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Extrapolating wind data at high altitudes with high precision methods for accurate evaluation of wind power density, case study: Center of Iran

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ABSTRACT

With growing wind turbine sizes and increasing demands for electricity, it is important to determine accurately wind shear profile, up to high altitudes, for large scale wind turbine installation. The installed wind turbine towers in Iran have hardly exceeded the height of 40 m. In this study, the effectiveness of different extrapolation methods are investigated to determine robustly wind speed and wind power density at higher altitudes. As a case study, wind data was collected from the center of Iran which consists of 35 wind stations in nine provinces. For precise evaluation, the wind speed data were recorded based on 10-min average at various heights ranging from 10 m to 100 m and the wind power potential was obtained on both seasonally and daily basis. The widely used Weibull distribution function is selected for which the shape factor and scale parameter are determined using the standard deviation method, the empirical method of Lysen and the power density method at different heights. From the extrapolated wind data, the mean wind speed, wind power density, optimal wind speed, probability and cumulative density distributions are obtained and the geographic information systems maps are produced and discussed. The results indicate that the power density method is the most accurate method for extrapolating wind characteristics. From the results, it is also observed that variation of power density with time is significant. In period I (spring and summer), most parts of the center of Iran have significant potential for installing large scale wind turbines. However in period II (fall and winter), the amount of wind power density decreases considerably. In overall, the north western and north eastern parts of the center of Iran are recommended for large scale wind turbine installation. The methodology discussed here can be equally employed for extrapolating of wind speeds data at any heights within any geographical region.

1. Introduction

Wind energy is one of the most favorable sources of renewable energies in the world [1]. For evaluating a wind site, a very detailed analysis of the wind characteristics is required [2]. In fact, mean wind speed, wind direction and parameters of Weibull distribution function can be considerably different from one wind station to another [3]. Therefore, feasibility studies of various wind stations are crucial for determining wind potential of a wind region. In recent years, lots of research have been performed for evaluating wind power potential of different areas. In 2011, Adaramola et al. [4] evaluated the wind potential in six wind stations in northern part of Nigeria. In addition, the economic feasibility for installation of small and medium size wind turbines was assessed in these stations. The results demonstrated that based on the Pacific Northwest National Laboratory (PNL) wind power classification, the studied wind sites stand into class 1 and the expense of electricity generation are 0.04 to 1.67 $/kW h. In 2013, Mostafaeipour et al. [5] investigated Binalud area in the north of Iran by analyzing wind speed data from 2007 until 2010 at three heights of 10, 30 and 40 m. The results showed that the wind potential was high enough for grid connection systems. In 2014, Mohammadi et al. [6] studied the possibility of installation of four types of large size wind turbines in Jirandeh. The data was collected from 2008 to 2009 at the height of 70 m. The results showed that the studied location has high power potential and is appropriate for installing wind turbines. In 2015, Pishgar-Komleh et al. [7] studied the wind energy resource in Firuzkuh, Iran. They concluded that based on PNL classification, wind power density is nearly 203 W/m^2 and is suitable for installing medium size wind turbines. In 2016, Ozay et al. [8] statistically analyzed wind characteristics in Alaçatı area of Turkey. The data was recorded at heights of 30, 50 and 70 m based on 10-min time intervals for about five years. Wind speed frequency distributions, wind directions, mean wind

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speeds and parameters of Weibull distribution function were determined.

Many investigations have been conducted using Pearson, Johnson, Log-normal, Weibull, Rayleigh and Gaussian distributions and among them Weibull distribution has advantages such as flexibility, accuracy and simplicity [9]. Evaluating the available numerical methods to compute more suitable one for determination of Weibull parameters is highly important. Nevertheless, there is lack of research in the literature on calculating the more suitable Weibull parameters estimation method at different altitudes to compute wind power density in each wind station. In 2009, Jowder et al. [10] investigated the effectiveness of two methods, graphical method and standard deviation method for computing Weibull parameters. The results revealed that the standard deviation method was more efficient in the studied area. Furthermore, wind speed distribution, mean wind speed and wind power density at three height of 10, 30 and 60 m in Kingdom of Bahrain were determined. Power density method which is known as a new method for calculating shape and scale parameters was introduced by Akdag and Dinler [11] in 2009. In this research, the results were compared with other methods like graphical method and maximum likelihood method and it was concluded that power density method had a better accuracy for computing wind speed distribution and wind power. Two and three-parameter Weibull distribution were compared with Wais [12] in 2016. The results indicated that in the areas with high frequency of low wind speed, three-parameter Weibull distribution had a better accuracy.

