-model median of the emission factors from the power sector in the

26by30+80by50_Def scenario reaches 23 g-CO₂/kWh (min 5.8 – max 39) from 376 g-CO₂/kWh in 2010. Although all the models replace fossil power with REs and/or non-RE low-carbon generators in the 26by30+80by50_Def scenario, the main contributors vary across models (Fig. 5). In AIM/Enduse-Japan and AIM/Hub-Japan, wind-power turbines account for more than 25% and 40% of the power supply in 2050, respectively, due to their low LCOE. DNE21, the only model that does not have the upper limit of electricity supply from nuclear, estimates that nuclear can account for more than 45% of the power supply. In addition, the biomass in DNE21 occupies more than 20% of the power

supply due to its assumption of the affordable and abundant biomass potentials. In IEEJ_Japan 2017, the share of hydrogen reaches more than 20% despite its high LCOE. The absence of biomass CCS and the upper limit of nuclear in IEEJ_Japan 2017 may result in hydrogen being used as a backstop technology. TIMES-Japan, which estimates a high solar PV share even in the Baseline_Def scenario, indicates an additional emission reduction by increasing the share of nuclear and wind in the 26by30+80by50_Def scenario.

There is a wide range of power sector CO₂ emissions and emission factors among the models in the Baseline_Def scenario. While IEEJ_Japan 2017 and TIMES-Japan

Fig. 5 Generation mix in 2050 in the Baseline_Def and 26by30+80by50_Def scenarios

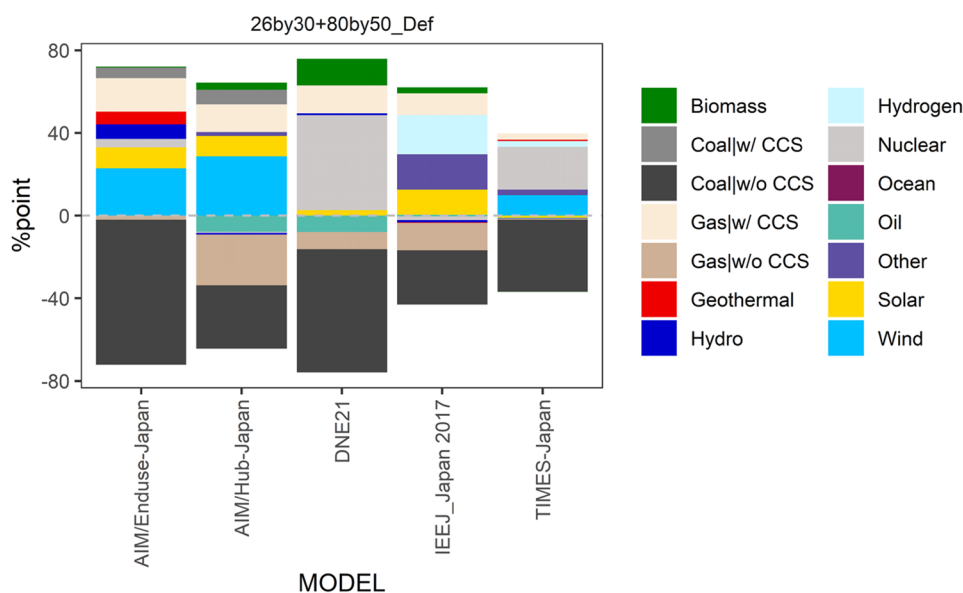
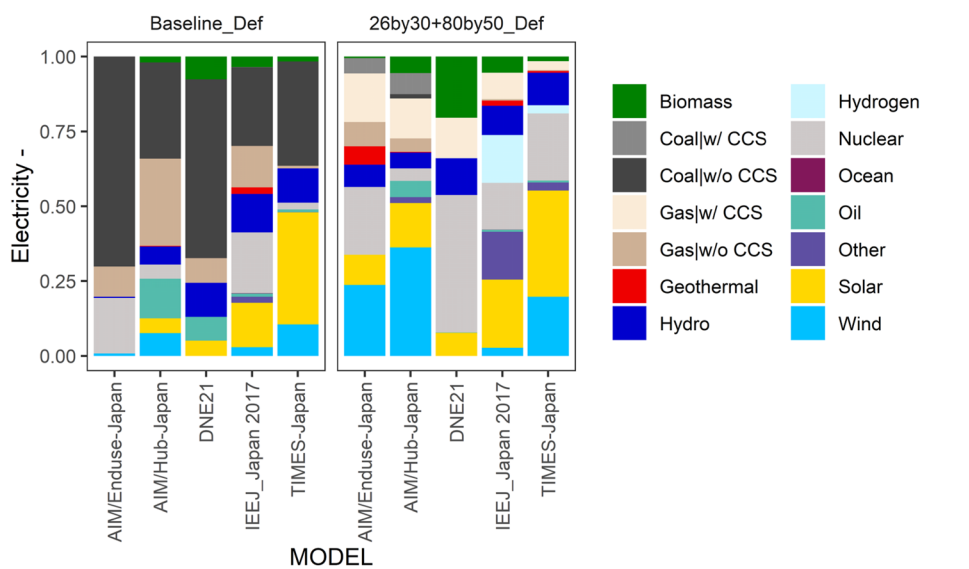


