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Performance of Wind Turbines at Three Sites in Iraq

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Abstract- Matching between wind site characteristics and wind turbine characteristics for three selected sites in Iraq was carried out. Site-turbine matching for potential wind power application in Iraq has not yet been well reported on. Thus, in this study, five years' wind speed data for sites located in Baghdad (33.34N, 44.40E), Nasiriyah (31.05N, 46.25E), and Basrah (30.50N, 47.78E) were collected. A full wind energy analysis based on the measured data, Weibull distribution function, and wind turbine characteristics was made. A code developed using MATLAB software was used to analyse the wind energy and wind turbines models. The primary objective was to achieve a standard wind turbine-site matching based on the capacity factor. Another matching based on the power density ratio of wind site and wind turbines was used to assure that the initially-selected turbines operate at the most-efficient capacity factor. Results from the wind-energy analysis revealed that the Basrah site ranked the highest with wind class (5-Excellent) according to the international system of wind classification. Results from the wind turbine-site matching showed that Wikov W2000-93 was the best-matched wind turbine model for the Basrah site from the viewpoint of capacity factor. The results also showed that Nordex N90 Beta was the best-matched wind turbine model from the perspective of energy capture.

Keywords Wind energy; wind turbine; Weibull parameters; capacity factor; site matching.

1. Introduction

The ongoing depletion of fossil-fuel sources in addition to the growing energy demand due to the growth of world population makes a move to renewable and environment-friendly alternatives like solar and wind very urgent. Also, this move could greatly mitigate consequences of greenhouse gases emission and the global warming. In this regards, wind power harvesting stands as a reliable technology for lowering the harmful carbon pollution due to fossil-fuel consumption besides reducing the high costs of electric power generation. In Iraq, the current dependence on the conventional power plants to meet the growing demand for electrical power approved not to be a trustful solution. Thus, the move to increase the share of renewable-based electricity started to receive a growing attention by the scientists and policymakers in the field of energy. Globally, numerous studies have been conducted to assess and analyze the wind energy potential to help in finding suitable wind sites for the wind energy projects.

The early use of wind as a source of power goes back to the seventeenth century BCE. The Babylonian emperor Hammurabi planned to use wind power for irrigation purposes in Mesopotamia (Iraq) [1]. Nowadays, wind power is usually used to generate electricity (wind turbines), or to pump water (windmills). Though that several studies were conducted to investigate the wind power potential at the candidate wind sites for wind energy projects. Habali and Amr [2] performed data evaluation, resource analysis, and matching between the systems and the sites' power distribution via reviewing the previous wind measurements in Jordan. The main conclusion was that the utilization of wind energy would highly reduce the national fuel bill, and decreases level of the environmental pollution. Bataineh and Dalalah [3] assessed the wind power potential for seven locations in Jordan using Rayleigh distribution. The results showed that all selected sites have high economic potential with unit cost less than $0.04/kWh of electricity and thus Jordan has high potential for exploitation of wind energy. Al-Nassar and Alhajraf [4] investigated the wind characteristics, annual average wind speed, wind power density, and wind energy density at six locations in the State of Kuwait. The study concluded that the highest wind power potential occurs during the summer season. Mohammadi and Mostafaeipour [5] evaluated the economic feasibility of electricity generation using six wind turbines in city of Aligoodarz situated in the west part of Iran. The wind energy potential was assessed for five years at 10 m height. The results showed that the E-3120 wind turbine was identified as the most attractive model for installation.

Asl et al. [6] investigated the wind energy potential at five selected sites in Kurdistan-Iran. The monthly and annual parameters in addition to the wind power rank of each site were estimated. Pachauri and Chauhan [7] explored the assessment of wind energy technology potential in India. The issues and challenges of wind technology in financial and technical context were discussed and identified for future work. Eltamaly [8] presented a procedure to choose the suitable wind turbines and the best site from many sites in Saudi Arabia based on the minimum price of kWh generated. The study used a computer program developed via Visual Fortran. The results showed that the best site is Dhahran and suitable wind turbine is KMW-ERNO with 5.85 Cents/kWh. Baseer and Meyer [9] analyzed the wind characteristics at seven locations in Jubail, Saudi Arabia. According to the output power of five commercially available wind machines, the results showed that Jubail industrial area is the most promising site.

Matching the candidate sites characteristics to the wind turbine specifications is usually done by using of the wind turbine capacity factor [10-14]. According to Sathyajith [15], the capacity factor is considered practically effective in the range , and very efficiently interacting in the range . The assessment of capacity factor has been a topic of interest to many studies in the literature. El-Shimy [16] developed a formulation of the capacity factor for site-wind turbines matching and validated it via long-term performance measurements at Zafarana wind farms-Egypt. Abul'Wafa [17] suggested the use of turbine performance index in coincidence with the minimum deviation ratio between the rotor-rated speed and the optimal speed for generating higher capacity factor within a lower cost of energy. Eltamaly [18] identified the best wind site from several sites in Saudi Arabia along with the most appropriate wind turbine based on the cost per kWh. Koussa et al. [19] estimated the capacity factor of four wind turbine generators at thirteen selected sites in different Algerian climatic zones. The most attractive wind turbine generator based on the energy produced and cost per kWh was identified.

Al Jowder [10] investigated the wind power potential at the Kingdom of Bahrain. The matching between the wind sites and wind turbines was achieved by estimating the capacity factor of wind turbines. Albadi and El-Saadany [20, 21] developed a new formulation of linear, quadratic, and cubic models for the capacity factor of any pitch-regulated wind turbines. Ucar et al. [11, 22] analyzed the wind characteristics, wind energy potential, and wind turbines characteristics in different sites in Turkey. The best wind turbine was identified via capacity factor and energy output of wind turbines. Ayodele et al. [23] investigated 20 commercially wind turbines of different specifications via estimating the capacity factor of wind turbines. The sites of the highest and lowest capacity factor were presented according to the wind power potential. Chermitti et al. [13] used the capacity factor of wind turbines in addition to the site effectiveness approach to assess the wind potential and identify the suitable wind energy applications for the sites.

