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Power Curve Evaluation of Micro-Scale Turbines for Harvesting Wind Energy in Malaysia

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Abstract: With wind energy gaining significant importance in recent years, many countries aspire to harvest this clean and cheap energy. In Malaysia, this goal is affected by slow wind speeds, which usually hinder the installation of wind turbines across the country. In this paper, we conduct a simulation study of the factors that affect wind power generation for several turbines. We use the power curves of five wind turbines (WTs) and compare their production with real wind speed data gathered from Sepang and Mersing regions of Malaysia as a case study. The data were recorded at a 15 m height from the ground level by the Malaysian Meteorological Department (MMD) throughout the year 2015. We fix the rated power of the turbines at 400 W, change the lengths of the turbine blades, and calculate the amount of energy produced in the two regions with reference to the turbines cut-in speeds of 4.0, 3.5, 3.0, 2.5, and 2.0 ms^{-1}, which correspond to turbine blade length (BL) of 0.62, 0.71, 0.82, 0.96, and 1.14 m, respectively. The results indicate that the amount of energy produced depends on the rated power, length of the turbine blade, rated and cut-in speeds of the turbine, and the characteristics of the wind speed in the area. We found that for one turbine, the highest annual energy rates that could be harvested were 357.5 and 373.15 kWh/year at a cut-in speed of 2 ms^{-1}, with total annual revenue generation (ARG) values of RM 201.0 and RM 193.50 during 6.95- and 7.25-year payback periods (PBP), respectively, in Mersing and Sepang. This study is the first of its kind to calculate the amount of energy produced using small-capacity wind turbines at different cut-in speeds and with different BLs. This study establishes the guidelines for a new era of small WTs in Malaysia and other countries with similar wind speeds.
Keywords: Cut-in speed; payback period; power curve; rated speed; small scale wind turbine.

1. Introduction

Over the past years, the production of electricity from renewable energy sources has gained considerable interest because these sources are abundant, inexhaustible, and non-polluting [1]. Wind energy is one of these sources that have been rising in importance in recent years [1]. Even though it is a non-depleting and clean source, the output power of a wind energy conversion system (WECS) depends strongly on the wind speed of the site under consideration [2 and 3]. In some regions such as Malaysia, where the wind speed is not strong enough to effectively turn the available large wind turbines, the possibility of generating power from wind sources is less realistic [4]. The WECSs produce power only when the available wind speeds are higher or equal to the cut-in speed of its turbine. However, most of the available large wind turbines have high cut-in wind speeds that are greater than most of the available wind speeds in low wind speed zones. In addition, the rated speeds of the available commercial wind turbines are far greater than the wind speeds of these zones. This means that such large turbines are unsuitable for these zones, and alternative methods to harness wind energy in these regions must be found. Smaller-scale wind turbines (30–300 kW) can harness power from low wind speed regimes. Thus, such WTs are a complementary option for power production in low wind speed zones [5].

Besides the wind speed, another important factor exists in the wind power equation, which can significantly affect the wind power generation. This factor is the wind turbine's BL. Increasing the BL and enhancing its aerodynamic design will improve its performance and can produce enough torque to drive small WT generators to reach their rated power in lower wind speed conditions. The upshifting of the power curve at lower wind speeds, which implies lowering the

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turbine's start-up speed, may possibly lower the cut-in speed, and hence increase the output power. [6-9]; this increases the possibility of generating power from low wind speed zones.

A turbine's power curve is a crucial element when assessing wind energy potential at a selected site. It enables predicting the turbine's output power and aids in the sizing and cost optimization of wind farms before and during the development stage [10 and 11]. In a graphical or tabular relationship, the power curve shows an electrical power output of the turbine's generator and the instantaneous wind speed. The curve is usually produced by the manufacturer to provide the wind farm developer with knowledge about the power quantity to generate based on the generator type and the site's wind speed [12]. As depicted in Fig.1, there are four operational regions in the WT output power curve. The first region occurs before the turbine reaches its cut-in wind speed. In this region, even if the turbine is rotating, it is not producing any power. The second region is between the cut-in and the rated speed, where the wind speed is enough to rotate the turbine such that usable power is extracted by the WT from the available wind. The third step is the optimal operating region, where the WT operates at its rated wind speed and generates the maximum power output it is designed for. The fourth region is the region beyond the cut-off speed, where the speed is excessively high and could damage the turbine. In the first and fourth operational regions, the turbine is shut down [11].

Thus, to harness efficient wind power from low wind speed zones, it is necessary to investigate the site's wind speed and the impacts of the WT's parameters on the turbine's output power.

The objectives of this study are: (i) Using the power curve of existing small-scale WT as a baseline, (ii) building a MATLAB base computer code to develop a new power curve by increasing the BL length and study the effect on the cut-in and rated speed, (iii) applying the developed power curve on the wind speed data of two sites in Malaysia to study the performance of the small scale WT by calculating its AEG, ARG, and PBP.

