Evaluation of Wind power energy potential in four sites in Saudi Arabia

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Abstract: -The energy potential of wind in four sites located in different parts of the Kingdom of Saudi Arabia is investigated in the present work. A statistical analysis of recently collected hourly wind data over a period of 7 years between January 2012 and December 2018 at 10 m height by using Weibull distribution function has been presented. It was found that the annual mean wind speed at 10 m AGL for Dhahran, Jeddah, Al-Hofuf and Rafah are 4.35 m/s, 4.12 m/s, 4.23 m/s and 3.86 m/s respectively, while the annual wind power density are 66.77 W/m^2, 43.58 W/m^2, 72.75 W/m^2 and 53.27 W/m^2, respectively. The mean annual values of the most probable wind are 5.41 m/s, 5.63 m/s, 5.83 m/s and 5.36 m/s for Dhahran, Jeddah, Al-Hofuf and Rafha, respectively. The results revealed that at 10 m height, the four studied sites fall under Class 1 (poor) since the highest reached values of the mean annual wind speed and the mean annual power density were 4.35 m/s and 68 W/m^2 respectively, registered in Dhahran city. The performance of selected commercial wind turbine models (with rated power between 500 kW and 200 kW)) for electricity generation and small scale application has been carried out.

Key-Words: - Weibull distribution, wind speed, power density, standard deviation method, wind turbine

1- Introduction

The highly relying on fossil fuel and crude oil for power generation in the Kingdom of Saudi Arabia causes many environmental issues such as pollution, climate change and resources depletion. In the framework of Saudi's vision 2030, renewable energy plan has been set up to ensure renewable energy growth. Saudi Arabia has set a target of deploying 9.5 GW of wind and solar capacity by 2023 [1]. In addition, the Saudi government aims to increase its renewable energy production to 60 GW, including 40 GW from solar energy and 20 from wind and other sources by 2030. Today, wind energy is the world's fastest growing renewable energy and it is widely used to produce electricity in many countries. If the wind turbine is sited in windy area and the type of wind turbine is carefully chosen to match the wind pattern of the site, wind energy can be

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harvested at an economical level. Thorough knowledge of the wind speed characteristics at a site of interest is substantial part in planning the harvest of wind energy. Detailed information about the wind characteristics and the distribution of its speed is essential for effective use of wind energy. Several studies have been conducted to assess the wind energy potential in different sites in the Kingdom of Saudi Arabia and Bahrain.

An evaluation of wind energy potential assessment for four coastal locations of the Kingdom of Saudi Arabia has been evaluated by [2]. Hourly mean wind speed and wind direction of 14 years were presented. It has been found that Yanbu and Dhahran are the best locations for extracting wind power.

A study of wind characteristics in Jubail city located in Saudi Arabia has been conducted by [3]. The results indicated that the mean wind speeds are 3.34 m/s, 4.79 m/s and 5.35 m/s at 10 m, 50 m and 90 m above ground level (AGL). In addition, the availability of wind speed above 3.5 m/s was more than 75% at 50 m and 90 m.

Wind resource assessment for the Kingdom of Bahrain has been done by [4]. The results indicated an annual mean wind speed of 4.6 m/s at 10 m height and mean Weibull scale and shape parameters c and k of 5.2 m/s and 1.9 respectively. In addition, it has been found that several locations in the less populated central and southern regions of the main island of the archipelago of Bahrain are potentially suitable for wind energy production.

Many technologies have been used for analyzing and modelling the wind power plant in order to enable decision makers to better optimize the system and to test many operational states before the building of the plant. Simulation is an essential step for designing and implementation of wind power plants like Simulink and PLECS. The type of generator system is one of the requested parameters for the analyzing and modeling of wind power plants. A study to analyze and test the doubly-fed induction generator (*DFIG*) system using Simulink and PLECS models has been conducted by [5]. It has been found that two studied models are suitable for practical analysis for different DFIG Wind Power System

This paper aims to evaluate the potential of wind energy in four sites located in the kingdom of Saudi Arabia (Dhahran, Jeddah, Al Al-Hofuf and Rafha), based on hourly wind speed data collected over 7 years from January 2012 to December 2018 by using Weibull distribution function. In addition, an extrapolation of wind speed and Weibull parameters at different heights has been estimated in order to assess the wind density at different heights.

2- Sites information and wind data source

The Kingdom of Saudi Arabia, which is the largest country in the Arabian peninsula, is situated in Southwest Asia. It is bordered by the Red Sea on the west, Yemen, Oman and the Persian Gulf *on* the south, Qatar, United Arab Emirates, Kuwait and Iraq on the east, and by Jordan on the north (Figure 1). The four studied sites are Dhahran, Jeddah, Al-Hofuf and Rafha. Dhahran and Al-Hofuf are sites located at the Eastern province of the Kingdom of Saudi Arabia on the Arabian Gulf coast, Rafha is a city located in the North of the Kingdom and Jeddah is located on the coast of the Red Sea. The geographical details of the studied sites are presented in Table 1. The hourly wind speed data, ranging from 2012-2019 period (7 years) and recorded at 10 m AGL for the studied sites, were collected from the meteorological weather website, Time and Date [6].

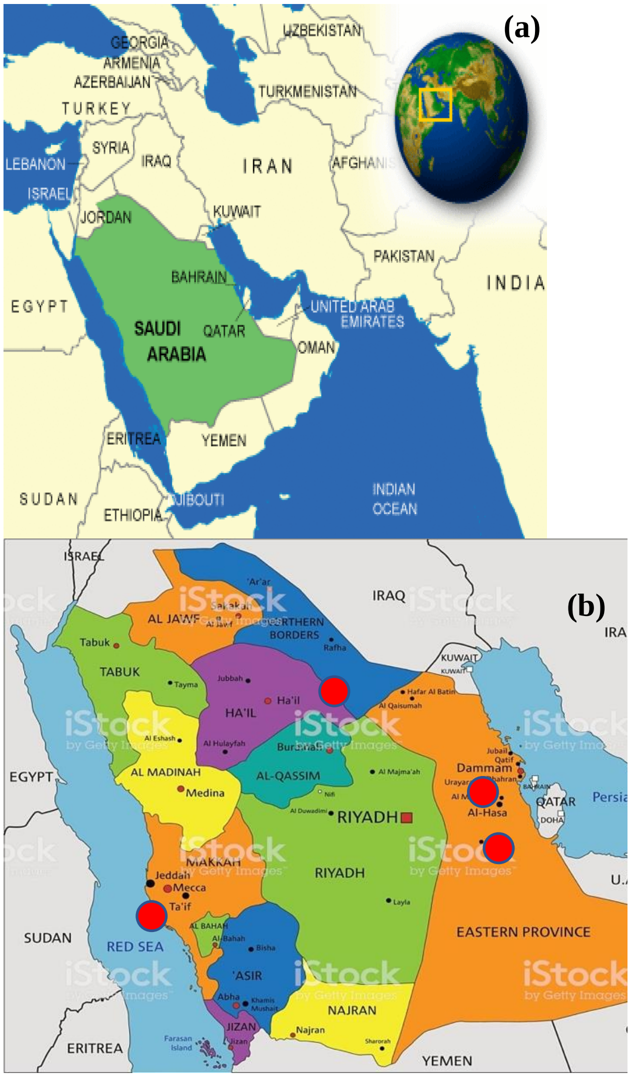

Figure 1 Map of the Kingdom of Saudi Arabia showing (a) the borders of the Kingdom (b) the studied sites

Table 1 Geographical details of the studied sites

City	Longitude (°)	Latitude (°)	Altitude (m)
Dhahran	50° 6' 50.7636" E	26°17′19.5684″ N	22
Jeddah	39°11′52″ E	21°32′32″ N	21
Al-Hofuf	49°37′47.67″E	25°18′50.96″N	154
Rafha	43° 29' 30" E	29° 37' 38" N	447

3- PNL wind power classification

The Pacific Northwest Laboratory (PNL) has made a classification of wind energy potential into seven classes. This classification depends on the wind speed and power density at specified heights AGL (10 m, 30 m and 50 m) and it is presented in Table 2.

