The wind energy potential in the coasts of Persian Gulf used in design and analysis of a horizontal axis wind turbine

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Abstract: There are many wind synoptic stations installed all over Iran. One of these stations in the coasts of Persian Gulf is Bardekhun station in Bushehr province. The goal of this study is to assess the wind energy potential of this region and to design a proper horizontal axis wind turbine for this site. The one-year measured hourly time-series wind speed data are extracted from measurements at a height of 10m, 30m and 40m above the ground level. The Weibull distribution gives the mean wind speed of 4.50 m/s, 5.36 m/s and 5.83 m/s and the power density per year of 125 W/m^2, 196 W/m^2 and 253 W/m^2 respectively for these heights. According to these results, a small wind turbine can be installed in the height of 30m and 40m. A MATLAB code using the blade-element-momentum theory has been developed to design and analyze the three-blade wind turbine rotor. After calculation of geometrical parameters of rotor blade, the rotor power coefficient versus rotor tip speed ratio is evaluated. The energy produced per year by this wind turbine using the Weibull distribution for wind speed will be 155MWh.

Keywords: *Wind potential, Weibull distribution, Wind turbine, produced energy*

1. Introduction

Annual growth in energy consumption and global warming are two important reasons for considering wind as an efficient and clean source of energy. Iran (Persia) is exposed to the continental streams from Asia, Europe, Africa, Indian and Atlantic Pacific. The first vertical axes and drag type windmills on record were built by the Persians in approximately 900 AD [1]. According to the research and studies, it has been estimated that the wind energy potential in Iran is more than 10000 MW for electricity production [2]. There are two wind farm producing electricity in Iran: a 70MW power plant in Manjil and a 28MW power plant in Binalood. Since Iran has many windy regions, utilization of this type of energy would not only be possible but also economically feasible. The Ministry of Energy has serious programs for the evaluation of the wind energy potential in the country. At the first stage, the country's wind energy potential evaluation is performed for a wide range of the country. At the second stage, after the exact investigation on the wind potential, the Iran's wind atlas is prepared. To prepare the wind atlas, 53 wind synoptic stations have been installed all over Iran [3]. These stations record wind data every 10 min. Also, the effects of thunderstorms and turbulences on wind stream are considered in the results.

In the recent years, many researchers have studied the wind energy potential in Iran. Mostafaeipour and Abarghooei [4] investigated the wind energy potential in Manjil area in the north of Iran. They reported it is one of the best locations in the world for installing wind turbine. Mostafaeipour [5] utilized wind speed data over a period of almost 13 years between 1992 and 2005 from 11 stations in Yazd province to assess the wind power potential at these sites. The results showed that most of the stations have annual average wind speed of less than 4.5 m/s which is considered as unacceptable for installation of the wind turbines. Keyhani et al [6] used the statistical data of eleven years wind speed measurements of the capital of Iran, Tehran to find out the wind energy potential. They concluded that the site studied is not suitable for electric wind application in a large-scale and the wind potential of the region can be adequate for non-grid connected electrical and mechanical applications, such as wind generators for local consumption, battery charging, and water pumping. Mostafaeipour [7] performed an analysis of offshore wind speed in global scale and also studied feasibility of introducing this technology for harnessing wind in Persian Gulf, Caspian Sea, Urmia Lake and Gulf of Oman. He suggested that policy makers to invest and pay more attentions toward harnessing renewable energy sources like offshore wind in Persian Gulf and Gulf of Oman in southern parts of Iran.

This paper presents a study of the wind energy potential in the Bardekhun station. Knowledge of the wind speed distribution is a very important factor to evaluate the wind potential in the windy areas. The Weibull distribution is the best one, with an acceptable accuracy level. A stall-regulated horizontal wind turbine with nominal power of 50kW is designed for this wind station. A MATLAB code was written based on the BEM theory. This code utilizes a generalized rotor design procedure in determining the final blade shape and performance iteratively considering drag, tip losses, and ease of manufacture.