exhibit a reduction in CO₂ emissions even without policy intervention, AIM/Hub-Japan and AIM/Enduse-Japan project a 1.5-to-twofold increase in CO₂ emissions in the power sector. This may be caused by the following reasons. For the two partial equilibrium models of AIM/Enduse-Japan and TIMES-Japan, the models tend to select the cheapest generation technologies (coal for AIM/Enduse-Japan and solar PVs for TIMES-Japan; see Figs. 1 and 5, respectively) based on the cost minimization approaches. AIM/Hub-Japan uses a logit function to determine the share of energy sources, and, thus, the share of generation technologies (and emission factor) does not change drastically without carbon prices. In addition, the high level of electrification in the final energy consumption increases the CO₂ emissions in the power sector. While the other models presuppose no climate policy in the baseline scenario, IEEJ_Japan 2017 sets a baseline scenario as an extension of the current condition, such as the development of REs and technological progress. This may have resulted in the reduction of the emission factor in IEEJ_Japan 2017—even in the Baseline_Def scenario.

Sensitivity of the RE shares to technological parameters

We intercompared four preconditions of the IAMs that would affect the results of the future RE share in the power sector in the *model intercomparison of the parameter settings and modeling* section. The technology sensitivity scenarios in EMF35 JMIP provide insights related to four conditions within and among the models: VRE cost sensitivity (LoVREcost and HiVREcost), VRE potential sensitivity (LoVREpot and HiVREpot), the difficulty of VRE integration (HighInt, LoInt, and LoStorageCost), and the availability of non-VRE low-carbon generators (NoCCS, LimNuc, and NoNuc) (the scenario prefix “26by30 + 80by50_” has been dropped in this paragraph for brevity in reporting).

Figure 6a shows the RE and VRE shares in the technology sensitivity scenarios. The REs supply more than 40% of the electricity in most of the models and scenarios when assuming an 80% reduction in 2050 (median 51.0%). On the contrary, the fluctuation in the VRE rate by the models is larger than those found in the technology sensitivity scenarios. The results, excluding scenarios that assume special conditions like continuous nuclear power growth and/or the affordable and abundant availability of domestic biomass and carbon-free hydrogen, showed that the median VRE share reaches 52.2% in 2050 in the 80% emission reduction scenario. On the contrary, the availability of the newly constructed nuclear power, affordable biomass, and carbon-free hydrogen can reduce dependence on VREs to less than 20%.