Based on the authors' knowledge, site-turbine matching for wind energy applications in Iraq has not been extensively investigated yet. An early study by Darwish and Sayigh [24] referred that wind farms are feasible as one-sixth of Iraqi lands enjoy annual wind speed higher than. Kazem and Chaichan [25] recommended investigating the offshore of the Gulf near Basrah as one of the most potential candidates for wind farms. Saeed and Ramli [26] mentioned that deserts in the provinces of Al-Anbar, Karbala, and Al-Muthanna in Iraq are suitable for wind energy applications. In the present study, three different sites: Baghdad (33.34N, 44.40E), Nasiriyah (31.05N, 46.25E), and Basrah (30.50N, 47.78E) were selected to investigate the wind power potential at hub heights (60m, 80m, and 100m). The power density ratio of the wind site and wind turbines was defined as new parameter to develop a new site-turbine matching in addition to the regular matching based on the capacity factor. The new matching facilitated obtaining an optimal capacity factor for the initially-selected turbines. A set of five commercially-available wind turbine models were selected for the investigation. The most-matched model was determined via estimating the capacity factor of each wind turbine at the selected sites. This study is the first of its kind regarding the wind energy applications in Iraq. It could serve as a guideline for planning, development, and construction of wind farm and other wind power applications.

2. Site Information and Data Sources

Geographically, Iraq is bounded by Turkey from the north, Iran from the east, Syria and Jordan from the west, and Kuwait and Saudi Arabia from the south. It is lies between latitudes 29 5′ and 37 22′ north, and between longitudes 38 45′ and 48 4′ east [27]. With the aim to identify suitable sites for installation of wind farms or small standalone applications in Iraq, three selected sites were considered. These sites, namely are Baghdad (33.34N, 44.40E), Nasiriyah (31.05N, 46.25E), and Basrah (30.50N, 47.78E). The selected sites in the present study are shown in Fig. 1. Baghdad is the capital of Iraq. It is located along the Tigris River at an elevation of (35) meters above the sea level. The climate is hot and dry in summer, cold and wet in winter. Nasiriyah is a city in the southeast of Iraq on the Euphrates River. It is located at an elevation of (5) meters above the sea level with a desert climate. Basrah is located in southern Iraq on the Shatt al-Arab bordered by Kuwait and Iran. It has hot desert climate due to its location near the coast. It is located at an elevation of (3) meters above the sea level.

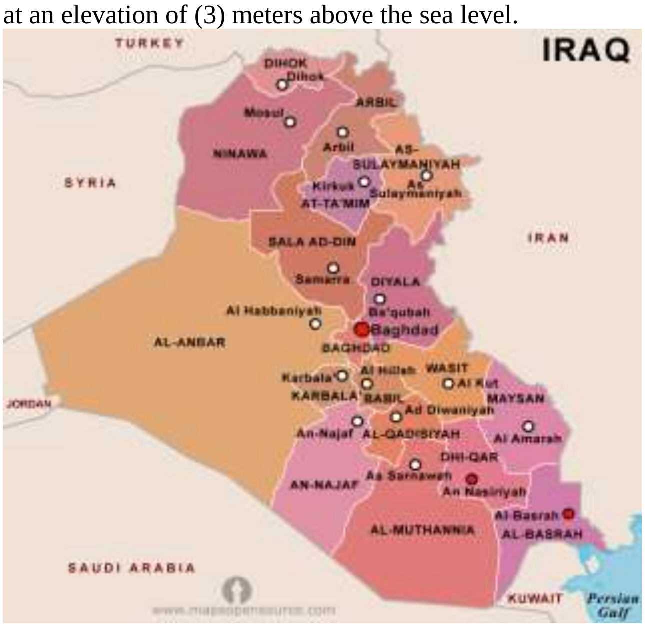


Fig. 1. Map of Iraq with the study sites marked as red circles [28]

Usually, wind sites with an annual average wind speed greater than 5 m/s are regarded feasible candidates for wind energy applications [15]. In this study, wind speed data over five successive years (2011-2015) for the sites above were collected from the metrological weather website (WUO) [29]. WUO is a commercial weather service serves numerous regions all over the world by providing real-time weather information. WUO website provides information and data on temperature, humidity, pressure and wind speed to most regions of the world. As for the wind, it provides the hourly, daily and monthly wind speed and wind direction. For daily data, it gives the maximum, minimum and average values for temperature, dew point, relative humidity, pressure on sea level, visibility and wind speed. It provides that data in the form of curves or tables. Moreover, this website provides information about the location of the study, such as elevation, latitude and longitude.

The monthly average, annual average and overall average of the successive five years were estimated at the station elevation from daily wind speed collected from WUO website. Then, an extrapolation of the station elevation and wind speed was performed to estimate the wind speed at specified hub heights of wind turbines models via wind shear power law. The Weibull shape factor, scale factor, wind power density, and wind energy potential at the hub heights of the selected wind turbine models were corrected and revealed.

3. Theoretical Analysis

3.1. Wind Energy Analysis

In the wind energy analysis, two distributions are commonly used, Weibull distribution and Rayleigh distribution. Weibull distribution is characterized by two parameters: shape factor (K) and scale factor (C). Three values are possible for the shape factor (K=1, 2, and ≥ 3). At (K=1), Weibull distribution turns into an exponential distribution, at (K=2) the Weibull distribution becomes Rayleigh distribution, and at (K≥3) the Weibull distribution becomes Gaussian distribution [30, 31]. Like solar radiation, the wind is considered stochastic quantity randomly varies with time and the nature of the terrain.

Thus, the average wind speed needs to be used in the wind energy analysis. The average of measured wind speed was calculated as [15]:

$$V_m = \left\{\left(\sum_{i=1}^{N} V_i^3\right)/N\right\}^{1/3} \tag{1}$$

Here, (V_i) denotes to the individual wind speed, and (N) is the number of collected data.
Deviation of individual wind speed from the average wind speed is called the standard deviation (σ). It can be estimated as [15]:

$$\sigma = \sqrt{\sum_{i=1}^{N} (V_i - V_m)^2 / N} \tag{2}$$

Air density is affected by the values of pressure and temperature at altitudes above the sea level. The expression that commonly used for air density correction in cases when variations in temperature, pressure, and elevation exist is:

$$\rho = \rho_o - [1.194 \times 10^{-4} \times H] \tag{3}$$

Here, $(\rho_o = 1.225\ \mathrm{kg/m^3})$ denotes the air standard density at a temperature of (15 ºC) and pressure of (1 atm), and (H) denotes the wind station elevation or the new selected height (hub height of the tested wind turbines).