Table 2 Wind power classes according to Battelle PNL[7]

Wind power class	10 m		30 m		50 m	
	Wind power density (W/m²)	Average wind speed (m/s)	Wind power density (W/m²)	Average wind speed (m/s)	Wind power density (W/m²)	Average wind speed (m/s)
1	≤ 100	≤ 4.4	≤160	≤5.1	≤200	≤5.6
2	≤150	≤ 5.5	≤240	≤6.0	≤300	≤6.4
3	≤200	≤ 5.6	≤320	≤6.5	≤400	≤7.0
4	≤250	≤ 6.0	≤400	≤7.0	≤500	≤7.5
5	≤ 300	≤6.4	≤480	≤7.5	≤600	≤8.0
6	≤ 400	≤ 7.0	≤640	≤8.2	≤800	≤8.8
7	≤1000	≤ 9.4	≤1600	≤11.0	≤2000	≤11.9

4- Mathematical model

4.1 Weibull distribution

The probability distribution function is used to analyze the wind data characteristic in any region. Wind data obtained with various observations methods has a wide range, therefore it is necessary to explain the behavior of a wide range of wind speed data in wind energy analysis [8]. The use of Weibull distribution function has presented the wind distribution in a better manner due to its simplest and most practical method [9, 10]. In recent years, this function has gained attention for wind energy analysis. It is characterized by simplicity, greater flexibility and by providing a reasonable matching with experimental data [11]. In addition, if the Weibull distribution is determined for the wind at a certain height, the distributions at other heights may be easily deducted [6, 12]. The Weibull distribution is characterized by two parameters: the dimensionless shape parameter (k); and the scale parameter (c) which has unit similar to the speed (m/s). Thus, it is essential to estimate these two parameters prior to any analysis. The Weibull probability density function for the wind velocity *v* is expressed as [13]:

$$f(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} e^{(-(\frac{v}{c}))^k} \quad (1)$$

The corresponding Weibull cumulative distribution can be obtained by integrating the Weibull probability distribution function and it is expressed as [14]:

$$F(v) = \int_0^{\beta} f(v)dv = 1 - e^{(-(\frac{v}{c}))^K} \quad (2)$$

The shape and scale parameters can be calculated by several methods such as Standard deviation method, Moment method, Energy pattern factor method and maximum likelihood method. The Standard deviation is used in this paper to estimate the values of the scale and shape parameters [15, 16]:

$$k = (\delta/_{\bar{v}})^{-1.090} \quad (3)$$

$$1 \leq k \leq 10$$

$$c = \frac{\bar{v}}{\Gamma(1 + 1/_k)} \quad (4)$$

where δ is the standard deviation, $\bar{v}$ is the mean value of wind speed and Γ is the Gamma function, it is expressed as:

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \quad (5)$$

The shape and the scale parameters present a great impact on the Weibull distribution function. The shape parameter affects the skewness of the curve, while the scale parameter stretches or squeezes the distribution.

A higher value of the scale parameter indicates that the wind distribution is dispensed over a wider range and the probabilistic average wind speed has a higher value. A value of shape parameter between 2 and 3 indicates that the distribution is skewed toward higher wind speed values, while a value of shape parameter between 1 and 2 means that the distribution is skewed toward lower wind speed values.

The parameter $\bar{v}$ is the mean wind speed and it can be estimated as follows:

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (6)$$

The standard deviation δ can be calculated by:

$$\delta = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{v})^2)} \quad (7)$$

The expected value of the wind speed which is known as the average wind velocity and the standard deviation can both be obtained from the Weibull distribution parameters of k and c:

$$\bar{v} = c\Gamma(1 + 1/k) \quad (8)$$

$$\delta = \sqrt{c(\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2(1+\frac{2}{k}))} \quad (9)$$

The wind power density indicates the amount of energy per unit of time and swept area of the blades at the selected area for conversion to electricity by a wind turbine. It increases with the air density and with the cube of the wind speed. The wind power density and the energy density are calculated by:

$$PD = {}^1\!/_2\,\rho v^3 \quad (10)$$

$$ED = PD\ T \quad (11)$$

where T is the time factor and it refers to the hour's number for the monthly and annual number of hours. ρ is the air density (kg/m^3) at sea level. The air density depends on the surface pressure as well as the air temperature; it can be calculated by using the following equation:

$$\rho = \frac{P}{RT}\ (kg/m^3) \quad (12)$$

where P is the surface pressure (Pa), R is the specific gas constant for air (287 J/kg °K) and T is the air temperature (°K).

Based on the Weibull probability density function, the wind power density and the energy density at any height are expressed as [17]:

$$PD = {}^1\!/_2\,\rho c^3 \Gamma(1 + {}^3\!/_k) \quad (13)$$

$$ED = PD\ T \quad (14)$$

The most probable wind speed (V_{mp}) represents the peak of the probability density. It can be estimated by using the following equation:

$$V_{mp} = c(\frac{k-1}{k})^{k-1} \quad (15)$$

The most energy wind speed (V_{max}) denotes the speed carrying the maximum quantity of energy and it is expressed by:

$$V_{max} = c(\frac{k+2}{k})^{\frac{1}{k}} \quad (16)$$

The wind speed increases with height by a power factor known as wind shear coefficient (α). The extrapolation of wind velocities with height can be calculated via the wind shear power law as [18]:

$$v_1 = v_0(\frac{z_1}{z_0})^{\alpha} \quad (17)$$

where v_0 is the original wind speed recorded at height z_0, v_1 is the wind speed to be determined at the desired height, α is the shear factor which is usually in the range 0,05-0,5. The wind shear power law will lead to under estimation of wind speed if the wind shear coefficient is greater than 1/7. Therefore, an accurate value of the wind shear coefficient is essential for wind power estimation.

The variation of Weibull parameters with different height can be estimated as [19]:

$$k_2 = k_1(1 - 0.0881\ln(\frac{z_2}{z_1}))^{-1} \quad (18)$$

$$c_2 = c_1(\frac{z_2}{z_1})^{(0.37-0.0881\ln(c_1))} \quad (19)$$

- Wind turbine energy output and capacity factor

The estimation of the mean power output during a period of time and the capacity factor are used to test the performance of a wind turbine installed in a given site. The capacity factor, also called the conversion efficiency, is defined as the ratio of the mean power output to the rated electrical power of the wind turbine.

