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Geographical Information System for Calculating the Potential of Off-Shore Wind Energy in Japan

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Abstract: Off-shore wind energy has been drawing interest recently. This research is focusing on the potential analysis of off-shore wind energy surrounding entire Japan coast using GIS Technology. Base on the economy and environment assessment, this research is evaluating the current situation and forecasting on future of wind energy technology in Japan. In order to reduce the green-house gas emission, also due to recent nuclear power problems in Japan, renewable energy (such as wind energy, solar energy, fuel cell) is considered to gradually substitute the primary energy resources (such as coal, oil). In this study, off-shore wind power is the centre of the focus. Based on GIS Technique, off-shore wind turbines in the surrounding of Japanese coast-line are considered. In the study, 2000 kW rated off-shore wind turbines are considered for further installation. As the result of this study, we have determined that 108,067 off-shore wind turbines are expected to be installed in 330 places with annual generation of 180.0 TWh. This is equal to 20% of annual total generated power made by a power companies in Japan in 2010.

Key words: GIS Technology, off-shore, wind energy, potential, green-house, Japan

INTRODUCTION

Recently, the Kyoto agreement on global reduction of green-house gas emission has prompted interest on renewable energy systems worldwide. Now-a-days wind power energy is one of the most popular renewable sources since it is clean, inexhaustible and requires little maintenance. In fact, the background of the world wide upward tendency for global warming prevention, wind power was introduced increasingly mainly in Europe and America from the 1990-2000's because of the low cost compared with the other renewable energy.

However, due to the important increasing introduction, several problems have been emerging as noise pollution, bird strike and grid-connection and grid-constraint problems. Moreover, lack of suitable on-shore sites is faced hence, the introduction of off-shore wind generation potential presents a good alternative. By the on-shore wind power at most about 40% wind energy, a kind of new energy can be converted into electrical energy. It is a kind of relatively efficient system. Present predominance in the carbon dioxide emissions per kWh and the generation cost, therefore the wind power especially the off-shore type is introduced positively in Japan. Present predominance in the carbon dioxide emissions per kWh and the generation cost, therefore the wind power especially the off-shore type is introduced positively in Japan. Accumulated production of wind power had reached 2,185,938 kW by the end of 2010. The production of wind power in 2010 did not exceed the half of the target value (3,000,000 kW) the target and just accounted for 1.6% of the total global production. So, it is necessary to produce positively not only the on-shore wind power but also the off-shore wind power. According to the wind power road map (Fig. 1) made by NEDO (2008), the production target value of the off-shore wind power is expected to be 3,800,000 kW in 2020 and 13,000,000 kW in 2030.

At present, researcher are making efforts on the study for spreading the environment-friendly renewable energy. When deciding the site location and anticipating the annual electric production of wind power, the whole Japanese wind speed distribution map, social conditions map and the marine natural condition map become

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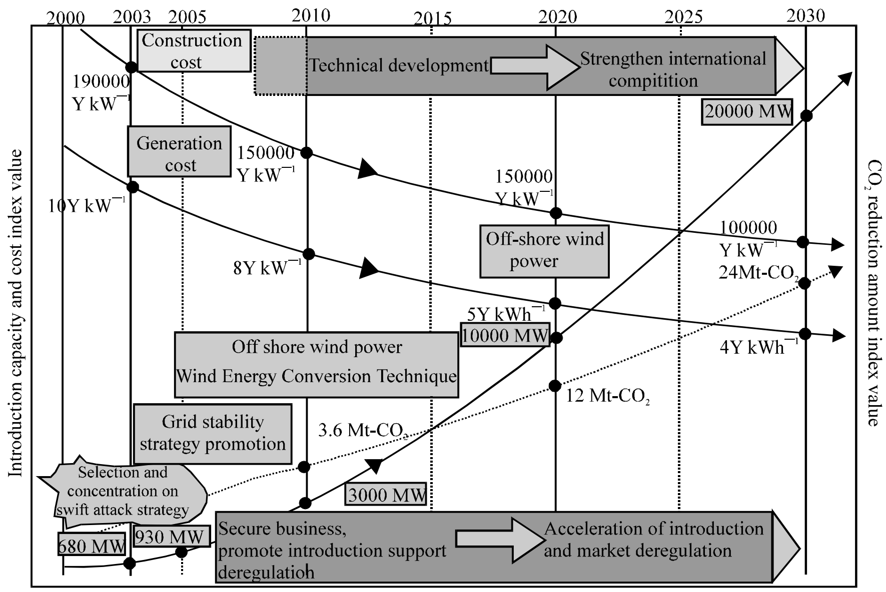

Fig. 1: Wind power road map

necessary for the future introduction of off-shore wind power. Additionally, researchers use the GIS when making these maps. Therefore, as the new type of electric power generation which have that with less carbon dioxide emissions and no environment burden, the expectation for wind power and solar power is growing than ever. The layouts of terrain and feature are different in every site location for wind power.

