

Research Article

Understanding Wind Speed Fluctuations and Their Effects on Wind Energy Development in Fukuoka, Kyushu, Japan

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Abstract

This research inspects characteristics of wind speed and corresponding wind power potential in the Fukuoka-shi, located in the Kyushu region of Japan, over the period from 2018 to 2022. By employing the comprehensive statistical approach, the study systematically evaluates time-series wind speed data in order to capture both seasonal variations and long-term trends. Probability density functions are derived to assess the distribution patterns of wind speeds, which serve as the foundation for the estimating the region's wind energy potential. Two widely recognized statistical models, the Weibull distribution and the Rayleigh distribution, are applied to monthly wind speed data. These models offer reliable and practical tools for the characterizing wind behavior, allowing for the accurate assessment of frequency and intensity of the wind speeds relevant for power generation. The analysis emphasizes variability of wind conditions across different months, underlining how seasonal changes influence the availability of the wind resources. The results approve the suitability of the Weibull and Rayleigh models in predicting wind power potential with the reasonable precision. This research not only contributes valuable insights into the renewable energy prospects of Fukuoka-shi but also provides the evidence-based guidance for policymakers, energy investors, and other stakeholders. Ultimately, the findings highlight the strategic importance of wind energy in advancing the sustainable development and strengthening the region's renewable energy portfolio.

Keywords

Wind Power, Weibull Distribution, Shape Factor, Wind Speed Data, Rayleigh Distribution

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1. Introduction

The Quranic verse of the Surah Az-Zumar (39:21): "Do you not see that Allah sends down rain from the sky, and We produce thereby fruits of varying colors? And in the mountains are streaks, white and red, of varying shades and pitch black." This verse highlights the natural cycles and phenomena, encouraging reflection on the natural world as a sign of divine wisdom and a basis for sustainable practices [1]. This principle articulated in this verse advocates for the thoughtful use of natural resources, which complements the goals of promoting renewable energy [2]. At present the global energy environment is changing due to advancements in renewable energy technologies, which also offer important insights into technological trends and advancements from time series data to assess wind speed distributions. [3]. The most common renewable energy resources are wind, solar, hydroelectric, and the geothermal power continue to evolve. They present solutions to challenges related to sustainable development as well as climate change. These current developments indicate a propitious future for renewable energy as it continues to evolve into a cornerstone of global sustainable development efforts [4]. By using the principle of renewable energy technologies, which contributing to reducing the harmful greenhouse gas emission as well as offering a rich overview of the evolving landscape of clean energy. These advancements encompass innovations in storage solutions, smart grids, and integration challenges associated with incorporating renewable power into existing infrastructure. Furthermore, the alteration towards renewable energy has pivotal implications for both human health and the environmental system [5]. By reducing air [6] and water contamination connected with typical fossil fuel-related power generation companies, renewable energy mechanism can lead to improve the quality of air as well as the consequence of health of public. Fundamentally, this development is consistent with ideas that encourage conscientious use of natural resources that are found in a sizable portion of cultural texts. The continuing advancement in renewables emphasizes the potential for the more durable future in which clean energy plays a central role in the addressing global natural challenges while progressing public well-being. Of all the renewable energy types, wind energy has become very popular due to its better efficiency, abundance and minor environmental effect and the ability to produce energy during the night [7]. At present wind energy is a rapidly evolving sector of renewable source of energy with a promising future [8]. Current developments in wind energy technology involve the development of offshore wind farms, the construction of larger and more intelligent wind turbines, and the standardization of digitalization performance. Indeed, the variations of wind for a typical site are mostly described by using well known Weibull probability distribution method [9-11]. In last few decades, many researchers have extensively studied wind power assessment globally. In the context of Japan, numerous studies have focused on wind power

optimization across various locations [12-18], evaluating them using the scale parameter (c) and shape parameter (k) of the Weibull distribution. Many researchers have conducted extensive studies on optimization techniques in deep learning [19-21], data processing strategies [22], with a particular emphasis on decision-making processes [23-25], survey based [26], simulation techniques [27-32], game theoretical approach [33-35], and other relevant approaches [36-40] in the world. Physical models, like NWP (numerical weather prediction) and the WRF (weather research and forecasting), normally take natural situations into consideration [41-46]. These factors consist of outward roughness, topography, temperature, wake effect, pressure, and humidity [47, 48]. All of these variables are then used in a complex mathematical model to predict the wind speed for that specific area. This wind speed will then be used to predict the wind power with the turbine wind power curve. Therefore, it can be said this forecasting method does not need to be trained with historical data nevertheless requires physical data. Studies have shown physical prediction models to have better performance compared to traditional statistical methods for predicting wind speed over the long and medium terms. However, this comes at the cost of being computationally complex, needing more computational resources [49]. Unlike physical models, statistical techniques are applied to historical data to identify both linear and non-linear correlations between power output and weather [2, 50-54]. These relationships are used to make predictions for future power outputs. Generally, this method is easy to model and requires less computational resources than physical models, but the forecasting error increases with a larger time horizon.

