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Wind Characteristics Analysis of Inani: An Offshore Region of the Bay of Bengal of Bangladesh

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ABSTRACT

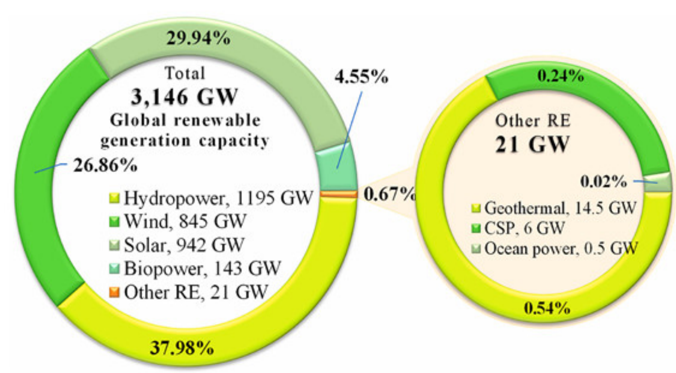
Wind energy is one of the most popular renewable energy sources. Bangladesh has huge energy demand and offshore wind energy can play a vital role in mitigating this demand. Modelling of wind energy is required to estimate wind resources of a typical site. In this study wind characteristics of offshore region near Inani, Cox's Bazar (20º 50' 29.4" N (Latitude) and 91º 10'1.2" E (Longitude)) have been analyzed using two parameter Weibull distribution function. Wind speed data for the period (2012-2023) have been collected from NASA?s power project. The daily, monthly, and annual wind speeds have been modeled and shown in both tabular and graphical formats. The mean value of wind speed is found as 5.41 m/s. The highest and lowest values of wind speed are observed in July and February respectively. The power density ranges from 38-251.71 w/m^2. The findings presented in this study will aid in evaluating the practicality of installing wind turbines in the subjected area.

1. Introduction.

There is energy crisis throughout the world. Wind energy can play a significant role in mitigating energy crisis. So, it is necessary to have comprehensive idea of wind patterns and characteristics to design and optimize wind energy systems effectively.

The demand for using renewable energy for electricity generation is increasing day by day as using fossil fuels for energy production has adverse effects on environment like greenhouse gas emissions, $CO_2$2 emissions, etc. Figure 1 shows the worldwide renewable energy production in 2021. From the figure it is seen that, about 3146 GW energy is produced worldwide using renewable energy sources. Among the sources wind energy produced 26.86% (845 GW) energy in 2021.

Figure 1: Worldwide renewable energy production in 2021.



Source: Mahbub and Islam, 2023.

Wind energy is now experiencing rapid growth and is considered one of the fastest-growing renewable energy sources globally. In last decade significant development has been seen in wind energy conversion technologies (Ayres et al., 2007; Bhattacharya and Deb, 2020). Wind energy can be harnessed from both onshore and offshore locations. But offshore wind energy has now become more popular. As it is scalable, cost

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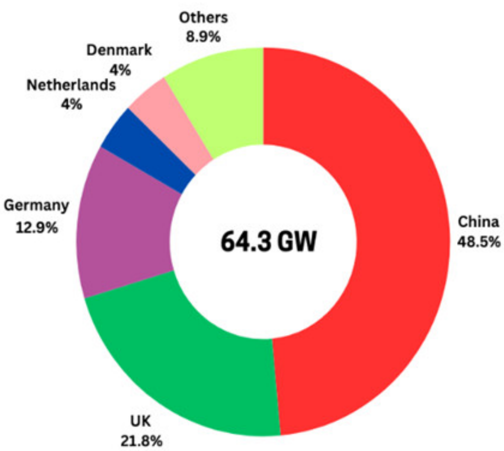
effective, more reliable, and has the potential to produce power consistently throughout the year. Figure 2 illustrates offshore wind energy production capacity of different countries in 2021. From the figure it is seen that 64.3 GW power produced globally from offshore locations in 2021. Among the countries China has the highest contribution (49%) in 2021.