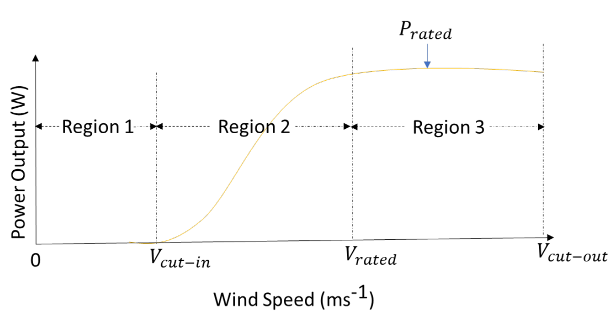


Fig 1. The power curve of a pitch-regulated wind turbine

Several attempts have been made to investigate the possibility of harnessing wind power from low wind speed areas in Malaysia. To study the feasibility of developing a wind farm in Kudat, [13] conducted an analysis to identify the best location to install a 22 kW rated power wind turbine that would generate efficient energy for the whole year. Their analysis leads to the discovery of a site with an annual wind power potential of 37.5–43.1 MWh/year. At the same site, [14] conducted another study to determine the optimal fit in tariff (FiT) that is best for wind power harvesting in Malaysia. At a 30 m hub height and based on 5 ms^{-1} wind speed, they have calculated the optimal FiT values of RM 0.74 and 0.91/kWh for utility-scale WT and RM 0.93–1.13/kWh for small-scale WT. Using different capacity WTs, [15] conducted an analysis of the capacity factor (CF) at Mersing and Chupping. Using 20 and 50 kW capacities WTs at the height of 36.6 m, a maximum CF of 4.39% was achieved at Mersing. Mersing also had the highest energy generation of 378 MWh/year and the lowest production costs, which ranged between 21 and 35 cents. An annual energy generation (AEG) of 254 MWh/year and the highest cost of production of 70 cents for 600 kW turbines was recorded at Chupping. Another assessment conducted by [16] in Kijal has found that an 850 kW WT was the most suitable, with a capacity factor of 26.8% and optimal FiT rates ranging between RM 0.81 and RM 1.38. It was noted that the FiT rate changes when the economic parameters change. However, when a large-scale WT with high rated power and speed designed for good wind speed areas is installed in areas with predominantly low wind speeds; low AEG, and C.F and high FiT are inevitable. Therefore, employing a small-scale WT at a similar rated speed as the wind speed of the area will improve the AEG, C.F, and FiT.

From the perspective of cost of energy (COE) of a renewable energy hybrid system, [17] assessed the performance of wind turbine, photovoltaic, and diesel generator (WT-PV- DG) hybrid system power in Johor Bahru. The hybrid system was tested with battery storage and then without the storage system. The values of COE were found to be between RM 1.365 and RM 1.638/kWh.On Pemanggil Island, [18] evaluated a hybrid WT-DG system and found it feasible for use with wind speeds greater than 3 ms^{-1}and with $1.02/liter or less for the cost of diesel. Similarly, a hybrid grid-WT-PV system was assessed by [19], who found grid-WT-PV configuration as the best with an optimal FiT rate of $0.5169/kWh. However, considering the monthly average wind speed, small-scale WT with a lower cut-in speed that will reach their rated power at lower wind speed will be the most suitable and will yield better COE for the considered sites.

In another study, considering the payback period, [20] installed 77 Leitwind wind turbines rated 1000 kW at Gebeng, Kota Belud, Kudat, Kerteh, and Langkawi. The lowest payback period of 4.25 years was achieved at Kota Belud due to it better wind profile. Similarly, a micro WT farm discharge strategy was proposed by [21]. The monthly mean wind data of 2009 for Mersing were used. A 20-year payback period was recorded with ten 300 W capacity WTs of 2.5 ms^{-1} cut-in speed. The long PBP recorded is attributed to the rated speed (12ms^{-1}) of the WTs used, which are much higher than the site's wind speeds. Also, [22] and [23] conducted feasibility studies for the wind energy potential of large-scale applications. Three 2.0 MW turbines, one 1.6 MW turbine, and one 1.5 MW turbine were deployed in locations in Sarawak and Terengganu. The results of their findings showed that large-scale turbines are not feasible for wind energy use in the selected areas.

Regarding the blade design, [24] chose to design a small WT blade for low wind speed regions as Malaysia. They employed lower Reynolds numbers (Re) of 0.2x10^6, 0.25 x10^6, 0.3 x10^6, and 0.35 x10^6, along with tip speed ratios (TSRs) of 5, 6, and 7. A WT blade with starting rotational speeds of 1.5 and 2.0 ms^{-1} and efficiency of about 49.31% was obtained. They generated turbine power curves with rated wind speeds of 6.5 and 7.0 ms^{-1} and applied these to the wind speed distributions in the Kuching, Miri, Kangar, Labuan, and Kudat areas. They found that the lower cut-in and rated speed turbines generated more power than the larger cut-in and rated wind speed turbines. Blade element momentum theory (BEM) was applied by [25] to study the performance of six constant speed horizontal axis wind turbines (CS-HAWTs). Airfoils, BW-3, NACA4412, S822, SG6040, SG6043, and FX63-137 models were considered for the design. Their low Reynolds number (Re) operation level, which was below 500,000, meant they were appropriate for small turbine applications in low wind speed regions. Re values of 250,000 and 300,000 were chosen, with TSR values of 5 and 6, respectively. Based on the annual energy generated (AEG), the blade designed with airfoil SG6043 outperformed all the others, with AEG values of 64 KWh/year and 66 KWh/year for TSR values of 5 and 6, respectively. Their results showed that aerodynamic performance of a WT blade can be improved by increasing the airfoil's Re, giving rise to a lower cut-in speed WT with a higher power coefficient. A TSR of 5 has a lower cut-in speed of 1.78 and a higher power coefficient of 5.2 as compared to a TSR of 6, which has a cut-in speed of 1.8 and a power coefficient of 0.51. Even though the WTs capacity are of a micro-scale with low cut-in and rated speed , however , the AEG is not encouraging for wind power harvesting. This low AEG is attributed to the small size of the WT blade length and the rated power. One study [6] showed the application of a small micro-scale wind turbine as an alternative means for rural electrification. The authors considered three micro-scale HAWTs with capacities of 0.5, 0.75, and 1 kW, and optimized the twist and chord distributions along the BLs. They pointed out that the delayed starting time was due to the resistive load on the generator site, and finally concluded that by increasing the size and number of the turbine's blade, the WT starting time and the power output can be improved.

In a similar study to the present one, [26] applied the power curves of 11 commercial WTs to a similar low wind speed distribution area in Korea's south-western coast to study the most suitable WT for harvesting wind power in the region. WT power curves for six different manufacturers with different rated powers, rated wind speeds, and rotor BLs were selected. The results of their AEG evaluation showed that WTs with lower-rated speeds and larger BLs generated more power than WTs with higher rated speeds.

A comprehensive review on wind energy research in Malaysia was performed by [27]. They reported a number of sites with good wind power potential and recommended the use of small-capacity WTs with longer blades and lower cut-in wind speeds for wind power harvesting.