Results from this study contain an extensive analysis of wind speed data that collected from 2018 to 2022 for Fukuoka-shi, Kyushu (33.5902 °N, 130.4017 °E), Japan [55, 56]. This analysis addresses a significant research gap, as no previous studies have specifically focused on wind energy systems founded on local wind speed data. The elementary purpose of this study is to evaluate the data of wind speed statistically as well as the prediction of the potential wind energy output for the selective region.

The subsequent sections of the paper are organized as follows: Section 2 addresses the theoretical analysis, Section 3 covers the results and discussion, and Section 4 presents the conclusion.

2. Theoretical Analysis

2.1. Frequency Distribution of Wind Speed

The wind speed distributions and their functional forms is essential in wind literature. To fit wind speed data for a specific location and period, the Weibull and Rayleigh distributions are typically used. The Weibull probability density

function is represented by [57],

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

$f(v)$ is the wind speed probability of the v ; the c is scaling parameter of Weibull distribution and the k is the factor of Weibull shape.

The cumulative probability function relied on Weibull distribution [58-60] is expressed as follows,

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

With a shape parameter k equal to 2, the Weibull distribution becomes the Rayleigh distribution. The Rayleigh distribution is expressed in Equation 1 as,

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

The standard deviation σ and mean value v_m in a Weibull distribution are computed as follows:

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

and

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

Where $\Gamma(\cdot)$ is the gamma function.

The most probable wind speed and the wind speed carrying the most energy are two crucial factors in wind energy estimation. The most probable wind speed represents the wind speed that occurs most frequently in the distribution of wind probability and can be displayed as follows,

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

The wind speed that carries the most energy can be shown as follows:

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

To assess the Weibull parameters, a variety of techniques are used to achieved desired outcomes. These methods include: 1. Standard deviation method, 2. Graphical method, 3. Maximum likelihood method, 4. Moment method, 5. Energy pattern factor method and 6. Power density method. Among these methods, the standard deviation method is considered to determine the values of the shape parameter k and scale parameter c .

Standard Deviation Method

The following equations can be used to calculate the

Weibull parameters,

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

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

2.2. Variance of Wind Speed with the Height

Height plays a vital role in the case of wind speed variation above the ground. Equation that is most commonly used to express this variation is,

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

Where v_1 and v_2 represents the average of wind speeds situated at the height of h_1 and h_2 respectively. There are several variables that affect the exponent p , including atmospheric strength and outward roughness.

2.3. The Density of Wind Power

The cube of the wind power speed that travels across the blade sweep area (A) increases, and this can be shown as,

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

where ρ is average air density (1.225 kg/m^3 founded on standard atmospheric conditions at sea level and 15°C). Factors including temperature, altitude, and air pressure has a great impact on this density.

Now applying the well-known Weibull probability density function, for the monthly or annual wind statistics, the potential wind power density per unit area can be calculated as follows:

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

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

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

Equation (9) can be used to illustrate the Rayleigh power density model by substituting $k = 2$.

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

In relation to the probability density distribution, $P_{m,R}$ specifies the wind power density, which can be displayed as

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

The error associated with the power densities calculated

using the probability distributions can be determined by means of the following expression,

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

Where the Rayleigh or Weibull formulas are used to determine the mean power density " $P_{w,R}$ ".

Using the Weibull function, the annual average error associated with the power density is now determined and may be found using the following formula:

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

2.4. The Statistical Analysis of the Distributions

The square of the correlation coefficient (R^2), chi-square (χ^2), and RMSE (root mean square error) are used to assess the degree to which the Weibull and Rayleigh distributions work. The following expressions can be used to determine these parameters:

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

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

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

Where N is the total number of observations, y_i is the i th observed data point, z_i is the mean value, x_i is the approximated data using Weibull or Rayleigh distributions, and n is the number of constants. Therefore, the probability distribution that best fits the data is selected for the largest values of R^2 and the minimum values of RMSE and χ^2 .

3. Results and Discussion

Numerous statistical approaches were utilized for evaluating the wind speed data from Fukuoka, Japan, at a height of 10 meters collected between 2018 and 2022. Here is a summary of the significant conclusions gathered from this analysis:

Table 1. Fukuoka's monthly mean wind speeds and standard deviations from 2018 to 2022.