The shape and scale of Weibull distribution are characterized by the Weibull shape and scale factors. At the station elevation of the selected sites, the Weibull shape factor (K_1) and the scale factor (C_1) can be expressed as [15]:

$$K_1 = (\sigma/V_m)^{-1.090} \quad \text{For} \quad (1 \le K_1 \le 10) \tag{4}$$

$$C_1 = \left(V_m K_1^{2.6674} / \left(0.184 + 0.816\, K_1^{2.73855}\right)\right) \tag{5}$$

Extrapolation of wind speed with height to estimate the wind speed at the new heights can be calculated via wind shear power law as [32]:

$$V_2 = V_1 (H_2/H_1)^{\alpha} \tag{6}$$

Here (V_1) is the wind speed at the station elevation (H_1), (V_2) is the wind speed at the new selected height (H_2), and (α) is the wind shear power exponent.

The wind shear power exponent (α) depends on the roughness height of the terrain. It can be formulated as [33]:

$$\alpha = \left[0.096 \log_{10}(Z_o) + 0.016 \left(\log_{10}(Z_o)\right)^2 + 0.24\right] \tag{7}$$

Here, (Z_o) denotes the ground roughness height which varies according to the nature of the terrain.

The variation of Weibull shape and scale factors with height can be corrected as [6]:

$$K_2 = K_1 [1 - 0.0881 \ln(H_2/H_1)]^{-1} \tag{8}$$

$$C_2 = C_1 (H_2/H_1)^n \tag{9}$$

$$n = [0.37 - 0.0881 \ln(C_1)] \tag{10}$$

Here (K_2) is the corrected shape factor at newly selected height, (C_2) is the corrected scale factor at newly selected height, and (n) is an exponent of Weibull scale factor.

The Weibull probability density function $f(V)$ and the cumulative distribution function $F(V)$ at the station elevations or the new selected heights can be formulated as:

$$f(V) = [K/C][V/C]^{K-1} e^{-(V/C)^K} \tag{11}$$

$$F(V) = \int_0^{\infty} f(V)\, dV = 1 - e^{-(V/C)^K} \tag{12}$$

Here (K) is the shape factor either at the station elevation or the new height (60 m, 80 m, 100 m) and (C) is the scale factor at the station elevation or the new heights (60 m, 80 m, 100 m).

According to Weibull distribution, the average wind speed (V_W) and its standard deviation (σ_W) either at the station elevations or the new selected heights can be estimated as [15]:

$$V_W = C\,\Gamma\,[1 + (1/K)] \quad (13)$$
$$\sigma_W = C\,\{\Gamma\,[1 + (2/K)] - \Gamma^2[1 + (1/K)]\}^{1/2} \quad (14)$$

Here, (Γ) refers to the gamma function that can be expressed as:

$$\Gamma(x) = \int_0^\infty t^{(x-1)}\, e^{-t} dt \quad (15)$$

Here (t) is a parameter equal to $((V/C)^K)$, and (x) is a positive number. Based on the Weibull shape and scale factors, the most frequent wind speed and the wind speed carrying maximum energy can be estimated as:

$$V_F = C[1 - (1/K)]^{1/K} \quad (16)$$

$$V_E = C[1 + (2/K)]^{1/K} \quad (17)$$

The individual measured wind power density (WPD_{mi}) and wind energy density (WED_{mi}) at any height can be calculated as [34]:

$$WPD_{mi} = (1/2)\,\rho\, V_{mi}^3 \quad (18)$$
$$WED_{mi} = WPD_{mi} \times T \quad (19)$$

Here (V_{mi}) is the monthly average wind speed, and (T) denotes the time factor.
Accordingly, the total average of measured wind power density (WPD_{mt}) and wind energy density (WED_{mt}) can be written as [34]:

$$WPD_{mt} = ((\textstyle\sum_{i=1}^N (1/2)\,\rho\, V_{mi}^3)/N) \quad (20)$$

$$WED_{mt} = WPD_{mt} \times T \quad (21)$$

In Weibull distribution analysis, the Weibull estimated wind power density (WPD_{EW}) and wind energy density (WED_{EW}) at any height can be expressed as:

$$WPD_{EW} = (1/2)\,\rho\, C^3\Gamma(1 + (3/K)) \quad (22)$$

$$WED_{EW} = (1/2)\,\rho\, C^3\Gamma(1 + (3/K))\, T \quad (23)$$

The accuracy of Weibull distribution in estimating the sites actual parameters with the predicted Weibull results can be checked via the determination factor (R^2) and the root mean square error $(RMSE)$ as [35]:

$$R^2 = \left[\left(\textstyle\sum_{i=1}^N (y_i - z_i)^2 - \sum_{i=1}^N (x_i - y_i)^2\right)/\left(\sum_{i=1}^N (y_i - z_i)^2\right)\right] \quad (24)$$

$$RMSE = \left[\left(\textstyle\sum_{i=1}^N (y_i - x_i)^2/N\right)\right]^{1/2} \quad (25)$$

Here (y_i), (x_i), and (z_i) is the actual data, the predicted Weibull results, and the average of the actual data respectively.

3.2. Wind Turbines Analysis

The rated electrical output power of the wind turbine can be estimated as [10]

$$P_R = (1/2)\,\rho\, A\, C_P\, \eta_m\, \eta_e\, V_R^3 \quad (26)$$

Here (ρ) is the air density; (A) is the rotor swept area; (C_P) is the power coefficient of wind turbine rotor; (η_m) is the efficiency of the mechanical system; (η_e) is the efficiency of the electrical system; and (V_R) is the rated wind speed.

The power produced by wind turbine at non-rated region (i.e., from cut-in speed to rated speed) and rated region (i.e., from rated speed to cut-out speed) can be used to estimate the average output power as:

$$P_{av} = \int_0^\infty P_V\, f(V)\, dV \quad (27)$$

Here, (P_V) denotes to the output power of the wind turbine as a function of wind speed.

The average output power (P_{av}) of wind turbine for the non-rated region and rated region can be rearranged as:

$$P_{av} = \begin{cases} 0, & V < V_{ci} \\ (1/2)\,\rho\, A\, C_P\, \eta_m\, \eta_e\, V^3, & V_{ci} \le V < V_R \\ (1/2)\,\rho\, A\, C_P\, \eta_m\, \eta_e\, V_R^3, & V_R \le V \le V_{co} \\ 0, & V > V_{co} \end{cases} \quad (28)$$

Here (V_{ci}) is the cut-in speed, and (V_{co}) is the cut-out speed.

