

In-Depth Analysis of Wind Speed Patterns and their Implications for Patenga, Chittagong District, Bangladesh

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Abstract: This paper focuses on evaluating the wind speed and characterize the wind power potential in Patenga, Chittagong District, Bangladesh. The real data over the duration from 2016 to 2020 have been used to assess the wind behavior. Using statistical analysis, the study derives probability density functions(PDF) from time series data to analyze wind speed distributions. Key statistical distributions, particularly Weibull and Rayleigh are used to evaluate monthly wind speed patterns. The Weibull distribution shows more accuracy with respect Rayleigh to investigate the wind behavior. The analysis provides crucial aspects of wind power of the proposed region which can be helpful and informative for any researcher who will go to harvest renewable power in the nearest future. It is highlighted that there are very significant impacts of wind energy potential in this proposed area.

Keywords: Wind power investigation; Rayleigh distribution; Weibull distribution; Shape factor.

1. Introduction

Bangladesh is a developing country which energy sector is fully depend on fossil fuel. Recently scientists and policy makers are trying to diverse its energy sources. As Bangladesh is situated in the region of tropic of cancer and in the coastal area of Bay of Bengal, it has a great opportunity to harvest renewable energy from the nature. A renewable based power

system is designed and showed that it will significantly decrease the consumption of fossil fuel [1]. A study of fuel cell based hybrid power system is done for a developed country like Japan so that it indicates more renewable penetration into the grid. This study shows a clear overview of integrating and promoting of renewable energy [2]. The continuous growth of renewable energy technology (RET) is reconstructing the energy orientation and gives the new dimension of future expansion and technological progress [3]. Now-a-days, more consumption of fossil fuel brings climate change and increases the global temperature gradually. This issue is a big concern for being sustainable development. There are several renewable energy sources like photovoltaics, wind, hydro-electric, biogas and biomass etc. These sources give a practical accomplishment with respect to using of fossil fuel [4]. Beyond declining greenhouse gas (GHG) emissions, RETs offer a great solution to introduce clean energy in the development of energy sector. Recent advancements include innovations in storage technologies, smart grid infrastructure, and strategies for integrating renewable power into existing energy systems. Moreover, the increasing adoption of renewable energy brings significant benefits for environmental sustainability and human well-being [5]. Integration of RET ensures more renewable penetration and less fossil fuel consumption. These technologies can improve the environmental indexes of air and water. So, a significant amount of water and air pollution is reduced from this perspectives [6]. The move to renewable energy is consistent with ideas found in many cultural traditions that support the prudent use and optimistic management of natural resources. The promise for a more sustainable future where clean energy plays a critical role. It has a crucial indication in tackling global environmental concerns while increasing social welfare is suggested by the ongoing advancements in renewable technologies. Wind energy has become a top choice among renewable energy sources because of its slow environmental effect, accessibility, high efficiency and capacity to provide electricity through the day long even if at night [7]. Wind energy has great promise and is growing quickly [8]. Larger, more effective turbines, more wind farms in the coastal area, and the use of advanced technology to boost performance are all results of recent technological developments in wind energy. The Weibull probability distribution is generally used in many statistical analyses. It is also used to describe fluctuations in wind speed at certain places [9–11]. Wind speed variations at specific locations are typically modeled using the Weibull probability distribution [9–11]. Over recent decades, wind power assessment has attracted significant research interest. In Bangladesh, studies have optimized wind energy across regions [12–18] using the Weibull probability distribution function. These analyses are particularly based on the key parameters called scale (c) and shape (k) factor.

A.P. Marugan et. al. explored a survey based on artificial neural network (ANN) to optimized wind energy system [19]. Some researchers are tried to introduced deep learning model to estimate the wind potential [20–22]. In addition, a lot of research work have been done to

evaluate the wind energy. Physical models, such as Weather Research and Forecasting (WRF) and the numerical weather prediction (NWP) model are extensively used in wind forecasting and wind data analysis for any specific site [23]. These models evaluate the data with environmental factors such as temperature, ambient pressure, humidity, surface roughness and terrain [24-25]. These factors are utilized in mathematical models to estimate wind speed at certain locations, which is then integrated with the power curve of the turbine to predict wind power. Instead than using historical data, this method uses physical data. Research shows that, while requiring more processing power, physical models typically perform better than conventional statistical models. The physical model shows a greater overview to forecast wind speed in the duration of medium- and long-term [26]. The statistical model reads the past historical data and analyze these. It tries to determine the linear and non-linear correlation and regression between weather ambient and power output [27]. These correlation and regression analysis are further used to forecast the wind behavior in future. These statistical analyses are less resource-intensive and simpler to use, but over longer time periods, their forecasting accuracy declines.

