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Analysis of wind data and assessing wind energy potentiality for selected locations in Egypt

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Abstract— The wind energy resource is available in large regions at Egypt. This paper investigates the wind energy potential at different locations at Egypt. The wind data for these regions was collected at 10m height for period of ten years. These data are used to find out the wind energy potential with help of 2-parameter Weibull distribution. The wind speed distribution is modeled by using Weibull distribution. Weibull parameters, shape and scale parameters are calculated using two different methods which are method of moments (MOM) and maximum likelihood method (MLM). The annual energy and the annual capacity factor of three different manufacturers wind turbines are calculated for the selected regions in Egypt. The highest annual mean wind speeds at 10 m height were 9 and 8.2 m/s at Gebel El Zeit and Ras Ghareb respectively. The maximum wind power density was found to be 445 W/m^2 and 344 W/m^2 at Gebel El Zeit and Ras Ghareb respectively. From this study, it is concluded that, Gebel El Zeit and Ras Ghareb are the most suitable for large-scale wind energy generation.

Index Terms— Wind Speed, Wind Power density, Weibull Distribution, Shape and Scale Factors.

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1 INTRODUCTION

Egypt occupies a geographical zone between 22 and 32°N latitude and 25 and 36°E longitude. Although the area of the country of Egypt is about 1milion km^2, only 3.5% of it can be said to be permanently settled, while the remainder being desert. Electricity production in Egypt depends heavily on imported oil and natural gas for its energy requirements. Fossil fuels are one of the non-renewable energy sources that found in nature in limited quantities. Egypt faces a serious challenge of energy crisis. Instead fossil fuels are preferred that are not only expensive but also lesser in this country. These fossils may become extinct within 2-3 decades if used continuously for this purpose [1], especially with the rapidly growing demand for electricity in Egypt. It was estimated that demand is increasing at a rate of 1,500 to 2,000 MW a year, as a result of rapid urbanization and economic growth. At the same time Fossil fuels involves many pollutants and particulates such as nitrogen oxides, sulfur dioxide, volatile organic compounds and heavy metals that are the main cause of air pollution.

In order to have a sustainable development, the government has to take measures to utilize the renewable energy in order to satisfy part of the energy demand in Egypt. It has richness in sources of renewable energy from the wind and the sun, where the highest rates of wind speed and the highest average solar radiation is available. The average level of solar radiation of between 2,000 to 3,200kWh per square meter a year and wind speed can be reached to 10 m/s in some area. So the efforts of the state are heading towards the exploitation of solar and wind energy. According to Egyptian Renewable Energy Strategy of 2013, the renewable energy share reaches 20% of the total generated energy by 2020 as 12% wind, 6% Hydro and 2% solar [2].

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Modeling and prediction of wind speed are essential prerequisites in the sitting and sizing of wind power applications. In recent years, many efforts have been made to develop models through which the wind distribution can be estimated. The extent to which wind can be exploited as a source of energy depends on the probability density of occurrence of different speeds at the site. To optimize the design of a wind energy conversion device, data on speed range over which the device must operate to maximize energy extraction is required, which requires the knowledge of the frequency distribution of the wind speed. Among the probability density functions that have been proposed for wind speed frequency distributions of most locations [4]. There are a lot of researchers estimated the potential of wind energy in different locations based on the Weibull and the Rayleigh models [5, 6]. Many studies have reached to the Weibull distribution is the most popular methods that gives a good result with experimentation data for wind energy estimation [5, 7]. This distribution is characterized by parameters the shape parameter K and scale parameter c, There are several methods (Graphical method (GM); Method of moments; Standard deviation method; Maximum likelihood method; Power density method; Modified maximum likelihood method; Equivalent energy method to calculate these parameters as reported by [6, 8].

Various wind resource assessment studies have been conducted around the world to determine the potentialities of local sites for wind power/electricity [9-19]. The case of Egypt is not left out and the researches are available. Some attempts have been made to analyze the potential in Egypt [20-24] and some experimental work [25,26] has been conducted. Each one of these reports considered different sites and presented analyses to justify their results.

In this paper, the Waybill distribution method is used to determine the average mean speed and the shape and scale parameters can be estimated by using the Maximum Likelihood Method (MLM) and Method of moments (MOM) as there are the most efficient methods and calculated of expected output power at different locations in Egypt to set up power plants using wind energy. The methodology of wind energy potential presented in this paper takes into consideration wind speed and transmission to grid. It predicts the wind turbine energy generated to summarize the energy generation. Theses algorithms are implemented into Matlab program. The methodology is applied to a case study for evaluating wind energy potential in Egypt.

