Evaluation of offshore wind power potential in the western coast of India: a preliminary study

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The possibility of locating wind turbines on the seabed can open up a new frontier for wind power as a significant domestic renewable energy source along the western coast of India. Space for much larger projects is available in shallow coastal waters compared to land. To assess wind power potential in the western coast of India, first the bathymetric data are divided into three regions, i.e. 0–10, 10–20 and 20–35 m respectively, suitable for fixed-bottom foundation technology. Next, the wind data of several meteorological stations are collected from WindSat satellite. For a given bathymetry, using the characteristics of wind turbine, calculations are made for estimating average wind speed, wind power density and average output of wind turbine. Results of the preliminary study show that there exists a total available area of 67,622 sq. km (up to a depth of 35 m), suitable for installation of offshore wind turbines. Further, results reveal that within the total effective area, the average annual power generation of 477 and 437 TWh respectively, could be achieved using GE 3.6s and Repower 5M commercial offshore turbines.

Keywords: Bathymetry, fixed-bottom foundation technology, offshore wind potential, wind turbines.

CLEAN technologies like solar power, wind power, biomass, biofuels, etc. for power generation are the key to reduce emissions of greenhouse gases and CO_2. Among these technologies, wind energy has a great potential for power generation with economic viability. Wind energy can be considered as an attractive solution to overcome regional and global energy challenges. The Indian renewable energy sector is sharing 86 GW out of total power generation of 302 GW. Wind energy has an installed capacity of 26.74 GW as of April 2016 (ref. 1). Over the past two decades, on-shore wind energy technology has seen a ten-fold reduction in cost and is now competitive with fossil fuels for electric power generation[2]. In comparison to a land site, offshore wind turbine may become attractive, because of higher and stable wind speeds[3]. Within the exclusive economic zone (200 nautical miles from the baseline), the coastal state has sovereign rights for utilizing all types of natural resources for the production of energy[4].

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Offshore wind farm designs and energy assessments are complex because they depend upon the constraints and challenges of each site as well as distance from the seashore. There is a need to motivate stakeholders such as developers, utilities and financiers to technically evaluate a project to discern its profitability and feasibility. Offshore wind exploration is becoming more and more feasible and several initiatives have succeeded in Europe. The European Wind Energy Association (EWEA) has identified 18.4 GW of consented offshore wind farms in Europe and plans for offshore wind farms capable of producing more than 140 GW of power. More than 90% of the world's offshore wind power is currently produced in the Baltic and Irish Seas, and the English Channel in northern Europe[5–9]. At the end of 2012, the International Energy Agency (IEA) Wind Member countries, installed more than 4.5 GW of offshore wind capacity, with the addition of 1.25 GW, including China, Denmark, Germany and the United Kingdom[7]. Going by the optimistic estimates, this is expected to grow to about 70 GW by 2017 (ref. 8). The National Institute of Wind Energy (NIWE; formerly Centre for Wind Energy Technology) provides official estimates of India's wind energy potential, and assists the Government in policy-making. With a cumulative installed capacity of over 26.8 GW (ref. 1), currently wind power accounts for almost 63% of the total installed capacity in the renewable energy sector of India. Recently, NIWE estimated detailed state-wise potential in India up to 80 m amsl. Despite the fact that India has a long coastline of about 7600 km, its wind resource is yet to be quantified properly. Based on preliminary studies, high-potential wind resources have been found in the offshore regions in the southern part of peninsula, Konkan–Maharashtra coast, Kutch region in Gujarat and parts of the eastern Odisha coast. A recent study conducted by Scottish Development International and NIWE shows that in the Tamil Nadu offshore region, about 1 GW of offshore wind power can be developed at Rameswaram and Kanyakumari. Dhanju *et al.*[10] proposed a method for assessing electricity production and the value of wind resources, especially for the offshore environment. This method is used for assessment of wind energy along the west coast of India. Assessment of offshore wind energy potential involves mapping two critical parameters: wind speed and bathymetric data of the offshore area. These are essential to explore the possibility of setting up an offshore wind farm or multiple farms. Combining the bathymetric and satellite data, a preliminary attempt has been made to evaluate offshore wind power potential in the west coast of India.

Bathymetry and turbine foundation technology

Bathymetric data play a crucial role in selecting the appropriate turbine foundation technology. Table 1 presents different technologies used for various ranges of water depth. Water depth in the offshore area has a direct impact on the design, construction and cost of turbine foundation technology. At present, monopile and gravity foundations are used at shallow depths up to 35 m. For initial development of offshore wind project, monopile foundation technology is more feasible in terms of economics.

