An Analysis of Wind Speed Distribution at Thasala, Nakhon Si Thammarat, Thailand

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Abstract: The main objective of this paper was to analyze the statistical wind data obtained from measurements for the 12 months period of January to December 2008 at Thasala district in Nakhon Si Thammarat province, southern Thailand. The wind speed at heights of 20 m, 30 m, and 40 m above ground level were measured using 3-cup anemometers attached to booms on a 45 m lattice met tower. The recording interval was 10 min. The statistical wind data set was analyzed using Weibull distributions in order to investigate the Weibull shape and scale parameters. The Weibull parameters obtained from WAsP 9.0 analysis as well as from the probability density function and cumulative distribution function of graphical methods were compared and the mean bias error between the methods was determined. Results showed that the monthly Weibull shape parameter was in the range of 1.1-2.8, while the monthly Weibull scale parameter was in the range of 2.27-5.94 m/s corresponding to monthly mean wind speeds in the range of 2.2-9.4 m/s. The mean wind speeds at 20 m, 30 m, and 40 m determined by WAsP 9.0 from the observational data were in the range of 2.4-7.8 m/s, 2.7-8.3 m/s, and 3.1-8.8 m/s respectively. The monthly power density was in the range of 5.8-480.3 W/m^2 corresponding to the wind power class ranging from class 1- to class 4+. Results showed that strong and sufficient winds for power generation occurred during the months of January to July and in the month of October.

Keywords: Weibull Distribution, Power Density, Wind Energy, Probability Density Function, Power Class.

1. Introduction

A proper analysis of statistical wind data is a very important step when performing a wind resource assessment campaign which supports a wind energy feasibility initiative. The performance of wind turbine generators (WTG) on a particularly site can be determined by the site's probability distribution of wind speeds and the corresponding WTG power curve. Consequently, since the WTG power curves are known, the probability distribution of wind speeds is the key information needed to estimate wind energy output at a given site for a particular WTG model. There are several works that deal with the use of probability density functions to describe wind speed frequency distribution [1]. In general, the Weibull probability density function can be used to estimate a site's probability distribution of wind speeds. The Weibull distribution technique is widely accepted and used in the wind energy industry as the preferred method for describing wind speed variations at a given site; some claim the Weibull distribution as the best fit for describing wind speed variations at a given site [2]. However, some researchers report that for sites having very low mean wind speeds, the Weibull distribution does not represent well the site's wind speed distribution [3]. Apart from the Weibull distribution, there are some distributions such as Gaussian distributions, exponential distributions, gamma distributions and logistics distributions that can be used to model a site's wind speed variation [4]. In previous studies, measured wind data in Thailand has been analyzed using the Weibull distribution technique [5-6].

The Weibull probability density function is given by Eq. 1.

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

where $f(v)$ is the probability of the measured wind speed, v, k is the Weibull shape parameter (dimensionless), and c is the Weibull scale parameter (m/s). The Weibull shape parameter, k, generally ranges from 1.5 to 3 for most wind conditions [7]. Wind speed distributions where the Weibull shape parameter is in the range of 1.5-3 are shown in Fig. 1.

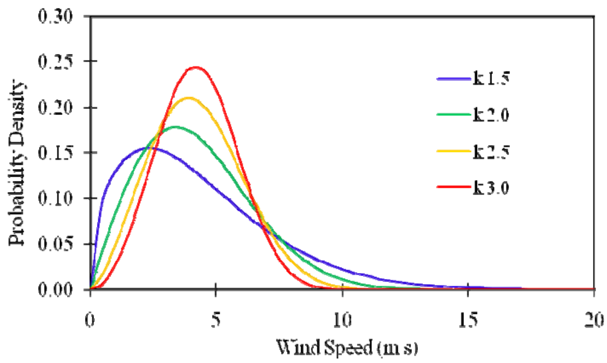

Figure 1. Weibull distribution of wind speeds where k = 1.5-3 and c = 4.8 m/s.

The cumulative frequency distribution is the integral of the Weibull probability density function, and is given by Eq. 2.

