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Wind Energy Density Calculation Based on Different Data Sources A Comparative Study for Al-Shehabi Site-Iraq

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Abstract

This research proposed a 5.0 MW wind power project at the Al-Shihabi site in Iraq. The wind speed was collected from the Al-Shehabi metrological station at heights 10, 30, 50, and 52 m with 10-minute time intervals; then those data were compared with the hourly wind speed measured at 50 m for one year above the ground level obtained from the NASA site. The data were modeled using the Weibull distribution function for all wind power heights. Three methods were used to estimate Weibull parameters: Maximum Likelihood, Least Squares, and WAsP, which were executed to determine the numerical values of Weibull shape parameter (k), scale parameter (c), and mean wind speed. It is concluded that the annual mean wind speeds and the annual mean wind power densities of the measured data at 10, 30, 50, and 52 m heights were 4.607m/s, 144.0W/m^2, 6.068 m/s, 257.0 W/m^2, 6.673m/s, 346.0 W/m^2, 6.91m/s, 359.0W/m^2 respectively, as 3rd class (Gentle Breeze), while the results of wind data from NASA at 50 m were 5.241m/s and 126 W/m^2 as 2nd (Light breeze). The predicted power density was analyzed using ten wind energy system models of rated capacity 10, 25, 50, 60, 100, 330, 500, 850, and 900 kW.

Keywords: Weibull distribution, RETScreen, WAsP

حساب كثافة طاقة الرياح بالاعتماد على مصادر مختلفة للبيانات دراسة مقارنة لموقع الشهابي– العراق

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الخلاصة

يعطي هذا البحث دراسة اولية لمشروع طاقة رياح افتراضي لتوربين من نوع 5 ميكاواط في منطقة الشهابي/ محافظة واسط – العراق. تمت دراسة قدرة الرياح الانتاجية للطاقة الكهربائية بالاعتماد على بيانات محطة أنوائية على ارتفاعات 10م، 30م، 50م، 52م لكل 10 دقائق فاصل زمني للقراءات. وبنفس الوقت قورنت النتائج مع نتائج بيانات ساعية مأخوذة من وكالة NASA لنفس الموقع وعلى ارتفاع 50م لسنة واحدة

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باستخدام برنامج windographer. استخدمت دالة توزيع ويبل لغرض حساب قيم معدلات سرع الرياح وقدرة الرياح وعلى مختلف الارتفاعات السابقة باستخدام التحليل الاحصائي بواسطة برنامج windographer. ولغرض حساب معاملات ويبل (k) و (c) ومعدل سرع الرياح. استخدمت ثلاث طرق : Maximum Likelihood، WAsP Least Squares، لتحديد القيم العددية لمعامل شكل Weibull (k) ومعلمة المقياس (c) ومتوسط سرعة الرياح.

استنتج أن متوسط سرعات الرياح السنوية والمتوسط السنوي لكثافة طاقة الرياح للبيانات المقاسة عند ارتفاع 10 م، 30 م، 50 م، 52 م كانت (4.607 م/ ث ، 144.0 وات/ م^2)، (6.068 م/ ث ، 257.0 وات/ م^2)، (6.673 م/ ث، 346.0 وات/ م^2)، (6.91 م/ ث ، 359.0 وات/ م^2) على التوالي، والتي تنتمي الى الفئة الثالثة (نسيم معتدل)، في حين أن نتائج بيانات الرياح من ناسا عند 50 م كانت 5.241 م/ ث و 126 واط / م^2 (الفئة 3 نسيم خفيف). حللت كثافة الطاقة المتوقعة باستخدام عشرة نماذج لأنظمة طاقة الرياح ذات السعة المقدرة ((10, 25, 50, 60, 100, 330, 500, 850, and 900 كيلوواط.

1. Introduction

Renewable energy sources have become essential to decreasing fossil fuel usage in recent decades. Clean energy generation includes non-polluting sources with few negative environmental impacts and currently replaces a portion of fossil energy in many parts of the world. Wind energy is one of the fastest-growing technologies in the global market. According to the Global Wind Energy Council (GWEC), the global wind capacity increased from 743GW in 2020 to 837 GW in 2021, where the capacitance increased by 93.6 GW (+12%) [1].

Iraq is facing an energy shortage due to increased demand for electricity and because traditional systems cannot keep up with the increased electrical load. Therefore, the alternative solution is to add electricity from renewable energy sources [1, 2].

The feasibility study represents the earliest stage of wind project construction to reduce the development and planning risks and to ensure that at the end of the development process. Prefeasibility study includes wind resource assessment, selection of wind turbines and preliminary layout design, investigation of key technical, environmental, and planning constraints (noise, access, and electricity grid constraints), preliminary energy yield, and financial modeling. Wind abundance is one of the most important factors that affect the economic viability of a wind power project. Knowing available wind resources is crucial for investors to determine whether a project is profitable in a particular location. Collecting good quality wind data and conducting the wind analysis allows the projects to move forward confidently, minimizing performance risk [3, 4].

