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Investigation of wind power density distribution using Rayleigh probability density function

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Abstract

When modelling the wind speed in a given location, the probability distributions prove to be a useful tool. In this paper, the wind power density in an urban and a suburban location in Constanta county, Romania, have been analyzed during the period January 2017 - December 2017, based on the hourly measured mean wind speed data. In this study, the Rayleigh probability density function was used to calculate the wind power density for each location in order to classify them in terms of wind energy. The Rayleigh distribution function has been derived from the available data and is fitted to the measured probability distribution on yearly basis. The power densities reported for the two stations varied from 295.39 to 194.5 W / m^2.

Keywords: Wind energy; Wind speed; Rayleigh distribution functions; Wind power density; Probability density function;

1. Introduction

Due to recent technological advances, the wind energy sector in Europe has experienced rapid and sustainable growth over the last 20 years. An important driver of this rapid growth is the need for Europe to benefit from a secure energy supply that is not dependent on foreign sources of oil and gas. A second major driver is the significant

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contribution that wind energy can make to reducing greenhouse gas emissions. As a clean and renewable resource, wind energy is already playing - and will continue to play an important role in mitigating climate change, bringing at the same time, benefits in terms of reducing emissions of air pollutants and associated cooling water consumption with many of the conventional energy generation technologies.

The calculation of wind resources for a given location and the corresponding energy production is based on the wind potential assessment by anemometric measurement, followed by wind data processing to calculate the expected wind power yield for the proposed site.

Typical resource assessment methods involve measuring wind speed and recording the arithmetic mean every 10 minutes or one hour for at least one year. These wind speed data are then used to obtain a relative frequency distribution to which a probability density function is fitted. This function and specific wind turbine power curve are required to calculate the amount of available energy and the electrical power generated in a specific region.

2. Site Location and Data Collection

This study aimed to examine the wind energy potential of Constanta by finding Rayleigh distribution parameter and determining the available power density.

The wind speed data used in this study were measured in Constanta in 2017 at two meteorological stations located near the Black Sea as shown in Fig.1. The meteorological stations are located in the south-east coastal region of Constanta, Romania. The daily wind speed data (in m/s) was collected using cup anemometer at the height of 10 m from ground level, with an hour interval over a period of 1 year, from January 2017 to December 2017. There were analyzed 17234 valid data from 17540 data recorded from both stations.

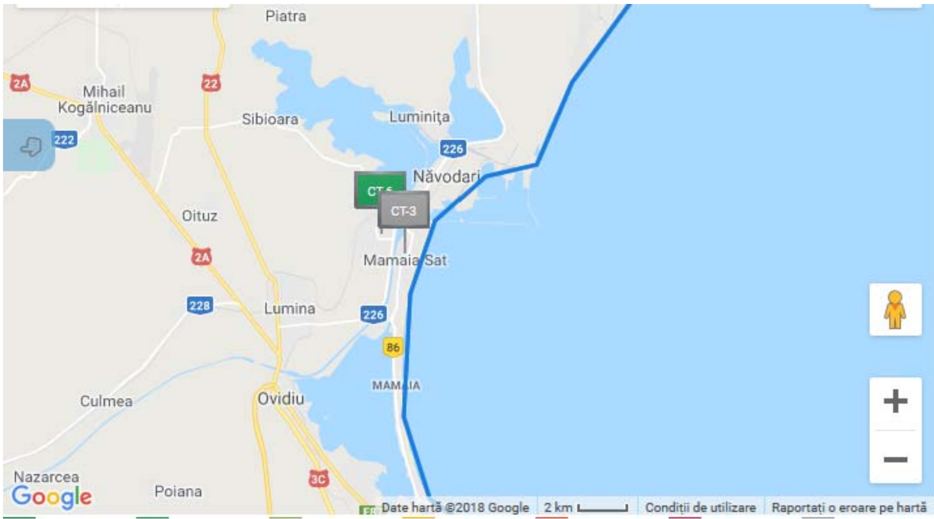

Fig. 1. Location of meteorological stations.

Because the wind speed tends to increase with height and depends mainly on atmospheric mixing and terrain roughness, therefore, we need to calculate the total wind energy potential, so the measured variation in wind speed with height at each site is defined by:

$$\frac{V(z_1)}{V(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha} \Rightarrow V_2 = V_1\left(\frac{z_1}{z_2}\right)^{\alpha} \tag{1}$$

Where, α is power law wind shear exponent, V is the mean wind speed, z_1 is the measurement height above ground level and z_2 is the turbine height (m).

