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Three-Parameter Weibull for Offshore Wind Speed Distribution in Malaysia

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ABSTRACT

It is usual practice to employ the probability density function in order to ascertain the wind energy potential. In this paper, the three-parameter Weibull model was suggested to distribute the low wind speed data at a site off the coast of Kijal, Terengganu. The maximum likelihood approach was used to determine the value of the distribution parameters. The Matrix Laboratory (MATLAB), better known for its user-friendly programming language, is used to carry out all of the analysis. The three-parameter Weibull was compared with the two-parameter Weibull and Rayleigh using the R-squared and the root mean square error (RMSE). These three distributions statistically model hourly ERA-5 reanalysis wind speeds. The three-parameter Weibull performs well since it appears between the best R^2 closest to 1 and RMSE the closest to 0. The R^2 for the three-parameter Weibull is 0.9898, the two-parameter Weibull is 0.9874, and Rayleigh is 0.5153. While the RMSE of Three-parameter Weibull is 0.0070, the two-parameter Weibull is 0.0082, and Rayleigh is 0.0677.

1. Introduction

Wind power is quickly establishing itself as one of the most significant contributors to the world's use of renewable energy. Renewable energy sources, such as wind energy, are becoming increasingly important as the world's population continues to increase and the effects of climate change become more apparent. Wind power is quickly becoming one of the most common forms of renewable energy, and various factors are driving this trend. To begin with, wind power is one of the cleanest forms of energy available, as the emissions produced by wind turbines are virtually non-existent. Second, there has been a significant drop in the price of utilizing wind power, making this form of renewable energy more financially viable.

Due to its location in the equatorial zone, Malaysia has a climate influenced by the alternating blowing of the Northeast and Southwest monsoons throughout the year. Many literatures discussed Malaysia's wind energy potential, including [1–13]. Beginning in the middle of May or early June and lasting through September, the Southwest monsoon season is characterized by relatively low winds

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throughout its duration [14]. The Northeast monsoon season starts around the beginning of November and lasts until March next year. During the southwest and intermonsoon seasons, the winds are typically not particularly strong and can be pretty variable.

70% of the world is to fall into the low wind speed zone, including Malaysia [15]. It is believed that electricity can be generated even in areas with low wind speed, provided there is a proper technique and reliable wind technology [16]. With the rapid development of wind turbine technology and the reduced cost per kilowatt hour produced, the potential of low wind regions is also increasing. This is due to the fact that wind turbines are becoming more efficient [17].

The wind speed distribution is one of the characteristics of the wind, and it is of great importance not only for statistical analysis but also for evaluating the wind energy potential and the performance of wind energy conversion systems. Much work has been done to develop an appropriate statistical model to characterize the wind speed frequency distribution [5]. The Weibull and the Rayleigh models are frequently utilized to fit the measured wind speed probability distribution.

The three-parameter Weibull is currently widely proposed for renewable energy data distribution in addition to the typical model, such as the two-parameter Weibull and Rayleigh [18,19]. The two-parameter distributions include a scale parameter and a shape parameter. The scale parameter indicates how windy the region is (statistically speaking, the distribution of the wind). The shape parameter indicates how peaked the region is (statistically indicating the most frequently expected wind speed). The three-parameter model includes a third parameter known as the threshold parameter, which contributes to understanding the lowest wind speed that can be expected in the region [20]. Several papers discussed the use of probability density functions in distributing the wind speed dataset, such as a study in Malaysia onshore [21], Indian Offshore [22], Palestine onshore [23], and a suburban area in Mongolia [24]. All of this literature compares those functions' fitting with the reference data.

In this paper, the three years of hourly ERA5 reanalysis data are statistically analyzed using three distribution functions at 10 meters above sea level height at Kijal water. This paper follows the following structure: In the second section, the research methods and sites chosen for the study are discussed. Section 3 discusses the study results and compares the three distribution functions. In the following section (section 4), the conclusions of this paper are presented.