In Iraq, many researchers have studied wind energy (e.g., Al-Tmimi, 2007; Kazem and Chaichan, 2012; Bashaer and Oday, 2020). After evaluating the wind energy potential in Iraq using monthly and annual average wind speeds for some meteorological stations, the results presented the wind characteristics and assessment of the wind power in the selected sites. The results proved that there is more than one promising site in Iraq where wind turbines can be installed, and energy from it economically can be obtained [5, 6, 7].

2. Study site characteristics

The study proposed to build a wind turbine farm in the Al-Shehabi area near the Wasit governorate [8]. The site is at 32.772053 N, 46.409200 E, 49 m above sea level surface, with 4.2 annual mean wind speed at 10 m height. Figure 1 shows the location of the chosen site area, which is in the eastern sector close to the border with Iraq.

Figure 1: The proposed wind farm location.

3. Data used description

Data were collected from towers installed in the Al-Shehabi area to study wind energy using the Weibull distribution function for data analysis. Data were recorded with a 10-minute time difference between reading and another and measured at the height of 10, 30, 50, and 52 m from 29 Nov 2014 to 10 Dec 2015. At the same time, MERRA data was downloaded from NASA with an hourly interval between one reading and another for one year, the same time as the data collected from the Al-Shehabi website. NASA's hourly wind data was converted to 10 min to be compatible with the measured data [9].

4. Wind Resources study and energy output

In order to anticipate power density and energy output and assess whether it is economically feasible to install wind turbines at a certain location, wind resource evaluation is essential. Weibull distribution and its parameters (scale factor c and shape factor k) were used to analyze wind speed at all four heights (10, 30, 50, and 52m), as well as NASA data at 50 m [6]. The wind data from measurements and NASA's simulations were compared. Utilizing wind speed data for the chosen site, the wind power density displays the anticipated electrical energy generated by the wind turbine. Ten wind turbine models from the Windographer software library were considered for this investigation, as indicated in Table 1.

Table 1: Selected wind turbine models [10, 11]

Turbine	Rated power (kw)	Hub height m	Rotor diameter m
Bergey Excel-S	10	30	6.7
Eocycle EO 25/12	25	30	11.7
Northern Power 100 ARCTIC	100	30	21.0
Northern Power 100-24	100	30	24.0
Northern Power 60-23	60	30	23.0
Seaforth AOC 15/50 50Hz	50	30	15.0
Gamesa G58- 0.85 MW	850	50	58.0
Enercon E-33 / 330 kW	330	50	33.4
EWT DW54-500	500	50	54.0
EWT DW54-900	900	50	54.0

The most suitable sites for wind farm development were classified as class 3 (Table 2) and higher according to the International Electro-Technical Commission (IEC61400-1) classification of wind power density at 50 m above ground level [4, 12]. Data were studied at heights of 10 and 30 m, in addition to 50 m, as they are real data taken from towers installed at the study site, so they are helpful for comparison and taking a complete idea of the wind speed at the study site. The average wind speed at hub height and the wind turbine's energy production curve were used to compute the energy produced by wind turbines.
A net energy calculation is made by using the following equation:-

$$E_{net,\ annual} = P_{net,\ overall} \times 8760hrs \tag{1}$$

$P_{net,\ overall}$, is the average net power production across the full data set [kW], and 8760 hours make up a year.

Table 2: Wind class and wind speed [13]

Wind Class	$\bar{v}$ at 10 m (m/s)	$\bar{v}$ at 50 m (m/s)	Description
1	0.0 - 4.4	0.0 - 5.6	**Poor**
2	4.4 - 5.1	5.6 - 6.4	**Marginal**
3	5.1 - 5.6	6.4 - 4.0	**Satisfactory**
4	5.6 - 6.0	7.0 - 7.5	**Good**
5	6.0 - 6.4	7.5 - 8.0	**Excellent**
6	6.4 - 7.0	8.0 - 8.8	**Prominent**
7	7.0 - 9.4	8.8 - 11.9	**Splendid**

5. Weibull probability distribution function

wind speed fluctuation over any period could be illustrated using the Weibull probability distribution function (abbreviated pdf), it is given by [14, 15],

$$F(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right), k > 0, v > 0, c > 1 \tag{2}$$

The form parameter is represented by k, and the scale parameter is represented by *c* (measured in m/s). Weibull distribution parameters could be confidently approximated using a straightforward curve-fitting method.

