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Regional Spatial Analysis of the Offshore Wind Potential in Japan

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Abstract: This study presents an approach for estimating the offshore wind potential of Japan. Bathymetry data (1 km mesh) and near shore wind speed data of the year 2018 were used to assess the potential. A turbine with a peak power of 10.6 MW was employed for the analysis. The potential was calculated for multiple regions. These regions are based on the service areas of the major electricity supply companies in Japan. Overall, the results show that Japan has the potential to produce up to 32,028 PJ electricity per year. The electricity demand of 2018 amounts to 3231 PJ. The potential is therefore large enough to cover Japan's electricity needs ten-times over. The capacity that could theoretically be installed amounts to 2720 GW, which is a multiple of the current worldwide installed capacity of 29.1 GW (2019). In addition to the huge potential, the regional assessment shows that the regions vary greatly in their potential; of all the considered regions, Hokkaido and Kyushu have the highest overall potential.

Keywords: offshore wind; Japan; offshore wind potential; regional analysis

1. Introduction

In this work, the Japanese offshore wind potential will be assessed. To date, only a limited number of studies have been conducted to estimate the offshore wind potential in Japan. A detailed study estimating the potential for all of Japan was published in 2002 [1]. In the study, a turbine capacity of 3.0 MW was used to calculate the potential. Furthermore, the study assumed that 50% of the total area was comprised of restricted zones. In the investigation, the offshore wind potential was estimated to be 708 TWh (or 2549 PJ) per year [1]. A study from 2014 assessed the offshore wind energy potential for the Kanto coastline [2]. In this study, a turbine with a 2.4 MW output was used for the calculation. The assumed foundations were fixed-bottom structures for depths of up to 20 m and floating structures for depths of up to 200 m. The potential for the Kanto coastline without any restrictions was calculated to be 287 TWh per year [2]. Due to technological advancements in the offshore wind sector, the assumptions made in both studies are not suitable for the state of the art in the offshore wind industry. While the first study evaluated the entire offshore wind potential of Japan, only the average wind speeds were used. Therefore, due to the intermittency of wind speeds, the potential was underestimated, as the power output increased exponentially until the rated power was reached. In the second study, only a small part of Japan was considered. The present study will provide a more accurate assessment of the total current offshore wind potential due to the consideration of technological changes, i.e., larger turbines with lower rated speeds, a higher power output, and better available data on nearshore wind resources.

To date, there are no large offshore wind farms in Japan, apart from a few pilot projects. This is influenced by several factors. First, it must be noted that the technology originated in Europe, more specifically, in Denmark. Additionally, the technology is still relatively young, with the first offshore wind farm having been installed in 1992 [3]. This, together with various other factors in Europe (i.e., a high population density, shallow water in the North Sea, and high greenhouse gas emission reduction targets), has led to the fact that most offshore wind farms are installed in Europe. Many of the technological advancements for offshore wind still originate in Europe. With decreasing costs and more know-how for solving engineering challenges (e.g., earthquakes and higher wave heights), more countries, including Japan, are getting involved in offshore wind [4]. A major factor influencing the offshore wind development in Japan is the Fukushima nuclear accident of 2011, which heavily influenced the country's energy policy. Before the accident, The Japanese Ministry of Economy, Trade and Industry's (METI's) energy policy was focused on the development of nuclear energy. Afterwards, renewable energy became a much bigger part of the energy policy [5]. To date, the long-term goal of the Japanese government, as stated in the Strategic Energy Plan, is to reduce greenhouse gas (GHG) emissions by 80% by 2050. Therefore, renewable energy technologies will gain an important role in the future energy sector in Japan [6]. Offshore wind technology is considered a possible renewable energy source. The Japanese Ministry of Economy, Trade and Industry (METI) has announced eleven sea areas from five prefectures which have been designated as offshore wind areas. For four of these areas, wind measurement and geological surveys will be carried out immediately [7].

The leading countries of the offshore wind market are all located in Europe, with China as the only exception. In Denmark the share of the offshore wind electricity supply is nearly 16%. In the United Kingdom, it is around 8% [4]. With the Offshore Wind Sector Deal, published by the Department for Business, Energy and Industrial Strategy, the United Kingdom aims to increase their offshore wind capacity by more than threefold to 30 GW before 2030 [8]. Based on these countries, it can be concluded that offshore wind can, in countries with good wind resources, play a major role in the currently ongoing worldwide energy transition to renewable energy.

Due to Japan's steep coast lines, especially compared to European waters, most of the potential can only be reached with floating wind turbines and not via fixed-bottom structures. Nevertheless, because of its position as an island nation with long coastlines, it can be expected that the offshore wind potential in Japan is high. Compared to the United Kingdom, Japan has more than double the coastline, which is one of the main factors for the total potential.

In this study, the offshore wind potential is evaluated under the assumption that fixed-bottom structures are suitable for depths of up to 50 m and floating structures up to 200 m. Japan is divided into several areas, which are selected based on the power supply area of the power companies (except for Okinawa Electric Power Company). For each of these regions, the total potential will be determined. Additionally, the number of turbines needed to fulfill the 2050 goal will be calculated based on different scenarios. The regions will be regarded as separate, decentralized systems.

1.1. *Offshore Wind Status*

This section provides a short overview of the current offshore wind status and developments, both worldwide and in Japan. The information on the current offshore wind status worldwide is mostly based on the new Offshore Wind Outlook 2019, published by the International Energy Agency (IEA) [4].

1.1.1. Worldwide

Currently, offshore wind electricity generation only accounts for 0.3% of the global electricity generation. While the market is still relatively small, it grew by around 30% from 2010 to 2018. Globally, around 29.1 GW is installed, of which 80% is installed in Europe, where the technology for offshore wind originated [9]. The total number of installed grid-connected offshore turbines is around 5500 in 17 different countries (as of 2019). The leaders of offshore wind in Europe are the United Kingdom, Germany, and Denmark. One of the main reasons for the prevalence of offshore wind in Europe is the relatively shallow waters, combined with high quality wind resources in the North Sea. The only other region with a noteworthy offshore wind capacity is China. In Europe, around 1.8% of the total electricity consumption is covered by offshore wind. While this number is relatively low, it has to be noted that in countries like Denmark, the United Kingdom, and Germany, offshore wind provides 15%, 8%, and 3% of the total electricity generation, respectively [4]. In countries where offshore wind is currently deployed, the technology is projected to play a key role in the ongoing transition to renewable energy [4].