Years	2018		2017		2018		2019		2022		Whole year	
Parameter	v_m	σ	v_m	σ	v_m	σ	v_m	σ	v_m	σ	v_m	σ
January	3.222	1.275	3.25	1.281	3.639	1.522	3.083	1.203	3.278	1.314	3.294	1.319
February	3.139	1.122	3.167	1.136	4	0.925	3.639	1.069	3	0.933	3.389	1.037
March	3.667	0.8	3.639	0.769	3.139	0.944	2.833	0.947	2.472	0.644	3.15	0.821
April	2.972	1.008	3.75	0.792	3.056	0.997	2.75	0.767	2.972	1.022	3.1	0.917
May	2.778	0.681	2.611	0.628	2.778	0.675	2.028	0.475	2.389	0.717	2.517	0.635
June	2.667	0.767	2.806	0.781	1.972	0.367	2.806	0.661	1.944	0.381	2.439	0.591
July	2.556	0.794	2.806	0.806	2.5	0.797	2.333	0.714	2.194	0.661	2.478	0.754
August	2.722	0.722	2.639	0.675	2.444	0.678	2.611	0.708	2.583	0.675	2.6	0.692
September	3.111	1.328	3.833	1.686	2.583	0.947	3.75	1.447	2.472	0.903	3.15	1.262
October	3.694	1.431	3.444	1.322	2.639	1.05	3.111	1.333	2.889	1.144	3.156	1.256
November	2.722	0.961	2.694	0.942	3.25	1.314	2.333	0.772	3.389	1.364	2.878	1.071
December	2.667	1.044	3.25	1.314	3.722	1.767	3.389	1.447	3.194	1.297	3.244	1.374
Yearly	2.993	0.994	3.157	1.011	2.977	0.999	2.889	0.962	2.731	0.921	2.95	0.977

Table 1 displays the monthly average wind speeds along with the standard deviations that were obtained from the time series data [46, 47]. Based on the data, February has the highest reported wind speeds during the year, while May has the lowest wind speeds. Figure 1 represents Fukuoka's

monthly mean speed of wind from 2018 to 2022. This diagram shows that the pattern of monthly average wind speeds over various years remains fairly stable.

Figures 2 and 3 display the monthly probability density and cumulative distributions derived from Fukuoka's time-series

data for the whole year. These graphs indicate that the wind speed trends shown by the cumulative density and probability density curves are comparable. The cumulative distribution and annual probability density distribution are also shown in Figure 4.

The annual averages of the monthly values for parameters k and c from 2018 to 2022, are displayed in Table 2. Over the years, there are noticeable monthly variations in the parameter

values k and c . Maximum values for both parameters, for example, are typically seen in the months of June (k) and January (c), suggesting greater unpredictability or intensity during these times. Although there is significant fluctuation, a general tendency of increasing values over time is indicated by the parameters' annual averages. In this regard, the average c values for the year differ from 3.047 to 3.512, and the typical range of k values is 3.255 to 3.445.