2. Methodology

Data Acquisition and Study Area

Recent years have seen significant improvements in reanalysis products, which has encouraged their use as a direct input for studies pertaining to wind energy. ERA5 is the fifth-generation global reanalysis product developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), within the Copernicus Climate Change Service (CDS). ERA5 is the global reanalysis product with the highest temporal resolution of one hour, and it also has the highest spatial resolution of 0.28125 degrees (31 kilometers) in addition to the highest wind speed height (100 m) [25,26]. ERA5 is now recognized worldwide as a trustworthy data source that can directly answer research on wind energy. ERA5, for instance, has been used to evaluate the potential for wind energy in various offshore locations around the world. These locations include northeastern Scotland [27], Lebanon [28], Qatar [29], south and southeastern Brazil [30], the Mediterranean Sea [31], the Caspian Sea [32], and the Indian Sea [33], as well as globally [34]. The correlation of ERA5 with the observed data is up to 0.90, as presented by [18-20].

The selected site is located 50 kilometers off the coast of Kijal, with the coordinates 4.360983 Latitude and 103.848867 Longitude. The wind data for 2019 to 2021, including the Northward component, v (m/s), and the Eastward component, u (m/s), were extracted and analyzed.

Probability Density Functions

The probability density function was used to model the wind speed distribution at a specific site, which can help to evaluate the wind resource at that site. The distribution curve is responsible for defining the distribution parameters used to depict the wind speed distribution. The following are the equations for the two-parameter Weibull distribution, the three-parameter Weibull distribution, and the Rayleigh distribution:

Rayleigh Distribution Function:

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

Two-Parameter Weilbull Distribution Function:

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

Three-Parameter Weilbull Distribution Function:

$$g(v) = \frac{k}{c-\varepsilon}\left[\left(\frac{v-\varepsilon}{c-\varepsilon}\right)^{k-1}\right]\exp\left[-\left(\frac{v-\varepsilon}{c-\varepsilon}\right)^k\right] \tag{3}$$

where v is the wind speed, c is the scale parameter, k is the shape parameter, and ε is the location parameter. Distribution parameters were estimated using maximum likelihood estimation (MLE) [35,36]. In order to solve the MLE, numerical iterations are performed, and the distribution parameters are determined as a result.

Statistical Comparison

The square of the correlation coefficient (R^2) and the root mean square error analysis (RMSE) were used to evaluate the performance of the two- and three-parameter Weibull and Rayleigh distributions. These parameters can be calculated using the following equations [37];

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \tag{4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - y_i\right)^2}{n}} \tag{5}$$

where y_i is the ERA5 frequency data, $\overline{y_i}$ is the average value, x_i is the PDF frequency data, and n is the number of data.

