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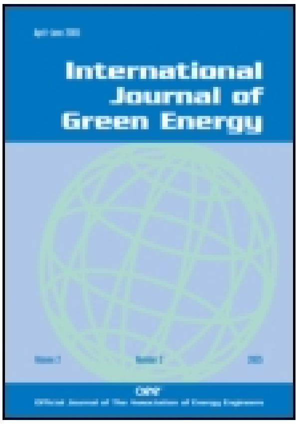

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WIND SPEED CHARACTERISTICS AND RESOURCE ASSESSMENT USING WEIBULL PARAMETERS

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The study utilized wind speed measurements made at three heights and the Weibull parameters to study the wind speed characteristics and assess the wind power potential of seven sites in Saudi Arabia. Weibull shape and scale parameters were estimated using maximum likelihood method. These parameters were found to fit the actual wind frequency distributions with acceptable coefficient of determination (>0.95) for all the sites considered in this study. The annual mean wind speed varied between 4.30 m/s and 5.9 m/s at 40 m above ground level corresponding to Gassim and Dhulom data collection stations. The local wind shear exponent calculated using measured wind speed values at 20, 30, and 40 m and the power law were established for future use and were found to vary from 0.06 to 0.34 corresponding to Gassim and Yanbo, respectively. The Weibull shape and scale parameters increased more at 30 m compared to at 40 m with increase in height from 20 to 30 m and 30 to 40 m. No regular monthly trends could be detected whereas monthly mean wind speed, shape, and scale parameters, most probable wind speed, and maximum energy carrying wind speed was concerned. The most windy sites (Dhulom, Arar, Juaymah, Rawdat Ben-Habbas, and Dhahran) were suggested for wind power development in Saudi Arabia.

Keywords: *Wind speed; Wind power density; Weibull distribution; Frequency; Most probable wind speed; Maximum energy carrying wind speed*

INTRODUCTION

Power of the wind is a clean, inexhaustible, free, reliable, and renewable source of energy. To further add to its advantages, it is quick to install, requires negligible maintenance, and it does not have any political or geographical boundaries. Power of the wind has become the power technology of choice for a number of countries around the globe. According to Global Wind Energy Council Report (2011), the world's wind power capacity grew by 22.5% in 2010, adding 35,802 MW to bring total installations to 194,390 MW. Almost half of these additions were made in China, which experienced yet another year of approximately 65% growth. Newly added capacity of 2,139 MW in India and some smaller

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additions in Japan, South Korea, and Taiwan make Asia the biggest regional market for wind energy in 2010, with more than 19,022 MW of new capacity.

However, the United States continues to have a comfortable lead in terms of total installed capacity. Against all odds, US wind energy market installed nearly 5,115 MW in 2010, increasing the country's installed capacity by 50% of the 2009's capacity and bringing the total installed grid-connected capacity to 40,180 MW (2011). Europe, which has traditionally been the world's largest market for wind energy development, continued to see strong growth, also exceeding expectations. In 2010, 10.5 GW were installed in Europe, led by Spain (1,516 MW) and Germany (1,493 MW). France, United Kingdom, and Italy added 1,086 MW, 962 MW, and 948 MW of new wind capacity, respectively. The 194,390 MW of global wind capacity in place at the end of 2010 will produce 418 TWh of clean electricity and save 250 million tons of CO_2 every year (2011).

The fast technological development and competitive costs of wind power generation, wind sources are being encouraged these days. The wind farms could be erected within months and last at least 20 years and require minimal operation and maintenance cost. In the present scenario, there are two important issues in the energy sector. First is the energy security and the second is the environmental damage due to the consumption of the conventional sources of energy. On top of it, the need of supplying electricity to remote communities is a critical task in developing and even developed countries.

Wind data analysis and accurate wind energy potential assessment is critical for proper and efficient development of wind power application and is highly site-dependent. Ackermann and Soder (2002) provided an overview of the historical development of wind energy technology and discussed the world-wide status of grid-connected as well as stand-alone wind power generation. Ganesan and Ahmed (2008) used wind speed and direction data measured at 10 m and 25 m above ground level for the assessment of wind power potential for Bhopal, India. The authors reported annual energy yields of 3.712 GWh and 4.431 GWh corresponding to hub heights of 50 m and 70 m, respectively. Moran and Sherrington (2007) presented cost–benefit analysis to assess the economic feasibility of a large scale wind farm project, taking into account positive and negative externalities of generation. Wind characteristics of the Kartalkaya-Bolu in Turkey were presented using wind speed data from 2000 to 2006 and Weibull and Rayleigh probability density functions (2009). Weibull shape and scale parameters were found to be 1.79 m/s and 6.64 m/s, and yearly mean wind speed of 5.90 m/s was obtained in Kartalkaya-Bolu for the 7-year period. The results showed that the investigated location has good wind energy potential (2009). Herbert et al. (2007) reviewed the wind resource assessment models, site selection models, and aerodynamic models. The study found out that the Weibull, Rayleigh distribution, and Markov chain models are suitable for prediction of wind speed at the site.

