Assessment of wind energy potentiality at Kudat and Labuan, Malaysia using Weibull distribution function

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A B S T R A C T

The wind resource is a crucial step in planning a wind energy project and detailed knowledge of the wind characteristic at a site is needed to estimate the performance of a wind energy project. In this paper, with the help of 2-parameter Weibull distribution, the assessment of wind energy potentiality at Kudat and Labuan in 2006–2008 was carried out. “WRPLOT” software has been used to show the wind direction and resultant of the wind speed direction. The monthly and yearly highest mean wind speeds were 4.76 m/s at Kudat and 3.39 m/s at Labuan respectively. The annual highest values of the Weibull shape parameter (k) and scale parameter (c) were 1.86 and 3.81 m/s respectively. The maximum wind power density was found to be 67.40 W/m² at Kudat for the year 2008. The maximum wind energy density was found to be 590.40 kWh/m²/year at Kudat in 2008. The highest most probable wind speed and wind speed carrying maximum energy were estimated 2.44 m/s at Labuan in 2007 and 6.02 m/s at Kudat in 2007. The maximum deviation, at wind speed more than 2 m/s, between observed and Weibull frequency distribution was about 5%. The most probable wind directions (blowing from) were 190° and 269° at Kudat and Labuan through the study years. From this study, it is concluded that these sites are unsuitable for the large-scale wind energy generation. However, small-scale wind energy can be generated at the turbine height of 100 m.

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1. Introduction

Energy is one of the most powerful devices to drive a nation from developing to developed or from stable to more stable position. Malaysia is one of the most developing countries in the world with Gross Domestic Product (GDP) of US$15,400 per capita (Purchasing Power Parity (PPP) basis), and steady GDP growth of 4.6% in 2009 and is expected to grow to 8% in 2010. The economy of Malaysia grew at the rate of 5.6% from 2000 to 2005 to reach 38.9 Mtoe in 2005. The maximum deviation, at wind speed more than 2 m/s, between observed and Weibull frequency distribution was about 5%. The most probable wind directions (blowing from) were 190° and 269° at Kudat and Labuan through the study years. From this study, it is concluded that these sites are unsuitable for the large-scale wind energy generation. However, small-scale wind energy can be generated at the turbine height of 100 m.

The strong growth in wind-installed generation capacity worldwide is attributable to three main reasons. First, the growing public awareness and concern about emissions, climate change, and environmental issues related to other competing sources of energy. Second, awareness about oil and gas reserves depletion and the predicted Global peaking of oil production. Third, the strong growth of wind power is the improvements in wind turbine technologies that have resulted in lower costs [5–7]. In Malaysia, green technology application is seen as one of the sensible solutions [8], which are being adopted by many countries around the world to address the issues of energy and environment simultaneously [9]. The Malaysian government declared the Eighth Malaysian Plan in 2001 where RE was regarded as the fifth fuel in the new five fuel strategy in the energy mix and set a target of 5% (600 MW) RE contribution in electricity mix by the year 2005. However, the development pace of RE in Malaysia is rather slow and still at its nascent stage, with its current contribution at around 1% only of the total energy mix, even though the fifth fuel policy had been announced a decade ago. The notion is further pursued in the 9th Malaysia Plan (2006–2010) which has also set a target of 5% RE in the country’s energy mix [10–19].