2. Site description and the wind data

This site is located in the vicinity of Deyer port in Bushehr province in the coasts of Persian Gulf. It is situated in the latitude of 27°98' N, the longitude of 51°49' W and the altitude of 4m. Its distance from capital city of Iran, Tehran, is about 1330 km. A well known wind in this region is North Wind which has effect on the architectural and environmental design of buildings. The one-year measured hourly time-series wind speed data, from January 1, 2007 to December 31, 2007 are extracted from Renewable Energy Organization of Iran, SUNA [2].

3. Wind data analysis

3.1. Weibull distribution

Statistical analysis can be used to determine the wind energy potential of a given site and to estimate the wind energy output at this site [1]. This type of analysis relies on the use of the probability density function, *p(U)*, of wind speed. One way to define the probability density function is that the probability of a wind speed occurring between U_a and U_b is given by:

$$p(U_a \le U \le U_b) = \int_{U_a}^{U_b} p(U)dU \tag{1}$$

Where U is wind speed and $\int_0^\infty p(U)dU = 1$.

In general, Rayleigh and Weibull probability density functions are used in wind data analysis. The Rayleigh distribution uses one parameter, the mean wind speed ($\overline{U}$). Determination of the Weibull probability density function requires knowledge of two parameters: *k*, shape factor and *c*, scale factor. Both these parameters are a function of wind speed, *U,* and standard deviation of wind speed, σ_U. The Weibull probability density function is given by:

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^k\right] \tag{2}$$

The cumulative distribution function of the speed *U* gives us the fraction of time (probability) that the wind speed is equal or lower than *U*. the cumulative distribution *F (U)* is given by:

$$F(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^k\right] \tag{3}$$

The parameters *c* and *k* are calculated based on the following empirical formulas [1, 8]:

$$k = \left(\frac{\sigma_U}{\overline{U}}\right)^{-1.086}, \frac{c}{\overline{U}} = \frac{k^{2.6674}}{0.184 + 0.816k^{2.73855}} \tag{4}$$

Annual energy produced by a wind turbine with performance curve $P_w(U)$ is [1, 9]:

$$\overline{P_w} = 365 \times 24 \int_0^\infty p(U)P_w(U) = 365 \times 24 \times \sum_{i=1}^{N_B} \frac{1}{2}(U_{i+1} - U_i)(p(U_{i+1})P_w(U_{i+1}) + p(U_i)P_w(U_i)) \tag{5}$$

3.2. Power density

The wind power per unit area, or wind power density, is proportional to the density of the air (for standard conditions sea-level, 15°C, the density of air is 1.225 kg/m^3), the area swept by the rotor (or the rotor diameter squared for a conventional horizontal axis wind machine) and the cube of the wind velocity. The average wind power density is:

$$\frac{\overline{P}}{A} = \frac{1}{2}\rho\int_0^\infty U^3 p(U)dU \tag{6}$$

4. Wind turbine aerodynamic design

The primary aerodynamic factors affecting the blade design are: design rated power and rated wind speed, design tip speed ratio, solidity, airfoil, number of blades, rotor power control (stall or variable pitch), rotor orientation (upwind or downwind of the tower) [1]. The analysis here uses momentum theory and blade element theory. Momentum theory refers to a control volume analysis of the forces at the blade based on the conservation of linear and angular momentum. Blade element theory refers to an analysis of forces at a section of the blade, as a function of blade geometry. The results of these approaches can be combined into what is known as strip theory or blade-element- momentum (BEM) theory. This theory can be used to relate blade shape to the rotor's ability to extract power from the wind. The analysis in this paper covers a simple optimum blade design including wake rotation and an infinite number of blades. This blade design can be used as the start for a general blade design analysis. The forces on the blades of a wind turbine can also be expressed as a function of lift and drag coefficients and the angle of attack. In this analysis, the blade is assumed to be divided into *N* sections (or elements) [1, 9].