The wind turbine power density (PD_{WT}) is the rated output power produced by the wind turbine to the rotor swept area of the wind turbine. It can be written as

$$PD_{WT} = (P_R/A) \quad (29)$$

This study proposes achieving an initial matching based on power density ratio (PDR) prior to the regular matching based on the capacity factor. The initial matching is to accurately identify the most-efficient turbine models for the succeeding regular matching. Thus the test space can be narrowed for facilitating the selection process. Power density ratio is defined as

$$PDR = (PD_{WT}/WPD_{mt}) \quad (30)$$

Capacity factor (C_F) is defined as the ratio of the average output power to the rated output power of the wind turbine:

$$C_F = (P_{av}/P_R) \quad (31)$$

The capacity factor (C_F) can also be calculated by integrating Eq. (28) over the intervals as:

$$C_F = \frac{1}{V_R^3}\int_{V_{ci}}^{V_R} V^3\, f(V)\, dV\Big|_{\text{non rated region}} + \int_{V_R}^{V_{co}} f(V)\, dV\Big|_{\text{rated region}} \quad (32)$$

The analytical derivation in Eq. (32) can be written as

$$C_F = \left(\frac{V_{ci}}{V_R}\right)^3 e^{-(V_{ci}/C_2)^{K_2}} - e^{-(V_{co}/C_2)^{K_2}} +$$

$$\frac{3\Gamma(3/K_2)}{K_2(V_R/C_2)^3}\left[\gamma\left(\left(\frac{V_R}{C_2}\right)^{K_2}, \frac{3}{K_2}\right) - \gamma\left(\left(\frac{V_{ci}}{C_2}\right)^{K_2}, \frac{3}{K_2}\right)\right]$$
(33)

Here, (γ) denotes to the incomplete gamma function that can be expressed as:

$$\gamma(u, a) = \frac{1}{\Gamma(a)} \int_0^u x^{a-1}\, e^{-x}\, dx \quad (34)$$

Where, $u = (V_R/C_2)^{K_2}$, and $a = (3/K_2)$.

The average energy production of wind turbine is usually accounted for as [23],

$$AEP = C_F\, P_R\, T \quad . \quad (35)$$

4. Results and Discussion

4.1. Results of wind energy potential

The assessment of wind power potential in the candidate sites typically requires analysing the wind site characteristics such as average wind speed, wind power density, and wind energy density. The daily average wind speed data for the sites: Baghdad (33.34N, 44.40E), Nasiriyah (31.05N, 46.25E), and Basrah (30.50N, 47.78E) was collected over the 5-year period (2011-2015). The monthly average, annual average, and an overall average of the five years were estimated from the available data on wind speed. The measured and Weibull estimated wind speed, probability density function, cumulative distribution function, the most frequent wind speed and wind speed carrying maximum energy, wind power density, and wind energy density were all determined and discussed. In the next sections, the results of the present wind energy analysis will be highlighted and discussed in details.

4.1.1 Wind speed

4.1.1.1. The monthly wind speed at station elevation

Fig. 2 illustrates monthly average wind speeds over the duration (2011-2015) at the station elevation (35m, 5m, and 3m) for the Baghdad, Nasiriyah, and Basrah sites, respectively. It can be seen that the average for measured and Weibull estimated wind speed are almost identical owing to the low value of root mean square error. There are several methods were used in previous studies for estimating Weibull parameters such us the standard deviation method (empirical method), graphical method, moment method, maximum likelihood method, and energy pattern factor method. In the present study, the empirical method was used to estimate the Weibull parameters. The average wind speed of Weibull distribution was compared with measured average wind speed via the determination factor (R^2) and root mean square error $(RMSE)$. The data from Table 1 indicate that the determination factor (R^2) is close to unity while the root mean square error $(RMSE)$ is close to zero. This implies that the empirical method shows an excellent accuracy in fitting the measured wind data. This indicates that the Weibull distribution is quite useful in fitting the measured data at the studied sites. It is worth mentioning that the temperature difference in the studied sites is higher in summer due to uneven heating of the site's surfaces while it is lower at the end of autumn and the beginning of winter. This explains why in Fig. 2, the windiest months were June and July, while the calmest months were November and December. In other words, the highest monthly average wind speed occurred in July, June, and June while the lowest monthly average was in November, December, and November for the Baghdad, Nasiriyah and Basrah sites respectively.

4.1.1.2. Wind Shear (variation of wind speed with the height)

Extrapolation between the station elevation and wind speed was performed to estimate wind speed at (60 m, 80 m, and 100 m) by using the wind shear power law. Indeed, roughness height is different from a site to another depending on the nature of the terrain. The suitable values of roughness height for different terrain were summarized in Table 2. In previous studies, the value of the wind shear power exponent is mostly assumed to be (1/7) [35]. An appropriate value of (1500 mm) for the roughness height of the studied wind sites was used from Table 2. Based on this value of roughness height, the wind shear power exponent was estimated to be (0.257). Fig. 3 shows the wind speed variation with height above the ground in the range (0-120 m) in the Baghdad, Nasiriyah, and Basrah sites. Consequently, the wind speeds at the hub heights of the tested wind turbines were concluded. The high wind speed was in the Basrah site, followed by the Nasiriyah site, and then in the Baghdad site.

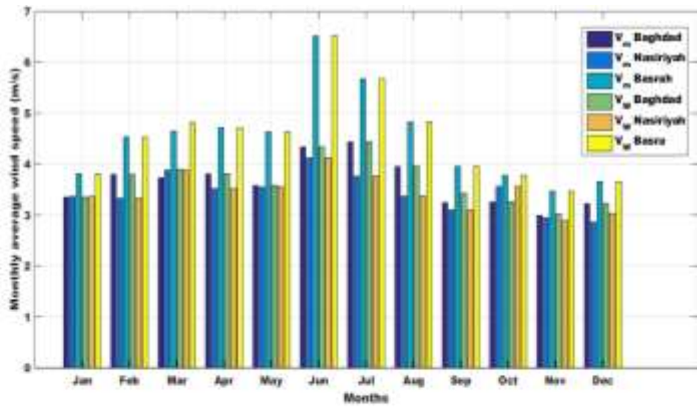


Fig. 2. The monthly average wind speed for the duration (2011-2015) at station elevation.

Table 1 Fit goodness between the measured wind speed and the Weibull estimated wind speed at the station elevation.