Among the sources of RE, the wind energy was the fastest growing energy technology in terms of percentage of yearly growth of installed capacity per technology source [7,20–22].
Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>area (m²)</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>Weibull scale parameter (m/s)</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>Weibull shape parameter</td>
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</tr>
<tr>
<td>f(v)</td>
<td>Weibull probability distribution function</td>
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<tr>
<td>F(v)</td>
<td>Weibull cumulative distribution function</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>anemometer height (m)</td>
<td></td>
</tr>
<tr>
<td>v_z</td>
<td>velocity of the wind at height, z (m/s)</td>
<td></td>
</tr>
<tr>
<td>v_0</td>
<td>velocity of the wind at height, z_0 (m/s)</td>
<td></td>
</tr>
<tr>
<td>v</td>
<td>observing wind speed velocity (m/s)</td>
<td></td>
</tr>
<tr>
<td>α</td>
<td>wind speed power law coefficient</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>number of observations</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>number of constants</td>
<td></td>
</tr>
<tr>
<td>P/A</td>
<td>wind power density (w/m²)</td>
<td></td>
</tr>
<tr>
<td>E/A</td>
<td>wind energy density (kWh/m²/year)</td>
<td></td>
</tr>
<tr>
<td>ρ</td>
<td>density of air (kg/m³)</td>
<td></td>
</tr>
<tr>
<td>σ</td>
<td>standard deviation (m/s)</td>
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</tr>
<tr>
<td>Γ( )</td>
<td>gamma function of ( )</td>
<td></td>
</tr>
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<td>R&amp;D</td>
<td>Research and Development</td>
<td></td>
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<tr>
<td>RE</td>
<td>Renewable Energy</td>
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</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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</tr>
<tr>
<td>PPP</td>
<td>Purchasing Power Parity</td>
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</table>

Hendry [23] reported that wind has advanced more quickly to commercialization than other technologies such as solar power, fuel cells and wave power with relatively little R&D expenditure. According to the World Wind Energy Association, wind energy is in a boom cycle. In Malaysia, little effort has been made on the use of wind energy. The potential for wind energy generation in Malaysia depends on the availability of the wind resource. The availability of wind resource varies with location. To build-up wind farm, it is essential to carry out a general assessment of the wind energy potential nationwide. This can then be followed with detailed assessment in promising locations [24]. These assessments must be completed before making any decision to install wind energy plant. The wind resource is a crucial step in planning a wind energy project and detailed knowledge of the wind at a site is needed to estimate the performance of a wind energy project. There is very limited research on the assessment of wind energy potentiality in Malaysia. Sopian et al. [25] selected 10 stations and found out the wind energy potential for the years 1982–1991 in Malaysia. In this paper, the wind energy potential has been estimated at 2 sites with latest wind speed data. It is expected that this study will fill up that gap.

2. General climate of east Malaysia

Malaysia, in the southeast part of Asia, has a geographic coordinate and it lies on latitude 2° 30’ N and longitude 112° 30’ E. Malaysia sits on the South China Sea in the center of Southeast Asia. The country is crescent-shaped, starting with Peninsular Malaysia (West Malaysia) and extends to another region, Sabah and Sarawak (East Malaysia), located on the island of Borneo. The total area of Malaysia is approximately 330,000 square km, with most of it located on the island of Borneo. Peninsular Malaysia only comprises approximately 40% of the total area.

The principal differences of climate within Malaysia are those arising from difference of altitude and the exposure of the coastal lowlands to the two monsoon regimes, namely, the Southwest Monsoon from late May to September, and the Northeast Monsoon from November to March. Temperatures vary little from month to month, humidity is high, and there is no large daily range of temperature so night-time temperatures are oppressive.

The main rainy season in the east runs between November and February, while August is the wettest period on the west coast. East Malaysia has heavy rains (November to February) in Sabah and Sarawak. However, it is difficult to generalize about the country’s climate, as rainfall differs on the east and west coasts according to the prevailing monsoon winds (northeast or southwest). The southwest monsoon is comparatively drier throughout the country except for the state of Sabah in East Malaysia. Sabah is relatively wetter (exceeding 200 mm) due to the tail effect of typhoons which frequently traverse the Philippine islands in their journey across the South China Sea and beyond [25,26].