In the above literature, a number of studies have been reported on wind energy harvesting using different capacities of WTs. However, there is no report on studying how the WT parameters affect its performance on harvesting wind energy under low wind speed conditions. In this work, using the power curve of small-scale WTs, we investigated the influence of increasing blade length and decreasing the cut-in and rated speed on the AEG, ARG, and PBP of two sites in Malaysia. Since the study is the first of its kind, calculating the amount of energy produced using small-capacity wind turbines at different cut-in speeds and with different BLs, it will serve as guidelines for small WTs as the solution for energy sustainability in Malaysia and other countries with similar wind speeds.

2. Site's Wind Data Evaluation

Resource assessment and evaluation of the site's wind power potential are crucial as they determine the selection and sizing of WT to be deployed. Different parameters are key indicators for assessing the wind power potential of a given site and its suitability for a wind power project [28]. The parameters include wind speed, air density, pressure, turbulence intensity, ambient temperature, as well as the topological nature of the candidate site.

2.1 Mean Wind Speed, Standard Deviation, and Turbulence Intensity

The most important parameter in the wind profile of a selected site is its mean or average wind speed; this is denoted by $\bar{v}$ and is calculated using Eq. (1):

$$\bar{v} = \frac{1}{N}\sum_{j}^{N} v_j, \quad (1)$$

where v_j is the site's wind speed observation at the jth time, and N is the number of wind speed data points.

The standard deviation of a given set of wind data is obtained using

$$\sigma = \left[\frac{1}{N-1}\sum_{j}^{N}(v_j - \bar{v})^2\right]^{\frac{1}{2}}. \quad (2)$$

Another key parameter that must be considered when conducting a site's wind resource assessment is the turbulence intensity. It is the fluctuation in the intensity of the wind velocity across a given site. High presence of turbulence intensity in wind farms will reduce the power output of the WTs and could stress their components [29].

The turbulent intensity I of wind power project sites is determined using Eq. (3):

$$I = \frac{\sigma}{\bar{v}}. \tag{3}$$

2.2 Air Density, Pressure, and Temperature

In addition to the other parameters mentioned above, the air density is another crucial factor to be considered when assessing the wind potential at a selected site. The available power from wind that will be captured by a WT is proportional to the air density. It is a function of the air temperature and atmospheric pressure of the site and varies with altitude. One of the established major factors that affects the operating condition of a WT at a wind site is the prevailing air temperature. For instance, if a substantial number of icebergs accumulate on the WT rotor blades, this will affect the airfoil design, which in turn will reduce the energy output of the wind energy conversion system (WECS). Depending on the number of icebergs accumulated on the rotor blade, this can cause the shutdown of the WT [29].

The air density of a wind power project site is calculated using Eq. (4):

$$\rho = \frac{P}{RT} e^{-\left(\frac{gh}{RT}\right)}, \tag{4}$$

where P is the air pressure, R is the molar gas constant, g is the acceleration due to gravity, h is the hub height, and T is the ambient temperature of the considered site.

2.3 The Power Law and Wind Shear

The power law given by Eq. (5) is used in wind speed extrapolation at different WT hub heights;

$$v = v_0 \left(\frac{z}{z_0}\right)^{\alpha}, \tag{5}$$

where v is the calculated wind speed at the new height, z, v_0 is the reference wind speed at the height z_0, and α is the shear exponent, which provides basic information on the site's topography and its exposure.

2.4. Weibull Distribution

This is one of the probability distribution functions that best describe a given area's wind speed distribution. It is widely applied for wind speed modeling of a location ahead of time [29]. Presented in Eq. (7), the Weibull distribution function is derived by differentiating Eq. (6), the Weibull cumulative distribution function, f(v), with respect to site's wind velocity, v.

$$\mathrm{f}(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right]. \tag{6}$$

$$\mathrm{f}(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right]. \tag{7}$$

The Weibull shape and scaling parameters, k and c, respectively, for the located site are obtained from Eq. (8) and (9) [30 and 31]:

$$k = \frac{\sigma}{\bar{\upsilon}}^{-1.089} \text{and} \tag{8}$$

$$c = \frac{\bar{\upsilon}}{\Gamma\left(1+\frac{1}{k}\right)}, \tag{9}$$

where Γ is the gamma function, which is defined as $\Gamma(k) = (k-1)!$

3. Materials and Simulation Procedure

3.1 Energy Conversion System

Wind energy conversion systems (WECSs) convert the kinetic energy of the wind into mechanical energy by the WT's blade and send it to an electrical generator, which converts it to electrical energy for the utility grid. It comprises of the wind turbine, electrical generator, control systems, and interconnection apparatus. The wind turbine is either connected directly or indirectly (by a gearbox setup) to the generator. Through its stator, the generator is connected either to standalone loads or to the utility grid by a suitable electronic power interface [32,33]. The block diagram of a WECS is shown in Fig.2.

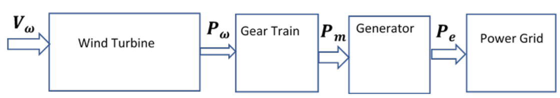


Fig. 2: Block diagram of a wind energy conversion system (WECS)

The power of the wind, as harnessed by the blades of the wind turbine, is given by Eq. (10) [34]:

$$P_{wind} = {}^{1}/_{2}\, \rho A V^3, \tag{10}$$

where ρ (kg/m3) is the air density, $A = \pi R^2$ is the WT's rotor-swept area, V is the speed of the wind, and R is the blade's length. The maximum extractable power by the WT from the wind is given by Eq. (11) [34]:

$$P_m = {}^{1}/_{2}\, \rho \pi R^2 C_p(\lambda, \beta) V^3, \tag{11}$$

where P_m is the extractable power (W) from the wind by the wind turbine, $C_p(\lambda, \beta)$ is the turbine's maximum efficiency, and V is the available wind speed (ms^{-1}) [7].