Globally, numerous studies have been reported in the literature on various aspects of wind speed and wind power characteristics. Some of these studies include Marafia and Ashour (2003) for offshore/onshore wind power project development in Qatar; El-Osta and Kalifa (2003) for a proposed 6 MW wind farm in Zwara, Libya; Al-Nassar et al. (2005) showed that the annual mean wind speed in Kuwait lied in the range of 3.7 m/s to 5.5 m/s; Hrayshat (2007) and Anagreh and Bataineh (2011) reported wind resource assessment of the different regions of Jordan; Elamouri and Amar (2008) for Tunisia; Radics and Bartholy (2008) for Hungary; Ucar and Balo (2008) for Manisa, Turkey; Ucar and Balo (2009) for Kartalkaya-Bolu, Turkey; Akpinar and Akpinar (2004) for Elazig, Turkey; Omer (2008) for Sudan; Bagiorgas, Mihalakakou, and Matthopoulos (2008) for Western Greece; Shahta and Hanitsch (2008) studied the technical and economic assessment of wind power

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for Hurghada in Egypt; Toğrul and Kizi (2008) for Bishkek, Kyrgyzstan; Jowder (2009) reported wind resource assessment for Bahrain; Akdağ and Güler (2010) for Amasra—Black Sea Region of Turkey and Himri, Himri, and Stambouli (2010) provided review of renewable energy in general and the wind in particular for Algeria. Raichle and Carson (2009) for the United States; Ohunakin (2011) for North-East geopolitical zone of Nigeria; Yu and Qu (2010) for China; and Sahin and Bilgili (2009) studied the wind characteristics of Belen-Hatay province of Turkey using hourly wind speed records between years 2004 and 2005.

The work on wind resource assessment in Saudi Arabia dates back to 1986, when Ansari, Madni, and Bakhsh (1986) used hourly wind speed data to develop a Wind Atlas for Saudi Arabia. This atlas provides contours of wind speed, monthly values, and information on prevailing wind direction. Rehman, Halawani, and Husain (1994) presented the Weibull parameters for ten anemometer locations in Saudi Arabia and found that the wind speed was well represented by Weibull distribution function. Rehman and Halawani (1994) presented the statistical characteristics of wind speed and diurnal variation. The autocorrelation coefficients were found to be matching with the actual diurnal variation of the hourly mean wind speed for most of the locations used in the study. Some of the other studies include Rehman, Halawani, and Mohandes (2003), Rehman and Aftab (2004), Rehman et al. (2007), Dahmouni et al. (2011), Keyhani et al. (2010), Islam, Saidur, and Rahim (2011), Kwon (2011), and Saidur et al. (2010).

Hence, the growing need of energy, participation of Middle East countries in wind power generation, global decrease in cost of wind power generation, and growing awareness of usage of green energy sources are some of the factors which motivated the authors for conducting detailed wind analysis at relatively windy site in the Kingdom of Saudi Arabia where measurements were made by deploying a 40-m tall tower. The objective of the present study is to assess the wind characteristics like maximum energy carrying wind speed, most probable wind speed, and wind power density using Weibull parameters.

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WIND DATA AND SITE DESCRIPTION

The geographical details including the latitude, longitude, and the altitude of all the data measurement stations (Rawdat Ben Habbas, Juaymah, Arar, Dhahran, Gassim, Yanbo and Dhulom) are summarized in Table 1. The wind speed measurements were made at 20 m, 30 m, and 40 m above ground level (AGL) and the wind direction sensors were installed at 30 m and 40 m AGL, as shown in Figure 1. The meteorological sensors to know temperature, relative humidity, pressure, and global solar radiation were installed at 1.5 m AGL. The technical specifications of all the sensors used in this study are summarized

Table 1 Site Specific Information of Data Collection Stations

Location	Latitude (°)	Longitude (°)	Altitude (m)
Rawdat Ben Habbas	29° 38’	43° 29’	443
Juaymah	26° 46’	49° 53’	0
Arar	30° 54’	41° 08’	542
Dhahran	26° 06’	50° 10’	22
Gassim	26° 18’	43° 58’	648
Yanbo	24° 07’	38° 03’	6
Dhulom	22° 12’	42° 03’	1117

Figure 1 Wind and meteorological data measurement tower. (color figure available online)

Table 2 Details of the Equipment Installed at an Isolated Village

Item description	Technical information
Wind speed sensor, NRG#40	AC sine wave, Accuracy: 0.1 m/s, Range: 1–96 m/s
Three cup anemometer	Output: 0–125 HZ, Threshold: 0.78 m/s
Wind direction vane, NRG#200P Potentiometer	Accuracy: 1%, Range: 360° Mechanical, Output: 0-Exc. Voltage, Threshold: 1 m/s, Dead band: Max - 8° and Typical 4°
Temperature sensor #110S Integrated circuit	Accuracy: ±1.1°C, Range: −40°C to 52.5°C, Output: 0–2.5 volts DC, Operating temperature range: −40°C to 52.5°C
Barometric pressure sensor BP20	Accuracy: ±15 mb, Range: 150–1150 mb, Output: Linear voltage
Relative humidity sensor RH-5 Polymer resistor	Accuracy: ±5%, Range: 0%–95 % Output: 0–5 volts, Operating temperature range: −40°C to 54°C
Pyranometer Li-Cor #LI-200SA Global solar radiation	Accuracy: 1%, Range: 0–3000 W/m^2, Output: Voltage DC, Operating temperature range: −40°C to 65°C

in Table 2. The Arar meteorological data measurement site was an open area from all directions.

