Statistical Analysis of Wind Power Density Based on the Weibull and Rayleigh Models of Selected Site in Malaysia

A. Albani
Renewable Energy Research Group
Department of Engineering Science
Universiti Malaysia Terengganu
21030, Kuala Terengganu
Terengganu, Malaysia
aliashim.albani@gmail.com

M.Z. Ibrahim
Renewable Energy Research Group
Department of Engineering Science
Universiti Malaysia Terengganu
21030, Kuala Terengganu
Terengganu, Malaysia
zam@umt.edu.my

Abstract

The demand for electricity in Malaysia is growing in tandem with its Gross Domestic Product (GDP) growth. Malaysia is going to need even more energy as it strives to grow towards a high-income economy. Malaysia has taken steps to exploring the renewable energy (RE) including wind energy as an alternative source for generating electricity. In the present study, the wind energy potential of the site is statistically analyzed based on 1-year measured hourly time-series wind speed data. Wind data were obtained from the Malaysian Meteorological Department (MMD) weather stations at nine selected sites in Malaysia. The data were calculated by using the MATLAB programming to determine and generate the Weibull and Rayleigh distribution functions. Both Weibull and Rayleigh models are fitted and compared to the Field data probability distributions of year 2011. From the analysis, it was shown that the Weibull distribution is fitting the Field data better than the Rayleigh distribution for the whole year 2011. The wind power density of every site has been studied based on the Weibull and Rayleigh functions. The Weibull distribution shows a good approximation for estimation of wind power density in Malaysia.

Keywords: Wind, Weibull distribution model, Rayleigh distribution model, Power density, Malaysia.

1. Introduction

Malaysia comprises Peninsular Malaysia, Sabah and Sarawak which are the part of Borneo Island. Malaysia lies in the equatorial zone and the climate is governed by the regime of the northeast and southwest monsoons which blow alternately during the course of the year as mentioned by Sopian et. al (1994). Malaysian Meteorological Department (MMD) in 2011 has highlighted, though the wind over the country is generally light and variable, there are, however, some uniform periodic changes in the wind flow patterns. Based on these changes, four seasons can be distinguished, namely, the southwest monsoon, northeast monsoon and two shorter periods of inter-monsoon seasons. The southwest monsoon season is usually established in the half of May or early June and ends in September. The existing wind flow is generally light. The northeast monsoon season usually commences in early November and ends in March. During the two inter-monsoon seasons, the winds are generally light and variable. During these seasons, the equatorial trough lies over Malaysia. As Malaysia is principally a maritime country, the effect of land and sea breezes on the general wind flow pattern is very significant especially during days with clear skies. On bright sunny afternoons, sea breezes very often develop and reach up to several tens of kilometers inland. On clear nights, the reverse process takes place and land breezes of weaker strength can also develop over the coastal areas.

The location of nine stations is shown in Figure 1. The stations are located at Mersing, Kuala Terengganu, Pulau Langkawi in Peninsular Malaysia; Kota Kinabalu, Tawau, Sandakan, Kudat in Sabah; and Kuching, Bintulu in Sarawak. Table 1 shows the location and elevation of the stations. The data were obtained from the Malaysian Meteorological Department (MMD) stations at the mentioned cities. Moreover, the data for this study consist of hourly wind records for the year 2011. The data consists of wind directions and wind speeds measured by pressure tube anemograph which were averaged over every hour and routinely checked for reliability. Most of the stations are at airports and are near the coast, where land and sea breezes may influence the wind regime.

In this study, the probability density distributions are derived from time-series data and distributional parameters are identified. Two probability density functions are fitted to the measured probability distributions on a monthly basis. The wind energy potential of the locations are studied based on the Weibull and the Rayleigh models.