6. Estimating Weibull parameters

6.1 Maximum Likelihood Method (MLM)

A Weibull distribution was fitted to a measured wind speed distribution using the maximum likelihood method (MLM). The Weibull *k* parameter was calculated iteratively using the following equation [7]:

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right)^{-1} \tag{3}$$

Vi is the wind speed at time step *i*, and *n* is the number of nonzero wind speed data points. The above equation must be solved using an iterative procedure; the following equation can be solved explicitly to estimate the scale parameter.

$$c = \left(\frac{\sum_{i=1}^{n} v_i^k}{n}\right)^{1/k} \tag{4}$$

6.2. Least Square Method (LSM)

If x_i and y_i are variables, a is the slope, and b is the intercept of the line on the *y*-axis, $F(v_i)$ The cumulative density function such that [16, 17]:

$$\begin{aligned} y_i &= \ln\left[-\ln\left(1 - F(v_i)\right)\right] \\ a &= k \\ x_i &= \ln v_i \\ b &= -k \ln c \end{aligned} \tag{5}$$

The idea is to determine the values of *a* and *b* in ($y_i = ax_i + b$) such that a straight line drawn through the (x_i, y_i) points has the best possible fit. Parameters k and c are given by [18],

$$k = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \tag{6}$$

$$c = \exp\left(\frac{k\sum_{i=1}^{n} x_i - \sum_{i=1}^{n} y_i}{nk}\right) \tag{7}$$

7. Net capacity factor calculation (NCF)

The capacity factor, given in Eq. (5), is the ratio of the energy produced by a wind turbine to the energy produced by a wind turbine working at its rated power [19, 20].

$$C_F = E_{net,annaul}/(Pr \times 8760hrs) \times 100 \tag{8}$$

C_F is the capacity factor; Pr is the rated power capacity of the wind turbines.

8. Results and Discussions

8.1. Data Analysis

The outcome of wind data analysis at specified heights of measured wind data and NASA data at 50m height using Windographer software were found as shown:-

- The diurnal wind speed profile Figure 2 shows that wind speeds decrease between 0:0 AM and 8:0 AM, then increase at the other hours of the day to maximum value from 1800 -2400 p.m. This indicates a better time of wind speeds when high electricity could be produced from wind energy.
- In Table 3, the largest monthly wind speeds at 10m were 8.024 m/s, 6.089m/s, and 5.169m/s in June, July, and August months, while the minimum wind speed values were found in Jan., Mar., Sep., Nov., and Dec., respectively.

➢ Both Figure 3 and Table 3 show that at the heights of 30m, 50m, and 52m, the same trend of largest average monthly wind speeds occurs during the summer months. The maximum monthly wind speeds were found to be 9.771m/s, 10.628m/s and10.847m/s at 30m, 50m, and 52m in June, respectively, while the average of NASA data was 7.284m/s in the same month.
➢ The annual mean of wind speeds of measured data were at 10m, 30m, 50m, and 52m were 4.607m/s, 6.068m.s, 6.673m/s, and 6.91m/s respectively, while the annual mean of NASA data was found 5.241m/s. It was found that a high difference between the mean of wind speed resulted from measured data and NASA data at 50m height.

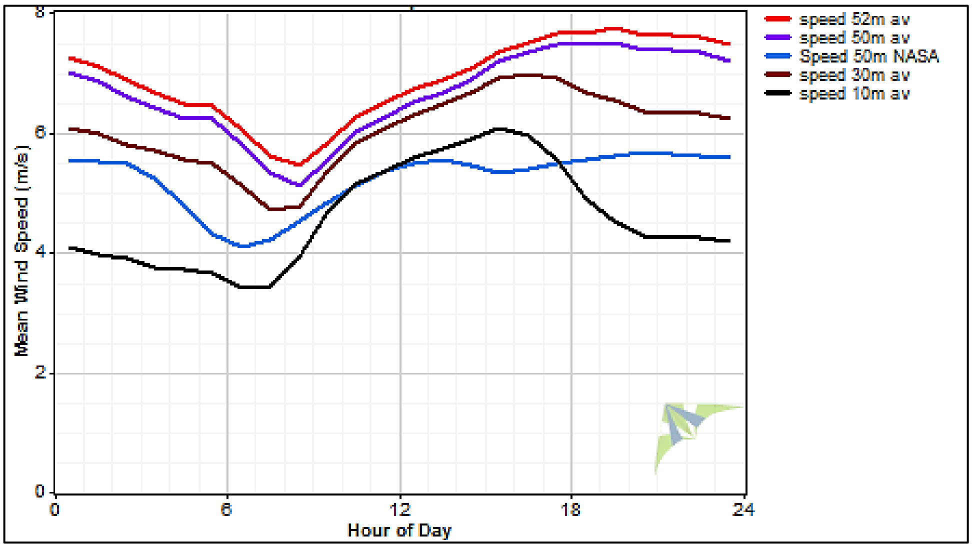


Figure 2: The diurnal wind speed profile at different heights at the AL Shihabi site.

Table 3: Annual mean of wind speeds, Weibull parameters, and power density.