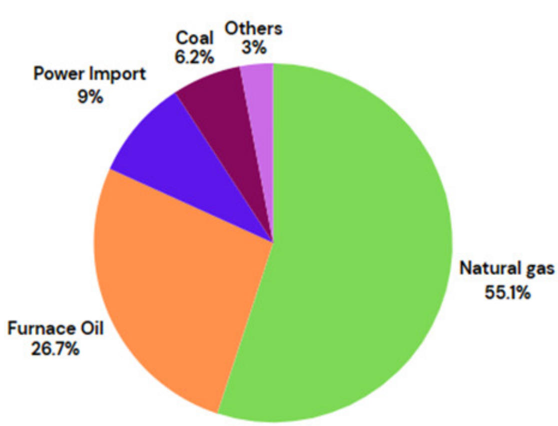
Figure 2: Offshore wind energy production capacity of different countries in 2021.



Source: GWEC, 2023.

Bangladesh is an overpopulated country with huge energy demand. The power sector of this country is mainly dependent on non-renewable energy sources. Figure 3 represents electricity generation in Bangladesh from different non-renewable energy sources in 2021-2022. From the figure it is seen that most of the electricity is generated using natural gas (55.1%) which is alarming. Besides, significant portion of electricity is generated using furnace oil and coal.

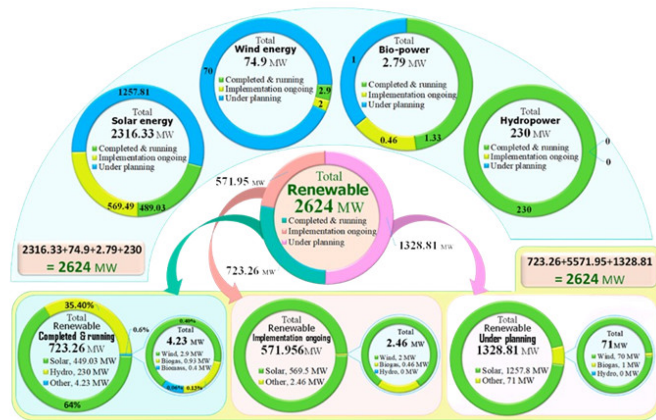
Figure 3: Illustration of electricity generation sources of Bangladesh in 2021-2022.



Source: BPDB, 2023.

The government of Bangladesh has taken initiative to utilize renewable energy sources. Figure 4 presents the current status of renewable energy generation capacity of Bangladesh. It is seen that currently 723.26 MW electricity is produced from renewable energy sources, while implementation for 571.95 MW is going on and about 1328.81 MW electricity production is under planning.

Figure 4: Current status of renewable energy generation in Bangladesh.



Source: Mahbub and Islam, 2023.

The government has planned to utilize both onshore and offshore renewable energy sources. The Bay of Bengal has huge potential for offshore wind energy, but the opportunities have not been explored yet. In this study wind characteristics of an offshore region of Bay of Bengal near Inani, Cox's Bazar have been studied using two parameter Weibull distribution. The Bay of Bengal is recognized for its diverse and dynamic wind conditions. This recognition makes it a prime location for wind energy harnessing. This study offers an in-depth examination of wind characteristics of the selected location, providing necessary data for stakeholders and researchers interested in utilizing the wind energy potential of this region.

2. Literature Review.

Several researchers have analyzed wind characteristics of different global locations using the Weibull distribution. Mahmood et al. (2020) studied the wind properties of the Al-Salman location in Iraq by utilizing the Weibull distribution. The authors applied the Maximum Likelihood Method (MLM) to determine the Weibull parameters. Based on the availability of power density determined using Weibull parameters, a small-scale wind turbine model was proposed by the authors. Saeed et al. (2019) performed a comparison of six distinct methodologies for assessing wind energy in the northern parts of Pakistan, specifically focusing on the Weibull distribution. The study determined that wind speed varies between 2.9 and 4 m/s across all mast heights. The annual Weibull wind power density varies between 26 and 82 w/m^2. The authors conclude that small-scale wind turbines are appropriate for harnessing wind power in the northern parts of Pakistan.

Souloukngā et al. (2018) used the Weibull distribution technique to statistically examine the monthly wind speed data of

Faya-Largeau over a span of 18 years. The monthly variation of the shape parameter k ranged from 3.01 to 4.19, whereas the monthly variation of the scale parameter c ranged from 2.44 m/s to 4.43 m/s. Based on the study findings, the authors put forward three wind turbine models. Wais (2017) compared the available techniques for evaluating wind energy using Weibull distribution. The study showed that three-parameter Weibull distribution give higher probability of the null wind than two-parameter Weibull distribution. The author concluded that the two parameter Weibull distribution is more suitable for sites with insignificant null velocities.