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 10.30 m/s or more. An average of 6–7 tropical cyclones traverses over the Philippines and South China Sea per year. More precisely, it occurred 7 times in 1996, 5 times in 1997, 4 times in 1998, 2 times in 1999, 7 times in 2000, 3 times in 2001, 5 times in 2002, 8 times in 2003, 12 times in 2004 and 4 times in 2005 [27]. For protect any unexpected incident of wind turbine, a control strategy which provides the Asian and Pacific area against the strong typhoon relates to the pitch and yaw system can be used. With the regulation of the pitch angle and the yaw angle, the load of blade, nacelle and tower structure could be reduced [28]. The Typhoon Il, a unique vertical axis wind turbine (VAWT), can also be applied in this region. It provides improved performance with both a substantially higher degree of efficiency and a wider range of exploitable wind speeds than those of the now prevailing horizontal axis wind turbines (HAWT) [29].

3. Wind data collection

The wind speed data for this study are taken from the Malaysian Meteorological Department (MMD) at Petaling Jaya, Selangor during the period of 2006–2008. The MMD collected wind speed data from different stations throughout Malaysia. A 10 m height mast, made of steel in solid tubular form was used to install the anemometer and wind vane for selected stations. Instrument used for measuring the surface wind speed is rotating cup type anemometer of which the cups are mounted symmetrically at a right angle to a vertical shaft. The temperature and the relative humidity were also measured using a thermometer and a hygrometer respectively. The reason for performing wind speed measurement at 10 m height was that according to Ref. [30], for climatological and practical reasons it has been agreed that this should be the standard meteorological reference level in order to achieve representative recording of the wind potential of the area. Furthermore, the wind speed at higher heights could be calculated using the power law. Wind speed was taken every 10 s and averaged over 5 min and stored in a data-logger. The 5-min averaged wind speed data were further averaged over an hour. At the end of each hour, the hourly mean wind speed was calculated and stored sequentially in a permanent memory [31–34].

4. Wind data adjustment

The variation in velocity with altitude, called wind shear, is most pronounced near the surface and the wind blows faster at higher altitudes because of the drag of the surface (sea or land) and the viscosity of the air. Typically, in daytime the variation...
follows the 1/7th power law, which predicts that wind speed rises proportionally to the seventh root of altitude. In night time, or better when the atmosphere becomes stable, wind speed close to the ground usually subsides, whereas at turbine hub altitude it does not decrease that much or may even increase.

As the wind speed changes with height and the anemometer at different meteorological stations are set at different levels, it is necessary, prior to any analysis, to adjust the recorded wind speed data to the same height. The wind power law has been recognized as a useful tool and is often used in wind power assessments where wind speed data at various heights must be adjusted to a standard height prior to use.

The wind profile power law relationship is expressed as [35,36]:

\[ n_z = n_0 \left( \frac{z}{z_0} \right)^{a} \]  

(1)

The exponent \( a \) is an empirically derived coefficient that varies depending upon the stability of the atmosphere. For neutral stable conditions, \( a \) is approximately 1/7, or 0.143, which is commonly assumed to be constant in wind resource assessments. This is because the differences between the two levels are not usually so great as to introduce substantial errors into the estimation (usually <50 m). The value of the coefficient varies from less than 0.10 for very flat land, water or ice to more than 0.25 for heavily forested landscapes and the typical value of 0.14 for low roughness surfaces [37,38]. The value 0.143 for the coefficient of \( a \) has been chosen for this assessment.

5. Site and data description

The wind data of two stations are chosen to analyze the wind energy potentials in this study. The detailed locations of the two stations (Kudat and Labuan) are shown in Table 1.

6. Analysis procedure

6.1. Wind speed distribution parameters

From the literature, it is seen that different wind speed distribution models (such as the Weibull, the Rayleigh and the Lognormal) are used to fit the wind speed distributions over a time period. Among them, the 2-parameter Weibull distribution function is accepted as the best all over the world. It is because the Weibull distribution function has its merits in wind resource assessment due to great flexibility and simplicity, but particularly it has been found to fit a wide collection of recorded wind speed data. This statistical tool also indicates how often wind of different speeds will be seen at a location with a certain average (mean) wind speed and knowing this, one can easily choose a wind turbine with the optimal cut-in speed (the wind speed at which the turbine starts to generate usable power), and cut-out speed (the speed at which the turbine hits the limit of its alternator and can no longer put out increased power output with further increases in wind speed) [37,39–44]. Weibull distribution model has been chosen for the assessment of wind energy potentiality in this study. However, it has limitation as well. The main limitation of the Weibull distribution function is that it is unable to represent the probabilities of observing zero or very low wind speed. However, for estimating wind energy potentiality for the commercial use of wind turbines, it is worthless as the energies available at low speeds are very negligible [40,45].