Variable	Monthly mean												
Data Column	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
speed 10m	3.8	4.5	3.5	5	4.4	8	6	5.1	3.9	4.1	3.4	3.4	4.6
speed 30m	5.2	5.8	4.8	6.5	5.9	9.7	7.6	6.8	5.5	5.5	4.7	4.8	6
speed 50m	5.8	6.5	5.2	7.1	6.4	10.6	8.4	7.5	6	6.1	5.2	5.3	6.6
Speed 50m NASA	4.1	4.5	4.8	5.7	5.2	7.2	6.3	6.3	5.3	5	3.8	4.3	5.2
speed 52m	6.1	6.7	5.5	7.3	6.6	10	8.6	7.7	6.2	6.3	5.4	5.6	6.9
Direction 10m	284	131	302	292	287	299	296	298	298	333	303	306	298
Direction 30m	314	119	301	286	285	291	287	290	290	325	293	301	291
Direction50m	1.5	71.3	336	308	306	308	306	310	315	354	317	325	313
Direction 50m	59.1	61.7	8.9	315	307	321	320	331	348	13.9	15.2	48.7	339
speed 10m av TI	0.22	0.23	0.29	0.24	0.26	0.17	0.24	0.24	0.3	0.25	0.23	0.23	0.24
speed 30m av TI	0.15	0.16	0.21	0.17	0.17	0.13	0.18	0.17	0.21	0.18	0.15	0.15	0.17
speed 50m av TI	0.13	0.15	0.2	0.16	0.17	0.12	0.17	0.16	0.2	0.17	0.14	0.13	0.16
speed 52m av TI	0.12	0.13	0.15	0.13	0.14	0.11	0.14	0.13	0.16	0.14	0.12	0.12	0.13
10m WPD	90	160	79	178	92	459	270	136	82	90	55	69	144
30m WPD	184	278	150	303	172	728	449	263	174	181	120	143	257
50m WPD	256	368	193	390	271	912	581	364	240	258	174	205	346
52m WPD	272	387	203	405	242	953	610	383	252	266	183	217	359
50m WPD	75	99	110	148	105	262	185	176	120	111	59	83	126

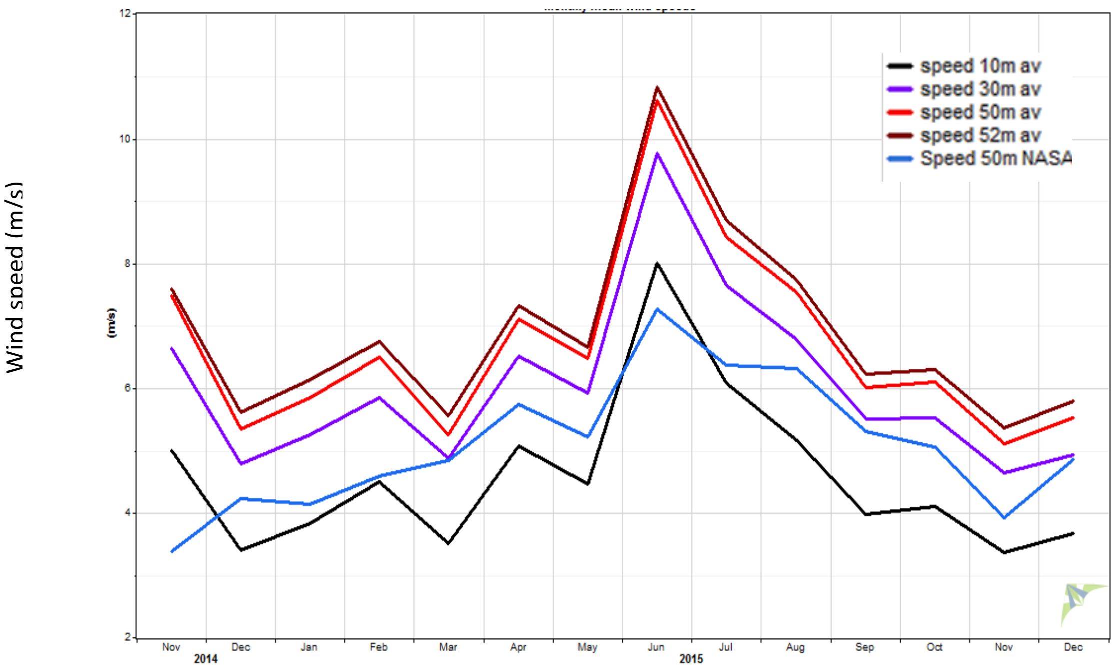


Figure 3: Mean monthly wind speed distributions at different heights at the AL Shihabi site.

The Histograms of observed wind speeds were illustrated in Figures (4-8); these figures show that most of the wind speeds observations lie in the range equal to and above 4.0 m/s (the most frequent wind speeds) at a probability of 83.26 %, 89.945%, 75.94% and 95.68% of the time at the heights 10m, 30m, 50m and 52m respectively which means the working time probability of wind turbines that would be installed at this site.