This work provides a thorough examination of wind speed data gathered in Patenga, Bangladesh's Chittagong District (22.2583°N, 91.7977°E), between 2016 and 2020 [28–29]. Using local wind speed data, no prior research has been done on wind energy potential. This study traces a meaningful gap about this location. The main goal is to forecast the area's potential for wind energy generation by statistically analyzing the wind speed data.

The paper is constituted as the given segmentation. Segment 2 explores and discusses the theoretical overview. Segment 3 discusses and analyses the results. And segment 4 concludes the study.

2. Theoretical Overview

2.1 Statistical distribution of wind speed

A key component of wind energy research is comprising wind speed distributions and their functional forms. The Weibull and Rayleigh distributions are frequently used to model and characterize wind speed data for a certain place with a specific time period. The expression for the Weibull probability distribution function is [30–31],

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

Where, $f(u)$ is denoted by the wind speed probability at the speed u ; the c and k are denoted as scaling parameter and the factor of Weibull shape.

The Weibull probability distribution is the multiplication of two functions, one is increasing ramp and other is exponential decaying. The cumulative probability density function (CPDF) of Weibull distribution [32–34] is represented as,

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

A modified distribution system is also introduced in statistical analysis called Rayleigh distribution. When the Weibull distribution has a shape parameter k of 2, it simplifies to the Rayleigh distribution. Therefore, the Rayleigh distribution is also multiplication of two functions. The Rayleigh distribution can be easily derived from Equation 1. It is represented as given below,

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

In the equation, the factor c is only the control factor. In the Weibull distribution, the standard deviation σ and mean value u_m is directly measured from the two factors k and c . The expression to determine σ and u_m have been given as,

$$\sigma = c \left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right) \right]^{0.5} \quad (4)$$

And,

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

Where $\Gamma()$ is a mathematical function which belongs the factorial of real and imaginary number arguments. This function is denoted as gamma function.

There are two important parameters for estimating wind potential. Though there have a lot of variables associated with wind behavior. The first variable is the most probable wind speed (u_{MP}). It is the value that is occurred statistically more frequent in the given PDF. That means the value in the density function that has shown the maximum frequency. The second variable is the wind speed (u_{MaxE}) in which one can obtain maximum energy. The u_{MP} can be written based on two factor k and c as below,

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

The wind speed, u_{MaxE} in the long range PDF that exerts the maximum inherent energy can be expressed in terms of the factor k as given below,

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

Various techniques have been employed in the literature to estimate the Weibull distribution parameters. These approaches include the power density method, the moment method, the graphical method as well as the standard deviation method. In addition, the maximum likelihood method the energy pattern factor method is also used in many cases. From these methods, the standard deviation method is mostly used to measure the parameter k and c .

The following relations using standard deviation method can be used to determine c and k ,

$$c = \frac{u_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (8)$$

And,

$$k = \left(\frac{\sigma}{u_m} \right)^{-1.086} \quad (9)$$

2.2 Variation of wind speed (u) with the height (h)

It is seen that the weather has so much uncertainties. Temperature, Pressure, Wind direction and other parameters are frequently changed with the height. So that, wind speed also varies with different height above the ground. The relationship between wind speed and height can be addressed in many ways. To establish the relation between these two parameters, it can be written as below,

$$\frac{u_1}{u_2} = \left(\frac{h_1}{h_2} \right)^p \quad (10)$$

Where, u_1 is the particular wind speed at height h_1 . In manner, u_2 indicates different wind speed at different level. The index p includes different environmental factors like temperature, pressure, surface roughness, terrain etc.

2.3 Wind Power Potential

Wind Energy is a form of mechanical energy that means kinetic part. So, usual kinetics is applied to determine the Wind power. The power (P) at speed u is determined by,

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

Where, the blade sweep area is A and ρ is average air density (1.225 kg/m^3 , based on STC at sea level and 15°C). This density depends on several environmental factors such as air pressure, temperature, altitude.

According to the discussed Weibull PDF, the estimated wind power density per unit area (P_w) may be measured for a specific time period,

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

Whether, the parameter c can be denoted by,

$$c = \frac{u_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (13)$$

The estimated power equations may be derived for Rayleigh distribution for $k = 2$.

$$P_R = \frac{3}{\pi} \rho u_m^3 \quad (14)$$

$P_{m, R}$ is the estimated wind power density with respect to the particular distribution such as Weibull and Rayleigh distribution.

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

It is most important to determine the error for measuring the wind power with different distribution.

$$\text{Error (\%)} = \left| \frac{P_{w, R} - P_{m, R}}{P_{m, R}} \right| \quad (16)$$

Where $P_{m, R}$ is estimated wind power density according to Rayleigh distribution and $P_{w, R}$ is the measured wind data.

