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Analyzing Wind Speed Trends and Statistical Insights for Panchagarh District, Bangladesh

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Abstract

This study analyzes wind speed pattern for evaluating the wind power potential of Panchagarh, Bangladesh, over a period between 2016 and 2020 by utilizing statistical methods. The Weibull and Rayleigh distribution have been used for modelling wind speed data. The wind speed data were obtained on a monthly basis, and the parameters of these distributions are obtained based on the data. The relevance of this study lies in its potential impact on decision-making processes related to wind power production. By comparing Weibull and Rayleigh probability distributions, the research aims to provide insights into how wind power varies over time and how it can be effectively harnessed for energy generation. Understanding the probability distributions of wind power is crucial for decision-makers to assess the renewable energy arena for planning, infrastructure investment, and resource allocation. Stakeholders can make a concrete decision about harnessing wind energy resources for a specific location by analyzing these distributions. Therefore, this paper's relevance stems from its focus on assessing the impact of wind power through comprehensive analysis of probability distribution functions, which can inform decision-making processes related to renewable energy utilization.

Keywords: Weibull distribution; Rayleigh distribution; Shape factor; Wind speed data; Wind power.

1. Introduction

A relevant quote from the Quran emphasizes the importance of environmental conservation: "And do not commit abuse on the earth, spreading corruption." This verse (Qur'an 2:60) underscores the beginning of good curator of mother nature and restraining from causing damaging to it. Wind is a significant environmental factor for harnessing green energy without causing any pollution. In contrast to traditional power sources such as fossil fuel-based sources: coal, gas, oil etc. wind power is benign to environment because this source of power hardly produces any greenhouse gas emission. Thus, wind power production is a source of non-polluting energy that supports environment and public health [1]. Additionally, wind power production saves money for long term as this source of power is long lasting [2]. Though, initial investment for setting up a wind turbine, and infrastructure is high, once operational, maintenance cost of wind power plant is relatively low compared to conventional sources of power production. Thus, wind power generation is financially viable for sustainable power production [3]. However, wind characteristics/variation is a significant factor that needs to be assessed beforehand for installment of wind power plant. The Weibull probability distribution is commonly employed for describing wind variations at a specific location [4]. This distribution evaluates the distribution of wind speeds which determines the potential of wind power production for a geographical location. Specifically, the Weibull distribution provides an actual interpretation of the frequency and intensity of different wind speeds for a geographical location for a period [5]. Thus, statistical distributions play a tremendous role in the implementation of efficient wind turbines and harnessing green energy from wind farms. These days, engineers are heavily using probability distribution for feasibility studying the potential of wind power production, by optimizing turbine design which helps to make a concrete decision [6]. Overall, the Weibull probability distribution provides an insight into the variation and strength of wind for a particular location that is crucial for effective harnessing wind power resources.

The Weibull parameters such as shape parameter; k [7] and scale parameter; c [8] are two significant factors to comprehend the potential of wind energy generation. The variability of wind speeds at a particular location can be analyzed using these two parameters that allow researchers for analyzing, modelling, and gaining insights for the optimization of a wind turbine [9]. Thus, an evaluation of shape and scale parameters in various location in Bangladesh is necessary to obtain a thorough understanding of the local wind conditions which in turn enables making a tangible decision regarding implementation and managing the wind power projects [11]. Thus, an optimization of wind resource is required in Bangladesh for obtaining highest power by improving efficiency for harnessing wind power [12-13]. Additionally, the Weibull parameters provide valuable insights into sustainable energy generation strategies, i.e., environmental concerns.

Panchagarh District (located at 26°3354/N and 88°5517/E) in Bangladesh has good wind speed with a good potential for wind power production [14]. Thus, an analysis of wind speed data over a period is required for wind power projects. Here, long-term wind data between 2016 and 2020 was obtained for achieving significant information on consistency and variability of wind speeds [15]. An analysis was carried out for Weibull parameters (shape parameter, k and scale parameter, c) for Panchagarh district to obtain local wind conditions. The outcomes of this research provide valuable insights on decision-making, and policy-making processes for green energy production. Further, this research contributes understanding of wind power potential in a localized district in Bangladesh over an extended period. At present, authors hardly find any research on wind power harnessing at Panchagarh, Bangladesh. Thus, the primary goal of this study is to determine whether the wind speed data at Panchagarh is statistically considerable for forecasting wind power generation.

The remaining of the paper proceeds as follows: Section 2 represents theoretical analysis; Section 3 illustrates results and discussion; Section 4 displays statistical analysis; and Section 5 provides conclusion.

2. Theoretical Analysis

2.1 Frequency Distribution of Wind Speed

The significant elements of wind speed are probability density distribution along with its functional forms. Two probability functions, such as Weibull distribution and Rayleigh distribution are commonly employed for the analysis of wind speed for a particular location over a period. The probability density function of Weibull distribution is expressed as follows [5,15-16],

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

Where, $f(v)$ represent wind speed probability of v, c and k are scaling parameter and shape factor of Weibull distribution, respectively.

The cumulative probability function for Weibull distribution [17-19] is represented as follows,

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

The probability density function of Rayleigh distribution obtained from the Weibull distribution for k=2 can be found as follows [5-6],

$$f(v) = \left(\frac{2v}{c^2}\right)\exp\left[\left(-\frac{v}{c}\right)^k\right] \quad (3)$$

Mean value v_m, and standard deviation σ, of Weibull distribution is calculated as [5-6],

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

and

Standard distribution, $\sigma = c\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right]^{0.5}$ (5)

Where Γ () represent gamma function.