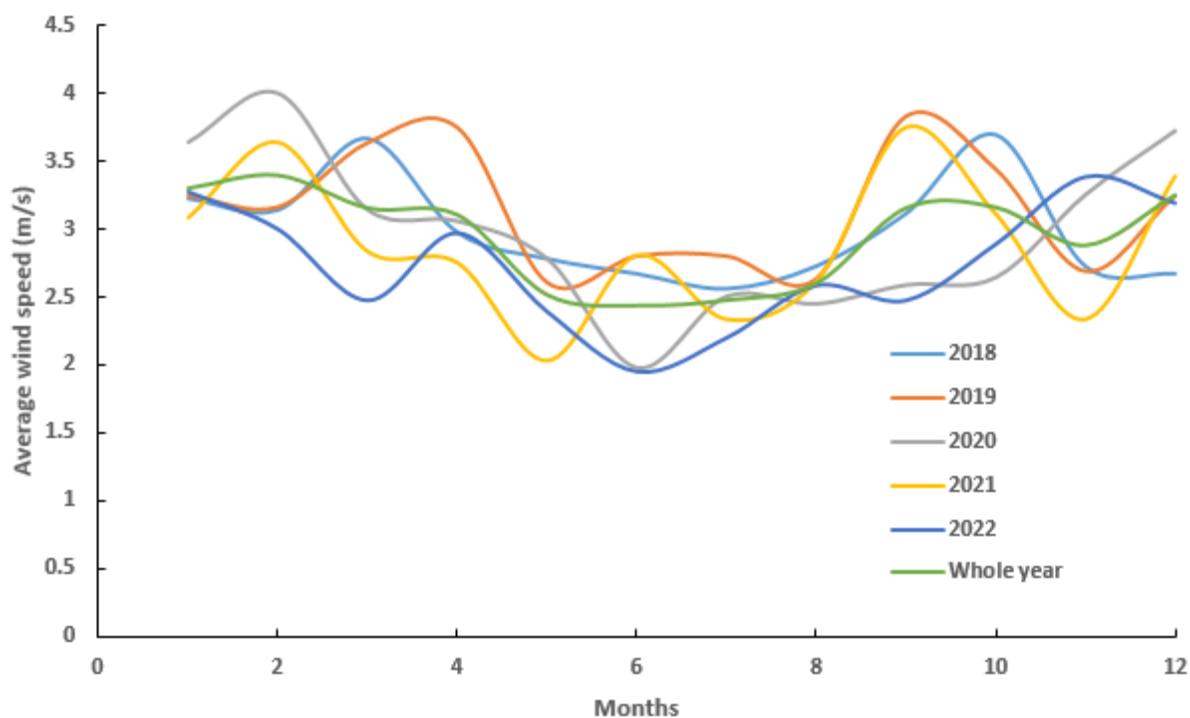


Figure 1. Fukuoka's monthly wind speed, 2018-2022.

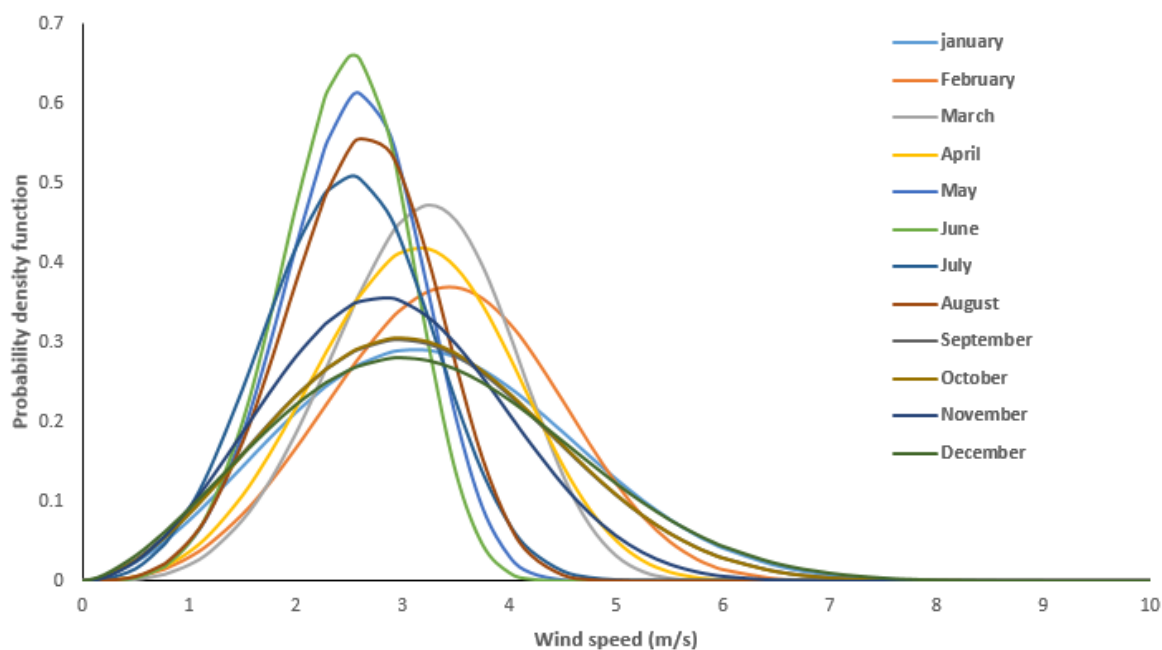


Figure 2. The monthly wind speed probability distributions obtained from the Fukuoka time series data.

