Contents list available at IJRED website
Int. Journal of Renewable Energy Development (IJRED)
Journal homepage: https://ijred.undip.ac.id

Research Article

Techno-Economic Analysis and Planning for the Development of Large Scale Offshore Wind Farm in India

Mohammad Mushir Riaz and Badrul Hasan Khan*

Department of Electrical Engineering, Faculty of Engineering & Technology, Aligarh Muslim University, Aligarh, India

ABSTRACT. Despite India's great potential for offshore wind energy development, no offshore wind farm exists in the country. This study aims to plan a large scale offshore wind farm in the south coastal region of India. Seven potential sites were selected for the wind resource assessment study to choose the most suitable site for offshore wind farm development. An optimally matched wind turbine was also selected for each site using the respective power curves and wind speed characteristics. Weibull shape and scale parameters were estimated using WAsP, openwind, maximum likelihood (MLH), and least square regression (LSR) algorithms. The maximum energy-carrying wind speed and the most frequent wind speed were determined using these algorithmic methods. The correlation coefficient (R^2) indicated the efficiency of these methods and showed that all four methods represented wind data at all sites accurately; however, openwind was slightly better than MLH, followed by LSR and WAsP methods. The coastal site, Zone-B with RE power 6.2 M152 wind turbine, was found to be the most suitable site for developing an offshore wind farm. Furthermore, the financial analysis that included preventive maintenance cost and carbon emission analysis was also done. Results show that it is feasible to develop a 430 MW wind farm in the region, zone B, by installing seventy RE power 6.2 M152 offshore wind turbines. The proposed wind farm would provide a unit price of Rs. 6.84 per kWh with a payback period of 5.9 years and, therefore, would be substantially profitable.

Keywords: Weibull Parameters; Windographer; RET Screen; Offshore Wind Farm; GHG; Preventive Maintenance.

Article History: Received: 8th Nov 2020; Revised: 16th Dec 2020; Accepted: 30th Dec 2020; Available online: 2nd January 2021
How to Cite This Article: Khan, B.H. and Riaz, M.M. (2021) Techno-economic analysis and planning for the development of large scale offshore wind farm in India. *International Journal of Renewable Energy Development*, 10(2), 257-268.
https://doi.org/10.14710/ijred.2021.34029

1. Introduction

Energy is one of the essential inputs for the socio-economic development of Nations. With an annual growth rate of 0.99 %, India's population has reached 1.38 billion in 2020 (Population of India, n.d.). As a consequence of the rapid population growth and enhanced developmental activities, the country's energy demands would increase tremendously in the coming years. However, the existing installed capacity is inadequate to meet the required energy demands of the country. Moreover, the primary dependence on fossil fuels for energy needs eventually leads to fuel depletion and greenhouse gas emissions that are highly detrimental to the environment.

To overcome these problems, we need to focus on the efficient utilization of renewable energy sources. The wind is a reliable energy source commercially accepted and economically at par with other conventional means among the various clean energy sources. The wind being an abundant and inexhaustible resource, can play a promising role in providing significant energy quantities to the developing world. India has a total of 7600 km of coastline, with three sides surrounded by the sea. The average wind speed is significantly high over the open water surfaces, which renders the coastal areas suitable for installing wind turbines. Due to the availability of a vast coastline area, India has great potential for offshore wind energy development. The powerful and consistent wind speeds, low sound problems, and visual constraints to the residents are the major advantages of offshore wind farms than onshore wind farms. Furthermore, the transportation of heavy equipment and larger turbines is relatively easy in the coastal regions, and the transmission costs and losses are also low. Despite these advantages, offshore wind farms need enormous investment costs to deal with the operation and maintenance problems. This stresses the need to assess the potential of offshore wind farm development in India and minimize investment in the operation and maintenance of offshore wind farms (Kiran *et al.*, 2017; Rajagopalan, 2018). Only limited studies have been carried to assess wind power potential and its offshore application aspects. These include wind energy trend estimation using different techniques (Chaurasiya *et al.*, 2018), wind farm layout design optimization (Bansal *et al.*, 2018), and wind power distribution analysis across different regions (Alluri *et al.*, 2017; Chaurasiya *et al.*, 2019; Indhumathy *et al.*, 2015; Kore & S, 2016; Mohsin & Rao, 2018; Sharma *et al.*, 2019). The large initial cost associated with offshore wind energy technology poses a hindrance to its promotion and development, particularly in developing countries like India. However, on a long-term basis, this technology could prove to be quite

* Corresponding author: drbhkhanamu@mail.com

beneficial and advantageous. Because of the availability of such a vast coastline and the increasing demands for electricity, energy generation through offshore wind farms may be a good option. However, at present, no offshore wind farm exists in India. The present study aims to select the most suitable site from several prospective sites mentioned in Table 2, and work out techno-economic strategies to plan and design large-scale grid-connected offshore wind farm while minimizing the cost of operation and maintenance. Such studies would be particularly crucial for policy/decision-makers in developing wind power technology in the country.

2. Wind resource assessment

The intermittent nature of wind poses a challenge for penetrating wind energy and maintaining the regular and assured supply of power. Hence, an accurate and complete understanding of wind's variable nature at different time scale is crucial for wind resource assessment and its profitable application. To investigate the feasibility of a wind energy project, the first essential step is to evaluate wind characteristics at the prospective site. Therefore, the detailed knowledge of wind is a prerequisite for assessing wind farm development's feasibility and performance accuracy. Wind speed frequency distribution is the most commonly used statistical tool for predicting wind energy yield at a specific site (Burton et al., 2011; Mathew, 2007). The variable nature of wind speed is better characterized by the Weibull distribution function that has been used for several locations worldwide to assess wind potential for the development of large wind farms (Akpınar *et al.*, 2018; Khahro *et al*., 2013; NA *et al*., 2017; Saeidi *et al*., 2011; Sumair *et al*., 2020). In Chad, central Africa, a site was selected to develop a wind farm based on wind resource assessment using two-parameter Weibull distribution (Didane *et al.,* 2017). Another study also analysed the wind speed data using two-parameter Weibull distribution to identify the best site for optimal energy production in Karnataka, India (Kumaraswamy et al., 2009).

A study conducted in Bohai Bay, China, has compared the four probability distribution functions viz. Weibull, Nakagami, Rician, and Rayleigh distributions for assessing wind potential in that region and found the Nakagami distribution to perform better than the other three distributions (Yu *et al*., 2019). However, in another study, three different methods were used to estimate the wind farm's monthly wind power density in Akal, Jaisalmer, Rajasthan. Weibull's two-parameter distribution function provided more accurate wind power density estimates than Weibull's three-parameter or Rayleigh distribution function. (Mohsin & Rao, 2018). The wind speed probability distributions, namely Weibull, Rayleigh, and Gamma distributions, have been compared to assess the wind power potential of four different geographical sites, and the gamma distribution was reported as the best option for the sites with low and high values of mean wind speeds. In contrast, the Weibull distribution was suggested to be the best for moderate wind speed sites (Sohoni *et al*., 2016). Weibull distribution is a two-parameter function, i.e., the scale and shape parameters that depict wind speed variations. Earlier studies have used several methods for the determination of these two parameters (Stevens & Smulders, 1979). Baseer *et al.* have investigated the wind characteristics of seven prospective sites in Saudi Arabia and calculated the two-parameters of the Weibull function using MLH, WAsP, LSR methods and found the MLH to be slightly better than the LSR method followed by the WAsP algorithm (Baseer *et al.,* 2017). Hemanth Kumar et al. have assessed the Wind energy potential in Tirumala, India, by Weibull parameter estimation using Multiverse Optimization and calculated the frequency distribution of wind speed, wind direction, and mean wind speeds for this region (Hemanth Kumar *et al*., 2019). The two-parameter Weibull distribution has been used to describe the wind speed in Bratislava-Mlynská Dolina, employing seven different methods to estimate the shape and scale parameters for wind speed in that region. It was observed that the weighted least squares method performed the best, followed by the maximum likelihood and the method of moments (Pobočíkova et al., 2018). Thus, the two-parameter Weibull distribution is apparently the most widely accepted probability distribution function as it is reasonably accurate in characterizing most of the natural wind regimes and is relatively simple to use. Several earlier studies have documented that the Weibull distribution could be useful in making a judicious choice of a wind site (Ayodele *et al*., 2012; Baseer *et al.,* 2017; Mohsin & Rao, 2018).