Increasing the share of low-carbon generators, such as REs, nuclear power, thermal power with CCS, and carbon-free hydrogen, helps to reduce the share of conventional

thermal power plants. The capacity factor of thermal power plants without CCS decrease rapidly after 2030 in all the technology sensitivity scenarios (Supplementary Fig. S4). In 2050, coal power plants without CCS are not used in almost any scenarios. The capacity factor of gas power plants without CCS in 2050 decreases to less than 15% in almost all the scenarios. These results imply that it is robust that the capacity factor of the thermal power plant without CCS sharply decreases under the 80% emission reduction scenario.

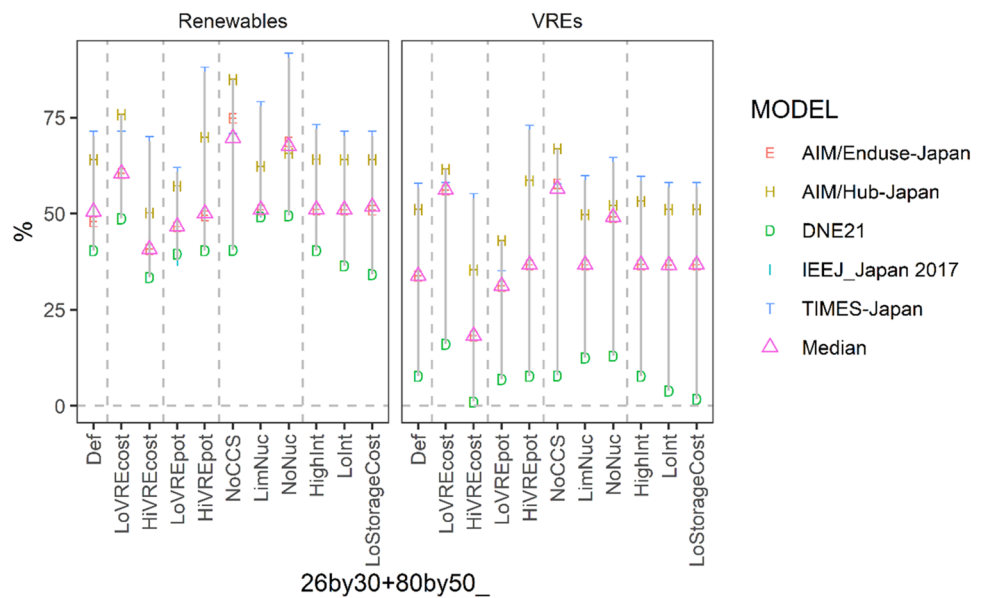
Figure 6b shows the difference in the RE and VRE shares in the technology sensitivity scenarios relative to the 26by30 + 80by50_Def scenario. The generation mix in 2050 in the technology sensitivity scenarios is shown in Supplementary Fig. S5. Compared to the absolute values of the RE and VRE shares, the differences in the RE and VRE rates have a certain level of consistency among the models. Among the parameters used in the technology sensitivity scenarios, halving/doubling the capital costs of the VREs has the highest impact on the VRE share (+ 10.5/-13.5 percentage points, from the median, compared to the default technology scenario).

TIMES-Japan has a strong sensitivity to VRE potential changes, since all the VRE potentials in TIMES-Japan are used—even in the 26by30 + 80by50_Def scenario. This resource exhaustion may also cause less sensitivity of the VRE cost reduction in TIMES-Japan.

