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Original article

Evaluation of wind energy potential for different turbine models based on the wind speed data of Zabol region, Iran

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ABSTRACT

Adverse consequences arising from the use of fossil fuels on the environment has led mankind to introduce renewable sources of energy. Wind energy is one of the best alternatives (after hydropower) for fossil fuel energy in Iran. To calculate the wind energy potential in the Zabol district, Iran, wind speed values were taken from the meteorological station of the district during a 10-year period (2002–2011). The results showed that the average wind speed in the region is almost 6.5 $m.s^{-1}$. The lowest and highest wind speeds occur in cold and warm seasons, respectively. The diurnal wind speed analysis demonstrated that the fastest winds blow from 3 a.m. to 9 a.m. The assessment of wind energy potentiality was carried out with the help of Weibull and Rayleigh distributions. The yearly total power density and wind energy density were 424 $W.m^{-2}$ and 3720 $kW.h.m^{-2}$, respectively, which indicates that the Zabol city ranks in class 6 (which is a suitable area for wind turbine establishment). The wind rose diagram revealed that the dominant wind direction with the highest contribution in the region blows between 112.5° to 135°. Finally, the performance of different turbine models was done based on the Zabol wind speed data.

Introduction

High growth of world population and socio-economic development in recent decades has caused the increase in energy demands considerably [1]. According to the International Energy Outlook (IEO) data, the world energy consumption will grow by 56% between 2010 and 2040. The total world energy consumption rises from 524 to 630 Btu between 2010 and 2020. This value will be 820 Btu in 2040 [2]. Security of energy supplies and the environmental consequences of greenhouse gas (GHG) emissions are the most important concerns, which make the government to enhance the production of different forms of renewable energy. Wind is one of the best renewable energy sources, which is clean and can be converted to electricity easily [3]. Wind is caused by the air moving, which comes from the differences in atmospheric pressure. When a difference in atmospheric pressure exists, air layer moves from the higher to the lower pressure area, resulting in winds of various speeds. Based on worldwide statistics the global wind capacity reached 254,000 MW by the end of June 2012, out of which 16,546 MW were added in the first six months of 2012. This increase is 10% less than the electricity produced in the first half of 2011 (i.e. 18,405 MW). The global wind capacity was 196,692 MW in 2010. This value was 273,000 MW at the end of 2012. Almost a total share of 74% belongs to five countries: China, USA, Germany, Spain, and India [4]. The total wind installed capacity of Iran in 2011 was 109.4 MW which the Manjil district had 66% of the country capacity. Based on the statistics from Iran Renewable Energy Organization (IREO), there is just one active wind turbine in Zabol city with power capacity of 660 KW [5].

In order to use wind energy efficiently, it is necessary to assess the potential and feasibility of wind energy in a specific location by knowing the wind characteristics. Many studies have been conducted in different countries such as Saudi Arabia [6], Jordan [7], Chile [8], Egypt [9], Turkey [10] and Nigeria [11] to find the potential of wind energy. In Iran, Mostafaeipour [12] analyzed the wind speed of some cities in the Yazd province. Results of wind speed analysis at different heights (10, 20 and 40 m) indicated that most of the stations in the area have annual average wind speed of less than 4.5 $m\,s^{-1}$, which is not suitable for installation of wind turbines. Mirhosseini et al. [13] analyzed the 3-h wind speed data from the Semnan province of Iran for years 2003–2007 to calculate the potential of wind power. Results of Weibull distribution showed that the Damghan city had better potential for installation of wind turbines in the province. In a similar study, Saeidi et al.

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[14] analyzed the wind speed data of 2007 for two provinces (North and South Khorasan) of Iran. Results illustrated that these provinces have good conditions for wind turbines installation. Keyhani et al. [15] evaluated 3-h data for eleven years in the Tehran province. The dimension and shape parameters (k and c) of the Weibull distribution were calculated; and according to the results, it was concluded that the region is not suitable for installation of large-scale wind turbines. Other similar studies estimating the potential of wind energy in different regions of Iran are those of Mostafaeipour and Abarghooei [16] in Manjil (Guilan province), Mohammadi and Mostafaeipour [17] in Zarrineh, Mostafaeipour et al. [18] in Zahedan.

The Zabol lies on the north of Sistan-Baloochestan province. This province is among the most underdeveloped and poorest provinces of Iran and in order to reverse this situation, the government of Iran has been implementing new plans regarding exploiting renewable energy resources as an income source in this region. Because the primary observations shows that this district has a high wind energy potential, this paper aims to examine the wind energy potential by finding the Weibull and Rayleigh distribution parameters, determining the available power and energy density and performing wind rose graph.