6.1.1. Weibull distribution function

The wind speed data obtained, with various observation methods, has usually wide ranges and cannot be considered sufficient for obtaining a clear view of the available wind potential. Therefore, it is necessary to have only a few key parameters that can explain the behavior of the wide range of wind speed data. In order to minimize the required time and expenses for processing long term, usually hourly, wind speed data, it is preferred to describe the wind speed variations using statistical functions. The 2-parameter Weibull function can be used for this purpose as one can adjust the parameters to suit for a period of time, usually 1 month or 1 year. This can be used widely both in wind speed and wind energy analysis. In Weibull distribution, the variation in wind velocity is characterized by two parameter functions, the probability density function and the cumulative distribution function [46–48].

The wind speed probability distribution function indicates the fraction of time for which a wind speed possibly prevails at the area under investigation. The wind speed probability density function can be calculated by the following equation [49–53]:

\[ f(v) = \left( \frac{k}{c} \right) \left( \frac{v}{c} \right)^{k-1} \exp \left[ -\left( \frac{v}{c} \right)^{k} \right], \quad (k > 0, v > 0, c > 1) \]  

(2)

Another important aspect should be considered during the statistical analysis is the prediction of the time for which an installed turbine could be potentially functional in this area. In order to achieve this, the determination of the cumulative distribution function is required. Since the cumulative distribution function of the velocity \( v \) indicates the fraction of time the wind speed is equal or lower than speed \( v \) by taking the difference of its values, it is possible to estimate the functional time of the wind turbine. Therefore, the cumulative distribution is the integral of the probability density function and can be expressed as [54–56]:

\[ F(v) = 1 - e^{-\left( \frac{v}{c} \right)^{k}} \]  

(3)

For calculating the mean wind speed \( \bar{v} \) and the variance \( \sigma \) of the known wind speed data, following expressions can be used:

\[ \bar{v} = \frac{1}{n} \sum_{i=1}^{n} v_i \]  

(4)

\[ \sigma = \left[ \frac{1}{n-1} \sum_{i=1}^{n} (v_i - \bar{v})^2 \right]^{1/2} \]  

(5)

Now using Equations (4) and (5), Weibull parameters \( c \) and \( k \) can be found by the following equations:

\[ k = \left( \frac{\sigma}{\bar{v}} \right)^{-1.086} \]  

(6)

\[ c = \bar{v} \int (1 + \frac{1}{c}) \]  

(7)

Where, \( \Gamma \) is the gamma function and using the Stirling approximation the gamma function of \( x \) can be given as follows:

\[ \Gamma(x) = \int_{0}^{x} e^{-u}u^{x-1}du \]  

(8)

<table>
<thead>
<tr>
<th>Station name</th>
<th>Station ID</th>
<th>Latitude °</th>
<th>Longitude °</th>
<th>Height above sea level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kudat</td>
<td>96477</td>
<td>6° 55' N</td>
<td>116° 55' E</td>
<td>3.5</td>
</tr>
<tr>
<td>Labuan</td>
<td>96465</td>
<td>5° 20' N</td>
<td>115° 14' E</td>
<td>29.3</td>
</tr>
</tbody>
</table>
6.2. Most probable wind speed

The most probable wind speed denotes the most frequent wind speed for a given wind probability distribution. From the scale parameter and shape parameter of Weibull distribution function, the most probable wind speed can be easily obtained from the following equation [32]:

\[ V_{mp} = c \left( 1 - \frac{1}{k} \right)^{1/k} \text{ (m/s)} \]  