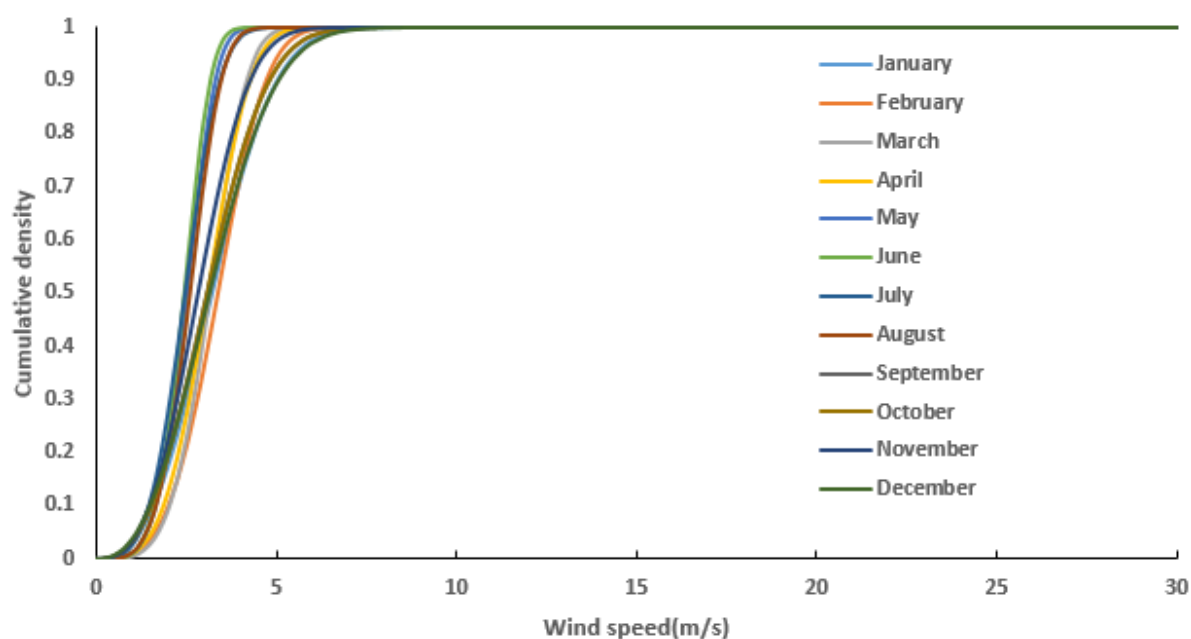


Figure 3. Representation of the annual cumulative probability distributions corresponds to monthly wind speeds, derived from Fukuoka data.

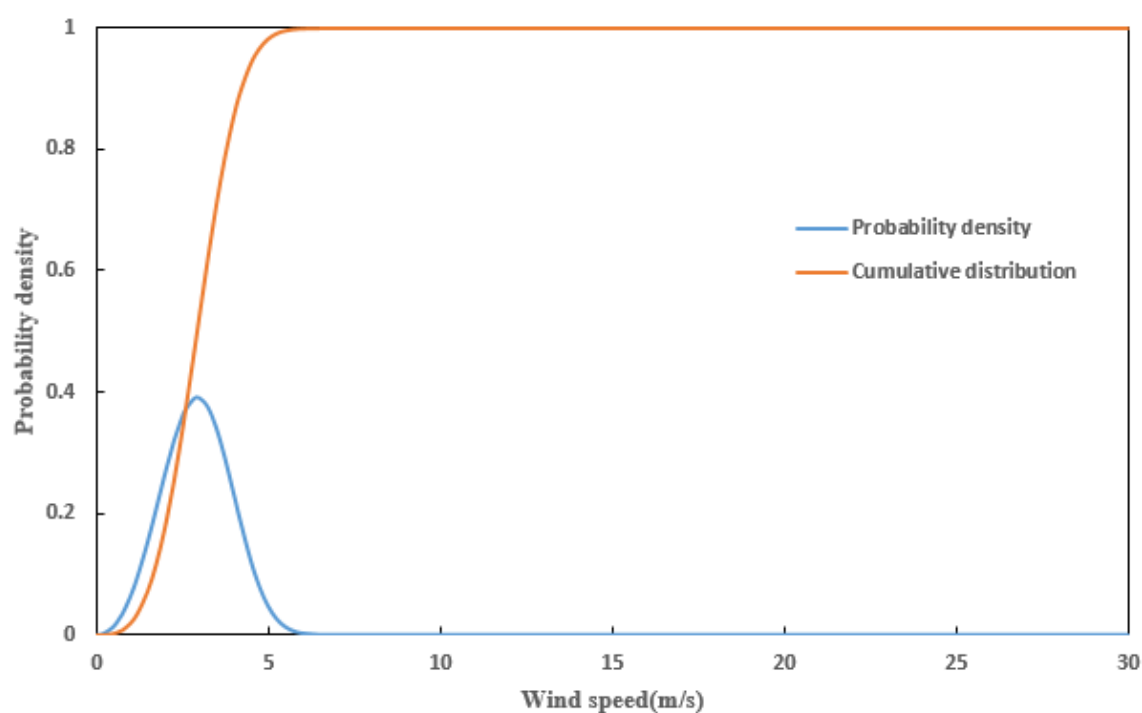


Figure 4. The wind speed probability density and cumulative distributions over the full year were computed using the data that Fukuoka had gathered.

Table 2. The Fukuoka scale parameter (c) and Weibull shape parameter (k) for each month from 2018 to 2022.