3.2 Wind Turbine Parameter Selection

3.2.1 Power Coefficient

A turbine's power coefficient describes the maximum mechanical power efficiency of a wind turbine. This is a non-linear function of the turbine's tip speed ratio , λ , and the blade pitch angle, β. It is denoted by $C_p(\lambda, \beta)$ and is given as in Eq.(12) [34 and 35]. The power coefficient has a maximum theoretical value of 0.593, as determined by Albert Betz:

$$C_p(\lambda, \beta) = k_1 \left(k_2 \frac{1}{\lambda_i} - k_{3\beta} - k_4 \beta^{k_5} - k_6 \right) Exp\left(-k_7 \frac{1}{\lambda_i}\right), \quad (12)$$

and $$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3}, \quad (13)$$

where the values for $k1 - k7$, λ, and β depend on the wind turbine.

The power coefficient is also determined numerically by equating the right-hand side of Eq. (11) with the value of the turbine's rated power and by substituting the values for air density and the turbine's BL with the rated speed, v_{rated}, then solving $C_p(\lambda, \beta)$ as follows:

$$P_{rated} = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v^3{}_{rated}, \quad (14)$$

hence,

$$C_p(\lambda, \beta) = \frac{2P_{rated}}{\rho \pi R^2 \, v^3{}_{rated}}. \quad (15)$$

For this research study, a 400 W rated horizontal power axis wind turbine (HAWT) was considered as the baseline. The BL was measured as 0.62 m, the values of its rated wind speed and cut-in speed were read from the turbine's specification manual as 12.0 ms^{-1} and 4.0 ms^{-1}. These values and the standard value of air density (1.225 kgm^{-3}) were entered into Equation (15), and the value for the turbine's power coefficient was determined as 0.313.

3.2.2 Blade Length, Rated Wind Speed and Cut-in Speed.

A simulation was performed using Eq. (11) by fixing the wind turbine's reference rated power at 400 W and increasing the BL from the initial 0.62 m; we then observed and recorded the new speed and the BL at which the WT attained the rated power. The value of the power output at the WT cut-in speed of 4.0 ms^{-1} was also determined. This power output was used as a reference power point to determine the new WT cut-in speed as the BL is increased. The simulation result is given in Table 1.

Table 1. New cut-in and rated speeds with increasing BL

BL *(m)*	Rated Speed (ms^{-1})	Cut-in speed *(*ms^{-1}*)*
0.62	12	4.0
0.71	11	3.5
0.82	10	3.0
0.96	9	2.5
1.14	8	2.0

We also observed that as the length of the blade increased, the WT produced more power at a lower wind speed. In addition, the WT reached the designed rated power at a lower-rated wind speed. This observation is in support of Eq.(16) and the simulation results obtained by [8 and 9], which shows that the increase in the BL increases the mechanical torque T_m of the turbine, meaning the turbine can be started at lower wind speeds and in turn increasing the output power, as described by Eq. (17):

$$T_m = {}^1\!/_2 \frac{\rho \pi C_p(\lambda, \beta) \omega^2}{\lambda^3} R^5. \quad (16)$$

$$P_e(v) = T.\omega, \quad (17)$$

where ω is the rotational speed of the WT.

3.3 Wind Turbine Power Curve Simulation

The power curve of a WT is generated as follows: Firstly, the generator's efficiency η is introduced into Eq. (11) to form Eq. (18):

$$P_e(v) = {}^1\!/_2 \, \rho \pi R^2 C_p(\lambda, \beta) \eta V^3 \quad (18)$$

such that

$$P_e(v) = \begin{cases} 0: & v_w < V_{in}, \; v_w > v_{out} \\ PC(v): & V_{in} \le v_w \le v_{out} \end{cases}, \quad (19)$$

where PC is the turbine's power curve, v_w is the available wind speed, and V_{in} and v_{out} are the turbine's cut-in and cut-out speeds, respectively [36 and 37].

Based on the results of Table 2, we then developed a MATLAB code using Eqs. (18) and (19) and generated five different turbine power curves at various cut-in speeds of 4.0, 3.5, 3.0, 2.5, and 2.0 ms^{-1}, respectively, with BLs of 0.62, 0.71, 0.82, 0.96, and 1.14 m.

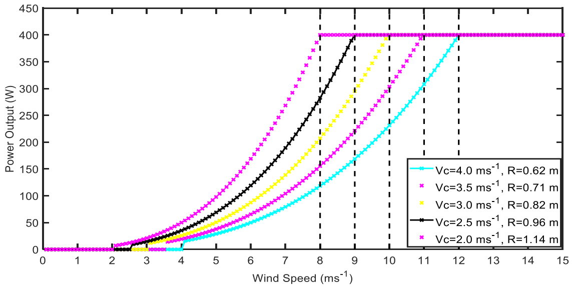


Fig. 3: Wind turbine power output (W) against wind speed (ms^{-1}) curve.

3.4 Annual Wind Energy Estimation

The power extracted by the wind turbine's rotor blades can be estimated using Eq. (11). The extracted mechanical power is further passed to the electrical generator through the drive train of the WT.

To estimate the site's wind power based on the WT's power curve, the site's measured wind speed is used as input to the WT's power curve equation, then electrical power output corresponding to the site's wind speed is evaluated.

By employing the turbine's power curve and the site's wind speed data, the electrical energy generated by the wind turbine for a period of time is estimated using Eq. (20) [29]:

$$E_T(v) = N_h \sum_{v_{in}}^{v_{out}} {}^1\!/_2\, \rho \pi R^2 C_p(\lambda, \beta) \eta V^3, \quad (20)$$

where v_{in} and v_{out} are the turbine's cut-in and cut-out wind speeds, respectively; N_h is the number of hours per day the wind speed occurs.