The land surface was comprised of small rocks. Rafha is located in the northeastern part of Saudi Arabia and is surrounded by small villages, which are not connected by national grid. The wind mast was located in a village (Rawdat Ben Habbas) approximately

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80 km east of Rafha. The measurement site was clear from all sites except two office buildings 3 and 10 meter high around 100 m away from the wind mast. In Gassim, the wind mast site was clear from all sites except with a few small trees here and there. Dhahran is located north of the Tropic of Cancer on the eastern coastal plain of Saudi Arabia and is nearly 10 km inland from the gulf coast. Two distinct seasons are noticed in this region viz., hot season from May to October and cold from November to April. The wind mast at Dhahran was surrounded by a single-story building of about 4 m height in the south, gulf sea-shore on its west, and the highway on the north of the tower. Yanbu is an industrial zone and the city is situated on the north-west coast of Saudi Arabia along the Red Sea. The wind mast site was an open area from all directions and there was no visible hurdle so far as wind flow was concerned.

METHODOLOGY USED

This section deals with the methodology used to calculate the Weibull shape (k) and scale (c) parameters, most probable wind speed (V_{mp}), maximum energy carrying wind speed ($V_{max,E}$), wind power density (WPD), and wind energy density (WED). The maximum likelihood method fits a Weibull distribution to a set of measured wind speeds. This method employs the following equation (Stevens and Smulders (1979)) for the calculation of shape parameter (k), using an iterative process:

$$k = \left(\frac{\sum_{i=1}^{N} V_i^k \ln(V_i)}{\sum_{i=1}^{N} V_i^k} - \frac{\sum_{i=1}^{N} \ln(V_i)}{N} \right)^{-1}, \tag{1}$$

where V_i is the wind speed in time step i and N is the number of time steps. Once the shape parameter k has been determined, the following equation could be used to calculate the value of scale parameter c:

$$c = \left(\frac{\sum_{i=1}^{N} V_i^k}{N} \right)^{\frac{1}{k}}. \tag{2}$$

The most probable wind speed simply provides the most frequently occurring win speed for a given wind probability distribution. The maximum energy carrying wind speed is the speed which generates maximum energy. The most probable wind speed can be calculated using the Weibull shape and scale parameters via the following equation, Keyhani et al. (2010):

$$V_{mp} = c \left(1 - \frac{1}{k} \right)^{\frac{1}{k}}. \tag{3}$$

Maximum energy carrying wind speed can be estimated from the Weibull parameters through the following relationship reported in Jamil, Parsa, and Majidi (1995):

$$V_{max,\,E} = c \left(1 + \frac{2}{k} \right)^{\frac{1}{k}}. \tag{4}$$

The wind power density is directly proportional to the cube of mean wind speed (V), the air density (ρ), and the swept area (A) of the turbine rotor and can be calculated using the following relationship reported in Pimenta and Garvine (2008):

$$WPD = \frac{1}{2}\rho V^3 A. \tag{5}$$

The wind power density can also be calculated using the Weibull distribution function as follows, [38]:

$$WPD = \int_0^\infty \frac{1}{2}\rho V^3 f(V)\, dV = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right), \tag{6}$$

where ρ is the standard air density at mean sea temperature of 15°C, and 1 atmospheric pressure that is 1.225 kg/m^3. Once the WPD has been estimated, the wind energy density can be obtained just multiplying by the number of hours (T). To get the annual wind energy density, one can multiply WPD by 8760 h and divide by 1000 to get the wind energy density in kWh/m^2.

$$WED = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) T. \tag{7}$$

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RESULTS AND DISCUSSION

State-of-the-art wind data analysis tool Windographer (2011) was used for obtaining the statistical summaries of all the data reported in this study. The derived parameters such as Weibull shape and scale parameters, wind power density, maximum energy carrying wind speed, most probable wind speed, and wind energy density were calculated using procedure explained in previous section. The mean wind speed during data collection period at all measurement heights, wind shear exponent (WSE), and other meteorological parameters are summarized in Table 3 for all the stations. The maximum mean wind speeds of 5.1 m/s, 5.5 m/s, 5.9 m/s at 20 m, 30 m, and 40 m AGL were observed at Dhulom while the corresponding minima of 3.5 m/s, 4.1 m/s, and 4.3 m/s at Gassim. Equally best site from energy harnessing point of view like Dhulom was Arar with mean wind speeds of 5.0 m/s, 5.5 m/s, and 5.8m/s. The site-dependent WSE values summarized in Table 3 are