Period	2018		2017		2018		2019		2022		Whole year	
Parameter	k	c	k	c	k	c	k	c	k	c	k	c
January	2.737	3.622	2.75	3.652	2.577	4.098	2.78	3.464	2.699	3.686	2.702	3.704
February	3.056	3.512	3.044	3.544	4.905	4.361	3.78	4.027	3.554	3.332	3.617	3.76

Period	2018		2017		2018		2019		2022		Whole year	
Parameter	<i>k</i>	<i>c</i>	<i>k</i>	<i>c</i>	<i>k</i>	<i>c</i>	<i>k</i>	<i>c</i>	<i>k</i>	<i>c</i>	<i>k</i>	<i>c</i>
March	5.224	3.983	5.405	3.945	3.685	3.479	3.287	3.159	4.306	2.716	4.307	3.461
April	3.235	3.317	5.415	4.066	3.374	3.403	4.003	3.034	3.187	3.319	3.753	3.432
May	4.606	3.04	4.702	2.854	4.648	3.038	4.837	2.213	3.697	2.647	4.462	2.759
June	3.872	2.947	4.012	3.095	6.216	2.122	4.805	3.063	5.879	2.098	4.661	2.667
July	3.557	2.838	3.877	3.101	3.46	2.78	3.619	2.589	3.68	2.432	3.638	2.748
August	4.225	2.994	4.396	2.896	4.027	2.696	4.124	2.876	4.295	2.838	4.212	2.86
September	2.521	3.506	2.44	4.323	2.973	2.894	2.812	4.211	2.986	2.769	2.7	3.542
October	2.802	4.149	2.829	3.867	2.721	2.967	2.51	3.506	2.734	3.247	2.719	3.548
November	3.098	3.044	3.132	3.011	2.674	3.656	3.323	2.6	2.687	3.811	2.927	3.226
December	2.768	2.996	2.674	3.656	2.246	4.202	2.519	3.819	2.661	3.594	2.543	3.655
Yearly	3.309	3.336	3.445	3.512	3.275	3.32	3.301	3.221	3.255	3.047	3.318	3.287

The Weibull and Rayleigh approximations of the real wind speed probability distribution for the entire year are shown in Figure 5. A comparison between these approximations and the real probability distribution is shown in Table 3, and from this table, a higher R^2 value and a lower RMSE indicate that the Weibull distribution corresponds to the real wind speed data more effectively than the Rayleigh distribution.

The average wind speed, wind power density, and annual Weibull parameters are presented in Table 4. Throughout the years, the average wind speed (v_m) varied but stayed quite constant; the highest mean wind speed was recorded in 2019. Significant fluctuation was seen in power density (P), with 2019 exhibiting the biggest potential for wind energy.

This suggests that the potential for wind energy might vary greatly from year to year constructed on wind circumstances. In general, the information demonstrates how differences in

distribution form and high wind speeds impact the annual evolution of wind speed characteristics and energy potential.

Figure 6 demonstrates a comparison within the power density that was acquired from computed probability density distributions and the values from Weibull and Rayleigh distributions. The Weibull model predicts lower power densities than the Rayleigh model, especially in months with greater wind speeds. Consequently, a further precise depiction of the energy potential and genuine wind conditions throughout these periods can be obtained using the Rayleigh model. Figure 7 demonstrates the variance in power densities across the actual computed probability distributions and the Weibull and Rayleigh distributions. It can be noted that the Weibull model has the highest error in December and the lowest in May. On the other hand, December is the time when the Rayleigh model exhibits the biggest inaccuracy.

Table 3. Comparison of Weibull and Rayleigh distribution approximations with wind speed data collected throughout the whole year.

$f(v)$	Actual data	Probability density function	Rayleigh
Wind speed			
1	0.05584581	6.27E-02	0.18145621
2	0.254620409	0.263201449	0.360791431
3	0.407600865	0.390281802	0.532034931
4	0.229095336	0.233755677	0.709379908
5	0.045210225	0.047846981	0.886724885
6	0.003132538	0.002580537	1.064069862
7	7.62071E-05	2.6987E-05	1.241414839

$f(v)$	Actual data	Probability density function	Rayleigh
Wind speed			
8	6.50929E-07	3.90724E-08	1.418759816
9	1.95214E-09	5.46571E-12	1.596104793
10	2.05555E-12	5.05999E-17	1.77344977
11	7.59948E-16	2.08944E-23	1.950794747
12	9.86459E-20	2.55673E-31	2.128139724
R2		0.998083694	0.421341892
RMSE		0.006124534	0.270625087

