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GIS-based approach for the evaluation of offshore wind power potential for Gujarat

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Abstract. In the current global scenario, India is increasing its focus towards the methods to enrich the benefits of non-renewable energy sources as much as possible due to their key advantage of having low carbon footprint. India has already emerged as a key global player in on-shore wind energy and to achieve its annual wind energy production demand of 50 GWh, avenues other than current options have been researched on. Offshore wind energy has experienced remarkable growth worldwide but has not yet been harnessed sufficiently in India, despite addressing many of environmental and economic concerns. The present study focuses on offshore wind resource assessment on Indian exclusive economic zone (EEZ) around Gujarat region. The geographical information system (GIS) methodology has been used to develop maps of wind speed, power density and capacity factor maps. Further, careful consideration has been accorded for expulsion of marine protected areas, shipping transportation lines, fishing zones, and migratory bird movements. The resultant available area has been considered for annual energy production considering data from Siemens Wind Turbine 3.6. The results obtained shows that offshore wind energy can offset twice the annual energy demand of entire country with a potential energy production of more than 2580 TWh.

1 Introduction

The Indian wind industry is nearly thirty years old, and now holds the 4th position in the world with installations of over 31 GW. According to the Conference of Paris (CoP-21), India has committed to produce 40% of its electricity from non-renewable sources by 2030. India committed to commission 60 GW of power production capacity from wind resources by 2022 [1].

Onshore wind turbines are associated with some negative environmental implications such as visual and noise impacts, impacts on birdlife and other types of environment impacts [2]. This decelerates future development of onshore turbine installations and makes it difficult for energy planners to localize suitable sites. The wind resource at offshore site is generally larger than at geographically nearby onshore sites, which can offset their higher installation, operation and maintenance costs. Successful offshore wind energy development relies to some extent on accurate prediction of wind resources, but since installing and operating a meteorological in situ is expensive, prospective sites must be carefully evaluated.

Gujarat has a long continental shelf over 50-60 per cent of its total coastline wherein the slope of the sea is gradual thereby setting up of offshore wind power is conducive. In addition, southwest winds come all over Gujarat from the Arabian Sea, thereby providing unhindered wind for at least six months. Hence, it has advantage compared to other states and huge potential to produce power from offshore winds from its coast [3]. The average wind speed in Gujarat recorded by the National

Renewable Energy Laboratory (NREL) is 8m/s and is sufficient speed to generate electricity by a wind turbine [4].
Carrying out wind measurement for several years is considered as the most suited approach to estimate wind energy potential of a region [5]. But to cover a large offshore area, it would be infeasible to perform that sort of measurement by add-on meteorological or measurement stations. Hence, depending on the situation, different methodologies are applied to assess wind energy accordingly. Moller [6] presented a model called Spatially Continuous Resource Economic Assessment Model for Offshore Wind Energy (SCREAM-offshore wind) based on GIS. It is not suitable for actual setting, as it does not precisely direct to the exact location. Dhanju et al.[7] presented a preliminary analysis for off shore wind potential on east coast of US by mapping wind speed and bathymetric data an exploring the possibility of setting up an offshore wind farm or multiple farms.
Thus, in lieu of offshore meteorological towers, some offshore wind resource studies extend land-based measurements to the areas over the ocean via modeling techniques [8], [9]. Others have characterized the resource by using offshore wind measurements from buoys or satellites and extrapolating those measurements to wind turbine hub height [7]. Furthermore, data collection on competing uses, such as environmental habitats, shipping and geologic conditions of the ocean is less complete than on land. Reference from the bathymetry data, shipping lines, fishing zones and protected marine areas have played a key role to obtain the useful area for the installation of the offshore wind turbines by excluding the other non-useful areas of the sea.
In this paper, a comprehensive wind power assessment has been performed to assess power generation potential in offshore region of Gujarat state in India. The results provide an estimate of Gujarat's feasible offshore wind energy resource. Offshore area of Gujarat was being assimilated based on bathymetric data to determine potential wind turbine foundation area. Thereafter this data was reanalyzed for potential wind area for power generation using wind speed data. The novel concept of exclusion of potential areas considering the detrimental effects such as environmental factors, shipping lines, marine protected area and fishing zones which have been uniquely identified using various sources. These factors are being subtracted to reanalyze the actual wind power potential. However, the results of wind energy harnessing potential obtained from this analysis are still greatly optimistic. We hope that this study will encourage further implementation of the offshore wind power resource and its ability to provide renewable electricity for coastal regions.