Table 3 Summary of Meteorological Parameters and Wind Speed at Different Heights

Location	Wind speed, (m/s)			WSE	T (°C)	P (mb)	RH (%)	Global Solar Radiation (kWh/m^2/d)
	20 m	30 m	40 m					
Rawdat Ben Habbas	4.76	5.36	5.74	0.286	24.24	941	21.70	5.66
Juaymah	4.87	5.37	5.69	0.274	26.58	1014	13.50	4.90
Arar	5.00	5.50	5.75	0.182	23.40	1009	34.00	4.51
Dhahran	4.17	5.13	5.37	0.151	28.90	1021	52.00	4.90
Gassim	3.50	4.10	4.30	0.241	28.50	992	41.00	5.10
Yanbo	4.51	4.71	4.82	0.081	29.70	—	49.90	4.70
Dhulom	5.10	5.50	5.90	0.193	24.70	919	38.00	4.94

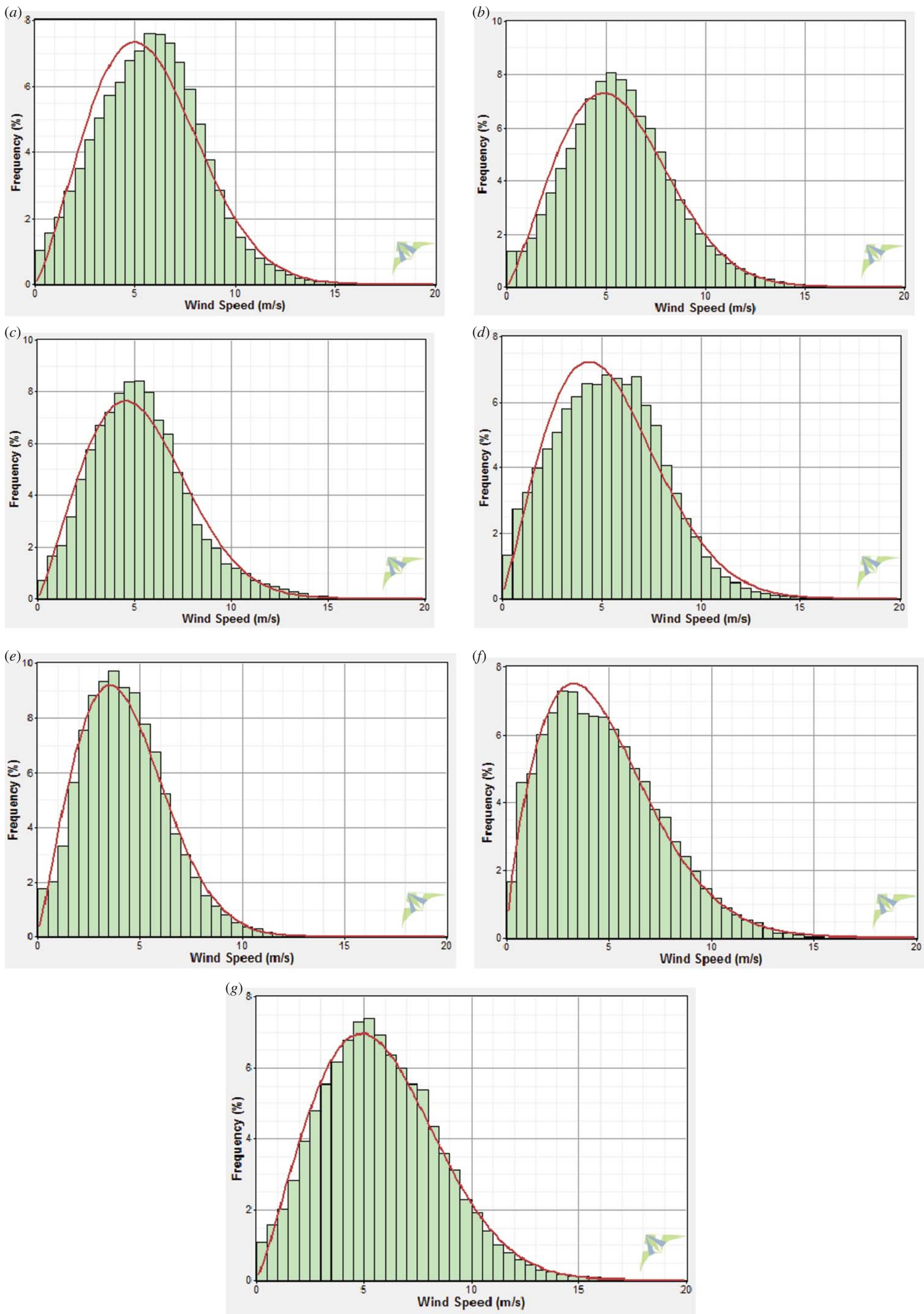

Figure 2 Weibull function representing the wind speed distribution at (a) Rawdat Ben Habbas, (b) Juaymah, (c) Dhahran, (d) Arar, (e) Gassim, (f) Yanbo, (g) Dhulom. (color figure available online)