Two influencing parameters of wind power production such as probable wind speed and wind speed that carries the maximum energy need to be analyzed for wind turbine. The most probable wind speed provides a value that supports most frequently in the wind speed probability distribution, which is expressed as follows [5],

$$v_{MP} = c\left(\frac{k-1}{k}\right)^{1/k} \quad (6)$$

The wind speed carrying maximum energy is found from [5],

$$v_{MaxE} = c\left(\frac{k+2}{k}\right)^{1/k} \quad (7)$$

Though numerous approaches are available in literature to evaluate Weibull parameters, standard deviation technique is preferred to estimate k and c because of its simple calculation.

2.1.1 The Standard Deviation Method

Weibull factors are calculated from the following equations [20],

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (8)$$

$$c = \frac{v_m}{\Gamma(1 + \frac{1}{k})} \quad (9)$$

2.2 Variation of Wind Speed with Height

Generally, a direct relationship exists between the variation of wind speed and height of the wind turbine. A commonly used equation that describes the relationship between variation of wind speed and height of the wind turbine is represented as follows [5-6],

$$\frac{v_1}{v_2} = \left(\frac{h_1}{h_2}\right)^p \quad (10)$$

Where v_1 and v_2 are mean value of wind speeds for heights $h_1$and h_2, respectively. The value of exponent p depends on stability of atmosphere and surface roughness.

2.3 Wind Power Density

The wind power speed through blade sweep area (A) rises as the cube of its velocity when air encounter a wind turbine blade that can be expressed as follows,

$$P(v) = \frac{1}{2}\rho A v^3 \qquad (11)$$

where ρ represents average air density. The average air density is 1.225 kg/m^3 for a temperature of 15° C and at atmospheric pressure.

According to the Weibull probability density function, the expected wind power density per unit area for a particular location is calculated for monthly or annual periods as follows,

$$P_w = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \qquad (12)$$

The Weibull scale parameter (m/s) is demonstrated as,

$$c = \frac{v_m}{\Gamma(1 + \frac{1}{k})} \qquad (13)$$

When $k = 2$, from equation (9), Rayleigh power density model can be represented as [5-6],

$$P_R = \frac{3}{\pi}\rho {v_m}^3 \qquad (14)$$

$P_{m,\ R}$ is the wind power density in terms of probability density distribution that can be found as,

$$P_{m,\ R} = \sum_{j=1}^{n}\left[\frac{1}{2}\rho {v_m}^3 f(v_j)\right] \qquad (15)$$

The error in power density calculations using probability distributions is determined using the following equation [5],

$$\text{Error}\ (\%) = \frac{\mathrm{P}_{\mathrm{w},\ \mathrm{R}} - \mathrm{P}_{\mathrm{m},\ \mathrm{R}}}{\mathrm{P}_{\mathrm{m},\ \mathrm{R}}} \qquad (16)$$

Where $\mathrm{P}_{\mathrm{w},\ \mathrm{R}}$ is the average power density achieved from either Weibull or Rayleigh function for error calculation? The yearly average error in power density using the Weibull function is calculated by the following expression,

$$\text{Error}\ (\%) = \frac{1}{12}\sum_{\mathrm{i}=1}^{12}\frac{\mathrm{P}_{\mathrm{w},\ \mathrm{R}} - \mathrm{P}_{\mathrm{m},\ \mathrm{R}}}{\mathrm{P}_{\mathrm{m},\ \mathrm{R}}} \qquad (17)$$

2.4 Statistical Analysis of the Probability Distributions

To evaluate the performances of Weibull and Rayleigh distributions few statistical parameters such as square of correlation coefficient (R^2), chi-square (χ^2), and root mean square error analysis (RMSE) are commonly estimated [5]. These parameters can be evaluated using the following expression,

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - z_i)^2 - \sum_{i=1}^{N}(x_i - y_i)^2}{\sum_{i=1}^{N}(y_i - z_i)^2} \qquad (18)$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{N - n} \qquad (19)$$

$$\text{RMSE} = \left[\frac{1}{\mathrm{N}}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{1/2} \qquad (20)$$

where y_i, z_i, x_i are ith measured data, mean value, predicted data, respectively for Weibull or Rayleigh distribution. N represents observation number, and n is number of constants [5-6]. Thus, a large value of R^2 is marked by minimum value of RMSE and χ^2.

3. Results and Discussion

The wind speed data for Panchagarh district of Bangladesh for a period between 2016 and 2020 were investigated at height of 10 meters above ground. Table-1 summarizes the outcome of statistical analysis of wind speeds data.

Table 1: Monthly mean wind speeds and standard deviation in Panchagarh, 2016-2020.

Year	2016		2017		2018		2019		2020		**Whole year**	
Parameter	v_m	σ	v_m	σ	v_m	σ	v_m	σ	v_m	σ	$\boldsymbol{v_m}$	**σ**
January	1.944	0.483	1.667	0.453	1.778	0.419	1.944	0.433	1.806	0.303	1.828	0.418
February	2.222	0.622	1.667	0.675	2.194	0.944	2.111	0.631	2.111	0.622	2.061	0.699
March	2.472	0.781	2.333	0.789	2.528	0.817	2.528	0.7	2.556	0.669	2.483	0.751
April	2.944	0.828	2.806	0.828	2.611	0.597	2.917	0.764	3.278	0.908	2.911	0.785
May	2.361	0.506	2.361	0.494	2.583	0.494	3.444	1.092	3.556	1.056	2.861	0.728
June	2.083	0.342	2.333	0.342	2.278	0.653	2.806	0.783	3.056	0.853	2.511	0.594
July	2.5	0.589	2.889	0.589	2.639	0.781	2.944	0.717	2.722	0.564	2.739	0.648
August	1.972	0.447	2.028	0.503	2.306	0.636	2.389	0.658	2.75	0.753	2.289	0.599
September	1.472	0.331	2.167	0.739	1.861	0.567	2.556	0.731	2.5	0.703	2.111	0.614
October	1.333	0.303	1.861	0.667	1.861	0.65	1.639	0.447	1.639	0.45	1.667	0.503
November	1.417	0.422	1.611	0.483	1.778	0.522	1.694	0.428	1.583	0.308	1.617	0.433
December	1.528	0.408	1.694	0.569	1.667	0.564	1.833	0.381	1.583	0.247	1.661	0.434
Yearly	2.021	0.505	2.118	0.594	2.174	0.637	2.4	0.647	2.428	0.62	2.228	0.601