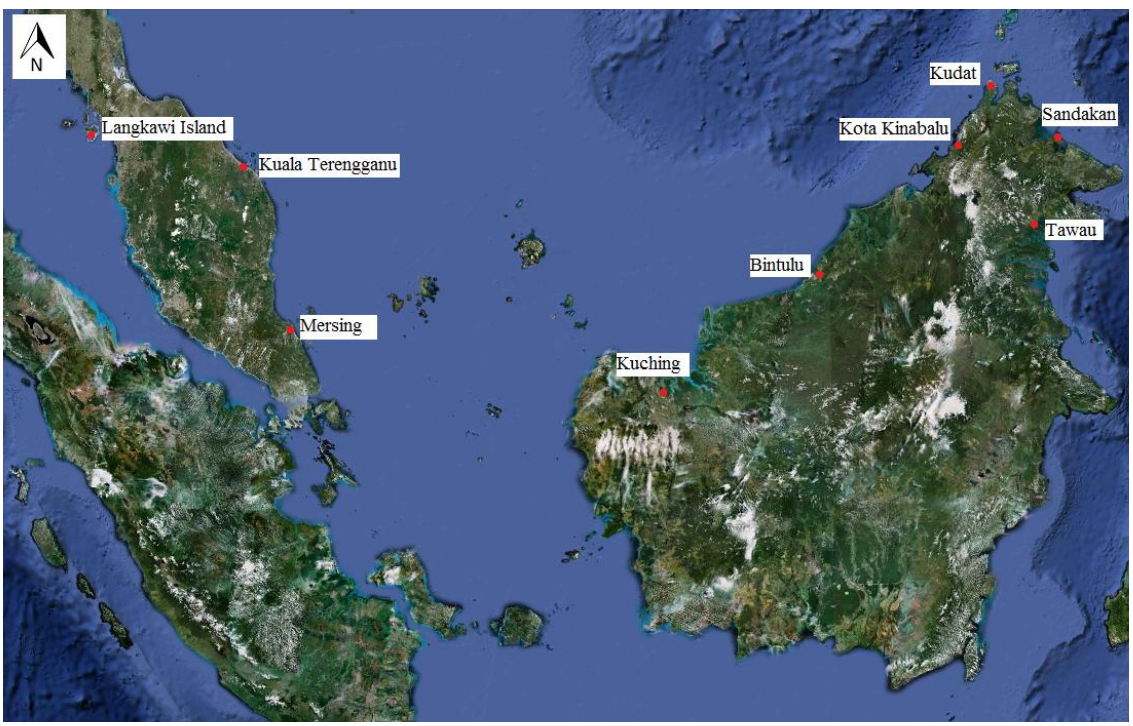


Figure 1 The location of Malaysian Meteorological Department (MMD) Stations

Table 1: The location and elevation of the stations

Stations	Latitude °N	Longitude °E	Height above mean sea level (m)
Kuala Terengganu	05° 23'	103° 06'	5.2
Mersing	02° 27'	103° 50'	43.6
Pulau Langkawi	06° 20'	99° 44'	6.4
Kota Kinabalu	05° 56'	116° 03'	2.3
Sandakan	05° 54'	118° 04'	10.3
Tawau	04° 18'	118° 07'	17.0
Kudat	06° 55'	116° 50'	3.5
Bintulu	03° 07'	113° 01'	23.1
Kuching	01° 29'	110° 20'	21.7

2. Calculation Methodology

2.1 Vertical extrapolation of wind speed:

Wind speed near the ground changes with height, this involves an equation that forecasts wind speed at different height by using the available wind speed data. Kantar and Usta (2008) has discussed, the most common equation used for the variation of wind speed with height is the power law as follows;

$$v_2 = v_1 \left(\frac{h_2}{h_1} \right)^{\alpha} \tag{1}$$

Where v_1 (m/s) is the actual wind speed recorded at height h_1 (m), and v_2 (m/s) is the wind speed at the required or extrapolated height h_2 (m). The exponent depends on the surface roughness and atmospheric stability.

2.2. Wind speed probability distribution

The wind speed data in time series format are usually arranged in the frequency distribution format since it is more convenient for statistical analysis, therefore the available time-series data were translated into a frequency distribution format as mentioned by Muzathik et.al (2009).

Kantar and Usta (2008) and Muzathik et.al (2009) has discussed that, two of the commonly used functions for fitting a Field data probability distribution in a given location over a certain period of time are the Weibull and Rayleigh distribution models. The probability density function of the Weibull of wind speed being v, $f_w(v)$ during any time interval is given, as following;

$$f(V) = \frac{k}{c} \left(\frac{V}{c} \right)^{k-1} e^{-(V/c)^K} \tag{2}$$

Zaid (2006) and Mathew (2006) summarized that, the shape (*k*) and scale (*c*, m/s) parameters can be estimated by using the Maximum Likelihood Method (MLH) as;

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n} \right)^{-1} \tag{3}$$

$$c = \left(\frac{1}{2} \sum_{i=1}^{n} v_i^k \right)^{1/2} \tag{4}$$

Where v_i is the wind speed in time stage *i* and *n* is the number of non-zero wind data points. The Rayleigh f_R (v) distribution is a special case of the Weibull distribution in which the shape parameter *k* is assumed to be equal to 2. Ali (2003) has discussed, from equation (2) the probability density functions of the Rayleigh distribution given by;

$$f_R(v) = \frac{2v}{c^2} e^{-\left(\frac{v}{c}\right)^2} \tag{5}$$

2.3. Wind power density function:

Mahyoub (2006) and Zhou et.al (2006) has mentioned the evaluation of the wind power per unit area is of fundamental importance in assessing wind power projects. The formula for wind power density as follow;

$$P_v = \frac{1}{2n} \sum_{i=1}^{n} \rho(v_i^3) \tag{6}$$

Where ρ (kg/m3) is the mean air density, the value 1.240 kg/m^3 is used in this work. This depends on altitude, air pressure and temperature. Adrian et.al (2003) has mentioned that the expected monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows;

$$P_w = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{7}$$

Where Γ is the gamma function and **C** is the Weibull scale parameter (m/s) given by;

$$P = \frac{V_m}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{8}$$

The two significant parameters k and *c* are closely related to the mean value of the wind speed V_m. By extracting *c* from equation (8) and setting *k* equal to 2, the power density for the Rayleigh model is found to be;

$$P_R = \frac{3}{\pi}\rho V_m \qquad (9)$$

Where;

$$V_m = c\Gamma\left(1+\frac{1}{2}\right) \qquad (10)$$

Ali (2003) and Mahyoub (2006) has shown, the errors in calculating the power densities using the distribution models (Weibull and Rayleigh) in comparison to the values of the probability density distributions derived from Field data values can be found using the following formula;

$$Error\% = \frac{P_{w,R} - P_{m,R}}{P_{m,R}} \qquad (11)$$

Where $P_{w,R}$ (w/m^2) is the mean power density calculated from either the Weibull or Rayleigh function used in the calculation of the error, and $P_{m,R}$ is the wind power density for the probability density distribution, derived from Field data values which serves as the reference mean power density.