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Table 4 Site Dependent Roughness Length, Class and Description

Location	WSE	Roughness length, m	Roughness class	Roughness description
Rawdat Ben Habbas	0.286	1.81	4.41	Suburban
Juaymah	0.274	0.239	2.72	Many trees
Arar	0.182	0.138	2.27	Few trees
Dhahran	0.151	0.056	1.52	Crops
Gassim	0.241	1.070	3.97	Suburban
Yanbo	0.081	0	0	Smooth
Dhulom	0.193	0.134	2.25	Few trees

Table 5 Annual Average Weibull Parameters Calculated Using Maximum Likelihood Method

Location	k			c, (m/s)		
	20 m	30 m	40 m	20 m	30 m	40 m
Rawdat Ben Habbas	2.13	2.29	2.31	5.32	6.01	6.42
Juaymah	2.13	2.22	2.23	5.44	6.00	6.36
Arar	2.13	2.25	2.26	5.57	6.14	6.36
Dhahran	2.14	2.24	2.20	5.39	5.81	6.01
Gassim	1.88	1.97	2.10	3.97	4.46	4.83
Yanbo	1.77	1.79	1.74	5.08	5.29	5.40
Dhulom	1.98	2.04	2.17	5.63	6.03	6.51

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suggested for future use for wind speed extrapolation to higher heights. The highest value of WSE of 0.34 was found at Gassim while the minimum of 0.06 at Yanbo, as shown in Table 3. Since temperature plays an important role where wind energy output is concerned, its mean values are also included in Table 3.

The site roughness indicators such as length, class, and description are put together in Table 4 for all the stations. Highest value of roughness length of 1.81 m with 4.41 roughness class and suburban roughness description was obtained for Rawdat Ben Habbas and minimum values with smooth roughness description for Yanbo. These parameters also help in defining the WSE and the suitability of the site for wind power development and utilization. The site-dependent mean values of Weibull shape (k) and scale (c) parameters over data collection period and at three measurement heights are summarized in Table 5. It is evident from Table 4 that both k and c values are site-dependent and vary between 1.77 and 2.14 corresponding to Yanbo and Dhahran and 3.97 m/s and 5.97 m/s corresponding to Gassim and Arar, at 20 m AGL, respectively. A significant increase of 1.13% to 7.51% in k values was obtained at 30 m compared to that at 20 m AGL at Yanbo and Rawdat Ben Habbas. At 40 m, the k values increased only by 0.5% in some cases and even decreased at Yanbo and Dhahran by more than 1.5% and significantly (>6%) increased at Gassim and Dhulom compared to those at 30 m. At Rawdat Ben Habbas, Juaymah, Arar and Gassim the scale parameter, c, increased by more than 10% at 30 m compared to that at 20 m while around 7% at rest of the stations. At 40 m, the scale parameter increased by only by 2% to 8% compared to that at 30 m. The Weibull shape and scale parameters were found to be comparable with the actual wind speed frequency distribution at all the sites, as can be seen from Figure 5. The correlation coefficient (R^2) value for Weibull fit was always greater than 95% at all the stations.

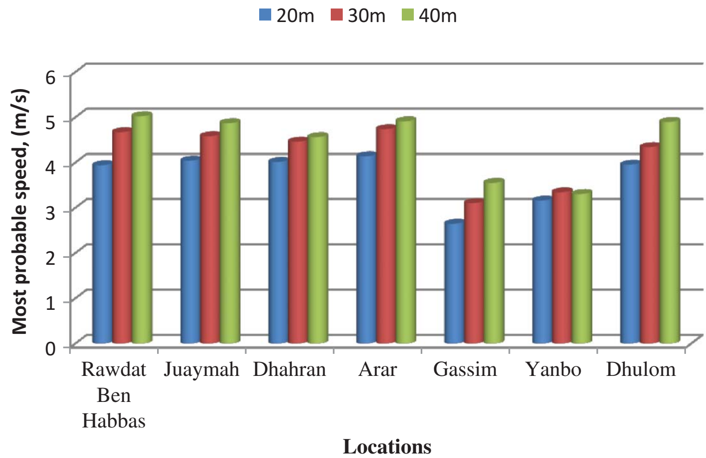

Figure 3 Most probable wind speed. (color figure available online)