5. Results and discussions

5.1. Wind energy potential

The data collected for an interval of 10 min have been used to analyze the wind energy potential of this site. All measurements in the wind station are recorded using the cup anemometer at a height of 10m, 30m and 40m above the ground level.

5.1.1. Wind speed distribution

The most critical factor influencing the power developed by a wind energy conversion system is the wind speed. Due to the cubic relationship between speed and power, even a small variation in the wind speed may result in significant change in power.

Results of wind data analysis at three different heights have been summarized in Table 1.The mean wind speed, mean cubic wind speed, standard deviation of wind data and the Weibull distribution parameters for each height are calculated. Maximum wind speed per year and its occurrence time can be used in control and structural analysis of wind turbines. These results obtained for one-year measured data.

Table 1. Results of wind data analysis at different heights

	Height		
	40m	30m	10m
Mean wind speed (m/s)	5.83	5.36	4.50
Mean cubic wind speed (m/s)	7.50	6.96	6.00
Standard deviation	3.313	3.042	4.506
Max. wind speed per year (m/s)	33 (11/4/2007 23:50)	31.1 (11/4/2007 23:50)	28.2 (15/3/2007 11:00)
Weibull distribution constants	k=1.848 c=6.568	k=1.850 c=6.037	k=1.737 c=5.058

The corresponding average wind speeds and best fits to the Weibull distribution at 30m and 40m height in comparison with the distribution of measured data are shown in Fig.1. The Weibull scale and shape factors can be found in Table 1 at each height. As shown in Fig. 1(a), the Weibull distribution function reaches the top point at about 4.00 m/s with a value of about 13.54%, however the Weibull distribution function in Fig. 1(b) reaches the top point at about 4.00 m/s with the value of frequency equal to 12.39%.

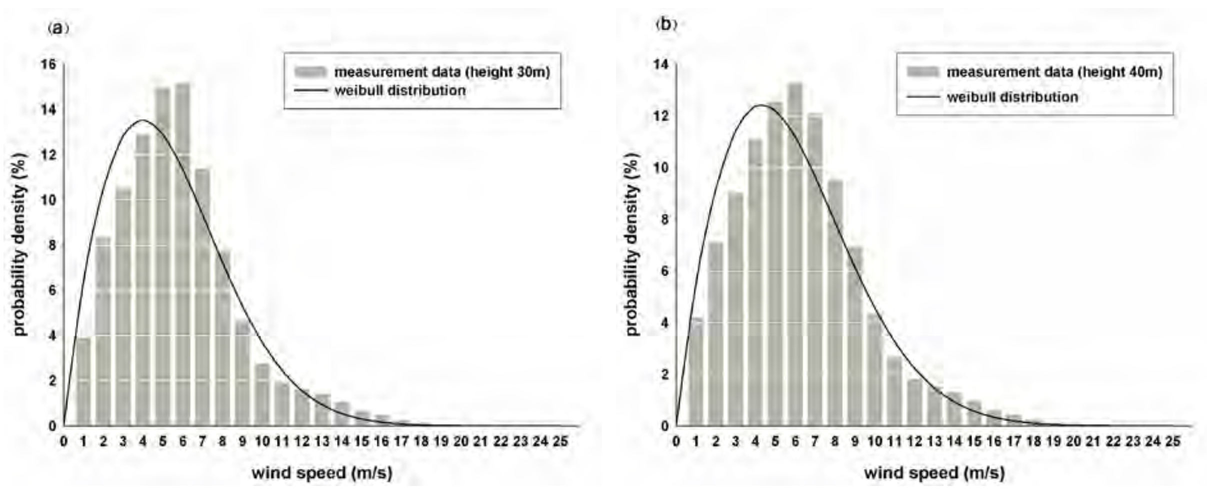

Fig. 1. Weibull probability distribution function at (a) 30m (b) 40m

Fig. 2(a) illustrated the Weibull distribution function at the height of 10m. The distribution of measured data can be seen in this figure. The Weibull distribution reaches to the maximum frequency of 15.61% at the wind speed around 3.00m/s. The cumulative distribution functions at three given heights are shown in Fig. 2(b). According to this figure, the cumulative density at 40m gets up to 56.50% for mean wind speed of 5.83m/s. This probability is 52.62% and 50.47% for mean wind speed of 5.36m/s and 4.50m/s at 30m and 10m heights, respectively.