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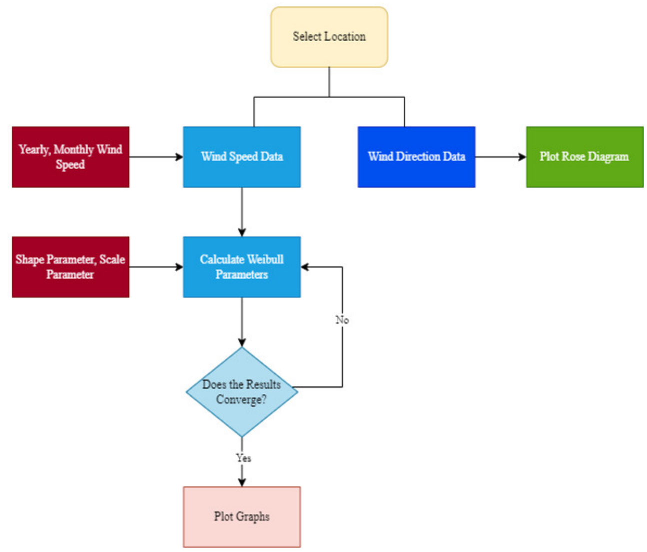
Azad et al. (2015) evaluated wind energy potential of Sandwip and Khagrachari using three Weibull distribution methods. The authors used power density method, least square method, and modified likelihood method for calculating Weibull parameters. The study showed that maximum wind speed is found in April and minimum wind speed is found in May. The study also found that Sandwip has more wind energy potential than Khagrachari. Bilir et al. (2015) studied seasonal and yearly wind distribution and power density using Weibull distribution. The study showed that highest power density is found in winter season in the studied area, Ankara, Turkey. By considering the power density of the site, the study concluded that wind energy can be exploited using small wind turbines.

Azad et al. (2014) investigated wind energy conversion system using Weibull distribution. The authors statically analyzed Weibull parameters using four different methods. The study found that Hatiya island is suitable for generating electricity using small wind turbines. The study concluded that the methodology proposed by the authors can be used in any medium windy site for analyzing the potentiality of that site. Fadare (2008) studied wind energy potential of Ibadan, Nigeria using Weibull distribution. The author showed that scale parameters are higher than shape factors in that region. The study recommended that, Weibull distribution function can be used in preliminary design stages.

3. Methodology.

In this study wind characteristics of offshore region near Inani, Cox's Bazar (20º 50' 29.4" N (Latitude) and 91º 10' 1.2" E (Longitude)) have been analyzed using two parameter Weibull distribution function. Weibull distribution is the most widely used method for determining wind characteristics (Azad and Alam, 2012). This study uses two parameters Weibull distribution for analyzing wind energy potential of offshore region near Inani, Cox's Bazar. The process followed during the study is shown in Figure 5.

Figure 5: Flow chart of the procedure of analyzing wind characteristics using Weibull distribution.

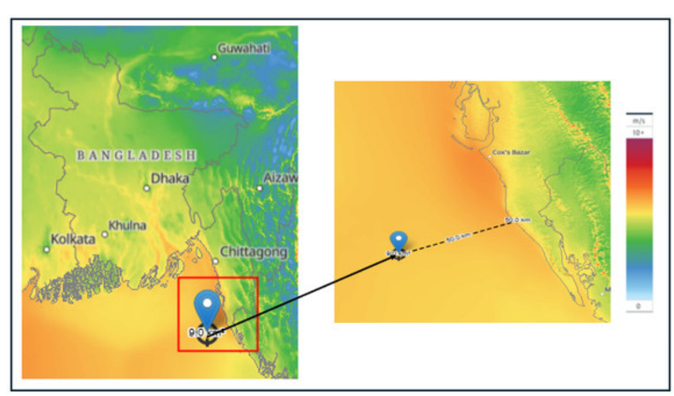


Source: Authors.