Figure 1 shows a comparison of major offshore wind-deploying countries [10]. The United Kingdom, Germany, China, and Denmark have the highest installed capacities worldwide. The figure shows the share of offshore wind capacity in the total amount of installed renewable capacity. It can be concluded that the United Kingdom and Denmark heavily rely on offshore wind energy to meet their renewable energy targets. While Denmark has the lowest total installed capacity of the four countries, it also has the highest share of electricity supplied by offshore wind of all countries worldwide. In comparison, while China added 1.6 GW of offshore wind capacity in 2018 alone, only 0.1% of their electricity is provided by offshore wind [4]. The United Kingdom and Germany together account for over 60% of the world's offshore installations, with a total installed capacity of around 17 GW.

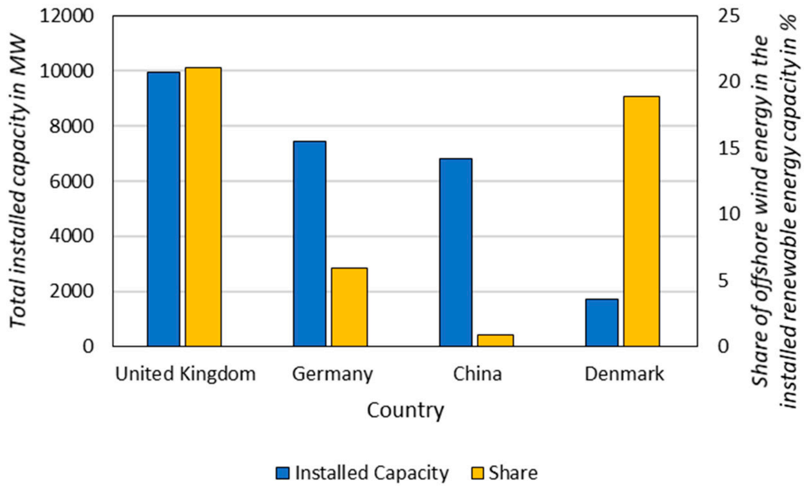


Figure 1. Comparison of offshore wind deployment and share of the offshore wind capacity in renewable generation in major markets (2019) [4,10].

At this point in time, there are up to 150 new offshore wind projects planned across 19 different countries. Table 1 shows the regions which have adopted policy targets for offshore wind with more than 10 GW [4].

Due to the know-how and in-place infrastructure, the European Union has the highest target for offshore wind. Compared to today, new countries such as the United States, India, Taiwan, and Korea will enter the offshore wind market. Based on their policies, they will quickly catch up to the individual installed capacity in different countries of the European Union. Several countries, such as Japan and Canada, have laid the foundations for the future development of offshore wind energy, but do not have a defined policy [4].

One of the reasons for the growing interest in offshore wind worldwide is the falling cost. In Europe, based on the most recent tenders and auctions, offshore wind will soon beat the new natural gas-fired capacity in cost. The levelized cost of electricity is projected to decline by nearly 60% by 2040 [4]. A large percentage of the cost reduction will be achieved by a lower upfront cost, mostly due to the lower costs of turbines, foundations, and installation. On the other hand, transmission costs are expected to increase due to new projects moving further away from the coast. While the infrastructure in Europe is quite advanced, other countries are lacking in comparison. For offshore wind to be competitive in cost, every region needs the necessary infrastructure and expertise. The similarity of offshore wind and offshore oil and gas activities is helping infrastructure development and know-how transfer. In particular, construction and maintenance display considerable similarities.

Table 1. : Offshore wind total capacity targets for different global regions.

Region	Policy Target for 2030 (GW)
European Union	65–85
United Kingdom	30 (up to)
Germany	15–20
Netherlands	11.5
Denmark	5.3
Other EU Countries	18.6 (up to)
China	5 (by 2020)
United States	22
India	30
Taiwan	10
Korea	12

The main aspects that need to be improved to ensure the continued growth of offshore wind energy are [4]

- The development of efficient supply chains to keep the cost down. It is therefore necessary to invest in larger support vessels and construction equipment.
- The expansion of onshore wind grid infrastructure, in order to ensure that large amounts of offshore wind power is not going to be unused.

1.1.2. Japan

As previously mentioned, Japan does not have an offshore wind target for 2030. Nevertheless, groundwork for offshore wind deployment is being developed. In 2012, the feed-in tariff (FiT) for wind power was approved. In 2014, a special FiT for offshore wind was approved by the Ministry of Economy, Trade and Industry (METI). Despite this, few FiT offshore projects were installed, due to market uncertainties and the complex Environment Impact Assessment (EIA) process. Further changes followed in 2017 and 2018, with the aim to streamline the regulation and encourage offshore wind development. In 2019, a new law took effect, allowing permits which authorize offshore farms to run for up to 30 years. Before this law, project permits could only be given out for up to five years, which hindered the investment in offshore wind in Japan. Furthermore, in 2019, the METI, in cooperation with the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), established eleven designated zones in five prefectures, where competitive auctions will take place. Four of the zones were nominated as promising areas in 2019 (Goto in Nagasaki, Choshi in Chiba, Yurihonjo in Akita, and Noshiro in Akita). Goto in Nagasaki was nominated as the first zone for promotion in December 2019. The auction for the Goto zone was launched in July 2020 and will run until December 2020. The operator will be selected in June 2021. Another four zones were nominated in 2020. In total, around 14.8 GW is in the EIA pipeline [9].

In July 2020, the METI and the MLT led a dialogue between the government and industry to promote the development of offshore wind energy. The government proposed the nomination of three or four candidate sea areas each year (with a capacity of about 300–350 MW). This would increase Japan's offshore wind capacity to around 10 GW by 2030 [9].

Several partnerships between experienced offshore wind companies and established Japanese companies have been announced, underlining the fact that offshore wind energy is gaining momentum in Japan. The following partnerships are of note [9]:

- Tokyo Electric Power Company (TEPCO)and Ørsted (memorandum of understanding to work jointly on offshore wind projects);
- Kyuden Mirai and RWE;
- J Power and Engie;
- Tokyo Gas Co. and Principle power;
- Van Oord and Nippon Yusen (NYK);
- Norther Offshore Group and NYK; and
- Mitsubishi Heavy Industries and Vestas (selected as the turbine supplier for several projects).