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

By transforming into logarithmic form, Eq. 2 could be then expressed by Eq. 3.

$$\ln[-\ln(1-F(v))]=k\ln v-k\ln c \tag{3}$$

In order to find the Weibull shape and scale parameters, a graphical method is introduced and used by plotting ln v against ln[-ln(1-$F(v)$)] in which a straight line will be obtained as shown in Fig. 2. The Weibull shape parameter, k, will be the slope of the line and the y-intercept will be the value of the term $-k$ ln c [8].

The aim of this paper is to analyze the measured wind data at Thasala, Nakhon Si Thammarat province in southern Thailand using the Weibull distribution technique. The analysis of Weibull shape and scale parameters based on the graphical method was compared to the WAsP 9.0 computer analysis [9] in order to investigate the percentage of absolute error between both methods.

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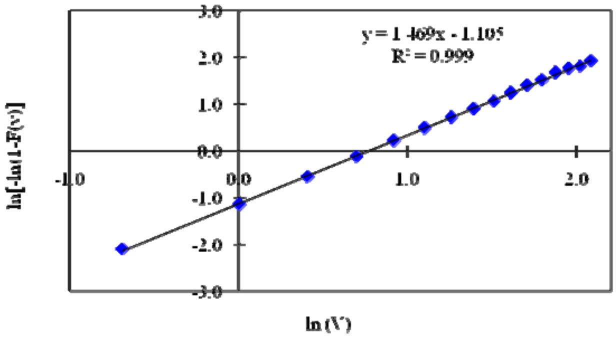

Figure 2. Example of graphical method used to obtain Weibull shape and scale parameters, *k* and *c*.

2. Experimental

2.1 Wind speed measurement and data acquisition system

A 45 m lattice met tower was installed near the coastline at Thasala district of Nakhon Si Thammarat province in southern Thailand. The site coordinates are: latitude 08°40'N and longitude 99°56'E. The elevation of the site is 9 m above mean sea level (AMSL). The met tower was equipped with wind speed and direction sensors, a data logger, an ambient air temperature sensor, and a lightening arrester for protecting the measuring equipment from a severe thunder storm. Wind speeds and directions at 20 m, 30 m, and 40 m as well as ambient temperature at 3 m above ground level (AGL) were measured between January to December 2008 with a 1 min sampling interval and a 10 min recording interval. Wind speeds were measured using 3-cup anemometers and wind directions were measured using standard wind vanes both of which were attached to the end of booms mounted on the met tower. The instruments were connected to a data logger which was powered by a PV-battery system. The resolution of wind speed measurements were 0.19 m/s and the resolution of wind direction measurements were 1.4°. Measurement accuracy as specified by the instrument manufacturer was ±3% for wind speeds of 17-30 m/s. Fig. 3 shows the lattice met tower along with data logger and several instruments. The measured wind speeds at 20 m, 30 m, and 40 m AGL were analyzed using the Weibull distribution technique. Weibull parameters were investigated based on the graphical method.

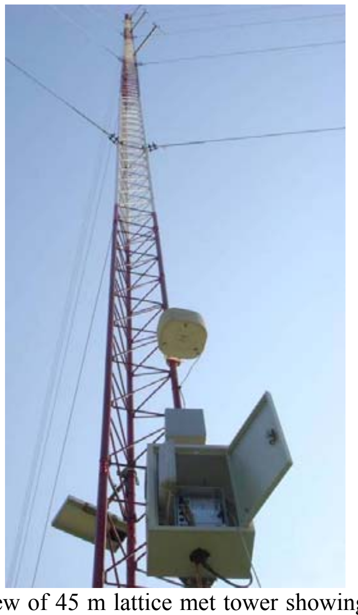

Figure 3. View of 45 m lattice met tower showing data logger and instruments.

2.2 Wind speed distribution analysis

The Weibull shape and scale parameters, *k* and *c*, corresponding to the wind speed distributions measured at 20 m, 30 m, and 40 m AGL and obtained from the graphical method were used in mean wind speed analysis by using the correlations expressed in Eq. 4

$$\bar{v} = c\Gamma\left(1+\frac{1}{k}\right) \tag{4}$$

where $\bar{v}$ is the mean wind speed and Γ is the Gamma function which is obtained from Eq. 5.

$$\Gamma(t) = \int_0^\infty e^{-x}x^{t-1}dx \tag{5}$$

Gamma function can be obtained using the Stirling approximation as is given by Eq. 6 [10].