The electric production of available energy is different depending on the scale of off-shore wind turbines. In addition when introducing off-shore wind turbines, it is necessary to discuss about the economic profit in detail and decide whether it is worth introducing by conducting the expectation simulation of electricity production in every candidate location. The off-shore power generation is introduced steadily mainly by some European countries where the wind power is popular such as German, Denmark and Spain. Considering about the less available places caused by the rapid introduction and some environmental problems (like noise pollution and landscape destruction), recently, equipment of wind power is moved to the off-shore areas. As the advantages of the off-shore wind power, it not only guarantees the places for large-scale wind farms but also has a high velocity and less turbulence therefore, high availability of suitable wind than the on-shore wind power is expected.

MATERIALS AND METHODS

In this study, by using the GIS ArcInfo and calculation of various scenarios, researchers overlapped all the wind velocity data which are based on geographical data (AMEDAS, 2008) and meteorological model by the GIS ArcInfo where is the abundance calculated by various scenarios. All the GIS data is formed by the Geometry Information and Attribute Information of Raster and Vector type.

As the conditions of introducing the off-shore wind turbines, the following data was used. The elevation data from the GIS (Geographical Survey Institute); 3-D mesh land-used data from the National Land Information Office of MLIT; the Bathymetric data from the Hydrographical Department of Japan Coast Guard, the 70 m-high sea level data from the wind map. On the basis of these data, researcher estimated the off-shore wind abundance in the sea areas where are <10 km away from the Japan coast. The sea areas that can be used to estimate wind condition are limited to the coastal waters because all the estimations of the wind condition in these data are based on the coastal observation data. However because of the regulations such as the Fishery Rights and the Natural Parks Act, it is difficult to construct large-scale wind farms at the coastal areas. In addition, there are a lot of cases of constructing the large-scale wind farms in the sea areas >1 km away from the coast because of the landscape problems in Europe. Therefore, it is necessary to estimate the abundance in the sea areas >1 km away from the coast when examining the large-scale off-shore wind farms (Earth Council Committee, 2008).

Data analysis

Altitude distribution of wind velocity: Affected by the frictions of the surface vegetation and buildings, the wind becomes weaker as approaching the surface. In addition, the more complex the terrain is the weaker the wind will be (we regard the roughness of the vegetation and buildings as the surface roughness). Off-shore wind turbines are established at the surface boundary layer. In respect of the altitude distribution of the inner-layer wind velocity (NEDO, 2008) researchers can obtain in theory:

$$V = V_1 \left\{ \frac{\ln(\frac{Z}{Z_0})}{\ln(\frac{Z_1}{Z_0})} \right\} \quad (1)$$

$$V(Z_2) = (\frac{Z_2}{Z_1})^{\frac{1}{n}} V(Z_1) \quad (2)$$

Where:

Z_1, Z_2	=	The on-ground height
$V(Z_1)$, $V(Z_2)$	=	The wind velocity at Z_1, Z_2
1/n	=	The exponent of the power law exponent

When estimating the wind velocity from the exponential law, the value of power index (1/n) will be changed with the surface roughness, n = 7 is used for the flat coastal areas, etc. and n = 5 is used for the interior (Table 1). The temporal change of wind speed is the main problem when selecting the site location for off-shore wind turbines. Wind is always changing in a short time. However, there are certain tendencies in wind changes according to the blowing cause. Wind diurnal variation will get frequently during the daytime. It occurs because of the compound of the unstable atmosphere which caused by the warmed ground wind in the daytime and the upper air.

Especially, the coastal areas are subject to the strong sea breeze in the daytime from Spring to Autumn. The tendency in the example is common. As the seasonal change of wind speed, it will change much more frequently in Winter in Japan. And it is subject to the strong monsoon from the continent in Winter.