The mean power output P is calculated by using the Weibull parameters and is expressed as:

$$P_{out} = P_r\left(\frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k}\right) \quad (20)$$

where v_c, v_r and v_f are the cut-in wind speed, rated wind speed and cut-off wind speed, respectively.

The capacity factor can be estimated by the following expression:

$$C_f = \frac{P_{out}}{P_r} \quad (21)$$

A value of capacity factor greater than 0.25 is recommended for a cost effective of an investment of wind power [18].

5- Results and discussion

In the present work, an hourly average wind speed data for four sites located in the Kingdom of Saudi Arabia (Dhahran, Jeddah, Al-Al-Hofuf and Rafah) from January 2012 to December 2018, have been collected and analyzed. The mean monthly and annually wind speed, shape and scale parameters, wind power density, Weibull cumulative distribution function and Weibull probability density function have been calculated and analyzed. In addition, an extrapolation of wind speed, shape and scale parameters at 60 m, 90 m and 120 m and the performance of some wind turbine models in the studied sites have been done.

5.1 Monthly wind speed

The mean monthly wind speed from 2012-2018 for the studied sites are presented in Table 3. The mean monthly wind speed for the different years registered at 10 m AGL varies between 3.05 m/s (in September 2018) and 6.27 m/s (in June 2013) in Dhahran city and varies between 3.21 m/s (in October 2016) and 4.72 m/s (in March 2012) in Jeddah city. In Al-Hofuf city, the mean monthly wind speed varies between 2.94 m/s (in September 2018) and 6.36 m/s (in June 2013), while it varies between 2.91 m/s (in November 2015) and 5.01 (in April 2014) in Rafha city. Therefore, it can be said that the monthly wind speed distribution presents a slight variation.

It can be noticed that the mean monthly wind speed for the whole years varies between 3.39 m/s in October and 5.19 m/s in June in Al-Hofuf and it varies between 3.72 m/s in October and 5.36 m/s in June in Dhahran. However, in Jeddah, it varies between 3.61 m/s in October and 4.36 m/s in March and it varies between 3.40 m/s in October and 4.51 m/s in March in Rafah.

Table 3 Yearly wind speed for the studied sites (m/s)

	Al-Hofuf								Dhahran							
	2012	2013	2014	2015	2016	2017	2018	Whole year	2012	2013	2014	2015	2016	2017	2018	Whole year
January	4,13	4,36	3,55	4,10	4,44	4,02	4,05	4,09	4,11	3,87	3,82	5,21	4,83	4,31	3,97	4,30
February	5,13	4,10	4,11	4,79	4,61	3,96	3,98	4,38	5,12	3,88	4,60	5,15	4,81	4,52	3,94	4,58
March	5,02	4,50	4,32	4,45	4,28	4,45	4,01	4,43	5,02	4,30	4,64	4,89	4,65	4,25	4,08	4,55
April	3,92	4,21	4,11	5,42	3,69	5,05	4,70	4,44	3,89	4,29	4,61	5,59	4,25	4,81	4,76	4,60
May	4,85	4,54	4,03	4,79	4,59	5,50	3,89	4,60	4,69	4,51	4,29	4,90	4,81	5,13	3,99	4,62
June	5,05	6,36	5,48	5,43	5,15	3,51	5,36	5,19	4,44	6,27	4,94	5,59	5,23	5,67	5,39	5,36
July	4,90	5,16	5,61	5,06	4,64	2,80	5,61	4,83	4,44	4,36	4,88	4,88	4,84	3,80	5,11	4,61
August	5,46	4,08	4,23	3,92	3,40	3,12	5,26	4,21	4,16	3,55	4,28	3,86	3,69	3,36	4,76	3,95
September	4,52	3,89	3,49	3,53	4,13	3,09	2,94	3,66	4,15	3,75	3,78	3,97	4,39	3,20	3,05	3,75
October	3,14	3,97	3,48	3,52	3,11	3,06	3,46	3,39	3,08	3,99	4,21	3,99	3,56	3,74	3,45	3,72
November	3,66	3,59	3,65	3,84	3,20	3,06	3,94	3,56	3,70	3,71	4,14	4,44	3,92	3,54	4,51	4,00
December	3,91	4,35	3,51	4,14	4,01	4,29	3,5.2	3,96	3,79	4,72	4,09	4,67	4,50	4,08	3,71	4,22
Average	4,53	4,43	4,13	4,42	4,10	3,92	4,23	4,23	4,21	4,27	4,36	4,76	4,46	4,20	4,23	4,35

	Jeddah								Rafah							
	2012	2013	2014	2015	2016	2017	2018	whole year	2012	2013	2014	2015	2016	2017	2018	Whole year
January	4,27	3,85	4,11	4,49	4,24	3,51	4,57	4,15	4,02	4,14	3,58	3,69	3,39	3,80	3,75	3,77
February	4,24	4,24	4,29	4,25	4,57	4,66	4,13	4,34	4,16	3,33	4,50	3,70	3,65	4,00	3,93	3,89
March	4,72	4,05	4,21	4,28	4,76	4,32	4,15	4,36	4,62	4,07	4,66	4,46	4,93	4,36	4,46	4,51
April	3,84	4,26	4,25	4,83	4,01	4,99	4,24	4,35	4,43	4,41	5,02	3,87	4,21	4,04	4,43	4,35
May	3,78	3,90	4,32	4,06	4,33	4,58	4,58	4,22	4,09	3,88	4,00	4,13	4,08	4,20	4,12	4,07
June	4,22	4,37	4,54	4,47	3,90	4,34	4,21	4,29	4,23	4,22	4,15	3,54	3,78	4,32	3,99	4,03
July	4,19	4,33	4,13	4,47	4,30	4,45	3,96	4,26	4,12	4,30	4,05	3,62	4,02	3,52	4,02	3,95

August	4,20	4,02	4,20	4,16	4,33	4,40	4,05	4,19	3,67	3,52	3,56	2,93	3,56	3,42	3,43	3,44
September	4,08	4,19	4,21	3,85	3,79	4,05	3,98	4,02	3,59	3,35	3,41	3,19	3,06	3,91	3,33	3,40
October	3,41	3,54	3,86	3,78	3,21	3,80	3,65	3,61	3,90	4,63	3,61	3,11	4,22	3,29	3,91	3,81
November	3,55	3,54	3,60	3,90	3,33	3,84	3,77	3,65	4,04	3,90	3,77	2,91	4,11	3,29	3,67	3,67
December	3,83	4,20	3,64	4,72	3,91	3,84	3,90	4,01	3,79	3,23	3,35	3,42	3,43	3,63	3,55	3,49
Average	4,05	4,04	4,11	4,27	4,06	4,23	4,10	4,12	4,05	3,91	3,97	3,55	3,87	3,81	3,88	3,86

Figure 2 shows the variation of monthly mean wind speed of the four studied sites for the whole year at 10 m height. The mean monthly wind speed varies between 3.78 m/s in October and 5.36 m/s in June in Dhahran city and between 3.61m/s in October and 4.36 m/s in March in Jeddah city. In Al-Hofuf city, the mean monthly wind speed varies between 3.39 m/s in October and 5.19 m/s in June while it varies between 3.4 m/s in September and 4.51 m/s in March in Rafha. It can be noticed that the highest value of wind speed of 5.36 m/s is recorded in June in Dhahran and the lowest value of 3.4 is recorded in October in Rafha.