The wind shear exponent depends on the complexity and roughness of the terrain for the specific site.

3. Rayleigh distribution

Rayleigh's distribution can be used to describe the wind variations in a wind regime with an acceptable level of accuracy without the need for data collected over short time intervals, as is the case of the Weibull distribution, because in many cases, such information cannot be available.

Rayleigh's distribution is a simplified case of the Weibull distribution, which is derived by assuming the shape factor as 2. Because of its simplicity, this distribution is widely used for wind energy modeling.

The average velocity is expressed as:

$$V_m = c \cdot \Gamma\left(1 + \frac{1}{k}\right) \tag{2}$$

Taking k = 2 in Eq. (2), obtain:

$$V_m = c \cdot \Gamma \frac{3}{2} \Rightarrow c = \frac{2V_m}{\sqrt{\pi}} \tag{3}$$

The probability density function indicates the fraction of time (or probability) for which the wind is at a given velocity V and it is given by:

$$f(V) = \frac{\pi}{2} \frac{V}{V_m^2} e^{-\left[\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2\right]} \tag{4}$$

Cumulative distribution is given by:

$$F(V) = 1 - e^{-\left[\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2\right]} \tag{5}$$

The validity of Rayleigh distribution in wind energy analysis has been established by comparing the Rayleigh generated wind pattern with long term field data. The probability of wind velocity to be between V1 and V2 is:

$$P(V_1 < V < V_2) = e^{-\left[\frac{\pi}{4}\left(\frac{V_1}{V_m}\right)^2\right]} - e^{-\left[\frac{\pi}{4}\left(\frac{V_2}{V_m}\right)^2\right]} \tag{6}$$

and the probability of wind to exceed a velocity of V_X is given by:

$$P(V > V_X) = e^{-\left[\frac{\pi}{4}\left(\frac{V_X}{V_m}\right)^2\right]} \tag{7}$$

In order to check how accurately the theoretical probability density function fits with observation data the root mean square error (RMSE) parameter test is performed. Best results are obtained when these values are close to zero.

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(y_i - x_i \right)^2 \right]^{\frac{1}{2}} \tag{8}$$

Where N is the number of observations, y_i is the frequency of observation, x_i is the frequency of Rayleigh.

4. Results and Discussion

The data of wind speed in the present calculation was obtained in 2017 from weather stations in Constanta. The hourly mean wind values measured throughout the total year at the two stations are shown in Fig. 2 and 3. It can be seen in Fig. 2 and 3, that the highest wind speed of 26.6 m / s at the CT-3 station and 24.3 m / s at the CT-6 station occurs in January.

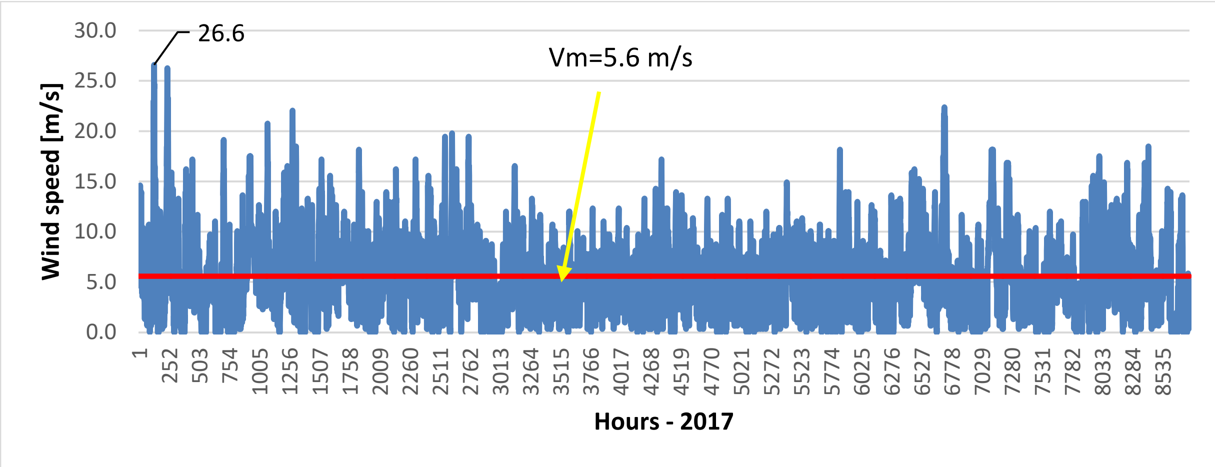

Fig. 2. Hourly variation of wind speed at CT-3 (2017)