The estimated mean wind speeds and standard deviations for monthly data between 2016 and 2020 is represented in Table 1. The outcome represents the highest wind speeds recorded in April during the summer in the whole year. However, the lowest value of wind speed was observed in November in the whole year. Fig. 1 illustrates monthly mean wind speeds for Panchagarh district between 2016 and 2020. A consistent result is represented in Fig. 1 for the trend in monthly mean wind speeds across different years. Fig. 2 and Fig. 3 demonstrate monthly probability density and cumulative distributions for Panchagarh district between 2016 and 2020 for whole year. A similar trend in data is exhibited by cumulative density and probability density. Fig. 4 shows annual probability density distribution and cumulative distribution for Weibull and Rayleigh distributions.

Table 2 shows the monthly values for two parameters k and c from 2016 to 2020 along with their yearly averages value. A fluctuation across the years is marked by these tow parameters k and c. For instance, the highest values for both parameters are generally observed in July (k) and May (c), indicating increased variability or intensity during this period. The yearly averages of the parameters showed a typical trend of increased values over the years, with some fluctuation. Particularly, average value for k varies from 3.792 to 4.508, whereas average value for c alters from 2.214 to 2.664.

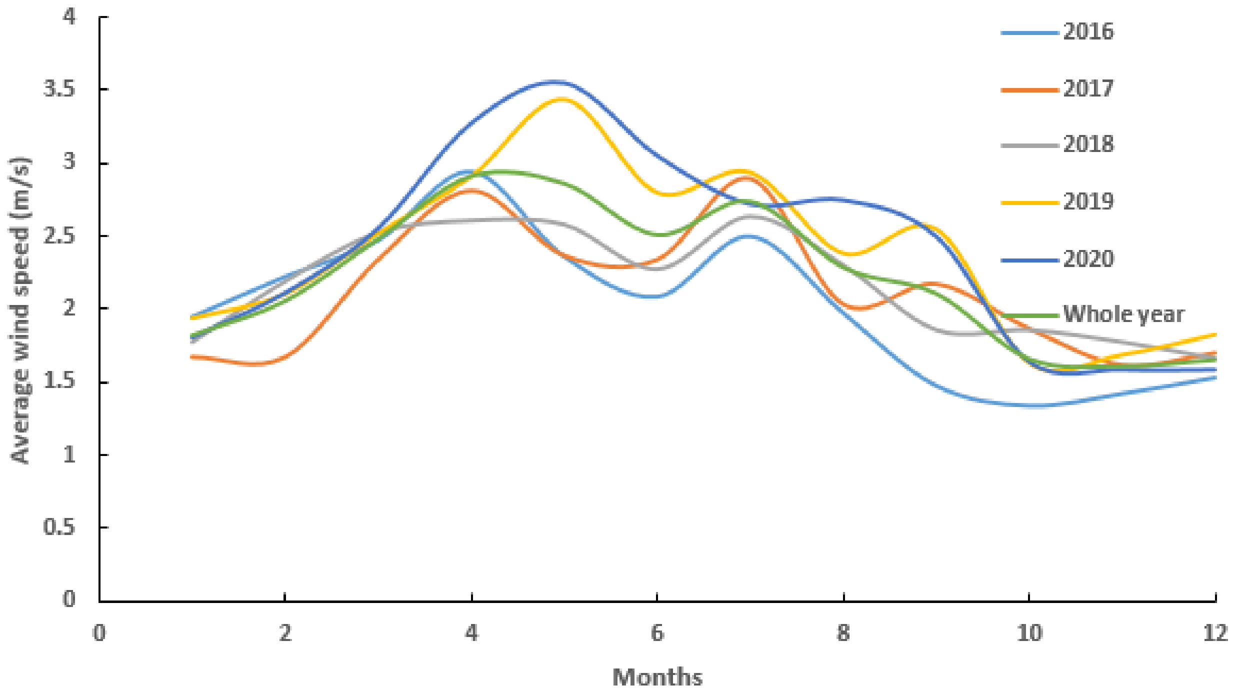

Fig.1: Demonstrate monthly wind speed of Panchagarh 2016-2020.

