Modeling Potential Installation of Solar and Wind Energy Considering Cannibalization Effect

Hideaki Obane*, Seiya Endo*, Yuji Matsuo**,*, Toru Genkai***, Yoshiteru Nagao***

Abstract
Increasing variable renewable energies with zero marginal cost cause the decline of wholesale electricity prices and undermine their own value by "cannibalization effect". While capital costs of renewable energies are expected to decline, their income is also to decrease because of declined wholesale electricity prices. This study integrated GIS (geographic information system) model that assesses business feasibility into an optimal power generation mix model that assess wholesale electricity prices. By developing an integrated model, it is possible to assess potential installation capacity of solar and wind energy by considering both economic rationality and land use restrictions. In the case of Japan, this study revealed that increasing solar and wind energies cause the significant decline of wholesale electricity prices in specific electric network area such as Hokkaido. Even if capital costs of these energies decrease through learning effect, economic potential of installed renewable capacities is significantly limited if business feasibility is considered. Thus, the decline of electricity prices by cannibalization effect can seriously stagnate installation of both solar and wind energies. This study implies that further cost reduction faster than previous trend is needed to realize "subsidy-free" energy sources.

Key words: Renewable energy, Solar energy, Wind energy, Energy model, Cannibalization effect

1. Introduction

Photovoltaic systems (PV systems) and wind energy systems are expected to a large-scale reduction of greenhouse gases. When examining future measures for the utilization of PV and wind energy systems, it is important to assess the installation potential of each system after considering such factors as economic rationality and land use restrictions.

Up to now, the Feed-in Tariff (FIT) has been introduced in Japan in July 2012. From April 2022, it will shift to Feed-in Premium (FIP), which adds a certain premium to wholesale electricity prices. Accordingly, the business potential of PV and wind energy systems in the future will be influenced by wholesale electricity prices that fluctuate depending on time and power generation mix.

On the other hand, previous studies [1)-4)] have shown that when large-scale PV and wind energy systems are installed occurs the "cannibalism effect", that the more power is generated by these systems, the lower the wholesale electricity price is during the time zone and the value of its own kWh. In the initial stage of the introduction of PV systems, it contributes a certain amount to reduce power demand peak and has the effect of reducing fuel costs such as gas-fired power generation with high fuel cost. However, as PV systems significantly increase, it replaces coal-fired power generation where fuel costs are low; thus, the effect of reducing fuel costs becomes smaller. Therefore, in order to assess the installation potential of PV and wind energy systems considering economic rationality over the long term toward 2050, it is important to consider the impacts of this "cannibalism effect."

Previously, there have been a number of studies that assess the economic potential of PV and wind energy systems considering economic rationality[5)-8)]. As an example, in a study in the United States[5)], the economic potential at each point is assessed from the difference between the levelized cost of electricity (LCOE) of each power supply and the levelized avoided cost of electricity (LACE) by using geographic information (GIS) system. In addition, the research of MacDougall et al.[9)] assesses the internal rate of return (IRR) according to the level of policy support by using GIS.

In Japan, several studies have assessed the economic rationality of renewable energy under the scenario of a certain selling price for a specific year[10)-12)]. For example, a report by the Japanese Ministry of the Environment[10)] assessed the economic potential of renewable energy using the premise that generated electricity is sold at a fixed price by FIT. Additionally, study assessing the potential of PV systems considering the distance from transmission line affecting the initial investment[13)] and study on the economic assessment of the installation of PV systems for residential use under the FIT have also been carried out[14)].

Like this, studies on the assessment of installation potential considering the economic rationality of PV and wind energy

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systems have been abundantly carried out. However, detailed research considering the influence of the cannibalism effect has not been conducted. In Japan, since the current FIT will shift to sales based on wholesale electricity prices, it is more important to consider the effects of cannibalism in chronological order in assessing the potential installation capacity of each power supply.

Following this fact, in order to solve such problems, this study aims to examine the potential assessment model of PV and wind energy systems considering the cannibalism effect by integrating the power generation mix model and the GIS model that spatially assess the economic rationality of each location. By using this model, it is possible to reflect the impacts of the wholesale electricity price decrease in the mass introduction of each power supply, and to assess the installation potential of PV and wind energy systems by considering economic rationality more clearly.

2. Potential Assessment Model

2.1 Overview

The potential assessment model proposed in this study is a model that integrates a power generation mix model, which outputs wholesale electricity prices every 8,760 hours using input values such as the amount of introduction of each power supply and the installed capacity, and a GIS model, which spatially assesses the IRR for each 100-500 m grid mesh using the wholesale electricity price and the capital cost of each power supply as input values (Fig. 1).

