Assessment of Wind Characteristics and Wind Potential Energy Yield in the Jordanian Southern Region

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Abstract: This study presents investigation and assessment of wind characteristics and wind energy potential for four sites at the Jordanian southern region (Hareer, Ma'an, Aqaba and Fujaij). Based on the available measured data sources, the data were analyzed using hourly and mean monthly WS (wind speed) data at different heights, using a two-parameter probability distribution of Weibull function. The recognized monthly and yearly Weibull functions were considered for the second analysis step. The wind potential energy yields assessment for an ideal capable wind turbine was implemented. Finally, for energy yield estimation, a wind turbine from Vestas with a 660 kW rated power was chosen. The wind turbine characteristics: AF (availability factor), CF (capacity factor) and wind turbine efficiency (η), were defined and calculated for each site. The result of the analysis showed that, all sites have good wind energy potential, the Hareer site at Tafila has the best wind resources.

Key words: Wind energy, Weibull distribution, probability, availability factor.

1. Introduction

Jordan is a very poor country in energy recourses such as oil and gas. The local energy resources including oil and gas cover less than 5% of the kingdoms energy needs and it totally depends on imported oil and gas. Energy cost forms a financial burden on the national economy, in the sense that Jordan spends more than 12% of its gross domestic product on the purchase of energy [1]. But at the same time, Jordan possesses good renewable resources such as wind, solar energy [2, 3], good oil shale and small hydropower resources. Therefore, it is important that the research and development activities should be concentrate on these resources. Regarding wind energy activities, wind measurements and studies indicated that Jordan has a good potential of wind, especially in the northern and southern regions [4]. Wind energy in Jordan is mainly utilized in electricity production and water pumping through the use of small size electrical

and mechanical wind turbines [5].

According to the earlier studies in Jordan, the researchers performed wind energy assessment for electricity generation in several Jordanian sites [6-8]. These studies indicate some unexplored sites. There is a great need to conduct more studies to assess the possibility of electricity generation by means of wind energy in other Jordanian sites which have not been explored yet.

The recent statistics and studies indicate that, the share of renewable energy in the total energy mixed is about 2% and expected to reach 5% by the next decade [9]. Therefore, in order to achieve this focal aim, the governments modernize the General Electricity Law and removed the legal obstacles. This should lead to increase the interest in utilizing wind energy and other renewable sources.

The environment for renewable energy sources has been changed completely, which enabled independent generators to be established in the country [10]. Local and foreign investors are invited to submit their financials and technical proposals to develop wind

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farms at the most promising sites.

2. Wind Data Measurements and Sites Description

By measuring and calculating the wind data for the certain locations, it provides fundamental information for the assessment of the wind energy by which it is possible to calculate the estimated annual average production of electric power (annual energy). Based on the available measured data sources [11], the study utilizes hourly mean WS (wind speed) or 10 min mean speed and direction at different height levels: (A) 50 m; (B) 40 m; (C) 20 m. In Table 1, the coordinate of geographical information is illustrated. At the first three sites, the anemometer stations were installed during the period 2006-2007. But at the fourth site, the wind measurement is of the period 2002-2008. The measurement masts were equipped from NRG (Natural Resource Generation Company), as shown in Table 2.

3. Analysis of Wind Data

The WS and direction were collected at different height levels. Analysis of each site data contains: the calculation of average WS for each wind sector and

Table 1 The Geographical coordinates for the sites included in the study.

Station No.	Station name	Location	Elevation (m)	Coordinates
1	Hareer	Tafila	1,529	30°43'39.5" N 35°41'18.7" E
2	Ma'an	Ma'an	1,196	30°15'43.2" N 35°41'11.6" E
3	Aqaba	Aqaba	78	29°48'17.3" N 35°04'20.0" E
4	Fujaij	Shobak	1,643	30°48'17.5" N 35°04'20.0" E

Table 2 The measuring equipments information.