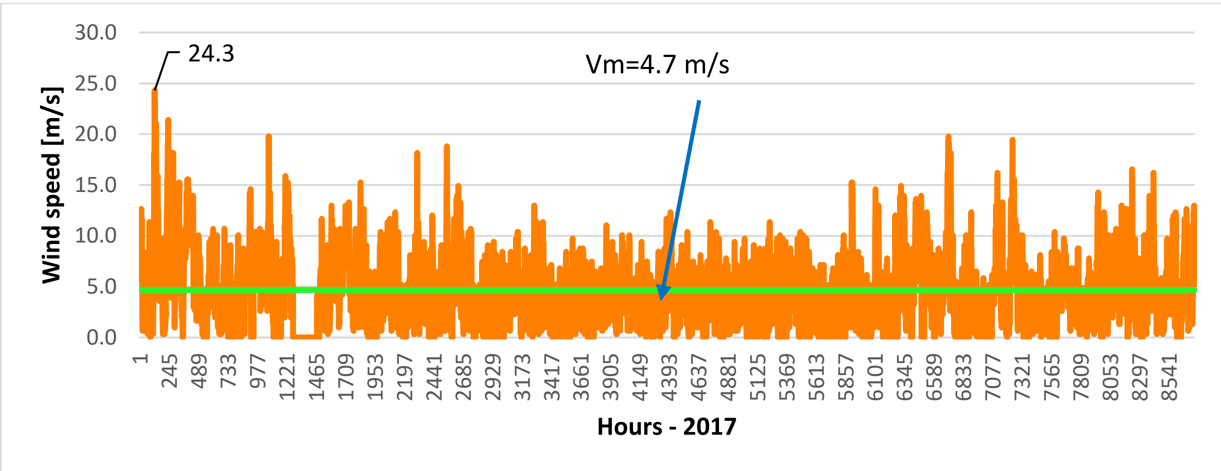

Fig. 3. Hourly variation of wind speed at CT-6 (2017)

The probability density distribution obtained from the Rayleigh model was compared to the measured distributions to study their suitability. The annual comparison shows that the Rayleigh model fit well with the measured probability density distribution as shown in Fig. 4 and 5.

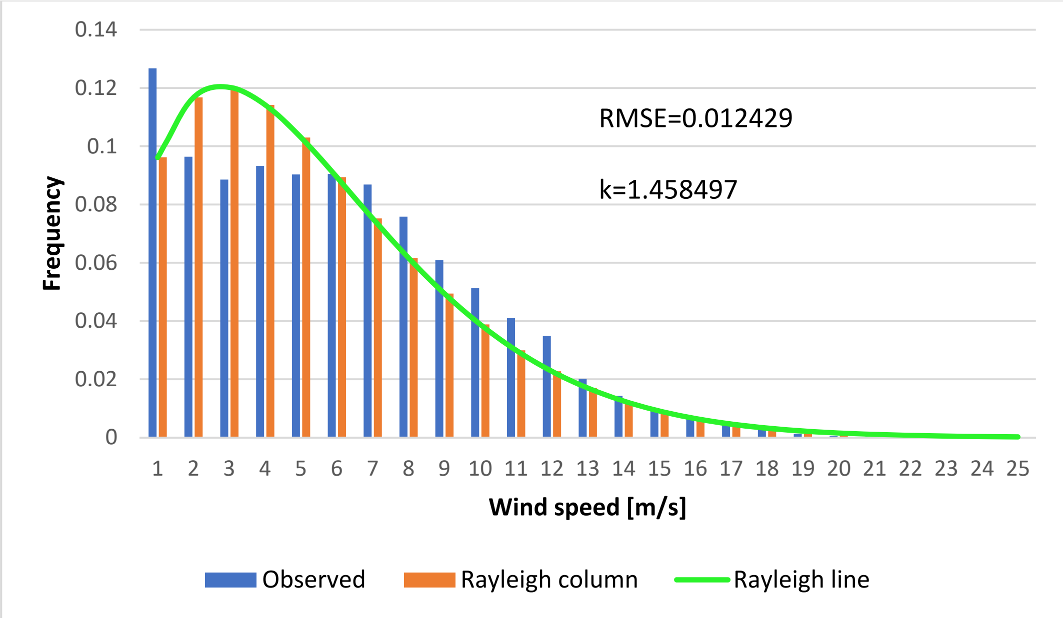

Fig. 4. Comparison of observed and predicted wind speed frequencies at CT-3 (2017)