3.5 Annual Revenue Generation (ARG) and Payback Period (PBP)

The annual revenue generated (ARG) was obtained by multiplying the annual energy generated (AEG) by the turbine with sustainable energy development authority (SEDA) tariff rates (RM 0.54/kWh) of Malaysia as of January 2020 [38 and 39]

The payback period provides the wind farm developer with an idea of the economic value of the wind farm project. It is defined as the time required to recover the investment. The PBP is calculated using Eq. (21) as follows:

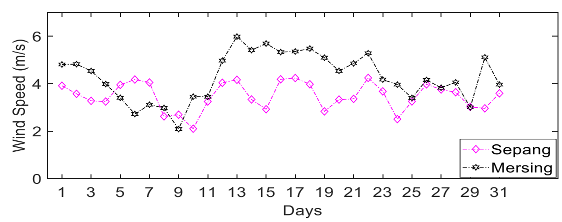
$$PBP = \frac{Total\ capital\ expenditure}{annual\ revenue\ generated}. \quad (21)$$

The total expenditure includes all expenditure related to the site's planning, the costs of the WTs and other connection materials, construction, transportation, maintenance, and installation costs. It is also assumed that the turbines are to be installed on top of buildings measuring 10 m in height. This will reduce the project costs related to the pole or mast height. These are estimated at RM 1400 per WT.

4. Results and Discussion

4.1 Daily Average Wind Speeds in Sepang and Mersing

As presented in Fig. 4, the daily average or mean wind speeds for each month during the whole year for the two locations were determined from the hourly data measured by the Malaysian Meteorological Department (MMD). The peak values of the maximum and minimum values of the daily mean wind speeds were extracted and plotted in Fig. 5. In Sepang, the maximum wind speed of 6.0 ms^{-1} was recorded in the month of July, while at Mersing, the maximum wind speed of 6.5 ms^{-1} was obtained in December. Both sites recorded a minimum daily mean wind speed of approximately 2.0 ms^{-1}. This minimum daily wind speed value shows that the proposed WT is suitable for wind energy generation at both sites since the minimum daily mean wind speed value is sufficient to effectively turn the WT to produce useful power. In addition, the prevailing wind speeds of the two sites are close to the 8.0 ms^{-1} rated speed of the proposed WT. This means an optimum operation of the wind turbine will occur throughout the day, and consequently, the energy that will be generated will be maximal. Moreover, the maximum value of the daily mean wind speed does not exceed the WT's cut-out speed (15 ms^{-1}), which will eliminate loss of power generation, as there will be no need to shut down the WT due to high wind speeds.



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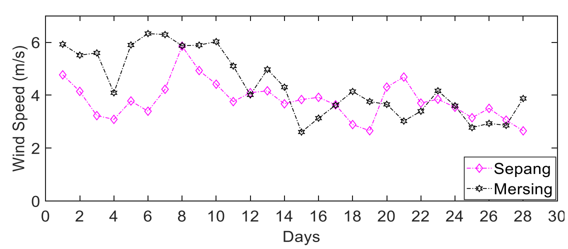

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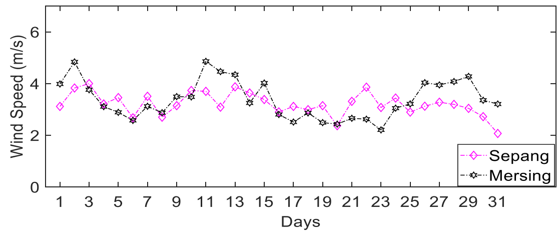

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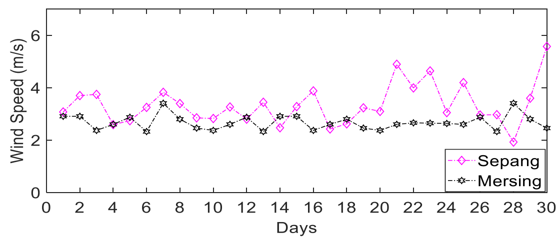

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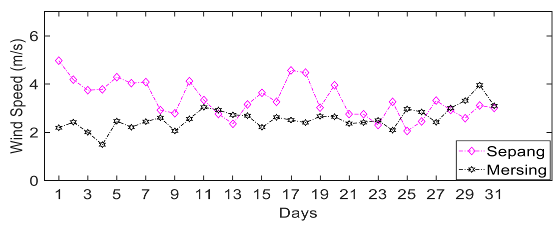

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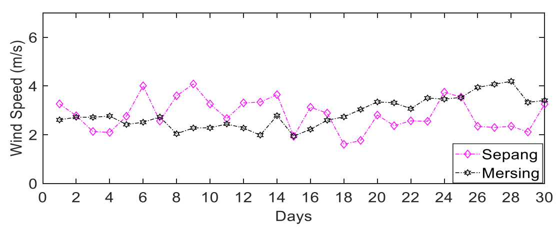

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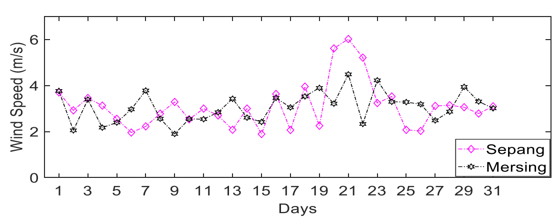

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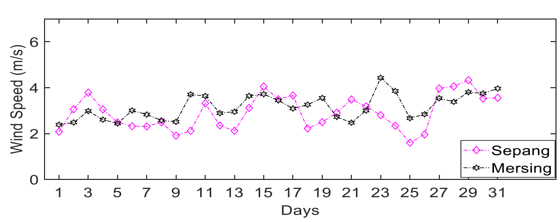

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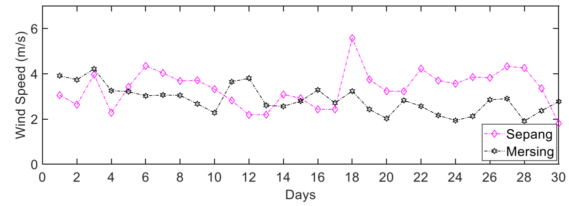

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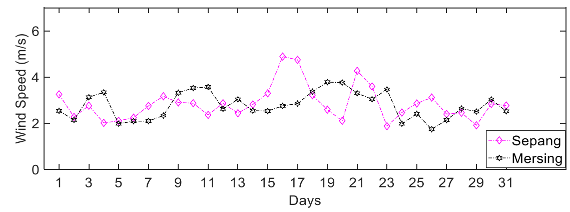