The yearly average error may be measured by,

$$\text{Error (\%)} = \frac{1}{12} \left| \sum_{i=1}^{12} \frac{P_{w, R} - P_{m, R}}{P_{m, R}} \right| \quad (17)$$

2.4 Statistical performance analysis of the distributions

The performance of any distribution can be evaluated some indicators called chi-square (χ^2), root mean square error (RMSE) and the square of the correlation coefficient (R^2). The Weibull and Rayleigh distributions are assessed within these three parameters. These parameters are given below,

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

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

And,

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

where y_i means the i^{th} measured data of wind profile. The value y_i indicates the actual data which is recorded for a specific time. Now, z_i is the average value of the phase i , this value is calculated by the average of actual data with the event i . x_i means the forecasts data using Rayleigh or Weibull distributions, n means the number of constants of the events and N is the total number of observations. Among the discussion, when the values of χ^2 and RMSE are minimized and R^2 is maximized, the probability distribution that provides the best accuracy to estimate wind power.

3. Results and discussion

For the study, the data of wind profile of the location Patenga, Bangladesh has been collected [28–29]. The recorded time series data at a height of 10 meters between the time duration 2016 and 2020, were extensively analyzed using several statistical methods. The observed results of this analyses are concise in Table 1. The calculated standard deviations and monthly average wind speeds are showed in Table 1 [28–29]. It is seen that there are some randomness in the variation of year to year data. In the year of 2016, the month of April shows a greatest average wind speed whether the month of June indicates for the year of 2017. Moreover, for the year of 2018, 2019 and 2020, the highest average wind speed was found in the month of July and August.

Table 1: The calculated average wind speeds and standard deviations in Patenga, over the years 2016 to 2020

Years	2016		2017		2018		2019		2020		Whole five year	
	u_m	σ	u_m	σ	u_m	σ	u_m	σ	u_m	σ	u_m	σ
January	2.278	0.481	2.889	0.625	2.667	0.417	3.111	0.597	2.972	0.542	2.783	0.532
February	2.472	0.556	2.417	0.944	2.306	0.631	3.333	0.764	3.222	0.708	2.75	0.721

March	2.5 83	0.75 8	2.8 33	0.91 7	2.5 83	0.611	3.25	0.91 7	3.111	0.931	2.872	0.82 7
April	4.6 67	0.519	4	0.87 5	2.8 61	0.58 3	3.88 9	1.06 9	3.80 6	0.90 3	3.844	0.79
May	3.5 28	0.54 7	3.13 9	0.91 7	3.5	0.611	5.194	0.80 6	4.361	0.86 1	3.944	0.74 8
June	3.8 61	0.39 7	4.8 61	0.63 9	4.3 06	0.42 5	4.77 8	0.73 6	5.22 2	0.55 6	4.606	0.551
July	4.7 5	0.361	4.6 39	0.68 1	4.9 17	0.45 3	6.05 6	0.66 7	5.38 9	0.56 9	5.15	0.54 6
August	4.1 67	0.47 2	4.0 28	0.54 2	4.3 89	0.361	4.83 3	0.75	5.77 8	0.611	4.639	0.54 7
September	3	0.381	3.0 83	0.72 2	2.9 44	0.48 1	4.05 6	0.62 5	4.05 6	1.40 6	3.428	0.72 3
October	2.3 33	0.36 9	2.6 39	0.73 6	2.3 06	0.49 2	2.80 6	0.59 7	3.333	0.68 1	2.683	0.57 5
November	2.1 67	0.42 5	2.3 89	0.58 3	2.11 1	0.38 9	3.139	0.59 7	3.08 3	0.48 6	2.578	0.49 6
December	2.0 83	0.39 7	2.3 61	0.52 8	2.7 5	0.35 3	3.30 6	0.5	3.25	0.47 2	2.75	0.45
Yearly	3.15 7	0.47 2	3.2 73	0.72 6	3.13 7	0.48 4	3.97 9	0.71 9	3.96 5	0.72 7	3.502	0.62 5

The mean wind speeds of our desired location (Patenga) for the five years have been depicted at the following Figure 1, which demonstrates a steady trend in wind speed patterns over time. As, every year has different monthly peaks which is more closely to July. The months of July and November had the highest and lowest wind speeds for the whole five years' data. It is also seen that the average wind speed of five years is 3.502 m/s and a standard deviation of 0.625. This profile shows a availability of wind throughout the year.