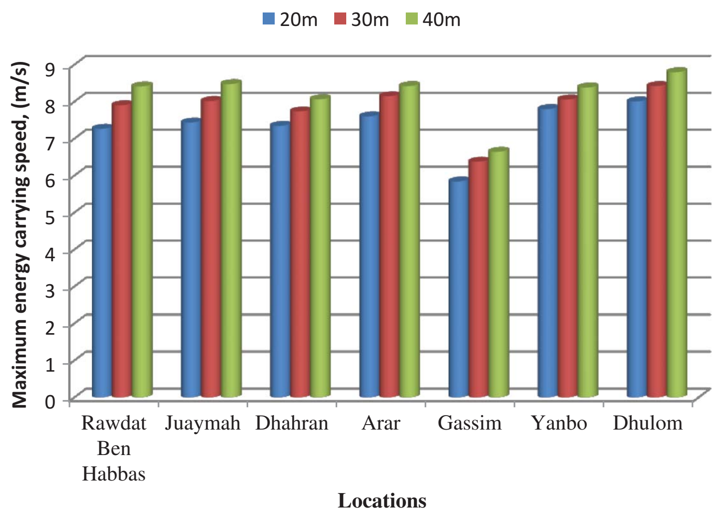

Figure 4 Maximum energy carrying wind speed. (color figure available online)

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The most probable and maximum energy carrying wind speeds were estimated using the procedure described earlier at the measuremnet heights and are compared in Figures 3 and 4, respectively. The V_{mp} values were 4 m/s at all the stations except at Gassim and Yanbo where these were <2 m/s. An increase of 6% to 19% was observed in V_{mp} values at 30 m height compared to those at 20 m corresponding to Yanbo and Rawdat Ben Habbas. At most of the stations the values increased by more than 11%. At 40 m height, the V_{mp} values increased by almost 50% compared to those at 30 m but decreased in case of Yanbo by about 1.5%. The maximum energy carrying wind speed $V_{max,E}$ was found to vary from 5.84 m/s to 8.0 m/s corresponding to Gassim and Dhulom at 20 m but was always >7 m/s at other locations. At 30 m, $V_{max,E}$ increased by 3% to 9% corresponding to Yanbo and Gassim, respectively. AT 40 m, $V_{max,E}$ values further increased by 3 to 6% compared to 30 m.

Table 6 Annual Average Variation of Wind Power Density (WPD) and Wind Energy Density (WED) at Different Sites

Location	WPD, (W/m^2)			WED, (kWh/m^2)		
	20 m	30 m	40 m	20 m	30 m	40 m
Rawdat Ben Habbas	117.10	156.40	191.30	1025.80	1370.06	1675.79
Juaymah	123.70	159.90	188.00	1083.61	1400.72	1646.88
Arar	126.20	156.40	174.50	1105.51	1370.06	1528.62
Dhahran	119.60	144.00	161.50	1047.70	1261.44	1414.74
Gassim	54.60	73.50	87.20	478.30	643.86	763.87
Yanbo	127.60	139.10	141.30	1117.78	1218.52	1237.79
Dhulom	146.70	174.40	207.80	1285.09	1527.74	1820.33

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The wind power density (WPD) and wind energy density (WED) were estimated using procedure defined in previous section (Equations 6 and 7) for all the sites using entire data-set and are summarized in Table 6 at different heights of measurement. The WPD density was found to be a maximum of 146.7 W/m^2 at Dhulom and a minimum of 54.5 W/m^2 at Gassim while at other stations it was more than 115 W/m^2, as given in Table 6. The WPD density increased by 9% to 34% at 30 m compared to that at 20 m corresponding to Yanbo and Dhulom stations, respectively. The percent increase in WPD at 40 m compared to that at 30 m was almost 50% of the increase at 30 m relative to 20 m with exception of Dhulom where the WPD density increased by the same magnitude as in earlier case. The WED was found to be varying between 763 kWh/m^2 at Gassim to 1820 kWh/m^2 at Dhulom while at remaining stations it was 1500 kWh/m^2. The increasing pattern of WED was almost the same as that in case of WPD.

The seasonal or monthly mean values of Weibull shape and scale parameters k and c are tabulated in Tables 7 and 8, respectively. The maximum values of k of 2.92, 2.49, 2.34, 2.35, 3.42, 2.79, and 2.08 occurred in the months of July, December, August, February, July, June, and October corresponding to Arar, Dhharan, Dhulom, Gassim, Juaymah, Rawdat Ben Habbas, and Yanbo, respectively. The corresponding minimum values of k of 2.07, 2.01, 2.02, 1.92, 1.88, 2.21, and 1.61 occurred in February, August, April, May, March, March, and June, as can be seen from data given in Table 7. No regular seasonal trend could be observed at any of the stations. At Arar, Dhahran, Dhulom, and Rawdat Ben Habbas, relatively higher values of c were observed during summer time and lower during end periods of the year, as given in Table 8. At remaining stations, no trend could be observed in the values of c over the year. The highest values of c of 7.45 m/s, 6.67 m/s, 7.47 m/s, 5.49 m/s, 7.61 m/s, 7.42 m/s, and 6.01 m/s were found in the months of July, April, March, April, January, June, and March at Arar, Dhahran, Dhulom, Gassim, Juaymah, Rawdat Ben Habbas, and Yanbo, respectively. The corresponding minimum values of c of 5.33 m/s,5.26 m/s, 5.60 m/s, 4.33 m/s, 4.41 m/s, 5.48 m/s, and 4.49 m/s were observed in the months of November, October, September, September, February, November, and December, respectively.