2.1 Wind speed data collection

In offshore wind farm development, site selection is a significant step that primarily involves large scale wind resource assessment. For the wind resource assessment, the historical wind data of at least one-year (on-site) measurements is needed to identify the appropriate sites that can generate sustainable output. However, in India, available offshore data is still in generalization. Therefore, wind data (from 2014 to 2019) was downloaded from Windnavigator site, ERA5 data Era Retrospective analysis for Research and Application published, European Centre for Medium-Range Weather Forecasts and provided by AWS Truepower, LLC, a UL Company (Windnavigator, AWS Truepower, a UL Company, n.d.). For the pre estimation of energy production, ERA5 reanalysis data can improve accuracy. In this study, ERA5 data were considered at 100m height above ground level (a.g.l).

3. Statistical models for wind speed data analysis

Using the two functions, i.e., the probability density function and the cumulative density function in Weibull distribution, the wind speed variations can be characterized. The Weibull probability density function $f_{weib}(V)$ that indicates the probability or fraction of time for which the wind is at a given velocity V is expressed by the following equation (Hemanth Kumar *et al.*, 2019; Mathew, 2007)

Table 1
Weibull shape and scale parameters of seven sites

For Zone-A

Algorithm	Weibull k	Weibull A (m/s)	Power Density (W/m²)	R^2
Maximum likelihood	2.147	7.914	376.4	0.8458
Least squares	1.92	7.998	435.7	0.8733
WAsP	2.549	8.174	364	0.767
Openwind	2.248	7.93	364	0.8269

For Zone-B

Algorithm	Weibull k	Weibull A (m/s)	Power Density (W/m²)	R^2
Maximum likelihood	2.741	9.546	556.1	0.8069
Least squares	2.217	9.779	690.4	0.7781
WAsP	3.672	9.874	551.9	0.7708
Openwind	2.814	9.565	551.9	0.8084

For Zone-C

Algorithm	Weibull k	Weibull A (m/s)	Power Density (W/m²)	R^2
Maximum likelihood	2.642	7.901	321.8	0.966
Least squares	2.38	7.997	357	0.9543
WAsP	2.992	8.052	320.2	0.9567
Openwind	2.68	7.909	320.2	0.9664

For Zone-D

Algorithm	Weibull k	Weibull A (m/s)	Power Density (W/m²)	R^2
Maximum likelihood	2.125	6.099	173.9	0.9979
Least squares	2.121	6.106	174.9	0.9977
WAsP	2.12	6.097	174.2	0.9978
Openwind	2.124	6.1	174.2	0.9978

For Zone-E

Algorithm	Weibull k	Weibull A (m/s)	Power Density (W/m²)	R^2
Maximum likelihood	2.376	7.761	326.9	0.9916
Least squares	2.217	7.839	355.6	0.9865
WAsP	2.492	7.831	324.8	0.9918
Openwind	2.413	7.774	324.8	0.992

For Zone-F

Algorithm	Weibull k	Weibull A (m/s)	Power Density (W/m²)	R^2
Maximum likelihood	2.522	7.529	286.4	0.9935
Least squares	2.388	7.58	303.3	0.9921
WAsP	2.647	7.594	285.4	0.9917
Openwind	2.543	7.534	285.4	0.9934

For Zone-G

Algorithm	Weibull k	Weibull A (m/s)	Power Density (W/m²)	R^2
Maximum likelihood	2.734	7.487	268.6	0.9756
Least squares	2.569	7.573	288.1	0.9595
WAsP	2.775	7.506	268.6	0.9781
Openwind	2.763	7.5	268.6	0.9774

$$f_{weib}(V)=\frac{k}{A}Fig.11\left(\frac{V}{A}\right)^{k-1}exp\left[-\frac{V}{A}\right]^{k} \quad (1)$$

Here, k is dimensionless and indicates the peak of wind speed at a wind regime and is known as the Weibull shape factor, while A, the Weibull scale factor, suggests the site's windy nature and is measured in m/s. The Weibull cumulative distribution Fc(V) is the integral of $f_{weib}(V)$ shown as under

$$F_c(V) = \int f_{weib}(V)dV = 1 - exp^{-\left(\frac{V}{A}\right)^k} \quad (2)$$

The average wind velocity of a regime under consideration can be described by

$$V_{avg} = \int_0^\infty V f_{weib}(V)dV \quad (3)$$

Substituting $f_{weib}(V)$ we get in the above equation we get,

$$V_{avg} = A\Gamma\left(1+\frac{1}{k}\right) \quad (4)$$

The standard deviation(σ_v)of the regime under consideration can be described as

$$\sigma_v = A\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]^{\frac{1}{2}} \quad (5)$$

The following four techniques have been used to find the Weibull shape and scale parameters using windographer software as described earlier (Riaz & Khan, 2019b)

(1) Least Square Regression Method
(2) Maximum Likelihood Method
(3) WAsP Algorithm Method
(4) Openwind algorithm method

Table 2
Sites under investigation

Site Name	Location	Degrees, Minutes, Seconds
Zone-A	Laccadive Sea	8°00'00.0"N 77°15'00.0"E
Zone-B	Laccadive Sea	8°00'00.0"N 77°45'00.0"E
Zone-C	Palk Strait	9°30'00.0"N 79°15'00.0"E
Zone-D	Laccadive Sea	14°15'00.0"N 73°45'00.0"E
Zone-E	Arabian Sea	20°30'00.0"N 71°45'00.0"E
Zone-F	Arabian Sea	20°45'00.0"N 71°30'00.0"E
Zone-G	Gulf of Kutch	22°45'00.0"N 69°15'00.0"E