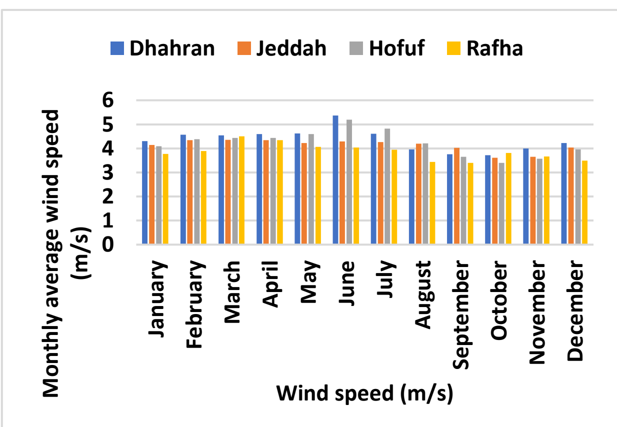

Figure 2 Monthly mean wind speed for the whole year

5.2 Variations of diurnal wind speed

Figure 3 illustrates the diurnal wind speed variations of the four studied sites for the whole years. It can be noticed that the daytime is windy while the night time is quiet for the four studied sites. The wind speed in Dhahran city starts to increase at 5:00 am and it reaches its maximum at 15:00, then it decreases to reach its minimum at midnight. In Jeddah city, the wind speed starts to grow at 7:00 am and it reaches its maximum at 15:00 and then it decreases to attain its minimum at 4:00 am. In Al-Hofuf city, the wind speed starts increasing at 3:00 am to reach its maximum at noon and then it decreases to attain its minimum at 23:00. In Rafah city , the wind speed starts to rise at 7:00 am and it reaches its maximum at 11:00 am and then it keeps a constant value until 17:00, and then it reduces again.

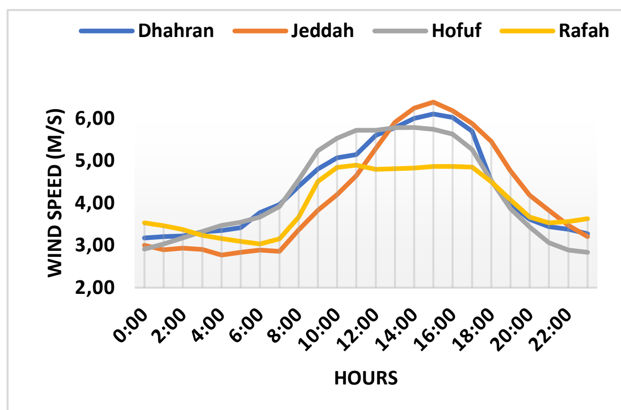

Figure 3 Diurnal variation of wind speed of the four studied sites for the whole years

5.3 Variations of Weibull parameters

The mean monthly and yearly Weibull parameters for the studied sites are illustrated in

Table 4. It can be observed from Table 4 that the least monthly value of the Weibull shape parameter in Dhahran city is 3.16 in December and reached the highest value of 4.69 in August. In Jeddah city, the Weibull shape parameter displays a least monthly value of 2.34 in October and reached the highest value of 2.93 in January while the least monthly value found for Al-Hofuf city is 2.45 in June and the greater one is 3.13 in December. The least monthly value of the Weibull shape parameter in Rafha city is 2.44 in July and August and reached the highest value of 2.89 in March. It can be concluded that the wind speed is most uniform in August in Dhahran city, in January in Jeddah city, in December in Al-Hofuf city and in March in Rafha city. The annual shape parameter values for Dhahran, Jeddah, Al-Hofuf and Rafha are 3.85, 2.72, 2.76 and 2.69 respectively.

The Weibull scale parameter shows difference from site to another. It can be noticed that the least monthly value of the Weibull scale parameter in Dhahran city of 4.07 m/s is obtained in October while the highest value of 5.96 m/s is registered in June. In Jeddah city, the least monthly value of the Weibull scale parameter of 4.05 m/s is recorded in October and the highest value of 4.89 m/s in March, while the least monthly value of the Weibull scale parameter in Al-Hofuf city of 3.81 m/s is registered in October and the highest value of 6.16 m/s is found in June. The least monthly value of the Weibull scale parameter in Rafha city of 3.73 m/s is registered in September and the highest value of 4.98 m/s in March.

The annual shape parameter values for Dhahran, Jeddah, Al-Hofuf and Rafha are 4.82 m/s, 4.59 m/s, 4.74 m/s and 4.35 m/s respectively.

In order to verify if the characteristics of the wind speed data are distributed according to Weibull probability distribution function, the annual Weibull cumulative frequency functions and the annual measured cumulative frequency functions for the selected locations of study are plotted in the same graph in Fig. 4. The similarity of both trends illustrates the good representation offered by such a model when compared to the actual measured data.