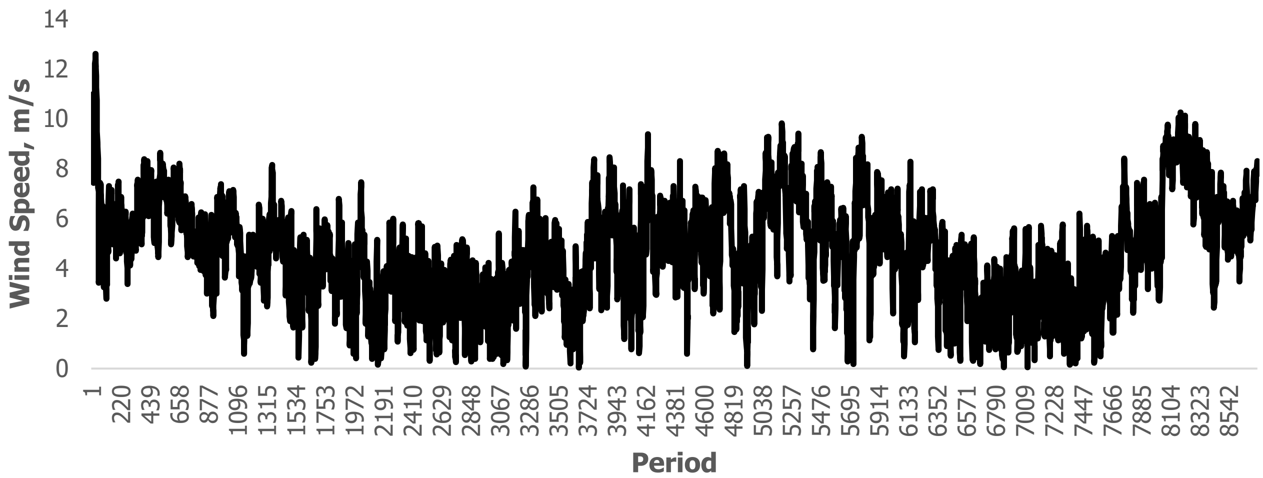
3. Results and Discussions

A set of three-year ERA5 data was illustrated in time series and inserted into ArcGIS for raster map plotting. The time series of data is presented in Figure 1. The higher wind speed occurred during the Northeast monsoon beginning in November and last in March of the following year. The wind speed is variable during the Southwest monsoon (May to September) and the intermonsoon (April and October). As presented in Table 1, the maximum values of the wind speed are 12.61 m/s (2019), 11.91 m/s (2020), and 12.45 m/s (2021). On the other hand, the minimum values of wind speeds are 2.03 m/s (2019), 1.96 m/s (2020), and 2.15 m/s (2021). The average wind speeds are 4.60 m/s (2019), 4.44 m/s (2020), and 4.46 m/s (2021).

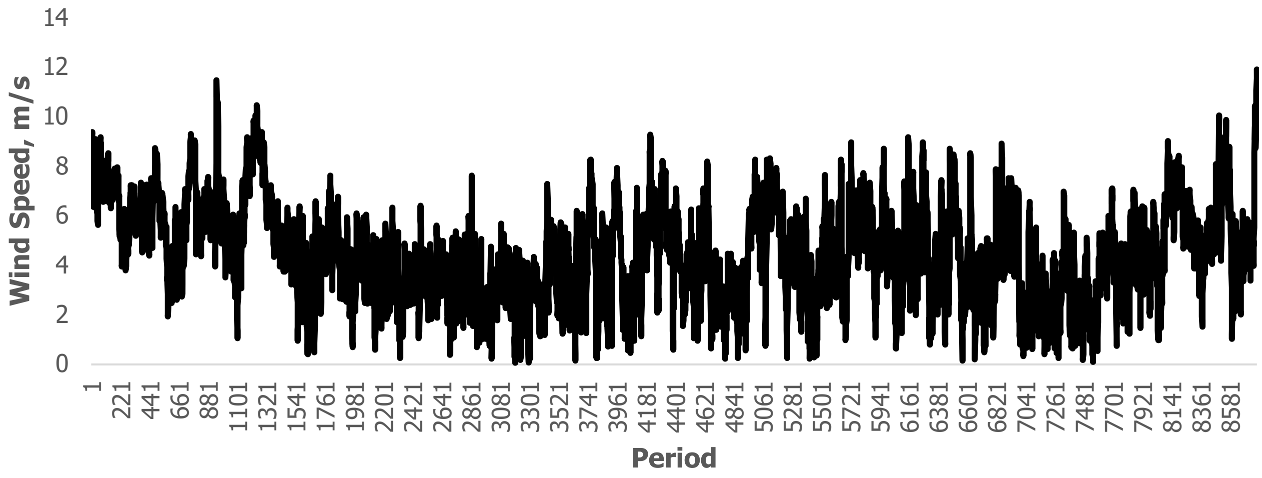
Figure 2 shows the plotted raster maps. These maps showed offshore wind speeds on the east coast of Peninsular Malaysia, presenting the promising site where the contour colour is prominently red (higher wind speed).