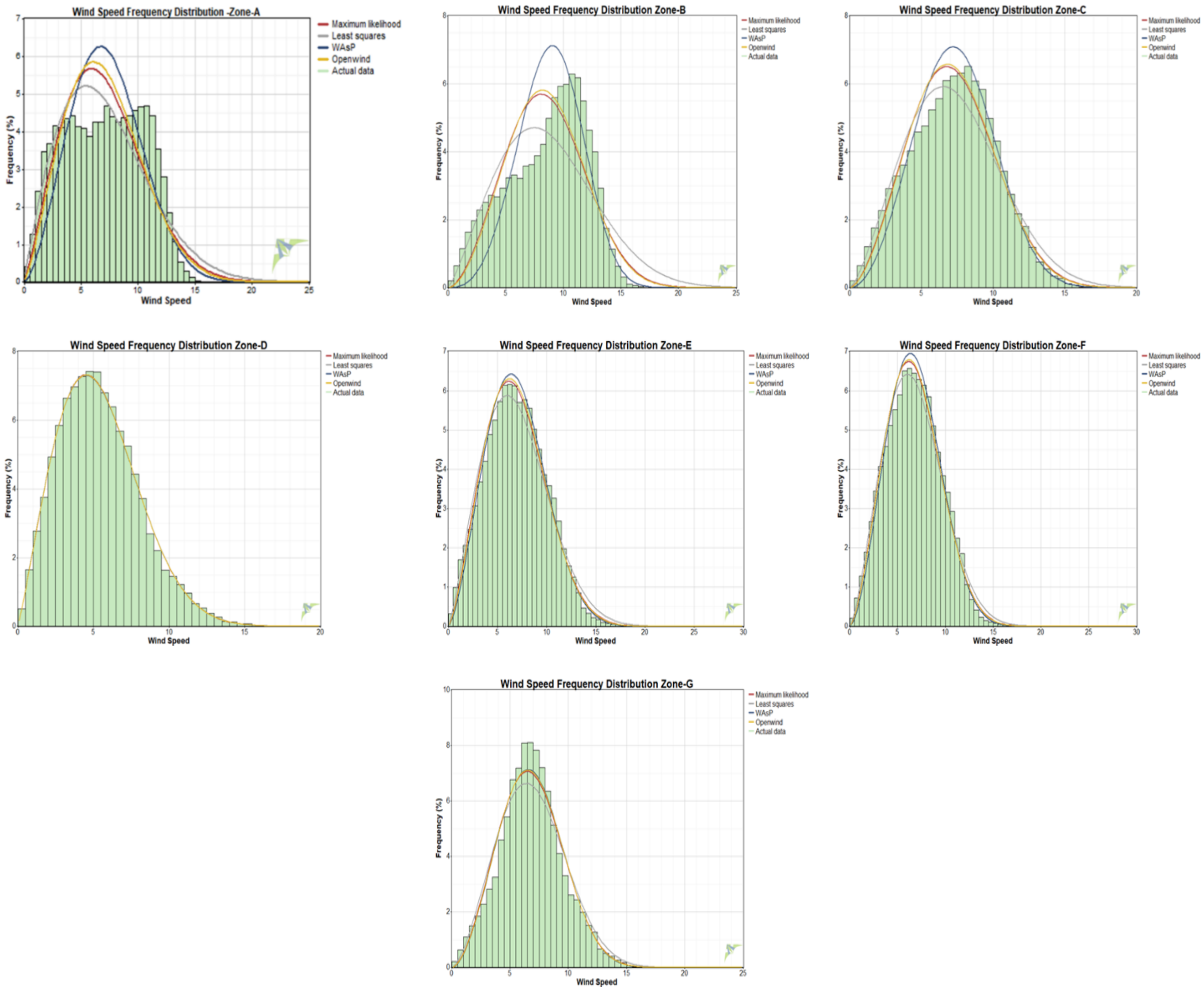

Fig. 1 Weibull probability distributions (four methods) and actual data of seven sites

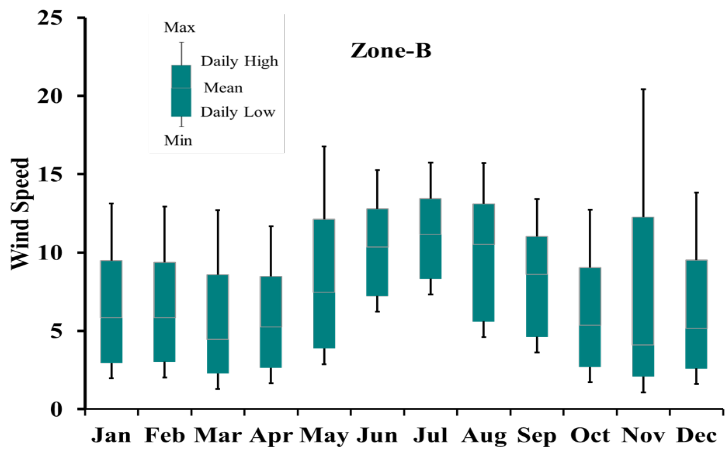

Fig. 2 Monthly wind statistics of Zone-B at 100m height

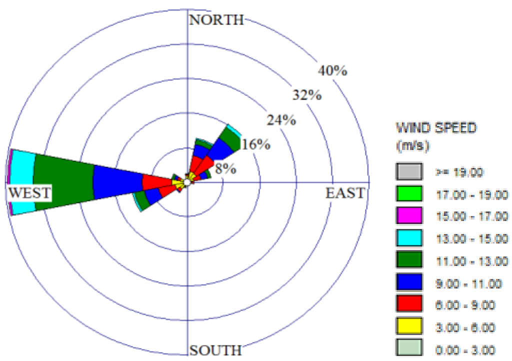

Fig. 3 Wind rose plot of Zone-B

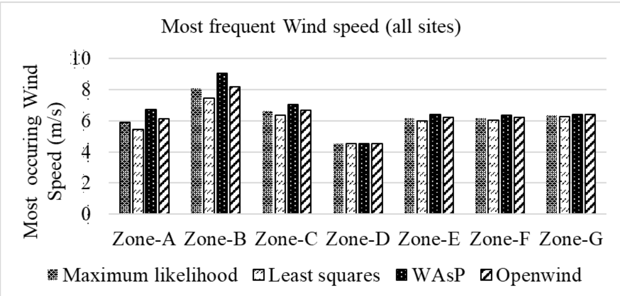

Fig. 4 Most frequent wind speed at all sites.

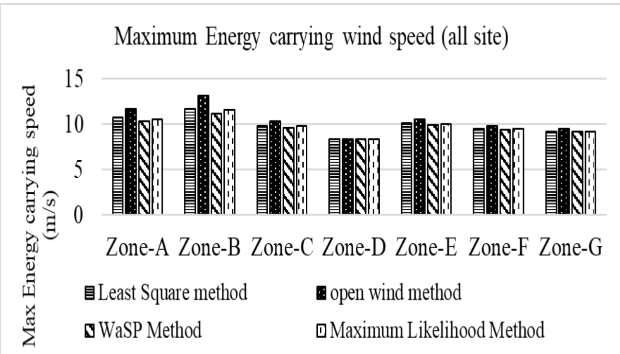

Fig. 5 Maximum energy-carrying wind speed at all sites

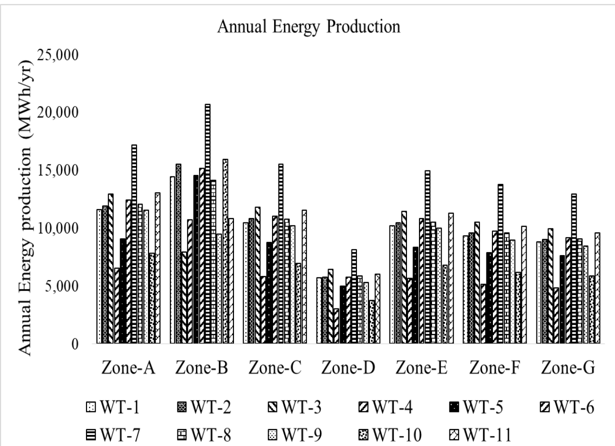

Fig. 6 The annual energy output of all turbines under consideration at all the sites