In this model, when the installed capacity of PV and wind energy systems in a specific year is given as an initial value, the wholesale electricity price for every 8,760 hours is output first by the power generation mix model. Then, the GIS assessment model outputs the installed capacity that satisfies the specified IRR using wholesale electricity prices as input values. The installed capacity obtained by considering a constant introduction rate in this installed capacity is again the input value of the power generation mix model. In this model, by performing the loop calculation every year, it is possible to assess the transition of wholesale electricity prices over the medium to long term and the transition of the installed capacity of PV and wind energy systems that satisfy economic rationality.

As the introduction of PV and wind energy systems progresses, the value of kWh during the time zone when each power supply is generating power decreases due to the cannibalism effect, but when electricity is sold through the wholesale electricity market, the IRR by the power generation business of each power supply contributes toward the decrease. On the other hand, if the capital cost decreases due to the learning effect of the power generation facility, it will contribute to the increase of IRR. In this model, considering these mutual effects, it is possible to assess the effect of the large-scale introduction of each power supply more clearly.

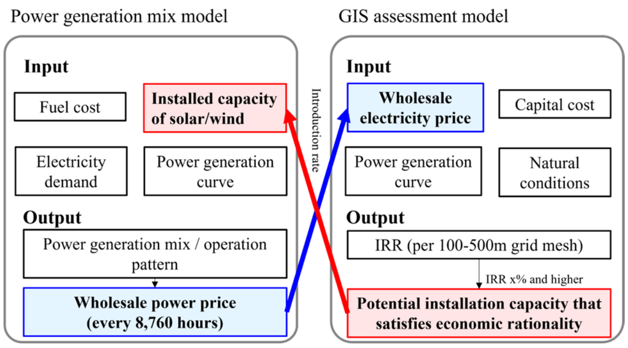


Fig. 1 Overview of Potential Assessment Model

2.2 Power Generation Mix Model

The power generation mix model used in this study was originally developed by the FUJII-KOMIYAMA Laboratory[15)] and improved by Komiyama et al. (2014)[16)], Komiyama et al. (2017)[17)], Matsuo et al. (2018)[18)], Nagatomi et al.[19)], and Matsuo et al. (2020)[20)]. This model outputs wholesale electricity prices and operation patterns of each power supply every 8,760 hours when the sum of capital cost and variable cost of the entire power system is minimized using the input value such as the installed capacity and fuel cost of each power generation facility. The objective function is obtained by equation (1).

$$min.TC = \sum_i \left(g_i \cdot pf_i \cdot K_i + \sum_{d,t} pv_i \cdot X_{i,d,t} \right) + \sum_j CS_j \quad (1)$$

$$CS_j = gs1_j \cdot pfs1_j \cdot KS1_j + gs2_j \cdot pfs2_j \cdot KS2_j + pfs3_j \frac{TCha_j}{cycle_j} \quad (2)$$

$$TCha_j = \sum_{d,t} Cha_{j,d,t} \quad (3)$$

Where, g_i: annual fixed cost factor of generator i, initial investment cost of generator i pf_i, K_i: generator i rated output [GW], generator i variable cost pv_i, $X_{i,d,t}$: generator i day d, output in time t [GW], $gs1_j$: fixed cost factor per output of storage battery j, $pfs1_j$: initial investment cost per output of storage battery j [JPY/GWh], $Ks1_j$: Rated output of storage [GW], $gs2$: fixed cost coefficient per storage capacity of storage battery j, $pfs2_j$: initial investment cost per storage capacity of storage battery j [JPY/GWh], $Ks2_j$: Rated storage capacity [GWh], $pfs3_j$: external cost associated with deterioration of storage battery [JPY], *cycle*: maximum number of charging and discharging of storage batteries, *Cha*: power charged to storage batteries [GW].

As constraints, power supply and demand constraints at each time, spare power constraints, and balance constraints of energy storage facilities are given. This study describe a linear planning problem by pyomo, a library of Python, and obtained a solution by operating Xpress, which is a solver.

The target areas of the power generation mix model were the 10 areas of Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu, and Okinawa, which are under the authority of general transmission and distribution business operators. Each area is connected by interconnection lines, and it is assumed that the interconnection lines are enhanced based on "power supply uneven distribution scenario (30 GW) of the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) [21]. In addition, the wholesale electricity price in each area was treated as a shadow price of the supply-demand balance constraint type of each area obtained as the optimal solution of the dual problem. Although there is no wholesale electricity market in the Okinawa area, it was treated as electricity sales based on the potential price.

The power generation amount of PV and wind energy systems was calculated in advance using a normalized power generation pattern based on the data of the regional meteorological observation system (AMeDAS) in each area and a value of 8,760 hours based on the installed capacity for each area. In practice, while the power generation pattern of each power supply changes gradually by the installation of power generation facilities in various places, the power generation pattern is constant in this model for simplicity.