(9)

6.3. Maximum energy carrying by the wind speed

The maximum wind energy carrying by the wind speed can be calculated from the scale parameter and shape parameter of Weibull distribution function. The wind speed which is carrying maximum wind energy can be expressed as follows [57]:

\[ V_{max,E} = c \left( 1 + \frac{2}{k} \right)^{1/k} \text{ (m/s)} \]  

(10)

6.4. Wind power density

The power of the wind that flows at a speed \( v \) through a blade sweep area \( A \) can be expressed by the following equations [58–61]:

\[ P(v) = \frac{1}{2} \rho v^3 A \]  

(11)

Besides, calculation of wind power density based on the wind speed provided by field measurements can be developed by Weibull distribution analysis using the following equation [32]:

\[ P = \int_0^\infty \frac{1}{2} \rho v^2 f(v) dv = \frac{1}{2} \rho c^2 I \left( \frac{k+3}{k} \right) \]  

(12)

Where, \( \rho \) is the standard air density at sea level with mean temperature of 15 °C and 1 atmospheric pressure that is 1.225 kg/m³ which, depends on altitude, air pressure and temperature. It is also seen from the above equation that wind power density increases with the cube of the wind speed [62–64].

6.5. Wind energy density

By knowing the wind power density as shown in Equation (12), wind energy density can be estimated by the following equation for the desired time, \( T \) [32]:

\[ E = \frac{1}{2} \rho c^2 I \left( \frac{k+3}{k} \right) T \]  

(13)

Equation (13) can be used to calculate the available wind energy for any specific period when the wind speed frequency distributions are different.

7. Results and discussions

To understand the weather behavior well, an adequate source of measuring weather data is very much essential. The relationship between the climatic data and energy performance of wind machines rely heavily on both the quality and quantity of the meteorological observations. Though it is believed that wind data of shorter periods, less than 30 years, may inherit variations from the long term average but most of the developing countries do not possess accurate long term data. As a result, information of shorter recording periods has to be used suffice for resource assessment [40,65,66].

Fig. 1. Diurnal variation of wind speed at Kudat.

Fig. 2. Diurnal variation of wind speed at Labuan.

Fig. 3. Monthly mean wind speed at Kudat.

Fig. 4. Monthly mean wind speed at Labuan.
The determination of the wind potential of the selected sites was made by analyzing the wind characteristics in details, such as the mean wind speed, the prevailing direction, their duration and availability, as well as, the resulting power density. The 10 m height wind speed data has been converted to 100 m height wind speed data by using Equation (1) and then the converted data have been used in this study.

### 7.1. Diurnal wind speed variations

The explanation of electricity capacities in small isolated power systems requires not only the monthly or seasonal probability distribution of wind velocities but also needs to assess at least hourly probabilities of wind speeds. The diurnal wind speed variations are illustrated in Figs. 1 and 2 at Kudat and Labuan respectively for a period of 3 years and evaluated by Equation (4). The bell shaped wind speed variations are found at Kudat and Labuan. It is found that during the daytime, from 8 a.m. to 6 p.m., was windy for all the years round, while the night time was relatively calm. The hourly means wind speeds increased at around 7 a.m. and reached at the peak at around 3 p.m. then it was decreasing. The highest average wind speed was observed at 3 p.m. for the study period for both sites. Since load duration curves of electricity demand vary significantly throughout the day and normally the energy demand is higher in the daytime, so it is seen that the demand curve coincides with the wind characteristics of these stations.