2 Methodology

The methodology developed for this study includes various steps such as –

1. Bathymetry data & Foundation base assimilation and categorization.
2. Exploring detrimental area: Fishing zones, shipping lines, environmental factors and marine protected areas.
3. Evaluation of potential area for power generation.
4. Calculation of theoretical number of turbines.
5. Wind speed data at hub height.
6. Power output per turbine.
7. Evaluating wind power potential

2.1 Bathymetry data and foundation base assimilation and categorization

Bathymetric data plays a crucial role in selecting the appropriate turbine foundation technology. Different technologies used vary with water depth as mentioned in table 1. Water depth in the offshore area has a direct impact on the design, construction and cost of turbine foundation technology. In the present study, bathymetry data has been retrieved from GEBCO (General Bathymetric Chart of the Oceans) with a spatial resolution of 30-arc second. Advanced jacket and floating foundations are under research & development. Based on bathymetry data, the study area has been processed and presented in figure1 (a). Monopiles are currently by far the most popular solution used worldwide, with 75% share, in comparison with only 5% for jacket/tripod options[10]. Within the area having water depth up to 30 m, maximum estimated available area is found near southern and western part of study area.

2.2 Exclusion zones

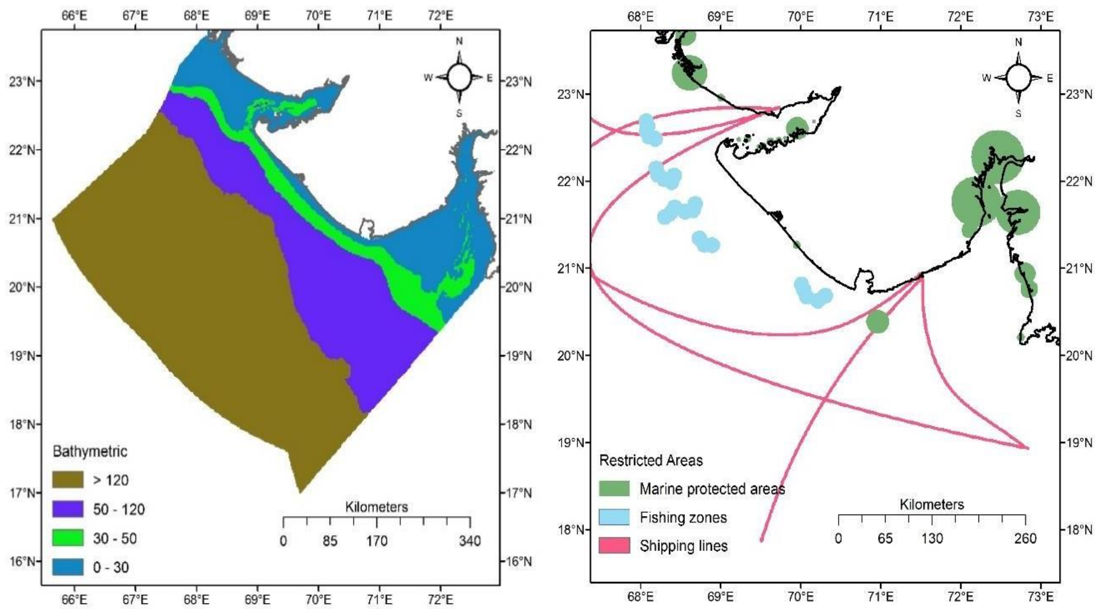
The 42 ports (one major, rest non-major) in Gujarat account for about a phenomenal 35% of the total traffic handled by all ports in India [11]. Suitable site for wind energy should not be located in a route junction or converging area of ships' routing or in any other way in the vicinity to maintain the risk to shipping at a minimum [12] A buffer of 2 km is provided on both side of shipping line considering full shipping constraint [13].