Material and methods

Site details and wind speed profile

The Sistan-Baloochestan province with area of 187,500 km^2 is one of the largest provinces of Iran. The province is subject to different seasonal winds and wind is the most common resource in this distinct which can be exploited for generation of profits. The Zabol city is located at latitude 31° N and longitude 61° E (see Supporting Information file, Fig. S1). There already exists a wind turbine with capacity of 660 kW in the Zabol; however, primary observations showed that there is higher wind potential in this area, which has not yet been promoted.

Data of wind speeds and directions between 2002 and 2011 were collected from the Zabol meteorological station, which is located at 31°2′ N and 61°29′ E at 489.2 m above sea level. At the Zabol station, data are measured every 3 h by an anemometer and weathercock label, placed at height of 10 m above the ground. Changes of height have significant effects on wind speed. Since, the common turbine hub heights are 40 and 50 m, the wind speeds were adjusted to the corresponding heights (see Supporting Information file).

Weibull and Rayleigh distribution

Different probability distributions have been used for describing and analyzing wind data. Among all distribution functions, Rayleigh and Weibull probability distributions are the most accurate and adequate ones in analyzing wind. These functions can describe the characteristics of prevailing wind profile precisely [19,20]. To use the Weibull probability distribution, it is necessary to calculate two parameters, the scale parameter (k) and the dimensionless shape factor (c). There are several methods to estimate Weibull parameters such as the Graphical, the Moment, the Standard deviation, the Maximum likelihood, the Energy pattern factor, and the Power density method [21]. According to Standard deviation method, the Weibull parameters (c and k) were calculated by using the following equations [22]:

$$k = \left(\frac{\sigma}{V_{avg}}\right)^{-1.086} \quad (1 \leqslant k \leqslant 10) \tag{1}$$

$$c = \frac{V_{avg}}{\Gamma(1 + \frac{1}{k})} \tag{2}$$

where V_{avg} is the average wind speed ($m.s^{-1}$), σ is the standard deviation of the wind speed data and Γ is the gamma function that can be expressed as [22]:

$$\Gamma(t) = \int_0^\infty e^{-x} x^{t-1} dx \tag{3}$$

where V_i is the wind speed, n the numbers of the wind speeds, and t is all complex numbers with a positive real part except the non-positive integers.

One the most common functions which shows the fraction of time in which an observed wind speed possibly prevails is Probability Density Function (PDF). The Weibull PDF is given by [19,22–24]:

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V_i}{c}\right)^{k-1} exp\left[-\left(\frac{V_i}{c}\right)^k\right] \tag{4}$$

where $f(V)$ is the probability of the measured wind speed V_i, c ($c > 1$) is the scale parameter and k ($k > 0$) is the dimensionless shape factor of distribution.

Many distributions, including the Weibull gives a null probability of observing null wind speeds. Takle and Brown [25] introduced the hybrid density probability to consider null wind speeds. Carta et al. [26] applied hybrid functions with several distributions and concluded that hybrid distributions do not offer advantages over the standard ones. Moreover, the frequency of calm and zero wind speeds in research area in average was just 0.015, therefore we decided to use standard Weibull distribution without any modification.

The Rayleigh distribution function is a simplified case of the Weibull distribution where the dimensionless shape factor of the distribution is fixed ($k = 2$).

To evaluate the accuracy of the distribution functions the coefficient of determination (R^2), the Root Mean Square Error (RMSE), and the Mean Absolute Percentage Error (MAPE) were applied. The coefficient of determination (R^2) is interpreted as the goodness of fit. This parameter shows that how much the model describes the amount of the variables and is expressed as [27]:

$$R^2 = \frac{\left(\sum_{i=1}^N (X_{obs} - \overline{X_{obs}}) \cdot (X_{pre} - \overline{X_{pre}})\right)^2}{\sum_{i=1}^N (X_{obs} - \overline{X_{obs}})^2 \cdot \sum_{i=1}^N (X_{pre} - \overline{X_{pre}})^2} \tag{5}$$

where Xobs is the observed values, Xpre is the predicted values, and N is the number of observations.

The RMSE which should be as close to zero as possible is widely used and expressed as [27]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (X_{obs} - X_{pre})^2}{N}} \tag{6}$$

The mean absolute of the percentage errors (MAPE) of forecasts shows the average of percentage deviation between the predicted values and the observed values and can be formulated as [17]:

$$MAPE = \frac{1}{N}\sum_{i=1}^N \left|\frac{X_{pre} - X_{obs}}{X_{obs}}\right| \times 100 \tag{7}$$

The corresponding Cumulative Probability Function (CDF) of the Weibull distribution is [20,23]:

$$F(V) = 1 - exp\left[-\left(\frac{V_i}{c}\right)^k\right] \tag{8}$$

where $F(V)$ is the CDF of the measured wind speed (V_i).