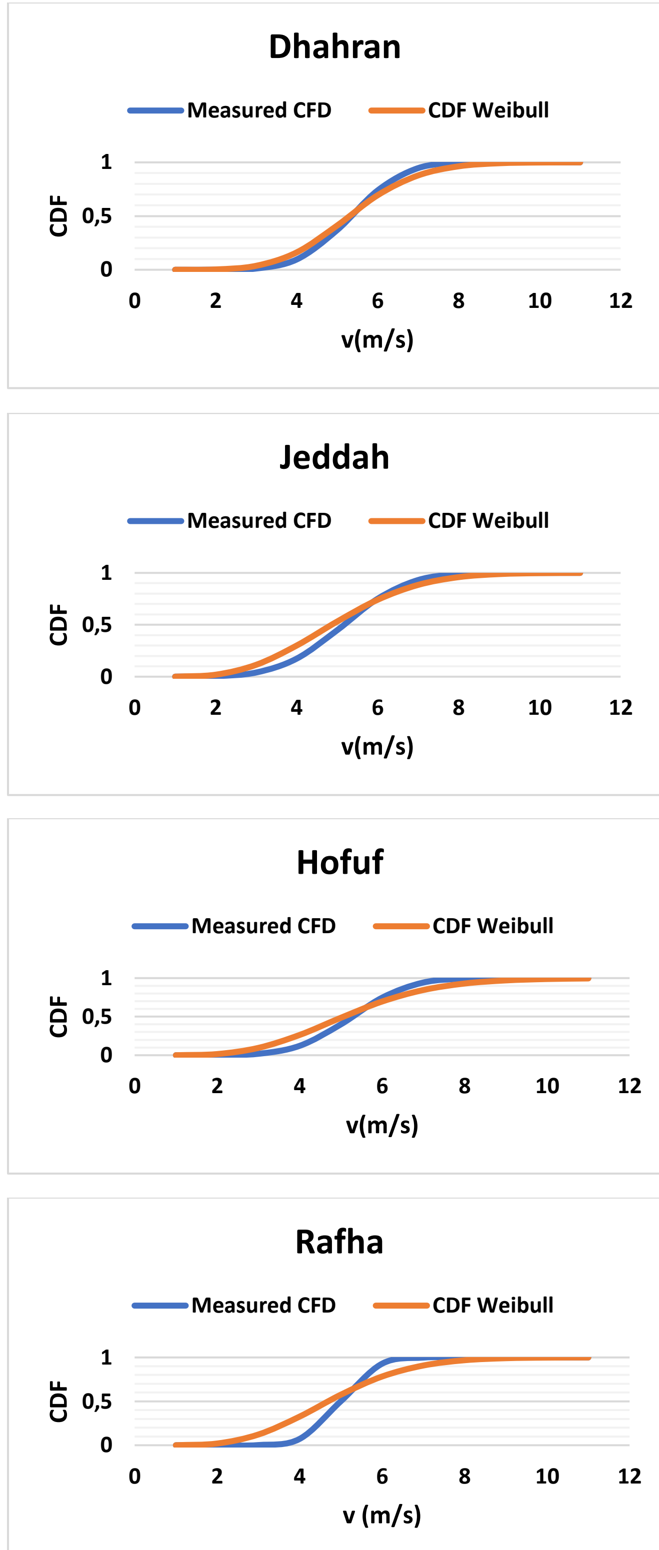

Figure 4 Comparison of the annual observed wind speed cumulative frequency and wind speed frequency simulated by Weibull for the four studies sites

Table 4 Mean monthly and annual Weibull parameters

	Parameter	January	February	March	April	May	June	July	August	September	October	November	December	Annual Average
Dhahran	K	3,84	3,72	3,25	3,82	3,57	3,57	3,60	4,69	4,60	4,61	3,78	3,16	3,85
	c (m/s)	4,77	5,08	5,08	5,10	5,13	5,96	5,13	4,32	4,11	4,07	4,43	4,72	4,82
Jeddah	K	2,93	2,85	2,74	2,74	2,75	2,77	2,62	2,64	2,69	2,34	2,62	2,90	2,72
	c (m/s)	4,64	4,58	4,89	4,87	4,73	4,82	4,79	4,93	4,40	4,05	4,09	4,29	4,59
Al-Hofuf	K	3,00	2,83	2,76	2,54	2,57	2,45	2,54	2,61	2,68	2,87	3,08	3,13	2,76
	c (m/s)	4,57	4,94	4,81	4,88	5,04	6,16	5,54	4,67	4,09	3,81	3,98	4,42	4,74
Rafha	K	2,80	2,71	2,89	2,78	2,65	2,48	2,40	2,40	2,62	2,81	2,84	2,87	2,69
	c (m/s)	4,20	4,40	4,98	4,95	4,62	4,48	4,51	3,86	3,73	4,37	4,10	3,97	4,35

5.4 Probability density and cumulative distribution functions

The annual probability density function and cumulative distribution function of wind speed for the four studied sites by using the Weibull distribution function are illustrated in Figures 5 and 6. Figure 5 shows that the most frequent wind speed expected in Dhahran, Jeddah, Al-Hofuf and Rafha are 5 m/s, 4.5 m/s, 4.5 m/s and 3.5 m/s respectively. It can be concluded that the highest spread of wind speed toward high wind speed is registered in Dhahran city.

It can be observed from Figure 6 that the frequencies of wind speed more or equal to the cut-in wind speed, 2.5 m/s in Dhahran, Jeddah, Al-Hofuf and Rafha are 98%, 93.5%, 91% and 93% respectively, while for a wind speed equal to or greater than 4 m/s, the frequencies in Dhahran, Jeddah, Al-Hofuf and Rafha are 56 %, 47 %, 51 % and 42 % respectively.

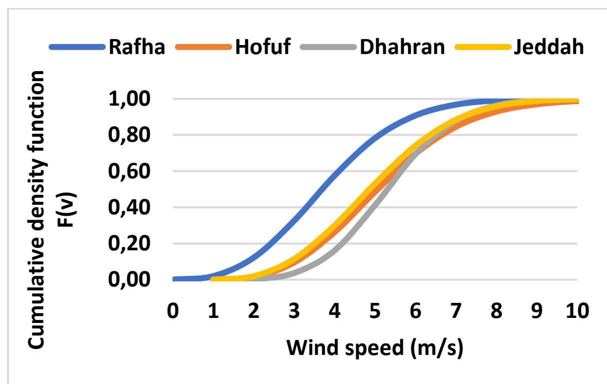

Figure 5 Cumulative density function of annual wind speed distribution of the fours studied sites

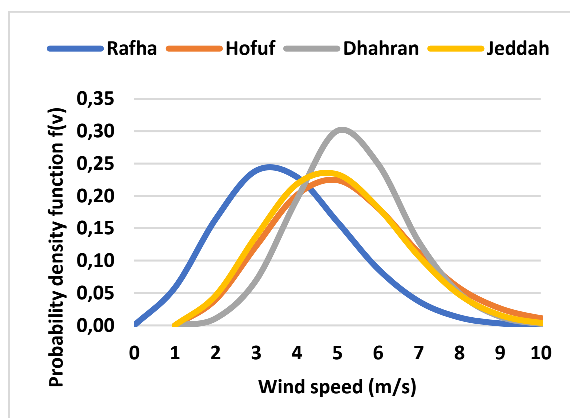

Figure 6 probability density function of annual wind speed distribution of the four studied sites

5.5 Power density and Energy density

The power density and energy density for the four studied sites are estimated by using Eqs. 13 and 14. Figures 7 and 8 illustrate the values of power density and energy density for the studied sites at 10 m height. The power density in Dhahran city varies between 36.75 W/m^2 in October and 119.48 W/m^2 in June, it varies between 30.43 W/m^2 in November and 50.88 W/m^2 in April in Jeddah city. In Al-Hofuf city, the power density ranges between 34.11 W/m^2 in October and 154.85 W/m^2 in June and it varies between 33.10 W/m^2 in September and 75.33 W/m^2 in March in Rafha. It can be noticed that the highest value of power density is registered in Al-Hofuf city in June while the lowest value is found in Jeddah in November. The mean monthly wind power density in Dhahran city falls into class 1 in all months except the month of June. Similarly, it falls into class 1 in Jeddah and Rafha for all months. For Al-Hofuf city, the mean monthly wind power density in Dhahran city falls into class 1 in all the months except the months of June and July. The mean monthly wind power density falls into class 2 in Dhahran city in June and in June and July in Al-Hofuf. It can be seen from Figure 8 that the highest value of energy density of 111.49 kWh/m^2 is registered in Al-Hofuf in June while the lowest value of energy density of 21.91 kWh/m^2 is obtained in Jeddah in November.

Figure 9 shows the mean annual power density and the mean annual energy density for the considered sites. The annual mean power density in Dhahran, Jeddah, Al-Hofuf and Rafha are 66.77 W/m^2, 43.58 W/m^2, 72.75 W/m^2 and 53.20 W/m^2 respectively. According to wind power classification (Table 2), the mean annual power density for the four studied sites falls into class 1 (PD ≤ 100 W/m^2). While, the annual mean energy density are 48.64 kWh/m^2, 31.79 kWh/m^2, 53 kWh/m^2 and 38.88 kWh/m^2 in Dhahran, Jeddah, Al-Hofuf and Rafha respectively.