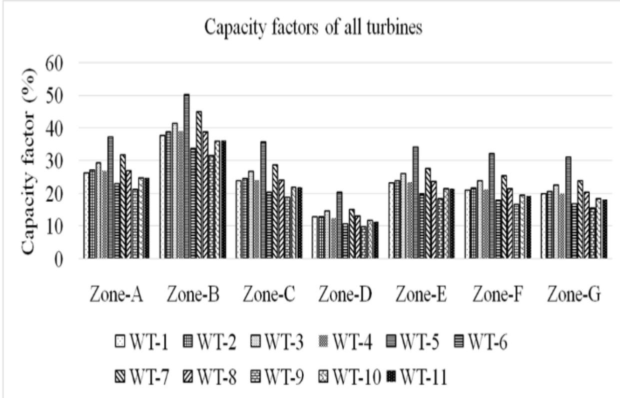

Fig. 7 Capacity Factor of wind turbines at all the sites

3.1 Goodness of fit R^2 test

To find the square of the correlation between the frequencies of Weibull to that of actual observations, the coefficient of the determinant test R^2 is used (Ayodele *et al.*, 2012; Chaurasiya *et al.*, 2018; R. Gasch, 2005)(Chaurasiya *et al.*, 2018). The value of R^2 closed to unity indicates a high correlation between wind speeds measured at adjacent heights. The correlation between the two wind speeds diminishes as the height difference between the two measurement points increases. R^2 can be calculated using :

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - V_{avg})^2 - \sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(y_i - V_{avg})^2} \quad (6)$$

Where y_i = frequency of observation, x_i = frequency of Weibull, V_{avg} = average wind speed, N = number of observations

3.2 Most frequent wind speed

It is the speed that occurs most of the time at a site and helps find the wind turbine having a rated wind speed close to this value. For a given wind probability distribution it is calculated with the help of Weibull shape (k) and scale parameters (A) as, (Ayodele et al., 2012)

$$V_{mf} = \left(1 - \frac{1}{k}\right)^{\frac{1}{k}} \quad (7)$$

The most frequent wind speed calculated for all seven sites at an altitude of 100 m using the four Weibull parameter estimation techniques is shown in Fig.4.

3.3 Maximum energy carrying wind speed

The maximum energy-carrying wind speed that represents the wind speed contributes to the maximum generation by the wind turbine and can be estimated by using the relationship mentioned below (Ayodele et al., 2012)

$$V_{maxEnergy} = A\left(1 + \frac{2}{k}\right)^{\frac{1}{k}} \quad (8)$$

The maximum energy-carrying wind speed was calculated for all seven sites at an altitude of 100 m using the four Weibull parameter estimation methods, is shown in Fig. 5

4. Wind energy assessment

The wind power extracted at the turbine hub height depends predominantly on the wind velocity available at this height. The extracted power from the wind turbine is estimated as

$$P = 0.5\rho v^3 \quad (9)$$

Where ρ= air density, A= area of the rotor, v= wind speed.

Betz discovered in 1926 that 100 percent of the energy cannot be extracted from the wind turbine, and only about 59 percent of the energy can be extracted. To evaluate the wind power output of the wind turbine, it is essential to assess the turbine's power coefficient so that the power output (P_{max}) of the turbine can be calculated(R. Gasch, 2005);

$$P_{max} = \frac{1 \text{ x } 16}{2 \text{ x } 27}\rho A v^3 \quad (10)$$

Substantially the power that can be extracted by way of a wind turbine is given as

$$P_{gen} = \frac{1}{2}\eta C_p(v)\rho A v^3 \quad (11)$$

Where
$Cp(v)$ = power coefficient of power = $P_{rotor}/P_{wind} < 16/27$,
η = Drive train efficiency = P_{gen}/P_{rotor}, (P_{rotor} is power extracted from rotor)
$\eta C_p(v)$= overall efficiency = P_{gen}/P_{wind}, (P_{wind} is total power in the wind)

Since the wind speed varies with height and the available wind data was collected at 100-meter height, it is required to know the wind speed values at wind turbine hub height to estimate the energy outputs from different commercially available wind turbines. The wind shear expression used is mentioned below (Di Piazza, A., Di Piazza, M. C., Ragusa, 2010)

$$U_2 = U_1\left(\frac{h_2}{h_1}\right)^{\alpha} \quad (12)$$

Where
U_2 = wind speed at hub (wind turbine nacelle) height h_2
U_1 = wind speed at the observed height h_1
α = Local wind shear (usually in the range 0.05 to 0.5); however, for water surface, the most frequently used value of wind shear is 0.14 (Akpinar & Akpinar, 2006), and the same value was used in this study.

Based on the commercially available wind turbine's power curve given by manufacturers and wind speed distribution of the seven sites, the energy output values were calculated to select an optimal turbine to develop an offshore wind farm (Fig.6). This study evaluates each turbine's annual energy output under investigation at all the sites using windographer software.

The capacity factor (C.F) is defined as the ratio of its actual annual energy output to its rated energy output. This capacity factor was estimated using the following equation below(Arikan *et al.*, 2014).

$$C.F. = \frac{\begin{array}{c}\text{Wind energy prduced by}\\ \text{a single turbine in a year}\end{array}}{\begin{array}{c}\text{Wind energy produces}\\ \text{at 100\% output X 8760}\end{array}} \quad (13)$$

Each turbine's capacity factors were calculated and compared, as shown in Fig. 7.

Table 3
Turbines under Investigation

Commercial Turbines	Hub Height (m)	Rated Power (MW)	Rotor Diameter (m)
Gamesa G128-5 MW Offshore	80	5	128
Gamesa G128-5.0 MW Offshore	80	5	128
Gamesa G132-5 MW Offshore	95	5	132
GE 2.75-100	85	2.75	100
GE 2.75-120	85	2.75	120
REpower 6.2M126 Offshore	85	6.15	126
REpower 6.2M152 Offshore	95	6.15	152
REpower 5M offshore	85	5.075	126
REpower 6M Offshore	85	6.15	126
Siemens SWT-3.6-120	90	3.6	120
Sinovel SL6000/128 Offshore	110	6	128

Description of selected wind turbine:
Model : REpower 6M 152-offshore, cut in speed = 3.5 m/s rated speed = 12 m/s , cut out speed = 30 m/s, hub height 95m, Rated capacity = 6015 kW

