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Use of Rayleigh Distribution Method for Assessment of Wind Energy Output in Cleveland–Ohio

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Abstract

The control of carbon emission in the atmosphere is possible only by mitigating the energy sources from fossil fuels to renewable energy resources such as the solar, wind, and tidal energies. These are abundantly available in the nature but the methods to capture and utilize these enormous potential resources are still under investigation due to the limited state of art of infrastructure and low-energy conversion efficiencies. In this work we focused our attention on the potential of the wind energy available around the Lake Erie region using the wind speed data for Cleveland, Ohio, USA. The major challenge in developing a model that generates a uniform output is to have many uncertainties that require deeper studies. In this work, we discussed the available wind energy throughout the year, and the pattern for the wind power output according to a monthly basis was discussed for the last ten years. A statistical method was utilized using the Rayleigh probability distribution function in order to estimate the mean wind speed and calculate the annual energy output from a windmill at the understudied location. An annual energy output of 1286.41 kWh/m^2 was estimated by the Rayleigh PDF method, whereas the actual energy output was 920.24 kWh/m^2 for the observed historical data in the period of 2009-2018. Due to the high uncertainties in the nature of wind flow and the limited research works in the field of renewable energy, the Rayleigh PDF approach overestimated the actual wind power output by 40% in this work.

Keywords: *Wind energy; Ohio; Rayleigh.*

1. Introduction

There are different factors that are important for a substantial energy development. Firstly, developing and adapting a new energy efficient technology helps to reduce energy consumption. Secondly, making an improvement in the energy production gives more electricity. Lastly, considering a renewable energy can replace fossil fuels. Reducing the greenhouse effect and fulfilling the energy supply are required to achieve a sustainable energy system. The world is moving toward renewable energies as the important sources of energy because of the limited resources of fossil fuels and substantial demands for energy resources. The population of the world has increased drastically after the industrial revolution, and it is directly proportional to energy consumption. In order to fulfill the requirements of approximately seven billion humans using the conventional energy methodology has caused excess CO2, NOx, and particulate pollutants in the air. The new age technology and the industrial processes have been a major contributors to global warming, and air and ocean pollution.

Under these circumstances, a sustainable development is a major challenge in front of the world. To achieve a sustainable development, energy is a major factor, and it should contribute to the existing economy with reducing the environmental adverse effects. All the states in the United States are looking toward eliminating 100% of greenhouse gases and reduce air pollution. There are different renewable energy sources available such as wind, solar power, hydroelectricity, geothermal, tidal, and wave [1]. Albeit much research work has focused on capturing and utilizing the solar energy, not much study has been carried out for wind power generation due to the inherent uncertainties in the wind flow patterns. The transportation industry is also going through major reforms where the next-generation technology such as battery-operated vehicles and hydrogen fuel cell vehicles are going to replace the conventional IC engine to reduce the environmental adverse effects.

The massive globalization and shrinking oil and natural gas reserves have led the world to the brink of an energy crisis. The current energy resources mostly depend on the oil for transportation and on the coal for power generation (electricity). Both oil and coal are non-renewable, and also emit harmful CO2 gas that affects our environment adversely. In view of many other factors, the UN has come up with new goals for the year 2030. By this year, the UN has the targets [2] to double the global rate of improvement in energy efficiency, increase substantially the share of renewable energy in the global energy mix, enhance the international cooperation to facilitate access to clean energy including renewable energy, energy efficiency, and advance cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.

Electricity is generated from the wind energy by transmitting the kinetic energy of the moving wind to rotate the wind turbines. For many decades, we have used windmills for water pumping and grinding grains, and now we have started to use turbines for electricity production. Normally, a turbine starts generating energy after the wind speed reaches 5 to 6 miles per hours and cuts around 55 miles per hours to avoid getting damaged. Wind farms, a group of windmills erected in a particular site, are installed at high wind density sites to harness a higher power and transfer it to electrical grid, thus acting as power plants. They are easy to install and are relatively cheaper compared with thermal power plants [3].