3. Results and Discussion

3.1 Wind speed variations

The differences in the temperature and pressure of the earth's surface during the daily radiation cycle influence the variations of wind speed. The wind speed varies every time of the day. This variation will determine the availability and amount of wind power will generated by the wind turbines in a day and annually. Mersing recorded the highest annual mean wind speed at 10 m height from ground level with value 2.90 m/s, followed by Kudat, 2.50 m/s and Sandakan, 2.30 m/s. Tawau showed the lowest annually mean wind speed with value 1.7 m/s.

Figure 2 showed the typical average wind speeds for every month over year 2011 in Malaysia. The highest monthly mean wind speed was 4.76 m/s at Mersing on January 2011. Kudat was the second site which had higher wind speed with value 3.19 m/s on September 2011, while the lowest mean wind speed was Pulau Langkawi with value 1.44 m/s on May 2011. The monthly average wind speed was higher during the northeast monsoon month (November-March) compared to the other month. This clearly reflects that the wind turbines would produce appreciably more energy during this season.

The frequency distribution histogram of hourly average wind speed for year 2011 is presented in Figure 3. The frequency is highly peak in range 1-6 m/s. This indicates that most of energy in Malaysia lies in this range. This distribution of wind speed is important in determining the percentage of time during a year, the power that could be generated from the wind turbines.