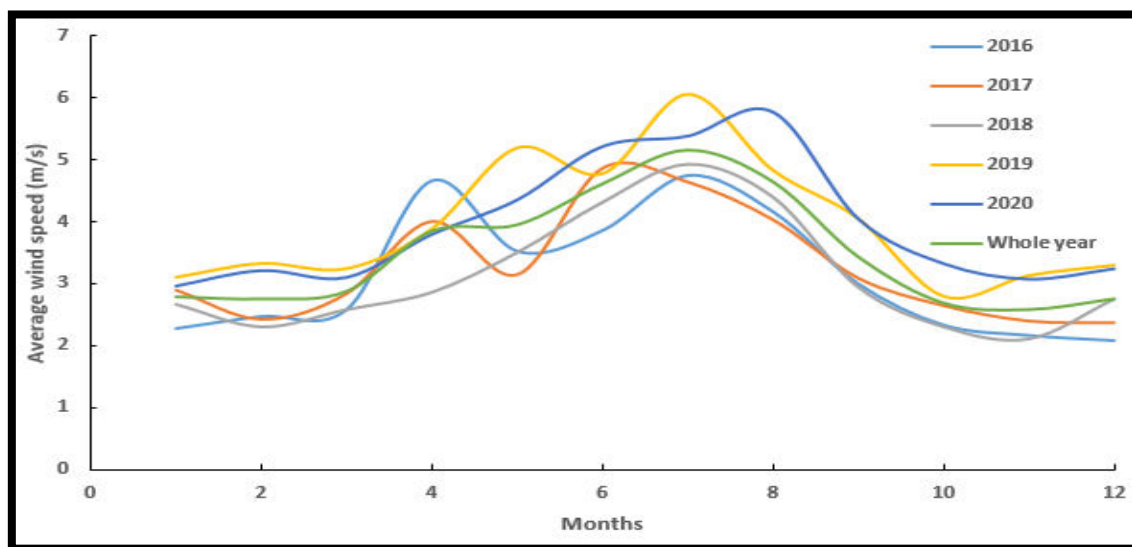


Fig.1: Representation of average wind speed of Patenga for five years.

In statistical analysis, the graphical representation of PDF and CPDF gives a clear overview of the parameter. Fig. 2 and 3 display the monthly PDF and CPDF derived from Patenga’s recorded data. It is analyzed for the entire year. Both figures have indicated similar pattern for the probability and cumulative density curves. Additionally, the annual PDF and CPDF are shown in Figure 4.

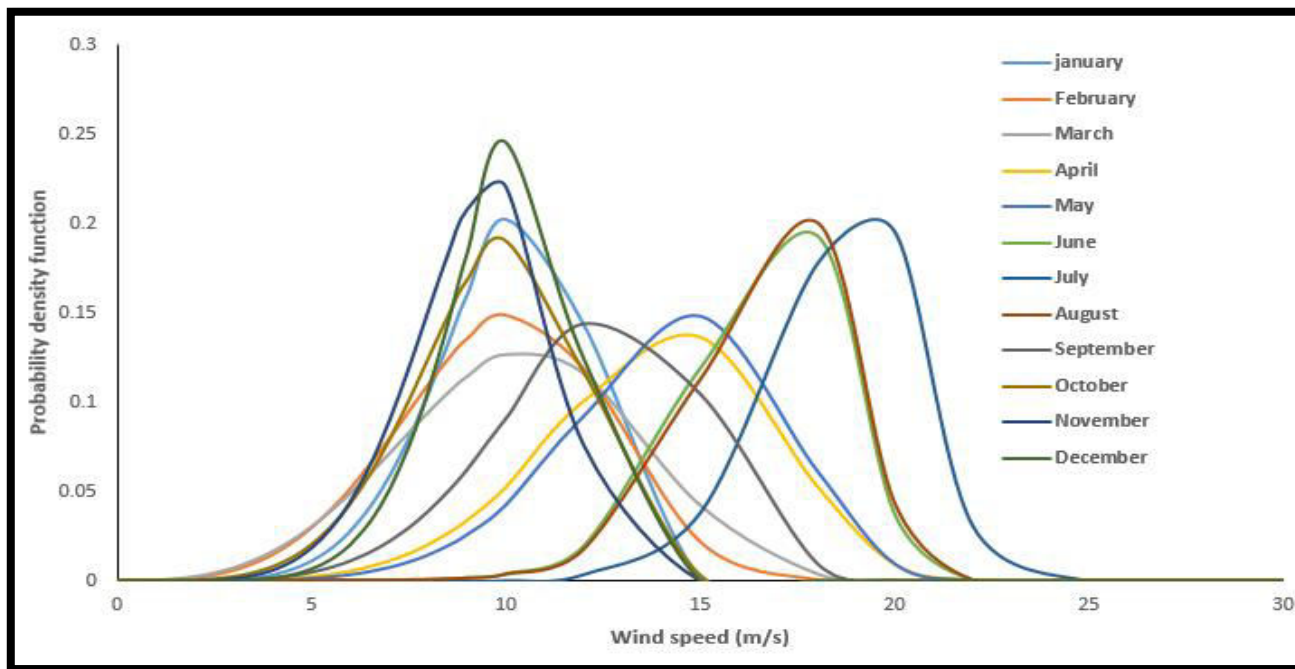


Fig. 2: The statistical PDF of monthly based wind profile for Patenga, Bangladesh.