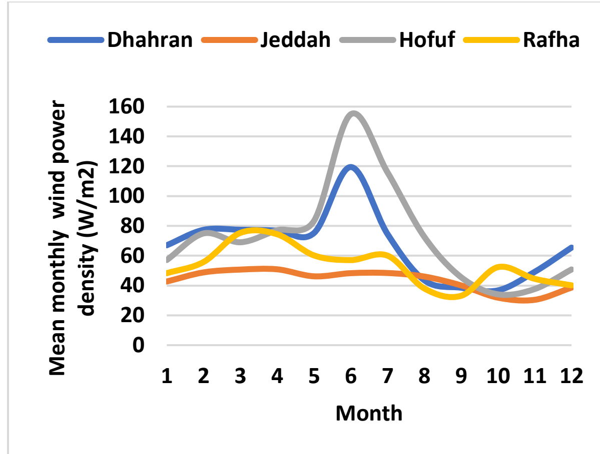

Figure 7 Mean monthly wind power density estimated by using Weibull distribution for the studied sites at 10 m height

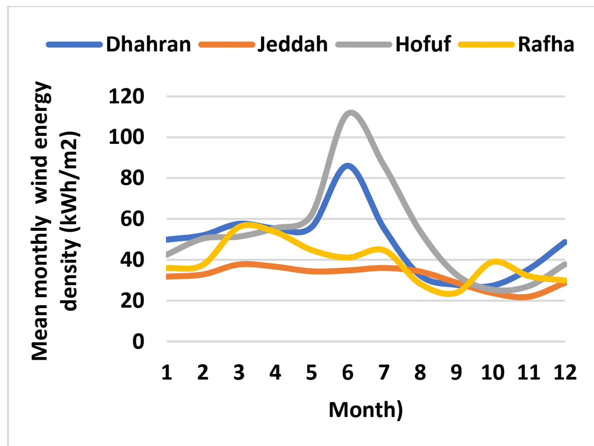

Figure 8 Mean monthly wind energy density estimated by using Weibull distribution for the studied sites at 10 m height

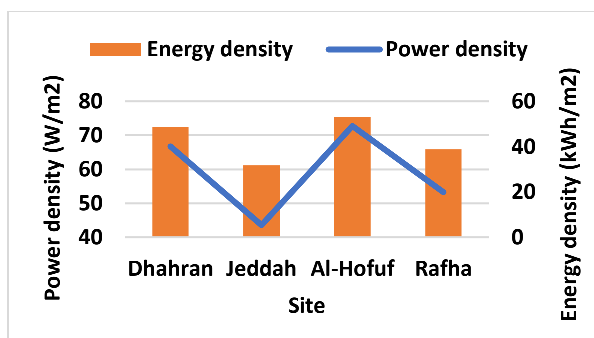

Figure 9 Annual mean power density for the considered sites at 10 m height

5.6 The most probable and most energy wind speed

Figure 10 depicts the mean monthly most probable wind speed for the studied sites. It varies between 1.71 m/s in October and 6.75 m/s in June in Dhahran city, while it ranges between 1.88 m/s in November and 2.26 m/s in August in Jeddah city. In Al-Hofuf city, The mean monthly most probable wind speed varies between 1.71 m/s in October and 2.88 m/s in June, while it varies between 1.71 m/s in September and 2.24 m/s in April in Rafah.

Figure 11 shows the mean monthly most energy wind speed for the studied sites. The mean monthly most energy wind speed varies between 4.40 m/s in October and 2.59 m/s in June in Dhahran city and between 5.08 m/s in November and 6.10 m/s in August in Jeddah city. For Al-Hofuf city, the mean monthly most probable wind speed ranges from 4.57 m/s in October to 7.85 m/s in June, while it varies between 1.71m/s in September and 6.02 m/s in April in Rafah. The highest value of wind speed carrying maximum energy of 7.85 m/s is recorded in Al-Hofuf city in June while the lowest value of 4.4 m/s is recorded in Dhahran city in October.

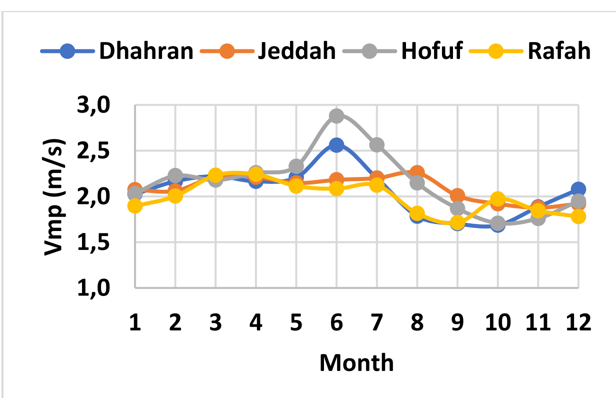

Figure 10 Mean monthly most probable wind speed for the studied sites

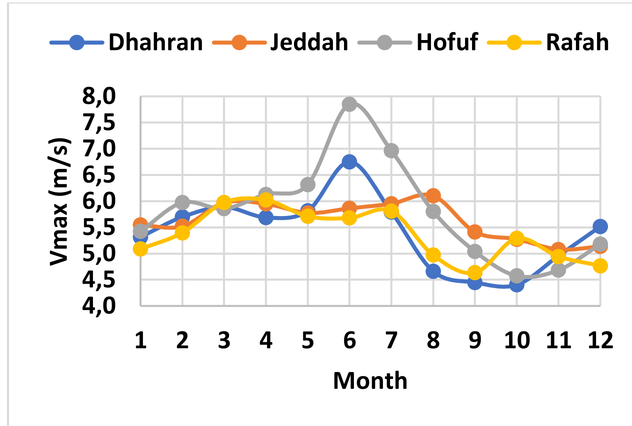

Figure 11 Mean monthly most energy wind speed for the studied sites

5.7 Extrapolation of wind speed at different heights

The extrapolation of wind speed at different heights (60 m, 90 m and 120 m) was estimated by using wind shear power law and is discussed in this part. Figure 12 displays the annual mean wind speed at 60 m, 90 m and 120 m. The results show that starting from a height of 60 m, values of annual mean wind speed become above 5 m/s for the four sites.

The highest annual mean wind speed at 60 m of 6.11 m/s is recorded in Dhahran city while the lowest value of 5.01 m/s is registered in Rafha city. At 90 m, Dhahran city has the highest annual wind speed of 6.6 m/s, while Rafha shows the lowest value of 5.31 m/s. A 120 m, The greatest annual wind speed of 6.97 m/s is registered in Dhahran city while the lowest of 5.54 m/s is obtained in Rafha city.