### 7.2. Monthly wind speed variations

The monthly wind speed variation has been determined by the Equation (4) as shown in Figs. 3 and 4. The trends of the monthly mean wind speed for the different sites and years are quite similar. Most of the monthly mean wind speed values are between 2.5 m/s to 4 m/s, but some are over 4 m/s and few are under 2.5 m/s. While February 2006 at Kudat showed the highest mean wind speed value to 4 m/s, but some are over 4 m/s and few are under 2.5 m/s. While February 2006 at Kudat showed the highest mean wind speed value with 4.76 m/s, August 2008 at Labuan showed the minimum wind speed value with 1.93 m/s. According to the Pacific Northwest National Laboratory (PNNL) classification system, these stations fall outside of the category if based on the year round wind speed. This means that under the current wind turbine technology, this area may not be suitable for year round large-scale electricity generation due to the cost factor. However for small-scale applications, and in the long run with the development of wind turbine technology, the utilization of wind energy is still promising.

### 7.3. Variations of monthly standard deviation, shape parameter (k) and scale parameter (c)

Table 2 describes the variations of the standard deviation, shape parameter and scale parameter by using the Equations (5)–(8). The

### Table 2 Monthly standard deviation and Weibull parameters (k, c).

<table>
<thead>
<tr>
<th>Month</th>
<th>Parameters</th>
<th>Kudat</th>
<th>Labuan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>σ</td>
<td>2.02</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>k</td>
<td>1.87</td>
<td>1.76</td>
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<tr>
<td></td>
<td>c</td>
<td>4.06</td>
<td>3.97</td>
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<td>Feb</td>
<td>σ</td>
<td>2.08</td>
<td>1.86</td>
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<td>k</td>
<td>2.46</td>
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<td>5.37</td>
<td>4.84</td>
</tr>
<tr>
<td>Mar</td>
<td>σ</td>
<td>1.68</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>k</td>
<td>2.05</td>
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<td>σ</td>
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<td>May</td>
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### Table 3 Yearly mean wind speed, standard deviation and Weibull parameters (k, c), wind power density, wind energy density, most probable wind speed and wind speed carrying max energy.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Kudat</th>
<th>Labuan</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ</td>
<td>3.37</td>
<td>3.36</td>
</tr>
<tr>
<td>k</td>
<td>2.06</td>
<td>2.09</td>
</tr>
<tr>
<td>c</td>
<td>1.71</td>
<td>1.67</td>
</tr>
<tr>
<td>P/A</td>
<td>3.79</td>
<td>3.76</td>
</tr>
<tr>
<td>P/E/A</td>
<td>57.38</td>
<td>54.58</td>
</tr>
<tr>
<td>E/A</td>
<td>471.15</td>
<td>478.16</td>
</tr>
<tr>
<td>V_{mp}</td>
<td>2.27</td>
<td>2.18</td>
</tr>
<tr>
<td>V_{max,E}</td>
<td>5.96</td>
<td>6.02</td>
</tr>
</tbody>
</table>
monthly standard deviation values range from 1.42 to 2.60 m/s. The range of the variation of the shape parameters and scale parameters are 1.26–2.49 and 2.08–5.37 m/s respectively. The average values of the shape parameter and scale parameter are 1.77 and 3.54 m/s respectively.

7.4. Wind power and energy density

Table 3 illustrates the yearly mean wind speed, standard deviation, Weibull parameters, most probable wind speed, wind speed carrying maximum energy, power density and energy density. These are calculated by using the Equations (4)–(8), (10)–(13). It is observed that the highest value of wind power density was 67.40 W/m² in 2008 at Kudat and lowest value of wind power density was 34.66 W/m² in 2008 at Labuan. The range of the values of wind energy density is between 303.62 and 590.40 kWh/m²/year. The highest value of the most probable wind speed and wind speed carrying max energy were 2.44 m/s at Labuan in 2007 and 6.02 m/s at Kudat in 2007. Since it is quite impossible for any device to convert all the output power to usable form, Betz relation [67] assigns a power coefficient of 0.593 for the maximum extractable power from an optimum wind energy conversion system. Thus at Kudat in 2008, the maximum power extractable is found to be $0.593 \times 67.40$ W/m² A (Swept area of the wind turbine).