Sensors	Manufacturer /model	Calibration/ offset	Orientation
Anemometer 50 m	NRG/40 C	$0.7679x + 0.413$	--
Anemometer 40 m	NRG/40 C	$0.765x + 0.350$	315°
Anemometer 10 m	NRG/40 C	$0.765x + 0.350$	270°
Wind vane 50 m	NRG/200P	-20	360°
Wind vane 40 m	NRG/200P	-65	45°
Temperature 5 m	Ammonit	10 – 273.1	North

distribution for all available periods. WS for each location may be characterized by a number of probability density functions. The commonly used functions for fitting a measured WS probability distribution in a given location over a certain period of time are the Weibull and Rayleigh functions [12]. Weibull distribution function is most widely used function for modeling the WS. The scale factor (c) of the Weibull distribution, which is related to the average WS at different heights, is calculated using the maximum probability reflects the breadth of the distribution. The values of Weibull parameters were calculated for annual WS distribution for all locations.

The average values of the WS for each site of observation and the distribution of the data are for whole periods, and the turbulence factor, which refers to fluctuations in WS on a relatively fast time-scale, which defined as the ratio of the standard deviation of the WS to the mean WS in a certain averaging time, usually 10 min. The Turbulence intensity is an important factor for energy production, and gust factor, which is simply expressed as the ratio of the gust to mean WSs.

Table 3 shows the average WS and frequency distribution versus direction for Hareer site. The average WS at 20 m height is 7.5 m/s, while the average WS at 40 m height ranges from 8 m/s to 10.8 m/s, the average WS at 50 m height ranges from 8.4 m/s to 11 m/s, and for more than 96% of the time the wind blows, the WS ranges from 4 m/s to 11 m/s.

Fig. 1 shows the daily speed wind analysis at different levels: (A) 50 m; (B) 40 m; (C) 20 m. It is abusively clear that, the average WS at different heights is about 8.8 m/s. Table 4 shows the turbulence factor and gust factor for Hareer site.

The WS probability distribution functions computation constitutes the first step to assess the wind energy potential, as it determined the performance of wind energy systems for a given location and time [13]. To observe the Weibull distribution by region, the Weibull probability functions and Weibull frequency

Table 3 The average WS and frequency distribution versus direction for Hareer site.

Period	Quantity	Wind direction																Average total
		S1 N	S2 NNE	S3 NE	S4 ENE	S5 E	S6 ESE	S7 SE	S8 SSE	S9 S	S10 SSW	S11 SW	S12 WSW	S13 W	S14 WNW	S15 NW	S16 NNW	
01 Jan, 2002 - 31 Dec, 2002	V_A (m/s)	4.0	3.9	3.9	4.3	5.4	6.6	8.2	9.6	9.5	7.2	8.8	10.7	9.6	7.6	6.1	4.8	8.4
	V_B (m/s)	3.8	3.7	3.7	4.1	5.1	6.3	7.3	9.3	9.3	7.1	8.8	10.4	9.3	7.3	5.8	4.5	8.1
	N	858	912	1,048	1,211	1,481	2,043	3,395	2,479	2,102	1,000	2,258	9,627	12,878	7,009	2,830	1,427	52,554
	N/N_{tot}	2%	2%	2%	2%	3%	4%	6%	5%	4%	2%	4%	18%	25%	13%	5%	3%	
01 Jun, 2003 - 28 Mar, 2003	V_A (m/s)	2.4	2.6	2.9	2.9	4.1	5.5	7.9	10.1	10.1	8.3	8.8	14.1	11.7	8.2	5.1	3.4	11.1
	V_B (m/s)	2.3	2.6	2.7	2.7	3.9	5.2	7.0	9.7	9.9	8.1	8.5	13.8	11.4	7.9	5.0	3.3	10.8
	N	37	40	59	54	104	178	474	582	711	422	925	3,751	2,693	707	72	56	10,884
	N/N_{tot}	0%	0%	1%	0%	1%	2%	4%	5%	7%	4%	9%	35%	25%	7%	1%	1%	
22 May, 2007 - 03 Sep, 2007	V_A (m/s)	5.2	4.7	4.6	3.4	4.0	4.0	5.5	7.0	8.0	4.9	6.1	8.3	10.2	8.7	7.7	6.2	8.7
	V_B (m/s)	5.2	4.7	4.5	3.4	3.9	3.9	5.5	7.0	8.2	4.9	6.1	8.3	10.3	8.1	7.8	6.3	8.5
	V_C (m/s)	4.8	4.4	4.1	3.3	3.9	3.8	5.5	7.0	7.9	4.5	5.8	6.8	7.8	8.4	7.4	5.8	7.5
	N	325	171	132	82	58	84	75	81	62	58	194	818	5,488	4,330	2,200	807	14,983
	N/N_{tot}	2%	1%	1%	1%	0%	1%	1%	1%	0%	0%	1%	5%	37%	29%	15%	5%

