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Evaluation of Wind Power Potential for the Generation of Energy at Marvast Synoptic Station-Yazd, Iran

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Abstract

At Marvast synoptic station (30°:30′N, 54°:15′E), Yazd, the wind speed data at an interval of three hours, at the height of 10 meters from ground level for a period of 10 years (1996-2005) has been taken from Yazd Meteorology, After calculating C and K parameters through least squares fitting, distinct wind speed data was distributed with Weibull distribution In the present research, wind energy potential has been studied for a period of ten function. Then, wind characteristics at 10 m height were converted to 50 m height (height of almost every axis of wind turbine). The conversion was brought about by applying one seventh power law. Wind power density at Marvast synoptic station is equal to 223.224 and 444.94 W/m^2 at the height of 10 and 50 meters, respectively. It can be inferred that high wind power density and the other influential characteristics effecting the determination of wind power potential at this station makes this location potentially favorable for the establishment of wind turbines.

Moreover, in the process of this study, a new method, easier and shorter, has been obtained that can be applied for computing wind existence hours at an area.

Keywords: *Wind Energy Potential; Wind Turbine; Weibull Distribution Function; Wind Power Density; One Seventh Power Law; Marvast.*

1. Introduction

The worldwide concern and environmental awareness of air quality created a move towards pollution free energy production such as solar and wind energies. Wind is an abundant resource available in nature that can be utilized by mechanically converting wind power to electricity. Wind turbines are especially meant for this purpose.

The gradual increase in the earth population and the increasing demand for energy from natural resources have been the major causes for man to search for an appropriate substitution for the sources of energy. Having been aware of the decrease of the earth's energy resources, scientists have cautioned against the surplus use of energy. Moreover, environmental pollutions resulting from the burning of fossil fuels in the power stations have led to energy loss. This phenomenon is a threat to every living creature on the earth. Thus, the appropriate use of energy and the involvement of new sources of energy have been the focus of study for a long time. An appropriate solution to lower the impact of energy loss is the substitution of renewable forms of energies such as wind.

World winds hold almost around 2700 TW potential energy - 25% of this energy occupies an environment of 100 meters above the ground level. It is noteworthy that 10% of this energy, i.e. 4 TW exceeds the capacity of the world's total water energy [10].

Although Iran has been a pioneer in the use of wind energy, we have yet to witness the applications of wind energy which have been extremely limited. But the remnants of the numerous windmills all over the country support our claim that undoubtedly wind energy must have been of importance.

This project attempts to discover not only potential power of wind energy but also the feasibility of using wind power at Marvast synoptic station in the south of Yazd.

2. Materials and method

Since wind is a vector quantity having direction and speed, it is subject to topographical and atmospheric changes. It is impossible to make an estimation of wind direction and wind speed at intervals in which wind speed is not reported. Moreover, this estimation is not error-free. To reduce the impact of this error, the researcher took raw data from Yazd Meteorology for a period of 10 years, between 1996 and 2005. The data reported wind direction and wind speed at Marvast synoptic station for the consecutive years. Then wind data were converted from Knot to m/s (1 Knot = 0.514 m/s).

All the graphs, tables and data in the project were analyzed by applying Excel and SPSS 17. In order to process the data the mathematical model Weibull Probability Distribution Function is used. Probability Distribution Function is the most applicable strategy to the study and calculation of wind statistics at a specific location. After the calculation of the components of this function, some parameters relating to the calculation of wind energy can be estimated.

3. Theory of analysis

There are several mathematical functions called probability density functions that can be applied to model the wind speed frequency curve by substituting the data obtained for the period of ten years from Yazd Meteorology. In wind power studies, Weibull and Rayleigh probability density functions are commonly used and widely adopted [8]. Herein Weibull distribution used since the Rayleigh distribution is only a subset of it.

3.1. Weibull distribution function of wind speed

Wind power is proportionate to the cubic power of the wind speed and rotor's diameter square root power [7]. Thus, wind speed is one of the most significant factors in the optimum use of wind energy.

In the calculation of wind energy, wind speed is considered a random variable which can take every quantity in a specific distance. However, practically wind speed data recorded every 3 hours at synoptic stations. The function of which is a disconnect function. In other words, the frequency distribution should be first replaced by the connected distribution function. For this purpose Weibull probability distribution function is reliable and is the most frequently used model to describe the distribution of the wind speed [3].