$$\Gamma(x) = \sqrt{2\pi x}\,x^{x-1}e^{x}\left[1+\frac{1}{12x}+\frac{1}{288x^2}+...\right] \tag{6}$$

By using the Weibull shape and scale parameters, *k* and *c*, the standard deviation of the wind speed, *σ*, can be expressed by Eq. 7 [11].

$$\sigma = \bar{v}\frac{\sqrt{\Gamma\left(1+\frac{2}{k}\right)-\Gamma^2\left(1+\frac{1}{k}\right)}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{7}$$

Furthermore, the most frequent wind speed, v_{mp}, and the maximum energetic wind speed, $v_{max\ E}$, can be expressed in terms of the Weibull shape and scale parameters, *k* and *c*, as shown by Eq. 8 and Eq. 9 respectively [11].

$$v_{mp} = c\left(\frac{k-1}{k}\right)^{1/k} \tag{8}$$

$$v_{\max E} = c\left(\frac{k+2}{k}\right)^{1/k} \tag{9}$$

Finally, the wind power density, *E*, (W/m^2) can also be expressed in terms of the Weibull shape and scale parameters, *k* and *c*, using the correlation shown by Eq. 10

$$E = \frac{1}{2}\rho c^3\left(1+\frac{3}{k}\right) \tag{10}$$

where *ρ* is the air density (kg/m^3) which is correlated to the air temperature [12].

In this study, instead of using a mean air density over a measurement period, the 10 min air density values were used in the wind power density calculations since 10 min average data of air temperature was available. In order to classify the wind resource at the measurement site, wind power classification at 50 m above ground level is used as shown in Table 1.

Table 1. Wind power classification at 50 m [13].

Wind Power Class		Wind Power Density (W/m^2)	Mean Wind Speed (m/s)*	Resource Potential
1	1-	0-100	0-4.381	Very Poor
	1+	100-200	4.381-5.588	
2	2-	200-250	5.588-6.035	Poor
	2+	250-300	6.035-6.393	
3	3-	300-350	6.393-6.706	Marginal
	3+	350-400	6.706-7.018	
4	4-	400-450	7.018-7.287	Good
	4+	450-500	7.287-7.510	
5	5-	500-550	7.510-7.778	Very Good
	5+	550-600	7.778-8.002	
6	6-	600-700	8.002-8.404	Excellent
	6+	700-800	8.404-8.807	

*Mean wind speed is based on Weibull shape parameter value of 2.

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3. Results and Discussion

The monthly probability density functions and the monthly cumulative frequency functions calculated from the measured wind speeds at 20 m, 30 m, and 40 m AGL at Thasala district in Nakhon Si Thammarat are shown in Fig. 4 and Fig. 5, respectively. It was found that the monthly Weibull shape parameters, *k*, at 20-40 m AGL were in the range of 1.1-2.8. The monthly Weibull scale parameters, *c*, at 20 m AGL were in the range of 2.27-5.46 m/s, thus corresponding to monthly mean wind speeds in the range of 2.2-6.8 m/s. Moreover, the monthly Weibull scale parameters, *c*, at 30 m AGL were in the range of 2.24-4.52 m/s, thus corresponding to monthly mean wind speeds in the range of 3.0-8.1 m/s. Nonetheless, the monthly Weibull scale parameters, *c*, at 40 m AGL were in the range of 3.26-5.94 m/s, thus corresponding to monthly mean wind speeds in the range of 3.0-9.4 m/s. A summary of monthly Weibull shape and scale parameters are given in Table 2.