Fig. 1 Daily speed wind analysis at different heights for Hareer site.**Table 4** Turbulence factor and gust factor for Hareer site.

Wind speed (m/s)	Turbulence factor	Standard deviation	Gust factor	Standard deviation	Values (%)
$V < 0.5$	1.8	-	2.77	-	0.0
$0.5 \leq V < 5$	0.23	0.12	1.38	0.25	12.1
$5 \leq V < 10$	0.10	0.05	1.16	0.10	55.9
$10 \leq V < 15$	0.06	0.03	1.09	0.07	29.4
$15 \leq V < 20$	0.04	0.02	1.05	0.05	2.6
$V \geq 20$	-	-	-	-	0.0

distribution were analyzed. The distributions obtained are illustrated in the wind histogram (Fig. 2) for Hareer site at 50 m height. WS frequency distribution of Hareer is characterized by mean WS of 8.34 m/s. With a Weibull parameter c of 10.114 and k of 3.262 (flat shape), which indicate that higher WSs occur more frequently, the Weibull distribution is fit to actual

distribution data. Fig. 3 shows the daily speed wind analysis at different levels from which the average WS at different. The average WS at 20 m height is 5.4 m/s, while the average WS at 40 m height is 6 m/s, the average WS at 50 m height 6.3 m/s, and for more than 74% of the time the wind blows, the WS ranges more than 4 m/s. Table 5 shows the turbulence factor and

Fig. 2 Probability functions and Weibull frequency distribution of Hareer site at 50 m.

Fig. 3 The daily speed wind analysis at different heights for Ma'an.

Table 5 Turbulence factor and gust factor for Ma'an site.

Wind speed (m/s)	Turbulence factor	Standard deviation	Gust factor	Standard deviation	Values (%)
$V < 0.5$	0.37	0.12	2.01	0.42	0.3
$0.5 \leq V < 5$	0.19	0.13	1.40	0.36	47.3
$5 \leq V < 10$	0.11	0.08	1.26	0.18	37.6
$10 \leq V < 15$	0.08	0.04	1.19	0.09	11.3
$15 \leq V < 20$	0.08	0.03	1.18	0.07	2.4
$V \geq 20$	0.08	0.03	1.18	0.06	0.3

gust factor for Ma'an site. The distributions that have been obtained are illustrated in the wind histogram (Fig. 4) for Ma'an site at 50 m height WS frequency distribution of Ma'an is characterized by mean WS of 6.077 m/s With a Weibull parameter c of 7.048 and k of 1.843, Hareer site has more flat shape than in Ma'an site.

Fig. 5 shows Aqaba Wind Rose of mean speed, and Fig. 6 shows Aqaba Wind Rose frequency distribution.

The average WS at 20 m height is 5.5 m/s, while the average WS at 40 m height is 6.6 m/s. The average WS at 50 m height 6.5 m/s and almost for all time the wind blows, the WS is more 4 m/s which is used to illustrate the average WS for each direction. WS frequency distributions have been estimated by Weibull and Rayleigh probability functions and compared with the measured probability distribution function. Fig. 7

Fig. 4 Probability functions and Weibull frequency distribution of Ma'an site at 50 m.

Fig. 5 Aqaba wind rose of mean speed.

