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Evaluation and Analysis of Wind Speed with the Weibull and Rayleigh Distribution Models for Energy Potential Using Three Models

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ABSTRACT

Medan has a tropical climate and has the potential to support additional renewable energy, one of which is wind energy. Analysis of wind speed in Medan in particular has not been conducted to determine the potential for renewable energy. Research on wind speed in Medan, which ranges from 3.5 m/s to 7.5 m/s, has been carried out, but its potential has not been analyzed and evaluated. This study was conducted to analyze the shape factor and scale for wind speed using the Weibull and Rayleigh distribution, and three evaluation models were proposed, namely the correlation coefficient (R^2), Chi-square ($\square^2$), and Root mean square error (RMSE). Wind speed data that is used to analyze and evaluate obtained from the Meteorology, Climatology, and Geophysics Agency for a period of 3 years, 2017-2019 in Medan. The probability density distribution function (Pdf) is described based on the shape (k) and scale (c) parameters obtained from the above data analysis. These two parameters are very important to be observed related to the potential of electrical energy produced in a place or area. The analysis result shows that Weibull is better than Rayleigh distribution based on Pdf. Meanwhile statistical analysis, Weibull distribution is better than Rayleigh distribution based on R^2. But on the other hand, the Rayleigh distribution is better than the Weibull distribution based on Chi-square and RMSE. In addition to the analysis and evaluation, the potential for wind energy to be obtained is around 79.5 Watt/m^2.

Keywords: Wind Speed, Pdf, Weibull and Rayleigh Distribution, Wind Energy Potential, R^2, $\square^2$, RMSE
JEL Classifications: C25, C36, C44, C93, L94, Q42

1. INTRODUCTION

The wind is a renewable energy source that can be used as an alternative energy source. Energy supply-demand is increasing throughout the world resulting in the depletion of the global energy supply, so it is necessary to find alternative energy as a source of energy reserves. This energy limitation has the potential to produce energy that is not used and is clean from air pollution and does not pollute the environment.

Public awareness of environmental problems is increasing due to the energy crisis, climate change, environmental problems (Skogen et al., 2018). These last few years, the company has been considering the condition of the environment to use energy consumption ecological clean and does not pollute the surrounding environment (Goncalves et al., 2016), (Jan Urban, Štěpán Bahník, 2019). Environmental problems can be overcome effectively by buying environmentally friendly products in daily consumption (Ramayah et al., 2010), (Nguyen et al, 2019), (Sheng et al., 2019). Wind speed probability distribution has been widely used for offshore wind farm planning and is used to estimate various amounts of power output and load (Morgan et al., 2011), (Mohammadi and Mostafaeipour, 2013).

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Wind speed information be useful to researchers involved in the study of renewable energy and wind energy use can reduce the things that are caused by fossil fuels and carbon dioxide emissions. Statistical analysis can help to predict the renewable energy conversion from wind energy and several attempts to model it, to obtain energy estimates by the facts on the ground (Weisser, 2003), (Bivona et al., 2003). In its application, the wind speed distribution is used to represent the distribution function (Van der Auwera et al., 1980), (Ashkar and Ouarda, 1996).

The statisticians are interested in using Weibull models in modeling and analysis of wind energy, as it can be approached by the measurement data (Ayodele et al., 2012). Mathematically, the two-parameter Weibull distribution function has been widely used compared to the three parameters (Bobee, 1975).

Characteristics of wind are one of the most important parameters in the design and performance analysis system to determine the potential energy conversion. Many researchers have developed statistical models to model the frequency distribution of wind speed. To determine the probability density function of wind speed using the Rayleigh and Weibull Model (Li and Li, 2005).

Geographically, Medan has daily and monthly wind speeds with varying duration and speed. Availability of wind speed data can help to analyze more accurately the distribution also can help in constructing wind power sources (Daut et al., 2011), (Suwarno et al., 2017). Wind speed characteristics in Medan are assessed from the amount of potential wind energy generally, these characteristics use Pdf and other functions. Pdf has been studied and applied in all regions of the world, but selecting Pdf is very important in analyzing wind energy because wind energy is formulated as an explicit function of several parameters of wind speed distribution (Suwarno and Rohana, 2021).