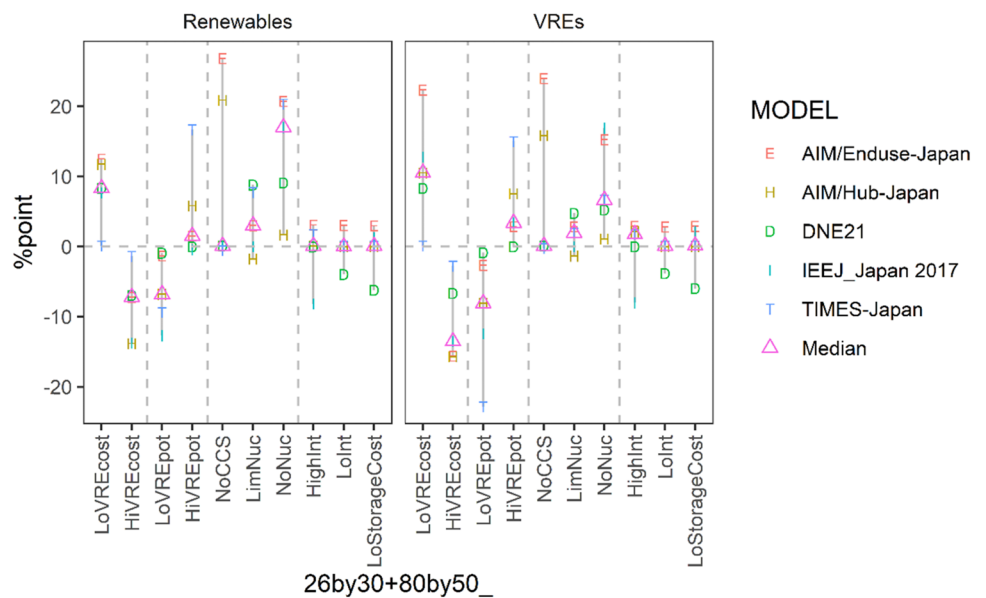
Except for AIM/Hub-Japan, while the unavailability of CCS increases zero-emission generators that can be used in the middle load, such as solar PVs and hydrogen, the unavailability of nuclear limits increases the zero-emission generators, which behave as a base load generator, such as coal with CCS, biomass, and wind. This result indicates that these four partial equilibrium models can capture the effect of the merit order due to their modeling of the chronological load curve. While AIM/Hub-Japan increases the wind share by 25 percentage points to offset the generators with CCS technologies, the impact of nuclear availability is small. The former may be caused by the low LCOE of wind in AIM/Hub-Japan along with their relatively simple representation of time-resolution. The latter is due to the low dependence of nuclear in the 26by30 + 80by50_Def scenario in AIM/Hub-Japan.

Changing the difficulty of VRE integration has a lesser impact than the other parameters in most of the models. In IEEJ_Japan 2017, high battery cost and no curtailment assumptions result in a 10 percentage point reduction in VRE share. In the scenarios with low battery costs, AIM/Enduse-Japan and IEEJ_Japan 2017 increase the VRE share with 278 GWh and 130 GWh of batteries, respectively. Interestingly, in DNE21, the battery cost reduction increases the nuclear and gas without CCS shares and, as a result, reduces the RE share. This is because the additional battery storage enables a flattening of the daily load curve like pumped

Fig. 6 RE and VRE shares in 2050 in the technology sensitivity scenarios



(a) absolute value



(b) relative changes from the 26by30+80by50_Def

hydro storage does at present and thus increases the room for baseload and mid-load generators like nuclear and gas generations.