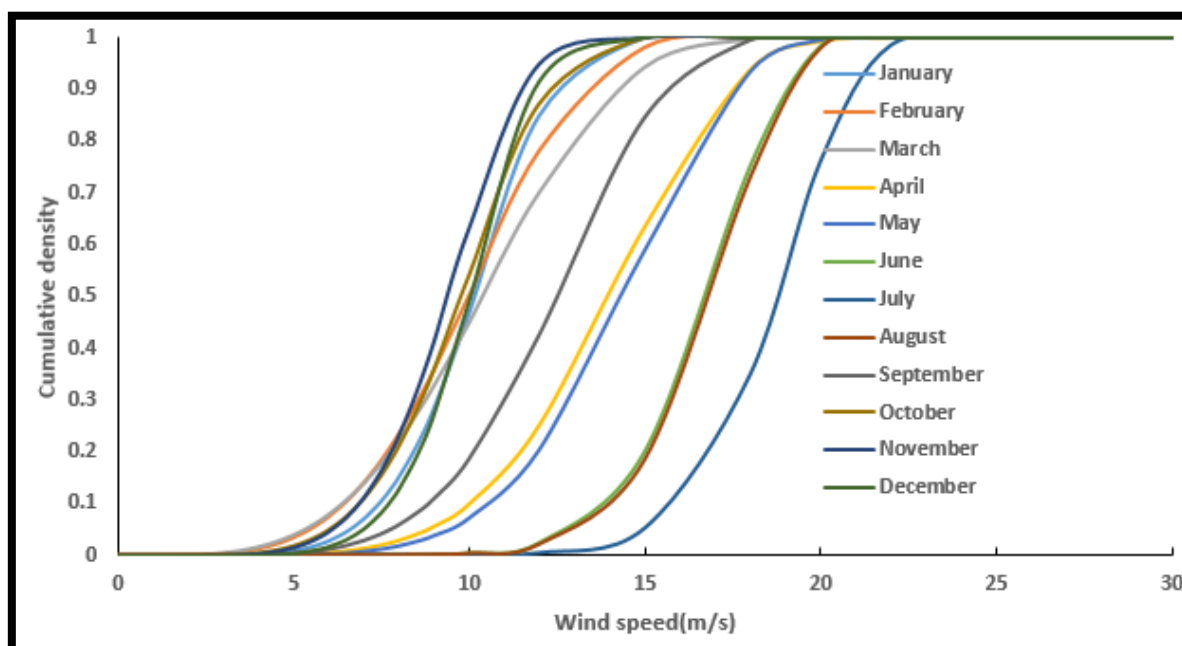


Fig.3: The cumulative probability distributions based on Patenga data for monthly average wind speeds over a 12-month period.

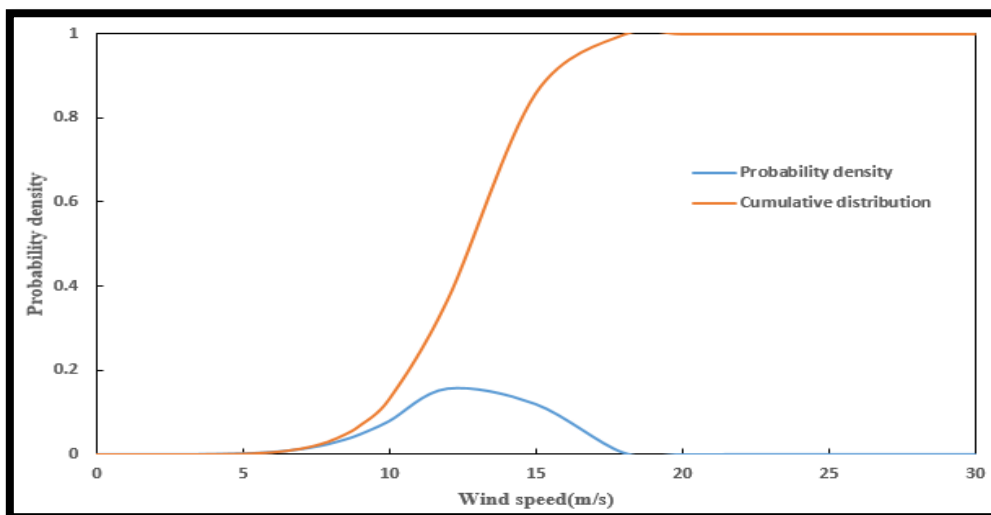


Fig. 4: The average wind speed PDF and CDF for Twelve months.