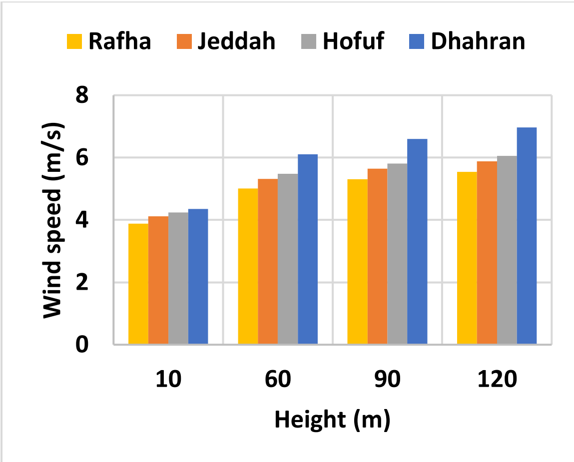

Figure 12 Annual mean wind speed extrapolated at different heights for the studied sites

5.8 Extrapolation of Weibull parameters at different heights

The extrapolation of Weibull parameters (shape and scale parameters) for the studied sites at different heights (60 m, 90 m and 120 m) are shown in Figures 13 and 14. The Weibull parameters, k and c, increase with the increasing of height. The highest values of shape parameter (4.93) and scale parameter (8.56 m/s) are both registered in Dhahran city at 120 m. However, the lowest values of shape of 3.44 and scale parameters of 7.90 m/s are recorded in Rafha city at 120 m. It can be seen that the shape and scale parameters increase with the heights.

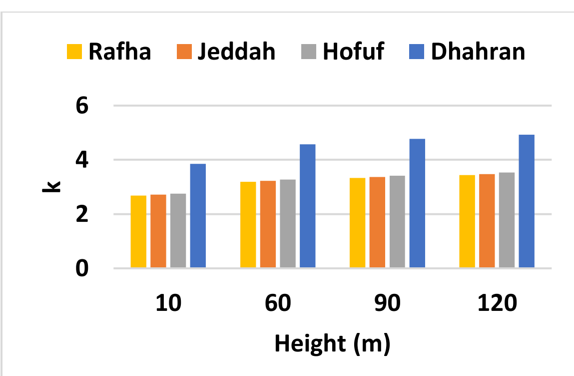

Figure 13 Extrapolation of shape parameter at different heights for the studied sites

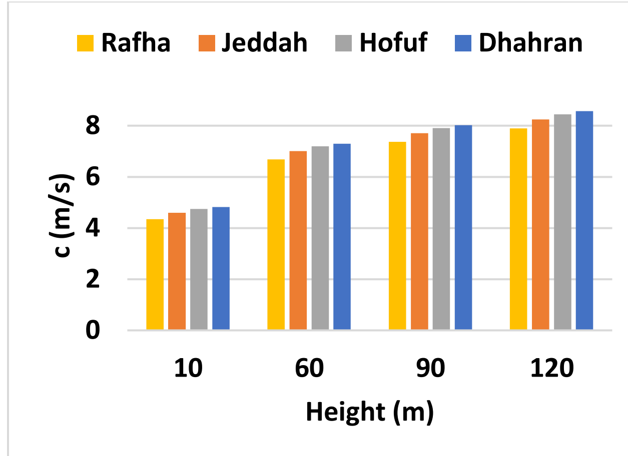

Figure 14 Extrapolation of scale parameter at different heights for the studied sites

6 Power density at different heights

The wind power density values at different heights for the studied sites are estimated in accordance with values of Weibull parameters (k and c) extrapolated at different heights.

The mean monthly wind power density value at heights of 60 m, 90 m and 120 m for the studied sites are illustrated in Figure 15. The wind power density in Rafha city increases from 52 W/m^2 to 281 W/m^2 and grows from 60 W/m^2 to 311 W/m^2 in Jeddah city as the height increases from 10 m to 120 m. Also, it increases from 70 W/m^2 to 347 W/m^2 in Al-Al-Hofuf city, while it extends from 64 W/m^2 to 337 W/m^2 in Dhahran city, as the height increases from 10 m to 120 m.

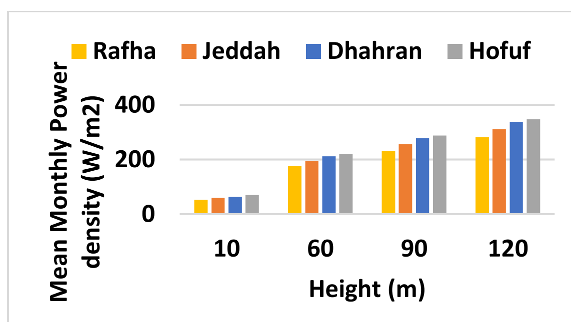

Figure 15 Mean monthly wind power values at different heights for the studied sites

5.9 Performance of some selected wind turbines

In order to study the performance of some wind turbine models in the studied sites, eight wind turbines models with different sizes ranging from 500 to 2000 KW have been selected. The characteristics of the selected wind turbine models are given in Table 5. An estimation of the capacity factor and the annual energy output based on Weibull parameters at the hub height of the selected wind turbine models have been carried out for all the studied sites.

Table 5 Characteristics of selected wind turbine models

	POLARIS P 50-500	POLARIS P 62-1000	Vergnet GEV HP 1000/62	ENERCON E-53	NEG NM 72/20G	STX 93-2MW	Gold-wind GW62/1200	Autoflug A 1200
Rated power (kW)	500	1000	1000	800	2000	2000	1200	1200
Hub height (m)	50	60	70	73	64	80	77	60
Rotor diameter (m)	50	62	62	52.9	72	93	62	62
Cut-in wind speed (m/s)	2.5	2.5	3	3	4	3	3	4
Rated wind speed (m/s)	12	12	15	12	14	11	12.5	13
Cut-out wind speed (m/s)	25	25	25	34	25	20	25	25

The mean annual energy output and the capacity factor of the selected wind turbine models for all the considered sites are illustrated in Figures 16 and 17. It can be observed that the highest annual energy output is obtained in all the studied sites by using the wind turbine model NEG NM 72/2000 among the selected wind turbine models. Figure 16 shows that Dhahran city has the highest mean annual energy output for all the selected wind turbine models among the studied sites. It ranges from 462 MWh/year with Polaris 50-500 to 4168 MWh/year with NEG NM 72/2000. It can be noticed that for Dhahran city:

- Among the 1 MW model wind turbines, the Vergnet 62 model generated the highest energy output of 1130 MWh/year, while the Polaris 1000 generated the least output energy of 1036 MWh/year. This obtained trend is linked to the cut-in speed (which is highest for the Vergnet 62 model, 3 m/s), the rated speed (which is highest for the Vergnet 62 model, 15 m/s), the hub height (which is highest for the Vergnet 62 model, 70 m) and the rotor diameter (the two models have the same rotor diameter, 62 m).
- However, among the 1200 kW model wind turbines, the highest energy output of 1848 MWh/year is obtained using the Autoflug A-1200 model and the least of 1604 MWh/year is acquired using the Gold-GW 62-1200 model. The Autoflug A-1200 has the highest cut-in speed (4 m/s) and rated speed (13 m/s) while, the Gold-GW 62-1200 model has the highest hub height (77 m). The two models have the same rotor diameter of 62 m.
- The NEG NM 72/2000 model produced the highest energy output (4168 MWh/year) among the 2 MW model wind turbines whereas the STX 23-2 model produced the least energy output (3003 MWh/year). The NEG NM 72/2000 model has the highest cut in speed (4 m/s), the highest rated speed (14 m/s) and the highest rotor diameter (72 m) while, the STX 23-2 model has the highest hub height (80 m).
- The energy output generated with the Enercon model (1068 MWh/year) is greater than the energy output generated with the Polaris 62-1000 (1036 MWh/year). The reason behind this is that the hub height of Enercon model (73 m) is higher than the hub height of Polaris 62-1000 (60 m).