2 WIND SPEED ANALYSIS MODEL

It is important to drive the probability distribution of the site's wind speed to evaluate the wind energy at this site. The Weibull density function is used to describe the wind speed frequency. It was the common wind speed distributions when both a mean and standard deviation of wind speed are known. The cumulative probability density function of the Weibull distribution is given by [17, 27]:

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

Where *f(v)* is the Weibull cumulative distribution function and represents the probability for the wind speed to be lower than a certain value, v is the wind speed (m/s), k is the shape parameter and c is the scale parameter (m/s) determined from the wind speed data. The scale parameter c indicates how windy a wind location is while the shape parameter k, indicates how peaked the wind distribution is.

The mean value of the wind speed, v_m, and standard deviation σ, for the Weibull distribution is defined in terms of the Weibull parameters, k and c as:

$$v_m = c\Gamma\left(1 + \frac{1}{k}\right) \quad (2)$$

$$\sigma = \sqrt{c^2\left\{\Gamma\left(1 + \frac{2}{k}\right) - \left[\Gamma\left(1 + \frac{1}{k}\right)\right]^2\right\}} \quad (3)$$

Where Γ *( )* is the gamma function of *(.)*.

The most probable and maximum energy carrying wind speeds can be evaluated from Eq. 4 and 5:

$$v_{mp} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (4)$$

$$v_{Emax} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (5)$$

Where v_{mp} is the most probable wind speed and v_{Emax} is the maximum energy carrying wind speed. There are many methods used to determine the parameter k and c. In this paper, two methods have been used: the Maximum Likelihood Method (MLM) and the method of moments (MOM).

2.1 Method of Moments (MOM)

When the mean wind speed v and standard deviation σ are available, shape and scale parameters can be estimated with this method using by these two equations [28].

$$k = \left(\frac{\sigma}{\bar{V}}\right)^{-1.086} \quad 1 \le k \le 10 \quad (6)$$

$$c = \frac{\bar{V}}{\Gamma\left(1+\frac{1}{k}\right)} \quad (7)$$

2.2 Maximum Likelihood Method (MLM)

The MLM was the most widely used method for estimating the parameters of the weilbull distribution. The weilbull shape parameter k is estimated using MLM method as expressed in Eq. 8.

$$k = \left(\frac{\sum_{i=1}^{N} ln(v_i)v_i^k}{\sum_{i=1}^{N} v_i^k} - \frac{\sum_{i=1}^{N} ln(v_i)}{N}\right)^{-1} \quad (8)$$

Once the value of the Wiebull shape parameter k is obtained, the Wiebull scale parameter c is estimated using the Eq. 9.

$$c = \left(\frac{\sum_{i=1}^{N} v_i^k}{N}\right)^{\frac{1}{k}} \quad (9)$$

3 TRANSMISSION GRID AND LOSSES

Transmission of power from wind farms to utility lines is generally very costly. New transmission lines can cost over $1 million per mile, and high capacity lines in urban areas can cost over $1 billion per mile [29]. Thus, locating wind turbines close to existing high voltage transmission lines can dramatically improve project economics. An equally important issue arises when transmission lines are near full capacity and unable to accept additional power generation. Maps identifying high voltage transmission lines can be obtained from local public utility commissions. In Egypt, high voltage transmission line maps are published by the Egyptian electricity holding company.

Power loss over distance is a common challenge in any transmission infrastructure. In AC transmission, 4 to 6% line loss per 1000km, though achieving that level of power loss would be expensive. As transmission distances increase from 500km to 1000km to 2000km and higher, this loss will add up more and more. Losing 2% of transmitted power, while certainly a loss, is acceptable for most utilities.

4 WIND POWER DENSITY

The average specific power available depends on the air density and the cube of the wind speed. It can be estimated by using Eq. 10:

$$p_w = \frac{1}{2}\rho v^3 \quad W/m^2 \quad (10)$$

Where P_w is the power density given in W/m^2, ρ is air density and usually taken as 1.225 kg/m^3 which depends on altitude, air pressure and temperature and v is the wind speed (m/s). The wind power density is directly proportional to the air density. By increasing the air density the wind power density become higher and vice vresa [19].