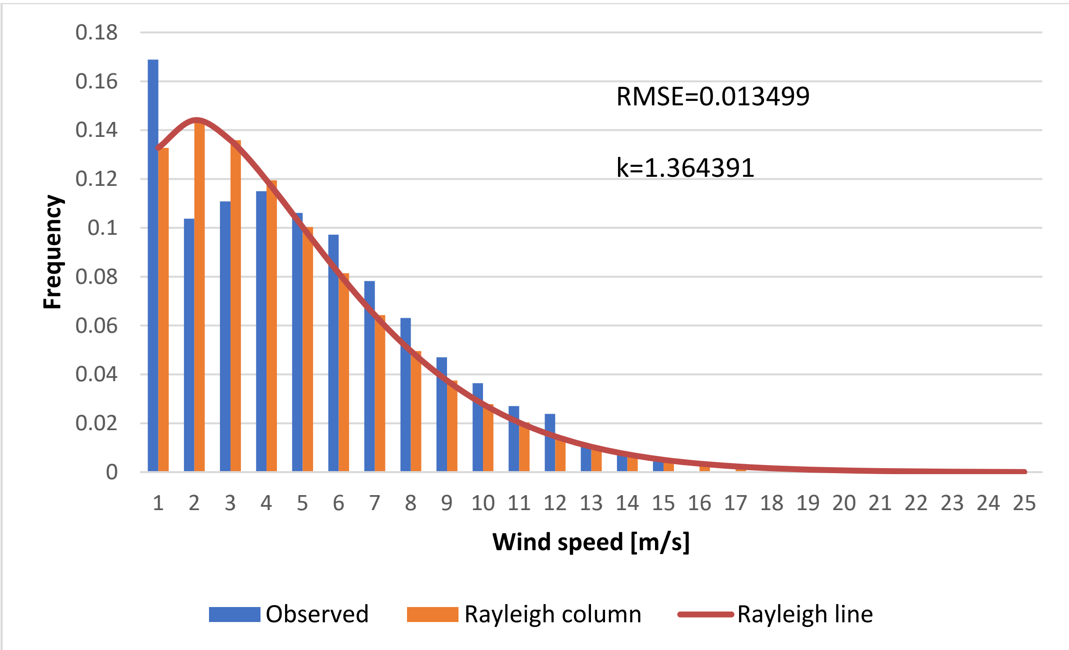

Fig. 5. Comparison of observed and predicted wind speed frequencies at CT-6 (2017)

Analysis of probability density function presented in Fig. 4 and Fig 5 shows the Rayleigh probability and cumulative distributions for all speed ranges observed during the 2017. The real data is presented on the same diagrams so that a comparison can be made between real data and resulted probability density functions. In Fig. 4, it is observed that most of the wind speeds are in the range of 1-7 m/s during all seasons.

Rayleigh seems to give a reasonable fit to observed wind speed data as distribution of observed data is not largely deviated from estimated Rayleigh during entire year.

Fig. 4 and 5 contain the values of RMSE for Rayleigh distribution and the values of correlation coefficient in both figures are very low (nearly 0), which indicates that the predictions made by Rayleigh are extremely accurate.

Errors in calculating the power densities using the distribution Rayleigh model in comparison to those using the measured probability density distribution are presented in Fig. 6. The highest error values occur for wind speed of 1-4 m/s with 4.03% for CT-3 and 3.16% for CT-6 respectively.