Pdf is suitable for evaluating the wind speed that will be used to estimate the power output. Rayleigh and Weibull distribution most used in the analysis of wind speeds, and the most common way to study wind energy estimation (Ahmed Shata and Hanitsch, 2006), (Akpinar and Akpinar, 2005), (Mirhosseini et al., 2011), (Petković et al., 2014), (Suwarno and M Fitra Zambak, 2021). So far, the Weibull distribution is most widely used to analyze the characterization of the wind speed and the most common among models (Celik, 2003).

In previous research, the analysis of the characteristics of wind speed using Weibull and Rayleigh distribution, but not many studies that relate to the evaluation of the feasibility of using the model data used correlation coefficient, Chi-square, and RMSE. Therefore, this study proposes Pdf analysis with the Weibull and Rayleigh distribution and evaluates it with statistical analysis models, namely R^2, $\square^2$, and RMSE

2. RESEARCH METHODS

This research, analyzes using two models of Weibull and Rayleigh. Then analyzed using a statistical probability density function (Pdf), then the results were compared to two models to find the most appropriate model to use in analyzing the characteristics of wind speed and potential electrical energy. The research step is to analyze the wind speed with Pdf using the Weibull and Rayleigh distribution, and then evaluate it with three models (R^2, $\square^2$, and RMSE) to see the suitability of the data studied and the results compared to select the best model proposed and to be applied, then calculate the energy potential electricity generated from the conditions of wind speed is being investigated.

This research was carried out according to the proposal using two models, namely the Weibull and Rayleigh distribution models. The analysis is performed using probability density function statistics, then the results of the two models are compared to find the most suitable model to be used to analyze wind speed and energy potential.

2.1. Wind Speed Distribution

Pdf function and other functions form an important aspect to analyze wind speed. The use of a probability density function for a variety of applications, including identification and analysis of the parameters of the distribution function of wind speed data (Bivona et al., 2003), (Akpinar and Akpinar, 2005). The Rayleigh and Weibull distributions are used to adjust the Pdf of the measured wind speed at the site over a specified period and the Weibull Pdf distribution is expressed as (Akpinar and Akpinar, 2005), (Ramrez and Carta, 2005), (Egbert Boeker, 1999):

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

here, $f(v)$ is the incremental probability, c and k represent scale and shape parameters, respectively.

The following equation to estimate the shape (k) and the scale (c) factor is expressed by (Carta and Ramirez, 2007), (Carta et al., 2009).

$$k = \left(\frac{\sigma}{v}\right)^{-1.086} \text{ and } c = \left(\frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)}\right) \tag{2}$$

The distribution for the Cdf is given by (Ramrez and Carta, 2005), (Akpinar and Akpinar, 2005), (Egbert Boeker, 1999), (Carta and Ramirez, 2007), (Celik, 2003).

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

The shape factor equal to 2, substituted for equation (1), will give the Pdf of the Rayleigh and is represented by (Akpinar and Akpinar, 2005), (Egbert Boeker, 1999), (Carta and Ramirez, 2007), (Algifri AH, 1998).

$$f(v) = \left(\frac{2v}{c^2}\right) exp\left[\left(-\frac{v}{c}\right)^{k}\right] \tag{4}$$

The average value (v_m) and standard deviation (σ) can be calculated, respectively (Celik, 2003), (Algifri, 1998).

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \tag{5}$$

$$\sigma = c\left[\Gamma\left(1+\frac{2}{k}\right)-\Gamma^2\left(1+\frac{1}{k}\right)\right]^{1/2} \tag{6}$$

here, Γ is the gamma function.