2.3 GIS Assessment Model

The GIS assessment model outputs the IRR for each mesh by inputting capital cost of power generation facilities and wholesale electricity price based on mesh information related to land use and sea area use. By applying a certain lower limit to this IRR, the installed capacity of the power generation facility which satisfies economic rationality is obtained. In this model, as in previous studies [24)-26)], the territory of Japan was divided into 100 m mesh and the territorial waters of Japan were divided into 500 m grid mesh using ArcGIS, and various data related to land and sea area use were stored in each mesh. Based on this developed data, this study extracted the places where PV and wind energy systems can be physically installed in advance, and calculated the IRR at each point from data such as sunlight and wind speed.

IRR is given by r in equation (4) and is determined by the initial investment amount CI [JPY] and annual cash flow CF_t [JPY]. The initial investment is mainly equivalent to the capital cost of the power generation facility in the year installed. In addition, the cash flow is determined by the sales revenue dependent on the power generation amount E_i [kWh] and the wholesale electricity price W_i [JPY /kWh], the premium FIT price which is the difference between FIP_{base} [JPY/kWh] and the FIP reference price FIP_{ref} [JPY/kWh], and the annual maintenance cost OM [JPY/kWh], and is shown in equation (5).

$$\sum_{t=1}^{30} \frac{CF_t}{(1+r)^t} - CI = 0 \tag{4}$$

$$CF_t = \sum_{i=1}^{8760} \left(E_i \cdot W_i + E_i\left(FIP_{base} - FIP_{ref} \right) \right) - OM \tag{5}$$

3. Assumptions

3.1 Target years and Power Sources

The forecast of cumulative introduction of PV and wind energy systems by 2030 was indicated at the Basic Policy Subcommittee (April 13, 2020)[22)], based on the lead time of construction and the implementation status of environmental assessments. Therefore, in this study, 2030 was the starting point of the assessment, and the target period of this assessment spanned until 2050.

In this study, the three types of power supplies were ground-based PV systems, onshore wind energy systems, and offshore wind energy systems. Since it is considered that the introduction incentives for building-based PV systems are considered to affect the introduction incentives such as self-consumption and mandatory installation of PV systems, this study excludes their assessment.

Referencing the installation capacity forecast indicated by the Basic Policy Subcommittee[22)], the initial value of the installation capacity of each power supply in 2030 was 41.6 GW for ground-based solar power, 15.3 GW for onshore wind power, 3.7 GW of fixed-type offshore wind power, 0.02 GW for floating offshore wind power, 19.3 for building-based solar power (detached houses) and 26.7 GW for building-based solar power (non-detached houses). The amount of introduction by grid area in 2030 was estimated by estimating the installed capacity certified by FIT as of June 2021 and the equipment capacity of the project in which the environmental assessment consideration and method documents were submitted by grid area and prorated from the total introduction volume forecast for all areas in 2030 (Fig. 2).

For building-based PV systems, the installation capacity is assumed to be advanced by self-consumption and mandatory installation of PV systems, and the installation capacity was given exogenically in the model. In this study, referencing the "social acceptability-oriented scenario" of the Central Research Institute of Electric Power Industry[23], the cumulative installation capacity in 2050 reached 45 GW of PV systems installed in detached houses and 62 GW of PV systems installed in non-detached houses.

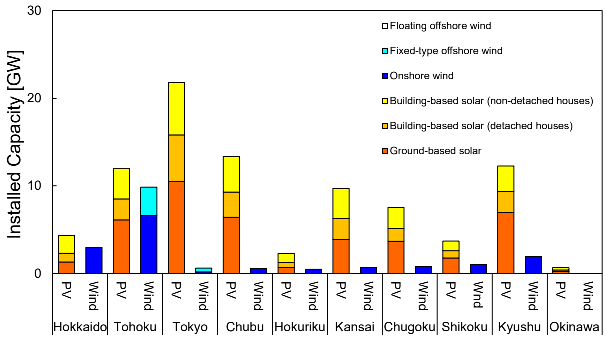


Fig. 2 Assumption of installed capacity by grid Area in 2030 [GW]

3.2 Correlation between Natural Conditions and Installed Capacity

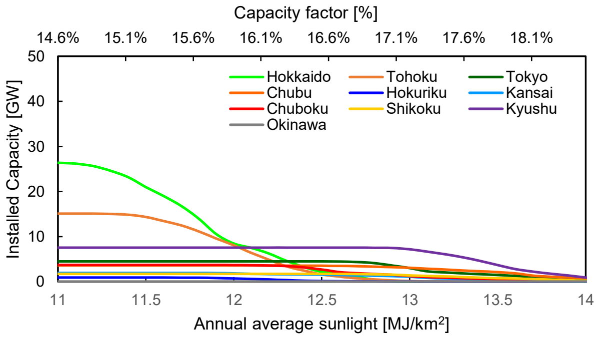
Referencing bane et al.[24), 25)], the site of ground-based PV systems and onshore wind energy systems were installed in places excluding natural parks, natural environmental conservation areas, and bird and animal sanctuaries (normal and special protection) among the four types of land categories: grassland, shinochi (bamboo grove), bare land, and difficult-to-regenerate degraded farmland, taking into account the land use competition and natural environment effects of each power source. Based on this approach, the Japanese contiguous land was divided into 100 m grid meshes, and the available area was estimated to be 3,321 km^2 when the in available area was extracted using the latest GIS data obtained as of April 2021. In addition, since it is assumed that land use competition will occur between ground-based PV systems and onshore wind power system when large-scale introduction of PV and wind energy systems is assumed, ground-based PV systems will be installed at a place with an average wind speed of less than 5.0 m/s per year (980 km^2) and onshore wind power at a location with an average wind speed of 5.0 m/s or more (2,341 km^2). In these places, up to 65.7 GW of ground-based PV systems and 23.4 GW of onshore wind power were assumed able to be installed.