Weibull distribution function is a derivative of Gamma distribution and has a higher flexibility in comparison with Rayleigh distribution. It can be defined as follows:

$$P(V) = \frac{k}{C} \cdot \left[\frac{V}{C}\right]^{K-1} \exp\left(-\left[\frac{V}{C}\right]^{K}\right) \quad (1)$$

where V [m/s] is the wind speed, K [-] is the Weibull shape parameter describing the dispersion data and C [m/s] is the Weibull scale parameter.

Values of the two parameters, K and C, can be calculated by using the least square fitting of the data [12] i.e.

$$Y = A + B \cdot X \quad (2)$$

Where

$$Y_i = \ln(-\ln(1 - p(V_i))) \quad (3)$$

And

$$X_i = \ln v_i \quad (4)$$

Where v_i [m/s] is the mean of wind speed classes, P[V_i]is the accumulative probability of the frequency of every mean speed classes. By quantities of X and Y, the values of A and B can be calculated using the following equation:

$$A = \frac{n \cdot \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n \cdot \sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} x_i} \quad (5)$$

$$B = \frac{1}{n}\sum_{i=1}^{n} y_i - \frac{A}{n}\sum_{i=1}^{n} x_i \quad (6)$$

Here, A is the gradient of the equation of a straight line Y=AX+B, B is the width of the intersection of the line by the Y axis. In this equation, the relationship between A and B and the Weibull parameters K and C is as follows [4]:

$$K = A \quad \text{and} \quad C = \exp\left(\frac{-B}{A}\right) \quad (7)$$

A brief presentation of the observations and measurements of wind speed at Marvast synoptic station, between the years of 1996-2005 is indicated in ***Table 1***.

Considering *equations (3)* and *(4)*, v_i and $P(V_i)$ are substituted with X_i and Y_i, so that A and B quantities can be calculated by liner regression equation or least square line of X_i and Y_i values. These values are shown in ***Table 2***.

After computing X_i and Y_i quantities, A and B quantities related to shape and scale parameters of Weibull function can be determined. Then, we are able to draw a line Y=AX+B which is the line nearest to points, when compared with X_i and Y_i.

The numerical values of A=K, B and C obtained from Marvast synoptic station are presented respectively as follows: 2.5814, -5.0093 and 6.9625.

Weibull probability function quantities (P_w) are presented in ***Table 1***. These quantities are computed using Weibull scale and Form parameters. Also, v_i numerical values, in ***Table 1*** (mean of wind speed classes) were computed through *equation 1*.

TABLE 1. Arrangement of the measured three hourly time-series data in frequency distribution format for 1996-2005 and the probability density distributions calculated from the Weibull function at Marvast synoptic station.

i	Wind speed classes [m/s]v	Mean of wind speed classes v_i[m/s]	Frequency f_i	Probability $p(_iv)$	accumulative probability $P(_iv)$	Probability in Weibull model $P_w(v_i)$
1	0.5 - 1.5	1	15	0.00100963	0.00101	0.0171176
2	1.5 - 2.5	2	110	0.00740392	0.008414	0.0495494
3	2.5 - 3.5	3	3757	0.25287743	0.261291	0.0873856
4	3.5 - 4.5	4	2862	0.19263647	0.453927	0.1215021
5	4.5 - 5.5	5	4838	0.32563775	0.779565	0.1435289
6	5.5 - 6.5	6	1164	0.07834691	0.857912	0.1482912
7	6.5 - 7.5	7	795	0.05351013	0.911422	0.1356503
8	7.5 - 8.5	8	483	0.03250993	0.943932	0.1103809
9	8.5 - 9.5	9	288	0.0193848	0.963317	0.0799678
10	9.5 - 10.5	10	279	0.01877903	0.982096	0.0515178
11	10.5 - 11.5	11	85	0.00572121	0.987817	0.0294419
12	11.5 - 12.5	12	73	0.00491351	0.992731	0.0148789
13	12.5 - 13.5	13	40	0.00269233	0.995423	0.0066253
14	13.5 - 14.5	14	22	0.00148078	0.996904	0.0025894
15	14.5 - 15.5	15	24	0.0016154	0.998519	0.0008847
16	15.5 - 16.5	16	10	0.00067308	0.999192	0.0002631
17	16.5 - 17.5	17	5	0.00033654	0.999529	0.0000679
18	17.5 - 18.5	18	1	0.00006731	0.999596	0.0000151
19	19.5 - 20.5	20	3	0.00020193	0.999798	0.0000005
20	20.5 - 21.5	21	1	0.00006731	0.999865	0.0000001
21	24.5 - 25.5	25	1	0.00006731	0.999933	0
22	25.5 - 26.5	26	1	0.00006731	1	0
		Total	14857	1		