5. Results and Discussion

The wind speed data (ERA5) collected from (Windographer) was statistically analysed, and energy yield was estimated using eleven offshore wind turbines of different rated power capacity. This analysis of results is presented in the forthcoming subsections in terms of monthly maximum-minimum wind speed values and the plotted mean value, and the daily high and low wind speed values. Weibull parameters, wind speed frequency, the wind rose analysis, wind energy yield, most probable wind speed, maximum energy-carrying wind speed, and capacity factor (CF) are also shown. The average wind speed values for each hour over the entire period of data collection for all sites under consideration were taken at 100 m height; however, wind data for only Zone-B is shown in Fig. 1. At site-B, the highest annual mean wind speed of 14.25 m/s was observed, whereas, at site-G, the lowest mean wind, 0.68 m/s, was observed with standard deviation values of 2.46 and 2.16 m/s, respectively. The seasonal variation of wind speed was evaluated by sorting the data month-wise. The monthly maximum and minimum wind speed values and the mean value were plotted, and the daily high and low wind speed values were found for site B (Fig. 2). For most of the sites investigated, i.e., A, B, C, E, & F, the highest monthly mean wind speed values were observed from May to September. This period coincides nicely with the regions' high energy demands. However, at sites D and G, the highest monthly wind speed was observed from June to August, coinciding well with both the regions' high energy demands. However, the lowest mean wind speed was witnessed in October/November at all sites except A and B, where the lowest wind speed was found in March/November and March/April, respectively. The wind pattern, including the wind speed and direction, was envisaged from wind roses, however wind rose plot of only Zone-B is shown (Fig.3). The wind rose plots help in wind farm layout decisions to optimize wind production. The most prevailing wind direction was towards West in Zone-B. The magnitudes for all the statistical analysis techniques showed values similar to each other for all the locations under consideration, as measured by the Goodness of fit test R^2 (Table 1). However, the open wind seems to be the most suitable method for estimating Weibull parameters, followed by MLH, Least Square Method, and WAsP methods, particularly for Zone-B. Moreover, the most frequent wind speed values and the speed contributing to the maximum energy generation were found almost similar using the four estimation methods. However, WAsP gave better results, followed by Openwind, MLH, and Least Square Method in Zone-B (Table 1). Thus, from all the seven investigated sites' wind resource assessments showed site-B as the best wind farm development location.

The geographic location and wind turbine selection directly affect the wind farm economics. An appropriate wind turbine was chosen based on annual energy production. As a first step, the power produced from eleven commercially available different offshore wind turbines with different specifications was estimated to select the best matching turbine for each site under investigation. Table 3 shows the offshore wind turbines' specifications, and Fig. 6 and 7 summarize the computed values of annual energy output and each wind turbine's capacity factor. It was noticed that the efficient choice of a wind turbine is determined not only by its annual production but also by the plant capacity factor. The analysis shows that the Repower 6.15 MW offshore wind turbine would be the best turbine for the site found most suitable and windy, i.e., Site B. The maximum energy-carrying wind speed was also found close to the rated speed of wind turbine REpower 6M 152 by open wind method, as shown in Fig.5.

6. Economic Analysis

Considering the high initial cost of developing renewable energy technologies, the present studies attempt to find techno-economic strategies for planning and designing large-scale grid-connected offshore wind farm while minimizing the cost of operation and maintenance. The Techno-economic analysis was done by RETScreen software using different performance indicators. The effect of increasing the government incentives and support on the proposed power system's viability has also been evaluated. The results obtained would be significant not only for decision-makers in the country but also for the continuous development of renewable energy sources in other developing countries.

Several studies have been conducted globally for financial feasibility (Kolovos *et al.*, 2011) and many of them have used RET screen software for techno-economic analysis (Chalikias *et al.*, 2010; Kyriakopoulos *et al.*, 2010; Kyriakopoulos, 2010; Tran & Chen, 2013). The economic feasibility analysis of a few sites in Myanmar was done by matching each site's wind data and characteristics of low wind speed turbines. To check the economic feasibility of this project, the parameters of net present value (NPV), internal rate of return (IRR), and simple payback period (SPB) were evaluated for verification of sustainable development (Soe *et al.,* 2015). Another study has been conducted to analyze the cost, financial, and risk assessment for Taşlıçiftlik Campus in Tokat province by using RETScreen software (Emeksiz & Dogan, 2016). Tran and Chen have reported designing a 99MW capacity wind farm in Bac-Lieu, Vietnam. They carried out wind energy potential and wind farm economic analysis using WAsP and RETScreen software (Tran & Chen, 2013). M. Mujahid Rafique et al. performed a feasibility analysis of a 100 MW grid-connected wind farm for five separate sites in Saudi Arabia using RET screen software. They reported the payback periods and substantial GHG reductions for wind farm applications (Rafique et al., 2018). The authors have recently reported an economic feasibility study for developing 100 MW offshore wind farms in India considering preventive maintenance models and using RET screen software (Riaz & Khan, 2019a). After selecting the best suitable site and an optimally matched wind turbine, the economic analysis was done using various financial indicators in the present study.

6.1. RET Screen economic analysis

The RETScreen software (RETScreen | Natural Resources Canada 2019, n.d.), an excel based modelling tool, dramatically helps in the comprehensive identification, assessment, and optimization of the technical and financial viability of potential renewable energy projects.

It has been widely used to evaluate energy production, sensitivity and risk, costs, financial viability, and greenhouse gas emission (GHG) reduction for various energy technologies.

6.2. Analysis of cost

The details of input for the RETScreen software used for the study are shown in Table 4. Since no offshore wind farm yet exists in India hence, for input data, the previous studies of such countries where offshore wind farms already exist were referred (Kiran *et al*., 2017; Maples *et al*., 2013; RETScreen | Natural Resources Canada 2019, n.d.; Soe *et al*., 2015).

7. Preventive maintenance cost

As no offshore wind farm yet exists in India, there is a lack of experience in working out suitable strategies to maintain offshore wind farms. Therefore we have formulated the maintenance methodology based on European/US offshore wind farm experiences(Maples *et al*., 2013). It was assumed that all turbines in the farm would have to be maintained at least once a year during the wind farm's entire life span. Also, a large preventive maintenance will be required every five years. It is assumed that the balance of plant (BOP) preventive maintenance would require a diving support vessel. Results (Table 5) show the estimated strategic criteria for maintaining the proposed offshore wind farm.

- Hiring/rental rate of technician/hour @ Rs. 8,000
- Calculated total annual preventive maintenance cost that includes wages of technicians + cost of parts +work boat access vessel rent cost + Diving support vessels rent cost = Rs.35,14,18,000,
- Diving support vessels hiring/rental rate (including mobilization de-mobilization, travel time, and harbour waiting time) = Rs. 2,13,75,000
- Workboat access vessel hiring/rental rate @ Rs. 1,500,000/day

8. Emission reduction analysis

Coal is the primary conventional fuel for energy generation in India, and it contributes about 75 % of the total power generated (Charles Rajesh Kumar & Majid, 2020). Therefore, coal was considered as a 'base case' for comparison with the 'proposed case,' which is wind energy in this study. GHG emissions from coal were found to be 1,126,225 tons of CO_2 (tCO_2) while the proposed wind farm would emit 78,835 tCO_2 when generating an equivalent amount of energy per annum (Fig. 8). Thus, a significant reduction of 1,047,389 tCO_2 GHG emissions would mean as if 191,829 cars and trucks were not used.

9. Financial analysis

Financial analysis is essentially required to confirm the viability of a wind energy project. It was done to evaluate the profitable sustainability of offshore wind farm at the selected site-B. For the development of a wind farm, an investor can raise the capital cost while the rest has to be borrowed from a bank or financial sector. The Indian renewable energy development agency can provide a loan of up to 70% of the project's total estimated cost. The agency provides this loan at an interest rate of 11.9 to 12.5 % for a period of 10 to 15 years. We have considered a 12 % debt interest rate for a time period of 12 years for the study. Several financial parameters were determined to carry the proposed wind farm's economic feasibility study (Table 6-7) and the yearly cash flow is shown in Figure 9.