In this paper, wind power density and wind characteristics for center of Iran were studied to assess the possibility of wind turbines installation. For this aim, in each wind site the long-term wind data were statistically analyzed. The heights of recorded wind data were different in each wind station and the common heights were 10 m, 20 m, 30 m, 40 m, 60 m, 80 m and 100 m in the time intervals of 10-min.

In this paper, a comprehensive research is conducted by extrapolation of wind power densities of wind stations, from which four GIS maps are produced to demonstrate suitable places for installation of wind turbines. This paper is structured as follows: In part 1 of Section 2, the methods for computing wind characteristics, extrapolating wind power density and probability density functions are discussed. In part 2 of Section 2, wind sites are introduced and their locations are specified on the map. The results and discussion is presented in Section 3. Section 4 concludes the achievements of this research paper.

2. Methods and materials

2.1. Methods for analysis

The first and the most important factor for construction of wind farm in an area is wind power density evaluation. It is shown that the amount of wind energy in two sites with the same average wind speed and wind power density are not necessarily equal. Therefore, the determination of wind power density would be more essential. According to Betz limit, wind turbines can only convert 59.3% of wind energy into electricity [13]. Wind power density can be computed based on measured data collected at a meteorology station precisely. Alternatively, distribution functions can be used to calculate wind energy potential. Weibull distribution function is a well-known method and is recommended by many researchers for this aim.

2.1.1. Wind power density

Wind power density at a specific wind site is related to the cubic of wind speed and can be determined based on Eq. (1). In this expression, ρ is air density, v is wind speed and n is the number of wind data over the studied time period [14].

$$\overline{P} = \frac{1}{2n}\rho\sum_{i=1}^{n} v^3 = \frac{1}{2}\rho\overline{v^3} \quad \left(\frac{\mathrm{W}}{\mathrm{m}^2}\right) \tag{1}$$

Since the elevation of each wind site is different and wind power density directly depends on ρ, Eq. (2) is used for calculating density. In Eq. (2), ρ_b is density of air at sea level with an average temperature of 15 °C and pressure of 1 atm and is equal to 1.225 kg/m^3, T_b is 288.15 K, L_b is 0.0065, h_b is 0 m, g_0 is 9.81 m/s^2, R^* is 8.3144598 N·m/mol·K and M is 0.0289644 kg/mol [15].

$$\rho = \rho_b\left[\frac{T_b}{T_b + L_b(h - h_b)}\right]^{\left(1+\frac{g_0 M}{R^* L_b}\right)} \tag{2}$$

It should be noted that the variation of air density at high altitudes is significant and these variations are more sensible in high wind power densities [16].

2.1.2. Weibull distribution function

Many probability distribution functions like Gamma, Lognormal and Rayleigh are recently developed [17]. Weibull distribution function is more favorable due to its simplicity, flexibility and adaptability features. The main disadvantage of Weibull distribution function arises in low and zero wind speeds [18]. However, most wind turbines operate between 3 and 25 m/s wind speeds. Therefore, this drawback is not problematic. Weibull distribution function can be obtained as follows [19]:

$$f(v,k,c) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (k > 0, v > 0, c > 1) \tag{3}$$

In Eq. (3), $f(v,k,c)$ is the wind speed probability, k is the shape factor and c is the scale factor. Furthermore, cumulative distribution function of Weibull distribution can be determined based on Eq. (4) by integrating from Eq. (3) [20].

$$F(v,k,c) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{4}$$

2.1.3. Weibull parameters

For computing Weibull probability density function, shape and scale parameters should be obtained primarily. For this aim, several analytical and empirical techniques such as Graphical Method (GP), Standard Deviation Method (SDM), Empirical Method of Lysen (EML), Maximum Likelihood Method (ML), Power Density Method (PDM) and Modified Maximum Likelihood Method (MML) were used in previous studies [21]. Among all, three of them are more accurate and are used in this research in order to obtain k and c. Shape factor, k, shows the wind distribution peak and the scale parameter, c, is an important parameter for representing the amount of wind in the studied area [22].

2.1.4. Standard deviation method

After calculating wind power density by using direct method, in the second approach standard deviation method is used. k and c factors are obtained by Eqs. (5) and (6) respectively [20].

$$k = \left(\frac{\sigma}{\overline{v}}\right)^{-1.086} \tag{5}$$

$$c = \frac{\overline{v}}{\Gamma(1 + 1/k)} \tag{6}$$

For calculating scale and shape parameters, mean wind speed and standard deviation should be defined according to Eqs. (7) and (8).

$$\overline{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{7}$$

where $\overline{v}$ is the mean wind speed and n is the total measurement periods.

$$\sigma = \left[\left(\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \overline{v})^2\right)\right]^{0.5} \tag{8}$$