The Weibull parameters k and c 's monthly values and annual averages from 2016 to 2020 are shown in Table 2. The values are calculated from the Weibull shapes that are the best fitted to the actual data. Over the years, there are discernible monthly changes of the Weibull's parameters. For instance, July often has the greatest values for both k and c , indicating higher wind unpredictability and intensity during this time. Although there have been significant variations, the annual averages show a general upward tendency over time. In particular, the average values of c range from 3.355 to 4.274, and the average values of k range from 5.134 to 7.877. For the whole five-year analysis, the maximum value of k and c have been found in the month of July with 11.438 and 5.384.

Table 2. The estimated parameter k and c for Patenga over the five years.

Year	2016		2017		2018		2019		2020		Whole year	
	k	c	k	c	k	c	k	c	k	c	k	c
January	5.419	2.469	5.273	3.137	7.508	2.841	6.004	3.353	6.352	3.194	6.029	2.999
February	5.06	2.691	2.774	2.715	4.088	2.54	4.953	3.632	5.182	3.502	4.282	3.022
March	3.785	2.859	3.406	3.154	4.785	2.821	3.953	3.588	3.709	3.447	3.867	3.175
April	10.85	4.889	5.21	4.346	5.624	3.095	4.063	4.287	4.771	4.156	5.576	4.161
May	7.567	3.756	3.807	3.473	6.655	3.752	7.569	5.531	5.823	4.709	6.081	4.249
June	11.82	4.031	9.059	5.132	12.36	4.488	7.623	5.085	11.398	5.46	10.042	4.84
July	16.41	4.905	8.04	4.925	13.33	5.111	10.98	6.341	11.481	5.633	11.438	5.384
August	10.6	4.36	8.8	4.25	15.0	4.544	7.5	5.147	11.47	6.04	10.18	4.872

t	4	8	36	7	6		64				8	
September	9.415	3.162	4.837	3.365	7.161	3.144	7.621	4.317	3.159	4.531	5.421	3.716
October	7.401	2.487	4.001	2.911	5.356	2.501	5.366	3.043	5.615	3.606	5.328	2.912
November	5.865	2.338	4.623	2.614	6.279	2.27	6.062	3.382	7.435	3.286	5.987	2.779
December	6.048	2.245	5.089	2.569	9.301	2.9	7.777	3.515	8.124	3.448	7.14	2.937
Yearly	7.877	3.355	5.134	3.559	7.614	3.339	6.414	4.274	6.31	4.262	6.494	3.759

The wind speed data have been used to approximate different PDF. The Weibull and Rayleigh PDF with the actual wind speed data have been shown in Fig. 05. The approximation was analyzed for the time period of whole year. It is clearly seen that Weibull PDF is very close to the actual wind data. The graphical data are contrasted in Table 3. The value of R^2 of Weibull and Rayleigh PDF are 0.9967 and 0.1769 respectively. And the value of RMSE of Weibull and Rayleigh PDF are 0.0078 and 0.1198 respectively. A higher R^2 value, a lower χ^2 statistic, and a smaller RMSE show that the Weibull PDF fits the actual wind speed data better than the Rayleigh PDF. In terms of R^2 and RMSE, which are typically seen as more direct measures of fit quality, the Weibull pdf model performs better overall.