At present, there are only a few operating offshore wind projects in Japan. The first one was commissioned in 2003. Table 2 gives an overview of all projects [5].

Table 2. Overview of Japanese offshore wind projects (2016).

Prefecture	Installed Capacit (MW)
Hokkaido	1.2
Yamagata	10
Fukushima	14
Ibaraki	14
Ibaraki	16
Chiba	2.4
Fukuoka	2.0
Nagasaki	2.0
Total	61.6

In total, eight projects have been installed. No project exceeds 16 MW and therefore, the projects are all small compared to their European counterparts. Moreover, many of the projects are installed in port areas rather than in the open sea. It must be mentioned that many of the projects are merely pilot projects. For example, the project in Fukushima represents one of the earliest implementations of floating wind technology worldwide. It is mainly used as a test to support the future development of commercial projects and gain know-how about the implementation of floating wind technology.

2. Materials and Methods

Methodology

The following section will give an overview of the methods used to assess the offshore wind potential in Japan.

First, the wind turbine on which the calculation is based will be introduced. The 10.6 MW reference offshore turbine, designed at the Technical University of Denmark (DTU), was selected for the calculations presented in this paper. The power curve is based on the simulations for the reference turbine [11]. Although this corresponds to the peak power of the wind turbines currently in use, it is predicted that turbines with up to 20 MW will be available in 2030 [4]. However, since the power curve for future turbines is still unknown, it is not possible to calculate the power yield for these turbines.

Figure 2 displays the power curve of the chosen offshore wind turbine [11]. The cut-in wind speed is 4 m/s, while the cut-off wind speed is 25 m/s. After the cut-in wind speed, the energy of the wind is large enough to turn the rotors and generate electricity. If the cut-off wind speed is reached, the system is shut down to avoid structural damage. The rated wind speed is around 12 m/s; after this point, the power output of the wind turbine is constant.

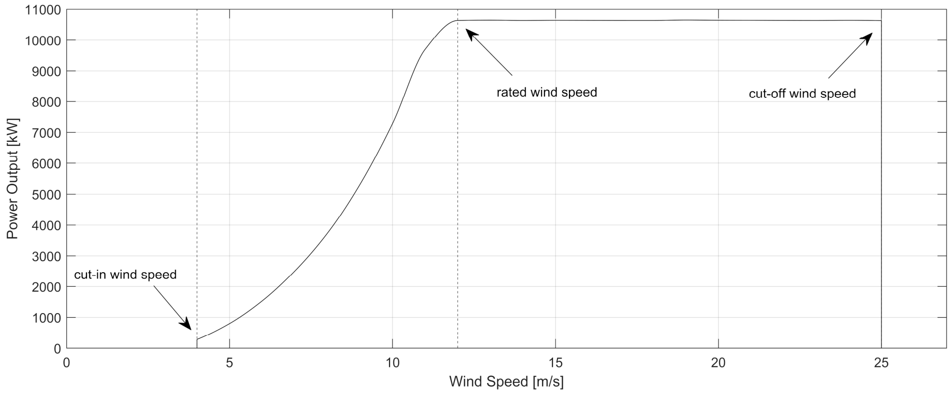


Figure 2. Power curve and power coefficient of the 10.6 MW reference wind turbine.

The turbine has the following technical specifications [11]:

- Peak power: 10.6 MW;
- Rotor diameter: 178 m;
- Hub height: 119 m.

For the calculation, suitable locations for offshore wind in Japan had to be identified. Therefore, the ocean surface topography will be discussed.

In Figure 3, the suitable locations for offshore wind in Japan are shown. The data were provided by the Japan Coast Guard. The data are given as 500 m gridded bathymetry data [12]. The suitable area is divided into shallow water (<50 m) and deep water (50–200 m). Based on the status of the offshore wind technology, it is assumed that in the shallow water, fixed-bottom structures (e.g., monopiles or jackets) will be used. In deep water, the use of floating technology is assumed [13]. Due to the distance from mainland Japan, Okinawa prefecture will not be considered in this study. Only the Exclusive Economic Zone (EEZ) of Japan is considered. The joint zone with Korea and zones where the ownership is disputed by other countries are not considered. Figure 3 shows that the area suitable for floating wind technology is much larger than the area suitable for fixed-bottom technology. It can also be seen that the seabed is very steep, especially in the north of Honshu and on the east side of Japan. Furthermore, proportional to the coastline, Hokkaido and south-west Japan have the largest suitable areas for offshore wind.

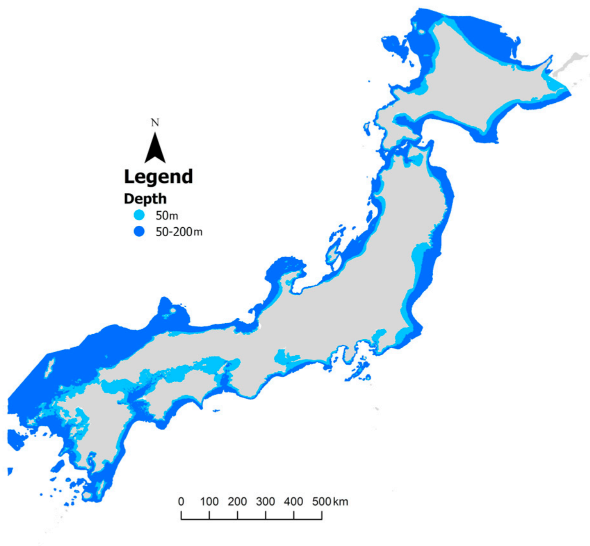


Figure 3. Simplified ocean surface topography of Japan.

In this study, it was assumed that the individual offshore wind turbines will have a distance of 1 km from each other. Based on this assumption, the total number of turbines which could be installed is about 256,619, of which about 64,198 could be installed in shallow water and 192,421 in deep water. Assuming 10.6 MW as the capacity for one turbine (see Figure 2), the total potential is about 2720 GW. Of this, about 680 GW represents fixed-bottom turbines and about 2040 GW represents floating turbines.