Weibull distribution: Researchers can get the approximate incidence distribution of wind speed by the following Weibull distribution (NEDO, 2005):

Table 1: The value of 1/n from the power law exponent (average value from Observations)

Surface state	n	1/n
Flat prairie landscape	7~10	0.10~0.14
Coast	7~10	0.10~0.14
Country	4~6	0.17~0.25
Urban area	2~4	0.25~0.50

$$f(v) = \frac{k}{c}(\frac{v}{c})^{k-1} \exp\left(-(\frac{v}{c})^k\right) \quad (3)$$

Where:

f(v)	=	The incidence of wind speed v
c	=	Scaling factor
k	=	Shape factor

From the Eq. 3, researchers can know that the scaling factor c equals the wind speed v from the area where the accumulated incidence is 63.2%. Researchers use k = 0.8~2.2 as the shape factor k for Japan. The annual average wind speed has an increasing tendency. When the annual average wind speed is >5 m sec^{-1}, researchers use k = 1.5~2.2. Researchers can get the approximate incidence distribution of wind speed by the Weibull distribution:

$$f(v) = \frac{\pi}{2} \exp\left(-\frac{\pi}{4}(\frac{v}{\overline{V}})^z\right) \quad (4)$$

The Weibull distribution holds good compatibility and it is necessary to know the scaling factor and the shape factor. Because researchers can get the average wind speed and inference the approximate incidence distribution of wind speed by the rere distribution and because of it is simplicity, the rere distribution is often used. According to the power law, researchers calculated the regional annual average 70 m high wind velocity in Japan coast. Figure 2 shows the regional annual average wind velocity and the distribution of the average 70 m high wind velocity.

Researchers created a map in GIS to show the regional annual average 70 m high wind velocity in Japan. The deep red areas are the regions where the annual average wind velocity is over 6 m sec^{-1}. The available geographic data and the wind abundance data have been transformed into GIS-readable data. With using the geo-processing function of GIS, researchers excluded the unelectable sea areas from the constraints and calculated the available generated energy.

Domestic situation of wind power: More recently, the earthquake and tsunami in Japan have raised questions again over the merit of building new nuclear power stations as a low carbon source of base load electricity generation.

On the other hand, solutions related to environment friendly energy sources as wind power in Japan, present an increasing cumulative capacity of wind turbine generation systems on land in recent years. However, installing a large number of on-shore wind turbines has

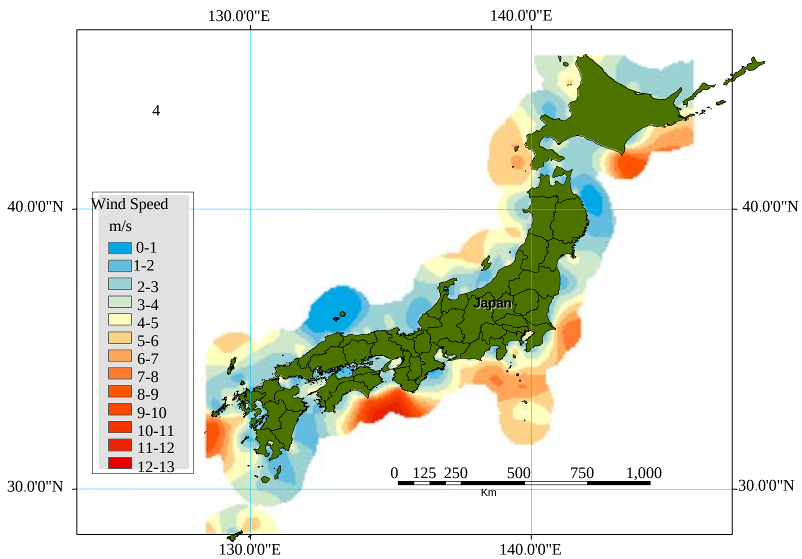

Fig. 2: About 70 m high annual average wind speed distribution map in Japan

inherent problems such as shortage of suitable land and inadequate infrastructure such as power cables and roads. Therefore, development of offshore wind turbine generation systems have become important concerns. As two criterions of the import volume of wind power in Japan, the total installed capacity had been over 2,185,938 kW and the total number of installed units had reached 1,683 units at the end of 2010.

RESULTS AND DISCUSSION

By creating the next generation cost distribution chart to calculate the location of off-shore wind turbines. Wind speed data used in the simulation, weather statistics from the ministry agency, using hourly wind data in 2008. Cut-in and Cut-out of wind speed are 3 and 25 m sec^{-1}, respectively (Fig. 3). When estimating the potentials, researcher used the accurate annual average 70 m high wind velocity map which shows the regional annual average wind velocity.