The Rayleigh scale (Cr) parameter is obtained from the equation (7) which is represented by

$$C_r = \sqrt{\frac{1}{2N}\sum_{i=1}^{N} v_i^2} \tag{7}$$

here, v_i is the i^{th} wind speed, the average Rayleigh value is determined by the equation (8), given by;

$$\bar{v}_r = C_r\sqrt{\frac{\pi}{2}} \tag{8}$$

2.2. Wind Power Density Function

The magnitude of the wind speed directly proportional to 3 times the wind speed (v) through a blade sweep area *(A)* so that its magnitude is as follows; (Akpinar and Akpinar, 2005), (Algifri, 1998), (Jaramillo and Borja, 2004).

$$P(v) = \frac{1}{2}\rho A v^3 \tag{9}$$

here, ρ is the average air density.

The power for the monthly or annual wind speed per unit area at a location can be expressed as:

$$P_w = \frac{1}{2}\rho v^3 \Gamma\left(1+\frac{1}{k}\right) \tag{10}$$

here, c is expressed as follows;

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \tag{11}$$

The parameters will affect the shape and scale of the average wind speed m_v (Algifri AH, 1998), (Jaramillo OA, 2004), (Ali Naci Celik, 2004). Model Rayleigh obtained by adjusting the shape parameter (k) is equal to 2 in the equation (8), then the parameters Rayleigh scale model can be expressed by (Celik, 2003), (Al-Mohamad and Karmeh, 2003).

$$P_R = \frac{3}{\pi}\rho v_m^3 \tag{12}$$

2.3. Modeling of Wind Data

The wind speed modeling will depend on the height of the installed instruments. Based on empirical, the wind speed model can be approached empirically in the following equation (13);

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{13}$$

here, $\bar{v}$ is the wind speed average;
V_i is the measured wind speed;
n is the number of measurement data.

2.4. Analysis of the Distribution Function

The analysis model uses Weibull and Rayleigh and is evaluated using the correlation coefficient (R^2), Chi-square and root mean square error (RMSE) which is stated by the following equation;

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - z_i)^2 - \sum_{i=1}^{N}(x_i - y_i)^2}{\sum_{i=1}^{N}(y_i - z_i)^2} \tag{14}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{N-n} \tag{15}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{1/2} \tag{16}$$

here, y_i the i^{th} measured data, z_i the average value, x_i the i^{th} predictive data with the Weibull or Rayleigh, N and n are the number of observations, and the number of constants, respectively (Li and Li, 2005).

3. RESULTS AND DISCUSSION

3.1. Shape and Scale Parameters

Variable wind speed is usually described using the density function of two parameters, ie the shape (k) and scale (c) factor. The shape and scale parameters for the 3 years are shown in Table 1.

The results were calculated approach to these two parameters, each year is shown in Table 1, wherein the shape parameter ranges

Table 1: Shape and scale parameters for 3 years

Years	2017		2018		2019	
Parameters	***k***	***c***	***k***	***c***	***k***	***c***
January	4.897	4.849	4.897	4.849	4.887	5.017
February	4.667	5.343	4.744	5.318	4.053	5.389
March	4.930	5.549	4.959	5.573	3.833	5.053
April	5.729	5.049	5.722	5.029	5.303	5.228
May	5.820	5.717	5.857	5.757	4.813	5.303
June	4.783	5.834	4.747	5.857	5.122	5.866
July	4.373	5.848	4.341	5.867	6.952	5.095
August	5.056	5.848	5.187	5.456	5.253	5.740
September	4.306	5.536	4.161	5.354	6.714	5.702
October	4.631	5.261	4.834	5.097	5.725	5.833
November	4.572	5.449	4.540	5.490	5.688	5.596
December	4.556	4.585	4.459	4.611	6.048	6.113
Years	4.560	5.373	4.916	5.347	5.266	5.496

from 4.560 to 5.266, and the scale parameter ranges from 5.347 to 5.496, and the average shape parameter is 4.914, and the scale parameter around 5.405. Comparison Pdf each year for the Weibull distribution is shown in Figure 1.