Table 4
Cost of components of the offshore wind farm

Description of cost	Amount (Rs.)
Wind Turbine cost	58,11,75,00,000
Feasibility cost	58,11,75,000
Development cost	2,13,87,24,000
Engineering cost	1,22,04,67,500
Balance of system & miscellaneous	7,66,56,98,250

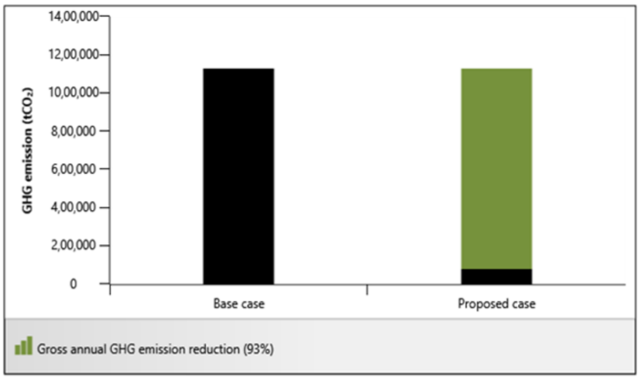

Fig. 8 Greenhouse gas (GHG) emission analysis.

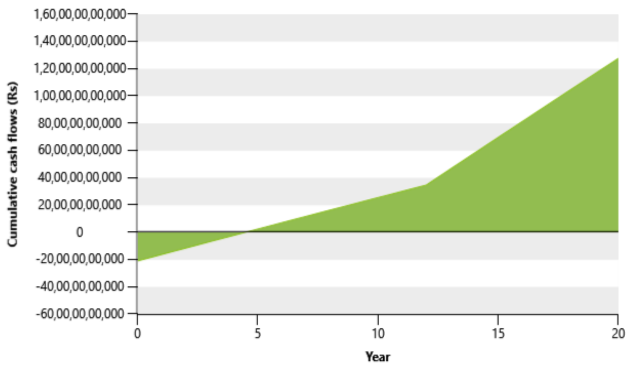

Fig. 9 Cumulative yearly cash flow

Table 5
Preventive maintenance cost data

	Maintenance Type		
	Preventive Maintenance	Large Preventive Maintenance	Preventive Maintenance (BOP)
No. of Maintenance/ 20 years	16	3	19
Duration per maintenance (Hrs.)	24	48	160
Crew size (no.)	3	6	
Wages of Technician INR/Turbine	9216000	6912000	24320000
Cost of parts per maintenance	9,37,500	28,12,500	9,37,500
Types of vessel required	Workboat access vessel	Workboat access vessel	Diving Support vessel

Source: (Riaz & Khan, 2019a)

Table 6
RET Screen Cost saving and Revenue

Cost- Savings-Revenue			
Feasibility study	0.83%	Rs	58,11,75,000
Development	3.10%	Rs	2,13,87,24,000
Engineering	1.80%	Rs	1,22,04,67,500
Power System	83.40%	Rs	58,11,75,00,000
Balance of system & miscellaneous	11%	Rs	7,66,56,98,250
Total initial cost	**100%**	**Rs**	**69,72,35,64,750**
Yearly cash flows -year 1			
Annual cost and debt payments			
O & M		Rs	35,14,18,000
Debt payments-12 yrs.		Rs	7,16,30,03,052
Total annual costs		**Rs**	**7,51,44,21,052**
Annual savings and revenue			
Electricity export revenue		Rs	12,23,81,22,481
GHG reduction revenue		Rs	0
Other revenue (cost)		Rs	0
CE production revenue		Rs	0
Total annual savings and revenue		**Rs**	**12,23,81,22,481**
Net yearly cash flow - year 1		**Rs**	**4,72,37,01,429**

Table 7
RET Screen Financial Analysis Parameters

Financial Parameters		
General		
Fuel cost escalation rate	%	2%
Inflation rate	%	3.34%
Discount rate	%	9%
Reinvestment rate	%	9%
Project Life	yr.	20
Finance		
Incentives and grants	Rs	0
Debt ratio	%	70
Debt	Rs	40,80,64,95,325
Equity	Rs	20,91,70,69,425
Debt interest rate	%	10
Debt term	yr.	12
Debt payment	Rs/yr.	7,16,30,03,052

10. Risk Analysis

Risk analysis is an analytical tool that assists in dealing with the uncertainties of a project. It is done with an objective to reduce the likelihood of carrying projects that would lead to loss while failing to accept profitable projects as costs and benefits are subject to uncertainties and may differ from the base case. The risk analysis gives a probability distribution that indicates the project outcome and assesses the risk level associated with the project. In the present study, risk analysis for the proposed wind farm has been done using RETScreen with a risk level of 10%, and the results are illustrated in Fig.10. Various factors, such as the initial cost, operating and management cost, and debt, have a different impact on the project's techno-economic feasibility, as shown in Fig. 10. The initial cost was found to be significantly high, followed by operation and management costs. As shown in Fig. 11, the probability distributions of the internal rate of return (IRR) and payback period indicate the feasibility of the studied project as the risk of loss is much lower than the profit. The IRR is large between 18.4% and 26.5%, with two predominant peaks at 18.4% and 26.5%. On the other hand, the payback mostly occurs for years less than 6, peaking in the 4th year and declines rapidly after the 6th year.

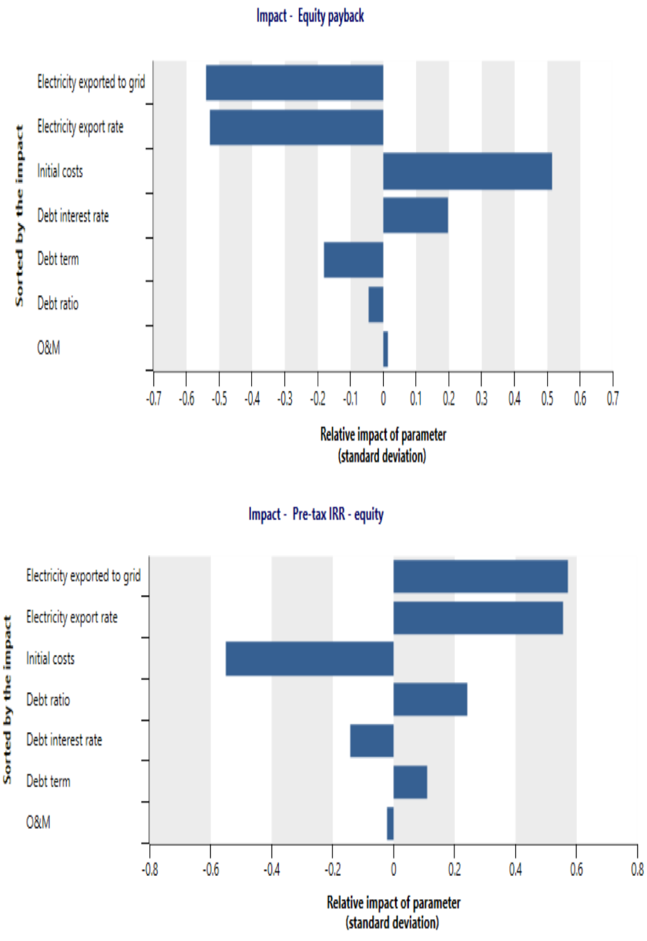

Fig. 10 Risk Impact – Payback (Year) , IRR (%)