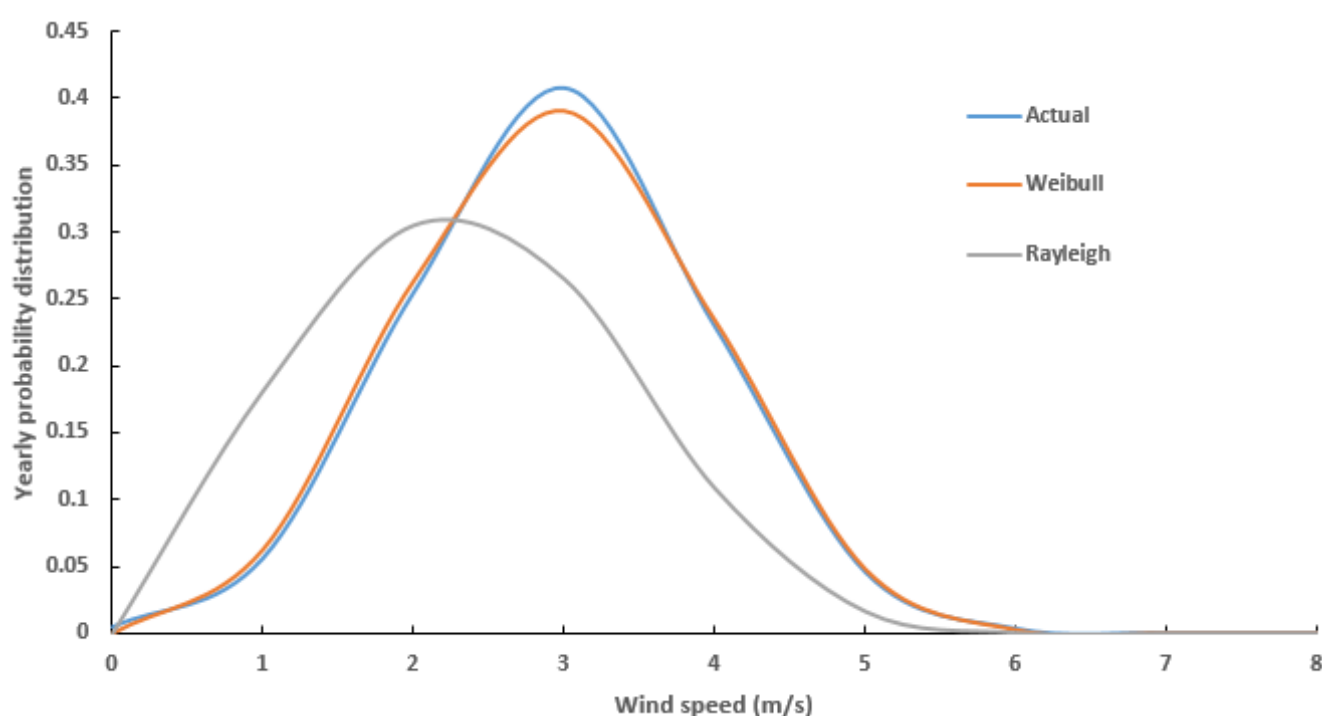


Figure 5. Weibull and Rayleigh estimates are compared to the observed wind speed distributions.

Table 4. Fukuoka's yearly wind speed trends collected from 2018 to 2022.

Year	v_m (m/s)	K	c (m/s)	v_{MP} (m/s)	v_{MaxE} (m/s)	P (W/m ²)
2018	2.993055556	3.308934709	3.336228872	2.992451901	3.848626557	21.92684074
2019	3.157407407	3.444843208	3.51215348	3.179392188	4.011322274	25.26486349
2020	2.976851852	3.274581915	3.319902437	2.970278933	3.840160055	21.68143636
2021	2.888888889	3.30071027	3.220521994	2.886940693	3.717528162	19.73976799
2022	2.731481481	3.255298692	3.318243222	2.964462477	3.844200738	21.69235036

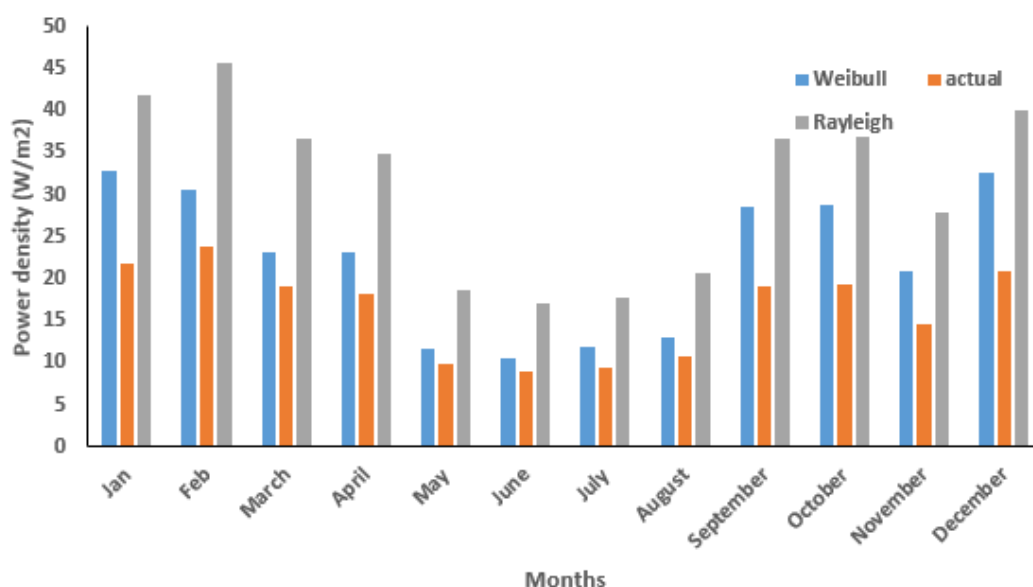


Figure 6. Actual data and densities computed using the Weibull and Rayleigh models are compared to determine the monthly wind power density.