Comparison Pdf each year for the Weibull distribution (WD) is shown in Figure 1. The amount Pdf of the Weibull distribution is influenced by two parameters related to the wind speed, the wind speed of about 5.34 m/s can be seen that the highest Pdf occurred in 2019, followed in 2018 and 2017.

Comparison Pdf each year for Rayleigh distribution is affected by the scale parameter is related to the wind speed, the wind speed of about 3.73 m/s is obtained Pdf highest in 2018, followed by 2019 and 2017, as shown in Figure 2.

The comparison between the Weibull and Rayleigh models for each year is shown in Figures 3-5.

Figure 3 shows a comparison between the Weibull and Rayleigh models for 2017, the difference of the two models for 2017 indicated by the red line in the amount of about 1.3253%.

Figure 1: Weibull Pdf 3 years

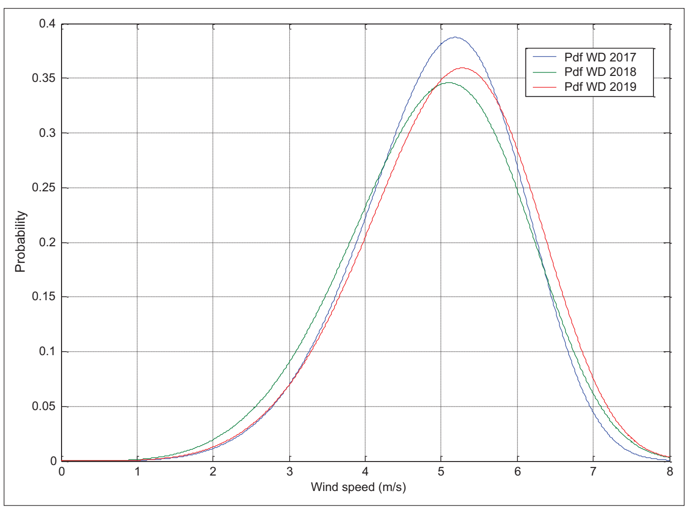

Figure 2: Rayleigh Pdf 3 years

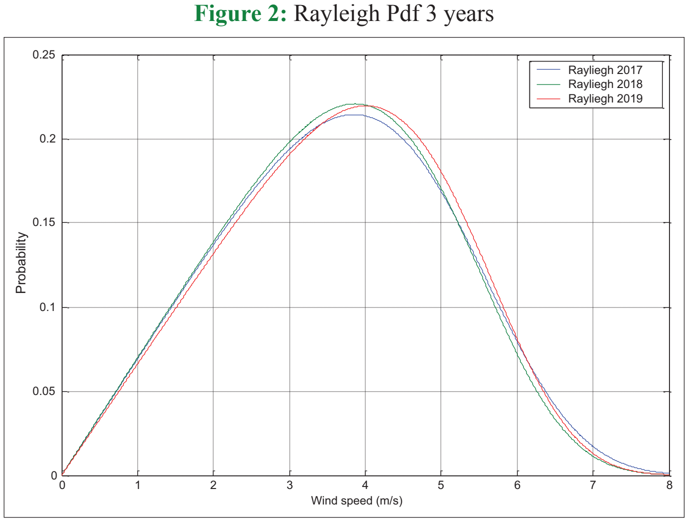

Figure 4 shows a comparison between the Weibull and Rayleigh models for 2018, the difference between the two models is indicated by the red line in the amount of about 0.7363%.