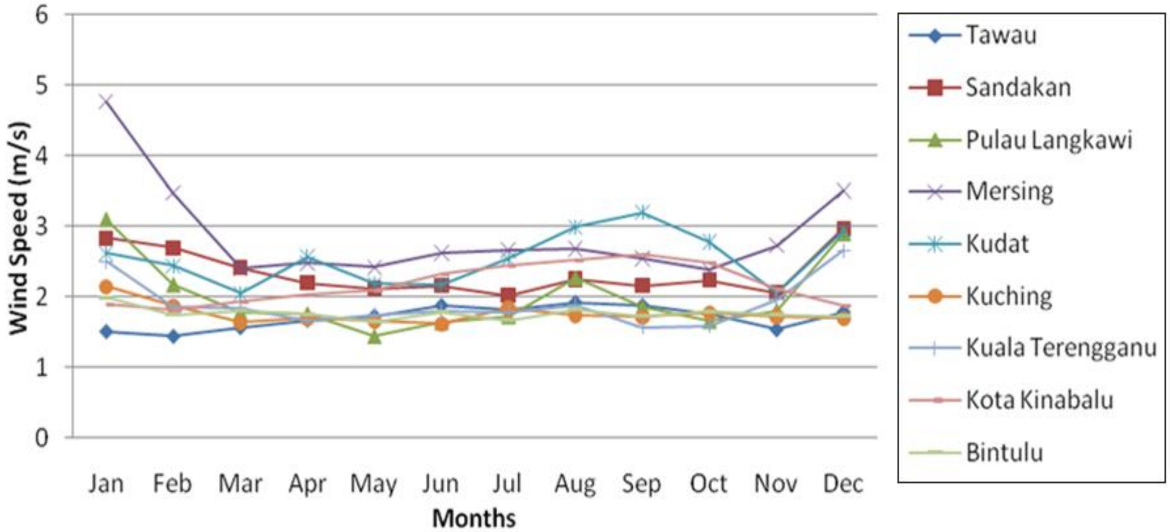


Figure 2 Monthly average wind speed in Malaysia for year 2011

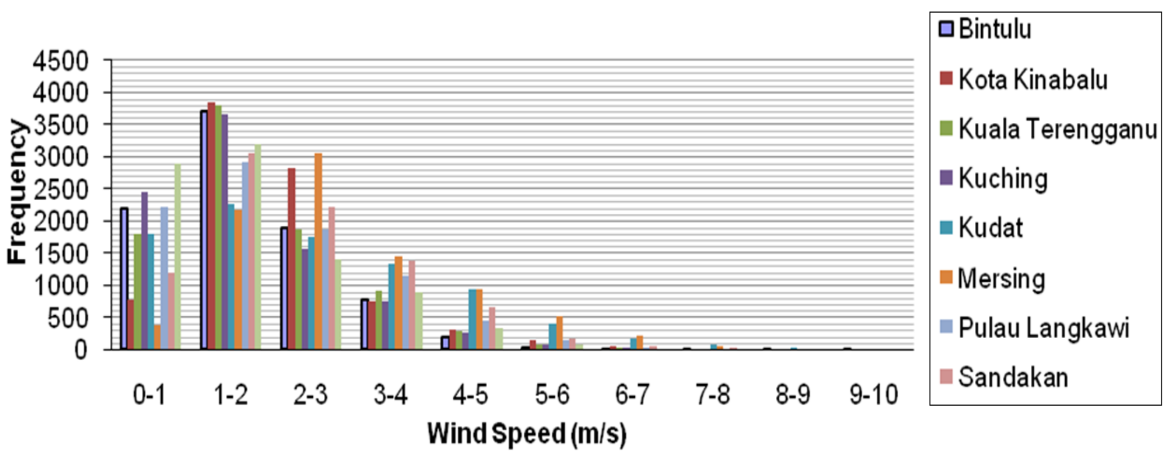


Figure 3 Frequency distribution of hourly average wind speeds for year 2011 in Malaysia.

Table 2: Average wind speed and Weibull parameters

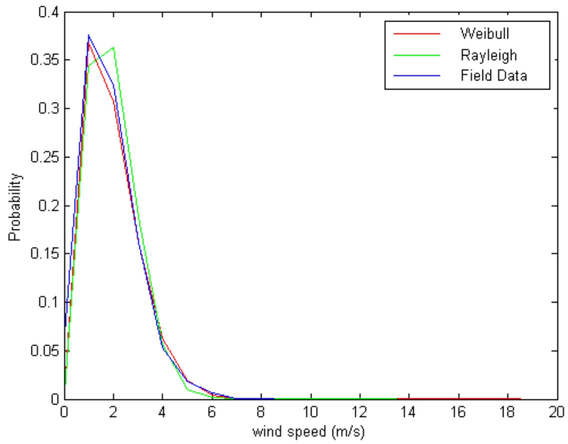
Months	Kuala Terengganu	Mersing	Pulau Langkawi	Kota Kinabalu	Sandakan	Tawau	Kudat	Bintulu	Kuching
January	2.49	4.70	3.10	1.88	2.83	1.51	2.61	2.00	2.14
February	1.86	3.40	2.17	1.81	2.7	1.44	2.44	1.70	1.86
March	1.84	2.40	1.77	1.92	2.41	1.56	2.05	1.80	1.64
April	1.66	2.40	1.76	2.02	2.19	1.67	2.56	1.80	1.69
May	1.75	2.40	1.44	2.09	2.11	1.73	2.18	1.60	1.65
June	1.79	2.60	1.63	2.33	2.16	1.88	2.17	1.80	1.61
July	1.79	2.60	1.72	2.44	2.02	1.81	2.53	1.70	1.84
August	1.87	2.60	2.26	2.53	2.24	1.92	2.99	1.80	1.74
September	1.57	2.50	1.85	2.6	2.16	1.88	3.19	1.70	1.71
October	1.59	2.30	1.65	2.48	2.24	1.76	2.77	1.80	1.77
November	1.96	2.70	1.80	2.11	2.06	1.53	2.05	1.70	1.72
December	2.65	3.50	2.90	1.87	2.97	1.79	2.93	1.70	1.69
Scale, c (m/s)	2.07	3.21	2.17	2.44	2.56	1.77	2.82	1.91	1.93
Shape, k	1.67	2.38	1.57	2.13	1.86	1.19	1.67	1.52	1.57

3.1 Distribution functions model

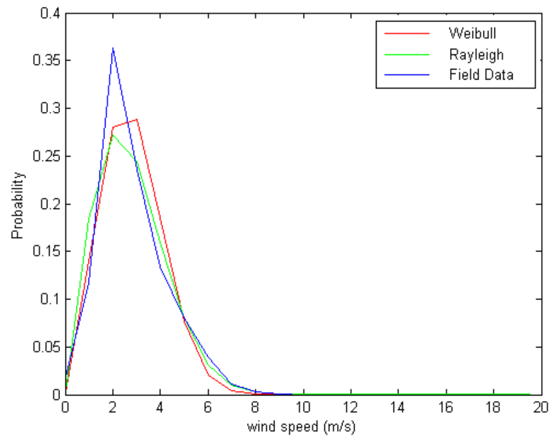
Analysis of wind speed distribution is very important to evaluate the wind potential and the economic feasibility. Paul (2004), Pimenta et.al (2004) and Khan (2006) has discussed that the most practical and simplest method is to use wind distribution function. There are several of distribution functions to describe a wind speed frequency curve. The Weibull and Rayleigh functions were used in this study because both were the most broadly used and accepted in the specialized research journal.

The variation of wind speeds often described using the Weibull two-parameter density function. This is statistical method which widely accepted for evaluation local wind probabilities and considered as a standard approach. Maximum Likelihood Method (MLM) was chosen to calculate both Weibull's parameters, scale and shape, as shown in Table 2, it is seen that, the scale factor varies between 1.77 m/s to 3.21 m/s, while the shape factor ranges from 1.19 to 2.38 for studied locations. The annual probability density distributions obtained from the Weibull and Rayleigh models were compared to the Field data distributions to study their suitability. The annual comparison for every selected site shows that the Weibull model better than the Rayleigh model to fit the Field data probability density distribution as shown in Figure 4. The graph line of Weibull distribution is more fitted and closely to the graph line of Field data compared to Rayleigh distribution model. Previous studies by Morgan (1995) and Keyhani et.al (2010) also have concluded that the Weibull distribution fits the observed wind speed frequencies quite well.