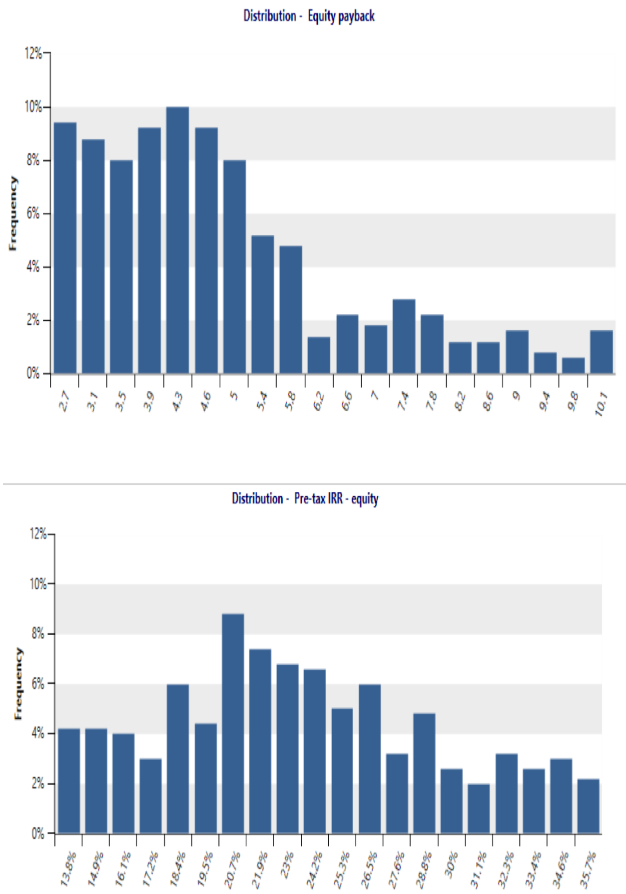

Fig. 11 Risk Distribution - Pay back (Year), IRR (%)

11. Conclusion

Results show that among the various wind turbines investigated in the present study (WT-1 to WT-11), the RE Power 6.2M 152 offshore wind turbine (WT-7), at the hub height of 95 meters, gave the highest wind energy yield per annum, particularly in Zone-B. The energy output calculated using the respective optimally matched wind turbines was significantly higher for Zone-B (20,677 MWh /turbine with a capacity factor of 45%) than for the rest of the sites. To conclude, South India's Zone-B coastal region was found most suitable for developing an offshore wind farm, preferably using RE Power 6.2 M 152 offshore wind turbines. Various financial indicators of the proposed wind power system at zone B were also evaluated. Even without considering the government's incentives on green energy, the power system seems to provide a unit price of Rs. 6.84/kWh, and therefore would be economically feasible and substantially profitable with a payback period of 5.9 years. Further it was found that the proposed power system at Zone-B would lead to a net annual GHG emission reduction of 1047389 tCO_2. The marked decline in harmful emissions would help achieve sustainable development in the country.

References

Akpinar, E. K., & Akpinar, S. (2006). An assessment of wind turbine characteristics and wind energy characteristics for electricity production. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *28*(10), 941–953. https://doi.org/10.1080/00908310600718817

Akpınar, E., Akpınar, S., & Balpetek, N. (2018). Statistical Analysis Of Wind Speed Distribution Of Turkey As Regional. *Journal of Engineering Technology and Applied Sciences*, *3*(1), 35–55. https://doi.org/10.30931/jetas.407141

Alluri, S. K. R., Shit, T., Dhinesh, G., Gujjula, D., Phani Kumar, S. V. S., & Ramana Murthy, M. V. (2017). Offshore wind to meet increasing energy demands in India. *Current Science*, *113*(4), 774–781. https://doi.org/10.18520/cs/v113/i04/774-781

Arikan, Y., Arslan, Ö. P., & Çam, E. (2014). Accepted on: 27.04. *Istanbul University - Journal of Electrical and Electronics Engineering*, *15*(1), 1907–1912. https://dergipark.org.tr/download/article-file/99301

Ayodele, T. R., Jimoh, A. A., Munda, J. L., & Agee, J. T. (2012). Statistical analysis of wind speed and wind power potential of Port Elizabeth using Weibull parameters. *Journal of Energy in Southern Africa*, *23*(2), 30–38.

Bansal, J. C., Farswan, P., & Nagar, A. K. (2018). Design of wind farm layout with non-uniform turbines using fitness difference based BBO. *Engineering Applications of Artificial Intelligence*, *71*(April), 45–59. https://doi.org/10.1016/j.engappai.2018.02.007

Baseer, M. A., Meyer, J. P., Rehman, S., & Alam, M. M. (2017). Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using Weibull parameters. *Renewable Energy*, *102*, 35–49. https://doi.org/10.1016/j.renene.2016.10.040

Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). Wind Energy Handbook, Second Edition. In *Wind Energy Handbook, Second Edition*. John Wiley and Sons. https://doi.org/10.1002/9781119992714

Chalikias, M. S., Kyriakopoulos, G., & Kolovos, K. G. (2010). Environmental sustainability and financial feasibility evaluation of woodfuel biomass used for a potential replacement of conventional space heating sources. Part I: A Greek case study. *Operational Research*, *10*(1), 43–56. https://doi.org/10.1007/s12351-009-0033-y

Charles Rajesh Kumar, J., & Majid, M. A. (2020). Renewable energy for sustainable development in India: Current status, future prospects, challenges, employment, and investment opportunities. In *Energy, Sustainability and Society*. https://doi.org/10.1186/s13705-019-0232-1

Chaurasiya, P. K., Ahmed, S., & Warudkar, V. (2018). Study of different parameters estimation methods of Weibull distribution to determine wind power density using ground based Doppler SODAR instrument. *Alexandria Engineering Journal*, *57*(4), 2299–2311. https://doi.org/10.1016/j.aej.2017.08.008

Chaurasiya, P. K., Kumar, V. K., Warudkar, V., & Ahmed, S. (2019). Evaluation of wind energy potential and estimation of wind turbine characteristics for two different sites. *International Journal of Ambient Energy*, *0*(0), 1–24. https://doi.org/10.1080/01430750.2019.1611634

Di Piazza, A., Di Piazza, M. C., Ragusa, A. (2010). Statistical Processing of Wind Speed Data for energy Forecast and Planning. *International Conference on Renewable Energies and Power Quality (ICRPQ, 10). Granada, Spain.*

Didane, D. H., Wahab, A. A., Shamsudin, S. S., Rosly, N., Zulkafli, M. F., & Mohd, S. (2017). Assessment of wind energy potential in the capital city of Chad, N'Djamena. *AIP Conference Proceedings*, *1831*. https://doi.org/10.1063/1.4981190

Emeksiz, C., & Dogan, Z. (2016). Wind Power Plant Feasibility Study in Tokat with RETScreen Analysis Program. *Journal of New Results in Science*, *5*(11), 56–63.