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

Foundation Technology	Water depth range (m)	Available area (km^2)	Percentage area
Monopile	0-30	23935	10%
Jacket	30-50	7585	3%
Advanced Jacket	50-120	60152	25%
Floating	>120	149008	62%
Total		240680	100%

The environmental impacts of any offshore wind project need to be analyzed prior to its construction and during its operation. About 75% of the total marine fish landings of Gujarat are of comparatively low economic value. At present, there are 5 developed fishing harbors with good infrastructure, 18 developed landing centers and 117 other landing centers without any major infrastructure [11]. In order to calculate the distances at which fish can be affected by noise, models of sound propagation under water have been combined with knowledge of hearing and reaction of fish towards sound. Some studies considered noise caused by piling which is 80 kilometers away was being perceived by fishes such as herring and cod [14].

Considering Gujarat, regions highlighted with blue contours in figure 1(b) are important in this regard. Although wind energy is considered as environmental friendly, its development has caused a negative impact on the birds. These include displacement from existing habitats, risk of collisions with wind turbine blades, and migration barriers for birds. Thus to avoid displacement, certain areas should be restricted from installation of wind farms. Even though local bird species have adapted to wind farms, many vulnerable species are severely impacted through wind farms being established in their traditional feeding or breeding areas [14].



(a) **(b)**

Figure 1. (a) Classification of bathymetric data based on offshore wind turbine foundation technologies. (b) Exclusion areas for different utilities such as Marine protected area, fishing zones and shipping lines.

3 Calculation of offshore wind power potential

3.1 Analysis of wind data

Studies utilizing reanalysis wind dataset (ERA-Interim) to provide a summary of offshore wind energy potential in the exclusive economic zone of India indicate that reanalysis data can be considered as fit for estimation of available wind energy potential within such zones. ERA-Interim offers the greatest serial correlation with high-quality observations and greatest internal consistency over time [15]. For estimation of available wind energy potential further reanalysis data can be considered.

The main advantages of reanalysis data are the space and time homogeneity and the long series simulated. Of the many reanalysis data sets, studies indicate for the sample points chosen, ERA-Interim offers the greatest serial correlation with high-quality observations and greatest internal consistency over time [15]. Further reanalysis data can be considered as fit for estimation of available wind energy potential. The offshore wind resource is obtained based on monthly average reanalysis wind data-sets ERA-Interim made available by the European Centre for Medium-range Weather Forecasting (ECMWF)[16]. Datasets are obtained for 14 years from 2001 to 2014 at a spatial resolution of 0.125^{o} (~12.5 km).

3.2 Wind energy analysis

The wind speed data is obtained at the height of 10 m above sea level, but we have to extrapolate it at a hub height of 80 m using equation (1).

$$V = V_{ref} \frac{\ln(z/z_o)}{\ln(z_{ref}/z_o)} \tag{1}$$

where, V is wind speed at hub height z, and z_{ref} is the height at which wind speed V_{ref} is measured. A surface roughness factor z_0 = 0.2 mm [17] is considered in the present study.

Power density is the amount of power generated at a particular wind speed per unit area swept by the wind turbine rotor (W/m^2). The mean wind speed and mean wind power density are estimated from equation (2) and equation (3).

$$\bar{V} = \frac{1}{N}\sum_{i=1}^{N} V_{\mathrm{i}} \tag{2}$$

$$\frac{P}{A} = \frac{1}{2}\rho\frac{\sum_{i=1}^{N} V_{\mathrm{i}}^{3}}{N} \tag{3}$$

Where V_i is the wind speed at observation i, ρ is wind density (1.225 kg/m^3) [19] and N is the number of observations.