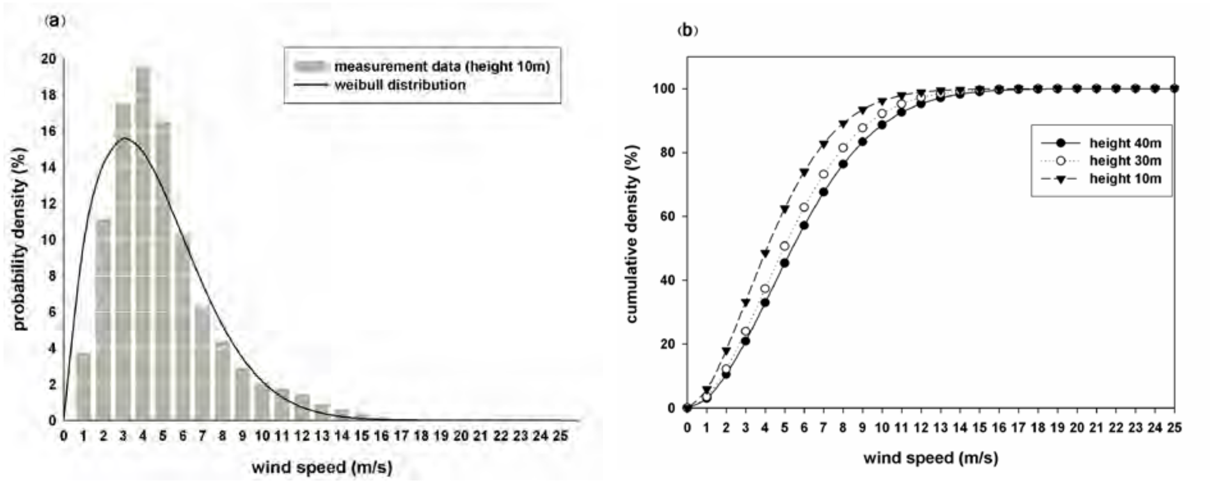

Fig. 2. (a) Weibull probability distribution function at 10m (b) Cumulative function at three heights

5.1.2. Estimation of monthly wind potential

The monthly distribution of the wind speed measured between January 1, 2007 and December 31, 2007 is plotted in Fig. 3(a). It can be seen from this figure, the wind speeds vary between 3.34 and 7.52 m/s. According to these results, the average speed for 10 m is 4.50 m/s. This is below the minimum speed, 5.0 m/s, required for effective wind turbines, but it is enough for water pumping applications. The monthly average wind power density at height of 40m is illustrated in Fig. 3(b). The wind potential of a site, i.e. average power density, which is proper to run a wind turbine, is qualitatively estimated based on the following [1]: $\overline{P}/A<100$ W/m^2 is a poor potential, $\overline{P}/A\approx 400$ W/m^2, is a good potential, and $\overline{P}/A>700$ W/m^2 is a great potential. Here, there is a poor potential in October, September and August, because the power density is near to 100 W/m^2 in these months. For the reminders of the year, there is a reasonable potential.