Table 1
Statistical Indices of The Wind Dataset

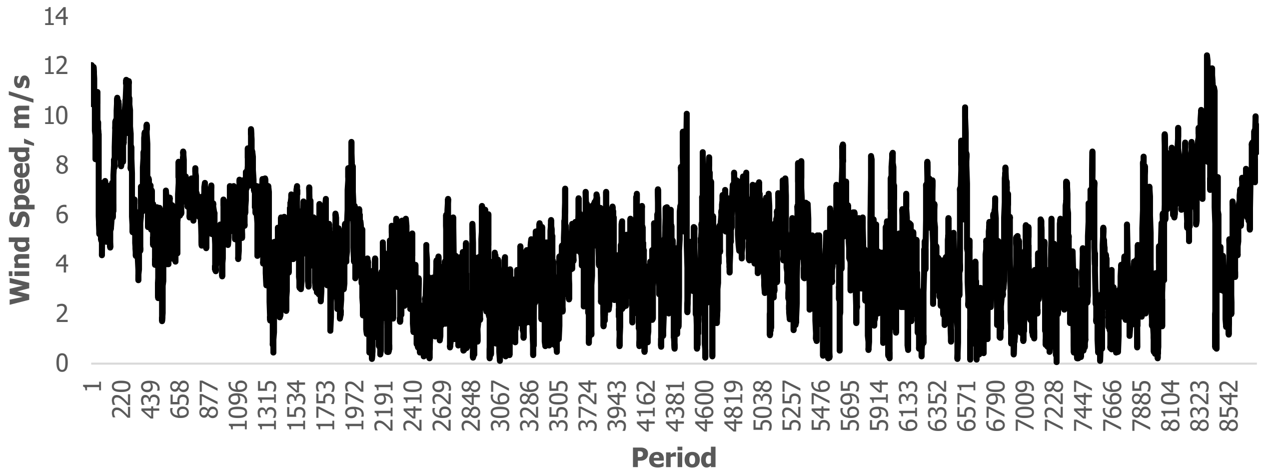
Years	Number of Data	Data Recovery	Average, m/s	Maximum, m/s	Standard Deviation, m/s
2019	8760	100%	4.60	12.61	2.03
2020	8784	100%	4.44	11.91	1.96
2021	8760	100%	4.46	12.45	2.15



(a)



(b)



(c)

Fig. 1. Data time series (a) 2019 (b) 2020 (c) 2021

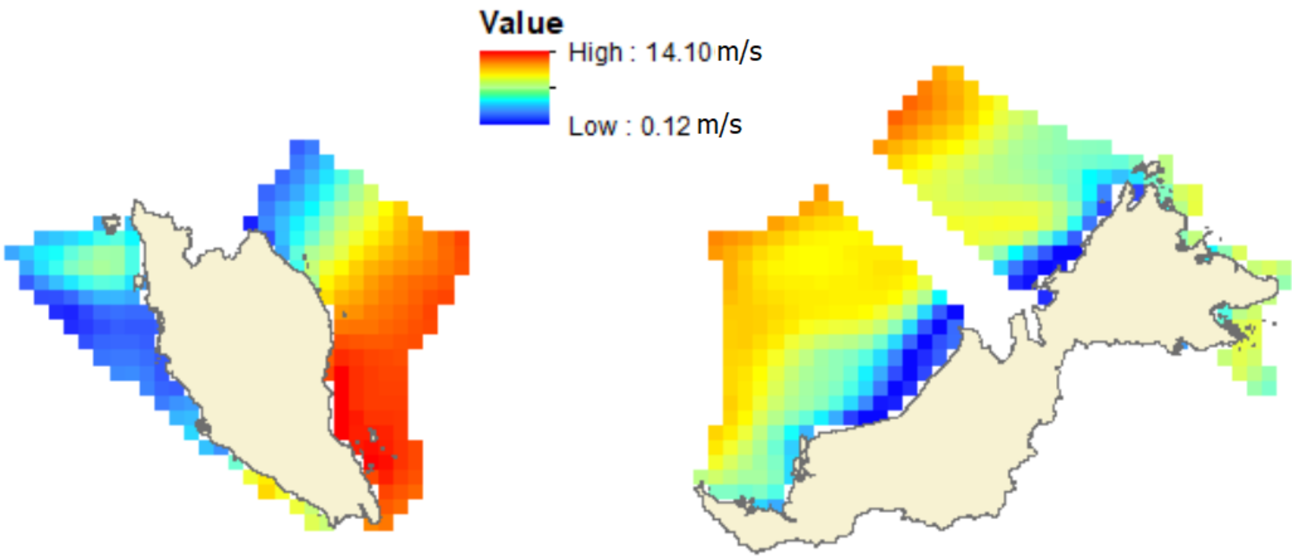


Fig. 2. ERA5 Wind Map for 10m (01/01/2021 12:00:00 AM)