The wind power varies linearly with the air density sweeping the blades. The air density varies with pressure and temperature in accordance with the gas law as:

$$\bar{\rho} = \frac{\bar{P}}{R.T} \quad (11)$$

Where, $\bar{P}$ = air pressure.
T = temperature on the absolute scale.
R = gas constant.

The corrected power available in wind at a height of 10 m can be calculated as follows:

$$p_{10} = \frac{1}{2}\bar{\rho}v^3 \quad (12)$$

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The maximum extractable power from any wind machine is limited by the Betz relation [5], which assigns the power coefficient Cp = 16/27 for the maximum performance of a wind machine. Maximum extractable power per meter square is given as

$$p_{max} = \rho C_p V^3 \quad W/m^2 \tag{13}$$

5 WIND SPEED VARIATION WITH HEIGHT

Wind speed generally changes with height Where V_o is wind speed at the measurement height h_o and V_h is the corresponding wind speed at height h, the wind speed measurements for this study were obtained at 10 m hub height above sea level. The variation in wind speed with height is known as wind shear or power law equation as defined in the following equation [30]:

$$V_h = V_{10}\left(\frac{h}{10}\right)^{\alpha} \tag{14}$$

Where α is the roughness factor, this parameter is the wind speed power law index which is considered to be 0.14, for surfaces with low roughness as given by the one-seventh power law [31]. The value of the coefficient varies from less than 0.10 over the tops of steep hills to over 0.25 in sheltered locations [17, 32]. α is chosen to be 0.25 which presents a suitable value for Egyptian terrain and wind conditions [20].

6 CAPACITY FACTOR OF WIND TURBINES

Capacity factor for wind turbines is the ratio of the actual output Energy E_{out} and rated output energy E_r of the turbine during all the 8760 hours of the year. The annual energy yield is the total number of kilowatt-hours actually produced by a wind turbine installation or a wind farm in a year (at a given hub-height). The capacity factor is an important indicator in measuring the productivity of a wind turbine [33, 34].

7 WIND SPEED DATA AND SITE DESCRIPTIONS

In this paper many different locations are chosen to be wind assessment and discussed. Most of these locations are located along the coast of Mediterranean and Red Sea in Egypt. These locations have an advantage of strong wind and spacious areas away from urban, which make an excellent position for the establishment of wind farms. The elevation map in Figure 1, indicates these locations. In Egypt more than 10 year meteorological data were collected from the Egyptian Meteorological Authority for these locations. The Meteorological stations were chosen to cover six regions: Northwest Coast, Northeast Coast, Gulf of Aqaba, Gulf of Suez, Red Sea and Western Desert. The selected locations and wind speed range of each region are specified as follows: the first region has high wind speed which has Average Annual Wind Speed (AAWS) greater than 7m/s (Red Sea region) at 10 m height. Zafarana, Abu Darag, Ras Ghareb and Gebel El Zeit are the windiest regions with the AAWS above 7.00 m/s and the seasonal maximum wind speed that occurred in summer and lower in winter are shown in Figure 2. The second region has medium wind speed which has AAWS smaller than 7 m/s (Mediterranean Sea region), along this coastal region, Sidi Barrani and Mersa mMatruh have the highest AAWS of 5.03 m/s, 5.3 m/s, respectively as shown in figure 3.

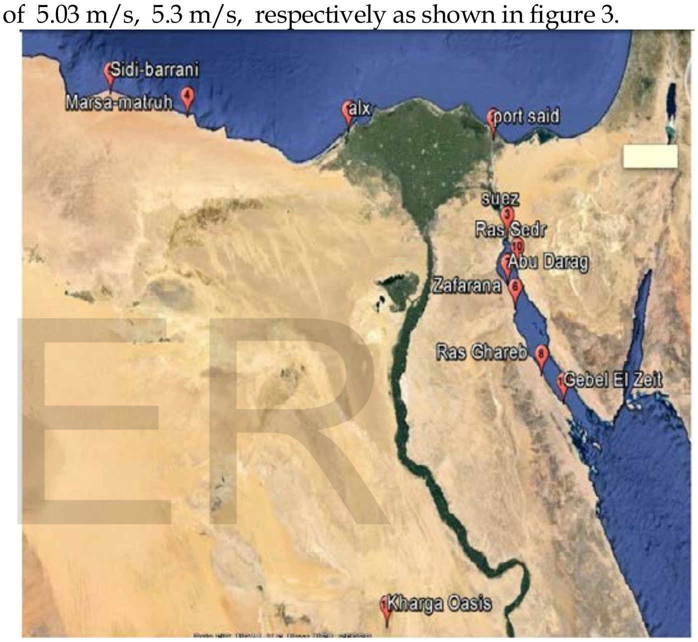

Fig.1 chosen regions along the coast of Mediterranean and Red Sea in Egypt

These locations were studied based on a monthly wind speed data measurement at 10 meters height above ground level for a period of more than 10 years by the Egyptian Meteorological Authority are shown in Table 1.