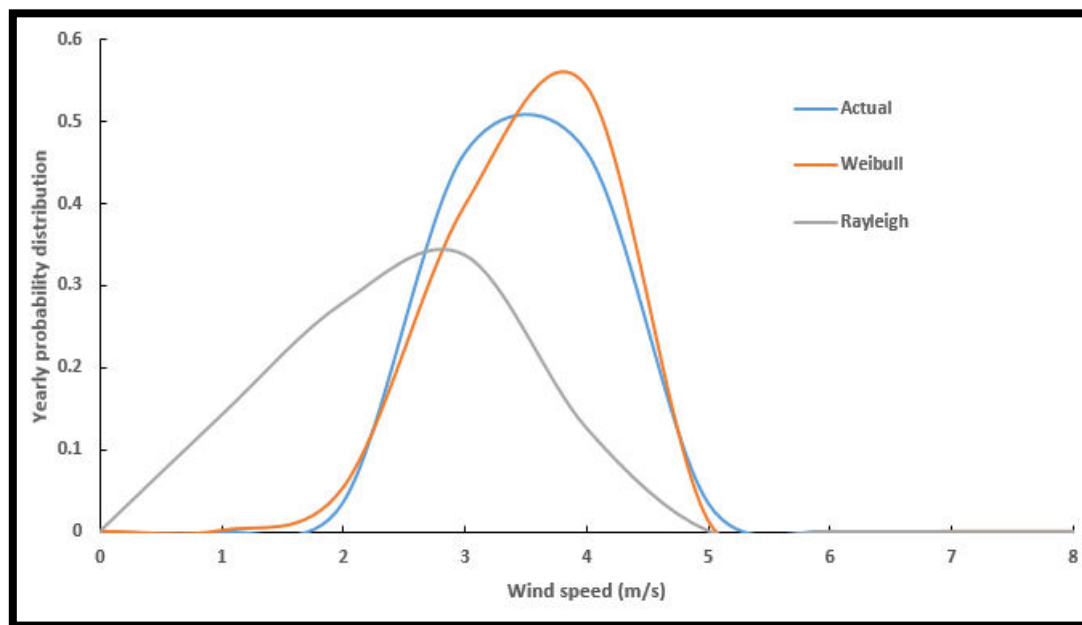


Fig.5: Contrasting the Weibull and Rayleigh approximations with the actual wind data.

Table 3: Estimation of Weibull and Rayleigh distribution are compared with wind speed data for the entire year.

$f(v)$			
Wind speed	Actual distribution	Weibull PDF	Rayleigh PDF
1	3.00019E-07	2.92E-07	0.141520694
2	2.68318E-06	1.31695E-05	0.27842859
3	1.97012E-05	0.000122158	0.336985703
4	0.000118763	0.000593133	0.126681029
5	0.000587776	0.002018461	0.001203756
6	0.002388287	0.005476188	7.60623E-10
7	0.00796718	0.012660669	2.38147E-25
8	0.02182058	0.025867122	2.88671E-59
9	0.049064966	0.047569707	1.6158E-126
10	0.090577491	0.079162696	4.0524E-250
R²		0.996755531	0.1769
RMSE		0.007808208	0.1198

The annual Weibull parameters (k and c) in addition average wind speeds (u_m) associating kinetic power densities are shown in Table 4. With 2019 having the greatest average wind speed, the mean wind speed (u_m) changed somewhat but stayed mostly constant across time. Power density (P) fluctuated more noticeably, with the highest wind energy potential in 2019. So, the power kinetics of wind behavior has a randomness. This indicates that depending on the prevailing wind conditions, the availability of wind energy can fluctuate significantly from year to year. Overall, the data show how changes in distribution form and extreme wind occurrences affect wind speed characteristics and energy potential on a yearly basis. In the year of 2019 and 2020, it is found that the most average wind energy of 42 W/m².

Table.4: Patenga's annual wind speed patterns between 2016 and 2020.

Year	u_m (m/s)	k	c (m/s)	u_{MP} (m/s)	u_{MaxE} (m/s)	P (W/m ²)
2016	3.15740740 7	7.87737098 3	3.355255017	3.29792633 1	3.453021224	20.55552529
2017	3.273148148	5.134215395	3.559420717	3.4123613	3.794956271	24.63391987
2018	3.136574074	7.61390069	3.338725221	3.27755037 6	3.442582015	20.23337863

2019	3.97916666 7	6.41402575 7	4.273566281	4.162114015	4.45828520 1	42.33741968
2020	3.96527777 8	6.30967775 1	4.26243628 2	4.14744908	4.45255470 9	42.01060904

The power density obtained from the actual values is compared with the predicted model by the Rayleigh and Weibull PDF in Fig. 6. The potential energy that may be taken from the wind is reflected in the power density, which peaks in July at 83.66191094 W/m². This indicates higher energy potential and stronger winds during this month. In comparison to the Rayleigh PDF, the Weibull PDF often forecasts lower power densities all over the year. But, the forecasting power of Weibull is closer to the actual wind power. More Specifically, the Weibull model predicts 86.41 W/m² in July, whereas the Rayleigh model predicts 159.86 W/m². The whole scenario indicates that Weibull PDF may be more accurate in capturing real wind conditions. The Weibull PDF more allies with the real wind profile.

The Weibull and Rayleigh models' power density prediction errors in comparison to the actual computed distributions are displayed in Figure 7. In general, the Weibull model outperforms the Rayleigh model in terms of prediction errors. The Rayleigh model has its largest inaccuracy in October which is almost 100% in error. But it is shown that the maximum inaccuracy of Weibull PDF is occurred in the month of March. The largest error shown by Weibull PDF is around 25%. In addition, it is also noticed that the minimum error is occurred in the time of June. So, it is very clear to that Weibull performs a maximum error of 25% whether Rayleigh performs around 100%. So, Weibull PDF may be a good choice to evaluate the wind behavior.