3.3 Calculating wind power output

Low wind offshore regions are the regions with mean wind speed less than 7 m/s at 80 m above sea level and therefore the generated energy is limited by the swept area of the rotor[18,19]. The performance of the WT rotor is assessed by the rated rotor productivity (RRP), which is given as the ratio of rated capacity to swept area of WT. At high speed wind speeds, higher RRP metric WT achieves a higher Capacity Factor (CF). Accordingly, Siemens SWT 3.6-120 wind turbine having relatively large rotor and small generator ratio are chosen for the present study. The performance characteristics of the selected WT is described in Table 2 [20].

The net electric power generation (P) given in equation (4) can be calculated using information about the power curve taken from product catalogues [20] and of Siemens SWT 3.6-120 (SWT-3.6).

Capacity factor (CF) can be defined as the ratio of actual power generation to the rated power generation at a particular location, over a given period (T) as given in equation (5). In this study, CF is evaluated based on 14 years of wind data.

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Table 2. Turbine characteristics for the sample wind turbine Siemens wind turbine

Operating data	SWT – 3.6 - 120
Rated Power (kW)	3600
Cut-in wind speed; V_{ci} (m/s)	3
Rated wind speed; V_r (m/s)	12
Cut-out wind speed; V_{CO}(m/s)	25
Rotor Diameter (m)	120
Swept Area (m^2)	11300
Hub Height (m)	site-specific

$$P = \begin{cases} 0 & V \le 3 \\ 1.138V_i^3 + 11.34V_i^2 - 2.526V_i - 98.18 & 3 < V \le 11 \\ 239.3V_i^3 - 8709V_i^2 + 105800V_i - 426200 & 11 < V \le 13 \\ 3600 & 13 < V \le 25 \end{cases} \tag{4}$$

$$CF = \frac{\text{Electric power generation } P(kWh/year)}{\text{Rated power}(kW) \times T(hours/year)} \tag{5}$$

3.4 Energy production

To calculate the power that could be produced by the offshore wind resource, first the number of turbines that could be fitted within the available area is determined. Subsequently, the wind regime power output of each turbine is analysed. The array spacing for the turbine is given by equation (6).

$$\text{Array Spacing} = (\text{rotor diameter})^2 \times \text{Downwind spacing factor} \times \text{Crosswind spacing factor} \tag{6}$$

Where, downwind space factor is 5 and crosswind space factor is 10.

$$\text{Number of turbines} = \frac{\text{Total available area}}{\text{Array spacing}} \tag{7}$$

Depending on array spacing, number of WTs that can be installed within the available area is estimated from the following equation (7). The nameplate wind capacity (i.e. total installed capacity) is found by multiplying the number of turbines by the nameplate capacity of a single turbine. The average output or Annual Energy Production (AEP) is more useful than installing nameplate capacity while comparing renewable energy resources such as offshore wind to traditional energy generation sources (i.e. coal, nuclear, natural gas). AEP is calculated by multiplying nameplate capacity with capacity factor as given in equation (8).

$$AEP = \text{CF} \times \text{nameplate capacity} \times \text{number of hours in the year} \tag{8}$$

The energy-produced regions of Gujarat area along with their corresponding depths were found and tabulated in Table 4. Given the available area, a plant with a potential of maximum 2580.46 TWh is feasible with SWT 3.6 on offshore conditions of Arabian Sea. The values of AEP represent the minimum assured power generation from the selected WT in the selected region.