3.1. *Wind Speed Data.*

In this study, Offshore region of Inani, Cox's Bazar is selected as study area. This location is selected because wind resource assessment of this area has not been done yet in Bangladesh. The study area is located at 20º 84'15.17" N (Latitude) and 91º16'70.38"E (Longitude) of Inani, Cox's Bazar. The study area is shown in Figure 6. The location is around 50 km away from the Inani beach. Daily, monthly, and yearly wind speed data for the selected region is collected for the period of 12 years from 2012 to 2023. Data is collected from the NASA's power project database (NASA Power Project, 2024). Wind speed data at 50 m height is considered in this study.

Figure 6: Selected area of the study.



Source: Authors.

3.2. Computation of Weibull Parameters.

Weibull distribution is a continuous probability distribution that can fit a wide variety of distributions of different geometries (Frost, 2022). In the statistical modeling of wind speed, the two-parameter Weibull (shape parameter k and scale parameter c) function has been widely applied by many researchers. The general form of Weibull Probability Density Function (PDF) is shown by Ramirez and Carta (2005) as follows:

$$f(v,k,c) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

Where $f(v,k,c)$ is the probability of wind speed. v is the wind speed, k is the dimensionless Weibull shape parameter and c is the Weibull scale parameter. Higher values of k indicate sharper peaked curves while lower values of k means more flat or more evenly distributed speeds. The variability of Weibull distribution is represented by the scale parameter. The extent to which the probability distribution expands is dependent on the scale parameter.

The corresponding cumulative distribution function (CDF) is shown by Fagbenle et al. (2011) as follows:

$$f(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

Here $f(v)$ is the cumulative distribution function (CDF). The relationship between mean wind speed v_m , shape parameter k and scale parameter c are determined by Mirhosseini et al. (2011) ; Ucar and Balo (2010) as follows:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \tag{3}$$

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \tag{4}$$

The mean velocity v_m, standard deviation σ is determined by Ucar and Balo (2010) in terms of Weibull parameters as follows:

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \tag{5}$$

$$\sigma = c\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]^5 \tag{6}$$

Where Γ is the standard gamma function. Using Stirling approximation gamma function can be obtained as follows:

$$\Gamma(x) = \int_0^\infty u^{x-1}e^{-u}du \tag{7}$$

Where, $x = v_m$ and $u = v_m - 1$.

It is important to know wind power density to assess the wind characteristics of a location. The wind power density for a given location can be calculated as shown below (Ucar and Balo, 2010):

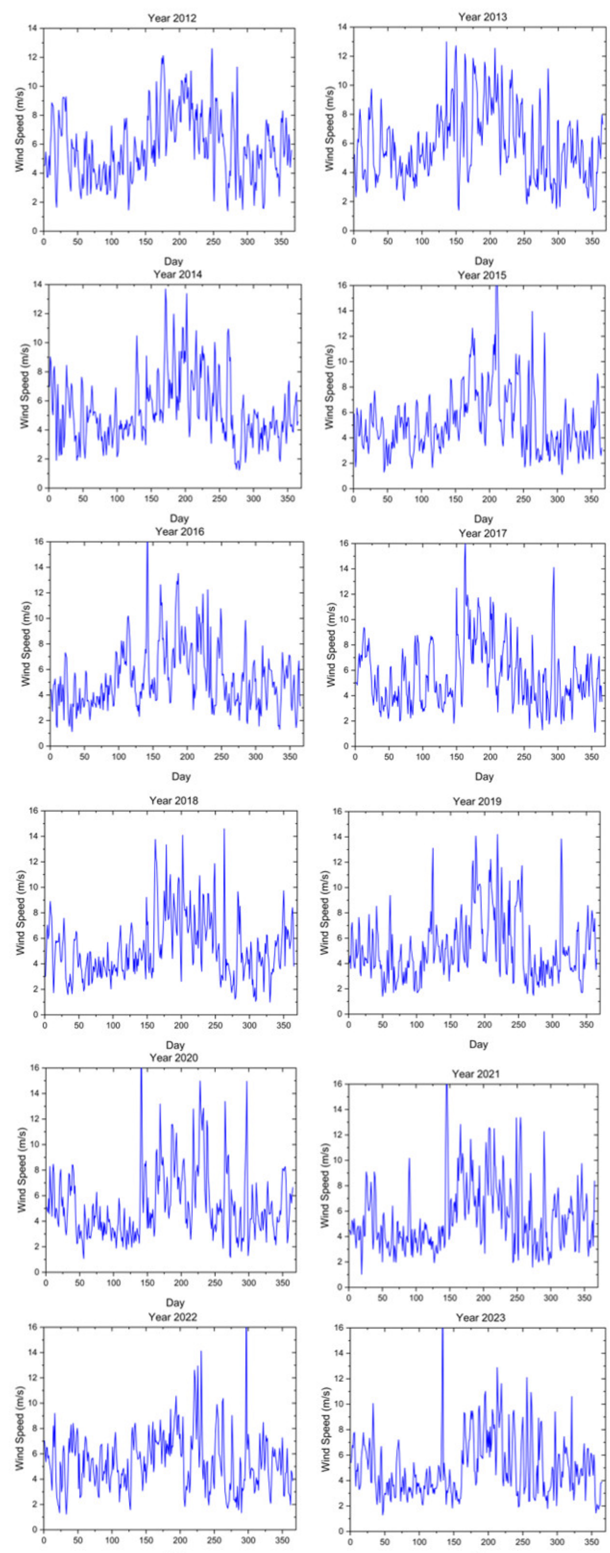
$$P_w = \frac{1}{2}\rho c^3\Gamma\left(1+\frac{3}{k}\right) \tag{8}$$