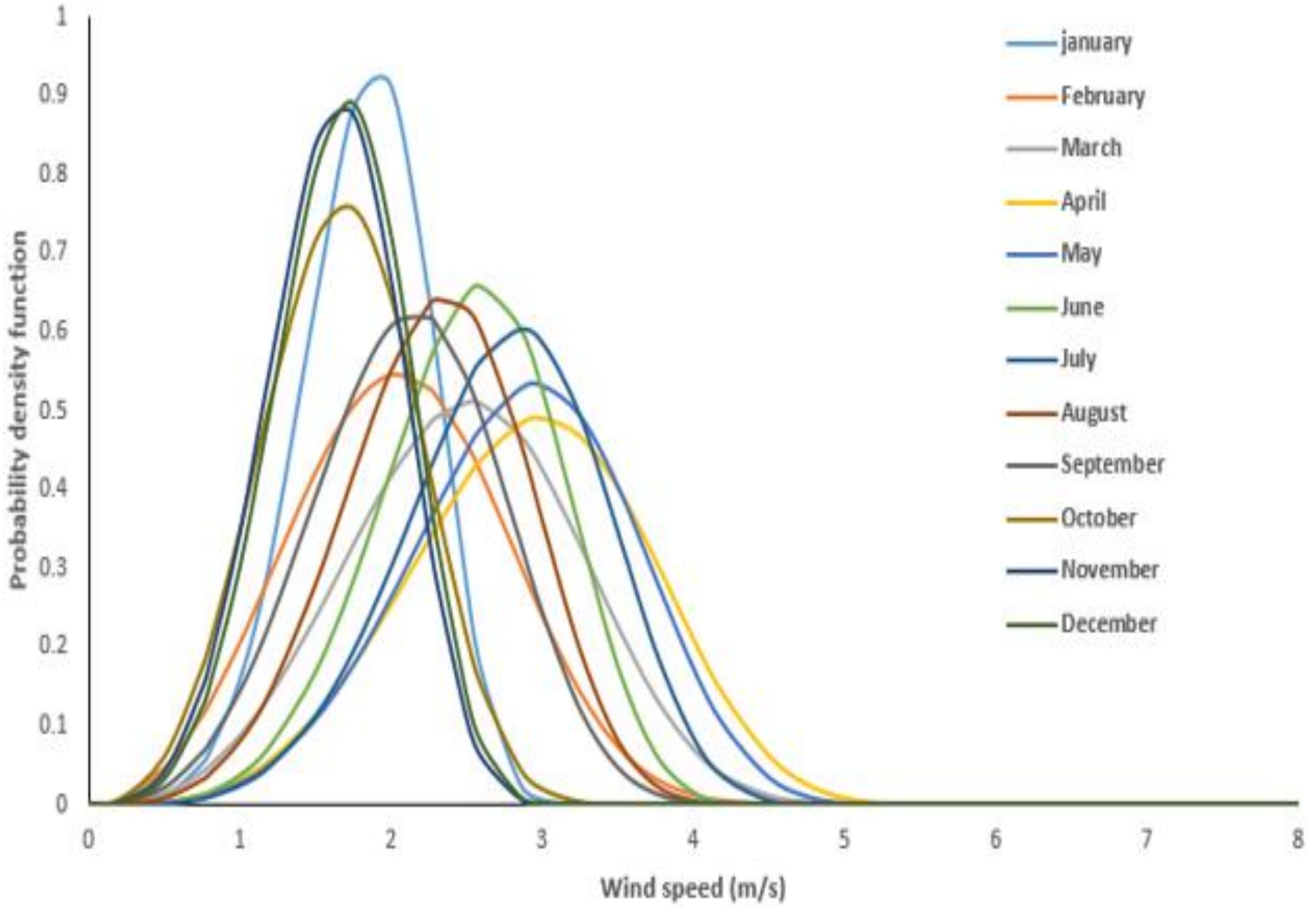

Fig.2: Illustrating monthly wind speed probability distributions obtained for 2016 to 2020 for Panchagarh district over the whole year.

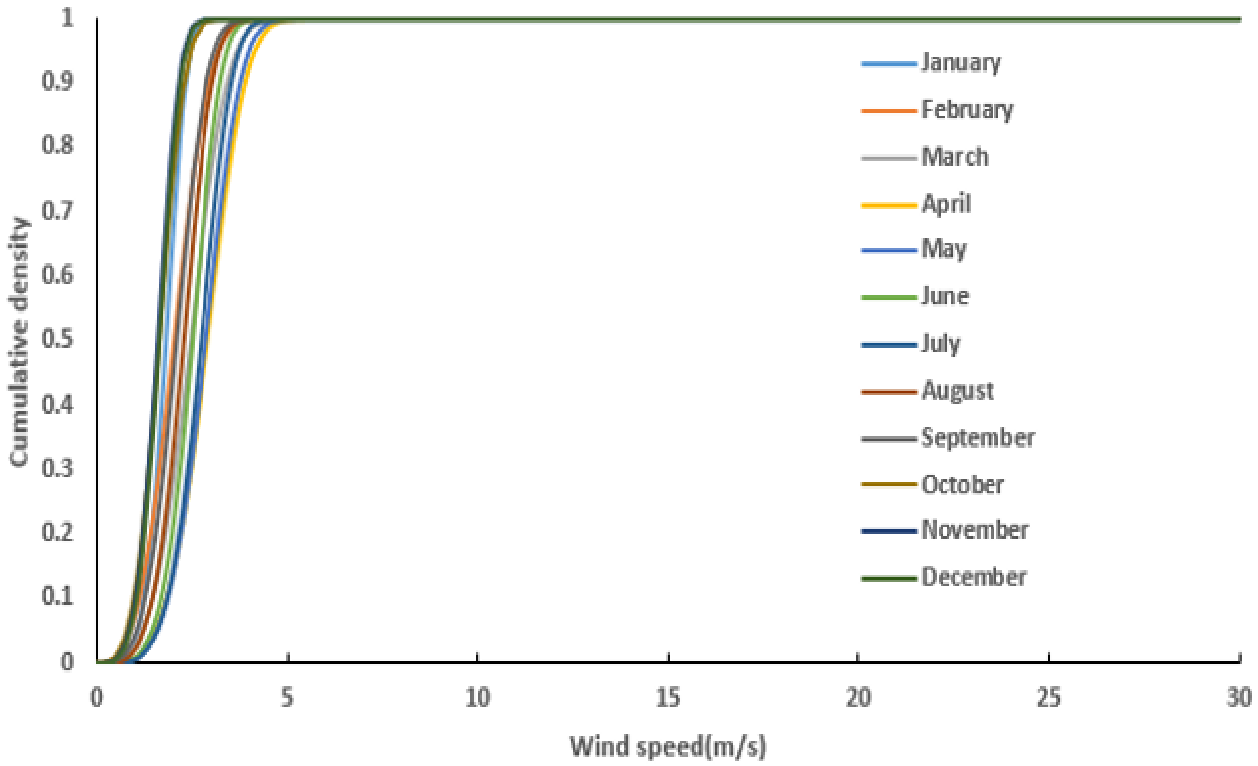

Fig.3: Illustrating cumulative probability distributions of the monthly wind speed obtained from measured data of Panchagarh over the whole year.