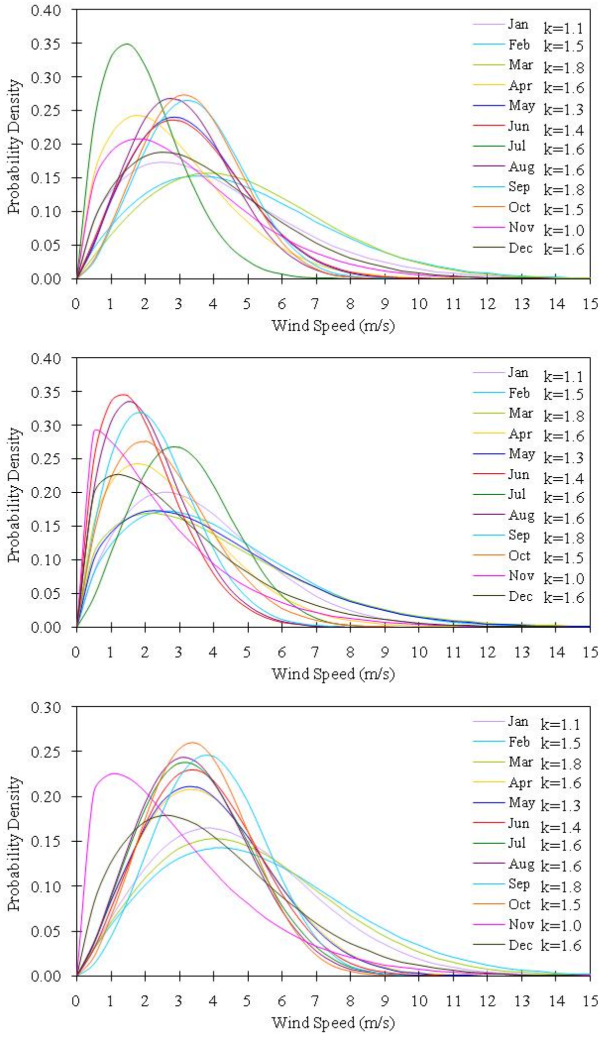

Figure 4. Monthly Weibull distributions at 20 m (top), 30 m (middle), and 40 m (bottom) AGL at Thasala district, Nakhon Si Thammarat province.

The monthly mean wind speeds at 20 m, 30 m, and 40 m AGL, obtained by both methods, the Weibull distribution analysis based on the graphical method and the computer software analysis, namely, WAsP 9.0, were compared and the results are shown in Fig. 6 - Fig. 8. The monthly mean wind speeds at 20 m, 30 m, and 40 m AGL obtained by the WAsP 9.0 analysis were in the range of 2.4-7.8 m/s, 2.7-8.3 m/s and 3.1-8.8 m/s, respectively. The mean absolute error of mean speed between the graphical method and the WAsP 9.0 analysis is shown in Fig. 9, where it can be seen that the average absolute error was 10%. The mean absolute errors of the Weibull shape and scale parameters, analyzed by difference techniques mentioned above, are shown in Fig. 10 and Fig. 11 respectively, where it can be seen that the mean absolute error of Weibull shape parameter was 20% in average. Although the mean absolute error of Weibull scale parameter was 30% in average, the mean absolute error of mean speed remained approximately 10%.

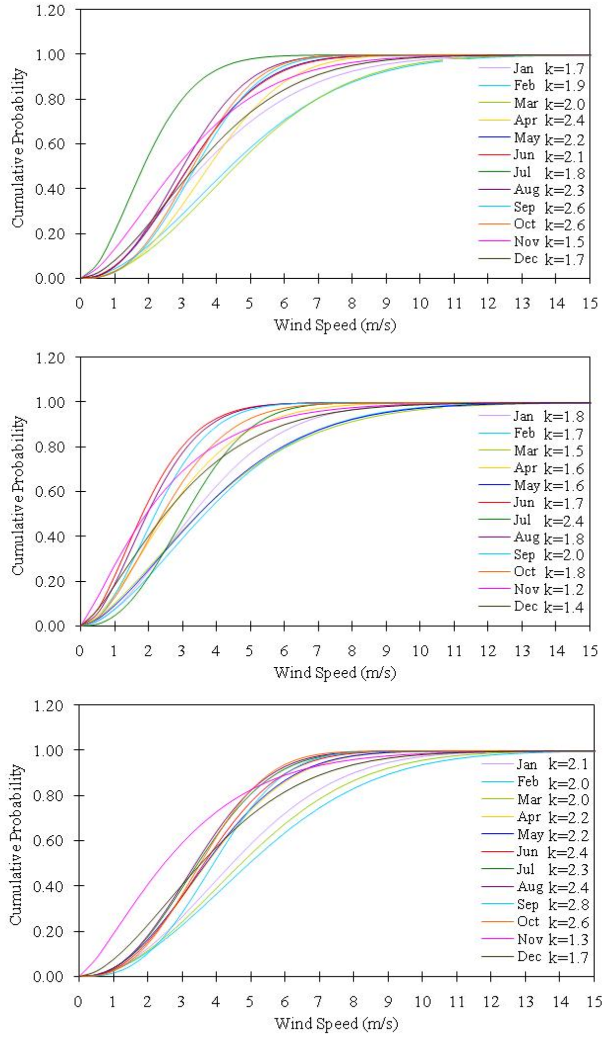

Figure 5. Cumulative probability functions at 20 m (top), 30 m (middle), and 40 m (bottom) AGL at Thasala district, Nakhon Si Thammarat province.