Figure 3: Comparison of Weibull and Rayleigh in 2017

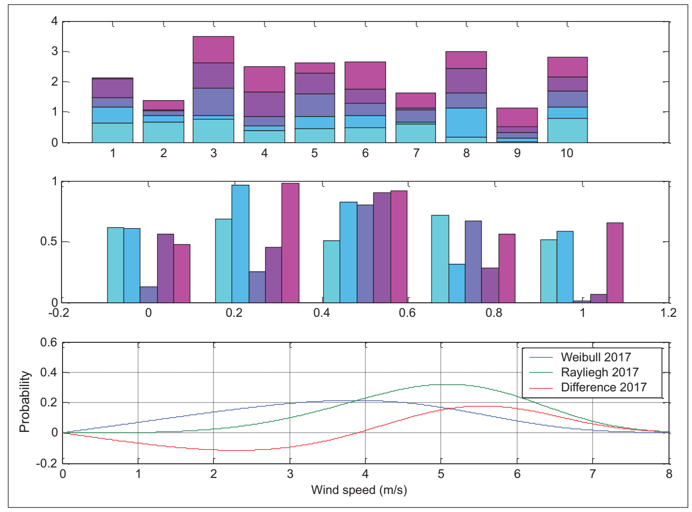

Figure 4: Comparison of Weibull and Rayleigh in 2018

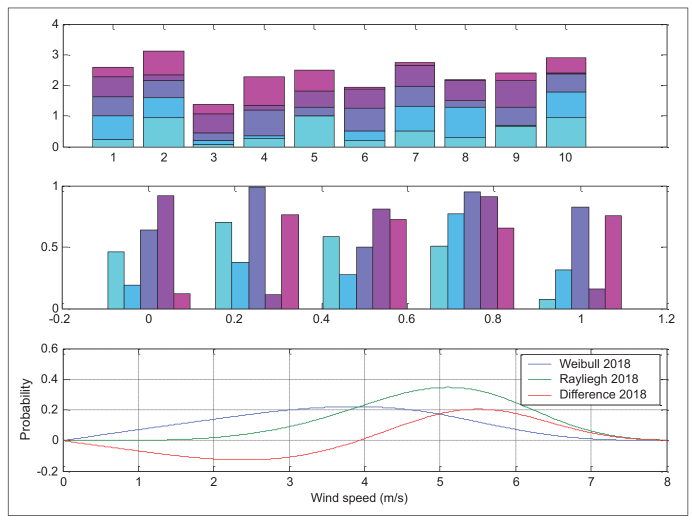

Figure 5: Comparison of Weibull and Rayleigh in 2019

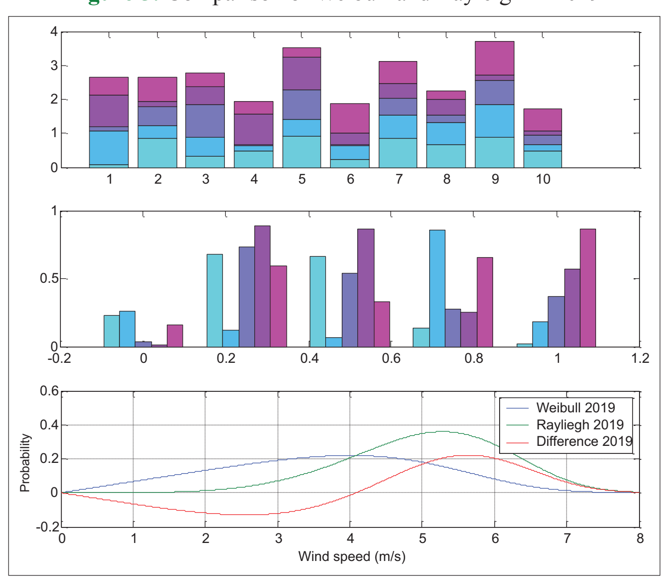

Table 2: The statistic analysis parameters for monthly wind speed distribution in Medan

Evaluation models	January	February	March	April	May	June
R^2						
Weibull	0.965	0.970	0.967	0.946	0.934	0.978
Rayleigh	0.311	0.663	0.630	0.309	0.641	0.788
□^{2}						
Weibull	0.041	0.041	0.045	0.048	0.072	0.046
Rayleigh	0.807	0.459	0.501	0.611	0.391	0.438
RMSE						
Weibull	0.198	0.190	0.208	0.211	0.264	0.208
Rayleigh	0.8839	0.6650	0.6959	0.7688	0.615	0.6506
	July	**August**	**September**	**October**	**November**	**December**
R^2						
Weibull	0.971	0.964	0.974	0.970	0.970	0.974
Rayleigh	0.726	0.610	0.609	0.502	0.646	0.195
□^{2}						
Weibull	0.049	0.044	0.040	0.039	0.043	0.031
Rayleigh	0.463	0.473	0.473	0.640	0.507	0.957
RMSE						
Weibull	0.218	0.207	0.207	0.193	0.200	0.173
Rayleigh	0.669	0.677	0.677	0.787	0.700	0.962