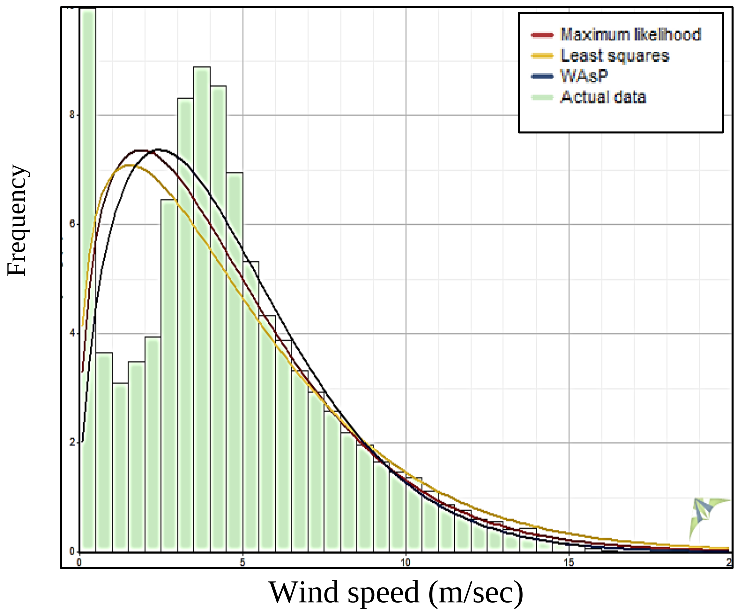
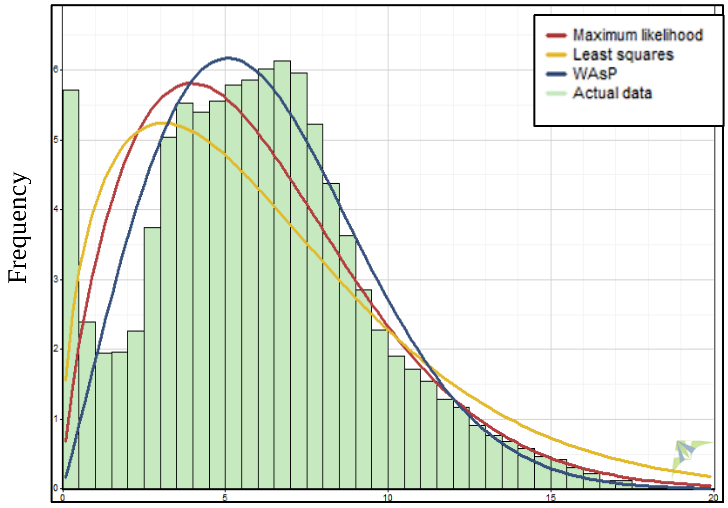
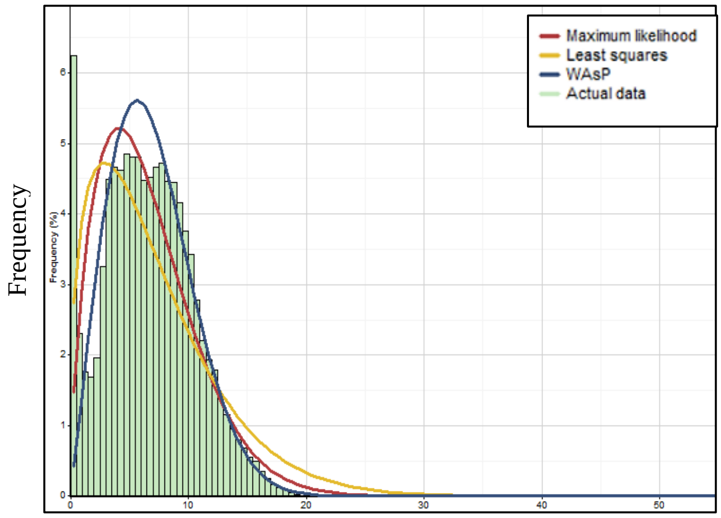


Figure 4 : Frequency distribution of wind speed at 10m.



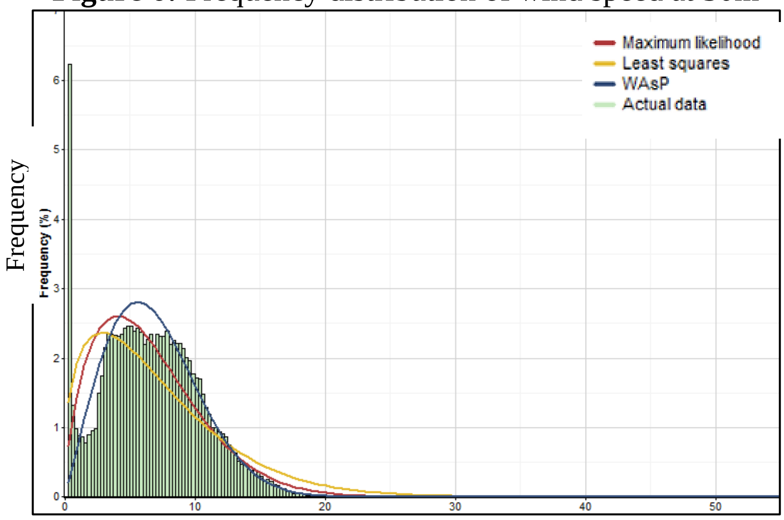
Wind speed (m/sec)

Figure 5: Frequency distribution of wind speed at 30m



Wind speed (m/sec)

Figure 6: Frequency distribution of wind speed at 50m



Wind speed (m/sec)

Figure 7: Frequency distribution of wind speed at 50m NASA.