Table 2. Monthly Weibull shape and scale parameters and mean speed obtained from graphical method.

Month	*c*			*k*			Mean Speed		
	20	30	40	20	30	40	20	30	40
Jan	4.45	4.02	5.30	1.65	1.82	2.06	5.03	6.45	9.12
Feb	5.35	4.52	5.95	1.86	1.69	1.98	6.72	7.80	9.36
Mar	5.46	4.40	5.64	2.00	1.51	2.03	6.85	8.12	9.23
Apr	4.39	3.16	4.39	2.40	1.63	2.20	5.05	7.04	8.19
May	3.78	4.37	4.35	2.17	1.58	2.21	4.35	6.70	8.02
Jun	3.78	2.24	4.23	2.13	1.69	2.38	4.33	6.59	6.84
Jul	2.27	3.60	4.03	1.76	2.37	2.34	4.51	6.40	4.82
Aug	3.53	2.40	3.95	2.31	1.80	2.36	2.16	3.03	2.96
Sep	3.91	2.64	4.46	2.58	1.95	2.77	2.38	3.29	3.37
Oct	3.80	2.94	4.05	2.59	1.84	2.63	4.27	5.91	6.08
Nov	3.59	2.61	3.26	1.53	1.19	1.32	2.55	4.06	4.10
Dec	4.18	3.24	4.38	1.73	1.36	1.71	3.18	4.02	4.27

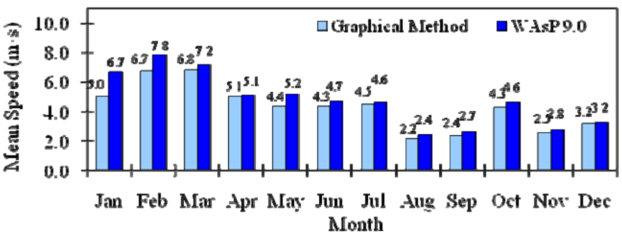

Figure 6. The comparison of mean speed at 20 m AGL between the graphical method and WAsP 9.0 analysis.

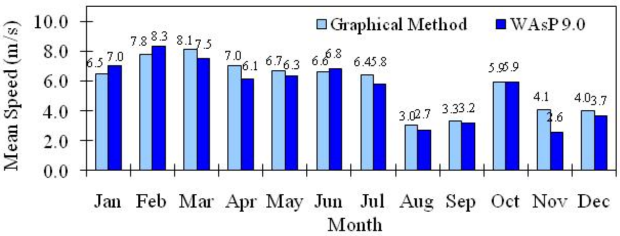

Figure 7. The comparison of mean speed at 30 m AGL between the graphical method and WAsP 9.0 analysis.

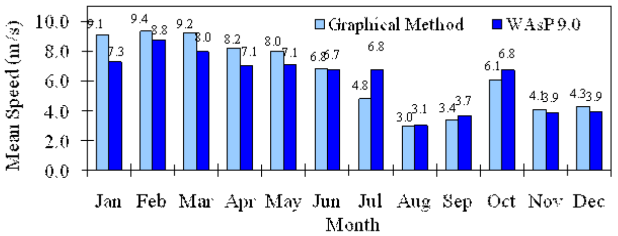

Figure 8. The comparison of mean speed at 40 m AGL between the graphical method and WAsP 9.0 analysis.