Figure 1 represents bathymetric map of the offshore region along the west coast of India obtained from the National Oceanic and Atmospheric Administration (NOAA). A major portion of the west coast is part of Gujarat and Maharashtra. Gujarat has the longest coastline of 1608 km, whereas Maharashtra has nearly 800 km coastline. In the present study, area within the western coastal region of India up to 35 m depth has been considered and divided into three regions, i.e. 1–10 m (green), 10–20 m (red), and 20–35 m (maroon) depth (Figure 1). Table 2 shows the offshore area calculations for selected bathymetric depth regions. Within the area having water depth up to 35 m, maximum estimated available area is found in the vicinity of Dandi and Kutch regions.

Due to various reasons (nautical hazards, shipping lanes, marine conservation sites, commercial fishing, range of military radar, biological and visual impacts of wind turbines, and uncontaminated mud disposal areas), the entire coastal area may not be available for installing wind farms. According to Dhanju *et al.*[10], the sum of all the above-mentioned areas (many of which overlap) is in the 10–46% range. Dvorak *et al.*[11] estimated the conflict areas as 33%. From the study of Dhanju *et al.*[10], a maximum limit of 46% as conflict area is considered in calculations of the present scenario for the west coast of India.

Table 1. Offshore wind turbine foundation technologies with appropriated water depth range

Foundation technology	Range of water depth (m)
Monopile (fixed-bottom foundation technology)	0–35
Jacket	35–50
Advanced jacket	50–100
Floating	100–700

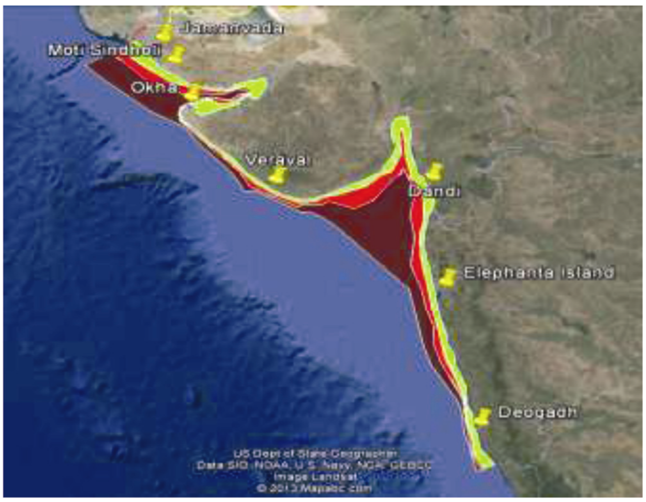

Figure 1. Bathymetry of selected offshore area and nearby meteorological stations of the western coast of India.

Wind data

For wind resource assessment, remotely sensed WindSat wind data and meteorological wind data have been used in this study. Satellite data have been extensively used for offshore wind resource assessment. Remote sensing wind data retrieved from NASA's WindSat data products over a period of five years from 2009 to 2013, at a spatial resolution of ~25 km have been considered for this study. The data obtained from WindSat satellite is 10 m amsl. Meteorological wind data over several years have been collected from NIWE in the form of yearly average wind speed and wind power density at 50 m height[12]. A typical hub height of multi-MW class wind turbines is 80 m. Thus, wind data need to be extrapolated to the required

Table 2. Available offshore area for appropriated water depth regions

Range of water depth (m)	Available area (sq. km)	Percentage
0–10	17,185	25.4
10–20	16,227	24
20–35	34,210	50.6

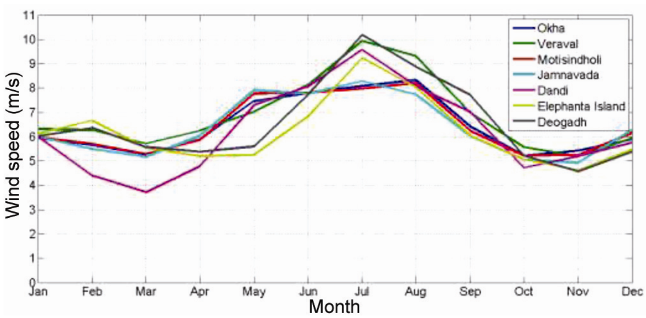

Figure 2. Monthly average wind speed at 80 m hub height.