Offshore wind energy has a great potential for energy production. According to the Department of Energy in the U.S., 20% of electricity should be produced from the wind energy by 2030. In this article, we will discuss the benefits of the wind energy and how much power we can generate from the wind energy in Cleveland, Ohio. In the recent years, the wind power production has raised due to the new turbine technology as well as the government promotional activity [4].

Cleveland is a city that houses the first wind turbines installed to produce electricity. The NASA Glenn Research Center based in Cleveland has also developed various technologies in improving the efficiency of the wind turbines [5]. Around 203 km2 of the Lake Erie area can fulfill 100% of the Cleveland energy requirements, and the offshore wind power of the Lake Erie has the potential to produce 2.959 MW/Km2 energy [6]. Buhairi [7] used the statistical analysis of wind speed data for assessment of the wind energy potential in Taiz, Yemen. In this work, we worked using a similar approach to estimate the wind energy potential for Cleveland, Ohio using the wind speed data for the last ten years. The Rayleigh distribution was taken as a statistical tool for this assessment. In this work, we constructed the Rayleigh probability distribution function for the wind data [8] and compared the results obtained with the actual data in assessing the wind energy.

2. Statistical Analysis

2.1. Probability distribution function

The historical monthly wind speed data from January 2009 to December 2018 provides a solid basis for calculating the available wind energy density at Cleveland, Ohio, U.S. Table 1 shows the data for the monthly mean distribution of daily wind speed taken from the National Centers for Environmental Information.

Determining the wind speed probability density distribution is detrimental in estimating the energy output from a windmill. The wind energy is abundantly available on the offshore regions, where the open water around an offshore site provides the wind to accumulate larger velocities, and thus the overall higher kinetic energy gives rise to the high energy densities. Albeit the installation of an offshore wind turbine is relatively expensive compared with onshore, the high-energy densities offered on the offshore site will offset the high capital investment. In a report published by the United States Department of Energy, it was predicted that with development in the wind energy power generation, the offshore wind technology, considered less mature to land-based wind farms, had a significant potential in the future cost reductions [9].

Weibull distribution is a probability distribution function that takes into account the average speed of the wind at a particular site and develops a curve that would fit the measured speed distribution [10]. The Weibull probability density function is shown in (1) [7, 10].

$$f(\vartheta) = \frac{k}{\sigma}\left(\frac{\vartheta}{\sigma}\right)^{k-1} \mathrm{e}^{-\left(\left(\frac{\vartheta}{\sigma}\right)^{k}\right)} \quad for\ \vartheta \geq 0$$
$$f(\vartheta) = 0 \ for \quad \vartheta < 0 \qquad (1)$$

k and σ are the shape and scale parameters of the Weibull distribution, and ϑ is the observed daily mean wind speed.

$$F(\vartheta) = 1 - e^{-\left(\left(\frac{\vartheta}{\sigma}\right)^{k}\right)} \quad for\ \vartheta \geq 0 \qquad (2)$$

The Rayleigh and exponential distributions are special cases of Weibull distributions. The Rayleigh distribution is often used to determine the

Probability Distribution Function (PDF) of wind speed. The Rayleigh distribution, in (3), is a special case of Weibull, where the shape parameter is taken as 2.0. The PDF of Rayleigh distribution can be calculated from (1) by substituting 2.0 as the value for k [7, 10].

$$f(\vartheta) = \frac{2\vartheta}{\sigma^2} \mathrm{e}^{-\left(\left(\frac{\vartheta}{\sigma}\right)^k\right)} \quad (3)$$

The expected value in a Rayleigh distribution (in our case, the mean wind speed ϑm) can be calculated using (4) [7, 10].

$$\vartheta_m = \sigma \sqrt{\left(\frac{\pi}{4}\right)} \quad (4)$$

Substituting (4) in (2) will give us the cumulative probability distribution (CDF) of the Rayleigh distribution to calculate the probability of wind speed below at the measured mean wind speed [10].

$$p(wind\ speed\ \leq\ \vartheta) = 1 - \mathrm{e}^{-\left(\frac{\pi}{2}\right)\left(\frac{\vartheta}{\vartheta_m}\right)} \quad (5)$$

2.2 Power Density Function (PDF)

The power in watts for any given wind speed (ϑ) and density of air (ρ) for a given swept area of the turbine A is given by [10]:

$$P = 0.5\rho\vartheta^3 A \quad (6)$$

To calculate the power density (*watts/m²*), we take the swept area of the turbine as 1.0 m^2.

$$P = 0.5\rho\vartheta^3 \quad (7)$$

At the sea level and under the average atmospheric pressure and 15 °*C*, the air density is taken as 1.225 kg/m^3.