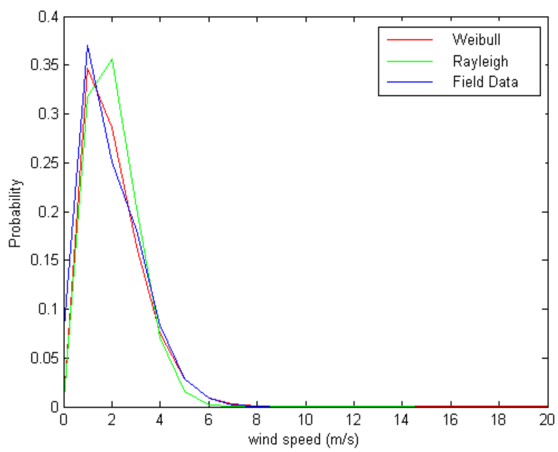
a) Kuala Terengganu



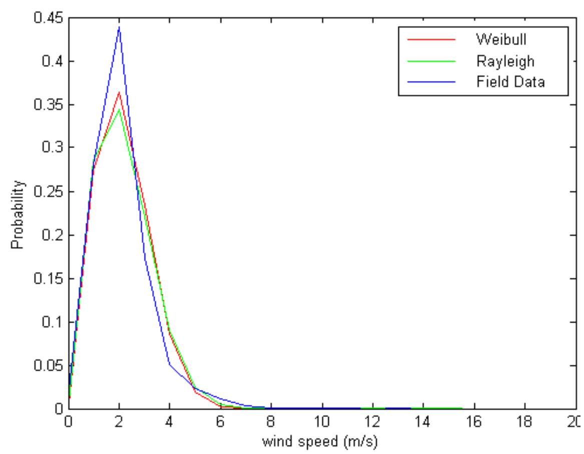
b) Mersing



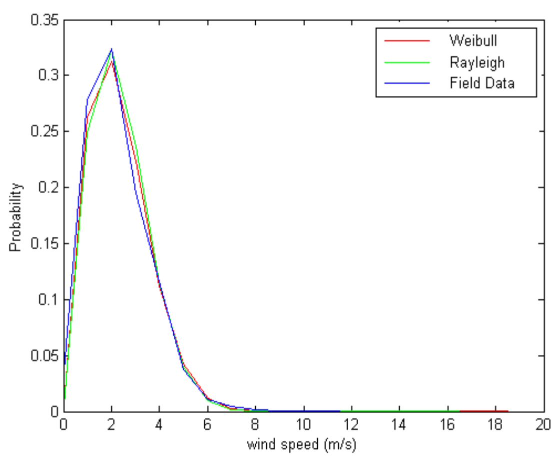
c) Pulau Langkawi



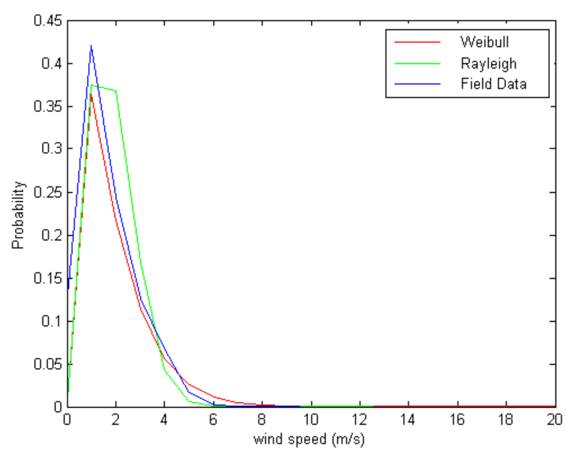
d) Kota Kinabalu



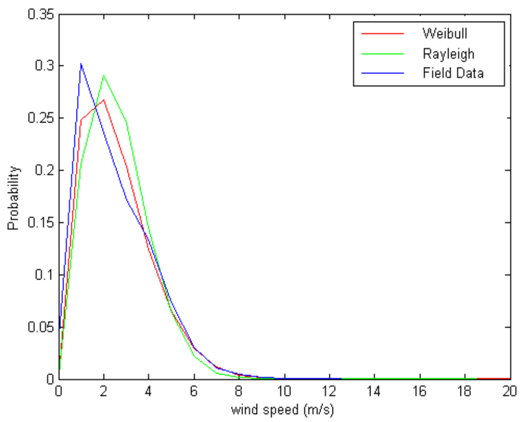
e) Sandakan



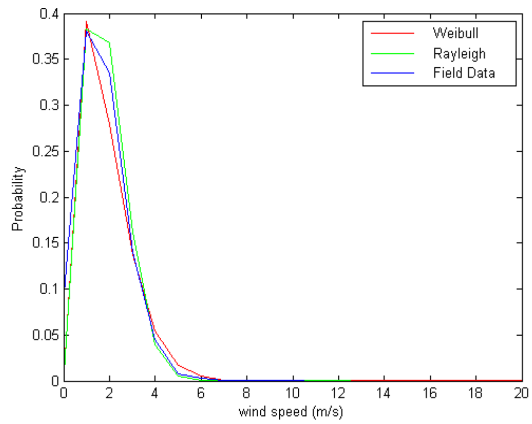
f) Tawau



g) Kudat



h) Bintulu



i). Kuching

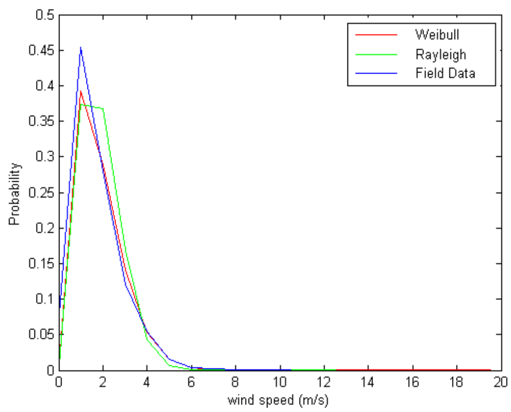


Figure 4 (a-i) Comparison of probability density distributions of year 2011 according to Field data with Weibull and Rayleigh functions.

The sites located in west coast of Malaysia were exposed to the southwest monsoon season which is usually occur in the half of May or early June and ends in September. The prevailing wind flow is generally South westerly. While, the sites located in east coast of Malaysia such as Kuala Terengganu, Mersing and sites in Sabah and Sarawak were exposed to the Northeast monsoon season which is usually commences in early November and ends in March. During this season, prevailing wind was Easterly and North easterly. It is worth mentioning that during the months of April to November, when typhoons frequently develop over the west Pacific and move westwards across the Philippines, southwesterly winds over the northwest coast of Sabah and Sarawak region may strengthen to reach 10.3 m/s or more.