Table 3. Comparison of meteorological station (Met) and satellite (WindSat) wind speeds at 50 m hub height

	Coordinates		Mean speed (m/s)		Power density (W/m^2)	
Station	Latitude (N)	Longitude (E)	Met	WindSat	Met	WindSat
Okha	22.64	69.04	5.93	6.22	260	190
Veraval	20.91	70.35	5.38	6.63	168	237
Moti Sindholi	23.16	68.78	5.35	6.22	204	192
Jamanvada	23.58	68.6	5.68	6.16	299	188
Dandi	20.89	72.81	4.43	6.00	106	197
Elephanta Island	18.95	72.93	4.93	5.95	158	189
Deogadh	16.37	73.37	5.04	6.31	172	225

Table 4. Wind power output of GE 3.6s and Repower 5M at 80 m hub height using WindSat data

Station	Mean speed (m/s)	Power density (W/m2)	GE 3.6s (kW)	Capacity factor	REpower 5M (kW)	Capacity factor
Okha	6.45	213	250,038	0.27	334,554	0.26
Veraval	6.89	266	279,711	0.30	376,047	0.29
Moti Sindholi	6.46	215	236,222	0.25	316,118	0.24
Jamanvada	6.40	210	233,304	0.25	312,064	0.24
Dandi	6.23	221	231,496	0.25	311,521	0.24
Elephanta Island	6.18	211	222,185	0.24	299,755	0.23
Deogadh	6.55	252	259,781	0.28	352,534	0.27
Mean				0.26		0.25

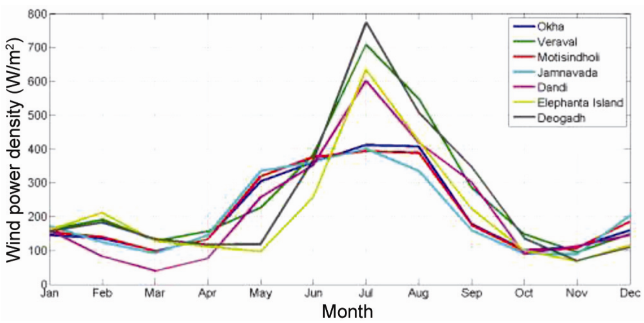

Figure 3. Monthly average wind power density at 80 m hub height.

height, i.e. 50 and 80 m amsl respectively. In order to extrapolate wind speed at the hub height over water, log-law has been used. The log-law states that velocity V at a given height z is given by

$$\frac{V(z)}{V(z_r)} = \frac{\ln(z/z_o)}{\ln(z_r/z_o)}. \tag{1}$$

where $V(z_r)$ is the wind speed measured at the reference height z_r and z_0 is the surface roughness. Neutral stability of the atmosphere and a surface roughness of $z_0 = 0.2$ mm, which is recommended as an average value for ocean surface have been assumed[13,14]. Weekly average wind speed data for seven nodes of the satellite grid, each closest to the seven stations (situated near the coastal area) have been extracted from WindSat data. Annual and monthly average wind speeds and wind power density (WPD), over the period of five years were also calculated. Tables 3 and 4 present wind speed and wind power computed from the meteorological stations (Met) and satellite (WindSat) data. Figure 2 illustrates variation of average monthly wind speeds at 80 m hub height of the seven stations near the coast. Average wind speed was observed to be the highest during monsoon season (June–August) in all the selected locations.

WPD is a true indicator of wind energy potential of a site, rather than wind power alone. WPD is defined as the wind power per unit area swept by the turbine blades and is proportional to the cube of wind speed.

$$\text{WPD} = \left(\frac{1}{2n}\right)\sum_{i=1}^{n} \rho V^3, \tag{2}$$

where n is the total number of observations in the measurement period, ρ the air density taken as 1.225 kg/m^3 and V is the weekly mean wind speed (m/s). Figure 3 illustrates variation of average monthly wind power density at seven stations, extrapolated to 80 m hub height using eq. (2).

According to some studies[15,16], satellite data show high uncertainty for wind speeds lower than 5 m/s. At lower wind speeds, the uncertainties of wind retrievals are higher as the smooth sea surface appears more as a reflector than as a scatterer, making it difficult to detect and distinguish the microwave backscatter from noise. Moreover, it has been observed that wind speed retrievals from satellite in near-shore stations (up to 54 km) are not as accurate compared to offshore stations due to land contamination[17]. Further, errors introduced due to height extrapolation might also be partially responsible for the observed difference between the satellite and mast data, since the ratio of equivalent neutral wind to the actual wind at 10 m is a function of both air temperature and wind speed, especially in the periods of high or low air temperature[18]. Mean wind speeds from satellite data are observed in the 7.5–13% range, which is higher than buoy data[15]. Oh *et al.*[19] showed that the mean wind speed from satellite data overestimates in the 1.8–16.3% range.