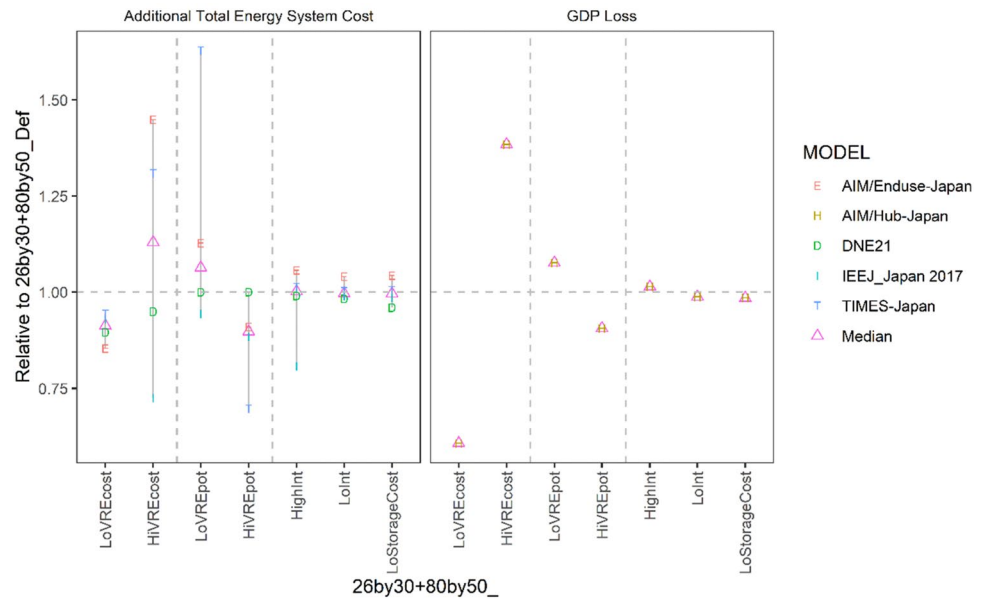
Sensitivity of policy costs to technological parameters related to REs

Figure 7 shows the relative discounted total policy cost in the technology sensitivity scenarios. The discounted total policy costs are calculated using the GDP losses (AIM/Hub-Japan) or additional total energy system costs (AIM/

Enduse-Japan, DNE21, IEEJ_Japan 2017, and TIMES-Japan) of the mitigation scenario in comparison to the baseline scenario discounted at 5% for the period 2010–2050. Since policy costs in different cost metrics were not directly compatible (Paltsev and Capros 2013), the parameters are depicted separately.

The results show that the capital costs and resource potentials of the VREs had much more impact than the battery costs. Specifically, while doubled capital costs of the VREs resulted in a 13.0% increase in the additional total energy system cost, halved capital costs of the VREs reduced 8.7%

Fig. 7 Relative discounted total policy cost compared to the 26by30+80by50_Def scenario. Policy costs in the four energy system models are measured as the additional total energy system cost compared to the baseline scenario, and that in the AIM/Hub-Japan is measured as the GDP loss compared to the baseline scenario