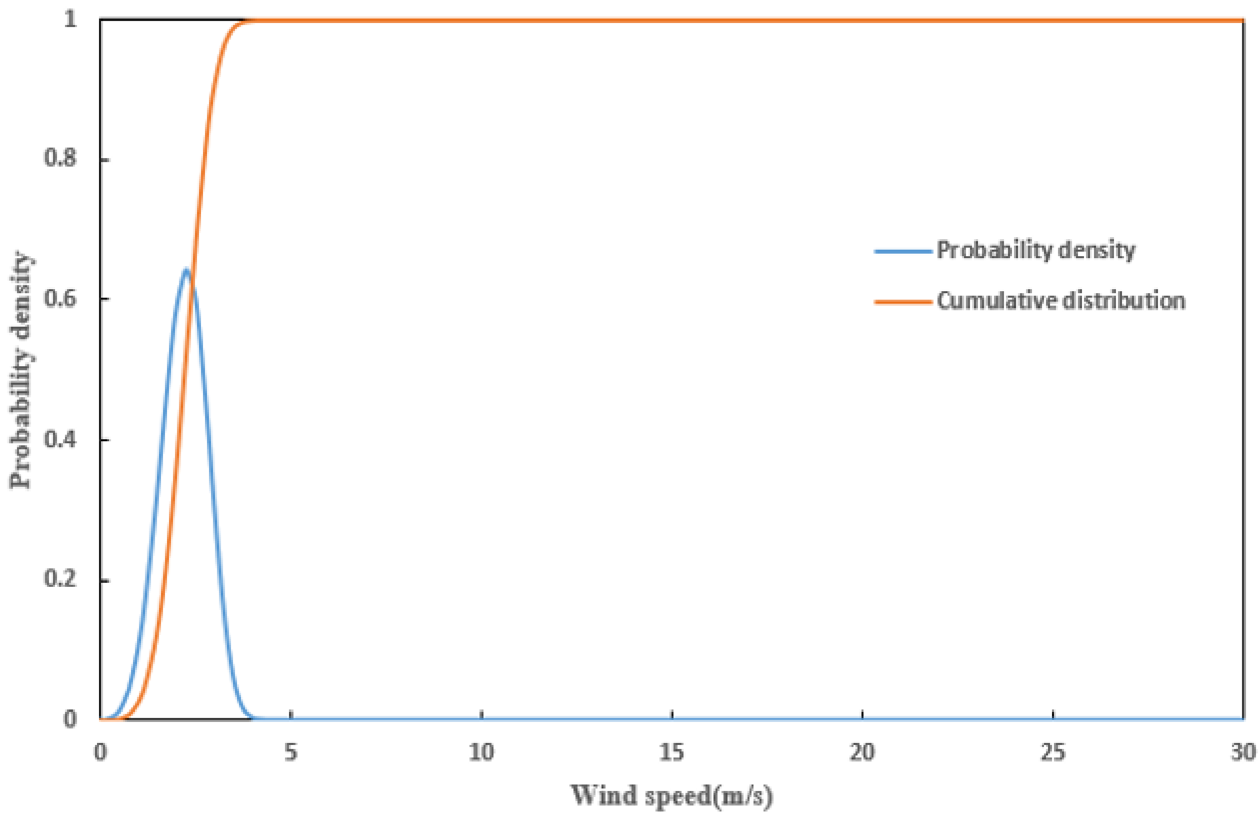

Fig.4: Demonstrating yearly wind speed probability density and cumulative probability distributions, for measured data of Panchagarh district for the whole year.

Table 2: Monthly data for shape parameter, k, and scale parameter, c, in Panchagarh district, 2016-2020.

Year	2016		2017		2018		2019		2020		Whole year	
Parameter	k	c	k	c	k	c	k	c	k	c	k	c
January	4.535	2.13	4.118	1.836	4.799	1.941	5.106	2.115	6.953	1.931	4.96	1.992
February	3.985	2.452	2.669	1.875	2.498	2.473	3.715	2.339	3.769	2.337	3.237	2.3
March	3.497	2.748	3.247	2.603	3.411	2.813	4.033	2.788	4.284	2.808	3.664	2.753
April	3.967	3.25	3.764	3.106	4.964	2.845	4.284	3.205	4.03	3.615	4.151	3.205
May	5.332	2.562	5.463	2.559	6.023	2.784	3.483	3.829	3.739	3.938	4.419	3.139
June	7.123	2.225	8.056	2.477	3.885	2.517	3.997	3.095	3.999	3.371	4.782	2.742
July	4.807	2.729	5.625	3.125	3.754	2.922	4.639	3.221	5.528	2.948	4.786	2.991
August	5.01	2.148	4.547	2.221	4.049	2.542	4.054	2.634	4.084	3.03	4.285	2.515
September	5.064	1.602	3.217	2.418	3.638	2.064	3.896	2.824	3.968	2.759	3.824	2.335
October	5.002	1.452	3.049	2.083	3.134	2.08	4.098	1.806	4.07	1.806	3.67	1.848
November	3.723	1.569	3.697	1.785	3.782	1.968	4.459	1.858	5.911	1.708	4.184	1.779
December	4.191	1.681	3.268	1.89	3.244	1.86	5.515	1.986	7.514	1.686	4.297	1.825
Yearly	4.508	2.214	3.976	2.338	3.792	2.405	4.153	2.643	4.407	2.664	4.153	2.453

