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

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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 (R²) 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.

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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; Moshin & 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

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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 scales 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 (Akpinar et al., 2018; Khadro et al., 2013; NA et al., 2017; Saedid 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 (Kumarsawamy 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 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 (Poböcková 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 \( f_w(V) \) 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):

\[
 f_w(V) = \frac{k}{\beta} \left(\frac{V}{\beta}\right)^{k-1} \exp\left(-\left(\frac{V}{\beta}\right)^k\right)
\]

where \( k \) is the shape parameter and \( \beta \) is the scale parameter.
Table 1
Weibull shape and scale parameters of seven sites

| Site     | Algorithm       | Weibull k | Weibull A (m/s) | Power Density (W/m²) | R²   |
|----------|-----------------|-----------|-----------------|---------------------|------|
| Zone-A   | Maximum likelihood | 3.044 | 12.714 | 376.4 | 0.8458 |
|          | Least squares    | 2.928 | 12.998 | 435.7 | 0.7833 |
|          | WAsP            | 2.549 | 8.174  | 364  | 0.767  |
|          | Openwind        | 2.248 | 7.93   | 364  | 0.8269 |
| Zone-B   | Maximum likelihood | 2.741 | 9.546 | 556.1 | 0.8099 |
|          | Least squares    | 2.617 | 9.779 | 690.4 | 0.7781 |
|          | WAsP            | 3.672 | 9.874 | 551.9 | 0.7728 |
|          | Openwind        | 2.814 | 9.565 | 551.9 | 0.8084 |
| Zone-C   | Maximum likelihood | 2.642 | 7.901 | 321.8 | 0.9660 |
|          | Least squares    | 2.361 | 7.997 | 357  | 0.9543 |
|          | WAsP            | 2.992 | 8.032 | 329.2 | 0.9567 |
|          | Openwind        | 2.681 | 7.909 | 320.2 | 0.9664 |
| Zone-D   | Maximum likelihood | 2.125 | 6.099 | 173.9 | 0.9979 |
|          | Least squares    | 2.121 | 6.106 | 174.9 | 0.9977 |
|          | WAsP            | 2.122 | 6.097 | 174.2 | 0.9978 |
|          | Openwind        | 2.124 | 6.1   | 174.2 | 0.9978 |
| Zone-E   | 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  |
| Zone-F   | 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 |
| Zone-G   | 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 | 286.8 | 0.9781 |
|          | Openwind        | 2.783 | 7.5   | 286.8 | 0.9774 |

\[ f_{\text{weib}}(V) = \frac{2}{\alpha} \sqrt{\frac{
abla}{\alpha}} \left( \frac{V}{\alpha} \right)^{k-1} \exp \left[ -\left( \frac{V}{\alpha} \right)^k \right] \quad (1) \]

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

\[ F_c(V) = \int_0^V f_{\text{weib}}(V) dV = 1 - \exp \left[ -\left( \frac{V}{\alpha} \right)^k \right] \quad (2) \]

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

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

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

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

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

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

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      | 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
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). 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:

$$R_M^2 = \frac{\sum y_i - \bar{V}_{\text{avg}}}{\sum y_i} - \frac{\sum x_i}{\sum y_i} - \frac{\sum x_i}{\sum y_i}$$

Where $y_i$ = frequency of observation, $x_i$ = frequency of Weibull, $V_{\text{avg}}$ = 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)

$$V_{XY} = F_1 - \frac{1}{k}$$

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)

$$V_{\text{max_energy}} = A \left(1 + \frac{1}{k} \right)$$
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

\[ P = 0.5 \rho v^3 \]  

(9)

Where \( \rho \) = 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 \( P_{\text{max}} \) of the turbine can be calculated (R. Gasch, 2005);

\[ P_{\text{max}} = \frac{1 \times 16}{2 \times 27} \rho A v^3 \]  

(10)

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

\[ P_{\text{gen}} = \frac{1}{2} \eta C_p(v) \rho A v^3 \]  

(11)

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

\[ U_2 = U_1 \left( \frac{h_2}{h_1} \right)^{\alpha} \]  

(12)

Where
- \( U_2 \) = wind speed at hub (wind turbine nacelle) height
- \( h_2 \) = 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).

\[ \text{C.F.} = \frac{\text{Wind energy produced by a single turbine in a year}}{\text{Wind energy produced at 100% output X 8760}} \]  

(13)

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

| turbine under Investigation | 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 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 R² (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; Kyriakopoulou et al., 2010; Kyriakopoulou, 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 (SBP) 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 (Emekszis & 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 1,126,285 tons of CO₂ (tCO₂) while the proposed wind farm would emit 78,835 tCO₂ when generating an equivalent amount of energy per annum (Fig. 8). Thus, a significant reduction of 1,047,389 tCO₂ 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 5
Preventive maintenance cost data

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

Source: (Riaz & Khan, 2019a)

### Table 6
RET Screen Cost saving and Revenue

| Cost- Savings-Revenue                    | Feasibility study | Development | Engineering | Power System | Balance of system & miscellaneous | Total initial cost |
|-----------------------------------------|-------------------|-------------|-------------|--------------|----------------------------------|-------------------|
| Yearly cash flows -year 1              | 0.83%             | 3.10%       | 1.80%       | 83.40%       | 11%                              | 100%              |
| Annual cost and debt payments          | Rs 58,11,75,000   | Rs 2,13,87,24,000 | Rs 1,22,04,67,500 | Rs 58,11,75,000 | Rs 7,66,56,98,250 | Rs 69,72,35,64,750 |
| Debt payments-12 yrs.                  | Rs 35,14,18,000   | Rs 7,16,50,03,052 |                              |                              |                    |
| 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                  | % | % | % | yr. | % | % | % | yr. |
|---------------------------------------|---|---|---|-----|---|---|---|-----|
| General                               |   |   |   |     |   |   |   |     |
| Fuel cost escalation rate             |   |   |   |     |   |   | 2%|     |
| Inflation rate                        |   |   |   |     |   |   | 3.34%|     |
| Discount rate                         |   |   |   |     |   |   | 9% |     |
| Reinvestment rate                     |   |   |   |     |   |   | 9% |     |
| Project Life                          |   |   |   |     |   |   | 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.

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 tCO₂. The marked decline in harmful emissions would help achieve sustainable development in the country.