The most probable wind speed ranged between 3.29 m/s and 4.93 m/s at 40 m AGL corresponding to November and June at Rawdat Ben Habbas, as given in Table 9. At Juaymah, the minimum and maximum most probable wind speeds of 2.38 m/s and 5.12 m/s occurred in the months of February and July, respectively, while at Dhahran the respective values of 3.42 m/s and 4.74 m/s were found in August and March. At Arar and Dhulom the maximum values of 5.73 m/s and 4.87 m/s of most probable wind speed

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Table 7 Monthly Mean Values of Shape Parameter, k at 40 m

Month	Rawdat Ben Habbas	Juaymah	Arar	Dhahran	Gassim	Yanbo	Dhulom
Jan	2.32	2.23	2.43	2.35	2.20	1.86	2.27
Feb	2.34	1.89	2.07	2.38	2.35	1.73	2.27
Mar	2.21	1.88	2.21	2.30	2.02	1.73	2.17
Apr	2.42	2.40	2.20	2.27	2.02	1.65	2.02
May	2.30	2.96	2.17	2.09	1.92	1.73	2.16
Jun	2.79	2.71	2.43	2.05	2.26	1.61	2.31
Jul	2.64	3.42	2.92	2.09	2.30	1.66	2.32
Aug	2.64	2.20	2.42	2.01	2.25	1.70	2.34
Sep	2.27	2.32	2.29	2.16	2.20	1.81	2.17
Oct	2.32	2.67	2.18	2.47	2.12	2.08	2.30
Nov	2.28	2.23	2.04	2.45	2.08	1.82	2.18
Dec	2.22	2.47	2.38	2.49	2.18	1.84	2.18

Table 8 Monthly Mean Values of Scale Parameter, c (m/s) at 40 m

Month	Rawdat Ben Habbas	Juaymah	Arar	Dhahran	Gassim	Yanbo	Dhulom
Jan	6.37	7.61	6.08	5.91	4.79	5.41	6.90
Feb	6.91	4.41	6.14	6.39	5.36	5.56	7.19
Mar	6.69	4.88	7.32	6.54	5.45	6.01	7.47
Apr	7.32	5.36	6.64	6.67	5.49	5.75	6.49
May	6.43	6.08	6.54	5.90	4.84	5.56	6.33
Jun	7.42	7.49	6.66	6.49	4.77	5.43	6.55
Jul	6.82	6.99	7.45	6.42	4.85	5.32	7.15
Aug	6.21	6.15	6.49	5.69	4.44	5.72	6.23
Sep	5.64	6.89	6.02	5.46	4.33	5.59	5.60
Oct	6.23	6.95	5.83	5.26	4.52	5.22	5.66
Nov	5.48	5.89	5.33	5.68	4.37	4.82	6.45
Dec	5.94	7.40	5.69	5.50	4.55	4.49	6.47

Table 9 Monthly Mean Most Probable Wind Speed at Different Locations at 40 m

Month	Rawdat Ben Habbas	Juaymah	Arar	Dhahran	Gassim	Yanbo	Dhulom
Jan	3.96	4.85	3.97	4.37	2.63	3.27	4.38
Feb	4.22	2.38	3.59	4.64	3.24	3.22	4.67
Mar	3.96	2.92	4.58	4.74	3.07	3.40	4.77
Apr	4.67	3.50	4.21	4.29	2.90	3.16	3.82
May	4.05	4.39	4.24	3.84	2.43	3.22	4.21
Jun	4.93	5.09	4.76	3.96	2.82	3.02	4.57
Jul	4.46	5.12	5.73	3.72	2.76	3.12	4.87
Aug	4.13	3.85	4.50	3.42	2.53	3.40	4.30
Sep	3.43	4.68	3.94	3.60	2.44	3.36	3.45
Oct	3.83	4.78	3.69	3.80	2.53	3.61	3.35
Nov	3.29	3.74	3.35	4.15	2.39	2.92	3.50
Dec	3.50	4.87	3.68	4.19	2.52	2.81	3.52

were found in July while the minimum of 3.35 m/s in November and October, respectively. Generally, in the northeastern region (Rawdat Ben Habbas, Juaymah, and Arar), higher values of most probable wind speeds were found in summer months and lower during winter time. The maximum values of maximum energy carrying wind speed ($V_{max,E}$) of 8.38 m/s,

Table 10 Maximum Energy Carrying wind Speed at Different Locations at 40 m

Month	Rawdat Ben Habbas	Juaymah	Arar	Dhahran	Gassim	Yanbo	Dhulom
Jan	7.23	8.98	6.96	7.05	5.62	7.16	8.41
Feb	7.88	6.00	7.79	7.41	6.09	8.01	8.66
Mar	7.82	6.42	9.21	8.03	6.78	8.83	9.40
Apr	8.38	5.92	8.24	8.00	6.84	8.76	8.24
May	7.40	6.21	8.18	7.74	6.05	8.31	7.53
Jun	8.06	7.89	7.70	8.40	5.49	8.50	7.43
Jul	7.36	6.85	8.10	7.98	5.66	8.05	8.41
Aug	6.46	7.08	7.30	7.11	5.27	8.40	7.27
Sep	6.16	7.85	6.89	6.92	5.09	8.02	6.66
Oct	6.82	7.74	6.79	6.15	5.35	6.56	6.56
Nov	6.13	7.07	6.45	6.57	5.36	6.58	8.05
Dec	6.76	8.47	6.48	6.31	5.49	6.05	8.17