Fig. 5 shows actual wind speed probability distribution for entire year obtained from the Weibull and Rayleigh distributions. A comparison of these two approximations for actual probability distribution is displayed in Table 3. A good fit for actual wind speed data is marked by a relatively higher R^2 value, and a lower RMSE. This is represented in table 3, i.e., higher R^2 value, and lower RMSE value obtained from probability distribution. Further, the Weibull probability distribution represents relatively accurately the probability density of wind speeds for the whole year.

Table 4 represents annual Weibull parameters, average wind speed, and wind power density. Though average wind speed v_m across the period remains almost constant, a small fluctuation is observed in v_m. Further, the highest mean wind speed is found in 2020 (as shown in Table 1). The shape parameter, k rises over time that is demonstrating a trend towards sharper peaks in wind speed distribution. However, a significant variation is found in power density, P and the highest wind energy potential was observed in 2020. Thus, wind energy varies considerably over time from year to year which alters the wind power generation potential. Overall, the data reflects a variation of wind speed characteristics and energy potential evolve annually. Fig. 6 shows the power density curve derived from probability density distributions using Weibull and Rayleigh distributions. Particularly, the Weibull model predicts relatively lower power densities than that of the Rayleigh model, especially in months with relatively higher wind speeds. Thus, the Rayleigh model provides a relatively accurate reflection of the actual wind conditions and energy potential between 2016 and 2020.

The error in power densities calculated using the Weibull and Rayleigh probability distributions is represented in Fig. 7. The Weibull model generally represents relatively lower error values in power densities compared to Rayleigh model. Specifically, the highest error for the Weibull model was observed in January, whereas the lowest error was found in October. Conversely, the Rayleigh model showed the greatest error in November.

Table.3: Comparison of the wind speed data of the actual probability distributions using the Weibull and Rayleigh probability distribution for an entire year.

$f(v)$			
Wind speed	Actual data	Probability density function	Rayleigh
1	0.082071711	0.097609853	0.325850247
2	0.617965215	0.579482084	0.647891725
3	0.290922671	0.317988636	0.955402482
4	0.008563161	0.003887089	1.273869976
5	1.57592E-05	7.01604E-08	1.59233747
6	1.81333E-09	4.29964E-17	1.910804964
7	1.30455E-14	7.3111E-33	2.229272459
8	5.868E-21	9.92158E-58	2.547739953
9	1.6503E-28	1.06945E-94	2.866207447
10	2.90186E-37	3.0963E-147	3.184674941
11	3.19032E-47	2.7177E-219	3.503142435
R^2		0.994608455	0.33651957
RMSE		0.014366679	0.27245406

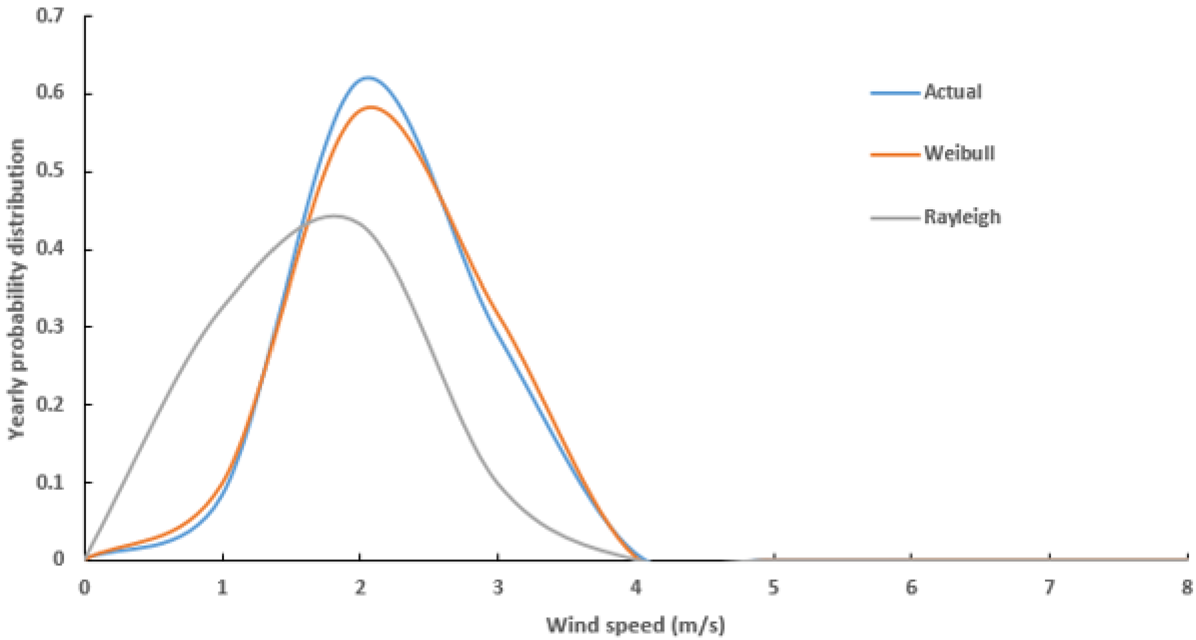

Fig.5: Demonstrating Weibull and Rayleigh probability distribution of the actual probability distributions of the wind speeds.