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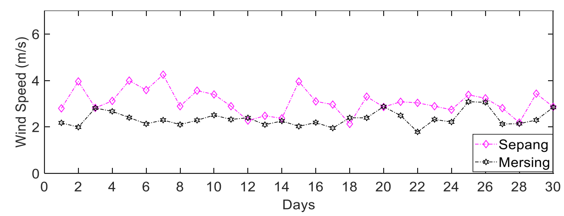

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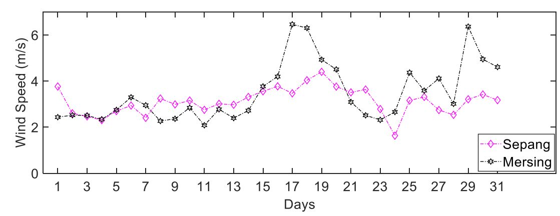
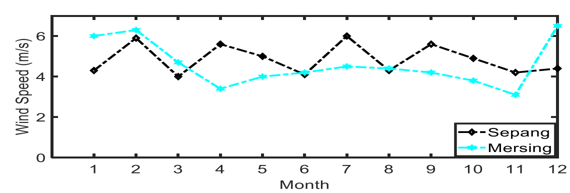
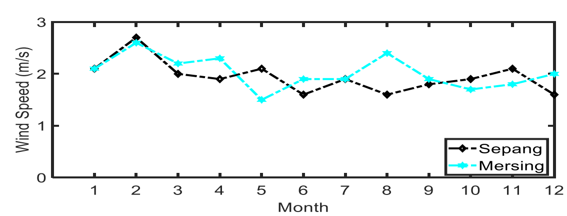


Dec

Fig. 4: The daily average wind speeds for each month for the two site locations



(a)



(b)

Fig. 5: (a) Maximum peak values and (b) minimum peak values of the average daily wind speeds

4.2. Monthly Average Wind Speeds, Standard Deviation, Turbulent Intensity and Weibull's Parameters for the Sepang and Mersing Sites

The average wind speed, the standard deviation, turbulent intensity, the Weibull distribution parameters, and the annual mean wind speed were computed and provided in Tables 2 and 3, respectively, for Sepang and Mersing.

We observed that the Weibull scaling parameters are close to the two sites' monthly average wind speeds. This was expected since the Weibull scaling parameter c provides information about the strengths of the wind speeds for the considered sites. The Weibull shape parameter k has a closed range, which means that the wind speed characteristics of the two sites have fewer fluctuations.

Table 2: Monthly average wind speeds, standard deviation, turbulence intensity, the Weibull parameters, and the annual mean wind speed at Sepang.

Month	**Parameter**				
	$\bar{v}$	σ	k	c	I
Jan	3.5	1.4	2.6	3.9	0.4
Feb	3.8	1.8	2.2	4.3	0.5
Mar	3.2	1.5	2.3	3.6	0.5
Apr	3.3	1.5	2.4	3.8	0.5
May	3.4	1.4	2.6	3.8	0.4
Jun	2.8	1.4	2.2	3.2	0.5
Jul	3.1	1.5	2.1	3.5	0.5
Aug	2.9	1.4	2.2	3.3	0.5
Sep	3.4	1.5	2.4	3.8	0.4
Oct	2.8	1.5	2.0	3.2	0.5
Nov	3.1	1.5	2.1	3.5	0.5
Dec	3.1	1.4	2.3	3.5	0.5
Mean	3.2	1.5	2.3	3.6	0.5

Table 3. Monthly average wind speeds, standard deviation, turbulent intensity, the Weibull parameters, and the annual mean wind speed at Mersing.

Month	Parameters				
	$\bar{v}$	σ	k	c	I
Jan	4.4	1.6	2.9	4.9	0.4
Feb	4.3	1.6	2.9	4.9	0.4
Mar	3.4	1.3	2.7	3.8	0.4
Apr	2.7	0.7	4.2	2.9	0.3
May	2.6	1.5	1.9	2.9	0.6
Jun	2.9	1.4	2.2	3.3	0.5
Jul	3.0	1.5	2.1	3.4	0.5
Aug	3.2	1.6	2.2	3.6	0.5
Sep	2.8	1.5	2.1	3.2	0.5
Oct	2.8	1.5	2	3.1	0.5
Nov	2.4	1.5	1.7	2.7	0.6
Dec	3.5	1.8	2.2	4	0.5
Mean	3.2	1.5	2.4	3.6	0.5

4.3 Monthly Energy and Annual Energy Generation Values from Sepang and Mersing

The developed power curve is employed with the hourly wind speed data for the two locations, then the monthly energy generated (MEG) and the AEG values for the two locations are estimated. The results presented in Figure 5 show the MEG values obtained by the WT with 2.0 ms^{-1} at different BL, while the AEG values obtained from all the WTs are provided in Tables 4 and 5 and are further depicted in Figs. 6 (a) and (b).

There was an observable increase in energy generation as the WT BL increased. In addition, we noted that the WT power production increased as the cut-in speed was lowered. This occurred due to the predominantly low wind speeds that are characteristic of the sites, meaning that the WTs with a lower cut-in wind speed can operate and generate usable power at almost all of the site's wind speeds, while the WTs with a higher cut-in wind speed can generate power only at the available higher wind speeds. The highest MEG and AEG values were obtained by the WT with the 2.0 ms^{-1} cut-in speed at the BL of 1.14m.