Referencing the Moderate conflict scenario of Obane et al.[26)] considering legal restrictions and social acceptability, the site of offshore wind power was assumed to be 5.0 - 22.2 km (in territorial waters), among sea areas that meet the designated requirements of "promotion zone" stipulated by the Act of Promoting Utilization of Sea Areas in Development of Power Generation Facilities Using Maritime Renewable Energy Resources where the traffic volume of ships equipped with automatic ship identification system is less than 21 ships/month, and sea areas that satisfy all the sea areas where fishery rights are not set. Following the study, when the sea area was extracted using the latest GIS data as of April 2021, the area was estimated to be 28,865 km^2. Of these, if fixed-type offshore wind power is installed in sea areas (5,137 km^2) with a depth of less than 60 m and floating offshore wind power in sea areas from 60 m to less than 200 m (23,728 km^2), the maximum installed capacity of fixed-type offshore wind power would be 30.8 GW and floating offshore wind force 142.3 GW.

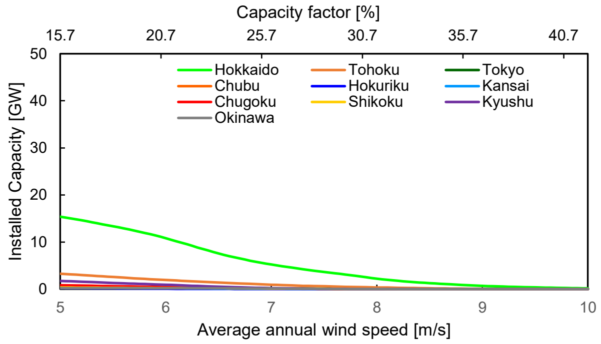
Fig. 3 shows the relationship between natural conditions and equipment capacity in each power area based on the above assumptions. The facility utilization rate is simply converted from the average annual wind speed and the average annual sunlight, as in each study[24)-26)], and it is assumed that overloading is performed for ground-based PV systems.

From Fig. 3(A) and (B), the available of ground-based PV systems and onshore wind power is mainly concentrated in the Hokkaido area. Since the wind conditions in the Hokkaido area are also better than the other areas, onshore wind power will be introduced preferentially with the decrease in capital costs of power generation facilities. On the other hand, since the irradiance in the Hokkaido area is lower than the other areas, ground-based PV systems will be introduced later when compared with other areas.

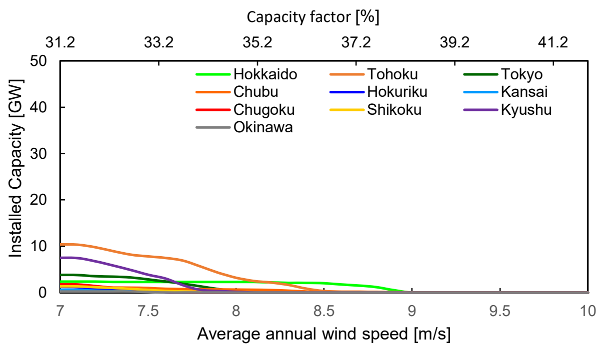
For fixed-type offshore wind and floating offshore wind power shown in Figures 3(C) and (D), there are many installation sites in Tohoku and Kyushu area. In particular, since the wind conditions are better in Tohoku, offshore wind power will be introduced preferentially.



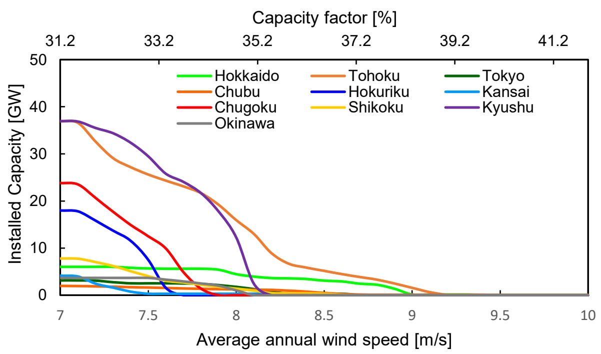
(A) Ground-based PV systems



(B) Onshore wind power



(C) Fixed-type offshore wind power



(D) Floating offshore wind power

Fig. 3 Correlation between Natural Conditions and Installed Capacity

3.3 Assumptions on Capital Costs and Required IRR

Assumptions such as capital costs and necessary IRRs in this study were based on actual or assumed values shown by the Procurement Price Calculation Committee[27]. Table 1 shows the preconditions related to these assumptions and the transition of capital expenses assumed in Figure 4 until 2050.

