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Optimum Selection of Wind Turbines Using Normalized Power and Capacity Factor Curves

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Abstract

The main objective of this paper is present a novel method to choice a certain wind turbine for a specific site by using normalized power and capacity factor curves. The site matching is based on identifying the optimum turbine rotation speed parameters from turbine performance index (TPI) curve, which is obtained from the higher values of normalized power and capacity factor curves. Wind Turbine Performance Index a new ranking parameter, is defined to optimally match turbines to wind site. The relations (plots) of normalized power, capacity factor, and turbine performance index versus normalized rated wind speed are drawn for a known value of Weibull shape parameter of a site, thus a superior method is used for Weibull parameters estimation which is called Equivalent Energy Method (EEM).

Keywords: Capacity factor, Normalized power, Turbine performance index.

الاختيار الأمثل لتوربينات الرياح باستخدام منحني القدرة المعياري وعامل السعة

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الخلاصة

الهدف الرئيسي من هذا البحث هو تقديم طريقة جديدة لاختيار توربين رياح أمثل لموقع معين باستخدام منحنيات منحني القدرة المعياري ومنحني عامل السعة. توافق الموقع مع توربين الرياح يحدد من خلال حساب معاملات سرعة دوران التوربين الرياح والتي تحسب من خلال منحني مؤشر أداء التوربين (TPI)، والذي يتم الحصول عليه من القيم الأعلى لمنحنيات القدرة المعياري وعامل السعة. مؤشر أداء توربينات الرياح هو معامل ترتيب جديد لمطابقة التوربينات بشكل مثالي مع موقع الرياح. يتم رسم العلاقات (المنحنيات) الخاصة بالقدرة المعياري وعامل السعة ومؤشر أداء التوربينات مقابل سرعة توربين الرياح المعيارية معروفة لمعلمة شكل Weibull للموقع، حيث تم استخدام طريقة الطاقة المكافئة (EEM)، وهي طريقة متفوقة لتقدير معاملات Weibull.

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Introduction

The process of generating electric power by wind turbine systems at a particular location depending on many factors, the most important of these factors is the wind speed at that location and most notably the wind turbine speed characteristics themselves; namely, rated speed (v_r), cut-in speed (v_c) and furling or cut-out speed (v_f) including wind turbine hub height [1]. Table 1 gives a description of some of the turbines currently available, which have also been used for the purpose of determining the most suitable turbine for the study site.

Table 1- Specification of Some Available Wind Turbine Generator System

Make	Rating Power [kW]	Operating Data			Turbine		Generator
		v_c m/s	v_r m/s	v_f m/s	No. Blades.	Rotor diameter [m]	Rated Power [kW]
Fortis	5	3	21	25	3	5	5
Aircon 10S	10	3.5	11	25	3	7.1	9.8
C&F energy	20	1.5	9	15	3	13.1	20
G3120	35	3.5	11	25	3	19.2	35
Orenda	49	4	10	25	3	18.9	49
Deimos	60	3	9	25	3	21.5	60
Electriawind	150	2.5	9	25	3	38	100
Micon	200	4	14	25	3	30	200
Endurance	225	4	15	25	3	29.1	225
Enercon	800	3	12	34	3	48	800
Vestas	850	4	14	25	3	52	850

The most important characteristic speed for wind turbine design is the rated speed [1]. If a low rated speed is chosen to take advantage of the low wind speed within an area, a lot of energy will be lost at the higher wind speed. Conversely, if the wind turbine rated speed is selected too high, the turbine rarely operates at its estimated capacity and will also lose a lot of energy at low wind speed. This means that the rated speed must be determined so that the turbine produces higher energy. Usually v_c is chosen approximately as half v_r , While v_f estimated as twice of v_r value [1]. The relation between turbine wind speeds as will be seen in this work are $v_c = 0.259 v_r$ and $v_f = 1.95 v_r$. Here, it is important to define an important factor which is called Capacity factor (C_f). This factor represents the ratio of the output expected energy from wind turbine over a period of time to the estimated power of the wind turbine generator. The TPI curve could be found by capacity factor and normalized curves and is plotted on the same axis of the normalized rated speed [2]. From the above, it can be said that it is advisable to choose the optimal wind turbine for a particular location in order to obtain the highest wind potential energy. These important aspects raise concerns regarding suitability, taking into account the energy potential of a particular site and selecting the appropriate wind turbines for a specific wind profile [3]. In this paper the Wind Turbine Performance Index (TPI) concept is introduced, there is an ideal TPI curve for each study site from which an optimized wind turbine speeds that will match the site optimally could be found.