Year	Baghdad (35m)				Nasiriyah (5 m)				Basrah (3m)			
	V_m (m/s)	V_W (m/s)	R^2	RMSE	V_m (m/s)	V_W (m/s)	R^2	RMSE	V_m (m/s)	V_W (m/s)	R^2	RMSE
2011	3.5112	3.5132	1.000	0.0076	3.6391	3.6399	1.000	0.0031	4.8783	4.8812	1.000	0.0086
2012	3.4070	3.4091	1.000	0.0084	3.3174	3.3187	1.000	0.0047	4.6046	4.6068	1.000	0.0057
2013	3.3968	3.3984	0.999	0.0057	3.4331	3.4356	1.000	0.0098	4.9025	4.9059	1.000	0.0074
2014	4.0712	4.0756	0.999	0.0145	3.4760	3.4797	0.999	0.0124	4.6138	4.6181	1.000	0.0133
2015	4.0371	4.0421	1.000	0.0159	3.5194	3.5231	1.000	0.0133	4.4474	4.4508	1.000	0.0105

Table 2 Roughness heights of different terrain [33- p.14].

Type of terrain	Z_0 (mm)	Type of terrain	Z_0 (mm)
Calm open sea	0.2	Many trees	250.0
Rough pasture	10.0	Forest	500.0
Crops	50.0	Suburbs	1500.0
Scattered trees	100.0	City center	3000.0

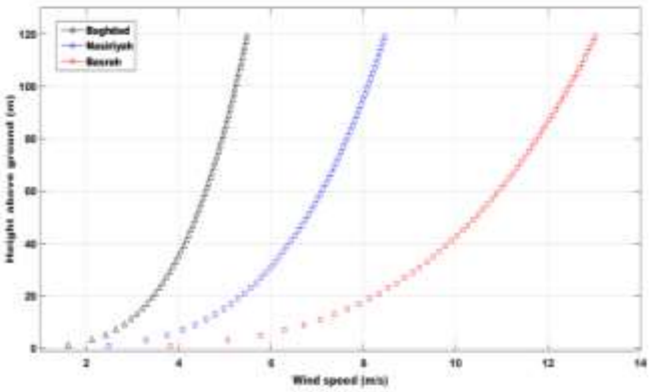


Fig. 3. Variation of the 5-year average wind speed with elevation.

4.1.2 Probability density function (PDF) and Cumulative Distribution Function (CDF)

Several statistical distribution models are available to be used for wind data analysis. However, Weibull and Rayleigh distribution functions are the most commonly used in the literatures. In Weibull distribution, the probability density function and the cumulative distribution function are used to characterize the wind speed variation. The shape and scale of Weibull distribution were characterized by the Weibull shape and scale factors. Weibull scale factor is the parameter that governs the uniformity of wind speed in the given site. The average of shape and scale factors for five successive years (2011-2015) is shown in Table 3. The probability density function and cumulative distribution function of the studied sites either at the station elevation or the new selected heights (60 m, 80 m, and 100 m) were illustrated in Fig. 4. The average Weibull shape and scale factors for the 5-year duration (2011-2015) were used to estimate the probability density function and cumulative distribution function. The probability density function is used to show the fraction of time for which the given wind speed prevails at the site. The accurate prediction of average wind speed and average wind power density was achieved by estimating the probability density function. The cumulative distribution function was used for calculating the time for which the wind speed lies within a certain speed interval. The results refer that both Weibull shape and scale factors are related to the average wind speed and standard deviation as they both change randomly within each period. It also noted that increasing the altitude from the station elevation to the selected height, curves of probability density function show a downward drop and expand towards the right. Also, the curves of cumulative distribution function retract to the right when the height increases.

Table 3. Average of shape and scale factors for five years (2011-2015).

Site	Station elevation		60 m		80 m		100 m	
	K_1 $(-)$	C_1 (m/s)	K_2 $(-)$	C_2 (m/s)	K_2 $(-)$	C_2 (m/s)	K_2 $(-)$	C_2 (m/s)
Baghdad	3.0368	4.1562	3.1882	4.7076	3.2753	5.0513	3.3463	5.3742
Nasiriyah	2.8761	3.9073	3.6822	7.2711	3.8057	7.8132	3.9073	8.2613
Basrah	2.6774	5.2849	3.6374	10.3179	3.7671	11.0025	3.8743	11.5647

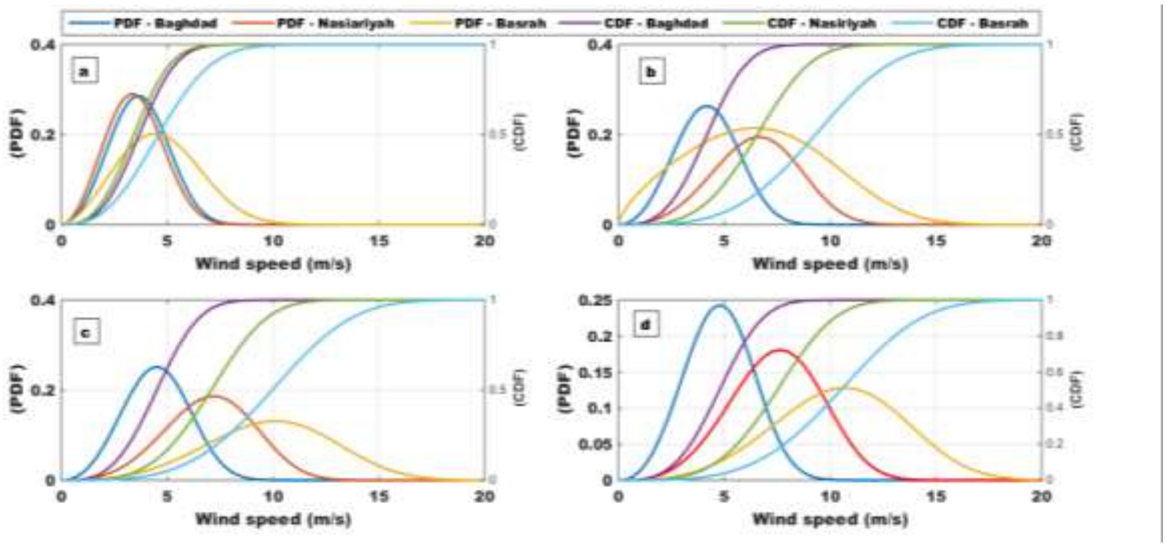
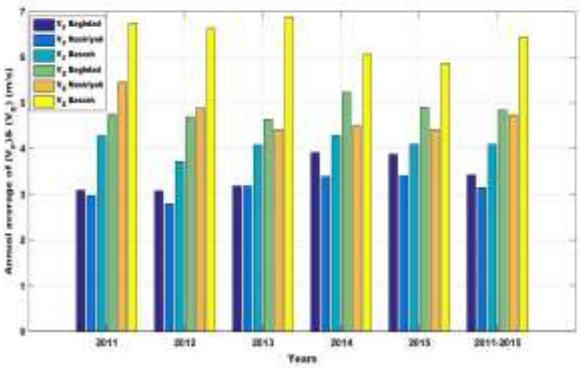