2.3. Wind Energy Calculations

The energy density can be calculated using the frequency, f, of the available wind speed and the power density, P [10].

$$E_{obs} = f.P \quad (8)$$

The estimated energy (E_{est}) can be calculated using the Rayleigh frequency (f_R) and the power density (P) [10].

$$E_{est} = f_R.P \quad (9)$$

2.4. Effects of Height and Seasons

The wind speed from the ground level to higher altitudes increases rapidly till a certain altitude, and further would grow less rapidly. Figure 1 shows the typical behavior of the wind speed as we go to higher altitudes from the ground. The relation between the wind speed and the altitude is given below [10] for a wind shear coefficient, α (typically, $\alpha = 0.2$).

$$\vartheta(h) = \vartheta(h_r)\left(\frac{h}{h_r}\right)^\alpha \quad (10)$$

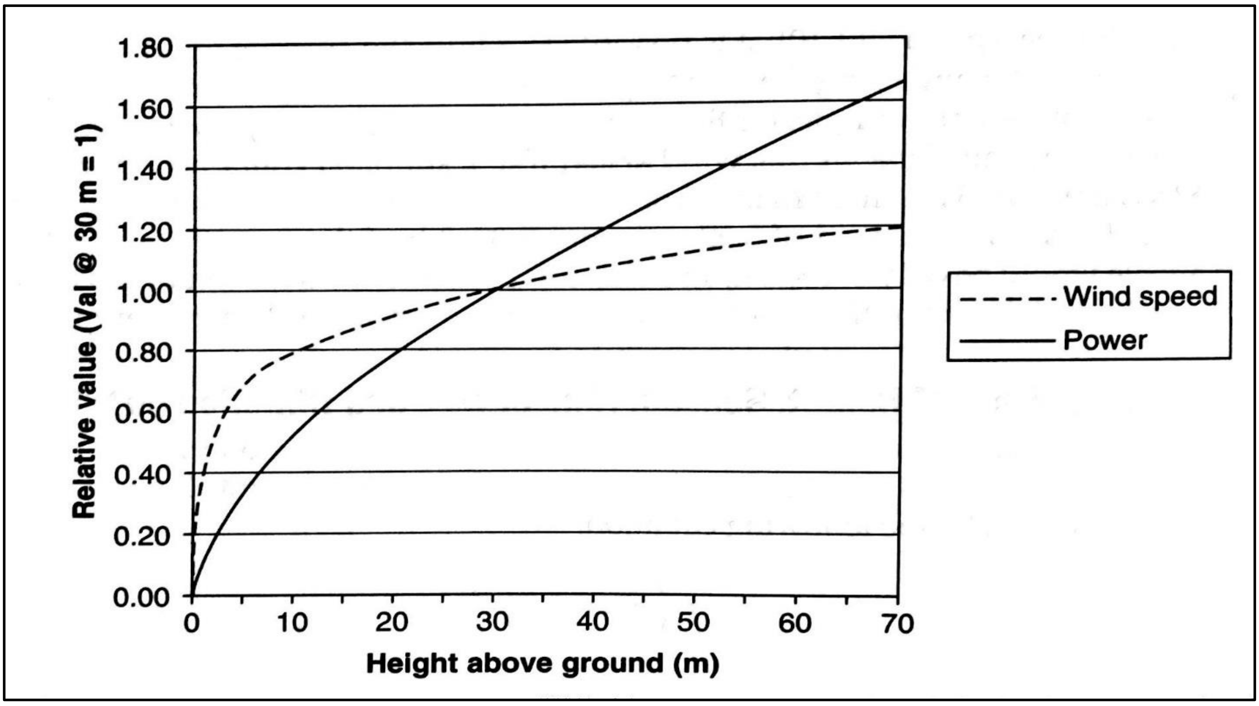

Figure 1. Behavior of wind speed as the altitude from the ground level increases [10].