Table 4: Yearly wind speed characteristics 2016-2020, Panchagarh district.

Year	v_m (m/s)	k	c (m/s)	v_{MP} (m/s)	v_{MaxE} (m/s)	P (w/m^2)
2016	2.020833333	4.507598381	2.214217261	2.094368911	2.402146551	6.001275075
2017	2.118055556	3.976187126	2.33756437	2.173319485	2.589809776	7.198267424
2018	2.173611111	3.791897932	2.405289579	2.218727157	2.689567557	7.918726376
2019	2.400462963	4.153030125	2.642663177	2.473060059	2.905026522	10.32129023
2020	2.428240741	4.406928954	2.664100286	2.512971491	2.900196772	10.48260864

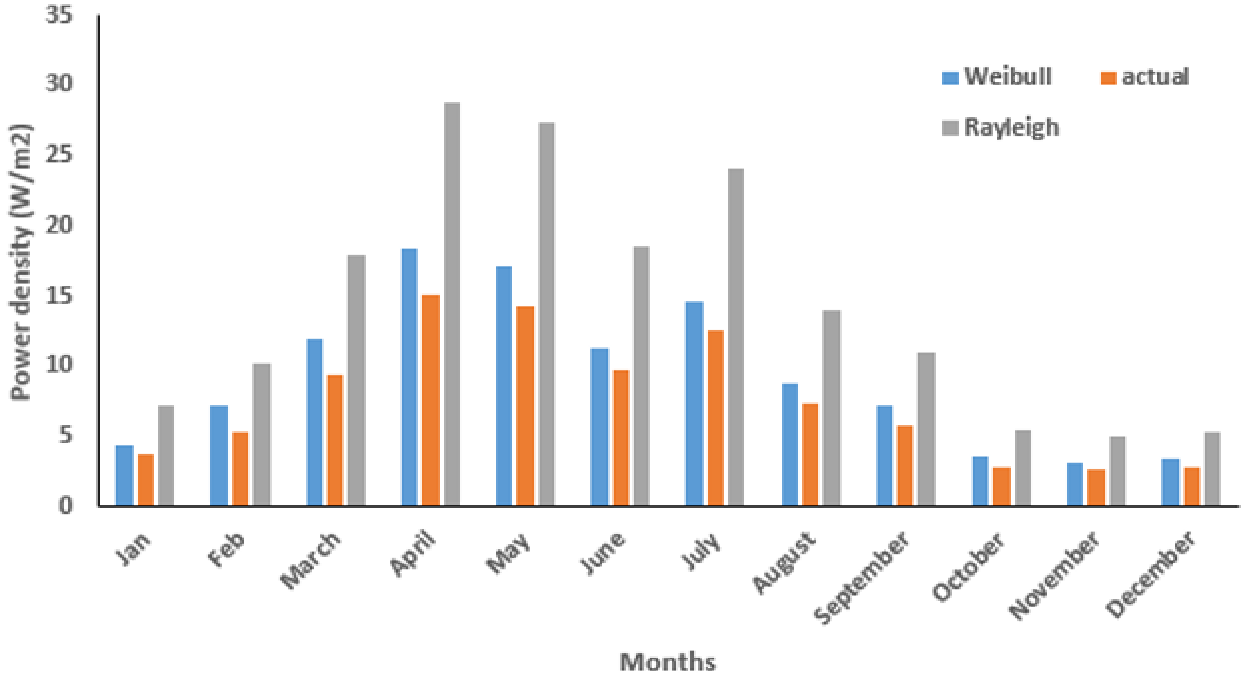

Fig.6: Showing the wind power density for every month of wind speed using the Weibull and Rayleigh models.