The capital cost is the sum of equipment cost, connection cost, and operation maintenance cost (O&M cost), and the equipment cost is assumed to decrease the cost based on the learning curve. In addition, the learning rate applied the value corresponding to the middle of the estimated value range shown in each literature[28], and the installation capacity used in the estimation of the learning curve was the assumed installation capacity of the entire world until 2050 in the Stated Energy Policies Scenario (STEPS) of IEA WEO 2020[29].

The actual value of equipment cost in FY2019 is the average value of the equipment for PV systems of 250-500 kW (204,000 JPY/kW) shown by the Procurement Price Calculation Committee, the estimated value of the equipment cost of onshore wind power in the FIT purchase price calculation (269,000 JPY/kW), and the estimated cost of offshore wind energy systems equipment (512,000 JPY/kW) in the "promotion area." Referencing Stehly et al.[30] for floating offshore wind power, it was assumed that the capital cost was 1.3 times larger than fixed-type offshore wind power, and the learning rate was the same as the fixed-type offshore wind power. In this study, all prices were treated as real prices in 2019.

The IRR required for each power supply to obtain economic rationality was 5% for ground-based PV systems, 7% for onshore wind power, 10% for fixed-type offshore wind power, and 10% for floating offshore wind power, referring to the Procurement Price Calculation Committee [27].

Table 1 Assumptions on Capital Cost and Required IRR

	Ground-based solar	Onshore wind	Offshore wind (fixed)	Offshore wind (floating)
Equipment cost (2019) [JPY/kW]	204,000	269,000	512,000	665,600
Connection cost [JPY/kW]	9,100	13,000		
O&M cost [JPY/kW]	4,900	9,300	18,400	18,400
Learning rate (equipment cost)	15%	7%	10%	10%
Required IRR	5%	7%	10%	10%

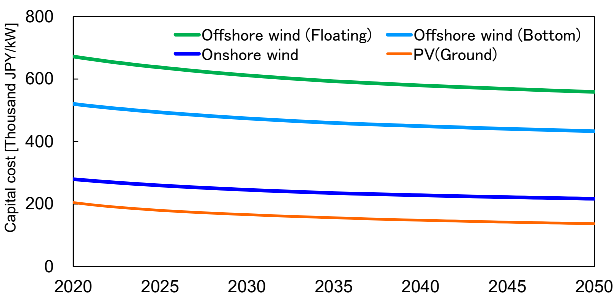


Fig. 4 Assumptions on Capital Cost [Thousand JPY/kW]

3.4 Assumptions on Thermal Power, Nuclear Power and Electricity Demand

The installed capacity of coal-fired power generation and gas-fired power generation in the power generation mix model is based on the capacity of existing equipment remaining in 2050 when operating for 40 years, and the lower limit was coal-fired power at 13.7 GW and gas-fired power generation at 24.7 GW. For nuclear power generation, 30.6 GW is set as a fixed value referring to the technical progress scenario of IEEJ Outlook 2021[31).

The coal and LNG prices used in thermal power generation referenced STEPS (2040) of IEA WEO 2020[29)], making coal: 77 USD2019/t and LNG: 9 USD2019/MMBtu. CO2 emissions were considered at carbon prices, and 52 USD2019/t-CO2 of STEPS (2040) was used.

The annual electricity demand in the power generation mix model was 1,027 TWh, which deducted the loss factor of plant-home use of 3.5% from the amount of power generated in 2030 in the long-term energy supply and demand outlook. Although fuel prices, carbon prices, and electricity demand fluctuate year by year, in this study, these were constant regardless of time, in order to clearly assess the decrease in capital costs of solar and wind energy systems and the decrease in electricity sales revenue due to the decrease in wholesale electricity prices.

3.5 Assumptions on FIP

In Japan, FIP will be introduced to be used to sell electricity generated by renewable energy by increasing the power price by adding a certain premium to the wholesale electricity price. Therefore, in this study, four types of cases were assumed for the FIP premium price determined by the difference between the FIP standard price and the FIP reference price (Table 2).

First, referencing the difference between current FIT purchase price and avoidable cost (assumed to be 8 JPY / kWh) as of 2021, the FIP premium price was 3 JPY /kWh for ground-based PV systems/ kWh, 9 JPY /kWh for onshore wind power, landing type offshore wind force 24 JPY/kWh for fixed-type offshore wind power, and 28 JPY / kWh for floating offshore wind power. This was set as the "(1) current FIT level case."