TABLE 1 AVERAGE MONTHLY AND ANNUAL WIND SPEED (M/S) (10 M HEIGHT).

location	Months												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Alexandria	4.40	4.40	4.60	4.30	4.00	4.00	4.40	4.00	3.70	3.10	3.40	4.10	4.03
Port- said	4.80	5.20	5.80	5.40	4.80	4.60	4.30	3.80	3.80	4.10	4.30	4.30	4.60
Suez	3.00	3.50	4.30	4.70	4.80	4.80	5.40	4.80	5.40	4.50	3.80	3.20	4.35
Sidi barrani	5.60	5.70	5.90	5.70	4.70	4.60	5.20	4.50	4.00	4.20	4.60	5.60	5.03
Marsa matruh	6.10	6.10	6.30	5.70	4.90	5.20	5.20	4.70	4.40	4.30	4.80	5.90	5.30
Zafarana	6.20	6.20	6.80	7.10	8.00	8.30	7.60	8.40	8.50	7.40	6.30	5.90	7.23
Abu Darag	5.80	6.00	6.60	7.00	8.60	8.10	7.60	8.20	8.70	7.50	6.20	5.80	7.18
Ras Ghareb	6.4	6.6	7.9	8.3	8.8	10.2	9.5	10	9.7	8.5	6.6	6.6	8.26
Kharga Oasis	4.31	4.37	4.80	4.87	4.91	5.03	4.83	4.75	4.80	4.69	4.19	4.19	4.64
Ras Sedr	4.68	4.60	5.02	5.10	5.06	5.24	4.80	4.77	4.88	4.69	4.31	4.48	4.80
Gebel El Zeit	8.42	8.42	9.31	9.49	9.53	9.98	9.29	9.16	9.27	8.99	7.95	8.12	8.99

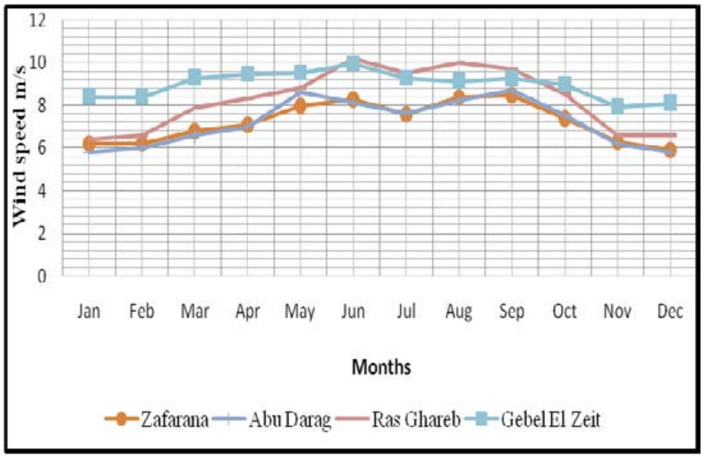

Fig. 2. Monthly variation of wind speeds of the year for high wind speed locations

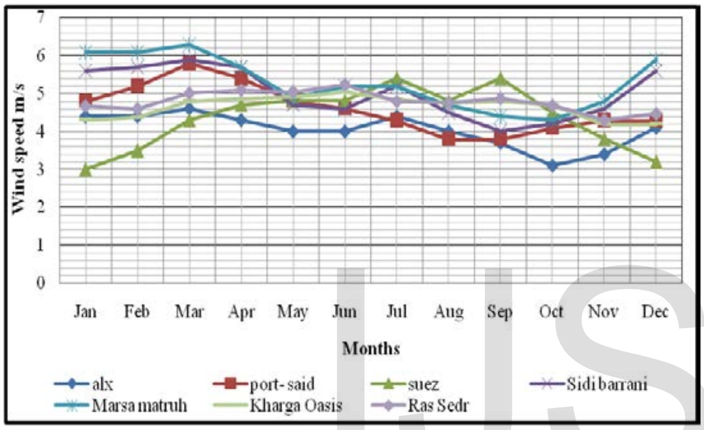

Fig. 3. Monthly variation of wind speeds of the year for High wind speed locations

The analysis of these locations in figures 2 and 3 show that locations have an annual mean wind speed more than 3m/s, the wind speed has a maximum value of 10.2 m/s at Ras Ghareb in June and a minimum value of 3.0 m/s at Suez in January.