For all the heights, the portion of wind speeds higher than the mean wind speed of more than 40% at all the methods (Maximum Likelihood, Least Square, WAsP, and actual data) as shown in Table 4 and Figures (4-8), the high wind speeds distribute around the mean wind speed this gives primary indications of the suitability of this site for wind farm construction and stability of wind regime.

Table 4: Accuracy results of applied algorithms for wind speed data

Height m	Algorithm	Weibull k	Weibull c (m/s)	Mean (m/s)	Power density (W/m2)
Wind speed at 10 m height	Maximum likelihood	1.427	5.036	4.577	172.2
	Least squares	1.28	5.194	4.813	241.2
	WAsP	1.503	5.047	4.555	156.9
	Actual data	(54,288 time steps)		4.604	156.8
Wind speed at 30 m height	Maximum likelihood	1.729	6.74	6.007	298
	Least squares	1.448	7.037	6.382	456.4
	WAsP	2.038	7.042	6.239	278.8
	Actual data	(54,288 time steps)		6.064	278.8
Wind speed at 50 m height	Maximum likelihood	1.630	7.349	6.578	421.6
	Least squares	1.352	7.768	7.121	709.5
	WAsP	2.061	7.792	6.902	373.5
	Actual data	(54,171 time steps)		6.673	373.5
Wind speed at 52m height	Maximum likelihood	1.932	7.766	6.888	395.9
	Least squares	1.847	7.829	6.954	427.9
	WAsP	2.079	7.907	7.004	387.1
	Actual data	(54,288 time steps)		6.905	387.1
Wind speed at 50 m height NASA	Maximum likelihood	1.631	7.344	6.573	420.5
	Least squares	1.353	7.761	7.114	706
	WAsP	2.059	7.785	6.896	372.8
	Actual data	(54,288 time steps)		6.669	372.8

8.2. Wind power analysis

1. The monthly mean wind power densities for all measured and NASA data are illustrated in Figure 9 and Table 5, which gives an attractive image of wind power availability in the studied site and its variation from month to month and season to season. It is evident that the summer months when the maximum load is advised, have the highest mean wind power density. The annual mean of wind power density presented in Table 6 was found at 144.0W/m^2, 257.0 W/m^2, 346.0 W/m^{2,} and 359.0 W/m^2 for measured wind data at heights 10, 30, 50, and 52 m, while it was found that for NASA the wind data at 50m is 126.0W/m^2. The difference is the result of the difference between simulated and real-world data.
2. It is evident from Table 5 that power density (calculated using predicted Weibull parameters) increases in the summer and reaches its highest value at June 953 W/m2 at a 321 direction and a 52m height. The lowest value is shown at November 183W/m2 at 15.2 direction and 52m height.

Table 5: Monthly and annual mean of power density and direction of energy content

Variable/ Units	**Monthly mean**												
Data	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	All
10m average/ °	284	131	302	292	287	299	296	298	298	333	303	306	298
30m average/ °	314	119	301	286	285	291	287	290	290	325	293	301	291
50m average/ °	1.5	71	336	308	306	308	306	310	315	354	317	325	313
52m average/°	59.1	61.7	8.9	315	307	321	320	331	348	13.9	15.2	48.7	339
10m WPD W/m²	90	160	79	178	92	459	270	136	82	90	55	69	144
30m WPD W/m²	184	278	150	303	172	728	449	263	174	181	120	143	257
50m WPD W/m²	256	368	193	390	271	912	581	364	240	258	174	205	346
52m WPD W/m²	272	387	203	405	242	953	610	383	252	266	183	217	359
50m WPD W/m²	75	99	110	148	105	262	185	176	120	111	59	83	126

Table 6: Annual mean power density and energy content

Variable	10m	30m	50m	50m NASA	52m
Measurement height (m)	10	30	50	50	52
Mean power density (W/m²)	144	257	346	126	359
Mean energy content (kWh/m²/yr)	1,260	2,255	3,027	1,106	3,145