In the calculations, no restrictions for the installation of offshore wind turbines were assumed. In reality, there are several reasons why some areas are not suitable, for example,

- Unsuitable soil conditions;
- The visual impact;
- Fishing routes;
- Shipping routes; and
- Uneconomical locations (because of bad wind conditions, etc.).

However, even if these restrictions are considered, Japan has a huge potential offshore wind market. Currently, Japan's electrical capacity is about 292 GW, which is about 11% of the total potential of offshore wind energy.

For the calculations, the ocean topography map from Figure 1 was divided into the following regions:

- Hokkaido;
- Tohoku;
- Tokyo (Kanto);
- Hokuriku;
- Kansai;
- Shikoku;
- Chugoku;
- Kyushu; and
- Chubu.

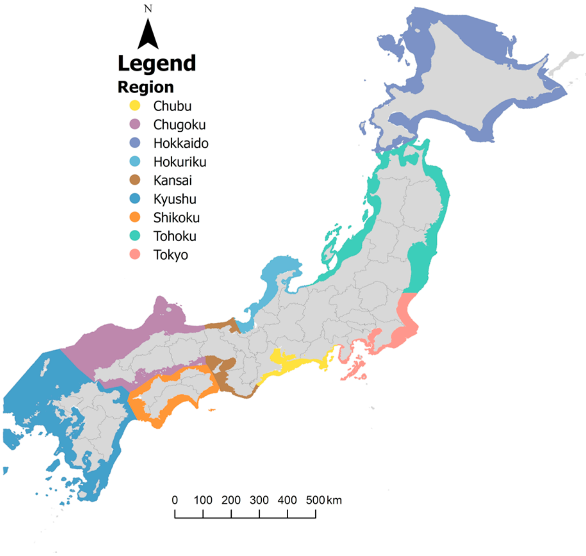
The regions corresponding to the supply areas of the 10 major electric power companies in Japan (without Okinawa) were chosen. The sea area shown in Figure 3 was assigned to each of the service areas of the ten companies. The results are shown in Figure 4a.

For each of the regions shown in Figure 4a, the total offshore wind potential was calculated separately (capacity and possible generated energy for the year 2018).

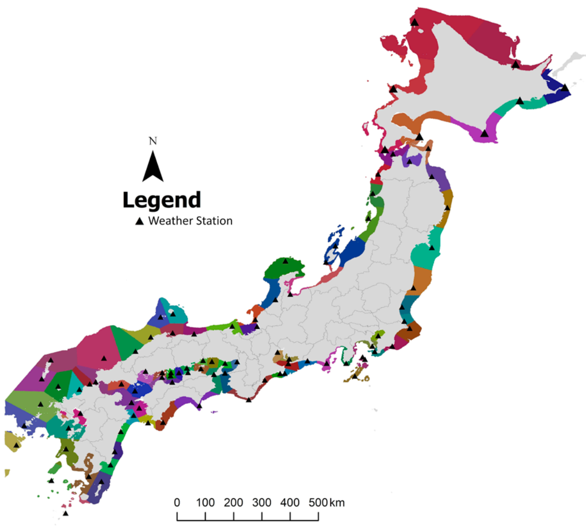
The starting point for the calculations was the 500 m gridded bathymetry data and the weather data obtained from multiple weather stations around Japan [12]. On current commercial wind farms, the distance between the individual turbines is about 7–8 times the rotor diameter [14]. The turbine selected in this study has a rotor diameter of 178 m, so the distance between the individual turbines is approximately assumed to be 1 km based on the aforementioned rule [11]. Based on this, the 500 m gridded bathymetry data were converted into 1000 m gridded bathymetry data. Each data point of the 1000 m gridded bathymetry data was assigned to one of the nine supply areas (shown in Figure 4a). Each data point marks a potential location where a turbine could be installed. The total potential capacity for each region could be calculated by multiplying the number of data points assigned to the region by the peak power of the turbine.

To calculate the produced electricity for each region, wind speed data were needed. Due to the lack of offshore wind measurement stations, data from nearshore weather stations (or lighthouses with measurement equipment) were used [12]. Figure 4b shows the weather stations. Based on the shortest distance, each data point from the 1000 m gridded data was assigned to one weather station. All of the data points belonging to one weather station made up an area, and these areas are shown in Figure 4b.

In each of the areas, the data points are only differentiated based on the water depth. In each area, the data points (potential turbine locations) distinguish between shallow and deep water. In principle, identical wind conditions are assumed for all shallow water data points and all deep water datapoints.



(a)



(b)

Figure 4. Suitable offshore wind locations split into (**a**) regions for each electric power company and (**b**) areas for each available weather station, where each color represents a different area.

The following steps give a more detailed explanation of the calculations performed. In general, the whole energy calculation was based on hourly values. Demand data and wind speed data were both from the year 2018. Steps 1–4 were sufficient to determine the potential capacity of offshore wind in each region. Steps 5–9 were required to calculate the generated energy of the potential capacity. In step 10, the results of the previous steps were used to compare the potential generated electricity with the demand for different supply scenarios. In step 11, the generated electricity of 100 turbines (1060 MW) in the area with the best wind conditions of each region was calculated. The calculation process included the following steps:

1. Filtering of the bathymetry data for all datapoints with a depth of less than 200 m;
2. Converting of the 500 m gridded bathymetry data into 1000 m gridded data (due to the assumption of a 1 km distance between each turbine), where each data point represents a possible location for a turbine;
3. Based on the service areas of the major Japanese electric power companies, each datapoint is assigned to one region (Figure 4a);
4. The potential capacity for each region is calculated from the number of assigned data points per region;
5. The allocation of individual data points to a weather station based on the shortest distance (use of the Haversine formula [15], Figure 4b);
6. Adjustment of the wind speeds measured by the nearshore weather stations by applying the power law to adapt to the hub height of the wind turbine and by using the average offshore wind data from the Global Wind Atlas [16]. The average of each hourly wind speed data set is brought to the same level as the average from the Global Wind Atlas for the location;
7. Calculation of the hourly produced electricity per turbine for each area, using the power curve from Figure 2;
8. Calculation of the amount of electricity produced in each area in one year by calculating the hourly amount of electricity produced by one turbine and multiplying it by the total number of turbines in the area;
9. Calculation of the annually produced electricity of all areas belonging to a region to calculate the total potential per region;
10. Calculation of the average hourly produced electricity per turbine for each region and comparison to the hourly electricity demand.