Table 3 (a-c) Monthly variation of wind power density.

a) Peninsular Malaysia

Months	Wind Power Density (w/m²)											
	Kuala Terengganu				**Mersing**				**Pulau Langkawi**			
	W	E_W	R	E_R	W	E_W	R	E_R	W	E_W	R	E_R
Jan	23.40	0.21	10.27	-0.47	83.31	-0.36	51.12	-0.61	28.72	-0.23	15.80	-0.58
Feb	9.20	0.14	3.99	-0.50	42.56	-0.13	21.06	-0.57	14.23	0.11	6.49	-0.49
Mar	8.82	0.13	3.82	-0.51	18.70	0.08	7.52	-0.56	7.81	0.13	3.60	-0.48
Apr	6.25	0.09	2.73	-0.52	21.18	0.23	8.19	-0.53	7.77	0.14	3.63	-0.47
May	7.26	0.08	3.15	-0.53	21.99	0.27	7.92	-0.54	4.41	0.18	1.98	-0.47
Jun	7.03	-0.02	3.26	-0.55	25.88	0.18	9.95	-0.55	6.24	0.15	2.85	-0.47
Jul	8.00	0.12	3.41	-0.52	28.84	0.31	10.72	-0.51	7.74	0.22	3.62	-0.43
Aug	8.75	0.07	3.93	-0.52	28.99	0.32	11.10	-0.49	17.88	0.24	8.13	-0.44
Sep	5.71	0.18	2.37	-0.51	23.90	0.22	9.24	-0.53	10.87	0.37	4.92	-0.38
Oct	5.62	0.12	2.37	-0.53	19.27	0.27	7.40	-0.51	7.27	0.29	3.28	-0.42
Nov	12.13	0.29	5.42	-0.42	27.58	0.12	10.93	-0.56	7.64	0.05	3.66	-0.50
Dec	22.86	-0.02	10.78	-0.54	53.57	0.00	22.69	-0.58	24.29	-0.20	13.19	-0.57

(W: Weibull distribution, R: Rayleigh distribution, E: Error)