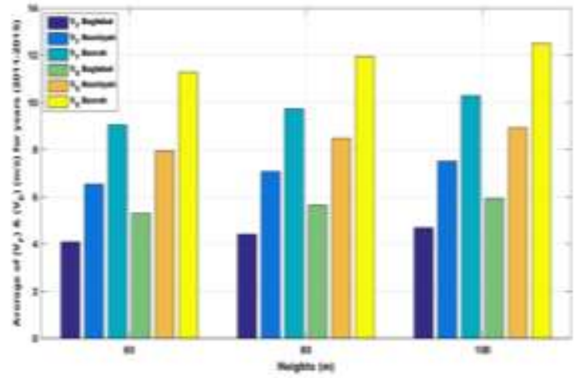
Fig. 4. Probability density function (PDF) and cumulative distribution function (CDF) : (a) at the station elevation, (b) at 60m, (c) at 80m, and (d) at 100m.

4.1.3 Most frequent wind speed (V_F) and wind speed carrying maximum energy (V_E)

The wind speed carrying maximum energy is always higher than the most frequent wind speed. In wind energy analysis, the most frequent wind speed for wind probability distribution is the most probable wind speed that represents the peak of probability density function curve. Based on the Weibull shape and scale factors, the most frequent wind speed and wind speed carrying maximum energy were formulated and analyzed. Fig. 5(a) shows the annual average and overall average behavior of the most frequent wind speed and wind speed carrying maximum energy at the selected station elevation. It is well known that the most frequent wind speed and wind speed carrying maximum energy each varies with time randomly. As can be seen from Fig. 5 (a), the Basrah site gained the highest values of the most frequent wind speed and the wind speed carrying maximum energy. The annual average of the most frequent wind speed was higher for the Baghdad site as compared to the Nasiriyah site. However, the annual average of the wind speed carrying maximum energy was higher for the Baghdad site only for the years (2013-2015). At the studied station elevation, the overall average of the most frequent wind speed and the wind speed carrying maximum energy were both higher for the Baghdad site as compared to the Nasiriyah site. Fig. 5 (b) displays the overall average behavior of the most frequent wind speed and wind speed carrying maximum energy at the new selected heights (60m, 80m, and 100m) over the duration (2011-2015). The overall average of the most frequent wind speed and wind speed carrying maximum energy was the best in the Basrah site, followed by Nasiriyah site, and then in the Baghdad site at any of the new selected heights.



(a)



(b)

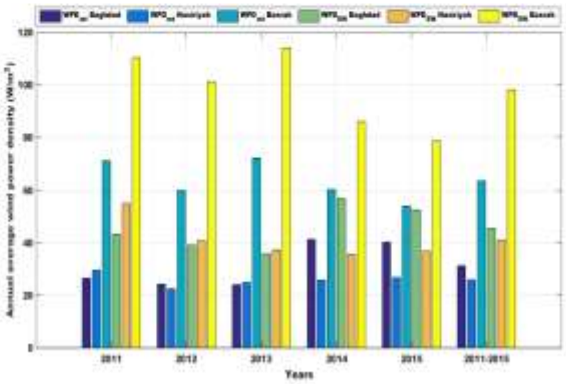
Fig. 5. Averages of (V_F) and (V_E): (a) at the station elevation, and (b) at the new selected heights

4.1.4 Wind Power Density

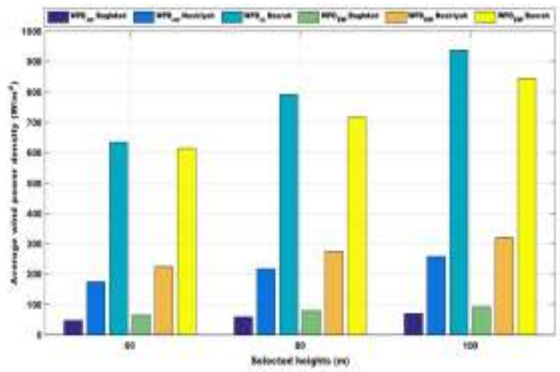
The wind power density and the annual average wind speed are the main parameters to be considered in the selection of wind sites for wind energy applications. The wind is classified into several classes depending on the wind power density at the specified height. The wind classes (1-7) are used by the international wind classification system to categorize how the specific wind is feasible for wind energy applications. The wind power density categorization in many previous studies was considered at heights (10m and 50m). The annual average of measured and Weibull estimated wind power density for the years (2011-2015) and the overall 5-years average at the station elevation of the selected sites were illustrated in Fig. 6(a). For every year as well as for the overall five years, the highest wind power density recorded was in the Basrah site. However, the Weibull estimated wind power density was higher only in (2011, 2012, and 2013) for the Nasiriyah site compared to the Baghdad site. Also, the measured wind power density was only higher in (2011 and 2013) for the Nasiriyah site compared to the Baghdad site. The average wind power density of the overall five years at the station elevation was the best in the Basrah site, followed by the Baghdad site, and then in the Nasiriyah site. Fig. 6(b) demonstrates the average wind power density for the overall five years at the new selected heights (60 m, 80 m, and 100 m). As can be seen from this figure, the average of measured and Weibull estimated wind power density in the overall five years were the best in the Basrah site, followed by the Nasiriyah site, and then in the Baghdad site, respectively.