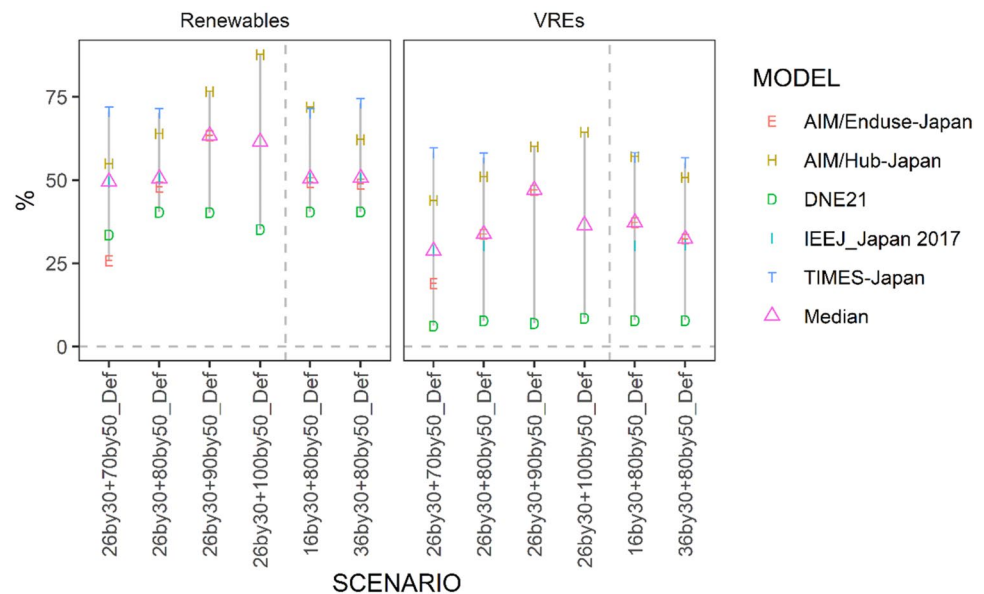


of the additional total energy system cost. A doubling/halving of the resources decreases/increases the additional total energy system cost by 10.2/6.3%, respectively. (Values in this paragraph are the inter-model median of four energy system models measuring policy cost as the additional energy system cost.) Note that the non-intuitive results for IEEJ_Japan 2017 (i.e., the lower policy costs in high VRE costs and low RE potential scenarios) are due to non-power sector interactions (for more details, see Supplementary Information).

Sensitivity of the RE shares to mitigation targets

The EMF35 JMIP study set six policy sensitivity scenarios that weaken or strengthen 2030 and 2050 emission targets. In the scenarios with 90% and 100% emission reductions by 2050, only three and two models with negative emission options found to provide feasible solutions, respectively (for the infeasibility in the 100% emission reduction target in AIM/Enduse-Japan, see Supplementary Information). Figure 8 shows the share of REs and VREs in the power supply in the policy sensitivity scenarios. The strengthening of the 2050 target increases the RE and VRE share in 2050 in all

Fig. 8 Shares of RE and VRE in the power supply in 2050 in the policy sensitivity scenarios



the models except for DNE21, which allows for growing nuclear power use.

The differences in the technology shares relative to the 26by30+80by50_Def scenario are shown in Supplementary Fig. S6. In the scenarios with a 100% emission reduction in 2050, while AIM/Hub-Japan increases the wind share to more than 50% of the power supply, DNE21 accelerates nuclear use, which reaches about 58% of the power supply. The former may be attributed to the low LCOE of wind along with the relatively simple representation of the VRE integration in AIM/Hub-Japan. The latter may be caused by the absence of an upper limit of the nuclear supply in DNE21.

Conclusion

Summary of the results

We analyzed the role of renewables in the future Japanese power sector using the scenario results from the model intercomparison project Energy Modeling Forum (EMF) 35 JMIP by varying the emission reduction targets and key technological conditions across the scenarios. The major findings are as follows:

The REs supply more than 40% of the electricity in most of the technology sensitivity scenarios (median 51.0%) when assuming an 80% emission reduction in 2050. The median of the VRE share reaches 52.2% in 2050 in the 80% emission reduction scenarios when excluding results that assume special conditions, like continuous nuclear power growth and/or the abundant availability of domestic biomass and imported carbon-free hydrogen.

On the contrary to the previous finding, the availability of newly constructed nuclear power, affordable biomass, and carbon-free hydrogen can reduce dependence on VREs to less than 20%.

The analysis of policy costs, which are scaled by GDP losses or the additional total energy system cost of the mitigation scenario compared to the baseline scenario, showed that the capital costs of VREs as well as the resource potentials of the VREs had a much greater impact than battery costs.

Only the models with the options to use negative emission technologies, specifically BECCS, provided feasible solutions for the scenarios with more than 90% reduction in 2050, which implies that negative emissions technologies would play a critical role in the deep decarbonization of the energy system.

Limitations and future steps

There are three notable limitations of this study. First, there is a wide variation in the representation of the VRE integration among the models. The participating models in this study include a model that has a high time-resolution and spatial resolution in the energy model itself, a model that has a soft link with the supplementary model for the power sector, and a model that has a simple time and spatial resolution. In addition, the flexible resources explicitly modeled vary by models, as shown in Table 1. To estimate the impact of VRE development quantitatively using a model intercomparison study, detailed temporal resolution, spatial resolution, and an explicit representation of flexible options are desirable.