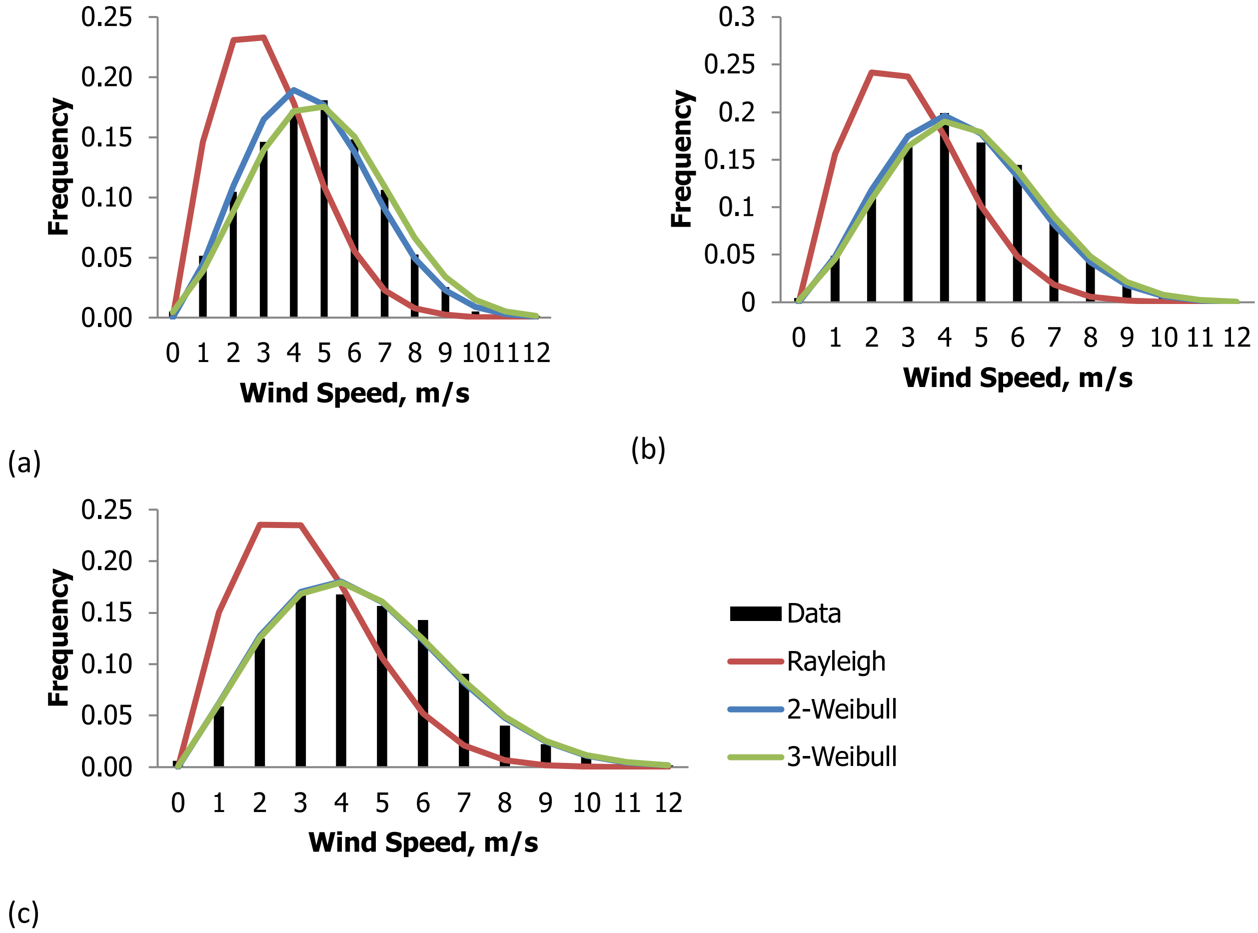


Fig. 3. The PDF (a) 2019 (b) 2020 (c) 2021

Table 2
The PDF parameters

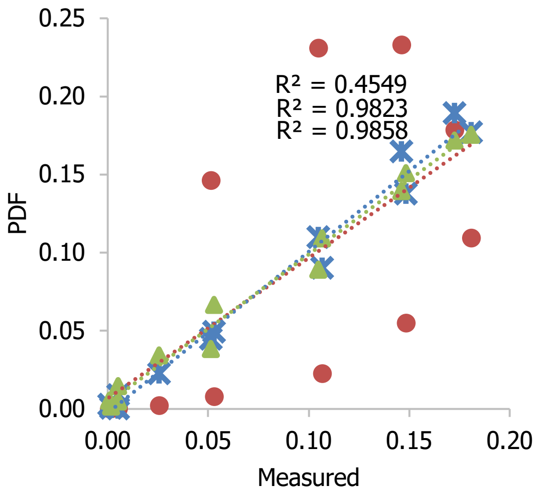
Years	PDF	Shape, k	Scale, c	Location, ε
	Rayleigh	2.00	3.55	
2019	**2-Weibull**	2.41	5.18	
	3-Weibull	2.65	5.59	-0.37
	Rayleigh	2.00	3.43	
2020	**2-Weibull**	2.42	5.01	
	3-Weibull	2.51	5.17	-0.14
	Rayleigh	2.00	3.50	
2021	**2-Weibull**	2.18	5.03	
	3-Weibull	2.20	5.07	-0.03

Figure 3 presents plot of three distinct PDFs as well as the histogram of the ERA5 wind data. The three-parameter Weibull was characterized by its shape, scale, and location parameters, respectively. The scale parameter, often known as c, is a unique numerical parameter form used for parametric probability distribution families. If the value of the scale parameter is greater, the distribution will become more spread out. The shape parameter, k, provides insight into the manner in which the data are dispersed. A curve with a right-skewed is produced by a small value of the shape