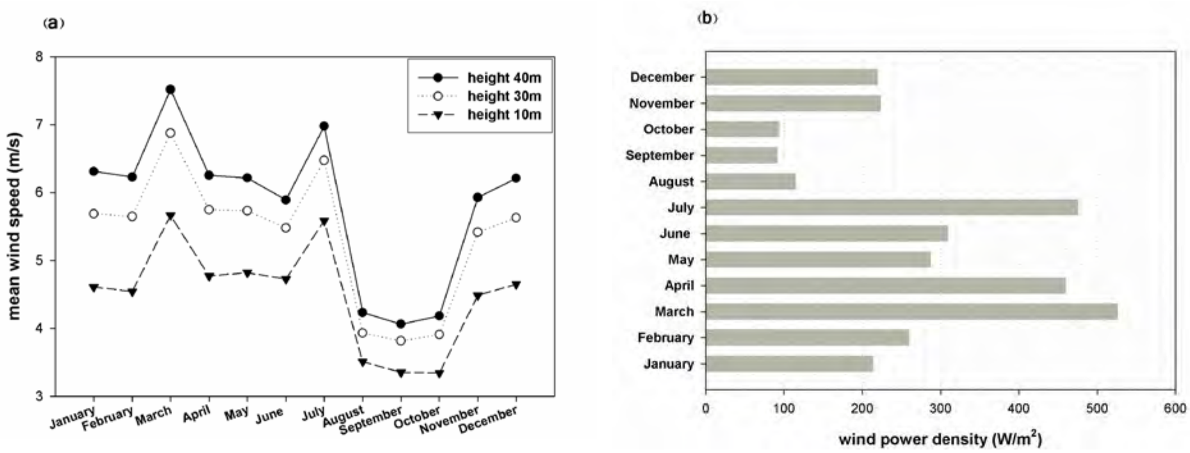

Fig.3. (a) Monthly average wind speed at three heighs (b) Monthly power density at 40m

5.1.3. Wind potential in the site

If annual average wind speeds are known for a certain site, the average wind power density can be found over these regions. Fig. 4 illustrates the power densities per year at three heights. These power densities are drawn for measured data and for the Weibull distribution function. The Weibull distribution function illustrates power density per year a little lower than measured data. The wind power density per year at height of 10m is suitable for water pumping, because it is not actually a good potential. The power density at height of 40m and 30m are more reasonable. A proper wind turbine can be run by the wind at these heights. In the next section, a wind turbine designed and proposed for installation at 40m.

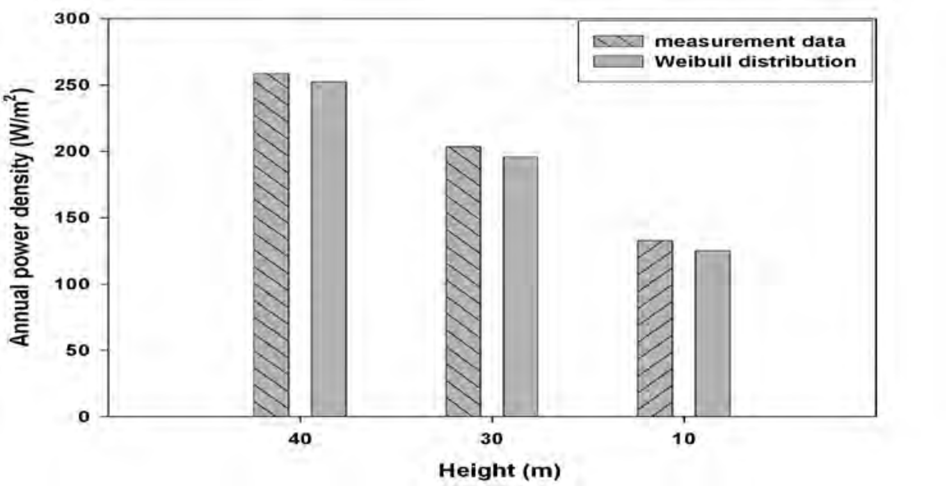

Fig.4. power density per year at three heights

5.2. Wind turbine design and performance results

In order to utilize the wind energy potential for the mentioned site, a power of 50kW is needed at 7.50m/s wind speed (mean cubic wind speed at 40m height). For this purpose, a 3-blade, stall-regulated and upwind horizontal axis wind turbine (HAWT) has been designed based on the BEM theory. The blade has NACA 4415 airfoil and has a tip speed ratio of λ=6.