Therefore, it is essential to choose the optimal height for the windmill as the height increases the cost of erection and also the rate of increase in the wind speed is slowed after an optimum height.

The effects of seasons and time of the day on the average wind speed is site-specific. It can be observed that in some regions, the average speed of the wind is higher at day times compared with night times, and vice-versa in the others.

3. Results and Discussion

The measured daily mean wind speed during the period 2009-2018 was obtained from the National Centers for Environmental Information, which was used to calculate the monthly mean wind speed at Cleveland, Ohio. The results obtained by analysis of the data are summarized below.

The monthly mean wind speed data for ten years was tabulated in table 1. The arithmetic mean of yearly data was 4.7 *m/s*. The maximum monthly mean wind speed of 6.91 m/s was noticed in December 2016, and the minimum value of 3.08 *m/s* was observed in July 2011. The maximum yearly mean wind speed of 5.16 *m/s* was noticed in the year 2016, and the minimum value of 4.5 *m/s* was observed during the year 2010. The mean monthly wind speed observed during the period 2009-2018 had a maximum value of 6.02 *m/s* during the month of January, whereas the minimum value of 3.60 *m/s* was found during the month of July.

Figure 2 gives the picture of the mean wind speed for a period of ten years (January 2009-December 2018) for each month. This shows the seasonality of the wind speed pattern, and we can notice that the abundant wind energy is available during the month of January and that the trend starts to gradually tend to slower wind speeds till the month of July and then it picks up from the month August. This seasonal trend helps to determine an effective plan of utilizing the wind energy during the higher wind speed durations and use alternative approaches such as solar during the other periods to compensate for the lower wind energy output, and there, by developing a uniform energy output.

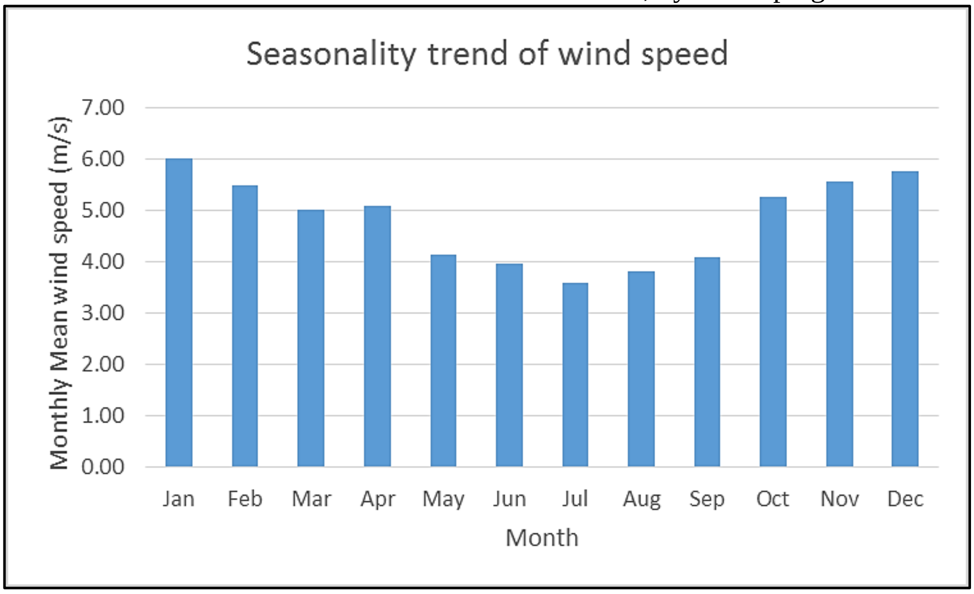

Figure 2. Wind speed distribution pattern over each year seasonality trend.