Fig. 6 Aqaba wind rose frequency distribution.

illustrates wind histogram, probability functions, Weibull and Rayleigh frequency distribution of Aqaba site at 40 m. From Fig. 7, it can be realized that, the Weibull distribution and the Rayleigh distribution are fit to actual distribution data and they are very close to each other.

Fig. 8 shows Fujiej Wind Rose of mean speed and Fig. 9 shows Fujiej Wind Rose frequency distribution. The average WS is 6.8 m/s, and almost for all time the wind blows, the WS for more than 94% is more 4 m/s WS frequency distributions have been estimated using Weibull and Rayleigh probability functions and compared those estimated with the measured probability distribution function, Fig. 10 illustrates wind histogram, probability functions, Weibull and Rayleigh frequency distribution of Fujiej site at 40 m height. From the graphical result, it can be seen that the Weibull distribution fits to the actual distribution data and closer than the Rayleigh distribution.

4. Wind Characteristics and Wind Potential Energy Yield

The wind energy estimation of wind machine output requires a detailed knowledge of the distribution of WS and wind power density for every particular site using the two-parameter probability distribution of Weibull. The identified monthly and yearly Weibull functions were considered for the following analysis of assessment of wind potential energy yields.

Fig. 7 Probability functions, Weibull and Rayleigh frequency distribution of Aqaba site at 40 m.

Fig. 8 Fujeij wind rose of mean speed.

Fig. 9 Fujeij wind rose frequency distribution.

The second step is to estimate the wind energy generated by an ideal wind turbine able to completely extract all energy available in the wind [14]. Finally, for energy yield estimation, a wind turbine from Vestas was chosen with 660 kW rated power. The main parameters of this turbine are: rotor diameter 47 m (the blade sweep area is $1,735 \text{ m}^2$) with a hub height of 45 m, the cut-in, rated, and cut-off speeds are 4 m/s, 15 m/s and 25 m/s, respectively [15]. The monthly and yearly actual wind energy generated by a generic wind turbine operated at cubic relation of power between cut-in, cut-off, rated WS and constant power (660 kW) between rated and cut-out WS is estimated. The following wind farm characteristics: AF (availability factor), CF (capacity factor) and η are defined and calculated.

The AF also defined as the measurement of the operation percentage for the wind turbine. It refers to the time percentage that the wind turbine is operating. The CF is an important factor for measuring the productivity of a wind turbine. The wind efficiency is defined as the ratio of the actual wind energy output from a wind turbine to the wind energy generated by an ideal wind turbine. For example, with a very large rotor and a very small generator, a wind turbine would run at full capacity in such a way that its CF remains high. But it could produce very little electricity, resulting in low wind turbine efficiency. On the contrary, for the same rotor together with a very large generator, the CF

Fig. 10 Probability functions, Weibull and Rayleigh frequency distribution of Fujeij site at 40 m.

will be lower as a result but the wind turbine efficiency could be higher. Consequently, for assessment of the annual potential energy yield, the AF, CF and η for a specific wind turbine should be considered together [16].

5. The Estimation Methodology

WS distribution is considered as an important factor to estimate the wind energy potential for the site. The Weibull distribution function for WS is given by the following expression [17]:

$$f(V) = k/c (v/c)^{k-1} \exp[-(v/c)^k] \quad (1)$$

where, c is the scale parameter, k is the shape parameter, and V is WS.

The Weibull parameters (c , k) are identified for each month of a given meteorological station based on wind measurements, using the maximum likelihood method [17].

The WS carrying maximum energy represents the WS, which carries the maximum amount of wind energy, and is expressed as follows [18]:

$$V_{MaxE} = c \left(\frac{k+2}{k} \right)^{\frac{1}{k}} \quad (2)$$

As it is known, the wind power density is directly proportional to the cube of mean WS (V), air density (ρ) and a blade sweep area (A). It can also be calculated using the Weibull distribution function as follows:

$$\frac{P}{A} = \int_0^\infty P(V) f(V) dV = \frac{1}{2} \rho c^3 \Gamma \left(\frac{k+3}{k} \right) \quad (3)$$

The wind energy density for the desired duration (for

example, a month or a year) can be expressed as:

$$\frac{E}{A} = \frac{1}{2} \rho c^3 \Gamma \left(\frac{k+3}{k} \right) T \quad (4)$$

where, T is the time period (or the duration), ρ is the standard air density at the mean sea temperature of 15 °C, and one atmospheric pressure, Γ denotes the gamma function.