Table 4 Comparison of wind power density (WPD) in the present study with that in Refs. [34, 36]

Wind class	Wind power density [previous studies] (W/m^2)	Wind power density [present study] (W/m^2)
(1-Fair)	WPD < 100 [34]	WPD (40.97-57.65) for Baghdad
(2-Fairly good)	100≤ WPD <300 [34]	WPD (151.630-197.61) for Nasiriyah
(5-Excellent)	WPD (540 – 590) [36]	WPD (551.41-552.29) for Basrah



(a)



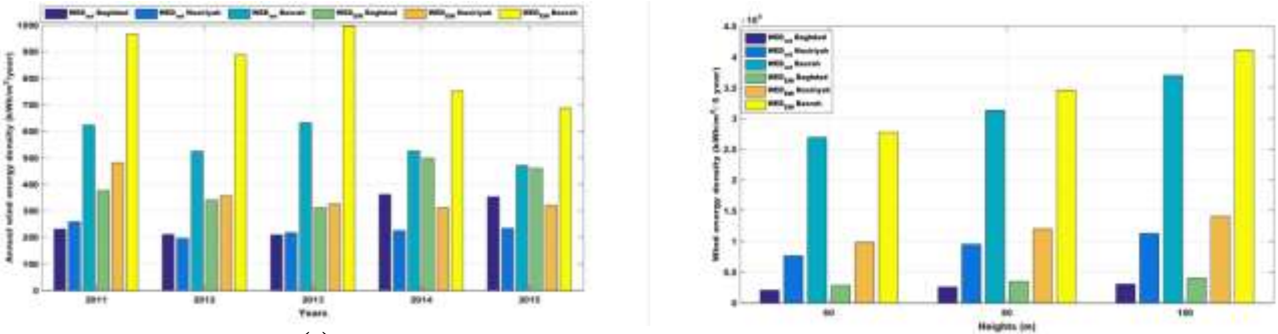
(b)

Fig. 6. The average wind power density: (a) at the station elevation, and (b) at the new selected heights

In the present study, the wind power density of the studied wind sites is also estimated at the height (50 m). A comparison of the wind classes of the studied wind sites with the previous studies Fazelpour et al. [34] and Bagiorgas et al. [36] was achieved and summarized in Table 4. The results showed that wind sites have wind classes, (1-fair) for the Baghdad site, (2-fairly good) for the Nasiriyah site, and (5-Excellent) for the Basrah site. In conclusion, the Baghdad site is suitable for small-scale applications in remote and populated areas like pumping water, batteries charging, and other some domestic applications. Furthermore, the Nasiriyah site is suitable for small-scale wind turbines of individual characteristics that could be appropriate for feeding the traditional power plants with the electrical power in addition to the applications mentioned above for the Baghdad site. The wind power analysis of the studied sites showed that Basrah site has a wind class of (5-Excellent). Thus, the Basrah site is suitable for wind farm installation.

4.1.5 Wind energy density

The annual sum and 5-year sum of the measured and Weibull estimated wind energy density over the period (2011-2015) at station elevation were illustrated in Fig. 7 (a). Wheather for every year or the overall five years, the highest wind energy density was in the Basrah site. However, the Weibull estimated wind energy density was only higher in (2011, 2012, and 2013) in the Nasiriyah site compared to the Baghdad site. Also, the measured wind energy density for the years (2011, and 2013) was higher in the Nasiriyah site compared to the Baghdad site. Whereas, the measured wind energy density for the years (2012, 2014, and 2015) were higher for the Baghdad site compared to the Nasiriyah site. Fig. 7 (b) displays the sum of the wind energy density for the overall five years at the new selected height (60 m, 80 m, and 100 m). The sum of the overall five years was the best for the Basrah site, followed by the Nasiriyah site, and then the Baghdad site.



(a) (b)

Fig. 7. The wind energy density for years (2011-2015) (a) Annual sum for all years (2011-2015) at station elevation, and (b) sum for all years (2011-2015) at the new selected heights.

4.2. Wind turbine-site matching analysis

Based on results obtained from the wind power analysis, the most suitable candidate wind site was assigned. This section is about the matching of wind turbines to the candidate site for wind energy applications. An analysis of the specifications and performance characteristics of different wind turbine models was conducted. The wind power density of the candidate site and the wind turbine power density were matched initially to select the most effective wind turbine model. The capacity factor which is considered an indicator for good matching between the wind turbine and the wind site was analyzed and revealed.

4.2.1. Initial selection of the wind turbines

The matching between the characteristics of candidate wind site and wind turbine characteristics was achieved via two stages to ensure an optimal performance of the selected wind turbines. At the first stage, the wind power density and rated power density of the selected wind turbines were initially matched via the power density ratio (PDR). A set of commercially-available wind turbines at hub heights (60m, 80m, and 100m) was selected to initially match to the Basrah site via the power density ratio. Then, a minor set of wind turbines just at hub heights (80m and 100m) were matched to the Basrah site. The power density ratio of five matched wind turbines was estimated within the range (0.4838, 0.3822, 0.3841, 0.4552, and 0.3707) and (0.4080, 0.3223, 0.3239, 0.3839, and 0.3126) at hub height (80m, and 100m) for wind turbines models (WT1-WT5) respectively.

This approach is to ensure that the initially-selected wind turbines operate at the most-efficient capacity factor. As far as the authors know, such approach for optimizing the selected wind turbine performance has not been reported on before. The estimation of capacity factor for the selected wind turbines is the second stage to achieve the final matching between the wind site and wind turbines characteristics. It is necessary for the efficient wind turbine to have rated speed being almost close or equal to the wind speed carrying the maximum energy of the candidate site. The wind speed carrying maximum energy of the Basrah site at heights (80m, and 100m) was (12.3031, and 12.8597 m/s) respectively. Apparently, the wind speed carrying maximum energy was close to the rated speed of the most selected wind turbines. This is an indicator that the tested wind turbines can greatly maximize the wind energy utilization at the candidate site.

4.2.2. Characteristics of the selected wind turbines

Five pitch-controlled wind turbines of several specifications that matching wind class (5-excellent) of the Basrah site at hub heights (80m and 100m) were selected via estimating power density ratio. Table 5 summarizes the specifications of the tested wind turbines. Fig. 8 shows the characteristics of selected wind turbines with specified values of the cut-in speed, rated speed, cut-out speed, and output rated power. It is apparent that the output power of wind turbine increases as the wind speed increases from the cut-in speed to the rated speed. Next, the output power comes to be constant when the wind speed increases from the rated speed to the cut-out speed due to power regulation. It is worth mentioning that the Senvion MM92 and Repower MM92 wind turbines models had the same specifications of cut-in speed, rated speed, cut-out speed, and approximate value of rated output power as shown in Table 5 and Fig. 8.

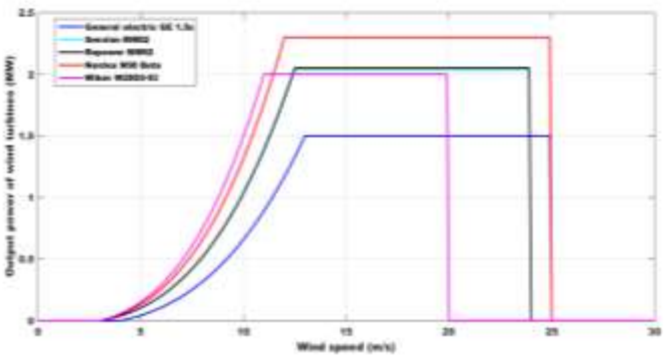


Fig. 8. Characteristics of power-wind speed curves of the tested wind turbine

Table 5 Specifications of the selected wind turbines [37].