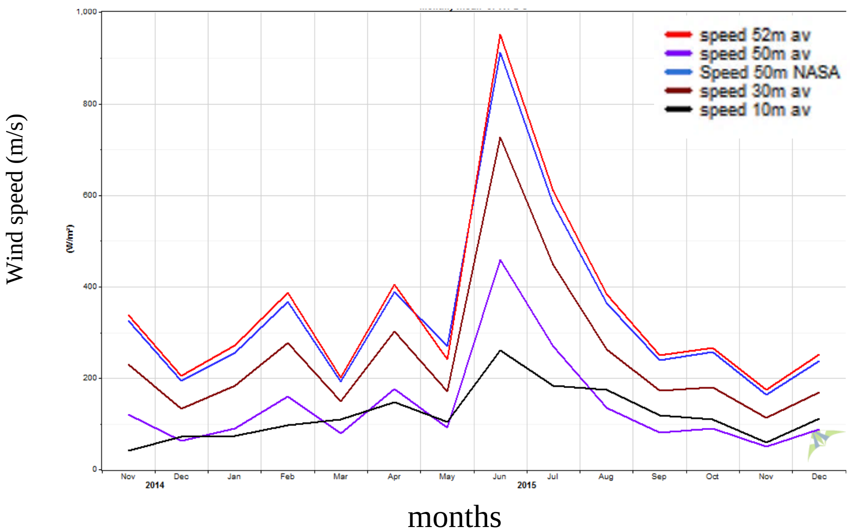


Figure 9: Monthly mean wind power densities

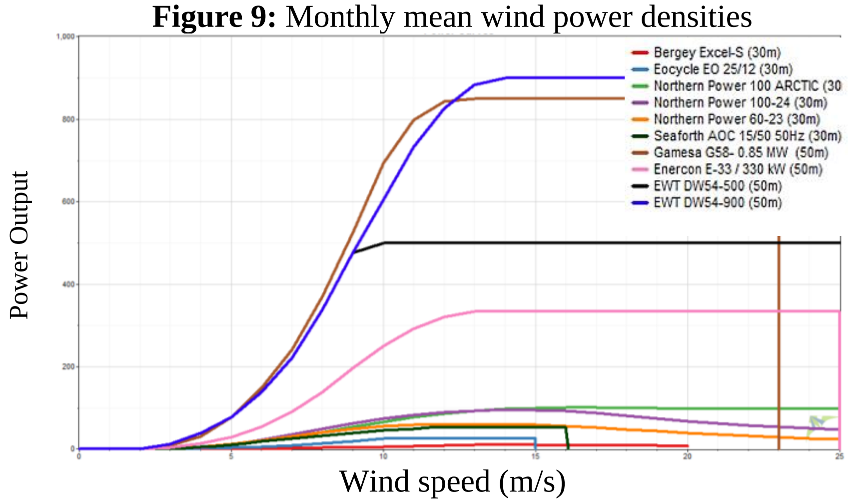


Figure 10: Power curve of selected wind turbines

8.3. Results of selected wind turbines

Ten wind turbines with hub heights between 30 and 50 m were chosen to evaluate wind energy output. The maximum rated power wind turbine was EWT 900kw. Table 7 shows that in June, when the highest wind speeds occurred, the net mean monthly power output was higher after losses.

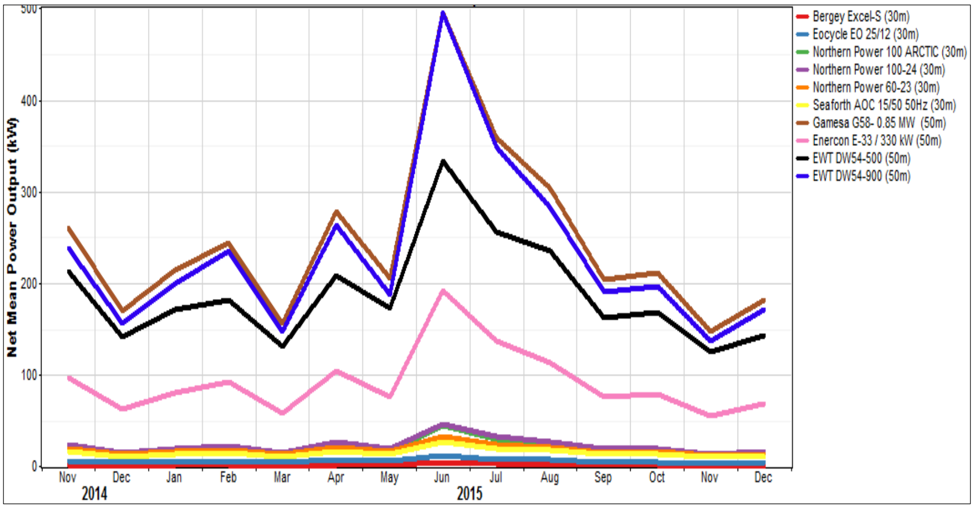
Table 7: Net monthly mean power output

Months	Nov14	Dec 14	Jan 15	Feb 15	Mar 15	Apr 15	May15	Jun 15	Ju-15	Aug15	Sep 15	Oct 15	Nov15	Dec15	Overall
Bergey Excel-S	1.8	1.2	1.6	2.1	1.3	2.4	1.6	4.8	3.2	2.3	1.6	1.6	1.1	1.4	2
Eocycle EO 25/12	7.1	4.6	5.9	6.5	4.6	7.7	6	12	8.9	8.3	5.7	5.8	4.1	5	6.6
Northern Power 100 ARCTIC	20	13	17	21	13.8	24	17	44	30	24.4	16	17	12	14	21
Northern Power 100-24	23	15	20	23	15.9	27	20	47	33	28.1	19	20	14	17	23
Northern Power 60-23	20	13	16	18	13.4	21	17	33	24	22.3	15	16	12	14	18
Seaforth AOC 15/50 50Hz	17	11	14	15	11.3	17	14	27	20	18.7	13	14	10	11	15
Gamesa G58-0.85 MW	260	169	214	245	157	278	205	496	359	304	204	211	148	182	247
Enercon E-33 / 330 kW	96	63.6	80	93	59.2	105	76	192	137	114	76	79	55	68	93
EWT DW54-500	213	142	171	182	131	209	174	334	256	236	162	168	125	144	190
EWT DW54-900	238	157	200	235	147	264	188	496	349	283	191	197	138	171	235