8 RESULTS AND DISCUSSION

The common expression for calculating the wind speed at any height based on the measured wind speed at the standard height (10 m) is given by the Eqs. 10 to 13. The annual wind speed at heights of 10, 30, 50 m for all stations were calculated using Eq.14. Power density of the wind above the ground level will be mainly affected by the increase in wind speed with height so, Annual mean corrected wind power at heights of 10, 30, 50m were calculated and the results listed in Table 2.

The annual average corrected power values at a height 10 m and uncorrected wind power values at a height 10 m (P10, Pwind). Annual values of corrected wind power, P10, are always smaller than the uncorrected wind power, Pwind. This deviation is important, because sizing and costing of any technical wind system depends mainly on the wind power. From table 2, Gebel El Zeit, Zafarana, Ras Ghareb and Abu Darag have the highest annual average corrected power values, so these regions can be selected to be the best for the establishment of wind farms.

TABLE 2. ANNUAL UNCORRECTED / CORRECTED WIND POWER AT HEIGHT 10 M AND AVERAGE WIND SPEED AND POWER AT HEIGHTS 30, 50 M.

Region	Pw (w/m²)	P10 (w/m²)	V_{30}	V_{50}	P_{30}	P_{50}
Alxandria	40.19	39.65	5.31	6.03	90.38	132.57
Port Said	59.62	59.08	6.06	6.88	134.67	197.54
Suez	50.42	49.88	5.73	6.51	113.69	166.77
Sidi Barrani	77.72	77.18	6.62	7.52	175.92	258.05
Marsa-Matruh	91.19	90.65	6.98	7.93	206.63	303.09
Zafarana	231.01	230.46	9.51	10.81	525.34	770.6
Abu Darag	226.24	225.70	9.44	10.73	514.49	754.67
Ras Ghareb	344.97	344.43	10.87	12.35	785.13	1151.67
Kharga Oasis	61.355	60.814	6.112	6.945	138.625	203.34
Ras Sedr	67.827	67.286	6.320	7.181	153.378	224.99
Gebel El Zeit	445.488	444.946	11.836	13.448	1014.258	1487.768

To determine Weibull frequency distribution and Weibull cumulative distribution, it is necessary to determine first the scale parameter *c* and the shape parameter *k*. Using the Matlab software, the Weibull parameters were calculated using Maximum Likelihood Estimator (MLM) and MOM methods as shown in Table 3.

TABLE 3. AVERAGE WEIBULL SHAPE AND SCALE PARAMETERS AT 10M HUB HEIGHT.

Region	MOM		MLM	
	c	*k*	*c*	*k*
Alexandria	4.36	1.49	5.2	2.42
Port- said	4.77	1.71	5.3	2.32
El-Suez	4.45	1.78	4.66	3.17
Sidi barrani	4.27	2	5.29	2.16
Marsa matruh	4.57	1.64	5.6	9.75
Zafarana	7.63	2.7	7.64	3.17
Abu Darag	7.68	3	7.64	3.5
Ras Ghareb	8.23	3.4	9.3	3.6
Kharga Oasis	4.06	2.56	7.4	2.57
Ras Sedr	4.85	3.03	8.5	3.06
Gebel El Zeit	8.5	3.17	9.5	3.9

For this study, three wind turbines from different manufacturers were selected. Table 4 lists the characteristic properties of the selected wind turbines. Also power curve of three selected turbines have been given at Figure 4.