Table 3: Wind energy in Medan

Potential	Years		
	2017	2018	2019
Power density (W/m^2)	74.7158	72.2078	79.4618

Figure 6: Power density (W/m^2)

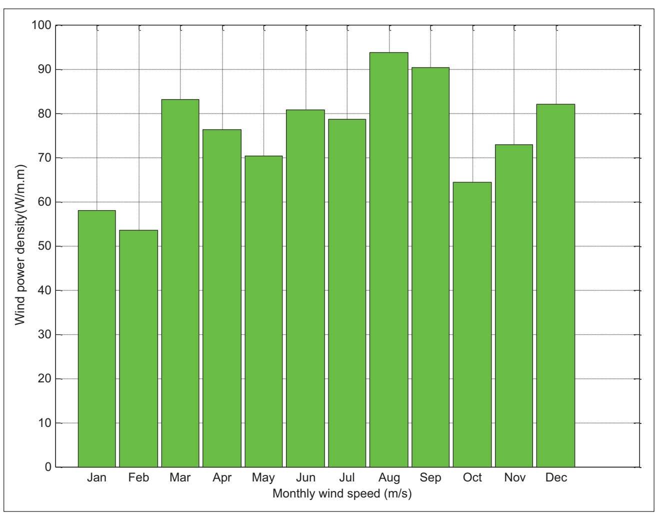

Figure 5 shows the comparison between the Weibull and Rayleigh models for 2019, the difference between the two models is shown by the red line which is about 0.3277%.

The difference in average for the 3rd year about 0.7964%, the difference in average for 3 years showed quite good, this shows that the two models are proposed to be well received by a probability density function and statistical tests.

3.2. Distribution Function Analysis

They analyze the potential of wind energy using the correlation coefficient (R^2), Chi-Square (□^{2}), and RMSE are shown in Table 2.

Table 2 shows the results of the evaluation using the correlation coefficient, Chi-Square and, root mean square error (RMSE). The correlation coefficient for the Weibull distribution ranges from 0.9338 to 0.9775, while for the Rayleigh distribution it ranges from 0.1946 and 0.7876. Weibull models maintain the correlation coefficient (R^2) is best for all distribution functions. However, for statistical analysis based on Chi-square and RMSE, the Weibull distribution has the lowest value compared to the Rayleigh distribution.

3.3. Energy Density and Power Density Potential

The power density of the monthly wind speed is shown in Figure 6. Wind speed for 3 years (2017-2019) has a minimum, maximum, and average speed between 2.33 and 2.71 m/s, 7.35 and 7.71 m/s, and 4.91 and 5.06 m/s, respectively. Meanwhile, the annual power density is shown in Table 3, with the power density between 72,2078 and 79.4618 W/m^2. This power density is only capable of producing a maximum power per square meter of 79.4618 Watts.

The potential wind speed converted to energy and power density in Medan based on actual wind speed data is shown in Table 3.

4. CONCLUSION

Wind speed characteristics in Medan were statistically analyzed and wind speed data collected for 3 years (2017-2019) were used for analysis. The results of the analysis and evaluation show that;

1. Comparison of Pdf that, Weibull model is better than Rayleigh.
2. Statistical analysis using the correlation coefficient (R^2), the Weibull distribution is best compared to the Rayleigh distribution. However, using Chi-Square and RMSE that, the Rayleigh distribution is better than the Weibull distribution.
3. The power density is only capable of producing a small amount of usable power for street lighting, which is around 79.5 Watt/m^2.

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