Second, these premium prices were set to 2/3 as "(2) 2/3 level case," and the same price was set to 1/2 in the "(3) 1/2 level case." In addition, assuming that each power supply will become a "subsidy-free power supply" that does not depend on the subsidy system in the future, the premium price of each power supply was set as 0 JPY / kWh in "(4) case without FIP."

It should be noted that in Japan, since offshore wind power is in the initial introduction stage, the assumed premium price of offshore wind power is significantly higher than PV systems and onshore wind power.

Table 2 Assumption of FIP Premium Prices (JPY/kWh)

	Ground-based PV	Onshore wind	Fixed-type offshore wind	Floating offshore wind
Current FIT Level	3	9	24	28
2/3 level	2	6	16	18
1/2 level	1.5	4.5	12	14
Without FIP	0	0	0	0

4. Results and discussion

4.1 Single Year Assessment Targeting 2030

Fig.5 shows the evaluated wholesale electricity price of each power area by the power generation mix model for 2030, the first year of the assessment. Since PV and wind energy systems are variable power sources, weights are given to wholesale electricity prices that fluctuate at each time by the amount of power generated at each hour, and the weighted average wholesale electricity price for one year is calculated.

As the result, it was shown that the weighted average wholesale electricity price tended to be comparatively lower in the Hokkaido area and Kyushu area out of 10 electric grid areas. One of the factors contributing to this is that the ratio of power generation by PV and wind energy systems is high compared to the electricity demand in these power areas. In particular, in the Kyushu area, 13 GW of PV systems will be introduced as of 2030. Hence, the wholesale electricity price in the daytime time zone, when PV systems are generated, will be particularly low.

Then, by inputting the wholesale electricity price of each power area and using the GIS assessment model, the potential installation capacity (hereinafter referred to as the installed capacity that satisfies economic rationality) of the power generation facility that satisfies the specified IRR was assessed for 2030 (Fig. 6). In the figure, the far right bar graph (gray) shows the technical potential determined only by the land use restrictions assumed in Section 3.2, and does not take economic rationality into account. In addition, the bar graph on far left (gray dashed line) shows the installation capacity as of 2030 assumed in Section 3.1. Since the installation capacity as of 2030 includes much equipment introduced under the high FIT price at the beginning of FIT introduction, the installation capacity is more than in the case where the subsidy by FIP is assumed to be the current level.

For ground-based PV systems, if the premium price of FIP is maintained at the current subsidy level of 3 JPY/kWh, the potential installation capacity that satisfies economic rationality will be 6.5 GW. Until now, under the FIT purchase price of 11 JPY/kWh (equivalent to the subsidy level of 3 JPY/kWh), certain PV systems have been certified by FIT auction. However, if the wholesale electricity price decreases in the future, economic rationality will not be obtained in many places except in those where sunlight conditions are enough.

For offshore wind power, on the other hand, when the premium price of FIP is maintained at 24 JPY/kWh (Bottom-fixed) and 28 JPY /kWh (floating), which corresponds to the current subsidy level, the installed capacity that satisfies economic rationality is equal to the maximum installation capacity determined by land use restrictions. However, this is because the supplementary level of FIT in 2020 is set high, and there is no guarantee that the same level will be maintained even after 2030. When the FIP premium price is 12 JPY/kWh (Bottom-fixed) and 14 JPY/kWh (floating), which is half of the current subsidy level, there are few facilities that satisfy economic rationality. Therefore, in order to install offshore wind power without subsidy in Japan, it is necessary to significantly reduce the cost.

In addition, when there is no subsidy in all power supplies, the potential installation capacity that satisfies economic rationality is almost zero under the assumed various conditions. Therefore, this indicates that it is difficult to achieve “subsidy-free” when cost reduction advances based on the learning rate estimated from the previous trends.

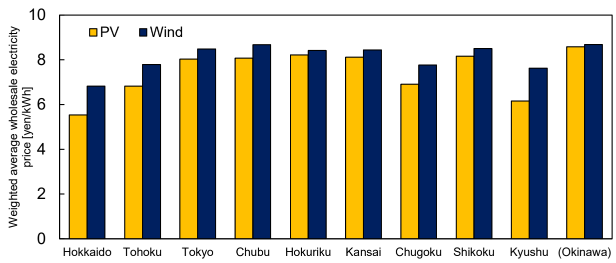


Fig. 5 Weighted Average Wholesale Electricity Price in 2030 (Shadow price for Okinawa area) [JPY/kWh]

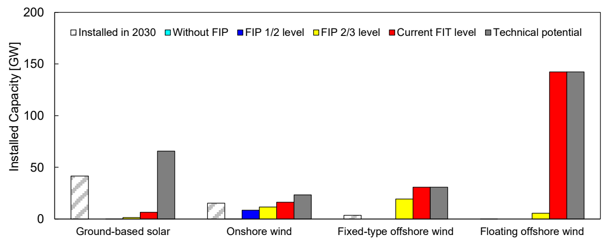


Fig. 6 Potential Installation Capacity that Satisfy Economic Rationality based on FIP Premium Price in 2030 [GW]