For an ideal wind turbine, the wind energy available from the wind can be completely extracted so that the turbine rotor starts from cut-in speed V_{cut-in} (V_1) and the power generated increases as WS increases until it reaches the rated WS (V_R). At WSs between the rated WS and cut-off WS $V_{cut-off}$ (V_0), a constant rated power is generated corresponding to the rated WS. When the wind velocities exceeding cut-off WS, the turbine shut down.

The wind energy generated by the ideal wind turbine is given by:

$$E_{TW} = T \int_0^\infty P(V) f(V) dV = T \left(\int_{V_1}^{V_R} P(V) f(V) dV + \int_{V_R}^{V_0} P_R f(V) dV \right) \quad (5)$$

Substituting $P(v)$, $f(v)$ and the constant rated power generated by the ideal wind turbine P_{rated} (V_R), the obtained expression will be:

$$E_{TW} = \frac{\rho}{2} T A \left(\int_{V_1}^{V_R} V^3 \frac{k}{c} \left(\frac{V}{c} \right)^{k-1} e^{-\left(\frac{V}{c} \right)^k} dV + V_R^3 \int_{V_R}^{V_0} \frac{k}{c} \left(\frac{V}{c} \right)^{k-1} e^{-\left(\frac{V}{c} \right)^k} dV \right) \quad (6)$$

The integrals in the last equation are calculated by numerical integration techniques such as Simpson's method [19]. The available wind energy from the wind cannot be completely extracted or implemented by any real machine. Because of the air mass would be stopped

completely in the intercepting rotor area. The machines that operate at constant power P_{rated} with maximum efficiency between rated and cut-out speed and by increasing the power between cut-in and rated speed, the actual wind power output from the wind turbine $P_T(v)$ determined by the turbine power curve, which approximated by the polynomial function as follows:

$$P_T(V) = \begin{cases} 0 & , V < V_I \\ (a_1 V^3 + a_2 V^2 + a_3 V + a_4) P_R & , V_I \leq V < V_R \\ 0 & , V \geq V_O \end{cases} \quad (7)$$

Using the power curve expression for wind turbine Vestas V47-660 KW, the wind energy output from a wind turbine can be calculated by the equation [14]:

$$E_T = T \cdot P_{rated} \int_{v_i}^{v_r} (a_1 V^3 + a_2 V^2 + a_3 V + a_4) \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv + T \cdot P_{rated} \int_{v_r}^{v_o} \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \quad (8)$$

The integrals are calculated by numerical integration techniques such as Simpson's method. The efficiency of the wind turbine is a function of wind turbine performance, and a function of WS distribution. The η is estimated monthly using the wind measurements for each meteorological station. Theoretically, the maximum power that can be extracted from the wind is 59% of the wind power available in the wind. Therefore, for any wind turbine, the wind turbine η should not exceed 0.59 [16].

The capacity factor is expressed by dividing the actual energy production of a wind turbine by the rated wind energy. The CF can be determined for a certain period T (one day, one month, and one year). For a given site, the estimated C_F have to be considered as a maximum value of wind potential energy yield in the wind energy assessment phase (resources estimation). In case of a wind farm implemented at the given site for estimation of electric energy production another factors have to be considered such as:

- the wake effect (internal and external);

- grid efficiency (electrical losses);
- generator efficiency;
- environmental (performance degradation, temperature, ice).

The measurement of the operation percentage of a wind turbine is defined as the availability factor. It depends on the percentage of time that a wind turbine is operating, which depends on wind turbine characteristics and wind energy potential.