Figure 11 displays the net mean power generation, and Table 8 recorded with the net annual energy output and the net capacity factor after losses. The greatest net annual energy production for the Gamesa G58- 0.85 MW wind turbine, the EWT DW54-900 wind turbine, and the EWT DW54-500 wind turbine was 2,191,918 (kWh/yr), 2,084,388 (kWh/yr), and 1,679,169 (kWh/yr), respectively. The Net AEP of the other models was lower. The highest capacity factor value, 38.34%, belongs to the EWT DW54-500 wind turbine model. Table 8 and Figure 12, which show the net yearly capacity factor, provide this information. The capacity factor reached its peak value in June month, when higher wind gusts were reported. All of the wind turbines used in this study had capacity factors higher than 20%, providing a crucial indicator that the AL Shihabi location is suitable for constructing a wind farm.

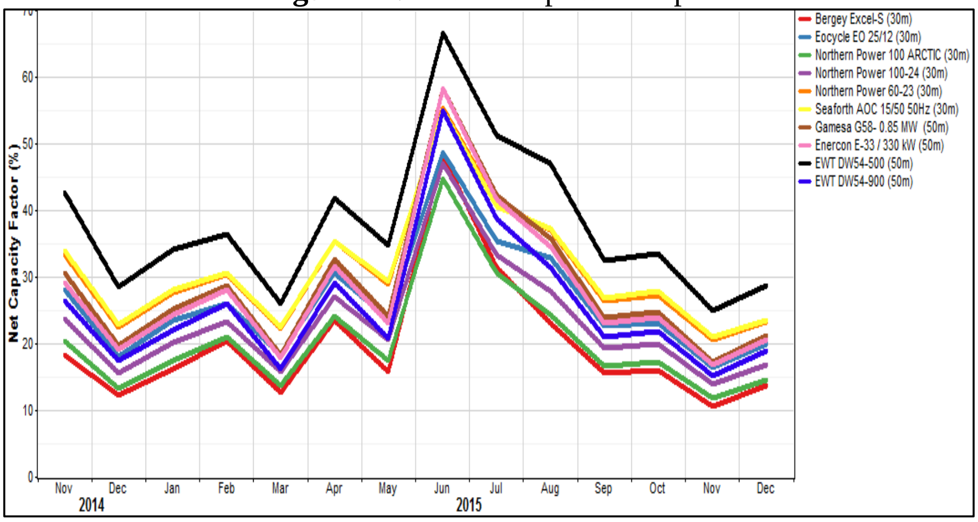
Table 8: Net mean power output, the net annual energy output, and the C_f.

Turbine	Hub Height m	Rated power	Hub Height Wind Speed m/s	Net Power (kW)	Net AEP (kWh/yr)	NCF (%)
Bergey Excel-S	30	10	6.06	2.1	18,115	20.68
Eocycle EO 25/12	30	25	6.06	6.7	58,701	26.8
Northern Power 100	30	100	6.06	21.2	185,678	21.2
Northern Power 100-24	30	100	6.06	23.9	209,010	23.86
Northern Power 60-23	30	60	6.06	18.8	165,091	31.41
Seaforth AOC 15/50	30	50	6.06	15.8	138,597	31.64
Gamesa G58- 0.85 MW	50	850	6.67	250.2	2,191,918	29.44
Enercon E-33 / 330 kW	50	330	6.67	94.8	830,134	28.72
EWT DW54-500 (50m)	50	500	6.67	191.7	1,679,169	38.34
EWT DW54-900 (50m)	50	900	6.67	237.9	2,084,388	26.44



Months

Figure 11: Net mean power output



Months

Figure 12: Net annual capacity factor

9. Conclusion

- The studied area can be classified into the third category according to the IEC classification, meaning the wind energy project can be completed in that region.
- From an economic point of view, there is a possibility to invest in the proposed study site. It is found that (EWT DW54) wind turbine 500kW can provide electric energy with the cost estimated at 0.0618 and 0.0786$/kWh based on LCOE and NPV, respectively: higher IIR and short SPB for the investor to recoup the investment costs with acceptable safety risk limits.
- The suggested wind farm has a 31.3% capacity factor, indicating that the performance of wind turbines and the electricity exported to the grid is evaluated by 13,703 MWh annually.
- It was noted that the best type of proposed wind turbine (5.0 MW) has lower cost, higher capacity, and the greatest amount of greenhouse gas reduction.
- The variance in the unit cost of electricity is due to the methodology used in calculating the electricity obtained using LCOE, NPV, and the RETScreen program.
- The results of measured wind data are more accurate than NASA wind data.

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