The monthly and annual mean observed air temperature is shown in Fig. 12. For the 12 months measurement period, the annual mean air temperature was 27°C. From Fig. 12, it can be seen that the air temperature at Thasala district in Nakhon Si Thammarat decreases during the rainfall season which is affected by North-East Monsoon during the months of October to February. Monthly mean wind power densities at 20 m at Thasala district in Nakhon Si Thammarat province calculated based on the varied air density were in the range of 5.8-187 W/m^2 as shown in Fig. 13. Furthermore, the monthly mean wind power densities at 30 m and 40 m were in the range of 16.2-311.6 W/m^2 and 15.1-480.3 W/m^2 as is shown in Fig. 14 and Fig. 15, respectively. Comparisons of monthly mean wind power densities were made between the constant air density method at 1.225 kg/m^3 and the variable air density method according to the measured air temperature. Results showed that the constant air density method overestimated the monthly mean wind power densities by up to 5.5% as is shown in Fig 16. This may lead to the overestimation of wind power from resource assessment unless the variable air density method is used in such analysis. Table 3 shows the monthly wind power classes at 20 m, 30 m and 40 m AGL at Thasala district in Nakhon Si Thammarat province. The monthly wind power class at 20 m AGL ranged from class 1- to class 1+; the monthly wind power class at 30 m ranged from class 1- to 3-; and the monthly wind power class at 40 m ranged from class 1- to 4+. From the observational data, it can be seen that strong and sufficient winds for wind power production at Thasala occurred during the period of January to June 2008.

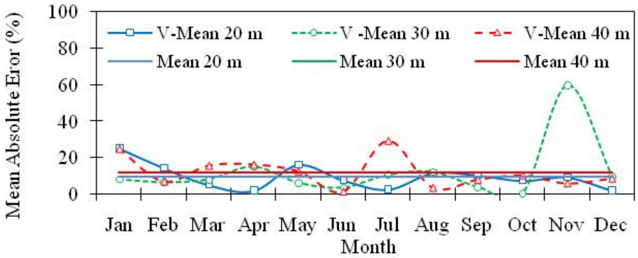

Figure 9. Mean absolute error of mean speed at 20 m, 30 m, and 40 m AGL.

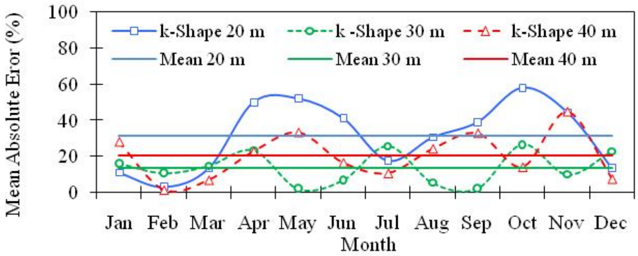

Figure 10. Mean absolute error of Weibull shape parameter at 20 m, 30 m, and 40 m AGL.

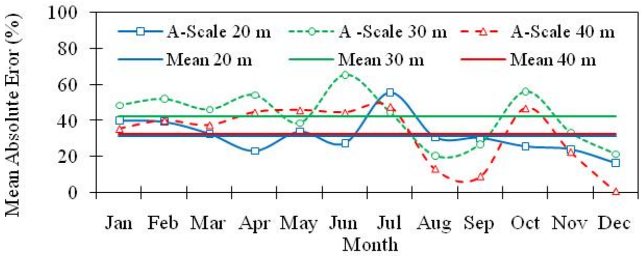

Figure 11. Mean absolute error of Weibull scale parameter at 20 m, 30 m, and 40 m AGL.

Table 3. Monthly wind power class at 20 m, 30 m, and 40 m AGL in Nakhon Si Thammarat.

Month	Power Density (W/m^2)		
	20 m	30 m	40 m
January	1-	1+	4+
February	1+	2+	4+
March	1+	3-	4+
April	1-	2-	3-
May	1-	1+	2+
June	1-	1+	1+
July	1-	1+	1-
August	1-	1-	1-
September	1-	1-	1-
October	1+	1+	1+
November	1-	1-	1-
December	1-	1-	1-

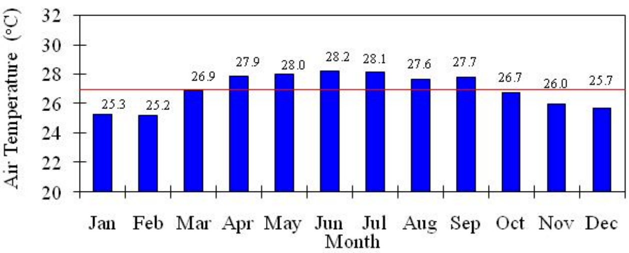

Figure 12. Monthly variation and annual mean air temperature at Thasala district, Nakhon Si Thammarat province.