TABLE 2. The numerical values of liner equations, between X and Y, for the determination of A and B, in relation to Weibull parameters K and C.

i	$Y_i = \ln(-\ln(1 - P(V_i)))$	$X = \ln V_i$
1	-6.897671187	0
2	-4.773691083	0.693147181
3	-1.194513763	1.098612289
4	-0.502521166	1.386294361
5	0.413534639	1.609437912
6	0.668500617	1.791759469
7	0.885367211	1.945910149
8	1.058204365	2.079441542
9	1.195569783	2.197224577
10	1.391960803	2.302585093
11	1.483359678	2.397895273
12	1.594140539	2.48490665
13	1.683936426	2.564949357
14	1.753985778	2.63905733
15	1.874135447	2.708050201
16	1.963093068	2.772588722
17	2.036053271	2.833213344
18	2.055976752	2.890371758
19	2.140961542	2.995732274
20	2.187519775	3.044522438
21	2.262411473	3.218875825
22	2.779942594	3.258096538

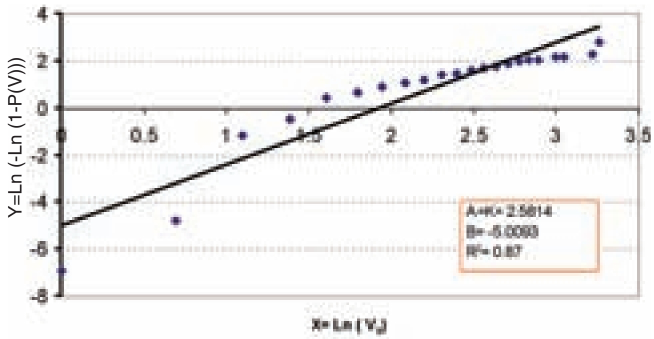

Figure 1. Least square line ,through which the parameters K and C are estimated.

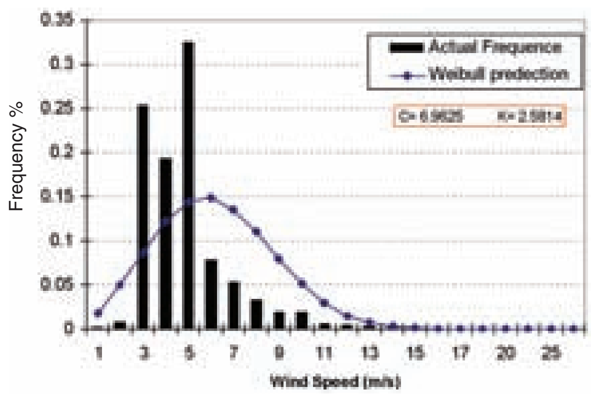

Figure 2. Wind speed frequency with fitted Weibull distribution for Marvast synoptic station at 10 m height.

In *Figure 2* with the help of Weibull distribution function the computation quantities for wind speed occurrence at Marvast synoptic station, and the factual wind speed occurrence has been drawn. Numerical representations of wind speed are distributed in the graph and are connected by the continuous line drawn with the help of Weibull function. By comparing them, the wind speed disconnected quantities substituted in a curve Contiguous can be observed.

3.2 Calculation of efficacious parameters in wind energy potential estimation

As the scale and shape parameters have been calculated, two meaningful wind speeds for wind energy estimation, i.e. the most probable wind speed and the wind speed carrying maximum energy, can be simply obtained. The most probable wind speed denotes the most frequent wind speed for a given wind probability distribution and is expressed as follows [11]:

$$V_{MP} = C\left(\frac{K-1}{K}\right)^{1/K} \tag{8}$$

The wind speed carrying maximum energy represents the wind speed which carries the maximum amount of wind energy, and is expressed as follows [4]:

$$V_{MaxE} = C\left(1+\frac{2}{K}\right)^{1/K} \tag{9}$$

The average wind speed (V) and wind speed standard deviation (σ) can be calculated through the following equations [11]:

$$V = C\Gamma\left(\frac{K+1}{K}\right) \tag{10}$$

$$\sigma = C\sqrt{\left[\Gamma\left(\frac{K+2}{K}\right)-\Gamma^2\left(\frac{K+1}{K}\right)\right]} \tag{11}$$

where Γ denotes the Gamma function.