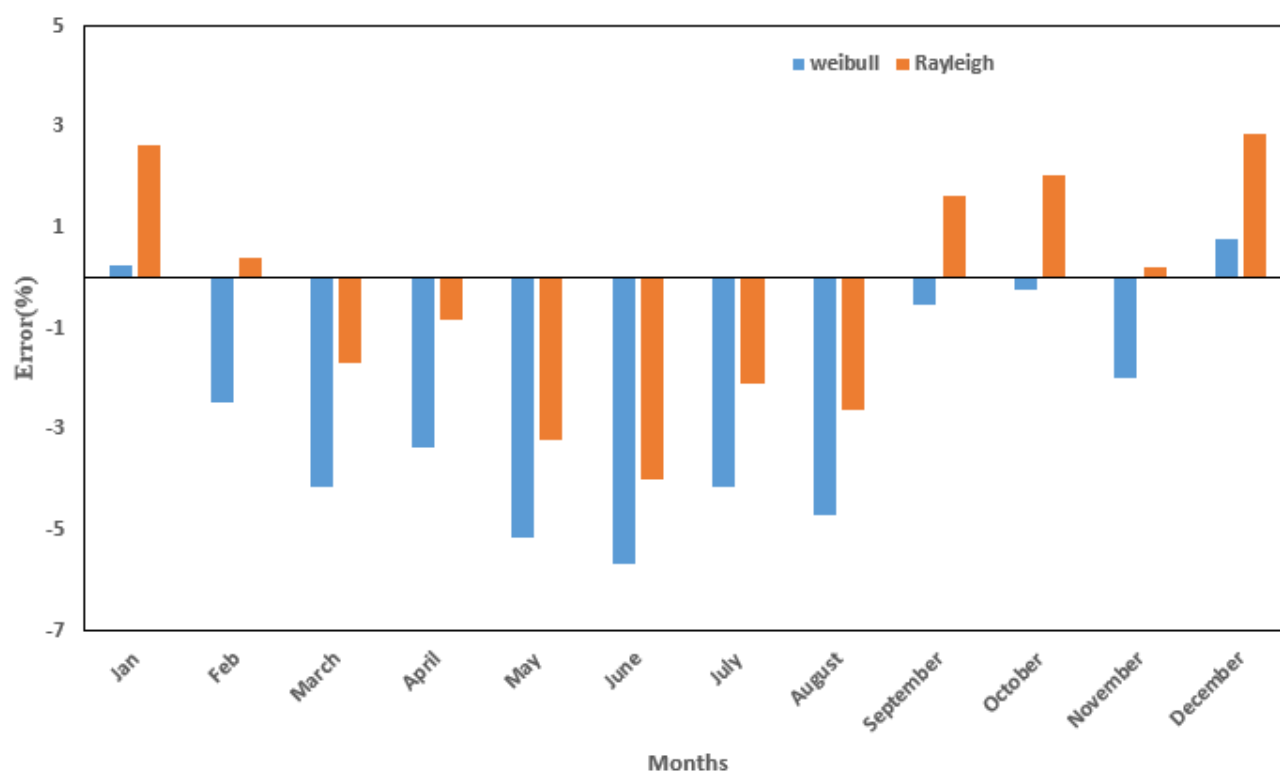


Figure 7. By calculating the differences between the power density estimations derived from the Weibull and Rayleigh models and the measured data, monthly errors of the wind power density are evaluated.

4. Conclusions

Statistical analysis of wind characteristics in Fukuoka, Kyushu, Japan, from 2018 to 2022 focused on the probability density and power density distributions derived from wind speed data over time. Monthly probability density functions

for wind speed were fitted using both Weibull and Rayleigh models. Higher R^2 and RMSE values demonstrate that, the Weibull distribution typically offers a better estimate of power density than the Rayleigh distribution. The wind power density at this location exhibits significant temporal variation, reflecting changes in wind speed throughout the period.

Abbreviations

NWP	Numerical Weather Prediction
WRF	Weather Research and Forecasting
RMSE	Root Mean Square Error

Conflicts of Interest

The authors declare no conflict of interest.

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