Area of Study

The study site is located in the holy area of Karbala - Republic of Iraq and specifically Al-Razzaza Lake. This Lake is located 15 km north west of Karbala. It is part of a wide valley that includes al-Tharthar, Al-Habbaniya, Al-Razzaza and Bahr Najaf (Najaf Sea). The lake is supplied by eight sources, including the River Euphrates; Lake Habaniya, east of Ramadi; Rashidiya, north of Karbala; groundwater springs in Ayn al-Tamr, 80km west of Karbala; rainwater and seasonal flows. Located to the west of the Iraqi holy city of Karbala with coordinates 323736 N, 435342E, as shown in Figure-1. This location has been chosen based on the global wind distribution map produced by Global Wind Atlas. Through this map, there is an abundance of high wind speeds in the western region of Iraq, where the average speed through the year ranges between 5.00-6.00 m/s at 50m height, and high speeds are concentrated almost in two areas,

Al-Razzaza and Tharthar lakes. In this research, Al-Razzaza lake was chosen to find suitable offshore wind generators for this site being one of the promising areas in Iraq (marginal class) [4].

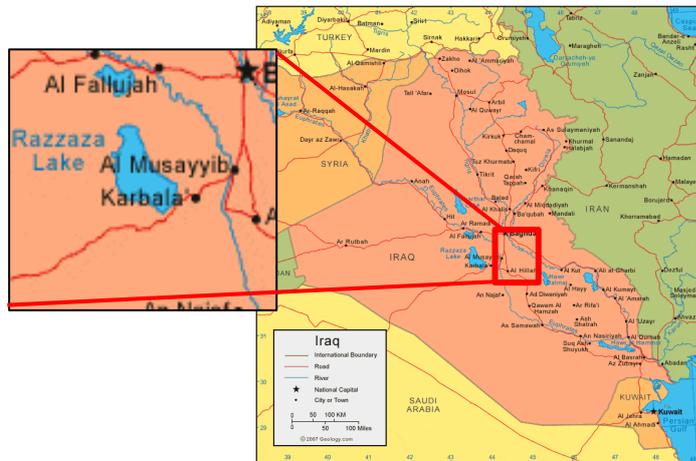


Figure 1- area of study in Iraq country

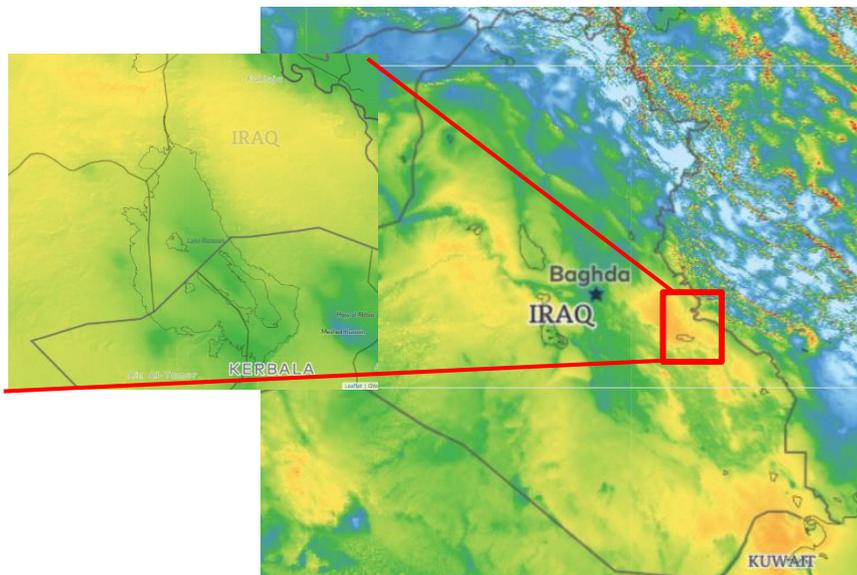


Figure 2- wind speed distribution in Iraq country at 50m height[4]

Data Specification work

MERRA data downloaded from Windnavigator using Windographer Data Downloader. This data is registered from NASA Global Modeling and Assimilation Office which provided from AWS Truepower, LLC, a UL Company, and contains hourly wind speed and wind direction for the period between 1979-2016. All readings are measured at 50m height from sea-surface and will be downloaded after giving the proceedings coordinates (Lat., Long.) [2].