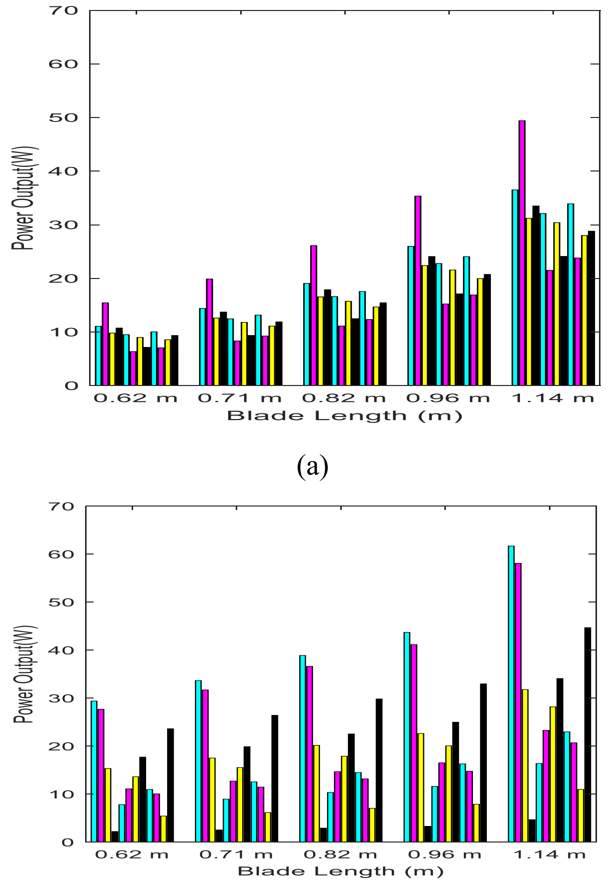


Fig. 6: The MEG values in Sepang and Mersing for the 2.0 ms^{-1} cut-in speed WT at increasing BL

Table 4: The AEG values at various WT BLs, rated speeds, and cut-in speeds in Sepang.

Blade length (m)	Rated speed (ms^{-1})	AEG (kWh/year) at different cut-in speeds				
		4.0 ms^{-1}	**3.5** ms^{-1}	**3.0** ms^{-1}	**2.5** ms^{-1}	**2.0** ms^{-1}
0.62	12	86.10	97.92	104.87	108.69	110.34
0.71	11	113.27	128.83	137.96	143.00	145.16
0.82	10	150.60	171.84	184.02	190.74	193.63
0.96	9	206.88	235.31	252.02	261.22	265.18
1.14	8	290.93	331.04	354.59	367.56	373.15

Table 5: The AEG values at various WT BLs, rated speeds, and cut-in speeds in Mersing

Blade length (m)	Rated speed (ms^{-1})	AEG (kWh/year) at different cut-in speeds				
		4.0 ms^{-1}	**3.5** ms^{-1}	**3.0** ms^{-1}	**2.5** ms^{-1}	**2.0** ms^{-1}
0.62	12	79.68	88.33	96.10	102.91	106.88
0.71	11	104.36	118.98	125.88	134.84	140.04
0.82	10	138.89	154.02	167.59	179.55	186.48
0.96	9	189.59	210.33	228.92	245.32	254.81
1.14	8	265.51	294.76	320.98	344.09	357.49

We also observed that the MEG and AEG values are highly proportionate to the daily average wind speed and moderately proportionate to the monthly average wind speed. The highest MEG values were obtained in the months of February and January, respectively, in Sepang and Mersing. The mean annual wind speeds (MAWS) had less effect on energy production since, despite the two sites exhibiting similar MAWS, the AEG values were not the same. The AEG value for Sepang was 373.15 kWh/year, while for Mersing the value was 357.49 kWh/year.

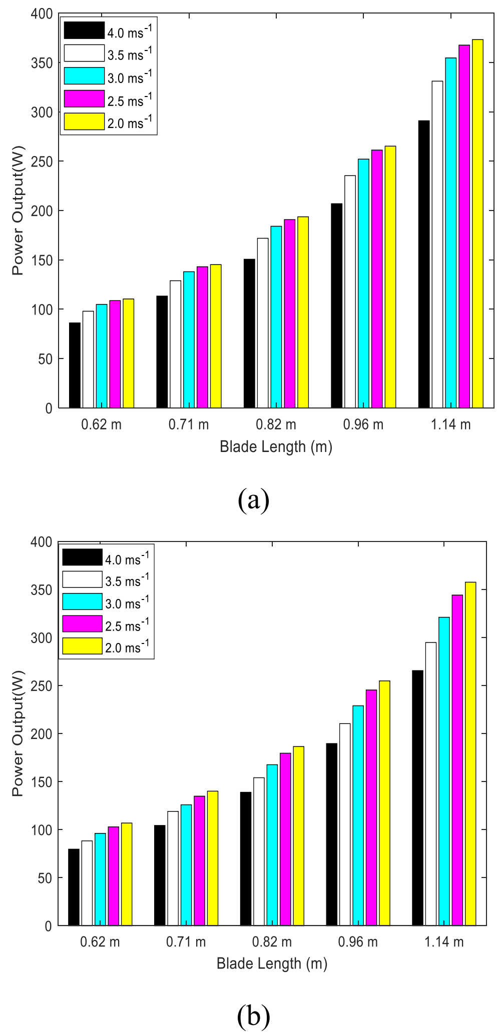


Fig. 7: The AEG values for the two locations with varying turbines cut-in speeds and BLs: (a) Sepang, (b) Mersing

4.4 The Annual Revenue Generation and The Payback Period Values In Sepang and Mersing

The annual energy generated (ARG) and the payback period (PBP) values at the two sites were estimated with WTS at various cut-in speed. The results for the ARG are provided in Tables 6 and 7, while the PBP results are given in Tables 8 and 9.

Based on the highest AEG value obtained, the WT with a cut-in speed of 2.0ms^{-1} and 1.14m BL generated the highest

ARG of RM 201.50 and the shortest PBP of 6.95 years at Sepang. Also, with the same WT, we estimated the ARG value of RM 193.0 at Mersing with a PBP of 7.25 years.