Hemanth Kumar, M. B., Balasubramaniyan, S., Padmanaban, S., & Holm-Nielsen, J. B. (2019). Wind energy potential assessment by weibull parameter estimation using multiverse optimization method: A case study of Tirumala region in India. *Energies*, *12*(11). https://doi.org/10.3390/en12112158

Indhumathy, D., Seshaiah, C. V, & Sukkiramathi, K. (2015). Estimation of Weibull Parameters for Wind speed calculation at Kanyakumari in India. *International Journal of Innovative Research in Science, Engineering and Technology*, *3*(1), 8340–8345. http://www.ijirset.com/upload/2014/january/33_Estimation.pdf

Khahro, S. F., Soomro, A. M., Tabbassum, K., Dong, L., & Liao, X. (2013). Assessment of wind power potential at Hawksbay, Karachi Sindh, Pakistan. *TELKOMNIKA Indonesian Journal of Electrical Engineering*, *11*(7). https://doi.org/10.11591/telkomnika.v11i7.2621

Kiran, S., Alluri, R., Dhinesh, G., Kumar, S. V. S. P., Murthy, M. V. R., & Atmanand, M. A. (2017). Feasibility studies for development of offshore wind in India. *OCEANS 2017 - Anchorage*, *2017-Janua*, 1–7.

Kolovos, K. G., Kyriakopoulos, G., & Chalikias, M. S. (2011). Co-evaluation of basic woodfuel types used as alternative heating sources to existing energy network. *Journal of Environmental Protection and Ecology*.

Kore, S. B., & S, L. A. A. G. D. A. S. S. (2016). Feasibility of Offshore Wind Farm in India. *International Research Journal of Engineering and Technology*, *3*(11), 995–998.

Kumaraswamy, B. G., Keshavan, B. K., & Jangamshetti, S. H. (2009). A statistical analysis of wind speed data in west central part of karnataka based on weibull distribution function. *2009 IEEE Electrical Power and Energy Conference, EPEC 2009*, 1–5. https://doi.org/10.1109/EPEC.2009.5420878

Kyriakopoulos, G., Kolovos, K. G., & Chalikias, M. S. (2010). Environmental sustainability and financial feasibility evaluation of woodfuel biomass used for a potential replacement of conventional space heating sources. Part II: A combined Greek and the nearby Balkan countries case study. *Operational Research*, *10*(1), 57–69. https://doi.org/10.1007/s12351-009-0034-x

Kyriakopoulos, G. L. (2010). European and international policy interventions of implementing the use of wood fuels in bioenergy sector: a trend analysis and a specific wood fuels' energy application. *International Journal of Knowledge and Learning*, *6*(1), 43–54. https://doi.org/10.1504/IJKL.2010.034482

Maples, B., Saur, G., Hand, M., Pietermen, R. van, & Obdam, T. (2013). Installation, Operation, and Maintenance Strategies to Reduce the Cost of Offshore Wind Energy. *Technical Report Nrel/Tp-5000-57403*, *July*, 1–106. http://www.nrel.gov/docs/fy13osti/57403.pdf

Mathew, S. (2007). Wind energy: Fundamentals, resource analysis and economics. In *Wind Energy: Fundamentals, Resource Analysis and Economics*. Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-30906-3

Mohsin, M., & Rao, K. V. S. (2018). Estimation of weibull distribution parameters and wind power density for wind farm site at Akal at Jaisalmer in Rajasthan. *3rd International Conference on Innovative Applications of Computational Intelligence on Power, Energy and Controls with Their Impact on Humanity, CIPECH 2018*, *3*, 14–19. https://doi.org/10.1109/CIPECH.2018.8724170

NA, U., A, O., & KA, I. (2017). Investigation of Wind Power Potential over Some Selected Coastal Cities in Nigeria. *Innovative Energy & Research*, *06*(01), 1–12. https://doi.org/10.4172/2576-1463.1000156

Pobočíkova, I., Sedliačkova, Z., & Simon, J. (2018). Comparative study of seven methods for estimating the weibull distribution parameters for wind speed in bratislava - mlynská dolina. *17th Conference on Applied Mathematics, APLIMAT 2018 - Proceedings*, *2018-Febru*(February), 840–852.

Population of India. (n.d.). Ministry of Statistics and Programme Implementation. Retrieved October 28, 2020, from http://statisticstimes.com/demographics/country/india-population.php

R. Gasch, J. T. (2005). *Wind power Plants, Fundamaental, Design, construction,& Operation*. James & James London.

Rafique, M. M., Rehman, S., Alam, M. M., & Alhems, L. M. (2018). Feasibility of a 100 MW installed capacity wind farm for different climatic conditions. *Energies*, *11*(8). https://doi.org/10.3390/en11082147

Rajagopalan, P. (2018). Challenges in grid integration of offshore wind in Tamil Nadu and Gujarat for policy makers and transmission planners. *2017 7th International Conference on Power Systems, ICPS 2017*, 206–211. https://doi.org/10.1109/ICPES.2017.8387294

RETScreen | Natural Resources Canada 2019. (n.d.). Web Site. Retrieved April 20, 2019, from https://www.nrcan.gc.ca/energy/retscreen/7465

Riaz, M. M., & Khan, B. H. (2019a). Economic feasibility study to design a large offshore wind farm near coastal region of Rameshvaram, India. *International Conference on Electrical, Electronics and Computer Engineering, UPCON 2019*, 3–7. https://doi.org/10.1109/UPCON47278.2019.8980119

Riaz, M. M., & Khan, B. H. (2019b). Estimation of Weibull parameters and selection of optimal wind turbine for the development of large offshore wind farm. *2019 International Conference on Electrical, Electronics and Computer Engineering (UPCON)*, 1–6. https://doi.org/10.1109/UPCON47278.2019.8980167

Saeidi, D., Mirhosseini, M., Sedaghat, A., & Mostafaeipour, A. (2011). Feasibility study of wind energy potential in two provinces of Iran: North and South Khorasan. *Renewable and Sustainable Energy Reviews*, *15*(8), 3558–3569. https://doi.org/10.1016/j.rser.2011.05.011

Sharma, P. K., Warudkar, V., & Ahmed, S. (2019). A comparative analysis of wind resource parameters using WAsP and windPRO. *International Journal of Green Energy*, *16*(2), 152–166. https://doi.org/10.1080/15435075.2018.1550783

Soe, T. T., Zheng, M., & Aung, Z. N. (2015). Assessment of economic feasibility on promising wind energy sites in Myanmar. *International Journal of Renewable Energy Research*, *5*(3), 699–707.

Sohoni, V., Gupta, S., & Nema, R. (2016). A comparative analysis of wind speed probability distributions for wind power assessment of four sites. *Turkish Journal of Electrical Engineering and Computer Sciences*, *24*(6), 4724–4735. https://doi.org/10.3906/elk-1412-207

Stevens, M. J. M., & Smulders, P. T. (1979). The estimation of parameters of the weibull wind speed distribution for wind energy utilization purposes. *Wind Engineering*, *3*(2), 132–145.

Sumair, M., Aized, T., Gardezi, S. A. R., Ur Rehman, S. U., & Rehman, S. M. S. (2020). Wind potential estimation and proposed energy production in Southern Punjab using Weibull probability density function and surface measured data. *Energy Exploration & Exploitation*, *166*, 014459872092074. https://doi.org/10.1177/0144598720920748

Tran, V. T., & Chen, T. H. (2013). Assessing the wind energy for rural areas of vietnam. *International Journal of Renewable Energy Research*, *3*(3), 523–528. https://doi.org/10.20508/ijrer.59861

Windnavigator,AWS Truepower, a UL Company. (n.d.). Retrieved September 16, 2019, from www.awstruepower.com

Yu, J., Fu, Y., Yu, Y., Wu, S., Wu, Y., You, M., Guo, S., & Li, M. (2019). Assessment of offshore wind characteristics and wind energy potential in Bohai Bay, China. *Energies*, *12*(15). https://doi.org/10.3390/en12152879