The potentials are on the supposition that one off-shore wind turbines with a rated output of 2000 kW was installed in every square kilometer in the available areas for wind power where the annual average 70 m high wind velocity is >6 m sec^{-1}. The annual electric energy production is getting increasing in the areas where the annual average 70 m high wind velocity is >6 m sec^{-1}.

Researchers made the distribution map by GIS to show the wind power generation on the supposition that one off-shore wind turbines with a rated output of

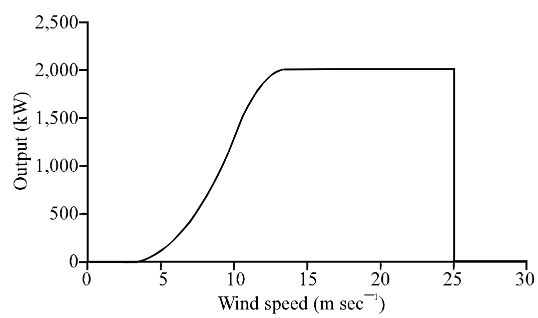

Fig. 3: About 2,000 kW scale off-shore wind turbine output characterristic

2000 kW was installed every kilometer square in the coastal areas of Japan (Fig. 4) (Abudureyimu and Nagasaka, 2009). On the other hand, for thermal power generation amount is adjusted according to demand, the marginal power thermal power is considered (Fig. 5).

Example application: Erimo Misaki is a cape in Hokkaido, located at 41.9244444°N 143.2483333°E. It is the de facto Southern tip of Hidaka mountains. Hot and cold fronts meet nearby of the cape thus, creating a dense mist which covers the cape for >100 days a year.

Wind blows here with the speed of 10 m sec^{-1} for almost 300 days a year. Winds in Erimo are strong enough that in addition to three off-shore wind turbines on the cape, Erimo Elementary School (built in 2000) is completely powered by electricity generated by its own off-shore wind turbines. From the calculation results of Weibull distribution, it determined the wind was blowing

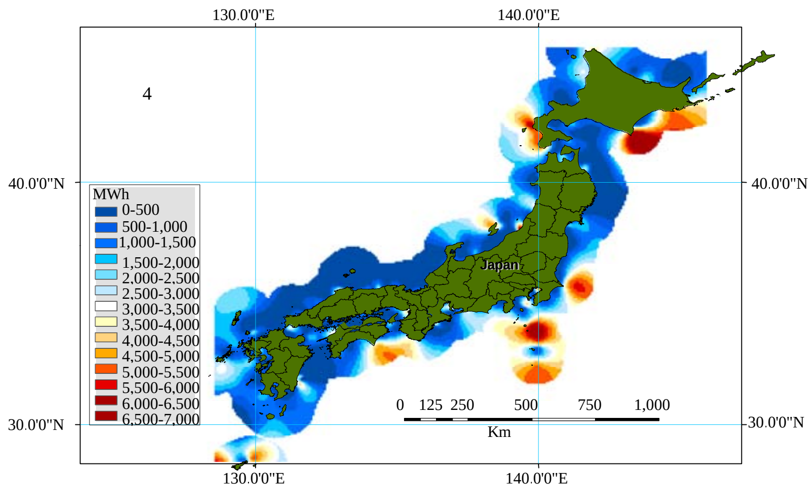

Fig. 4: Annual energy production distribution map >100 km distance from the coasts