Here P_w is the wind power density. The unit is w/m^2.

4. Results and Discussions.

4.1. Average Wind Speed.

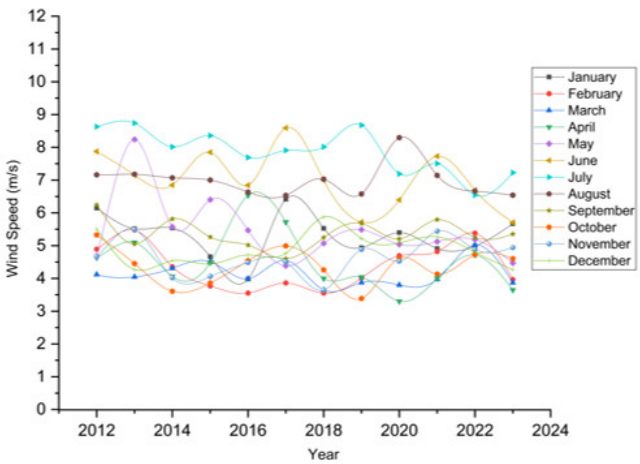
Figure 7: Daily mean wind speed variation in offshore region of Inani (Lat. 20º 84'15.17" N and Long. 91º 16'70.38"E), Bay of Bengal for 2012-2023.



Source: Authors.

Figure 7 shows the daily average wind speed data for the chosen area for a 12-year period (2012-2023). The figure shows that wind speed fluctuates considerably throughout the year. The monthly average variation in wind speed for the years 2012-2023 is shown in Figure 8. The illustration makes it clear that February has the lowest wind speed values whereas July has the highest values.

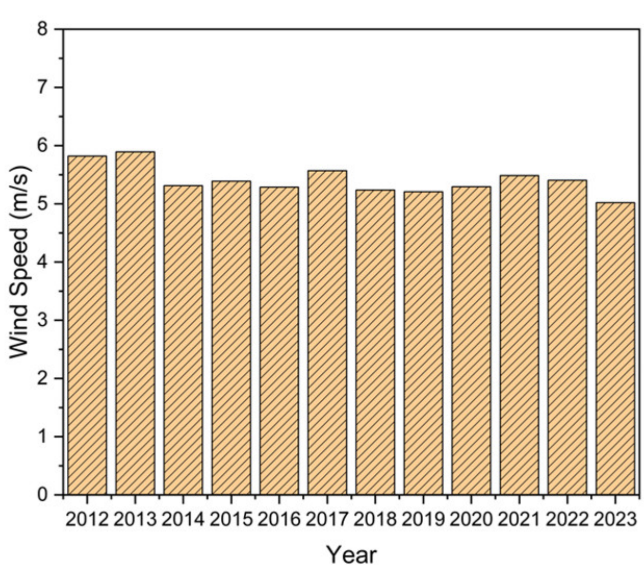
Figure 8: Monthly mean wind speed variation between 2012-2023.



Source: Authors.