5.2.1. Blade geometry

To develop the maximum possible power coefficient (C_p) requires suitable blade geometry. The geometrical parameters for blade design are shown in Table 2. Assume the mechanical efficiency and the overall rotor power coefficient are 0.99 and 0.40, respectively. With these assumptions, the radius of rotor will be R=13m. The blade is divided into *N* elements (usually 10-20). The first column, r/R, is fraction of rotor radius. The straight line connecting the leading and trailing edges is the chord line of the airfoil, and the distance from the leading to the trailing edge measured along the chord line is designated as the chord, *c*, of the airfoil (second column in Table 2). The section pitch angle (θ_p) is the angle between the chord line and the plane of rotation. $\theta_{p,0}$ is the blade pitch angle at the tip. The relative wind is the vector sum of the wind velocity at the rotor and the wind velocity due to rotation of the blade. The angle between the chord line and the relative wind is the angle of relative wind ($\varphi = \theta_p + \alpha$).The blade twist angle is the difference between section pitch angle and the blade pitch angle at the tip, i.e. $\theta_T = \theta_p - \theta_{p,0}$. The design aerodynamic condition occurs when C_d/C_L is at a minimum for each blade section. The aerodynamic properties of the airfoil at each section, i.e. C_L-α (lift coefficient vs. angle of attack) and C_d-α (drag coefficient vs. angle of attack) can be obtained from the empirical curves.

Table 2. Blade design of a 26m-diameter Rotor

r/R	Chord (m)	Twist angle (degree)	Angle of relative wind (degree)	Section pitch (degree)
0.0500	2.0091	42.5590	48.8672	42.8672
0.1000	2.6631	33.0493	39.3575	33.3575
0.1500	2.6778	25.7003	32.0085	26.0085
0.2000	2.4742	20.2288	26.5370	20.5370
0.2500	2.2268	16.1518	22.4600	16.4600
0.3000	1.9939	13.0615	19.3696	13.3697
0.3500	1.7907	10.6673	16.9753	10.9756
0.4000	1.6174	8.7717	15.0793	9.0799
0.4500	1.4704	7.2405	13.5474	7.5488
0.5000	1.3453	5.9818	12.2870	6.2900
0.5500	1.2380	4.9307	11.2330	5.2389
0.6000	1.1450	4.0412	10.3374	4.3494
0.6500	1.0634	3.2794	9.5639	3.5876
0.7000	0.9903	2.6201	8.8820	2.9283
0.7500	0.9225	2.0443	8.2625	2.3525
0.8000	0.8558	1.5373	7.6712	1.8455
0.8500	0.7825	1.0876	7.0541	1.3958
0.9000	0.6856	0.6861	6.2952	0.9943
0.9500	0.5029	0.3255	4.9618	0.6338

5.2.2. HAWT performance curves

The Betz limit, $C_{P,max}= 0.59$, is the maximum theoretically possible rotor power coefficient. In practice three effects lead to a decrease in the maximum achievable power coefficient: rotation of the wake behind the rotor, finite number of blades and associated tip losses, and non-zero aerodynamic drag [1]. Although the blade has been designed for optimum operation at a specific design tip speed ratio, the performance of the rotor over all expected tip speed ratios needs to be determined. The results are usually presented as a graph of power coefficient versus tip speed ratio, called a C_P-λ curve, as shown in Fig. 5(a). The maximum value of C_P in C_P-λ curve, Fig. 5(a), is 0.4586 at λ=6. C_P-λ curves can be used in wind turbine design to determine the rotor power for any combination of wind and rotor speed. They provide immediate information on the maximum rotor power coefficient and optimum tip speed ratio.