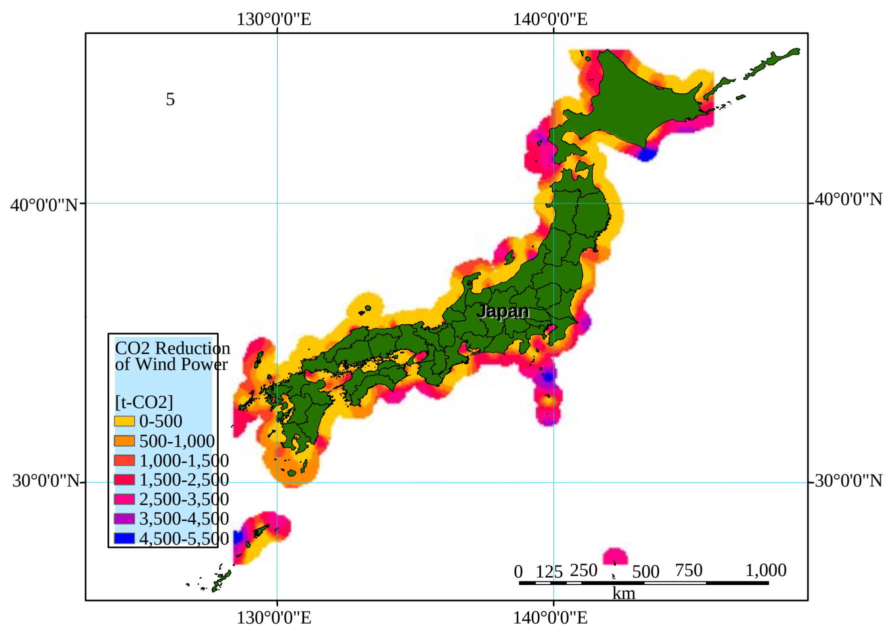

Fig. 5: Distribution CO_2 reduction of Japan

Northeast and Westerly (Fig. 6) direction commonly with average speed 7-8 m sec^{-1} (Fig. 7) at Erimo Misaki area. Currently, there are 3 units of small wind turbine with total capacity 1200 kW operating in this area (on-shore). Based on the GIS calculation, the effective wind area in Erimo Misaki area is 1200.6 km^2 with possible number of off-shore wind power turbine installation is 11206 units (total annual generating capacity is 25.8 TWh). By using Hokkaido Erimo Misaki 3-D dimensional map (Fig. 8), researcher can easily and more accurately to determine the suitable location for off-shore wind turbine installation at particular targeted area. Basically, the wind velocity on the sea will increase as being away from the coast. But even if at a certain distance from the coast, there will be greatly differences in the regional annual average wind velocity. So, the selection of off-shore wind turbines site location is still consequential although on the sea. On the basis of analyzed data, researchers made a simulation on each region.

Researchers estimated the data and get the distances away from the coastal areas by GIS. We calculated the wind power potentials on the supposition that off-shore wind turbines with a rated output of 2000 kW were installed with interval of 100 m apart from each other in each coast. In addition, researchers assumed the windmill off-shore wind turbines to run in 6 m sec^{-1} wind velocity for 3000 h $year^{-1}$ when calculating the yearly wind power potentials.

Off-shore wind power potential for the Japanese off-shore is investigated based on GIS analysis performed for 3-D landscape. In fact, GIS-based maps investigation for 3-D visualization allows better accuracy and time improvement for optimal site selection to install potential wind farms.

As the result of this study, we have determined that 108,067 off-shore wind turbine units in the investigated areas outcomes an annual generation of 180.0 TWh (Table 2).