Figure 3 shows the trend of monthly mean wind speed during the period 2009-2018. It can be observed that the peak wind speed is in January, and that it gradually slows down as it approaches summer around the June-July period, and then again picks up from there till January. This trend is critical in developing the alternative power sources such as solar power during the summer months, which is available abundantly during this period.

Table 2 summarizes the ten years mean wind speed data. For the calculation purposes, we imagined a bin with a minimum and maximum wind speed variation of 1 m/s. A total of 15 bins was created for wind distribution from 0 *m/s* to 15 *m/s*. The total hours during the period from 2009-2018 was calculated, and the following frequency of average bin speed was calculated. The average wind speed for Cleveland was calculated to be 4.79 *m/s*, and using the Rayleigh PDF, the Rayleigh frequency was calculated for the data. Figure 4 shows a comparison of the observed and the Rayleigh estimated probabilities of wind speed for a particular bin. It can be clearly observed that the Rayleigh PDF fits the observed wind speed approximately, except at the high-frequency zone of 2-6 *m/s* wind speeds; at these wind speeds, Rayleigh is underestimating the probability compared with the observed values.

Furthermore, for calculating the annual output in *kWh* of the wind energy, we calculated the power available for the average bin speeds and multiplied the number of hours available per year. The calculated annual output for the observed and the Rayleigh distribution is shown in table 3. It was calculated that the annual output for the observed wind speed was 920.24 kWh/m^2, whereas the Rayleigh estimation was 1286.41 kWh/m^2. It can be clearly seen in figure 5 that the Rayleigh PDF is overestimating the annual energy output by a factor of 40%. This can be attributed to the high uncertainties and the unknown parameters that are prevalent in the wind flow patterns, which indeed are to be further investigated, and thorough research works are needed to be conducted for capturing the enormous potential of the wind energy.