4 Result and discussion

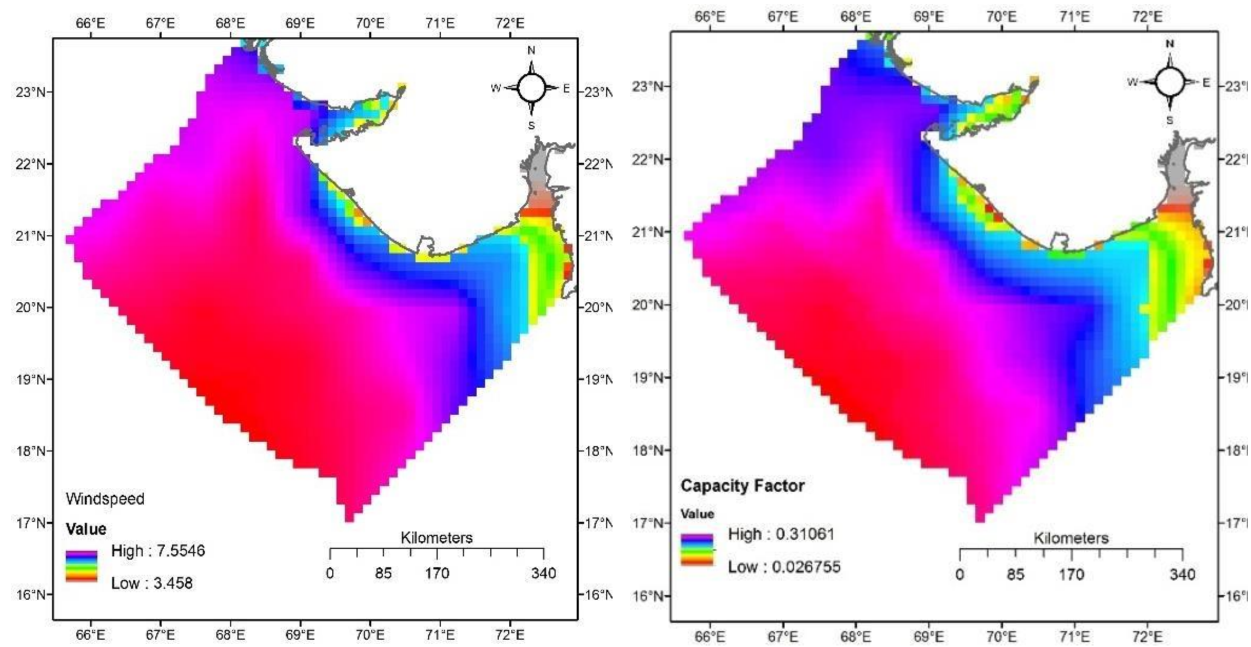
Foundation technology specific areas were calculated based on bathymetry data and wind speed. Available area in km^2 and the percentage of the total area for various water depths and corresponding

foundation technology are as given in Table 1. Firstly, currently used monopile and jacket type foundation technology has 23935 km^2, which cover 10 % of the total area, and 7585 km^2, which covers 3% of the total area respectively. Secondly under R&D phase advanced jacket and the floating type foundation technology has 60152 km^2, which cover 25 % of the total area and 149008 km^2, which cover 62% of the total area respectively. From the Table 1 the net available area out of the total offshore area for the installation of wind turbine is obtained by eliminating the exclusion areas like shipping lines, fishing zones and protected marine areas. Hence, this net area must be used as efficient as possible for harnessing the offshore wind energy.
Spatial distribution of wind speed over study area at 80 m height is shown in figure 2(a). It depicts that the Kutch region state has highest wind speed along its coast as compared to the other coastal regions of the Gujarat. The Saurashtra region of the state has lower wind speed along its coastal region as compared to that of Kutch region but has greater value as compared to southern region of the state, which includes cities like Surat, Valsad, Vapi and many industrial areas.
Spatial distribution of capacity factor over study area at a 80 m height is shown in figure 2(b). It shows that the topmost region i.e. the Kutch region of the Gujarat state has the highest capacity factor as compared to the Saurashtra and the southern region of the state. The Saurashtra region has the capacity factor far less than that of the Kutch region but higher than that of the southern part of the state.
Results obtained from the available area, power potential and energy generation depth are shown in Table 3 below. Data like available area in km^2, number of wind turbines, nameplate capacity in (MW), average output (MWs), capacity factor and total annual generation (TWh/year) is obtained for various depths at which the turbine hub is placed. The value of all data as mentioned in the above statement is highest for the wind turbine at a depth greater than 120 m. The exclusion of area leads to a minor loss of potential of 225 TWh, with the conflict by designated shipping lines being the highest contributing factor. This exclusion amounts to energy potential of 121.7 TWh and an area subtraction of 11010 km^2. Thus, the heavy ship traffic significantly reduces the available area for offshore wind projects. Yet, the annual energy production is still substantial to provide feasibility of an offshore wind farm. Though the energy potential of the areas having water depth of 0-30 m & 30-50 m can substantiate a large amount of energy requirement for Gujarat, technological up gradation in floating turbines can help exploit wind potential at water depth greater than 50 m which is economically feasible.
Power potential and energy generation from the entire study area before and after subtracting exclusion areas like the shipping lines, fishing zones and marine protected areas is mentioned in table 3. Data like available area in km^2, number of wind turbines, nameplate capacity (MW), average output (MWs) and total power generation (TWh/year) is obtained for two different cases; firstly for the data for before considering restricted area and the second includes after subtracting the restricted areas. Here, the restricted area includes the shipping lines, fishing zones and marine protected areas. Table 4 summarizes that by considering the exclusion zones, the gross available area for offshore wind production decreases.