1. Mathematical Formulation

Before entering into the theoretical concepts of the work, basic concepts about the mathematical structure of research must be taken, as follows

1.1. Weibull Distribution of Wind Speed

The wind speed Weibull distribution function can be given by wind speed frequency curve (probability density function) [1]:

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

Where, the cumulative distribution function for wind speed (v) is given by [1]:

$$F(v) = 1 - \exp[-(v/c)^k] \tag{2}$$

Where, c represents the scale factor (has unit of speed) and k represents the shape factor (without dimension). A new method for estimating Weibull parameters is called the Equivalent Energy Method (EEM) which examined by [5]. This method is based on the energy content of the distribution and has been developed to improve the accuracy of the parameters. This new determines Weibull parameters that best fit the measured wind speed distribution and is equal to the wind speed cubic. According to the Weibull distribution, the probability of a wind speed greater than or equal to a specified value, v, is defined by [5]:

$$P(v) = \exp[-(v/c)^k] \tag{3}$$

Now, it is possible to represents the probability of wind speeds which is lower than v and greater than or equal to v-1 and (i.e. v-1 ≤ v < v) is:

$$P(v) = P(v - 1) - P(v) \tag{4}$$

$$P(v) = \exp[-\left(\frac{v-1}{c}\right)^k] - \exp[-\left(\frac{v}{c}\right)^k] \tag{5}$$

Statistically, a stochastic variable Pv could be represented by the probability function Pv added to a stochastic term ε, such as:

$$P_v = P(v) + \varepsilon = \left(\exp\left[-\left(\frac{v-1}{c}\right)^k\right] - \exp\left[-\left(\frac{v}{c}\right)^k\right] \right) + \varepsilon \tag{6}$$

Using the condition of energy content equivalence between the observed wind speeds and the Weibull distribution, the scale factor, c, can be written from the mean cube expression as:

$$c = \left(\frac{(v)^3}{\Gamma\left(1 + \frac{3}{k}\right)} \right)^{1/3} \tag{7}$$

Eq.7 in Eq.6 yields:

$$P_v = \exp\left[-\left(\frac{(v-1)\Gamma\left(1 + \frac{3}{k}\right)^{1/3}}{\bar{v}}\right)^k\right] - \exp\left[-\left(\frac{v\Gamma\left(1 + \frac{3}{k}\right)^{1/3}}{\bar{v}}\right)^k\right] + \varepsilon \tag{8}$$

Where \bar{v} represents the mean wind speed. The Weibull shape factor, k, can be estimated by applying the least squares technique to the following expression [6]:

$$\sum_i^n = 1 \left[P_{v_i} - \exp\left[-\left(\frac{(v_i-1)\Gamma\left(1 + \frac{3}{k}\right)^{1/3}}{\bar{v}}\right)^k\right] + \exp\left[-\left(\frac{v_i\Gamma\left(1 + \frac{3}{k}\right)^{1/3}}{\bar{v}}\right)^k\right] \right]^2 = \sum_{i=1}^n (\varepsilon_i)^2 \tag{9}$$

Where P_{v_i} is the probability of having wind speeds for i^{th} bin, n = is the number of bins of the wind speed histogram, v_i is the highest wind speed value of the i^{th} bin, \bar{v}_m^3 = the mean cube (observed). After k is compute, the scale factor is calculated from Eq.7.

1.2. Capacity Factor

The capacity factor can be obtained from the following equation [7]:

$$C_f = \frac{\exp[-(v_c/c)^k] - \exp[-(v_r/c)^k]}{(v_r/c)^k - (v_c/c)^k} - \exp[-(v_f/c)^k] \tag{10}$$

Where, C_f is the capacity factor, while v_c , v_r , and v_f are defined before, (v_r/c) is normalized rated speed. It is clear that the capacity factor is a function of the main turbine parameters v_c , v_r , and v_f also the site parameters c and k.

1.3. Normalized Power

The resulting power of the wind turbine generator can be written as follows [1]:

$$P_e(v) = 0.5 C_p \eta_m \eta_e \rho A v^3 \quad (11)$$

Where η_m , η_e = the efficiencies of the mechanical transmission system and the electrical generation system,

ρ = air density, A = turbine sweep area, C_p = power coefficient of the turbine. The models of pitch controlled blades are based on three characteristic speeds v_c , v_r , v_f and on the rated power P_r , while the rising curve between v_c and v_r can be well approximated with a quadratic model. Therefore, $P_e(v)$ can be written as follows [1]:

$$P_e(v) = P_r \begin{cases} 0 & v < v_c \text{ or } v > v_f \\ \frac{v^2 - v_c^2}{v_r^2 - v_c^2} & v_c \leq v \leq v_f \\ 1 & v_r \leq v \leq v_f \end{cases} \quad (12)$$

Where $P_r(v) = 0.5 C_{pr} \eta_{mr} \eta_{er} \rho A v_r^3$, C_{pr} = the coefficient of performance at rated wind speed v_r , η_{mr} = the mechanical interface efficiency at rated power, η_{er} = the generator efficiency at rated power. By integrating the multiplication of Eq. 12 and Eq. 1, the average electrical power produced by a wind turbine can be represented by:

$$P_{e,av} = \int_0^{\infty} P_e(v) f(v) dv \quad (13)$$

Where $f(v)$ is a probability density function of wind speeds, using the method of Pe,

$$P_{e,av} = P_r \left\{ \int_{v_c}^{v_r} \left[\frac{v^2 - v_c^2}{v_r^2 - v_c^2} \right] \frac{K}{c} \left(\frac{v}{c} \right)^{K-1} \exp \left[- \left(\frac{v}{c} \right)^K \right] dv + \int_{v_r}^{v_f} \frac{K}{c} \left(\frac{v}{c} \right)^{K-1} \exp \left[- \left(\frac{v}{c} \right)^K \right] dv \right\} \quad (14)$$