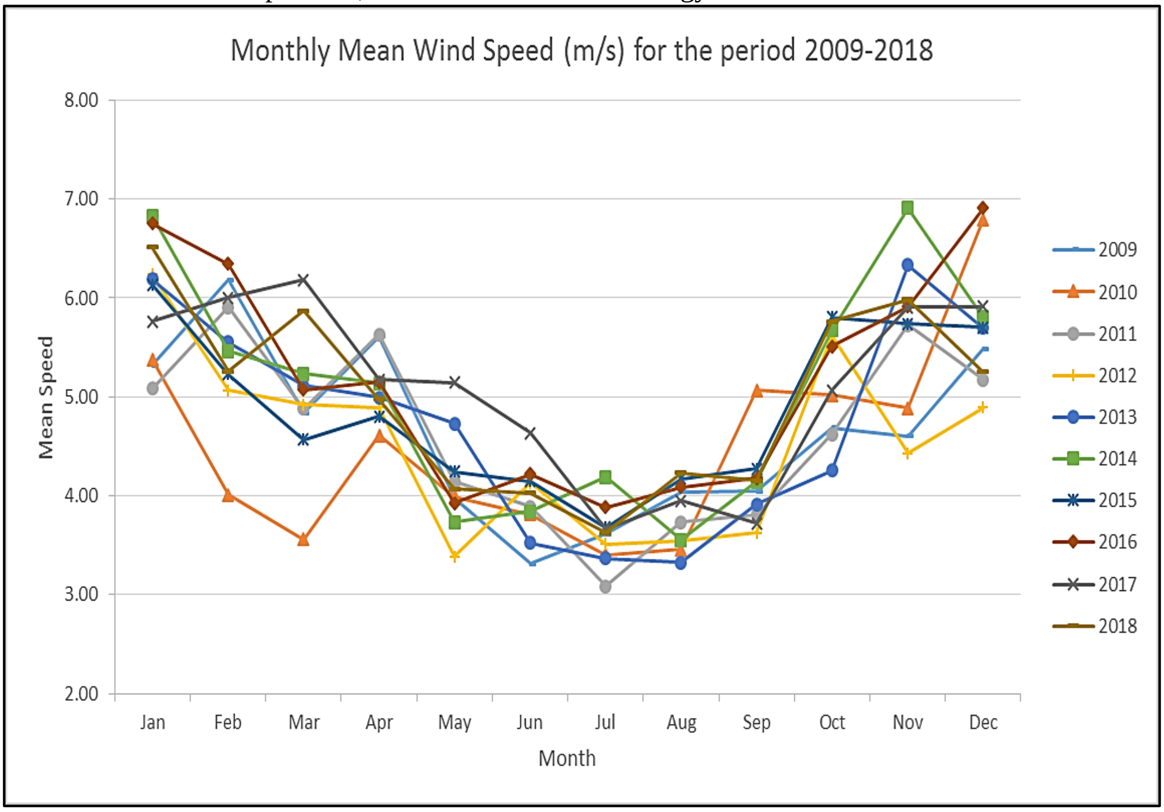

Figure 3. Monthly mean wind speed distribution for the period 2009-2018.

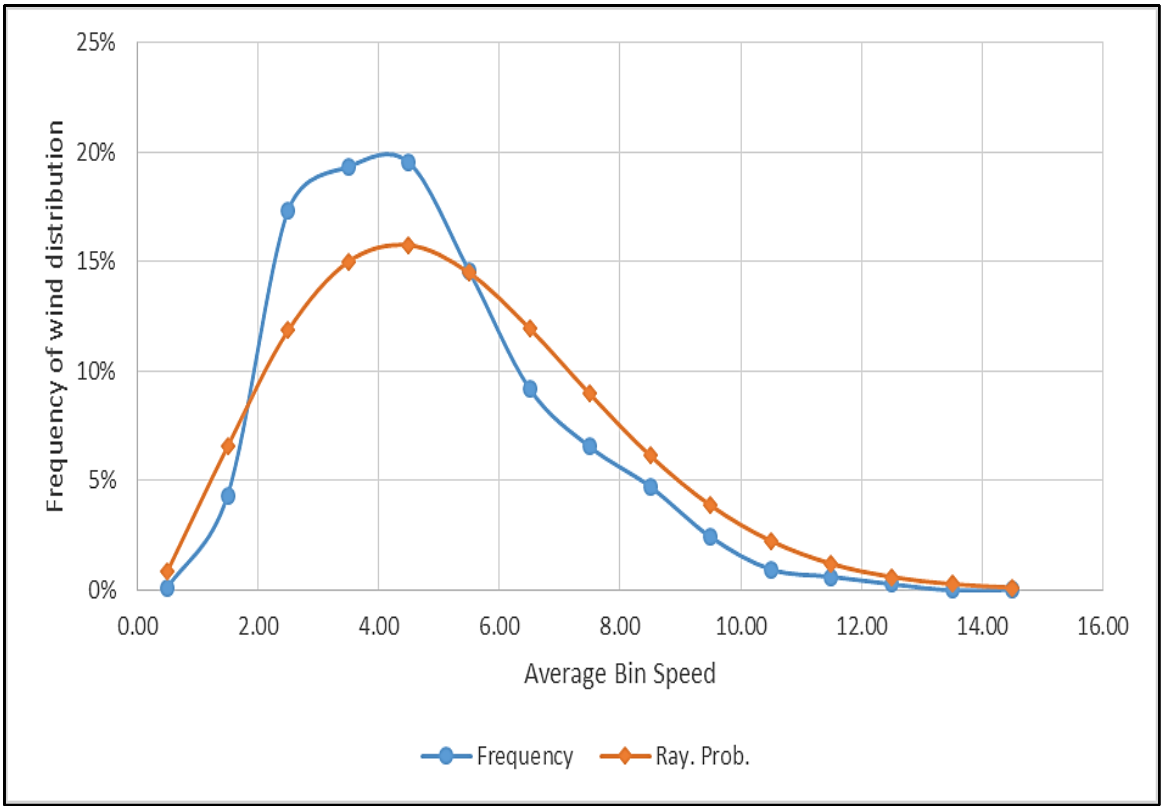

Figure 4. Comparison of the Rayleigh and observed probability distribution of the average bin speed.