7.5. Weibull distribution and cumulative distribution

The yearly values of Weibull parameters, the scale parameter $c$ (m/s) and shape parameter $k$ (dimensionless), are shown in Table 3. The yearly values of $k$ range between 1.44 and 1.86 with an average value of 1.68. The lowest value of the scale parameter $c$ is 2.97 m/s and is found in 2008 at Labuan, while the highest value is 3.81 m/s, which occurred at Labuan in 2007. From the result, it is obvious that the shape parameter $k$ has a much smaller variation than the scale parameter $c$. The Equations (2) and (3) are used to evaluate the Weibull probability distribution function and Weibull cumulative distribution function respectively. Figs. 5 and 6 illustrate the annual variation of observed and Weibull wind speed frequencies for 2008 at Kudat and Labuan respectively. Maximum percentage error between Weibull wind speed frequencies and observed frequencies occurs at less than 2 m/s wind speed is 25% but more than 2 m/s wind speed, the maximum variation is about 5%. This is because Weibull distribution function is unable to represent the probabilities of observing zero or very low wind speed. It is observed that Weibull distribution fits the observed distribution reasonably well.
in the higher wind speed range. Previous studies have also concluded that the Weibull distribution fits the observed wind speed frequencies quite well [32,68]. Cumulative distributions are shown in Figs. 7 and 8 for Kudat and Labuan in 2008 respectively. It is observed that the Weibull cumulative frequency distributions are closer to the observed cumulative frequency distributions.

7.6. Polar diagrams

In order to use the wind energy properly, it is very important to determine the wind direction with other parameters. WRPLOT software is used to draw the polar diagram of wind speed to show the wind direction. The wind direction is illustrated in polar diagrams and is measured clockwise in degrees. The cycle (360°), which represents the cardinal points, is divided into 16 sectors and each of them covers an arc of 22.5°. Based on the observed wind speed data, the frequencies (%) are plotted in polar diagrams with respect to the cardinal point to show the wind direction. It is noticed that the direction of wind blow in the same area of different years is characterized by a significant stability which is shown by Figs. 9 and 10. The most probable wind directions (blowing from) for all the years were 190° and 269° at Kudat and Labuan respectively.

8. Conclusions

In this assessment three-year data of each site has been analyzed. The analysis has been done based on 2-parameter Weibull distribution function. The crucial outcomes of this study are summarized below:

- The highest average diurnal wind speeds are observed at 3 p.m. The diurnal maximum average wind speeds were found to be 5.55 m/s and 4.75 m/s at Kudat and Labuan respectively.
- Based on monthly mean wind speed, two types of wind speed were found. Wind speeds were higher in January, February and December than the rest of the months in a year. The monthly highest average wind speeds were 4.8 m/s and 4.3 m/s at Kudat and Labuan respectively.
- The yearly average wind speed at Kudat was 3.37, 3.36 and 3.00 m/s for the year 2006, 2007 and 2008 respectively. At Labuan the average wind speeds were 3.50, 3.81 and 2.67 m/s for the year 2006, 2007 and 2008 respectively.
- The yearly highest mean wind speed was found to be 3.81 m/s at Labuan in 2007. From the yearly mean wind speeds, it is found that the variation of mean wind speed was very small.
- The maximum wind power density for the two sites has been found 67.40 W/m² and 50.81 W/m² at Kudat and Labuan respectively.
- The maximum wind energy density has been found to be 590.40 kWh/m²/year and 445.12 kWh/m²/year at Kudat and Labuan respectively.
- The most probable wind speed and wind speed carrying maximum energy are 2.44 m/s at Labuan in 2007 and 6.02 m/s at Kudat in 2007.
- It has been found a 25% deviation between the observed frequency and Weibull frequency distribution. However, this is happened at the wind speed less than 2 m/s. At the large wind speed more than 2 m/s, the deviation is 5%.

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References

[9] Leo MA. Keynote address: Bakun Hydro electric project seminar, Kuala Lumpur, 1996.