Normalizing the average electric power ($P_{e,av}$) equation by rated output power is defined as:

$$P_N = \frac{P_{e,av}}{0.5 C_{pr} \eta_{mr} \eta_{er} \rho A c^3} = c_f \left(\frac{v_r}{c} \right)^3 \quad (15)$$

Where P_N the normalized power.

1.4. Turbine Performance Index (TPI)

Obviously, the increase in normalized power (with a corresponding value v_r/c) is associated with a decrease in the power factor and vice versa. Therefore, a value of (v_r/c) is expected, at which the product of the variables P_N and C_f for (v_r/c) will obtain maximum individual values of P_N and C_f .

This value (v_r/c) that corresponds to ($P_N * C_f$) max is between the values of (v_r/c) for $P_{N,max}$, and $C_{f,max}$. This means that it is possible to choose (v_r/c) for a site at which the total energy product is closer to maximum at a higher capacity factor. This means that it is possible to choose (v_r/c) for a location where the total power output is closer to the maximum in a higher power factor. This value (v_r/c) and the corresponding optimal cutting and reduction speeds are evaluated using $v_c = x_1 v_r$ and $v_f = x_2 v_r$. where x_1 and x_2 are two practical values. Thus, on the basis of the above discussion, the TPI is defined as [8]:

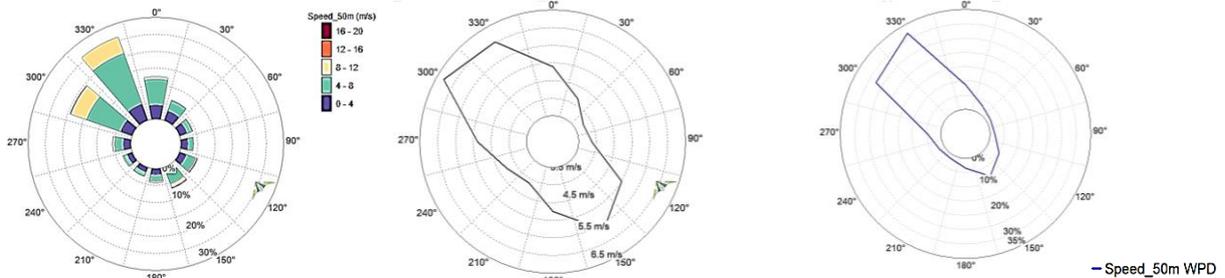
$$TPI = \frac{P_N \times C_f}{P_{N,max} \times C_{f,max}} \quad (16)$$

The TPI is a function of the usual rated speed, and is drawn with normalized power and power factor curves. Optimization (v_r/c) corresponds to the maximum TPI. Apply natural strength, capacity factor and turbine performance index curves to determine the optimal wind turbine parameters for the site.

Results and Discussions

Wind roses are constructed using a composite of data wind speed which measured at 50m height from earth sea level. Three types of information can be presented in Figure- 1. (1) The percentage of time from which it can be receive the wind from a particular direction. This can show the direction from which it can be get most of the wind. As for the study area, it is clear from the figure that the main

prevailing wind sector is 330, followed by sector 300 and both sectors are located in the northwest direction. In addition, approximately 5%, 15% and 5% of total time the wind blows at 8-12m/s, 4-8m/s, and 0-4m/s, respectively, from the sector 330. (2) The multiplication between the percentages of time from which it can be receive wind from a particular direction and the average wind speed at this direction. This tells us the average strength of the wind spectra at sector 300 is more than the others (which corresponds to the direction North-West). (3) The product of time percentage and cube of the wind velocity. This helps us in identifying the energy available from different directions, and the highest value lie at sector 330.



Frequency of speed vs. direction at 50m height, Mean of speed vs. direction at 50m height, Proportion of total wind energy vs. direction at 50m height

Figure 1- Wind Roses as frequency, speed, and energy (1/1/1979-29/2/2016)

Figure- 2 shows monthly based wind rose for 50 meter height, it helps in understanding the variability in the wind direction in every month. Simply, it could infer that the main prevailing wind direction in study area is North-West, while the dominant wind directions in all months were arranged between North-West 300 and 330 sectors. In more details, winds blow from 300 and 330 sectors have occurrences between 10-40%, thus sector 330 is the most dominant one, and it reaches its maximum value at approximately 40% from total records in Jun.