Figure 9 represents the yearly mean wind speed variation throughout the study period. From the figure it is evident that wind speed followed a similar pattern during these years. The highest average wind speed (5.89 m/s) was recorded in 2013, while the lowest average wind speed (5.02 m/s) was reported in 2023. The average wind speed data for the specific offshore area in the Bay of Bengal has been determined to be 5.41 m/s.

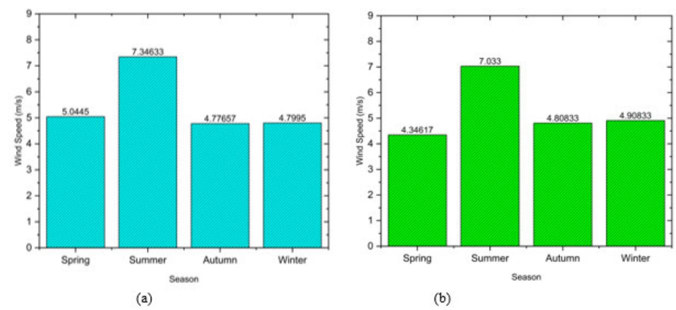
Figure 9: Yearly mean wind speed variation between 2012-2023.



Source: Authors.

Seasonal wind speed variations for the years 2012-2017 and 2018-2023 is presented in Figure 10. The figure illustrates that, for the period 2012-2017 the maximum average wind speed (7.35 m/s) is found in summer on the contrary the minimum average wind speed (4.77 m/s) is found in autumn. Moreover year 2018-2023 indicates similar wind characteristics. For these years the maximum (7.03 m/s) and minimum (4.35 m/s) average wind speed is found in summer and spring respectively. From the analysis it is evident that, in recent years wind speed has comparatively decreased during spring season.

Figure 10: Seasonal mean wind speed variation (a) in between 2012-2017 and (b) in between 2018-2023.



Source: Authors.

Table 1: Monthly average wind speed, standard deviation, shape parameter, scale factor and power density of the study area from 2012-2023.

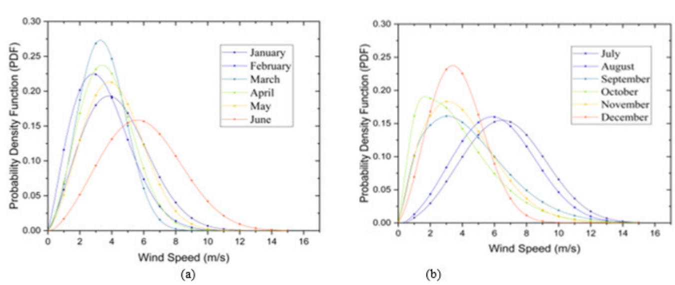
Month	v_m (m/s)	σ	c (m/s)	k	Power Density (w/m^2)
January	5.31	2.00	4.89	2.29	82.32
February	4.36	1.75	3.90	2.07	45.82
March	4.14	1.39	3.91	2.68	38.00
April	4.52	1.61	4.20	2.46	49.52
May	5.43	1.79	4.72	2.49	69.73
June	7.03	2.41	6.69	2.65	190.56
July	7.87	2.46	7.47	2.94	251.71
August	6.99	2.38	6.88	2.77	202.14
September	5.38	2.58	4.92	1.74	109.99
October	4.37	2.37	4.00	1.54	72.08
November	4.63	2.19	4.54	1.91	78.59
December	4.89	1.61	4.20	2.46	49.52

Source: Authors.

The monthly mean wind speed, Weibull parameters k and c, standard deviation, and monthly wind power density are presented in Table 1. The table shows that the wind speed changes between 4.14 and 7.87 m/s. In September, the highest standard deviation recorded was 2.58, whereas in April and December, the lowest standard deviation was 1.61. The highest value of the shape parameter (2.94) is observed in July, while the lowest value (1.54) is observed in October. The upper limit of the scale parameter is 7.47 m/s, while the lower limit is 3.90 m/s. Furthermore, the scale parameters reach their highest level in July and reach their lowest level in February. The power density varies between 38.00 w/m^2 to 251.71 w/m^2. The highest power density is observed in July, while the lowest power density is observed in March.