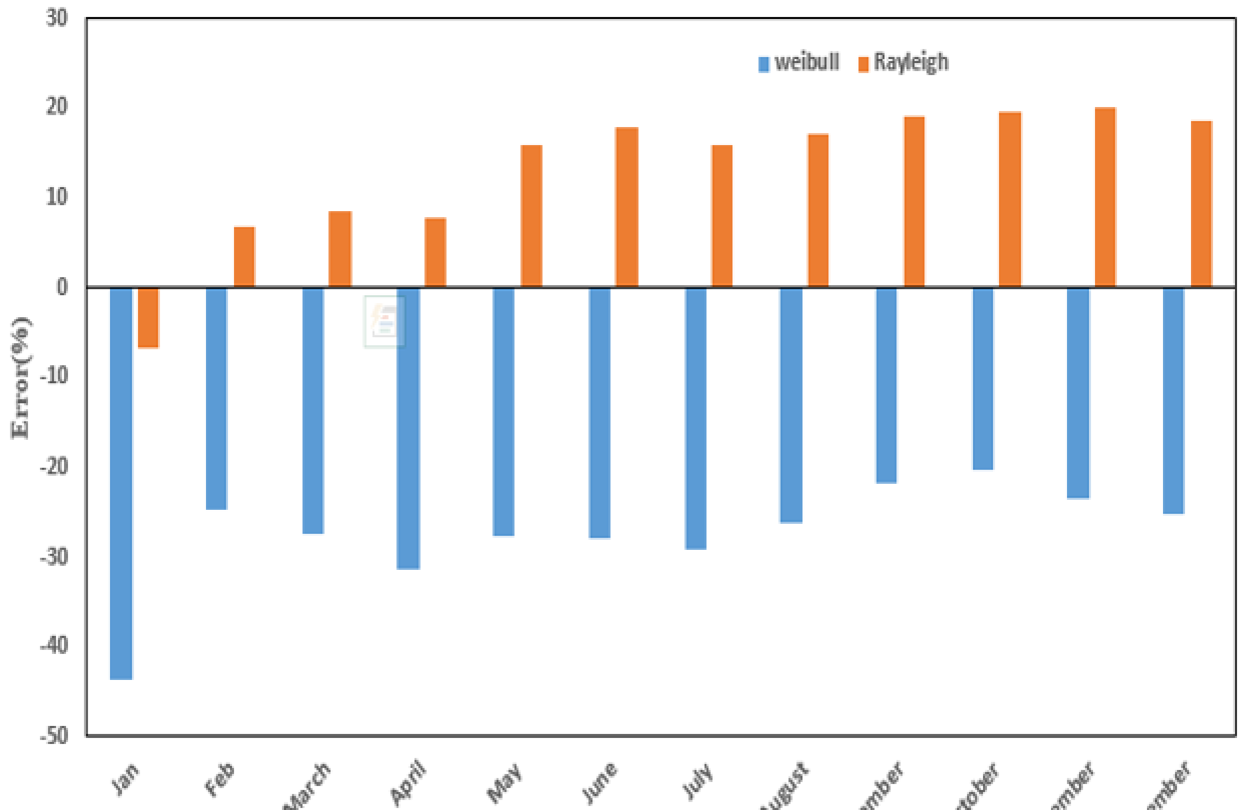

Fig.7: Illustrating error values of the wind power density for every month derived from the Weibull and Rayleigh models.

4. Statistical Analysis

To determine which year provided the best fit for the data based on R-squared values, an analysis of the performance over the year and months were performed. The summary of the R-squared values and their significance for each year from 2016 to 2020 is represented in Table 5, high R-squared values across all months, with values mostly above 0.85. All p-values are extremely low (well below 0.05), indicating significant models for each month. Regarding 2017, slightly lower R-squared values compared to 2016, but still high for most months. All p-values are also very low, indicating the models are significant. With respect to 2018, high R-squared values, but with more variability. Months like July show notably lower R-squared values (almost 0.50). All p-values are very low, showing that the models are statistically significant, despite the variability in R-squared. In 2019, Similar to 2018, with generally high R-squared values but some variability. July and August show lower R-squared values (0.84). All p-values are very low, confirming the models are statistically significant. During the year of 2020, very high R-squared values across all months, often 0.85. All p-values are extremely low, showing that the models are highly significant. 2020 offers the best fit with the highest R-squared values and consistent model performance across all months. 2016 and 2017 also show high R-squared values and statistical significance but generally fall slightly short of 2020 in terms of R-squared values. 2018 and 2019 exhibit more variability, particularly in months like July and August where R-squared values drop noticeably, though they are still statistically significant.

Table 5: Statistical analysis of the year 2016 to 2020.

	2016		**2017**		**2018**		**2019**		**2020**		
Months	R-square value	P-value	R-square value	P-value	R-square value	P-value	R-square value	P-value	R-square value	P-value	Sig,/not significant
January	0.90118	4.1E-16	0.875746	1.15E-14	0.925821	6.33E-18	0.887721	2.63E-15	0.965114	1.1E-22	Significant
February	0.94536	1.41E-18	0.901319	1.37E-14	0.797644	1.64E-10	0.769061	9.29E-10	0.805146	1E-10	Significant
March	0.95793	1.67E-21	0.833674	8.08E-13	0.884237	4.11E-15	0.900944	4.25E-16	0.928889	3.43E-18	Significant
April	0.892388	4.4E-15	0.892388	4.4E-15	0.904981	7.66E-16	0.837537	1.45E-12	0.851603	4.04E-13	Significant
May	0.939691	3.13E-19	0.933596	1.27E-18	0.933596	1.27E-18	0.790897	2.29E-11	0.775138	6.62E-11	Significant
June	0.898671	1.89E-15	0.898671	1.89E-15	0.874524	3.81E-14	0.754253	4.99E-10	0.719897	3.18E-09	Significant
July	0.887295	2.78E-15	0.887295	2.78E-15	0.499748	8.77E-06	0.837728	5.64E-13	0.851022	1.62E-13	Significant
August	0.887702	2.64E-15	0.88881	2.28E-15	0.869917	2.25E-14	0.837288	5.87E-13	0.731849	8.74E-10	Significant
September	0.86932	6.76E-14	0.769032	2.07E-10	0.890702	5.48E-15	0.783357	8.39E-11	0.774126	1.51E-10	Significant
October	0.855572	1.03E-13	0.760726	0.760726	0.756292	2.15E-10	0.77120	8.54E-11	0.77532	6.55E-11	Significant
November	0.923977	3.34E-17	0.852709	3.64E-13	0.860227	1.74E-13	0.877589	2.69E-14	0.894204	3.46E-15	Significant
December	0.950325	1.87E-20	0.84593	2.65E-13	0.843422	3.35E-13	0.893821	1.17E-15	0.923395	1.01E-17	Significant

5. Conclusions

The wind characteristics of Panchagarh district between 2016 and 2020 have been statistically analyzed. The probability density distribution and the power density distribution were obtained from wind speed data. Two probability density functions such as Weibull and Rayleigh models are fitted to calculate the probability distributions. The comparison of Weibull and Rayleigh distributions was carried out using R^2, and RMSE values which are crucial for analyzing wind speed data. The outcome identifies that the Rayleigh distribution demonstrates relatively better power density than that of Weibull distribution for wind data. Additionally, the significant variation in wind power density due to changes in wind speed over time is an important outcome. This variability highlights the dynamic nature of wind energy potential in Panchagarh and underscores the need for comprehensive data analysis to understand for harnessing the renewable resource effectively. These findings contribute to our understanding of how different probability distributions can be used to model wind speeds and power densities that provide valuable insights for decision-making processes related to wind energy projects in Panchagarh district and for similar locations.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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