In mathematical definition considering a wind turbine having the cut-in speed V_I and cut-off speed V_O , the AF is the probability of $P(V_O \geq V < V_I)$, which can be calculated using the following equation:

$$A_F = P(V_O \leq V < V_O) = \int_{V_I}^{V_O} \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \quad (9)$$

The availability factor increases by the decreasing the cut-in WS of a wind turbine and the increase of the cut-off WS and mean WS. Most modern wind turbines have high values of the availability factor. However, mostly it can be utilizing part of the power in the wind and it will be generating at less than full capacity, which is determined by the other two factors, i.e., the wind turbine efficiency and the capacity factor. The wind turbine availability factor is estimated monthly for each year of the wind measurements at each meteorological station.

6. Wind and Wind Turbine Characteristics for Different Sites

The annual value of AF, CF and η referring to the year 2002, 2003 and 2007 for Hareer Site are reported in Table 6.

The annual values of the annual values of AF, CF and η for Ma'an site are: AF = 72.6%, CF = 29.9% and η = 40.0%.

The annual value of AF, CF and η referring to years 2004 and 2007, are reported in Table 7 for Aqaba site.

The annual value of AF, CF and η referring to years 2004, 2005, 2006 and 2007, are reported in Table 8 for Fujiej site.

Table 6 The annual value of AF, CF and η for Hareer site.

Year	Availability factor (%)	Capacity factor (%)	Wind turbine efficiency (%)
2002	87.4	44.3	39.3
2003	89.4	61.1	51.3
2007	95.3	53.3	37.3

Table 7 The annual value of AF, CF and efficiency for the Aqaba site.

Year	Availability factor (%)	Capacity factor (%)	Wind turbine efficiency (%)
2004	95.1	40.0	37.8
2007	92.9	32.4	42.7

Table 8 The annual value of AF, CF and η for Fujiej site.

Year	Availability factor (%)	Capacity factor (%)	Wind turbine efficiency (%)
2004	80.3	29.1	39.5
2005	85.7	31.8	38.9
2006	85.1	30.9	39.1
2007	79.1	22.9	41.7

7. Conclusions

This study is responsive to the government's stated policy to encourage private sector investment in renewable energy generation by utilizing the promising wind energy in the country, environmental protection and sustainable development. In this paper, an evolution of the wind resources at four Jordanian sites in the southern region (Tafila, Shobak, Ma'an and Aqaba) has been presented to provide basic information of wind resource. The annual average WS, frequency distribution versus direction at the standard heights (20 m, 40 m and 50 m), turbulence, gust factors, wind histogram, probability functions and Weibull frequency distribution have been calculated. The annual average WS for the considered sites ranges from 5.56 m/s (Aqaba) to 8.34 m/s (Hareer) and the mean wind power density varies from 222 (Fujiej) to 589 W/m² (Hareer) at standard height of 40 m.

In the second part, we calculated the: AF, CF and η for commercial wind turbine used in this study. The wind energy generated by an ideal turbine, the actual wind energy and the monthly values of wind turbine characteristics are calculate.

The results show the general availability of wind

characteristics and wind turbine characteristics. For Hareer site, the AF for measurement duration varies from 0.874 to 0.953, the CF is in the range 0.443-0.611 and the η of wind turbine is between 0.373 and 0.513. For Fujiej site, the AF for measurement duration varies from 0.929 to 0.951, the CF is in the range 0.324-0.49, and the η of wind turbine is from 0.378 to 0.427. For Ma'an site the AF for one year measurement duration is 0.726, the CF is 0.299 and wind turbine η is 0.40. For Aqaba site, the AF for measurement duration varies from 0.929 to 0.951, the CF is in the range 0.324-0.490 and wind turbine η located from 0.378 to 0.427.

The results shows that the Hareer site in Tafila has the best wind resources: the highest Weibull parameter, the longest observed duration wind measurements parameters, the highest mean wind power density, AF, CF and η , therefore this area is the most promising location on commercial scale wind energy exploitation among the studied sites.

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