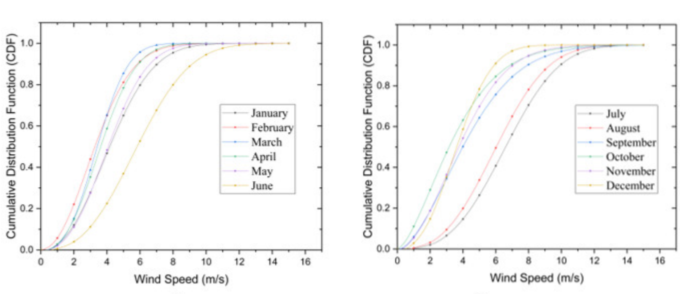
By applying Equations (3) and (4) to the available wind speed data, the Weibull parameters are calculated, and the findings are displayed in Table 1 and illustrated in Figure 11 and 12. However, figure 11 shows the monthly probability density function (PDF) on the basis of daily wind data and Figure 12 illustrates the cumulative distribution function (CDF) generated using the wind speed data observed in the selected offshore location. Upon examining these visuals, it becomes evident that the curves exhibit a consistent trend in wind speed for both cumulative density function and probability density function. The result of the analysis reveals that the parameters show variability across different months during the study period. This suggests that there are distinct differences in the distribution of wind speeds on a monthly basis. The curves for June, July, and August approximates normal distribution. Moreover, for June, July and August the values of shape parameter (k) and scale parameter (c) are relatively higher than others as a result, the distribution stretches further right and the height decreases. On the other hand, for the month February, March and December the distribution shrinks to the left and the peak increases as the values of shape parameter (k) and scale parameter (c) are comparatively lower during these months.

Figure 11: Probability density function (PDF) distribution for (a) January-June and (b) July-December.



Source: Authors.

Figure 12: Cumulative distribution function (CDF) distribution for (a) January-June and (b) July-December.



Source: Authors.

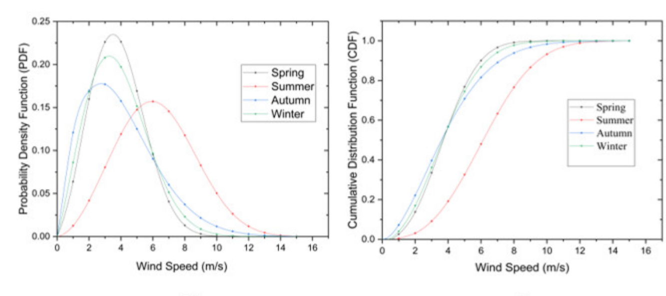
The Bay of Bengal is located in the northern hemisphere. The seasons in the northern hemisphere are as follows: Spring (March-May); Summer (June-August); Autumn (September-November); and Winter (December-February). Table 2 presents the values for seasonal mean wind speed, Weibull parameters k and c, standard deviation, and wind power density. It can be pointed out from the table that the wind speed ranges from 4.69 to 7.29 m/s. The highest and lowest wind speeds are observed during the summer and spring seasons, respectively. The highest standard deviation, 2.43, is observed during the summer, while the lowest standard deviation, 1.63, is observed during the spring. The highest and lowest values of shape parameters are found in summer and autumn respectively. The maximum value of the scale parameter is 6.99 m/s, while its minimum value is 4.29 m/s. The power density varies between 212.61 w/m^2 and 52.29 w/m^2. The highest power density is recorded during the summer, while the lowest power density is found in the spring.

Table 2: Seasonal average wind speed, standard deviation, shape parameter, scale factor and power density of the study area from 2012-2023.

Season	v_m (m/s)	σ	c (m/s)	k	Power Density (w/m^2)
Spring	4.69	1.63	4.29	2.49	52.29
Summer	7.29	2.43	6.99	2.77	212.61
Autumn	4.79	2.34	4.44	1.74	82.14
Winter	4.85	1.86	4.34	2.18	59.72

Source: Authors.

Figure 13: (a) Seasonal distribution of probability density function (PDF) and (b) cumulative distribution function (CDF).

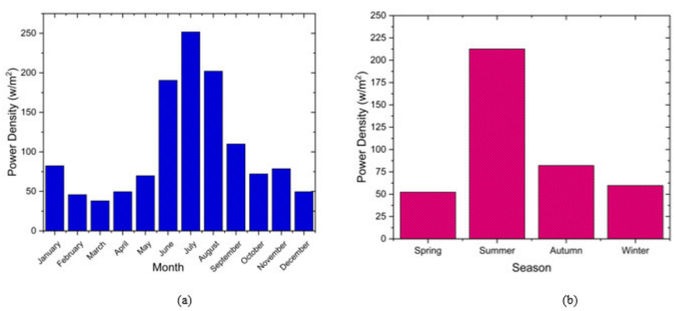


Source: Authors.