Table 3 shows a comparison between available Met data and WindSat data at 50 m height. In most of the locations, mean speed calculated from WindSat is 5–26% higher that from Met data. The satellite data lead to an average overestimation of 16% wind speed, which will cause 56% overestimation of WPD. The present calculations show that at a height of 80 m, the western coastal area experiences offshore average annual wind speeds between 6.18 and 6.89 m/s, while WPD varies from 210 to 266 W/m^2 (Table 4).

In present study, GE 3.6s and the REpower 5M wind turbines have been selected for the calculation of electricity generation. Figure 4 shows the power curves for the two turbines. Theoretically, the maximum power an ideal rotor can extract from wind is 59.3%, which represents the Betz limit or maximum theoretical efficiency of a turbine rotor. Compared with the theoretical maximum of 59%, about 45% of wind energy is harvested presently by wind turbines[13,14]. For simplicity, a turbine hub height of 80 m amsl is assumed. The turbine has a minimum speed, called the 'cut-in' speed, below which it does not produce power. It also has a maximum or 'cut-out' speed above which it shuts down for self-protection and will not produce power. The rated capacity is achieved for wind speed greater than 14 and 13 m/s respectively, for GE 3.6s and REpower 5M (Table 5)[20,21].

Estimation of power produced

Annual energy production (AEP) has been estimated based on power curve [$P(v)$] of the selected wind turbine model and the wind speed frequency distribution [$f(v)$], using eq. (3).

$$\mathrm{AEP} = n \sum_{\text{cut-in}}^{\text{cut-out}} P(v) f(v). \tag{3}$$

For the different locations in the area of study, the capacity factor (CF) of each turbine has been calculated (Table 4) using eq. (4)

$$\mathrm{CF} = \frac{\mathrm{AEP}}{\text{Rated power} \times n}. \tag{4}$$

As shown in Table 4, mean CF is 0.26 and 0.25 for GE 3.6s and Repower 5M respectively. To calculate the power that could be produced by the offshore wind resource, first the number of turbines that would fit within the area is calculated. Then, the wind regime power output of each turbine is analysed. The array spacing for the turbine is given by

$$\text{Array spacing} = (\text{Rotor diameter})^2 \times \text{downwind spacing factor} \times \text{crosswind spacing factor}. \tag{5}$$

According to the recommendation of Maxwell *et al.*[14] and the procedure outlined by Sheridan *et al.*[22], spacing factors for crosswind and downwind are 5 and 10 rotor diameter respectively, in order to minimize the inter-turbine wake losses. Thus, the corresponding array spacing values are 0.54 and 0.79 sq. km respectively, for GE 3.6s and REpower 5M. Using the array spacing, the number of turbines that could be installed in different depth zones is calculated as shown in eq. (6).

$$\text{Number of turbines} = \frac{\text{Total available area}}{\text{Array spacing}}. \tag{6}$$

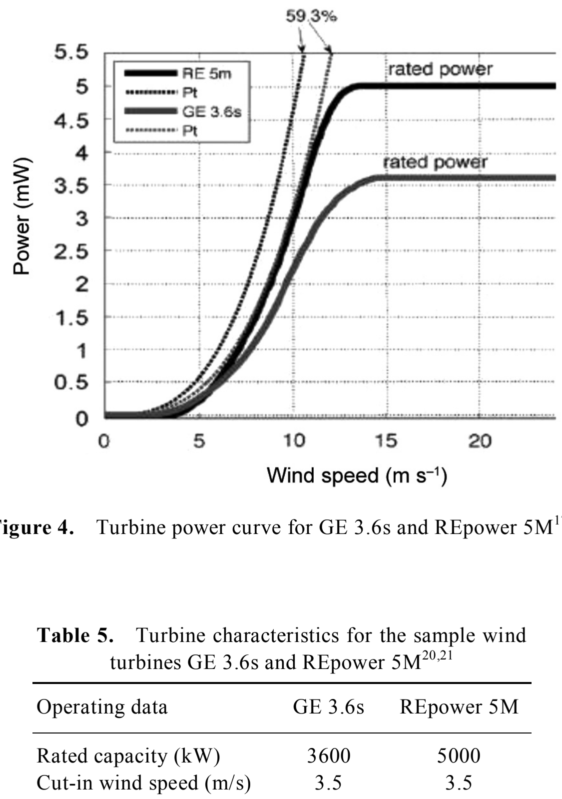

Figure 4. Turbine power curve for GE 3.6s and REpower 5M[17].