Table 3. Power potential and energy generation from the entire study area before and after subtracting exclusion areas.

	Available area (km^2)	Wind Turbines	Nameplate Capacity (MW)	Average Output (MW)	Total Annual Generation (TWh/year)
Before subtracting restricted area	240680	334278	1203401	320345	2806
After subtracting restricted area	218737	303801	1093684	294573	2580

Gujarat had energy requirement of approximately 94.9 GWh, while it produced annual surplus of 232MWh, and the country faced a deficit of 23 TWh [21]. Table 4 shows that within the 0-30 m depth range of offshore wind turbine allows the installation of nearly 24138 turbines, which on average could supply annual energy generation of 135 TWh, roughly 142% of the Gujarat Energy Requirement. And considering a depth of 0- 50 m, offshore wind has the potential to fulfil 522% of Gujarat's load. If fully developed out to greater depth, offshore wind power has the potential of total annual generation of 2580 TWh per year, which is twice the India's electric consumption of 1162 TWh/year.



(a) **(b)**

Figure 2. (a) Spatial distribution of wind speed over study area at 80 m height. (b) Spatial distribution of capacity factor over study area at 80 m height

Table 4. Available area, power potential and annual energy generation corresponding to various depth.

Depth (m)	Available area (km^2)	Number of Wind Turbines	Nameplate Capacity in (MW)	Average Output (MW)	Capacity factor	Annual energy Generation (TWh/year)
0-30	17380	24138	86897	15496	0.18	135
30-50	5330	7403	26651	5659	0.21	49
50-120	52254	72575	261270	66044	0.25	578
>120	143773	199685	718866	207373	0.29	1816
Total	**218737**	**303801**	**1093684**	**294573**		**2580**

5 Conclusion

The potential annual energy production using SWT 3.6-120 is found to be 2580 TWh, more than twice the annual energy demand of India in 2016.

The study used reanalysis and bathymetric data show that wind potential in 0-30m depth has potential of 135.8 TWh per year which is feasible with current technologies.

Due considerations for marine protection zones, fishing zones, shipping lines and migratory bird movements have been accorded and corresponding area expulsion is done. The available area is found to be 90.91% of total area. Shipping lines corresponding to highest reduction with to 4.57% of total available area. The resulting reduction of 8% in wind resource potential is not significant to adversely affect the feasibility of wind farm project.

The study methodology presented a robust wind farm assessment with a consideration of environmental, shipping transportation and fishing zones for offshore areas on Gujarat. A careful consideration of overall impact of such offshore wind projects would be helpful for policy formulation.

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