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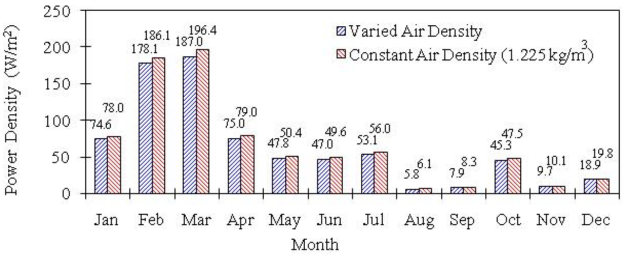

Figure 13. The comparison of monthly wind power density at 20 m height AGL obtained by the varied air density and constant air density at 1.225 kg/m^3.

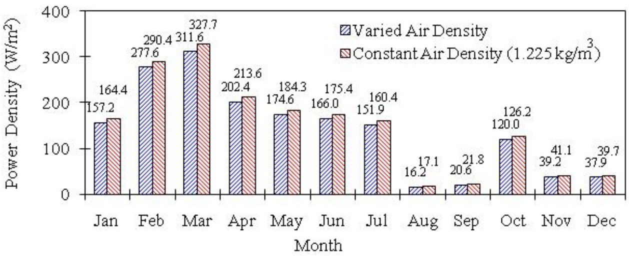

Figure 14. The comparison of monthly wind power density at 30 m height AGL obtained by the varied air density and constant air density at 1.225 kg/m^3.

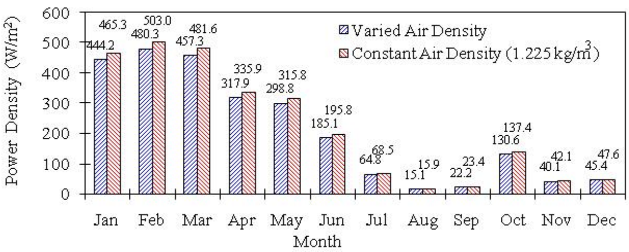

Figure 15. The comparison of monthly wind power density at 40 m height AGL obtained by the varied air density and constant air density at 1.225 kg/m^3.

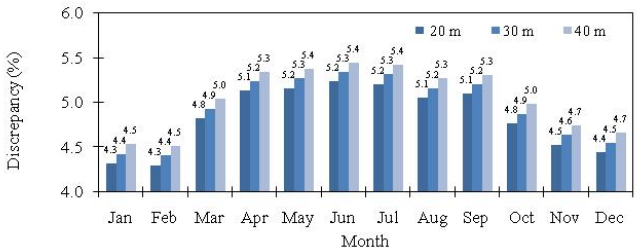

Figure 16. Percentage of discrepancy of wind power density at different heights obtained by the varied air density and constant air density at 1.225 kg/m^3.

4. Conclusions

It is concluded that the Weibull distribution using the graphical method is a useful technique to conduct wind speed analysis from observed wind speed data at Thasala district in southern Thailand. From the observed wind speed data during January to December 2008, the monthly Weibull shape parameters were in the range of 1.1-1.8 and the monthly Weibull scale parameters were in the range of 2.27-5.94 m/s corresponding to the monthly mean wind speeds in the range of 2.2-9.4 m/s. The mean wind speeds obtained by WAsP 9.0 analysis at 20 m, 30 m, and 40 m AGL were in the range of 2.4-7.8 m/s, 2.7-8.3 m/s, and 3.1-8.8 m/s respectively. The effect of air density on wind power density is less than 5.5% of discrepancy. The monthly mean wind power densities were in range of 5.8-503 W/m^2 corresponding to the wind power classes ranging between class 1- to class 4+. Finally, analysis showed that strong and sufficient wind for power generation occurred during the months of January to July and in the month of October 2008.

Acknowledgments

The authors gratefully acknowledge the National Research Council of Thailand (NRCT) for providing the research fund in wind resource assessment. The authors also acknowledge Thaksin University and University of Moncton for supporting the research grant under the framework of an international collaborative research project.

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