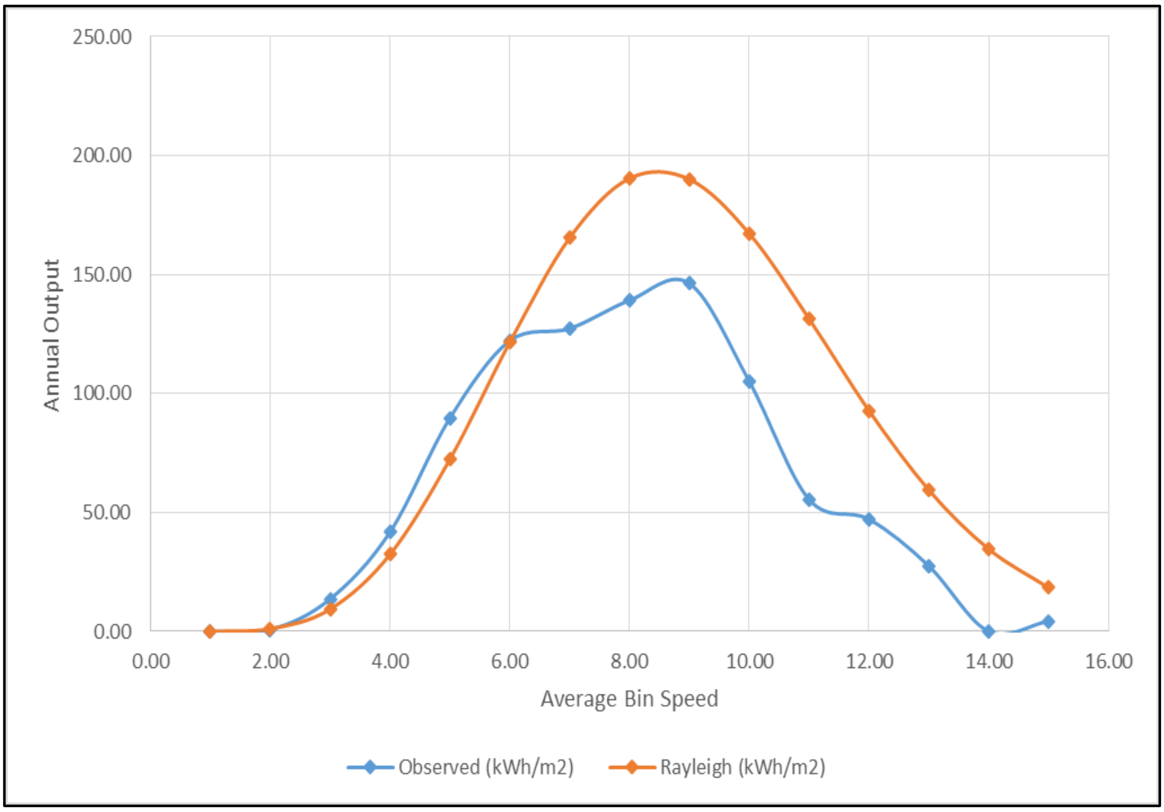

Figure 5. Comparison of the Rayleigh and observed annual energy output.

Table 1. Summary of monthly mean wind speed (m/s) for the period 2009-2018.

Month	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Yearly mean
Jan	5.32	5.38	5.09	6.24	6.19	6.83	6.14	6.75	5.76	6.51	6.02
Feb	6.18	4.01	5.91	5.06	5.55	5.27	5.23	6.35	6.00	5.26	5.48
Mar	4.84	3.56	4.88	4.92	5.11	5.23	4.56	5.07	6.18	5.87	5.02
Apr	5.61	4.61	5.63	4.89	5.00	5.14	4.80	5.15	5.18	4.98	5.10
May	3.97	3.99	4.14	3.39	4.73	3.74	4.25	3.92	5.14	4.07	4.13
Jun	3.20	3.81	3.89	4.13	3.52	3.84	4.15	4.22	4.63	4.03	3.94
Jul	3.61	3.40	3.08	3.51	3.37	4.19	3.68	3.88	3.66	3.63	3.60
Aug	4.04	3.46	3.61	3.54	3.32	3.44	4.17	4.09	3.95	4.23	3.78
Sep	4.05	5.07	3.81	3.62	3.39	4.14	4.27	4.18	3.72	4.15	4.04
Oct	4.69	5.02	4.62	5.44	1.51	4.94	5.81	5.51	5.07	5.76	4.84
Nov	4.60	4.89	5.73	4.28	0.63	6.45	5.74	5.91	5.90	5.98	5.01
Dec	5.48	6.80	5.17	4.89	3.12	5.80	5.70	6.91	5.91	5.25	5.50
Yearly mean	**4.62**	**4.50**	**4.62**	**4.49**	**3.78**	**4.91**	**4.87**	**5.16**	**5.09**	**4.98**	**4.70**