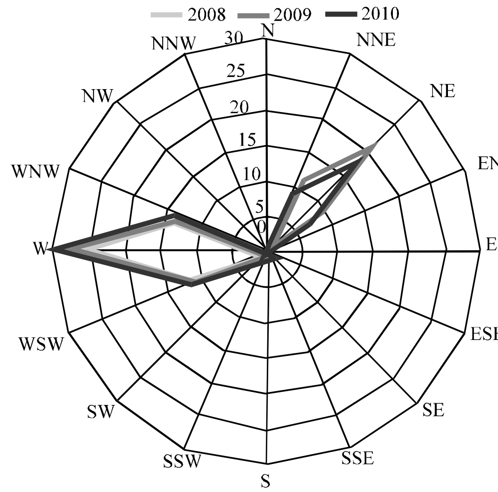

Fig. 6: Annual wind direction map

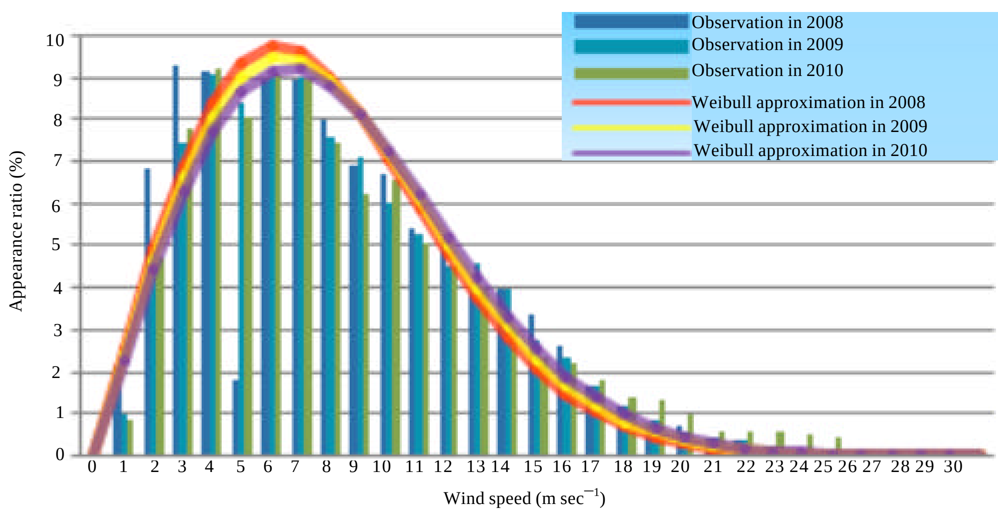

Fig. 7: Frequency distribution of wind speed at different level

Table 2: Off-shore wind power optimal potential in Japan

Candidate wind turbine installation sites	Annual average wind speed at 70 m high (m sec^{-1})	Power generation (kWh)	Candidate coastal areas at 20 km off-shore (km^2)	Expected installation (Unit)	Annual wind power potential (TWh)
Erimo Misaki	8	2,305,800	1,201	11,206	25.8
Kushiro	7	1,615,200	2,533	23,644	38.2
Yagishiri	6	1,060,000	188	1,759	1.9
Yoneoka	6	1,424,300	737	6,877	9.8
Okushiri	8	2,245,400	1,184	11,047	24.8
Aikawa	6	1,506,100	516	4,813	7.2
Choshi	6	1,582,500	1,121	10,458	16.6
Haneda	7	1,721,100	61	572	1.0
OoshimaKitanoyama	6	1,166,700	276	2,574	3.0
Miyake Tsubota	7	1,816,300	1,643	15,336	27.9
Miyakezima	6	1,357,500	587	5,476	7.4
Koudushima	6	1,037,500	836	7,807	8.1
MisakiMuroto	6	1,288,600	696	6,498	8.4
Total	-	20,126,900	11,579	108,067	180.0

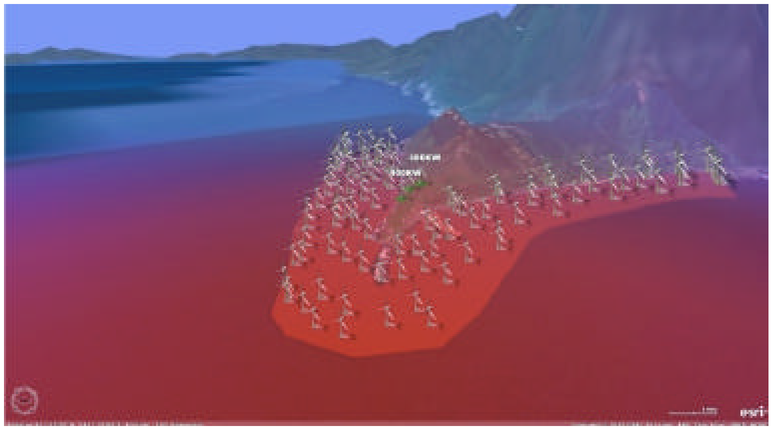

Fig. 8: The 3-D image map of Hokkaido Erimo Misaki with off-shore wind turbines

CONCLUSION

In this study, the off-shore wind power generation potential of entire Japan is investigated, regarding to the increasing need to find suitable sites. In fact, off-shore sites are less turbulent than on-shore sites regarding to stability and favour able wind availability conditions. In this study, the GIS technology is used to assist the determination of finding the potential. The GIS (Geographic Information Systems) technology can create a distribution map of wind speed where suitable off-shore sites can be optimally determined. Simulation around Japan coast areas was investigated on the assumption that off-shore wind turbiness with a rated output of 2000 kW will be installed in with interval of 100 m apart horizontal basis resolution of 20 R^2 distance from the coast line where the annual average of wind velocity at 70 m high is >6 m sec^{-1} in the candidate sites for installing off-shore turbines. The simulation results determined that 108,067 off-shore installed wind turbine units in the investigated areas outcomes an annual generation of 180.0 TWh which represent an important energy source for the Japanese power supply.

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