Second, the technology options are not consistent across the models. For example, DNE21 assumes that nuclear power can be expanded, while other models set upper limits on the nuclear power supply due to public perception. IEEJ_Japan 2017, which has a technology option of imported hydrogen derived either from fossil fuels with CCS or REs, tends to have a lower VRE share than the models that do not assume imported hydrogen. Some models do not explicitly distinguish offshore and onshore wind generation. The most important problem is that these technologies, which are treated differently among the models, are key technologies in the mitigation scenarios in the models that assume these technologies. To analyze the future uncertainty of each technology by comparing the models, it is essential to analyze technology scenarios, each of which provides a unifying assumption for major technological options.

Third, the preconditions of the baseline scenario with the default technology are not unified among the models. For example, AIM/Enduse-Japan and AIM/Hub-Japan assume no climate policy for the baseline scenario, but IEEJ_Japan 2017 presupposes a baseline scenario as an extension of the current policy conditions, such as the development of REs and technological progress. Since policy costs are calculated as the difference from the baseline scenario, the different preconditions of the baseline scenario among the models have impacts on the results. In addition, some parameter settings not stated in the scenario protocol are also inconsistent among the models. For example, while some models assume to halve the capital costs of VREs from the beginning of the calculation periods, others assume to halve them after 2030. Although we suggest that this inconsistency in assumptions does not affect our main qualitative conclusions related to the impact of the capital costs of VREs, it may potentially underestimate the qualitative magnitude of the impact of the capital costs of VREs. It is necessary to set comparable baseline scenarios while ensuring the diversity of future visions envisioned by each model team.

Future steps to address the above three limitations include the following: first, the implementation of a model

intercomparison between energy system models and power dispatch models; second, the harmonization of key technology options among the participating models; and, third, the harmonization of the policy conditions of a baseline scenario among the participating models.

Policy implications

There are two major policy implications in achieving Japan's mid-century strategy to be garnered from the results of this study. First, it would benefit to bring the capital costs of VREs closer to international levels. Lowering of power generation cost for any kinds of generator result in reduction of total energy system costs, but the room of cost reduction varies by generators and that for VREs is greater than for other generators. As mentioned in the *policy environment* section, since the current capital cost of Japanese solar PVs is twice that of other countries, the scenario of halving the capital cost of VREs is equivalent to reducing the VRE cost in Japan to the international level. In other words, the result of the scenario of halving the VRE cost shows that reducing the renewable energy price in Japan to an international level can reduce 8.7% (inter-model median) of the additional total energy system cost. As for the commercial scale of solar PV, the procurement of overseas modules, a reduction in domestic module prices, and the application of installation technology from other countries can reduce the cost difference (Kimura and Zissler 2016). In addition, cost analysis using actual data showed that the top 0.1% of companies could offer solar PV systems at less than 60% of the national average cost (Agency for Natural Resources and Energy 2018). Thus, there is an opportunity to converge the cost to the international price by encouraging price competition through the auction system, for example.

Second, it would be important to promote non-RE low-carbon generators to complement REs. The results of the policy sensitivity analysis showed that it is necessary to reduce CO₂ emissions from the power sector to almost zero or negative to achieve or intensify the mid-century target. The results also showed that non-RE low-carbon generators compensate for remaining electricity demand not supplied by RE—although there is no consensus regarding promising technology among fossil power plants with CCS, hydrogen, and nuclear power. This result is consistent with findings from studies using a single power dispatch model and a single energy system model (Matsuo et al. 2018; Kato and Kurosawa 2019). The common view among the models is that there will be almost no room for the operation of fossil power plants without CCS in 2050. It would be better to identify and promote promising non-RE low-carbon generators.

Indeed, some of these policy implications have been discussed in the existing studies, which employed single energy

system models. A major point of our study is that our policy implications are derived from the results of a multi model comparison study and thus have robustness. Future steps of multi model comparison study described in the previous section would expand and provide more robust findings.

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