Table 2. Calculated frequency and hours/year for the data analyzed.

Bin	Wind speed		Hours/Year	Average Bin Speed	Frequency
	Max. (m/s)	Min. (m/s)			
1	0	1	9.804141	0.50	0%
2	1	2	379.91046	1.50	4%
3	2	3	1517.1908	2.50	17%
4	3	4	1693.6654	3.50	19%
5	4	5	1710.8226	4.50	20%
6	5	6	1276.9894	5.50	15%
7	6	7	806.3906	6.50	9%
8	7	8	573.54225	7.50	7%
9	8	9	414.22496	8.50	5%
10	9	10	213.24007	9.50	2%
11	10	11	83.335199	10.50	1%
12	11	12	53.922776	11.50	1%
13	12	13	24.510353	12.50	0%
14	13	14	0	13.50	0%
15	14	15	2.4510353	14.50	0%

Table 3. Calculated annual output for each bin for the observed data and the Rayleigh PDF.

Bin	Power Density (W/m3)	Annual Output	
		Observed (kWh/m2)	Rayleigh (kWh/m2)
1	0.07	0.00	0.01
2	1.94	0.74	1.12
3	8.98	13.63	9.33
4	24.65	41.75	32.39
5	52.40	89.64	72.32
6	95.67	122.16	121.47
7	157.91	127.34	165.42
8	242.58	139.13	190.40
9	353.12	146.27	190.04
10	492.99	105.13	167.27
11	665.63	55.47	131.37
12	874.50	47.16	92.85
13	1123.05	27.53	59.42
14	1414.72	0.00	34.60
15	1752.96	4.30	18.41
Total		920.24	1286.41

4. Conclusion

The wind speed distribution for Cleveland, Ohio, USA was statistically estimated using the Rayleigh distribution method. The wind speed data for a ten-year period from January 2009 to December 2018 was used for the analysis. The seasonality trend of wind speed distribution was clearly shown and discussed for the data set considered. Furthermore, the probability of wind speed was estimated using the method of dividing the data into bins for the ease of estimation. Wind speed in a particular bin was calculated for the observed data, and power density of the same was calculated using the statistical methods. Later, the Rayleigh PDF was used to calculate the annual energy output, and the results obtained were compared with the observed actual wind energy output. The annual observed power output calculated was 920.24 kWh/m^2, whereas the Rayleigh distribution method was estimated to be 1286.4 kWh/m^2. It was noticed that the Rayleigh PDF overestimated the annual wind energy output by a factor of 40%, which was too high considering the given conditions. The higher estimation of the Rayleigh distribution can be attributed to the larger uncertainties in the prediction of wind speed and also the measurement of wind speed. Other factors such as natural disturbances like storms and tornados also influence the wind speed pattern. Overall predicting a perfect wind map for the following years require a much robust study by considering multiple parameters, which is out of the scope of our discussion. The results obtained from this work can be used for developing a wind farm near Cleveland, Ohio for the purpose of generating a renewable source of power generation. The current work shows the potential for developing wind farm and the expected output each month considering the seasonality effect of the wind speeds.

Nomenclature

A	Swept Area of the turbine
$f(\vartheta)$	Probability of observing wind speed ϑ
h	Height above the ground
h_r	Reference height above the ground
k	Dimensionless Weibull shape parameter
α	Wind shear coefficient (typically 0.2)
$\vartheta(h)$	Wind speed as a function of time
$\vartheta(h_r)$	Wind speed at reference height
ϑ_m	Mean wind speed

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