The probability of wind speeds between v_1 and v_2 is given by [13]:

$$P(v_1 \langle v \langle v_2) = \exp\left[-\left(\frac{v_1}{C}\right)^K\right] - \exp\left[-\left(\frac{v_2}{C}\right)^K\right] \tag{12}$$

Wind turbines are designed with a cut-in speed, or the wind speed at which it begins to produce power, and a cut-out speed, or the wind speed at which the turbine will be shut down to prevent the drive train from being damaged. For most wind turbines, the range of cut-in wind speed is 3.0_4.5 m/s, and the cut-out speed can be as highly as 25 m/s [13].

3.3 Wind power density

The evaluation of wind power density per unit area is of fundamental importance in assessing wind power projects. Wind power density, expressed in Watt per square meter (W/m^2), takes into account the frequency distribution of the wind speed and the dependence of wind power on air density and the cube of the wind speed [1]. Therefore, wind power density is generally considered a better indicator of the wind resource than wind speed. Wind power density of a site based on a Weibull probability density function can be expressed as follows [8,4]:

$$\frac{P}{A} = \frac{1}{2}\rho C^3\Gamma\left(\frac{K+3}{K}\right) \tag{13}$$

where ρ is the mean air density (usually taken as equal to 1.225 kg/m^3 which depends on altitude, air pressure, and temperature) [6], and Γ denotes the Gamma function. Once wind power density of a site is given, the wind energy density for a desired duration (a month or a year) can be expressed as [5]:

$$\frac{E}{A} = \frac{1}{2}\rho C^3\Gamma\left(\frac{K+3}{K}\right)T \tag{14}$$

Where T is the time period (or duration), for example, T is 720 hr for monthly duration.

The problem of transforming Weibull parameters at the hub heights of the wind turbines can be easily solved with the compatible features of Weibull distribution. Weibull function facilitates the presentation of the wind speed distribution thereby making it possible for the researcher to transform the wind speed distribution at 10 m height to the distribution at any other height. This is done by applying the so called one seventh power law [2]:

$$\frac{C_2}{C_1} = \left(\frac{Z_2}{Z_1}\right)^{1/7} \tag{15}$$

where c_2 and c_1 are the Weibull scale parameters at heights z_2 and z_1, respectively. Even if the Weibull shape parameter, k, varies with height, the variation is small.

4. Computing wind existence hours at an area

In the previous studies, in order to obtain total wind hour existence wind hours in each speed class throughout a year were computed and then the cumulative quantities were achieved.

In the present research, a new equation is obtained which provides a simpler and easier method to estimate wind hour existence at an area. The equation is as follows:

$$WE_{(h/y)} = \left(\frac{\sum f_i}{N}\right).T \tag{16}$$

where WE stands for Wind Existence, (h/y) is the unit of measuring the parameter, hour by year, f_i is the frequency of wind speed classes or the quantities presented in *Table 1*, column 4. N is the length of the statistical period under study in a year, and T is the time interval between the wind data records in hours. Quantities for the parameter in Marvast synoptic station are 14857, 10 and 3, respectively.

The total amount of wind hour existence at the synoptic station under study was 4457.1 h/y.

Conclusions

Wind power density is an essential factor in locating places suitable for the installation of wind turbines. At Marvast synoptic station, wind power density was 223.22 and 444.94 W/m^3 at a height of 10 and 50 meters from ground level, respectively. In the classification of areas suitable for wind turbine installation, wind power density raging from 200 to 250 W/m^3 is considered. The lowest wind speed recorded at the station under study was 4.84 m/s at a height of 50 m in the month of September, and the most probable yearly wind speed at the same height were 7.25 m/s.

According to *equation (12)*, the probability of a wind speed between 3 and 25 m/s was 94% of total wind hour existence (4457.1 h/y) at the height of 50 m. Therefore, the economical operation for wind turbines in this place is estimated to be about 4190 h/y.

The average monthly wind speed at 50 m height for all the months of a year, except September which is 4.99 m/s, is estimated to be more than 5 m/s. It is to be noted that the maximum wind speed recorded was in the month of March and April, 7.14 and 7.1 m/s, respectively. The yearly average of wind speed is 7.78 m/s. Each of these speeds can be the working speed level for wind turbines.

The difference between the most probable wind speed and the wind speed carrying maximum energy in the place under study, annually, is less than 3.7 which show the trivial difference between the maximum probability of wind speed and the wind speed which provides the highest amount of energy.

The wind speed standard deviation at the height of 10 m -based on real observations- is less than 2.66 in monthly and yearly computation. That is, the observed wind speed in the place under study is of acceptable stability and high harmony.

Relating to the high wind power density at 50 m and the other influential factors, Marvast synoptic station, Yazd can be a suitable site for the establishment of wind turbines leading to cost free natural energy source.

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