Figure 13 shows the distribution of the probability density function (PDF) and cumulative distribution function (CDF) for different seasons during the study period. The summer season tends to follow a regular normal distribution. Spring and winter also display similar types of distribution. In addition, the wind speeds on each curve tend to be identical for both the probability density function and the cumulative density.

The monthly power density and seasonal power density are calculated using equation (8) and the values are listed in Table 1, 2 and illustrated in Figure 14. From the figure it is seen that March has the lowest possible power density whereas July has the highest possible power density. Moreover, Summer is the most potential season for harnessing wind energy as wind power density is higher than other seasons. The seasonal wind power density indicates that the study area belongs to wind power class 2 for summer (as wind power density greater than 100 w/m^2 and smaller than 240 w/m^2) and wind power class 1 for rest of the seasons.

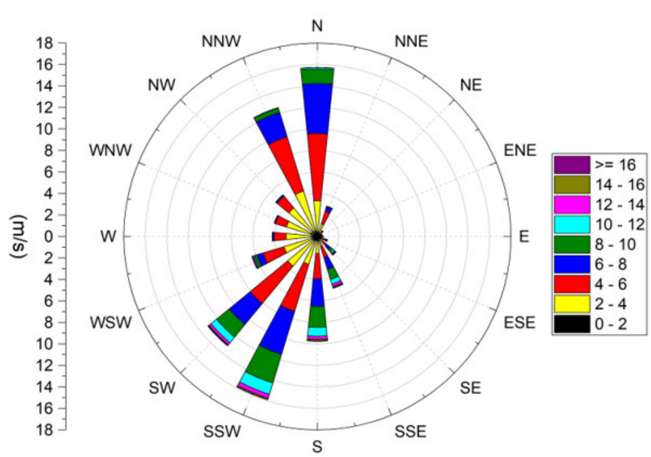
Figure 14: Power density distribution (a) monthly and (b) seasonal.



Source: Authors.

Moreover, the Wind rose diagram is used to show the wind direction and speed for each sampling period. For the year 2012-2023 the wind rose diagram has been prepared and is shown in Figure 15. It is seen that the maximum wind blows from the North and South-South West (SSW) direction and the minimum wind blows from the East-South East (ESE) direction. Besides, no wind blows from the North-East (NE) and East direction.

Figure 15: Wind rose diagram of the study area.



Source: Authors.

Conclusions.

Wind speed distribution plays a crucial role in determining the wind energy potential and the effectiveness of an energy conversion system at a specific site. When there is only a limited set of wind data available for a particular location, statistical methods can be employed to analyze wind characteristics. In this study two parameter Weibull distributions are used to analyze wind distribution of the offshore region near Inani, Cox's Bazar. The findings of this study can be summarized as follows:

a. During the study period, the highest value of wind speeds is found in July and the lowest value of wind speeds are found in February. The mean yearly wind speed is found to be 5.41 m/s.
b. Summer is more windy than other seasons in the Bay of Bengal. The wind speed varies in the range of 4.69-7.29 m/s for different seasons.
c. The highest value of the shape parameter is observed in July, while the lowest value is observed in October. In addition, the scale parameters are found to be maximum in July and minimum in February.
d. The scale parameters (c) shows consistently have larger values and greater variation than the shape parameters (k) throughout the daily, monthly, seasonal, and annual distributions.
e. The power density varies between 38.00 w/m^2 to 251.71 w/m^2. The research area is categorized as wind power class 2 during the summer and class 1 during the remaining seasons based on the seasonal wind power density.
f. The maximum wind blows from the South-South West (SSW) direction and the minimum wind blows from the East-South East (ESE) direction.

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Nomenclature.

v	Wind velocity (m/s)
k	Shape parameter
c	Scale parameter
v_m	Mean wind velocity (m/s)
σ	Standard deviation
Γ	Gamma function
ρ	Density of wind (kg/m^3)
P_w	Power density(W/m^2)

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