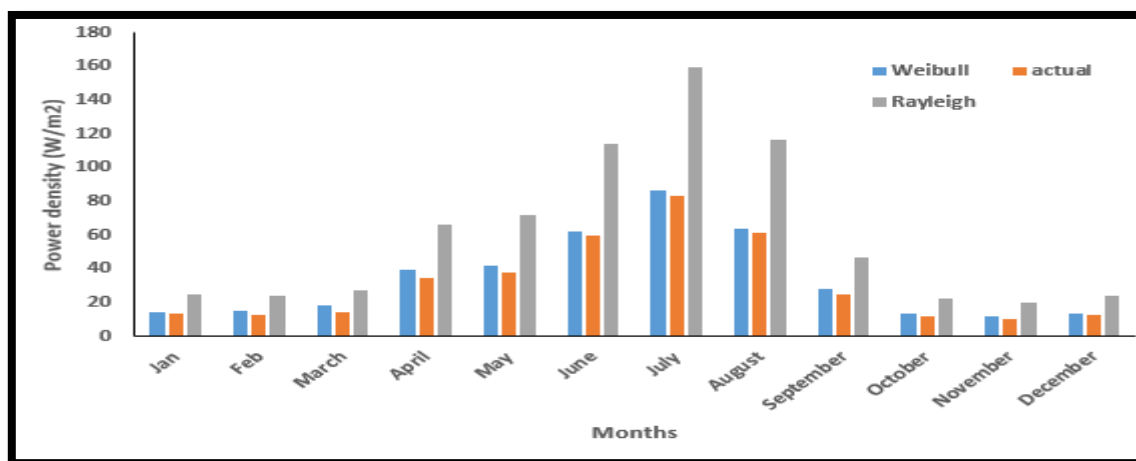


Fig.6: The power densities of Weibull and Rayleigh PDF are compared to actual data.

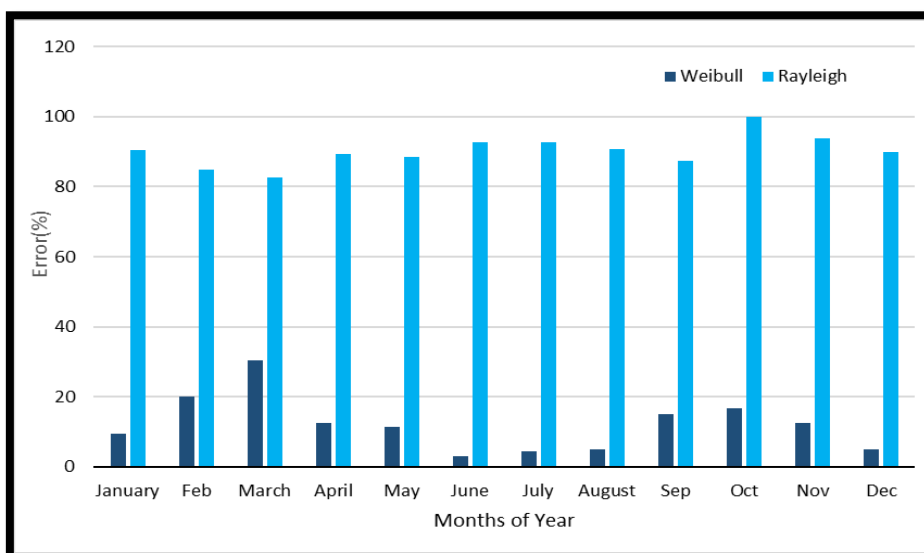


Fig.7: By comparing observed data with power density estimations from Weibull and Rayleigh models, monthly errors in wind power density are evaluated.

4. Conclusions

The PDF and power potential obtained from recorded wind data were analyzed statistically for wind characteristics in Patenga, Chittagong District, Bangladesh, from 2016 to 2020. Weibull and Rayleigh distributions were used to simulate monthly wind speed probability density curves. Higher R^2 and lower RMSE values indicate that the Weibull PDF provides good fit to actual data. That means the Weibull model predicts accurately wind power profile with respect Rayleigh PDF, though there also a negligible error in estimation of wind potential by Weibull PDF. The maximum error of Weibull PDF is around 25% whether Rayleigh shows around 100%. This site's wind power potential varies significantly over time, indicating changes in wind speed over the research period.

Some recommendations are suggested to the researchers who will intent to harvest renewable energy in the location Patenga or nearby. The site has a significant variation in wind potential. Optimization of hybrid system needs more backup energy sources in respect of wind turbine. The battery energy storage system may a good choice for daily wind potential fluctuation. And Pump storage hydro-plant can be a choice for seasonal fluctuation. Moreover, the wind power can be a significant part during a design of hybrid energy system in Patenga Region.

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