4.2 Time-series Assessment to 2050

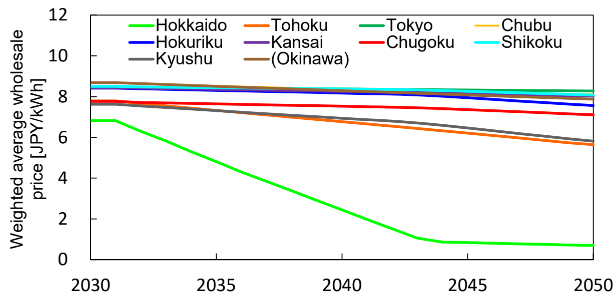
The assessment for 2030 showed that it was difficult to introduce PV or wind energy systems without subsidies such as FIP. Therefore, assuming that support by FIP will continue after 2030 for the expansion of PV and wind energy systems, under the assumption that the FIP premium price corresponding to 2/3 of the current subsidy level is set, the transition of the potential installation capacity that satisfies economic rationality by 2050 was assessed. The premium unit price of FIP assumed here is 2

JPY/kWh for ground-based PV systems, 6 JPY/kWh for onshore wind power, 16 JPY/kWh for fixed-type offshore wind power, and 18 JPY/kWh for floating offshore wind power. In particular, it should be noted that a significantly high FIP premium unit price is set here for offshore wind power.

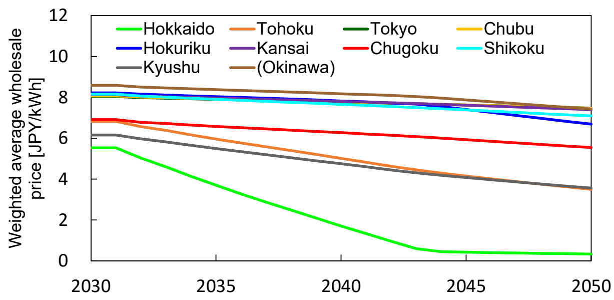
When focusing on onshore wind power, wholesale electricity prices in the Hokkaido area where electricity demand is low gradually decrease because onshore wind power is introduced mainly from the Hokkaido area (Fig. 7 [A]). As a result, the installed capacity of onshore wind and fixed-type offshore wind that satisfies economic rationality also decreases because electricity sales revenue also decreases (Fig. 8 [A]). In other words, under the conditions assumed in this study, economic rationality cannot be obtained after a specific year because the influence of the decrease in electricity sales revenue caused by the decrease in wholesale electricity prices exceeds the decrease in capital costs of onshore wind energy systems. Here, focusing on the relationship between potential installation capacity and cumulative installed capacity in the Hokkaido area (Fig. 9), it has been shown that the introduction of onshore wind power will stagnate after 2035, since the cumulative installation capacity reaches the installed capacity that satisfies economic rationality in 2035.

From the potential installation capacity (Fig. 8 [B]) which satisfies economic rationality nationwide, the capacity of the onshore wind power decreases with the passage of time. As shown earlier, this is mainly due to the decrease in wholesale electricity prices in the Hokkaido area.

On the other hand, for ground-based PV systems and floating offshore wind power, the installed capacity that satisfies economic rationality tended to increase because the influence of the decrease in capital costs was greater than the decrease in electricity sales revenue due to the decrease in wholesale electricity prices. However, although potential installation capacity will increase due to the decrease in capital costs, the growth of the increase will plateau around 2040. Although The technical potential of ground-based PV systems considering only land use restrictions was 65.7 GW, the potential installation capacity that satisfies economic rationality remains at 14.6 GW in 2050. This is due to the fact that many of the places to be installed ground-based PV systems are in the Hokkaido area where irradiance is poor and wholesale electricity prices are decreasing. Hence, almost all PV systems do not satisfy economic rationality.

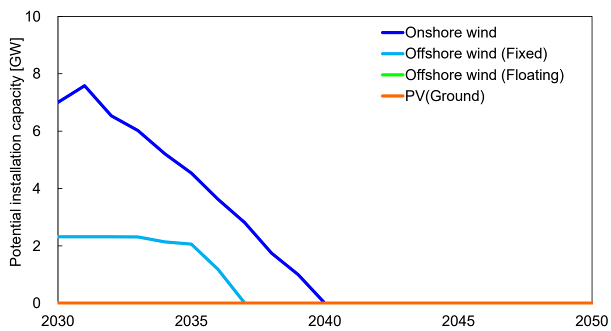


(A) PV systems

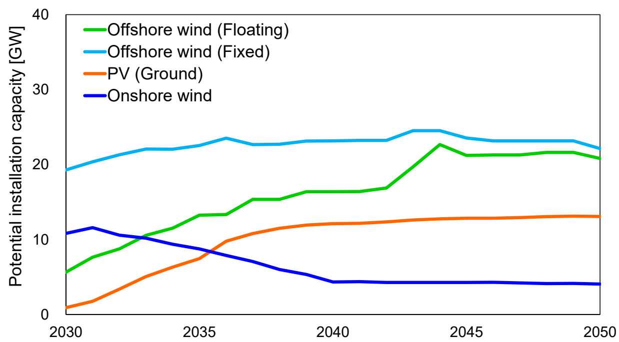


(B) Wind energy systems

Fig. 7 Weighted Average Wholesale Electricity Price up to 2050 [GW] (FIP premium price: 2/3 current level case)