b) Sabah, Malaysia

Months	Wind Power Density (w/m²)															
	Kota Kinabalu				**Sandakan**				**Tawau**				**Kudat**			
	W	E_W	R	E_R	W	E_W	R	E_R	W	E_W	R	E_R	W	E_W	R	E_R
Jan	7.74	-0.07	2.22	-0.73	35.08	0.24	3.29	-0.88	3.00	-0.30	1.67	-0.61	26.76	0.20	3.04	-0.86
Feb	6.63	-0.11	2.13	-0.71	25.41	0.03	3.18	-0.87	2.70	-0.28	1.59	-0.58	20.55	0.13	2.82	-0.84
Mar	6.48	-0.27	2.26	-0.74	16.58	-0.05	2.85	-0.84	8.37	0.76	1.74	-0.63	11.34	0.05	2.43	-0.77
Apr	8.75	-0.15	2.37	-0.77	8.47	-0.36	2.02	-0.85	8.47	0.45	1.84	-0.68	23.03	0.10	3.00	-0.86
May	10.21	-0.11	2.43	-0.79	11.72	0.00	2.45	-0.79	5.33	-0.18	1.91	-0.70	13.86	0.07	2.56	-0.80
Jun	14.34	-0.09	2.73	-0.83	10.66	-0.15	2.53	-0.80	7.02	-0.15	1.97	-0.76	16.93	0.33	2.52	-0.80
Jul	15.24	-0.16	2.88	-0.84	10.46	0.01	2.32	-0.77	9.57	0.29	1.96	-0.74	26.26	0.30	2.94	-0.85
Aug	19.29	-0.05	2.98	-0.85	13.80	-0.02	2.64	-0.81	7.00	-0.21	2.09	-0.76	52.66	0.58	3.39	-0.90
Sep	22.45	0.02	3.09	-0.86	14.05	0.12	2.49	-0.80	7.10	-0.15	2.02	-0.76	49.59	0.22	3.73	-0.91
Oct	19.13	0.00	2.95	-0.85	13.39	-0.05	2.62	-0.81	11.64	0.71	1.90	-0.72	33.46	0.26	3.22	-0.88
Nov	9.85	-0.16	2.48	-0.79	9.87	-0.10	2.41	-0.78	7.63	0.70	1.67	-0.63	12.12	0.13	2.40	-0.78
Dec	6.36	-0.22	2.19	-0.73	28.47	-0.13	3.50	-0.89	8.10	0.13	1.95	-0.73	27.12	-0.14	3.45	-0.89

(W: Weibull distribution, R: Rayleigh distribution, E: Error)

c) Sarawak, Malaysia

Months	Wind Power Density (w/m²)							
	Bintulu				**Kuching**			
	W	E_W	R	E_R	W	E_W	R	E_R
Jan	11.14	0.11	2.33	-0.77	15.51	0.27	2.46	-0.80
Feb	7.38	0.20	2.03	-0.67	9.55	0.19	2.15	-0.73
Mar	8.00	0.10	2.07	-0.72	6.71	0.22	1.88	-0.66
Apr	10.64	0.46	1.93	-0.73	6.67	0.11	1.95	-0.68
May	7.39	0.44	1.84	-0.64	7.01	0.25	1.90	-0.66
Jun	7.93	0.09	2.04	-0.72	6.34	0.22	1.86	-0.64
Jul	9.54	0.55	1.83	-0.70	9.83	0.26	2.11	-0.73
Aug	9.48	0.30	2.07	-0.72	7.97	0.21	2.03	-0.69
Sep	8.35	0.36	1.93	-0.69	8.11	0.30	1.96	-0.69
Oct	9.14	0.25	2.03	-0.72	8.30	0.20	2.05	-0.70
Nov	7.27	0.18	2.02	-0.67	7.72	0.21	1.98	-0.69
Dec	7.66	0.25	1.94	-0.68	6.81	0.13	1.94	-0.68

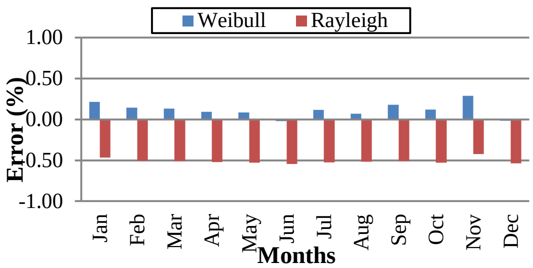
(W: Weibull distribution, R: Rayleigh distribution, E: Error)

Error values in calculating the wind power density obtained from the Weibull and Rayleigh models, in reference to the wind power density obtained from the Field data, on monthly basis are presented in Figure 5 and Table 3.

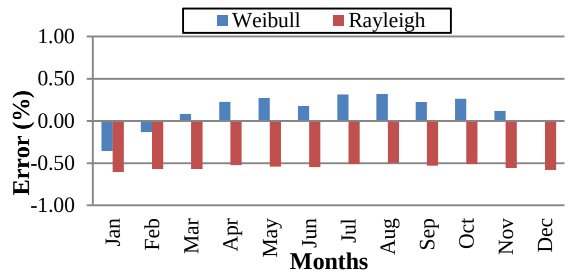
From the results in Peninsular Malaysia, the highest error for Weibull-Field data is occurring in September at Pulau Langkawi with 37%, while for Rayleigh-Field data is occurring in January at Mersing with 61%. In Sabah, the highest error for Weibull-Field data is occurring in March at Tawau with 76%, while for Rayleigh-Field data is occurring in September at Kudat with 91%. In Sarawak, the highest error for Weibull-Field data is occurring in July at Bintulu with 55%, while for Rayleigh-Field data is occurring in September at Kuching with 80%.

The Weibull model returns smaller error values in calculating the power density when compared to the Rayleigh model. The monthly analysis shows that the error values in calculating the power density using the Rayleigh model are relatively higher.