    (a) First Scenario: Self-sufficient supply without storage:

    - Calculation of the number of turbines required if 80% of the electricity is generated by offshore wind;
    - The following boundary conditions are assumed: There are no storage facilities and the electricity is only used in the producer region;
    - This scenario was chosen based on the Japanese government's goal to reduce greenhouse gas emissions by 80% by 2050. It is assumed that if 80% of the electricity is supplied by offshore wind energy, GHG emissions from the electricity sector will also be reduced by 80%.

    (b) Second Scenario: Net-balance of produced and consumed electricity

    - Calculation of how many turbines are needed, if the net produced electricity per year should match the net demand per year.
    - In other words, during the year, the amount of electricity produced is equal to the amount of electricity consumed. This does not mean, however, that the electricity produced covers the demand at all times;

11. In the final step, the generated electricity of a wind farm of a commercial size (in this case, 100 turbines with a total capacity of 1060 MW) is calculated for each region under the best wind conditions.

    - Note: Only wind speed data from 2018 were used in the calculation. The wind speed is different for each year, so the total potential will differ when data from other years are used. However, since the mean wind speed from the Global Wind Atlas was used as a baseline, the hourly wind speed data only represent the hourly variation. Therefore, the total potential will vary only slightly if different wind speed data are used.

3. Results and Discussion

In this chapter, the results of calculations are presented. Hereby, the calculation method employed for the Hokkaido region is explained in detail. Afterwards, an overview of all the regions is given. The calculations applied for the other regions were performed in the same way as for the Hokkaido region. The electricity demand data for the other regions were obtained from the electric power company of the respective region.

3.1. Detailed Results for the Hokkaido Region

Figure 5a gives a detailed look of the suitable offshore wind area in Hokkaido. As expected, most of the suitable area has a depth of 50 to 200 m. In addition, the north of Hokkaido has the highest potential, as depths of over 200 m are reached at a greater distance from the coast. The total number of data points of the 1000 m gridded bathymetry data belonging to the Hokkaido area is 58,989. About 75% of these data points are located in deep water (suitable for floating) and 25% in shallow water (suitable for fixed-bottom). Based on the selected wind turbine, the region has a potential offshore wind capacity of up to 625 GW.

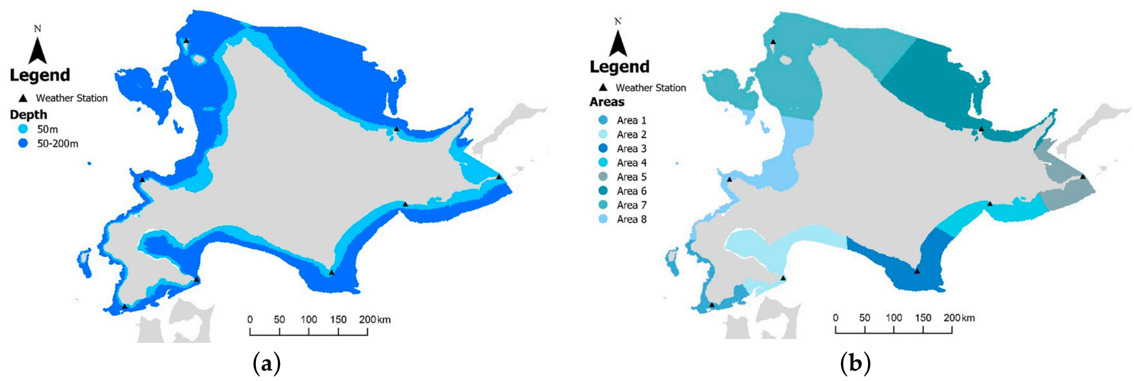


Figure 5. Suitable offshore wind locations in Hokkaido: (**a**) Divided into fixed-bottom (<50 m) and floating foundation suitable locations (50–200 m), and (**b**) divided into areas based on the weather station locations.

The region was divided into smaller areas based on the location of the weather stations (Figure 4). The Haversin formula was used to determine the weather station to which the distance of each data point is the shortest [15]:

$$d = 2r \times \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_{Turb} - \phi_{station}}{2}\right) + \cos(\phi_{station}) \times \cos(\phi_{Turb}) \times \sin^2\left(\frac{\lambda_{Turb} - \lambda_{station}}{2}\right)}\right) \quad (1)$$

- d: Distance between the turbine and weather station;
- r: Radius of the earth (average: 6371 km);
- λ: Latitude (respectively of the turbine or weather station);
- ϕ: Longitude (respectively of the turbine or weather station).

This calculation resulted in the areas shown in Figure 5b, where each area belongs to a weather station and is made up of the allocated data points. An exception was only made if there was a lot of land mass between the possible turbine location and the weather station; in this case, the assigned weather station was selected manually. Table 3 displays the number of wind turbines in each area corresponding to Figure 5b.

Table 3. Distribution of wind turbines in Hokkaido.

Station Name	Number of Shallow Turbines (<50 m)	Number of Deep Turbines (50–200 m)	Total Number of Turbines
Area 1	363	1587	1950
Area 2	1917	3945	5862
Area 3	1370	4169	5539
Area 4	1418	2377	3795
Area 5	2399	1337	3776
Area 6	1744	11,266	13,010
Area 7	3379	15,692	19,071
Area 8	1928	4058	5986
Sum	14,518	44,471	58,989

To calculate the potential produced electricity, the power curve from Figure 2, in combination with the measured wind speeds from the weather stations, was used. First, the hourly wind speed data of the nearshore weather stations was adjusted. The adjustment was based on the average wind speed of the Global Wind Atlas [16]. The reason for this is that the weather stations are located nearshore and therefore, the measured wind speed does not correspond to the wind speed offshore. If the wind data were not adjusted, the potential would be underestimated. For the adjustment, the average wind speed (respectively for data points below 50 and 50–200 m) was estimated, based on the data of the Global Wind Atlas [16] (only the average annual wind speed was available). The average wind speed of hourly measured wind speed data was calculated and the difference between the averages was determined. The difference was then added to each data point of the hourly measured wind speed data. Therefore, the average wind speed was then equal to that given in the Global Wind Atlas. The following equation shows the calculation:

$$w_{adj,i} = w_{on,i} + \left(w_{off,avg} - w_{near,avg}\right). \quad (2)$$

- $w_{adj,i}$: Adjusted wind speed (hourly data);
- $w_{on,i}$: Onshore wind speed data (hourly data);
- $w_{off,avg}$: Average wind speed of offshore data (yearly data—global wind atlas);
- $w_{near,avg}$: Average wind speed of nearshore data (yearly data—weather stations).