(A) Hokkaido area



(B) Nationwide

Fig. 8 Installed Capacity that Satisfies Economic Rationality [GW] (FIP premium price: 2/3 current subsidy level case)

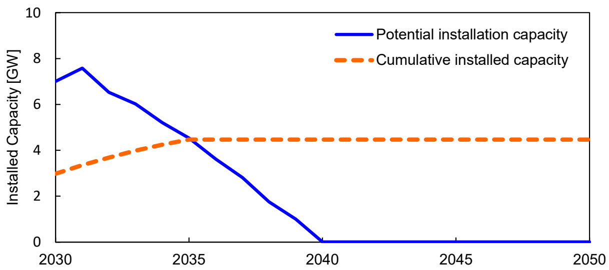


Fig. 9 Correlation of Potential installation capacity and Cumulative Installed capacity of Onshore Wind Power in the Hokkaido Area [GW]

4.3 Single Year Assessment for 2050

Focusing on 2050, the last year of the assessment period, this study assessed potential installation capacity that satisfies economic rationality according to the FIP premium price as in Section 4.1 (Fig. 10).

Focusing on the potential installation capacity of ground-based PV and onshore wind power, the result showed that the potential installation capacity of the case where the same level was raised to 2/3 was slightly lower than the case where the FIP premium price was set to 1/2 of the current level. This is because in the current level of 2/3 cases, the wholesale electricity price decreases due to the priority introduction of offshore wind power, and the electricity sales revenue of ground-based PV systems and onshore wind energy systems decreases. Following this, when a specific power plant is intensively introduced, it may have a large influence on the economic rationality of other power sources.

Focusing on the case without any subsidies for each power supply, even if the capital cost decreases toward 2050, the potential installation capacity that satisfies economic rationality was limited. Here, even if the FIP premium price was raised to 2/3 of the subsidy level of the current FIT, the potential installation capacity did not increase significantly compared with 2030 because the influence of the decrease in electricity sales revenue due to the decrease in wholesale electricity prices is large. Following this, in order to promote the expansion of PV and wind energy systems by 2050, it is necessary to reduce costs at a pace that greatly exceeds the previous learning effect.

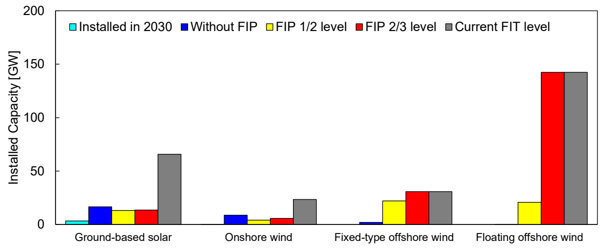


Fig. 10 Potential installation capacity that Satisfy Economic Rationality based on FIP Premium Price in 2050 [GW]

5. Conclusion

This study examined the potential assessment model of PV and wind energy systems considering the cannibalism effect by integrating the power generation mix model and GIS model which spatially assess the economic rationality of each location. As the result, it was shown that the decrease of the wholesale electricity price by the expanded introduction of PV and wind energy systems was assessed in chronological order, and the effect on the economic rationality of each power supply could be quantitatively assessed.

Issues posed by this model include consideration of capital cost of power generation facilities different by geographical factors such as water depth and consideration of the influence of self-consumption. Especially in the case of self-consumption, even during times when wholesale electricity prices are decreasing, the power purchased by retail electricity charges can be offset with power generated by PV or the other systems. Thus, considering the power of this offset, the substantial business income of the power generation business may increase. It is expected that more practical assessments will be carried out on these issues in future improvements.

In the previous model for assessing the economic potential of PV and wind energy systems, the sale of electricity at a fixed price by FIT was assumed. However, when electricity is sold based on wholesale electricity prices in the future, the potential installation capacity that satisfies economic rationality is limited, suggesting the possibility that the introduction may be sluggish. In order for PV and wind energy systems to become subsidy-free power sources, it is necessary to reduce costs at a pace that greatly exceeds the previous learning effects.

The potential assessment model examined in this study is effective for the assessment of the economic rationality of PV and wind energy systems from a medium- to long-term viewpoint, and it is expected to contribute to the examination of the policy making for the expansion of PV and wind energy systems in the future.

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