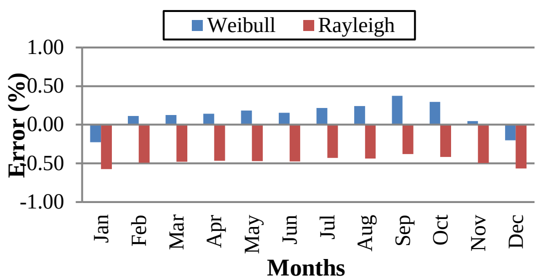
a) **Kuala Terengganu**



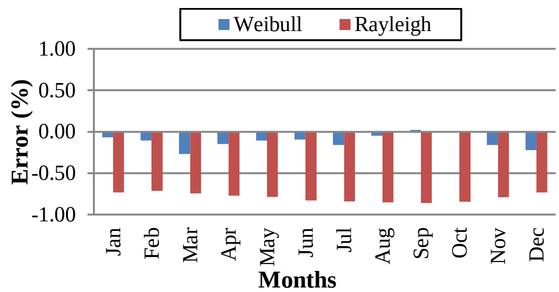
b) **Mersing**



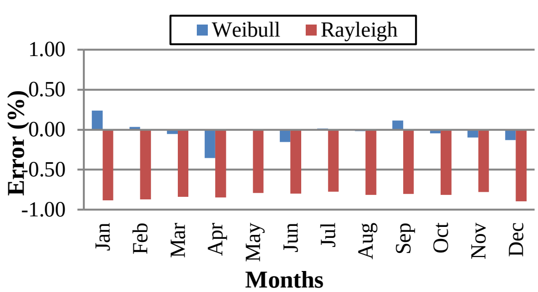
c) **Pulau Langkawi**



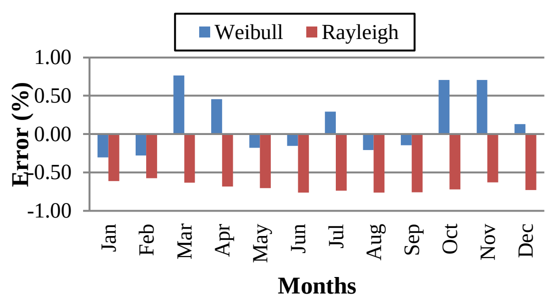
d) **Kota Kinabalu**



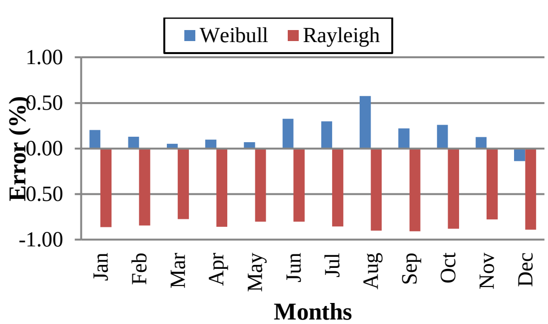
e) **Sandakan**



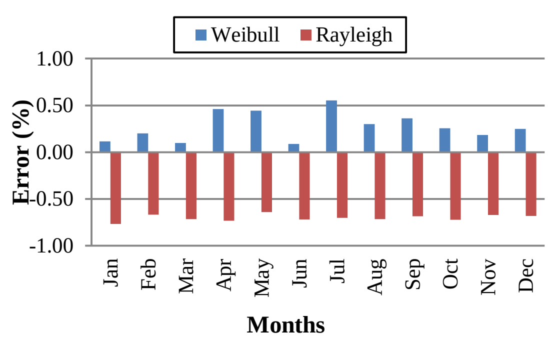
f) **Tawau**



g) **Kudat**



h) **Bintulu**



i). Kuching

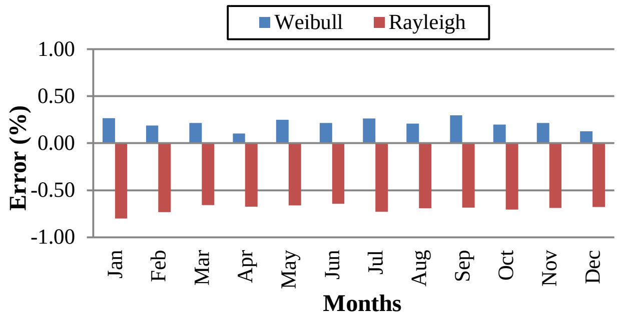


Figure 5 (a-i) Error values in calculating the wind power density on monthly basis obtained from the Weibull and Rayleigh models in reference to the wind power density obtained from the Field data.

4. Conclusion

The study was presented nine stations which have a variation of wind speed data. Wind characteristics of selected regions in Malaysia have been analyzed statistically, wind speed data were collected for a year 2011. The probability density distributions and power density distributions were derived from the wind data. Two probability density functions have been fitted to the Field probability distributions on a monthly basis, based on the Weibull and Rayleigh models. The Weibull distribution is fitting the Field data monthly probability density distributions better than the Rayleigh distribution for the whole year 2011. The Weibull model provided better power density estimations in all 12 months than the Rayleigh model.

Acknowledgements

The authors would like to thank to Department of Engineering Science, University Malaysia Terengganu (UMT) and Ministry of Science, Technology and Innovation of Malaysia (MOSTI) for providing supervision and financial support.

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