The average wind speed taken from the Global Wind Atlas was the value at a height of 100 m. Therefore, the next step was the adjustment of the hourly wind speed to the hub height of the selected wind turbine of 135 m. The power law was used for the conversion [17]:

$$w_{hub} = w_{adj,i} \times \left(\frac{z_{hub}}{z_{adj}}\right)^{a}, \quad (3)$$

- w_{hub} : Adjusted wind speed at hub height (hourly data);
- $w_{adj,i}$: Adjusted wind speed (hourly data);
- z_{hub} : Hub height of turbine (119 m);
- z_{adj} : Height at which the average wind speed data from the Global Wind Atlas is given (100 m);
- a : Power law exponent (0.11 for water [17]).

Since a distinction is made between shallow and deep water (fixed-bottom and floating foundations), the described calculations were performed twice for each weather station/area: Once with the average offshore wind data for shallow water locations and once with the average offshore wind data for deep water locations (obtained from the Global Wind Atlas). As a result, there were two adjusted wind speed data sets for each weather station/area: One for shallow water and one for deep water. With these datasets and the given power curve (Figure 2), the power output of one representative floating turbine and one representative fixed-bottom turbine was calculated. When multiplied by the respective number of turbines, the total potential of electricity generated was calculated for each area and is shown in Table 4.

Table 4. Annual electricity generation potential per area (Hokkaido, 2018).

Station Name	Percentage of Total Turbines in %	Generated Average Electricity per Turbine in TJ/unit	Total Generated Electricity in PJ
Area 1	3.31	172	336
Area 2	9.94	140	822
Area 3	9.39	147	817
Area 4	6.43	119	451
Area 5	6.40	155	584
Area 6	22.05	122	1592
Area 7	32.33	165	3163
Area 8	10.15	140	451
Average	-	145	1076
Sum	100	-	8602

The total potential for offshore wind in Hokkaido is approximately $E_{pot,Hokkaido} = 8602$ PJ. The average capacity factor could therefore be calculated by

$$\begin{aligned} c_{turb} &= \left(E_{pot,Hokkaido}/n_{total}\right)/\left(t_{year} \times P_{Turb,Peak}\right) \\ &= \left(\frac{8602\ PJ}{58989}\right)/\left(8760\ h \times 10.6\ MW \times 3600\frac{s}{h} \times 10^{-9}\frac{PJ}{MJ}\right) \\ &= 0.44. \end{aligned} \quad (4)$$

- c_{turb} : Capacity factor;
- $W_{Sum,year}$: Total wind energy potential in Hokkaido;
- n_{total} : Total number of wind turbines that can be installed;
- $P_{Turb,Peak}$: Rated peak power of the wind turbine.

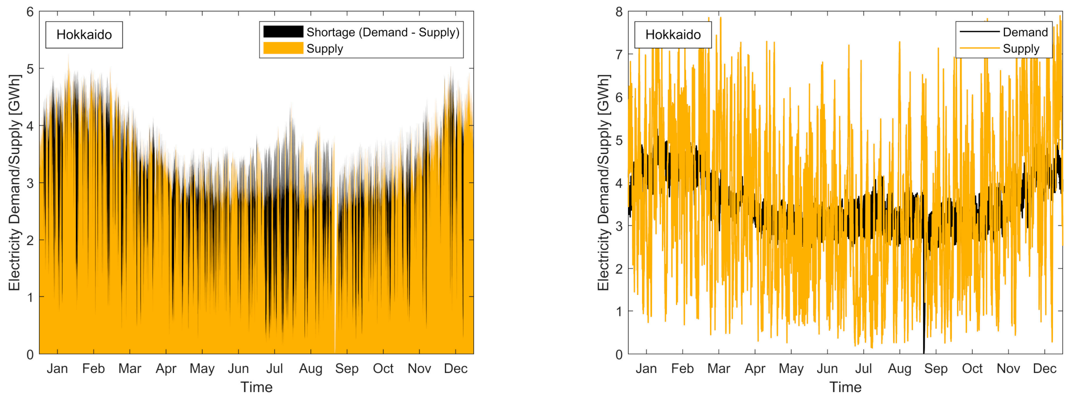
Compared to the average offshore wind capacity factor in Europe ($c_{turb,europe} = 0.37$), the capacity is a lot higher [18]. This shows that the wind conditions in Hokkaido are above average in Japan and on par with above average European conditions. The capacity factor in some areas in Hokkaido will be even higher due to the following reasons:

- There are no offshore wind measuring stations in Hokkaido, so the measured nearshore wind data were adjusted, but the calculation does not reflect the generally much higher peaks in offshore conditions. The peaks play a large role in the high capacity factor of offshore wind farms, because the peak power of the turbine will be reached much more frequently;
- The distinguished areas are relatively large and within these areas, all fixed-bottom and floating turbines are viewed as equal. Under normal circumstances, additional measurements are taken before commissioning an offshore wind farm. These measurements ensure that the wind farm will be located in above average wind speeds for the region;
- The used data are from 2018. For different years, the capacity factor of the turbines can vary because the wind speed changes.

Hokkaido Demand–Supply Scenarios

In this chapter the power supply is discussed in connection with the demand. The total electricity demand of Hokkaido amounts to $E_{Hokkaido} = 110.8$ PJ for 2018 [19]. The demand is much lower than the total potential for Hokkaido of $E_{pot,hokkaido} = 8602$ PJ (see Table 4). From this, it can be concluded that a fraction of the area under consideration is sufficient to cover a large part of the electricity demand.

Figure 6a shows the electricity supply for the scenario where 80% of the electricity is supplied by offshore wind turbines, with no storage options or grid options. No grid options in this context means that the electricity is only consumed in the Hokkaido region. Hereby, the black areas must be supplied by other means. It is clear that the supply varies greatly over the year and that on some days, nearly all the electricity must be supplied by other energy sources.