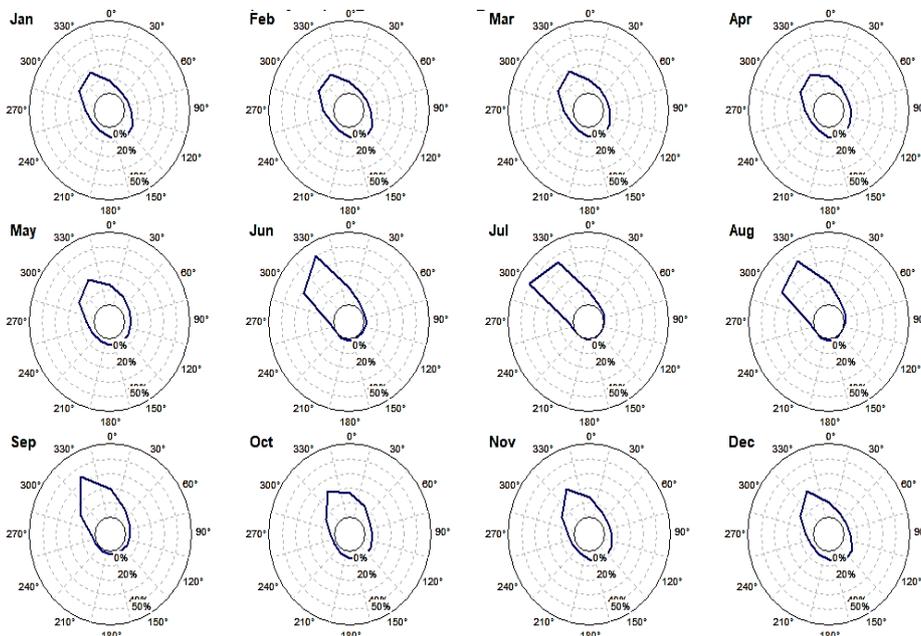


Figure 2- Monthly frequency of speed at 50m height vs. direction, 1/1/1979-2/29/2016

Figure-3 shows the rate of change in average wind speed during the months of the year. From this figures, it can be infer generally, that the mean wind speeds are high at first morning hours of the day (0 am), after that the mean wind speed will begin to be stable or with little change till 6 pm, where the mean wind speed will begin to increase again.