Table 5. Turbine characteristics for the sample wind turbines GE 3.6s and REpower 5M[20,21]

Operating data	GE 3.6s	REpower 5M
Rated capacity (kW)	3600	5000
Cut-in wind speed (m/s)	3.5	3.5
Cut-out wind speed (m/s)	25	30
Rated speed (m/s)	14	13
Number of blades	3	3
Rotor diameter	104	126
Swept area (m^2)	8495	12,469

Table 6. Available areas, number of turbines and average output

	0–10 (m)	10–20 (m)	20–35 (m)	Total
Available area (km^2)	17,185	16,227	34,210	67,622
No. of GE 3.6s turbines	31,825	30,050	63,352	125,226
GE 3.6s nameplate capacity (GW)	115	108	228	451
GE 3.6s average output (GW)	26	24	51	101
No. of RE Power 5 MW turbines	21,754	20,541	43,304	85,598
RE Power 5 MW nameplate capacity (GW)	109	103	217	428
RE Power 5 MW average output (GW)	23	22	47	92

Table 7. Annual power generation before and after subtracting conflict area of western coast of India

	Turbine	Available area (km^2)	No. of turbines	Nameplate capacity (GW)	Average output (GW)	Total annual power generation (TWh/year)
Before subtracting conflict area	GE 3.6s	67,622	125,226	451	101	884.6
After subtracting conflict area		36,516	67,622	243	55	477.6
Before subtracting conflict area	REpower 5M	67,622	85,598	428	92	809.8
After subtracting conflict area		36,516	46,223	231	50	437.3

The nameplate capacity (i.e. total installed capacity) is determined by multiplying the number of turbines and nameplate capacity of each turbine. Table 6 provides details of the offshore area for different bathymetric depth regions. The total available area evaluated up to 35 m depth is 67,622 sq. km. This was partitioned into 17,185 sq. km located between the isobaths of 0 and 10 m, 16,227 sq. km between 10 and 20 m and 34,210 sq. km between 20 and 35 m. Average yield is calculated by multiplying the nameplate capacity of the turbines by 'all-in' capacity factor which is calculated by multiplying capacity factor of each turbine, wake effect and availability.

Wake effect refers to the reduction in generation due to increased turbulence caused by windward turbines. Availability is the fraction of time that a wind project is ready to operate, taking into account planned and unplanned outages. For the present study, a wake effect of 10% average power production and availability of 95% has been assumed[10]. Further an 'all-in' capacity factor of 0.222 for GE 3.6s and 0.213 for REpower 5M turbines is evaluated, which includes wake effect and wind turbine availability. On this basis, average GE 3.6s turbine power output between the shore and the 10 m isobaths is 26 GW. Further extending the limit up to 20 m, average power output goes up to 50 GW. Up to 35 m, average power output touches 101 GW (Table 6). The total area for offshore wind development could be in conflict with different factors. Subtracting the 46% conflict area from the total available area provides an estimation of the total effective area available for offshore wind development (Table 7). A total of 67,622 and 46,223 turbines of GE 3.6s and Repower 5M respectively, can be installed within the total effective area. This translates into average annual power generation of 477 and 437 TWh for GE 3.6s and REpower 5M respectively.

Here, it has to be noted that even though the nameplate capacity of REpower 5M is higher than that of GE 3.6s, the power generation obtained from the latter is higher than that obtained from the former turbine model. This is because wind turbines with higher nameplate capacities tend to have larger rotor diameters, which translates into larger array spacing (according to eq. 5), thus resulting in installation of fewer turbines, and thereby reducing the net power generation. Hence while selecting wind turbine models for installation, a balance needs to be achieved between the nameplate capacity and array spacing, in order to extract maximum power from the available wind resource.

Approximately 75% of the total cost of energy for a wind turbine is related to upfront costs such as those of turbine, foundation, electric equipment, grid connection, etc. As offshore wind farms involve high investments, plant profitability can be reached by increasing the installed power capacity. In this case, power loss reduction constitutes an important issue. Distance from shore involves higher cost for transmission system. On the other hand, greater distance from shore usually involves greater depths, that have effect on foundation costs. Therefore, more detailed analysis is required with respect to legal policies and techno-commercial feasibility in order to identify attractive opportunities for investment in offshore wind power development in the west coast of India.

Conclusions

- The results indicate that offshore wind resource in the west coast of India is large enough to significantly contribute to the electricity needs of the country.
- Densely populated cities are located in the western coastal region. They can gain from this resource in

addition to the conventional thermal electrical power. Higher offshore wind power production can bring about reduction in carbon emissions.

- Using existing monopile foundation and accounting for conflict areas, the available wind resource can generate an annual power of 477 and 437 TWh for GE3.6s and RE Power 5M respectively. It is nearly equal to one-fifth of the installed capacity of all the present energy sources in India.
- While selecting wind turbine models for installation, a balance needs to be achieved between the nameplate capacity and array spacing, in order to extract maximum power from the available wind resource.

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