(a) **(b)**

Figure 6. Electricity supply and demand for Hokkaido: (**a**) Based on 80% of the electricity being supplied by offshore wind without storage (762 turbines) and (**b**) based on the assumption that the net produced electricity is the same as the net electricity demand (760 turbines).

Figure 6b shows a scenario where the annual produced electricity is equal to the annual electricity demand. Over the whole year, there is an electricity balance between production and consumption. In this scenario, the electricity supplied by the offshore wind turbines does not meet the demand at all times. The produced electricity varies greatly over the year. Therefore, at many points, the electricity has to be either fed into the grid or taken out of the grid. Another option would be large-scale storage. The figure shows the need for good storage options in energy systems in which renewable energies are used.

Table 5 shows an overview of the discussed results for Hokkaido. As a reference, the percentage of the electricity demand that can be met by 100 turbines (1060 MW park) located in the highest-yielding region was calculated.

Table 5. Overview of the electricity supply and demand scenario in Hokkaido.

Category	Description	Hokkaido	Unit
Potential—electricity generation	Total potential (wind energy)	8602	PJ
	Capacity (power)	625	GW
	Average turbine supply	145	TJ/unit
Potential—number of wind turbines	Total	58,989	-
	Floating	44,471	-
	Fixed-bottom	14,518	-
Electricity demand	Total	111	PJ
	80% of total	89	PJ
Number of wind turbines	Coverage of 100% (net balance)	760	-
	Coverage of 80% (without storage)	762	-
Percentage of electricity supply	1060 MW (100 turbines) installed capacity	15.4%	-

3.2. Overview of the Offishore Wind Potential for all Regions in Japan

This chapter will give an overview of the total offshore wind potential in Japan. As mentioned before, the demand data and wind speed data, which were used to calculate the potential electricity supply, are based on data from 2018.

The following key points can be derived from Table 6. Firstly, the total potential for Japan in the year 2018 can be estimated to be 32,028 PJ. At the same time, the demand for 2018 is around 3231 PJ. Therefore, only around 10% of the total potential would have to be utilized to cover 100% of the electricity demand. In other words, Japan would be able to meet nearly ten-times its demand based on its technical potential. It is therefore clear that with a corresponding grid and storage options, all of Japan's electricity consumption could be supplied by only offshore wind turbines. The maximum number of turbines that can be installed in Japanese waters, while assuming that the distance between turbines is 1 km, is around 257,000. Around 75% are in waters from 50-200 m (floating) and 25% are in waters below 50 m (fixed-bottom). While the fixed-bottom structures only account for 25% of the total number of possible turbines, these 25% would still be sufficient to match the Japanese electricity demand. Furthermore, if each region is regarded as self-sufficient, without storage usage and with the constraint that the electricity can only be used in the producing region, around 33,598 turbines are needed to supply 80% of Japan's electricity demand. There are three regions which can just barely cover 80% of their energy demand self-sufficiently, consisting of Kansai, Chubu, and Tokyo. These regions are Japan's most important economic centers and have the highest populations of all the regions. Due to that, they also have the highest demands of all the regions. At the same time, the number of turbines that can be installed is relatively low.

To reflect on the calculated potential, it has to be mentioned that, in reality, the number of turbines that could realistically be installed, especially in regions like Tokyo and Kansai, is even lower. Several interest groups and stakeholders impose economic and social constraints, such as

- The tourism sector;
- Animal and nature protection zones;
- The fishing industry;
- The shipping industry;
- Other offshore-related industries (e.g., military activities);
- Coastal communities (e.g., complaints due to visual impacts).

For the net-balance scenario for each region, a total of around 26,210 turbines would have to be installed in Japan.

The regions with the highest electricity supply per turbine are Hokkaido, Tokyo, and Tohoku. Additionally, Kyushu and Hokkaido have the highest overall potential, mostly due to the fact that around half of Japan's total suitable locations for offshore wind turbines are located in both regions. While the supply per turbine is high in Tokyo, the limited number of possible turbine locations constrains the overall potential. The huge potential in Hokkaido and Kyushu could be used to supply regions with a lower potential and a high demand, e.g., Tokyo, Kansai, and Chubu. To achieve that, the electrical grid must be adapted, so that a higher proportion of renewable energies can be integrated.

The last row of Table 6 shows the percentage of wind energy that is supplied per year if 100 turbines are installed in the highest-yielding area for each region. In total, the 900 turbines, or around 9.5 GW offshore wind capacity, can cover around 4.2% of the Japanese electricity consumption. In regions like Hokkaido and Shikoku, more than 13% of the total electricity demand can be supplied by just 100 offshore turbines. In contrast, there are regions like Tokyo and Kansai where only around 2% of the energy consumption can be covered.

Table 6. Offshore wind potential for each region in Japan (2018).

Category	Description	Hokkaido	Tohoku	Tokyo	Hokuriku	Kansai	Shikoku	Chugoku	Kyushu	Chubu	Japan	Unit
Potential—electricity generation	Total potential (wind energy)	8602	4552	1574	1398	840	1469	4773	8034	787	32,028	PJ
	Capacity (power)	625	376	119	127	86	154	459	706	66	2720	GW
	Average turbine supply	145	128	140	117	103	101	110	121	127	121	TJ/unit
Potential—number of wind turbines *	Total	58,989	35,502	11,268	11,990	8156	14,575	43,318	66,617	6203	256,619	-
	Floating	44,471	26,128	6626	10,086	4086	9820	35,332	53,206	2666	192,421	-
	Fixed-bottom	14,518	9374	4642	1904	4070	4755	7987	13,411	3537	64,198	-
Electricity demand	Total	111	300	1048	110	532	101	221	316	492	3231	PJ
	80% of total **	89	240	838	88	426	81	177	253	394	2586	PJ
Number of wind turbines	Coverage of 100% (net balance) ***	760	2340	7503	941	5162	997	2007	2621	3879	26,210	-
	Coverage of 80% (without storage) ****	762	2359	9609	1427	6797	1244	3191	3255	4954	33,598	-
Percentage of electricity supply	1060 MW (100 turbines) installed capacity *****	15.4%	5.8%	1.7%	11.6%	2.4%	13.8%	6.4%	5.0%	3.1 %	4.2%	-

* Assumption of one turbine per square km. ** Current goal of the Japanese government is to reduce GHG emissions by 80% (2050). Assumption that 80% offshore wind is equal to 80% GHG reduction. *** The net produced energy over the whole year is as high as the demand. The profiles of supply and demand do not match and therefore, a storage system would have to be used. Another option would be to use the grid to feed-in or take out electricity. **** In this case, it is assumed that there is no storage and no feed-in of excess electricity. It is therefore assumed that the produced electricity can only be used in the producing region. ***** In this case, it is assumed that there is no storage and no feed-in of excess electricity. It is therefore assumed that the produced electricity can only be used in the producing region. The wind speeds from the area with the highest potential for each region are used.