In Al-Hofuf city, The annual energy output ranges from 434 MWh/year using Polaris P 50-500 model to 3963 MWh/year with NEG NM 72/2000 model. On the other hand, it ranges from 374 MWh/year using Polaris P 50-500 model to 3601 MWh/year with NEG NM 72/2000 model in Jeddah city. In Rafha city, The annual energy output varies from 310 MWh/year using Polaris P 50-500 model to 3145 MWh/year using NEG NM 72/2000.

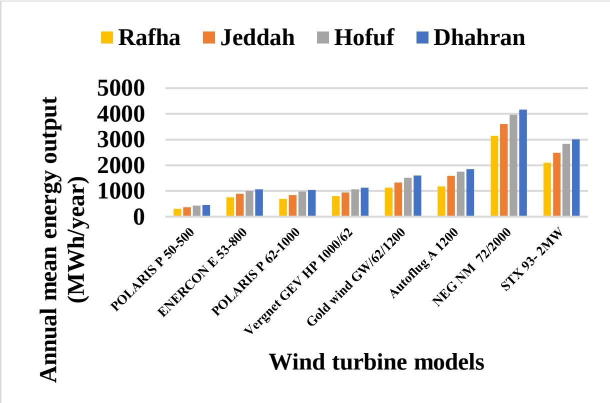

Figure 16 Mean Annual energy output produced from the selected wind turbine for all the studied sites

The capacity factor is used to estimate the cost effectiveness of a wind turbine. The cost of electricity generation by using wind turbine is inversely proportional to the capacity factor [17]. The NEG NM 72/2000 model has the highest values of capacity factor (more than 20%) among the considered wind turbine models for all the considered sites except for Rafha city. The Polaris P 50-500 model has the lowest values of capacity factor for all the studied sites except for Rafha city. The values of capacity factor using the NEG NM 72/2000 model are 18%, 20.5%, 22.6% and 24% for Rafha, Jeddah, Al-Hofuf and Dhahran, respectively. However, the values of capacity factor using the Polaris P50-500 model are 19%, 8.5%, 10% and 10.5% for Rafha, Jeddah, Al-Hofuf and Dhahran respectively.

The highest capacity factor of 24% for Dhahran city is obtained by using NEG NM 72/2000 model. This value is compliant with the recommended limitations prior to the consideration of a wind turbine investment. Therefore, it is recommended that the wind turbine model NEG NM 72/2000 model or similar will be adopted for electricity generation in Dhahran city. Values of capacity factor between 10% and 18% are obtained by using the wind turbine models Enercon E 53, STX 93-2000, Autoflug 1200 and Gold wind GW-62-1200. However, it varies between 9% and 13% using the Vergnet 1000-62 model.

Based on the obtained annual energy output and capacity factor, the following wind turbine design parameters are proposed to meet the minimum advisable capacity factor for electricity generation (25%): cut-in speed less than 4 m/s, rated speed around 14 m/s and minimum hub height and rotor dimeter of 64 m and 72 m, respectively. Whereas, the others considered wind turbine models or with similar designed characteristics are suggested for small scale applications such as water pumping for the four studied sites.

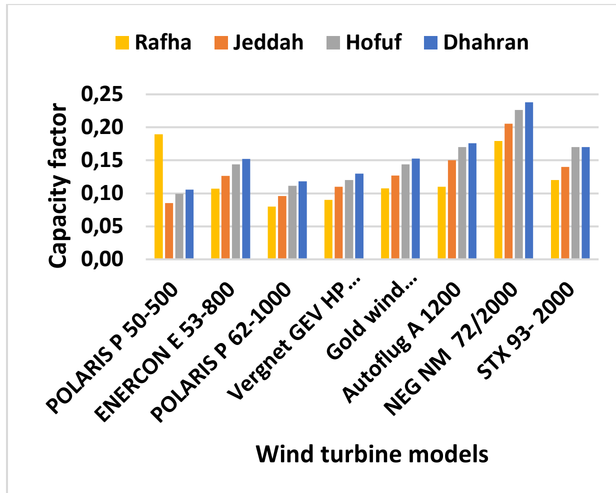

Figure 17 Capacity factor of the selected wind turbine for all the studied sites

6- Conclusions

Assessment of wind energy potential for wind turbine applications is conducted for four sites in Saudi Arabia. The sites involved in this study are: Dhahran, Al Al-Hofuf, Jeddah and Rafah. The most important findings in this research are summarized as follow:

- The annual mean wind speeds for Dhahran, Jeddah, Al-Hofuf and Rafha are 4.35 m/s, 4.12 m/s, 4.23 m/s and 3.86 m/s, respectively at 10 m AGL;
- The annual values of wind speed carrying the maximum energy for Dhahran, Jeddah, Al-Hofuf and Rafha are 5.41 m/s, 5.63 m/s, 5.82 m/s and 5.36 m/s, respectively;
- Based on the analysis of diurnal variation of wind speed for the four studied sites,

the daytime is evaluated as windy while the nighttime is quiet.

- The mean annual values of Weibull shape parameters vary between 2.69 in Rafha city and 3.85 in Dhahran city;
- The annual values of Weibull scale parameters vary between 4.35 m/s in Rafha city and 4.82 m/s in Dhahran city;
- The values of mean monthly wind energy density at 10 m height for Dhahran, Jeddah, Al-Hofuf and Rafha are 66.77 W/m^2, 43 W/m^2, 73 W/m^2 and 53 W/m^2 respectively. According to Wind Classification, all the studied sites fall under class 1.
- The mean monthly power density for Dhahran varies between 37 W/m^2 and 119 W/m^2. It varies between 30 W/m^2 and 51 W/m^2 in Jeddah city. For Al Al-Hofuf, it ranges between 34 W/m^2 and 155 W/m^2, and between 33 W/m^2 and 75 W/m^2 in Rafha city. Based on the monthly wind power density, Dhahran and Jeddah fall under class 2 for some months.
- The extrapolation of wind speed at different heights (60 m, 90 m and 120 m) shows that the values of annual mean wind speed in all four sites are above 5m/s starting from the height of 60 m.
- The analysis of power density at different heights show that Dhahran city has the highest range of wind variation with respect to the other sites. As the height increases from 10 m to 120 m, the wind power density rises from 64 W/m^2 to 337 W/m^2.
- Based on the obtained annual energy output and capacity factor, the following wind turbine design parameters are proposed to meet the minimum advisable capacity factor for electricity generation (25%): cut-in speed less than 4 m/s, rated speed around14 m/s and minimum hub height and rotor dimeter of 64 m and 72 m, respectively.

Data Availability

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.
The wind speed data analyzed during this study are described in the following metadata record: https://www.timeanddate.com/

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