TABLE 4 SELECTED WIND TURBINE CHARACTERISTICS

Characteristics	Turbine (1)	Turbine (2)	Turbine (3)
Turbine Model	AN Bouns	Vestas V47	Gamesa G52
Rated output power (kW)	300	660	850
Hub height (m)	30	40	44
Rotor diameter (m)	33.4	47	52
Swept area (m2)	876	1735	2124
Number of blades	3	3	3
Cut in wind speed (m/s)	3	3	4
Rated wind speed (m/s)	14	15	15
Cut off wind speed (m/s)	25	25	25

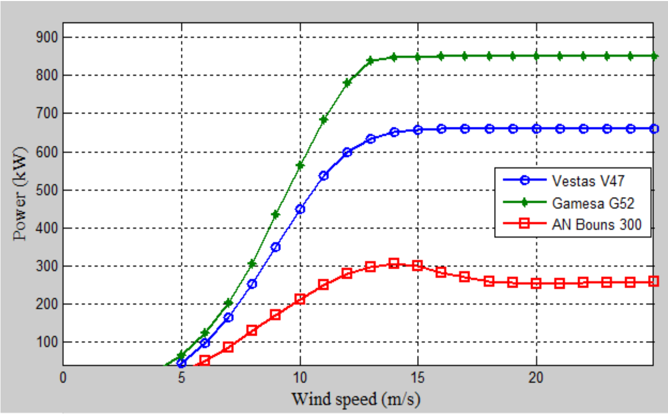

Figure 4 Wind turbine power curve

The algorithms described above have been incorporated into a computer program, WindSim [35]. WindSim simulates annual turbine electrical generation using hourly wind speeds or the annual average wind speed. The principle outputs of the software are annual available wind energy, annual electricity generation, and the distribution of wind energy and electricity generation over the year. Summaries of annual energy generation for each wind turbine at the selected locations are shown in Table 5.

TABLE 5 ANNUAL WIND TURBINE ENERGY OUTPUT

Turbine Type	Annual turbine electrical generation(kWh)		
	AN Bouns	Vestas V47	Gamesa G52
Alexandria	294480	866210.4	1046304
Port- said	468900	1365739	1652918
El-Suez	401328	1189188	1455178
Sidi barrani	637200	1849925	2097590
Marsa matruh	762480	2178605	2492150
Zafarana	1633680	4378651	5284778
Abu Darag	1599624	1913585	5186976
Ras Ghareb	2003760	4929034	6165972
Kharga Oasis	488160	1385906	1574438
Ras Sedr	531360	1564538	1782158
Gebel El Zeit	2344320	5516453	7093548

The selected sites for this study identifiy several areas with different average annual wind speeds thus, simulations were performed for each of the selected three wind turbines at each location.

TABLE 6 CAPACITY FACTOR OF THE THREE TURBINES

Turbine Type	Capacity Factor CF		
	AN Bouns	Vestas V47	Gamesa G52
Alexandria	0.1136	0.1519	0.1425
Port- said	0.1809	0.2395	0.2251
El-Suez	0.1548	0.2086	0.1982
Sidi barrani	0.2458	0.3244	0.2856
Marsa matruh	0.2941	0.3821	0.3394
Zafarana	0.6303	0.7679	0.7196
Abu Darag	0.6171	0.3356	0.7063
Ras Ghareb	0.7731	0.8644	0.8396
Kharga Oasis	0.1883	0.2430	0.2144
Ras Sedr	0.2050	0.2744	0.2427
Gebel El Zeit	0.9045	0.9674	0.9659

The calculated capacity factors are shown in table 6. It can be noticed that, the capacity factors are almost equal or very near to it with a slight deviation for the three turbines at each location.

9 CONCLUSION

This paper described a preliminary assessment of regional wind energy potential in Egypt. It calculates the wind energy production using the monthly average wind data was presented. The monthly data method adjusted for differences in height, air density and the proposed turbine. These data is used to generate a Weibull distribution of wind speed over the year. Wind turbine electricity generation was calculated using the average wind speed data and the turbine power curve. The following conclusion derived from the results of this study:

- There are four regions (Zafarana , Abu Darag , Ras Ghareb and Gebel El Zeit) have high wind power densities ranging from 1014 - 1487 W/m² and 514 – 754 W/m² at the heights of 30 to 50 m, respectively. So these regions are suitable for building wind turbines, like the Turbine (3).
- There are five regions (Sidi barrani , Marsa matruh , Port-said, Kharga Oasis and Ras Sedr) have medium wind power densities ranging from 206 - 303 W/m² and 134 - 197 W/m² at the heights of 30 to 50 m, respectively. So these regions are suitable for building wind turbines, like the Turbine (1 and 2).

Therefore wind farms can be installed in Zafarana, Abu Darag, Ras Ghareb and Gebel El Zeit using a large number of Gamesa G52 turbines for electricity generation.

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