Figure 7 shows the ranking of regions based on their electricity generation potential. Additionally, the capacity factor for each region is shown. The highest capacity factor belongs to Hokkaido, with 0.44, and the lowest belongs to Shikoku and Kansai, with 0.30 and 0.31, respectively.

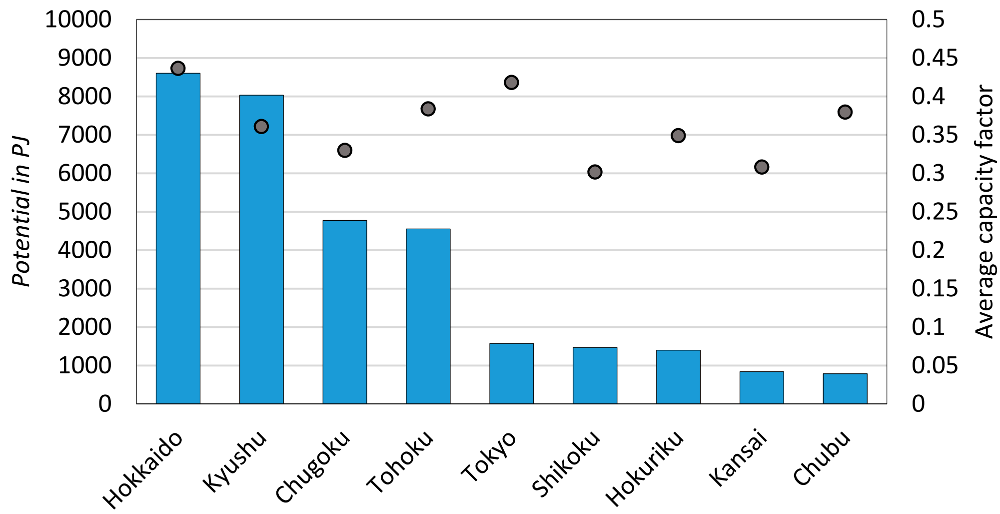


Figure 7. Total electricity potential (blue bars) and average capacity factor (gray dots) per region (2018).

In the following Figure 8, the average produced energy per wind turbine (average of all the regions) for every month is displayed.

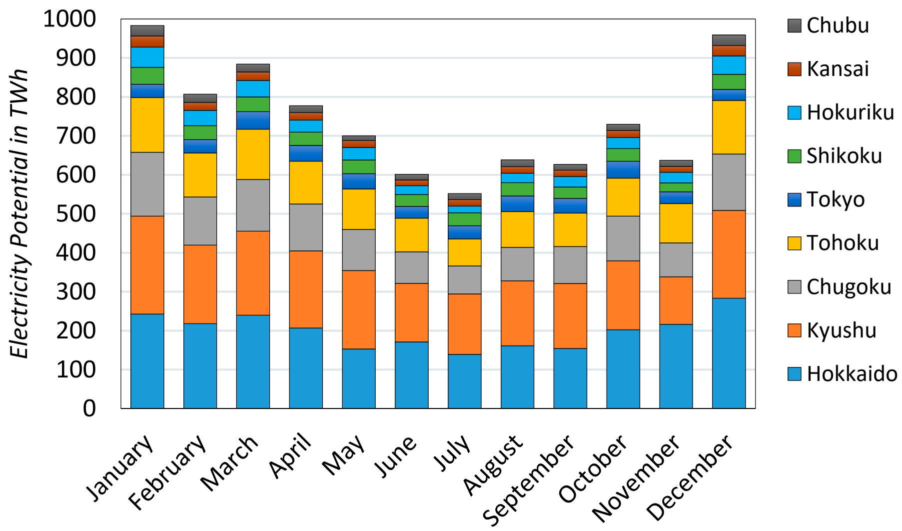


Figure 8. Total electricity potential per month divided by region (2018).

Figure 8 shows that, in the winter months, the produced energy per turbine is higher than the produced energy during the summer months. Peaks are reached in December and January. Generally, this is expected for most countries. Because solar power has its peaks during the summer months, wind power and solar power should be combined to achieve a more constant supply of renewable energy. A combination would lead to smaller amounts of necessary storage and would lower the baseload that has to be supplied by conventional energy sources. As mentioned before, Kyushu and Hokkaido have the highest potential of all the regions, and their total combined potential for every month is higher than all of the other regions combined.

4. Conclusions

This study presents the offshore wind potential for defined regions based on the power supply companies in Japan. The analysis was conducted with wind data from 2018. The theoretical potential for offshore wind energy in Japan was estimated to be very large, with the possibility of meeting up to five to six times Japan's electricity needs with offshore wind energy alone. Regional differences are shown and it is clear that Hokkaido and Kyushu have the highest potential for offshore wind in Japan. These regions could supply more than enough electricity to meet the current demand. The regions with the highest average electricity supplied per turbine are Hokkaido, Tokyo, and Tohoku. The average turbine in regions like Kansai and Shikoku supplies up to 30% less electricity per year.

Nearly all the regions have enough potential to cover their electricity demand. Exceptions are areas with a high population, such as Tokyo or Kansai. They have a high electricity demand combined with less suitable areas and therefore, their offshore wind potential is not high enough to meet the demand.

Based on the current plan of the Japanese government to reduce GHG emissions by 80% by 2050, it can be expected that offshore wind will gain a more important role in the Japanese power sector. On the basis of this work, regions can be selected where offshore wind energy is to be developed due to its high potential.

In future works, the wind speeds for different years should be considered. Ideally, offshore wind measurements should be carried out to ensure a more accurate assessment of the potential. Additionally, a cost analysis for different locations of Japan should be carried out. If specific areas are chosen for deployment in the coming years, the areas should be assessed further by analyzing soil and metocean data.

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