parameter, while a large shape parameter value produces a curve with a left-skewed. As presented in Table 2, the shape parameter for each of the three distinct PDFs falls within the range of 2.00 to 2.65, which exhibited a bell-shaped curve with a right-skewed.

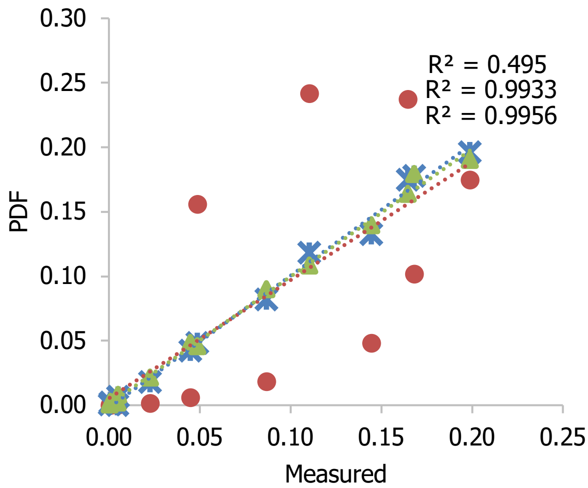
The location parameters also go by the threshold parameters, which characterize the distribution shift away from zero. These parameters are also referred to as threshold parameters. A threshold with a negative value pushes the distribution to the left, whereas a threshold with a positive value moves the distribution to the right. All data has to be larger than the threshold; the location parameter for this site displayed a negative result. The real times have an amount of time deducted from them, and the negative value of the location parameter represents this. In the scenario in which there is zero value for the location parameter, the distribution in question is known as the two-parameter Weibull distribution.