Wind turbines models	Sorts of Wind Turbines	Speed (m/s)			Rated power (MW)	Rotor diameter (m)	Hub height (m)
		V_{ci}	V_r	V_{co}			
WT1	General electric GE 1.5s	4	13	25	1.5	70.5	80, 100
WT2	Senvion MM92	3	12.5	24	2.04	92.5	80, 100
WT3	Repower MM92	3	12.5	24	2.05	92.5	80, 100
WT4	Nordex N90 Beta	3	12	25	2.3	90	80, 100
WT5	Wikov W2000-93	3	11	20	2	93	80, 100

4.2.3. The capacity factor of the selected wind turbines

The capacity factor is an indicator identifies how the selected wind turbine is efficient at the candidate site for electricity generation. It represents the ratio of average output power produced by the wind turbine to its rated power. Fig. 9 displays the average capacity factor of the tested wind turbines for five years (2011-2015) at hub heights (80m and 100m) of Basrah site. The values of average capacity factor at hub height of (80m and 100m) was (0.5033, 0.5446, 0.5446, 0.5865, and 0.6701) and (0.5580, 0.5990, 0.5990, 0.6397, and 0.7185) for wind turbines models (WT1-WT5) respectively. As mentioned earlier, the wind turbines have an economical and attractive performance, if the capacity factor is within the range $(C_F \geq 0.4)$ [15]. This implies that the selected wind turbines are optimal for operating at the Basrah site according to the initial matching based on the power density ratio and final matching based on the capacity factor.

The rank of capacity factor for wind turbines models was Wikov W2000-92 model, followed by Nordex N90 Beta model, followed by Senvion MM92 and REpower MM92 models, and then followed by General Electric GE 1.5s model. As can be seen from this figure, the Wikov W2000-92 wind turbine model showed higher capacity factor compared to other models. This due to the low value of cut-in speed (3 m/s), rated speed (11 m/s), and cut-out speed (20 m/s) compared to those in others models. Furthermore, the average wind speed over the 5-years duration (2011-2015) at hub heights (80m and 100m) for the Basrah site was close and higher than the rated wind speed of Wikov W2000-92 wind turbine model. The average wind speed over the 5-years duration was (10.9334, and 11.5798 m/s) at hub height (80m, and 100m) respectively. This confirms that the extracted wind energy often lies within the rated region of the wind turbine power curve. This explains why the Wikov W2000-92 wind turbine model shows the highest capacity factor.

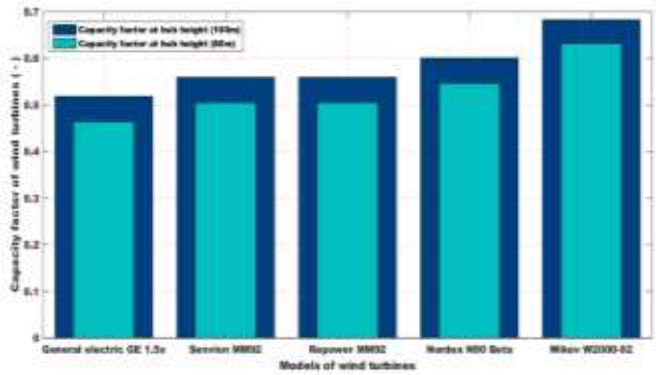


Fig 9. The capacity factor of the wind turbines for five years (2011-2015) at a hub height of 80m and 100m.

4.2.4. Energy produced by the selected Wind turbines

Fig. 10 illustrates the average energy produced by the tested wind turbines for the entire duration (2011-2015) at the hub heights (80m, and 100m). Again, the rank of tested wind turbines at (80m, and 100m) according to energy produced was: Nordex N90 Beta model, Wikov W2000-92 model, Repower MM92 model, Senvion MM92, and General Electric GE 1.5s model respectively. Thus, the Nordex N90 Beta wind turbine model was the best model.

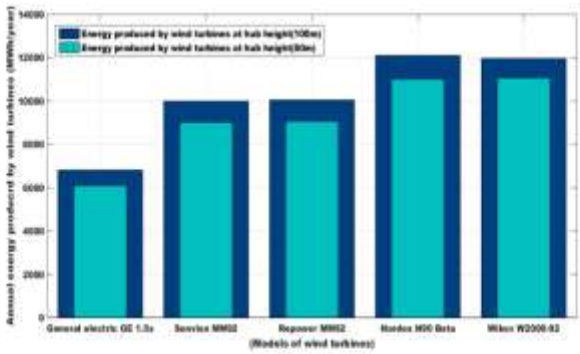


Fig. 10. The energy produced by the tested wind turbines for five years at a hub height of 80m and 1

5. Conclusions

Matching between the wind site characteristics and the wind turbine characteristics at three selected sites in Iraq: Baghdad (33.34N, 44.40E), Nasiriyah (31.05N, 46.25E), and Basrah (30.50N, 47.78E) for the duration (2011-2015) was performed and analyzed. The wind speed, wind power density, and wind energy density at station elevation and hub heights of tested wind turbines models were computed. The Weibull distribution was used to analyze wind energy. Meanwhile, the goodness fit between Weibull estimated wind speed and measured wind speed was achieved via the empirical method of Weibull distribution. The results indicated that the Basrah site enjoys higher wind speed along with higher wind power density than the other sites. The wind power potential analysis showed that the Baghdad site, the Nasiriyah site, and the Basrah site are of wind classes: (1-fair), (2-fairly good), and (5-Excellent), respectively. Five commercially-available wind turbines models having different operating specifications were tested for the Basrah site. The initial matching based on the power density ratio as a new parameter for matching was proposed and recommended for the use. The final matching based on the capacity factor of wind turbines models (WT1-WT5) was achieved to select the most efficient wind turbine model. From the capacity factor perspective, the wind turbine-site matching analysis showed that Wikov W2000-92 wind turbine model was the most suitable for the Basrah site at heights (80m and 100m). From the energy capture perspective, the analysis revealed that Nordex N90 Beta wind turbine model was the best-matched wind turbine at height (80m, and 100m). The procedure developed in this study regarding the wind energy analysis and the wind turbine-site matching can be extended to include different heights, different sites, and different wind turbine models for better planning of wind power generation.

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