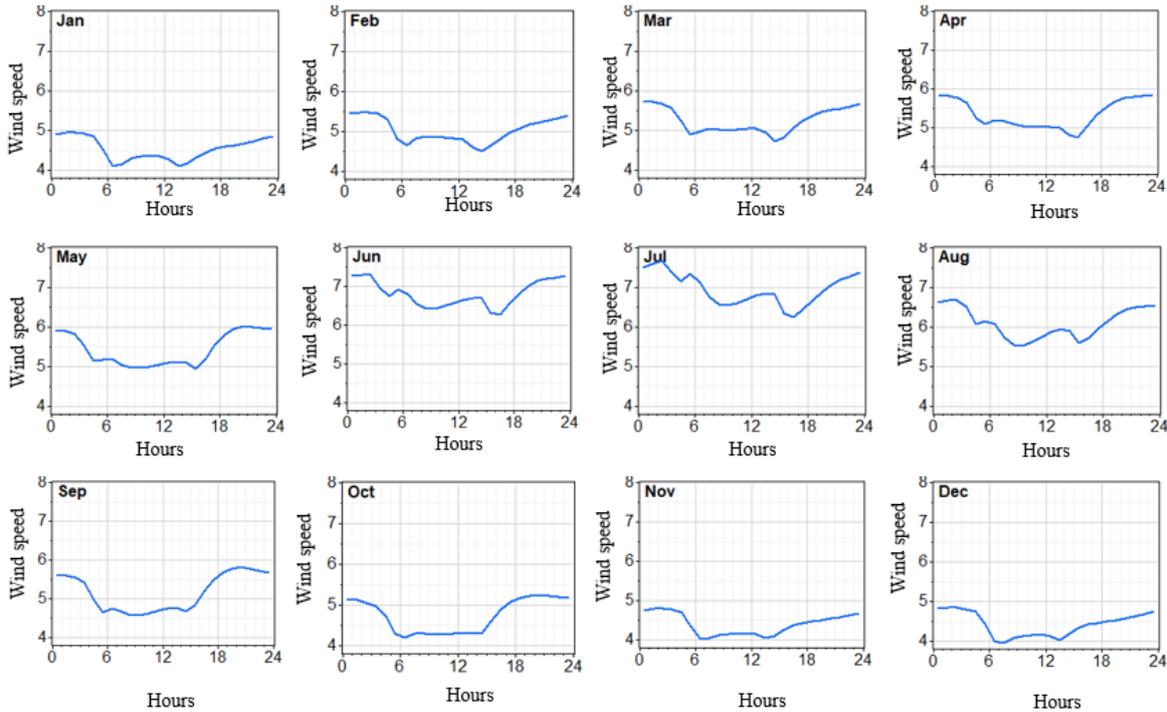


Figure 3- Hourly wind speed variation for each month

A computer program has been built by researchers to determine the optimum site matching of wind turbines. Al-Razzaza site in Iraq has been used in this study for mean wind speed 5.4 [m/sec] at height 50m. Capacity factor and normalized power are computed for different values of k and (v_r/c) . Figure- 4 shows two sets of general normalized curves drawn on common x-axis. One set of curves represents the capacity factors and the second set represents normalized power. For both curves, k is varied from 1 to 2.6 in steps of 0.4 and (v_r/c) is varied from 0.0–3.94 in steps of 0.3.

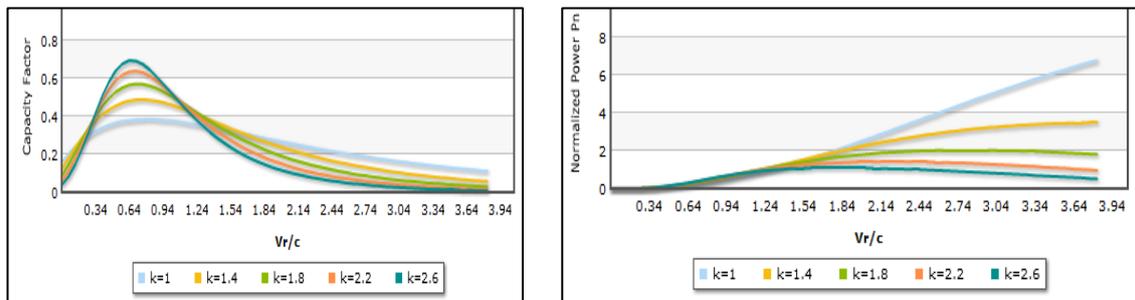


Figure 4- Normalized power and capacity factor curves at height 10m

A set of values of k and (v_r/c) are chosen to include the different sites and turbine specifications. By replacing the relationship $v_c=x_1v_r$ and $v_f=x_2v_r$ in Eq. 10, the normalized power can be fully expressed in terms of rated wind speed (v_r/c) and Weibull shape parameter (k). To reach both x_1 and x_2 values, a survey was conducted by many researchers, such that more than 120 types of wind turbines with different rated power and turbine speed parameters was used. From this survey, it was observed that the value of x_1 ranging from 0.252 to 0.266 with 0.259 average such that the standard deviation error is 0.0374 with 95% confidence. The value of x_2 ranging from 1.906 to 1.998 with average value 1.95 such that the standard deviation error is 0.258 with 95% confidence. In this paper, the average values of x_1 and x_2 were used, thus, the wind turbine speed parameters relationships can be expressed as follows:

$$v_c=0.259 v_R \tag{17}$$

$$v_f=1.950 v_R \tag{18}$$

Figure-5 shows the following: When the capacity factor C_f reaches its highest value, the normalized power P_N value is very low, and vice versa. When the normalized power reaches its highest value, the capacity factor have a small value.

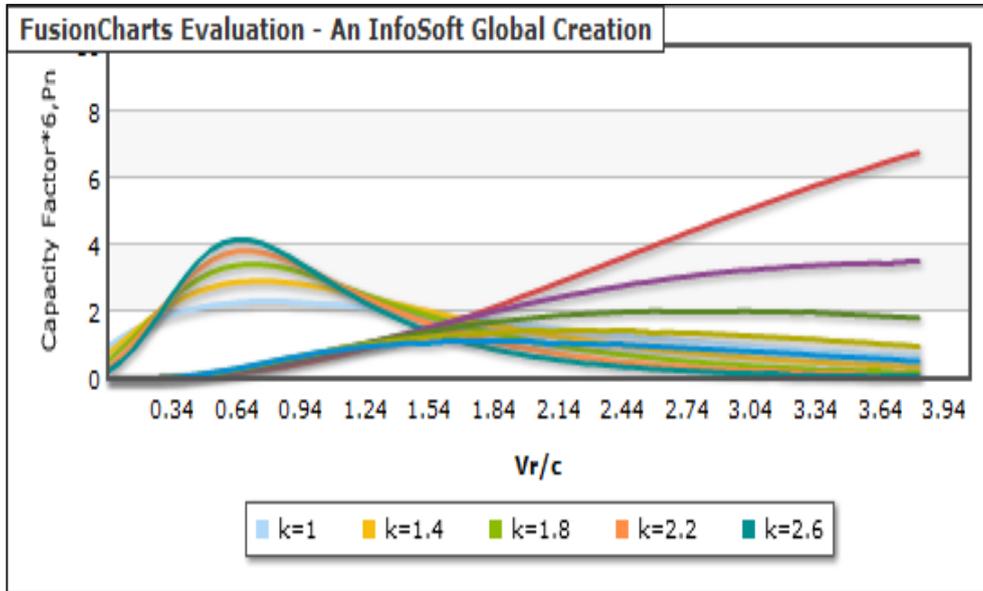


Figure 5- Normalized power and capacity factor curve.