Graphically in Figure 4, it is observed that the three-parameter Weibull curve presents a better curve fit with the histogram of the ERA5 wind speed compared to the two-parameter Weibull and Rayleigh. This fact is clearly validated using statistical tests, i.e., RMSE and R^2.

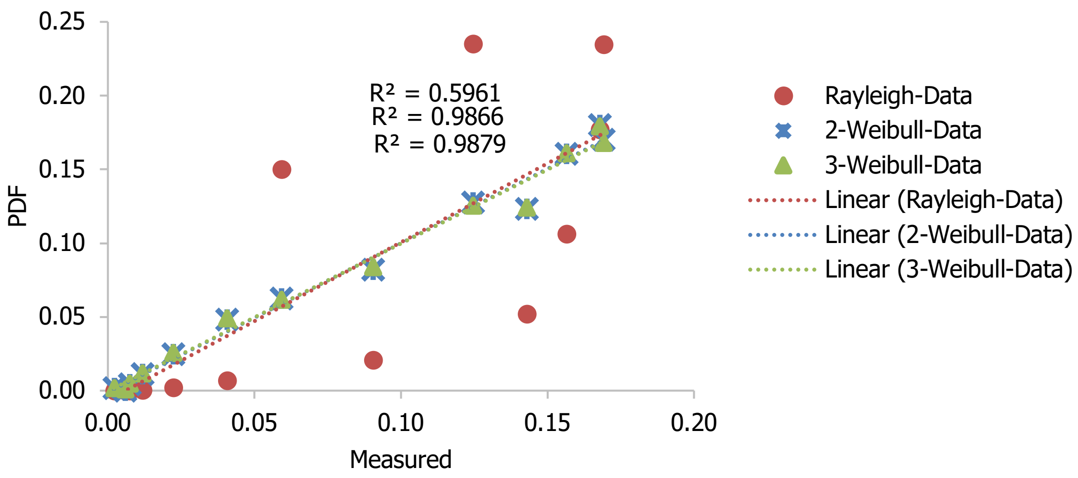
Figure 4 and Table 3 show the statistical analysis results for the three PDFs. The three-parameter Weibull performs well since it appears between the best R^2 closest to 1 and the best RMSE closest to 0. The R^2 for the three-parameter Weibull is 0.9898, the two-parameter Weibull is 0.9874, and Rayleigh is 0.5153. While the RMSE of the three-parameter Weibull is 0.0070, the two-parameter Weibull is 0.0082, and Rayleigh is 0.0677. The results are encouraging and compare favourably to similar research conducted by [38], which found that the three-parameter Weibull model was appropriate for the low wind speed dataset.



(a)



(b)



(c)

Fig. 4. The correlation (a) 2019 (b) 2020 (c) 2021

Table 3
The Statistical Analysis of PDFs

Years	PDF	Rayleigh-Data	2-Weibull-Data	3-Weibull-Data
2019	R-squared	0.4549	0.9823	0.9858
	RMSE	0.0709	0.0100	0.0082
2020	R-squared	0.4950	0.9933	0.9956
	RMSE	0.0703	0.0064	0.0050
2021	R-squared	0.5961	0.9866	0.9879
	RMSE	0.0618	0.0083	0.0078
Averaged	R-squared	0.5153	0.9874	0.9898
	RMSE	0.0677	0.0082	0.0070

4. Conclusions

In the field of renewable energy that deals with wind power, consulting the wind speed statistics for that location is required to decide whether an investment will be made for a proposed wind plant.

In this paper, the three years of ERA5 reanalysis data were used in the analysis. The PDFs, two-parameter Weibull distribution, three-parameter Weibull distribution, and Rayleigh distribution functions of offshore wind speed at Kijal in Malaysia were compared with the histogram of the ERA5 wind speed. The results showed that the three-parameter Weibull distribution function provides a fitter to the obtained data than the two-parameter Weibull and Rayleigh distribution.

Therefore, as the three-parameter Weibull suit the wind speed distribution at the Kijal site, the capacity factor of the wind turbine can be predicted using the capacity factor equation by combining the wind turbine power curve and PDF equations.

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