Table 11 Monthly Mean wind Power Density (W/m^2) at 40 m

Month	Rawdat Ben Habbas	Juaymah	Arar	Dhahran	Gassim	Yanbo	Dhulom
Jan	168.7	204.4	143.7	145.7	80.7	125.8	200.4
Feb	223.6	261.3	162.7	180.3	108.2	151.7	224.2
Mar	219.4	207.8	268.9	197.7	130.8	185.0	265.3
Apr	219.6	170.6	207.6	207.8	134.0	171.3	189.9
May	166.6	161.0	190.8	151.4	99.1	140.1	170.5
Jun	201.0	315.7	191.0	201.6	78.6	138.7	176.7
Jul	180.7	218.3	228.2	189.0	81.0	128.6	229.1
Aug	120.6	89.4	159.3	136.8	63.4	150.9	145.3
Sep	112.0	103.4	137.1	115.0	59.3	139.6	111.4
Oct	148.0	95.5	149.1	94.7	69.2	101.3	109.4
Nov	115.3	173.0	109.4	123.3	65.1	97.1	168.1
Dec	143.4	205.8	121.0	112.0	70.0	74.8	169.3

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8.98 m/s, 8.40 m/s, 9.21 m/s, 6.84 m/s, 8.83 m/s, and 9.40 m/s were observed in the months of April, January, June, March, April, March, and March at Rawdat Ben Habbas to Dhulom in order, respectively. In general, higher values of maximum energy carrying wind speed were observed during summer months starting from April till September and lower during starting and ending months of the year, as can be seen from Table 10.

The monthly mean wind power density and wind energy density values are summarized in Table 11 and 12, respectively. In general, higher values of both the derived parameters were found in the first half of the year while lower in the second half of the year as can be seen from these two tables. From wind energy harnessing point of view Juymah, Arar, and Dhulom were identified as the most suitable sites while Rawdat Ben Habbas and Dhahran were the other two good sites.

CONCLUSIONS

Wind speed and wind power characteristics were studied in this paper using the wind measurements made at 20 m, 30 m, and 40 m AGL at Rawdat Ben Habbas, Juaymah, Arar, Dhahran, Gassim, Yanbo, and Dhulom in the Kingdom of Saudi Arabia. At 20 m, 30 m, and

Table 12 Monthly Mean Wind Energy Density (kWh/m^2) at 40 m

Month	Rawdat Ben Habbas	Juaymah	Arar	Dhahran	Gassim	Yanbo	Dhulom
Jan	125.5	152.0	106.9	108.4	60.0	93.6	149.1
Feb	150.2	175.6	109.3	121.2	72.7	101.9	150.7
Mar	163.3	154.6	200.1	147.1	97.3	137.6	197.4
Apr	158.1	122.8	149.4	149.6	96.5	123.3	136.7
May	123.9	119.8	142.0	112.6	73.7	104.2	126.8
Jun	144.7	227.3	137.5	145.1	56.6	99.9	127.2
Jul	134.4	162.4	169.8	140.6	60.3	95.7	170.5
Aug	89.7	66.5	118.5	101.8	47.2	112.2	108.1
Sep	80.7	74.5	98.7	82.8	42.7	100.5	80.2
Oct	110.1	71.1	110.9	70.5	51.5	75.4	81.4
Nov	83.0	124.5	78.8	88.8	46.9	69.9	121.1
Dec	106.7	153.1	90.0	83.3	52.1	55.7	126.0

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40 m; the maximum wind speeds of 5.1 m/s, 5.5 m/s, and 5.9 m/s were found at Dhulom while minimum of 3.5 m/s, 4.1 m/s, and 4.3 m/s at Gassim. The highest value of WSE of 0.34 was found at Gassim while the minimum of 0.06 at Yanbo. Both k and c values were established to be site-dependent and varied between 1.77 and 2.14 corresponding to Yanbo and Dhahran and 3.97 m/s and 5.97m/s corresponding to Gassim and Arar, at 20 m AGL, respectively. The most probable wind speed values were 4 m/s or more at all the stations except at Gassim and Yanbo where these were <2 m/s. The maximum energy carrying wind speed was found to vary from 5.84 m/s to 8.0 m/s corresponding to Gassim and Dhulom at 20 m but was always >7 m/s at other locations. In general, higher values of all the parameters related to wind speed were observed duirng summer time and lower during winter time with some exceptions. Based on annual mean wind speeds, Dhulom, Arar, Juaymah, Rawdat Ben Habbas, and Dhahran are suggested as the potential sites for wind power development point of view.

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