The high rated speed values are accompanied by a decrease in capacity factor which in turn means that the turbine will work in relatively less amount of time. This requires to obtain v_r/c which is corresponding to maximum value of TPI, then by knowing Weibull scale factor (c) it is possible to calculate the rated speed of wind turbine (v_r). Finally, by using equations (17) and (18) it is possible to calculate the other wind turbine velocities v_c and v_f that make the output energy production close to its maximum value. Table 2 shows the results of applying the above mechanism for Al-Razzaza site and the identical turbine speed parameters for that area. Figure- 6 represents the wind frequency (graph bars) and the Weibull distribution (continuous line) over all sectors with a height of 50 meters, plus the values of Weibull statistics; scale parameter, shape parameter, mean wind speed, and wind power density. The normalized rated speed can be obtained corresponds to any point on the normalized power curve. With Weibull scale parameter (c) known for the location, the rated speed of the turbine can be estimated. Other two turbine parameters, namely cut-in and cut-out velocities, are estimated using the relations (17) and (18).

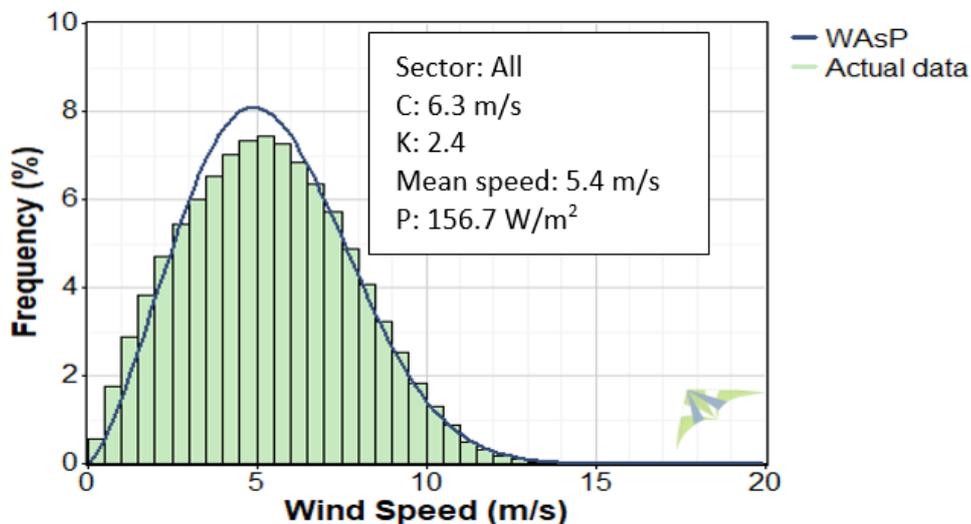


Figure 6- Weibull distribution of wind speed for Al-Razzaza site

In Figure-7, the normalized power P_N , capacity factor C_f and turbine performance index TPI curves are drawn for a site whose Weibull shape parameter ($k=2.4$) and scale parameter ($c=6.3$ [m/s]) are known. The normalized rated speed (v_r/c) at $P_{N,max}$ and TPI_{max} are obtained from the curve as listed in Table 2. After that, the rated speed of turbine corresponding to $P_{N,max}$ and TPI_{max} can be determined using Weibull scale parameter. The cut-in and cut-out speed parameters of the turbine are computed using the relationships mentioned in Equations (17) and (18).

Table 2- Turbine speed parameter estimation for a site

Parameters	at $P_{N,max}$	at TPI_{max}
v_r/c	02.08	01.18
v_r	03.50	01.99
v_c	12.72	07.22
v_f	23.53	13.36
P_N	01.21	00.82
C_f	00.67	00.50