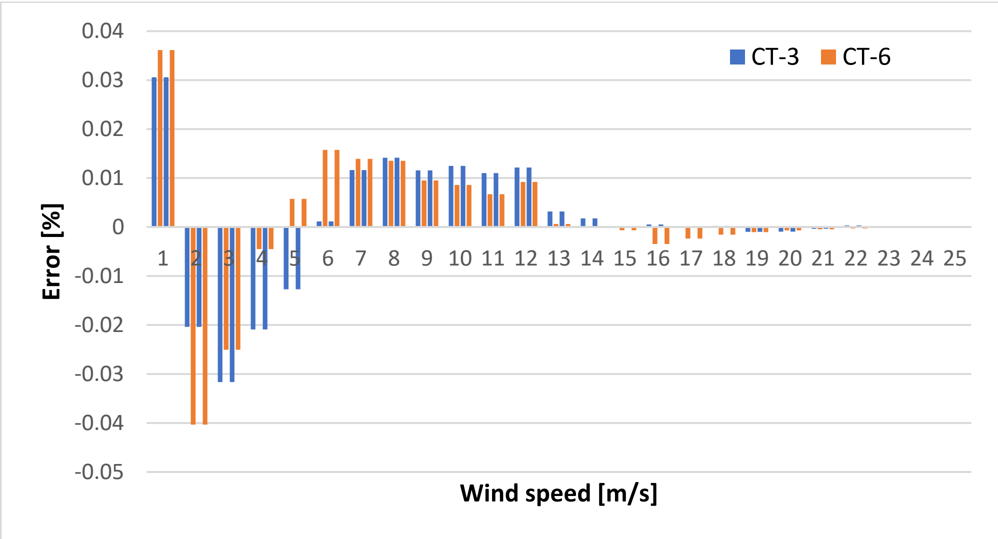

Fig. 6. Error values in calculating the wind power density obtained from the Rayleigh models in reference to the wind power density obtained from the measured data.

The CT-3 station reported an average power density of 295.4 W/m^2 and the CT-6 station reported a value of 194.5 W/m^2 as shown in Fig. 7.

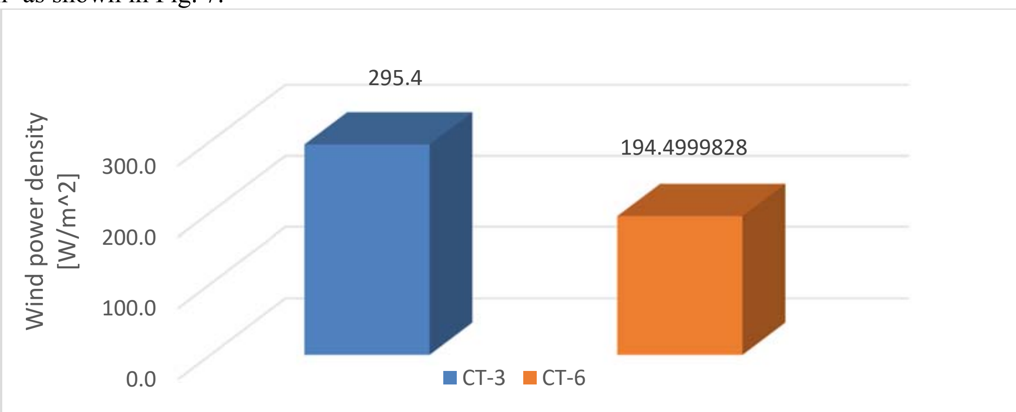

Fig. 7. Average power density

In agreement with the commercially international system of classification for wind power scale, the CT-6 location correspond to the wind power class 3, since the density value is lower than 200 W/m^2. Therefore, this urban location present wind characteristics that are not suitable for wind power development.

The CT-3 location corresponds to the wind power class 4 which is generally accepted as a feasible class for commercial wind power development.

5. Conclusion

This study analyzed wind characteristics and wind energy potential in Constanta, Romania.

For this, wind speed data was analyzed at two monitoring stations over a one-year period at one-hour intervals to predict the wind behavior as accurately as possible.

Based on this analysis, the following conclusions can be drawn:

1. The average wind speed was 5.6 m for CT-3 and 4.7 for CT-6, respectively.
2. RMSE for Rayleigh distribution was 0.012429 for CT-3 and 0.013499 for CT-6, respectively.
3. The average wind energy density based on the average wind speed approach was 295.4 W / m^2 for CT-3 and 194.49 W/ m^2 for CT-6, respectively. Wind power density calculations have indicated that the CT-3 region is in Class 4, which is a suitable area for wind turbine installation.

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