Table 6. Estimated ARG values with various WT BLs, rated speeds, and cut-in wind speeds in Sepang

Blade length (m)	Rated speed (ms^{-1})	ARG (RM) at different cut-in speeds				
		4.0 ms^{-1}	**3.5** ms^{-1}	**3.0** ms^{-1}	**2.5** ms^{-1}	**2.0** ms^{-1}
0.62	12	46.50	52.90	56.60	58.70	59.60
0.71	11	61.10	69.60	74.50	77.20	78.40
0.82	10	81.30	92.80	99.40	103.00	104.60
0.96	9	111.70	127.10	136.10	141.10	143.20
1.14	8	157.10	178.80	191.50	198.50	201.50

Table 7. Estimated ARG values with various WT BLs, rated speeds, and cut-in wind speeds in Mersing

Blade length (m)	Rated speed (ms^{-1})	ARG (RM) at different cut-in speeds				
		4.0 ms^{-1}	**3.5** ms^{-1}	**3.0** ms^{-1}	**2.5** ms^{-1}	**2.0** ms^{-1}
0.62	12	30.10	26.48	24.72	23.85	23.50
0.71	11	22.90	20.12	18.79	18.13	17.86
0.82	10	17.22	15.09	14.09	13.59	13.39
0.96	9	102.40	113.60	123.60	132.50	137.60
1.14	8	143.40	159.20	173.30	185.80	193.00

Table 8: Estimated PBP values with various WT BLs, rated speeds, and cut-in wind speeds in Sepang

Blade length (m)	Rated speed (ms^{-1})	PBP (year) at different cut-in speeds				
		4.0 ms^{-1}	**3.5** ms^{-1}	**3.0** ms^{-1}	**2.5** ms^{-1}	**2.0** ms^{-1}
0.62	12	30.10	26.48	24.72	23.85	23.50
0.71	11	22.90	20.12	18.79	18.13	17.86
0.82	10	17.22	15.09	14.09	13.59	13.39
0.96	9	12.53	11.02	10.29	9.92	9.78
1.14	8	8.91	7.83	7.31	7.05	6.95

Table 9: PBP values with various WT BLs (BL), rated speeds, and cut-in wind speeds in Mersing

Blade length (m)	Rated speed (ms^{-1})	PBP (year) at different cut-in speeds				
		4.0 ms^{-1}	**3.5** ms^{-1}	**3.0** ms^{-1}	**2.5** ms^{-1}	**2.0** ms^{-1}
0.62	12	32.54	29.35	26.98	25.19	24.26
0.71	11	24.84	21.79	20.60	19.23	18.51
0.82	10	18.67	16.83	15.47	14.44	13.90
0.96	9	13.67	12.33	11.33	10.57	10.17
1.14	8	9.76	8.80	8.08	7.53	7.25

We compared our findings with those of [1,21,40,41]. As for [1], they obtained the highest AEG value of 375,000 kWh/year at Kota Belud and the lowest PBP of 4.5 years, however, with a greater hub height and larger capacity WTs. Further, [21] obtained a PBP of 20 years at Mersing with a 300 W capacity WT. The high PBP is attributed to the smaller size (0.56 m) of the turbine blade length used in the study.

In [41], the authors obtained the highest AEG of 125 KWh/year at Kudat with a 50W wind turbine of 0.5m blade length, which operated at a cut-in speed of 2 ms^{-1} with a power coefficient of about 0.593.

5 Conclusions

In this research, five different WT power curves were developed through computer simulation with MATLAB program software. A 400 W rated power WT with a 12 ms^{-1} rated speed, and 0.62 m blade length was chosen, and its power coefficient was determined as 0.313. The power curve was developed at a cut-in wind speed of 4.0 ms^{-1} and was further applied to wind speed data from a height of 15 m from the ground at Sepang and Mersing for the year 2015, as measured by MMD. Additionally, power curve simulations were carried out with the same WT rated power but with increasing blade lengths. The observed effects showed a decrease in the WT's rated speed and an increase in capacity at lower wind speeds. We observed that WTs attained their rated power levels at 11, 10, 9, and 8 ms^{-1} when the blade lengths were 0.71, 0.82, 0.96, and 1.14 m, respectively. The developed power curves were again mapped with the wind speed data for the two locations, then the AEG, ARG, and the PBP values were estimated at decreasing cut-in wind speeds of 3.5, 3.0, 2.5, and 2.0 ms^{-1} for each WT blade length. The highest AEG value of 373.15 kWh/year and the lowest PBP of 6.95 years were estimated with the lowest cut-in speed of 2.0 ms^{-1} in Sepang. Additionally, an AEG of 357.49 kWh/ year and a PBP of 7.25 years were estimated at Mersing.

Based on the obtained results, the following conclusions can be drawn:

(i) Increasing the BL of a fixed rated power WT reduces the cut-in and rated speed and, in turn, improves its energy harvesting performance under low wind speed condition.

(ii) WTs with cut-in speeds below 2.0ms^{-1} and BL of 1.14m and above, which can attain rated power at a wind speed of 8.0ms^{-1} and below, is the complementary option for harvesting efficient wind energy from areas with low wind speeds like Malaysia.

(iii) We further concluded that the WT with the cut-in speed of 2.5 ms^{-1} and blade length of 0.96 m could be employed in wind power development for off-grid rural electrification.

(iv) Furthermore, Sepang and Mersing have shown good wind potential for power development. Their estimated 6–7-year period required to recover the project costs is appealing for investors.

(v) This study provides the guidelines for using small-scale wind turbines for harvesting efficient wind energy in Malaysia and other countries with similar wind speeds.

Since the present study was conducted by considering wind speed at 15m hup height, similar research should be performed with wind speeds measured at a height greater than 15 m to compare AEG values and how the increases in the project expenditure will affect the PBP. Additionally, further simulation studies with different rated power levels at different rated wind speeds should be carried out. Most of the published research works used MMD data. These data collection points are in airport areas with low wind speeds. Therefore, it is recommended that further wind speed measurements be carried out at different hub heights in locations far from airport areas with good wind profiles. Furthermore, aerodynamic studies aiming to select the best airfoils that produce high-efficiency turbine blades that will be suitable for operation in low wind speed areas should be conducted.

Acknowledgment

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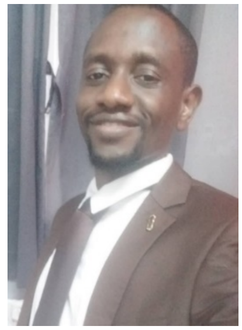

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