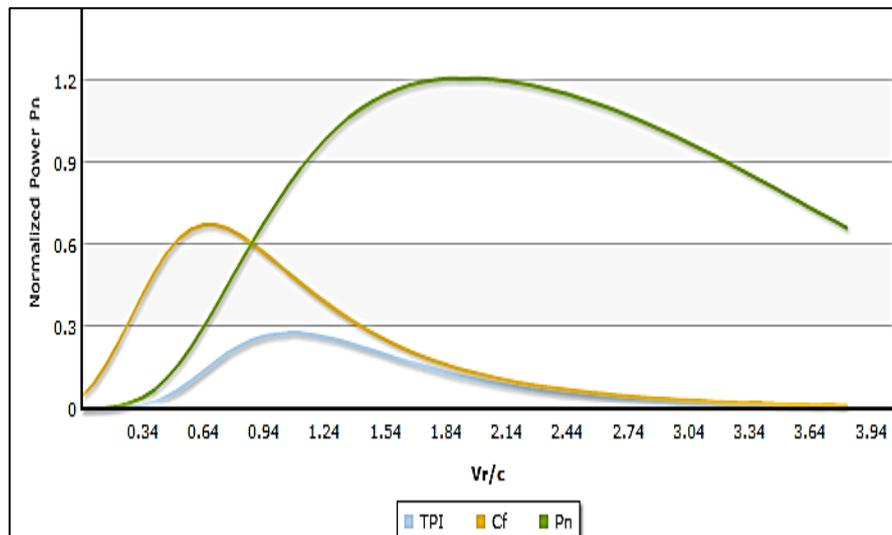


Figure 7- Normalized power, capacity factor and turbine performance index curve for Al-Razzaza site

Table 2 suggests the wind turbine parameters for Al-Razzaza site that give high output power generation. The Weibull scale and shape parameters for Al-Razzaza site are 6.3 [m/s] and 2.4. The normalized power P_N , capacity factor C_f and turbine performance index TPI curves are shown in Figure-7 and the necessary computations are given in Tables 2 and Table 3. Table 3 is dedicated to identify the best matched wind turbine for Al-Razzaza site from eleven turbines. From Table 3, it is found that the maximum turbine performance index and most suitable turbine from eleven systems are belong to C&F Green energy 20 [kW], Deimos DT2160 60 [kW] and Electriawind Garbi 150 [kW] wind turbines which they have the same TPI. The decision of which turbine is to be selected for installation will depend upon the load demand, installation costs and reliability aspects.

Table 3- Performance of wind turbines if installed at Al-Razzaza Site
($c = 6.3$ [m/s]; $k = 2.4$; $P_{N,max} = 1.24$; $C_f = 0.66$)

No.	Make	Rate Pwr [kW]	Operating Data			$\frac{v_r}{c}$	P_N	C_f	$\frac{P_N}{P_{N,max}}$	TPI
			v_c [m/s]	v_r [m/s]	v_f [m/s]					
1.	Fortis Montana	5	3	21	25	3.33	0.94	0.02	76.0	0.02
2.	Aircon 10S	10	3.5	11	25	1.74	1.20	0.22	96.5	0.17
3.	C&F Green energy	20	1.5	9	15	1.42	1.05	0.35	84.3	0.23

4.	Endurance G3120	35	3.5	11	25	1.74	1.20	0.22	96.0	0.17
5.	Orenda Skye	49	4	10	25	1.58	1.14	0.27	91.8	0.20
6.	Deimos DT2160	60	3	9	20	1.42	1.05	0.35	84.3	0.23
7.	Electriawind G.	150	2.5	9	25	1.42	1.05	0.35	84.3	0.23
8.	Micon	200	4	14	25	2.22	0.86	0.11	69.0	0.08
9.	Endurance X30	225	4	15	25	2.38	1.22	0.08	98.1	0.06
10.	Enercon E48	800	3	12	34	1.90	1.23	0.17	99.1	0.13
11.	Vestas V52	850	4	14	25	2.22	0.86	0.11	69.0	0.08

Conclusions

From the resultant wind rose it is obvious that the appropriate direction for the wind farm is northwest, specifically distributed between sectors 330 and 300. A new method of matching wind turbine generators systems to a site using Turbine performance index, normalized power, and capacity factor curves is presented in this work. The most suitable wind turbine to our chosen site (Al-Razzaza) can be found by calculating optimum wind turbine speed parameters from TPI curve, which is obtained from the normalized curves, so as to yield high output energy production. Maximum peak curve for TPI expressed by normalized rated wind speed can help us to find wind turbine parameters. This peak can be found from plots of normalized power, capacity factor and TPI versus normalized rated wind speed for a known value of Weibull shape parameter of a site. For our case of study, an eleven wind turbines are studied for site matching in order to show the usefulness of this technique in finding optimum wind turbine generator parameters. It is found that C&F Green energy 20 [kW], Deimos DT2160 60 [kW], and Electriawind Garbi 150 [kW] have highest and same TPI. Also, depending on results, the C&f will turning and generating electricity for about 90% of the time, then Deimos 84% and Electriawind Gabri 90%. Then in order to decide which wind turbine is the best for installation will depends on installation cost, reliability and load demand. From above it can infer that this tool is useful to make a good choice of a wind turbine having ideal speed parameters to give higher output energy.

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