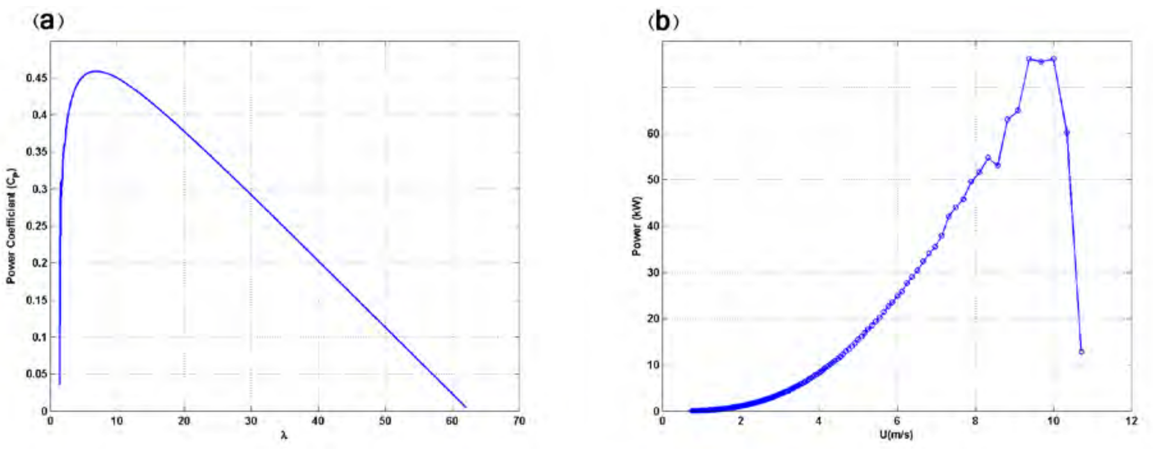

Fig. 5 (a) C_P-λ curve (b) Rotor power vs. wind speed

Fig. 5(b) illustrates the power produced by the wind turbine in various wind speeds. In order to estimate the energy captured per year by this wind turbine, $p(U)$ and $P_w(U)$ are obtained from Fig. 1(b) and Fig. 5(b) respectively and are put in the Eq. (5). So, the energy of the wind turbine per year will be 155 MWh.

6. Conclusions

In this study, a site in the coasts of Persian Gulf was evaluated for wind potential. Statistical analysis of wind data at three heights, 10m, 30m and 40m, showed that there is a promising wind potential for installing wind turbine at height of 30 and 40m. The power density per year at these two heights was 253 and 196 W/m^2, respectively. In the second part of paper, a 50kW horizontal axis wind turbine was designed for installing at 40m. The energy produced per year by this turbine was 155MWh. The wind potential in this coastal region can be utilized for both water pumping and electricity generation by small wind turbine. It might be suitable for the rural parts of Bushehr.

References

[1] J.F. Manwell, J.G. McGowan, A.L. Rogers, Wind Energy Explained: Theory, Design and Application, John Wiley & Sons Ltd, 2002.

[2] Renewable Energy Organization of Iran, http://www.suna.org.ir/ .

[3] M. Ameri, M. Ghadiri and M. Hosseini, Recent Advances in the Implementation of Wind Energy in Iran, The 2nd Joint International Conference on Sustainable Energy and Environment (SEE 2006), Bangkok, Thailand, November 2006.

[4] A. Mostafaeipour and H. Abarghooei, Harnessing wind energy at Manjil area located in north of Iran, Renewable and Sustainable Energy Reviews, 12(6), 2008, pp. 1758-1766.

[5] A. Mostafaeipour, Feasibility study of harnessing wind energy for turbine installation in province of Yazd in Iran, Renewable and Sustainable Energy Reviews, 14, 2010, pp.93-111.

[6] A. Keyhani, M. Ghasemi-Varnamkhastia, M. Khanalia, and R. Abbaszadeh, An assessment of wind energy potential as a power generation source in the capital of Iran, Tehran, Energy, 35(1), 2010, pp. 188-201.

[7] A. Mostafaeipour, Feasibility study of offshore wind turbine installation in Iran compared with the world, Renewable and Sustainable Energy Reviews, 14(7), 2010, pp. 1722-1743.

[8] A. Balouktsis, D. Chassapis and T.D. Karapantsios, A nomogram method for estimating the energy produced by wind turbine generators, Solar Energy, 72(3), 2002, pp. 251-259.

[9] T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, Wind Energy Handbook, John Wiley & Sons Ltd, 2001.