Journal of Engg. Research Vol. 11 No.(1B) pp.349-361 **DOI:10.36909/jer.18167**

The potential of wind energy in Kuwait: a complete feasibility investigation

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Submitted: 03-05-2022

Revised: 19-08-2022

Accepted: 04-09-2022

ABSTRACT

Wind turbines, Onshore and offshore wind energies, Weibull shape parameter, Wind farms.

INTRODUCTION

In 1938, oil is discovered in Kuwait and remained the main source of the capital income. The quick development of industrial and urban sectors necessitates the expansion of electrical power production (Alam, 2022). The first electric power plant is built in 1934 of a capacity of 60 kW (Al-Nassar, 2005), and the capacity reaches 18.8 GW in 2017 produced in seven power plants (Statistical year book, 2017). The power plant capacity is increased significantly since 1992 to accommodate almost a linear growth of electrical power consumption. In the year 2017, 48.5 million barrels of heavy oil and 378.5 Bcf of natural gas were consumed (Statistical year book, 2017). Due to the high consumption rate of fuel in the power plants, these plants are considered as the main source of pollution in Kuwait (Ettouney et al., 2010). In the Alzour steam power plant only, eight steam turbines consume 281.34 tons/hour of heavy oil and emit 1563 g/s of SO_2 and 480.3 g/s of NOx (Ramadan, 2008). As the trend of electric power consumption continues to increase in future, the locally produced natural gas and heavy oil will not be enough to cover the power plants demand for fuel in next ten years, and the level of toxic gases nearby the residential areas will reach dangerous levels. Therefore, the need of other sources of energy becomes a vital. Producing energy from wind and solar, are proven to be successful to satisfy long-term demand for energy. However, they are not effectively utilized in Kuwait. Currently, there are few experimental sites for evaluating the potential of wind and solar energies, with no large-scale energy production facilities.

Energy prospectors and national governments are seeking to diversify the energy resources, reduce air pollution, and protect the economy from unstable crude oil prices. Wind energy is an attractive source of renewable energy and growing at a high rate (Murthy and Rahi, 2017). Since 2009, the annual average market grew by about 10% to just under 45 GW, and the cumulative market growth is almost 19%. In beginning of 2018, the total wind power capacity in the world is 539.1 GW of wind power (Global wind report 2017). Increasing awareness of the economic and environmental benefits of wind energy leads to significant growth utilization of wind power since 1996. By the end of the year 2020, it is anticipated that wind power capacity will reach 639.5 GW of (Global wind energy outlook 2016) to become the third largest source of electricity after thermal and hydropower. Asia continues to be the world's largest regional market for wind energy, and 15 GW of wind capacity is added every year. China has increased its total capacity from 25.8 GW in 2009 to 188.4 GW in 2017. USA has increased its wind power capacity to reach 89.1 GW in 2017. In 2017, a study from the European Wind Energy Association (EWEA) indicate that total capacity of wind turbines is 111.4 GW in the European Union. Germany has the total wind capacity of 56.1 GW and then Spain that has 23.2 GW. Brazil's national energy planning agency (EPE) is planning to install 1.4 GW wind power capacity each year from 2013 to reach 16 GW by year 2018. China is leading the in the total wind energy by 35%, followed by the USA by 17% (Global wind report 2017).

In the State of Qatar, Al-Marri et al. (2018) investigation indicates that energy effect use is significant through learning to promote performance improvement. In Jordan (Ammari et al., 2015), the assessment of wind energy at five regions is presented with wind turbines power of 100 kW to 3000 kW. The analysis indicates that the Aqaba Airport area provides the maximum energy output, while Queen Alia Airport provides the minimum energy output. Additionally, frequency stability analysis for using PV cells with wind power plants is accomplished by Feilat et al. (2018). The results show that grid frequency stability is achieved if the percentage of the renewable energy accounts up to 40% of the total energy produced. For a wind farm close to islands, research accomplished by Argueso and Businger (2018) for the island of Hawaii indicated that the areas with the largest and consistent capacity factor values are in corners of the island. The wind energy features in Shark El-Ouinat city in Egypt is presented by Ahmed (2018). The study shows that the electrical energy is at a yearly rate of 730,791 MWh and the capacity factor is 56%. Chancham et al. (2017) presents the offshore wind resource evaluation in Thailand. The average wind speed is between of 5.5 and 6.5 m/s, and the capacity of the wind turbines is between 3.3 and 8.0 MW. In Kuwait, wind energy potential at coastal and offshore locations is investigated by Alkhalidi et al. (2019) for selecting the suitable and attractive site for offshore windmills in.

In this paper, the potential of wind energy generated in wind farms in four locations is statically predicated and assessed. Three of these stations are onshore and one offshore. The average speed from four weather stations in Kuwait from 2009 to 2017 is adopted in the investigation. The dimensionless Weibull shape, scale parameters, the maximum annual value for shape parameter, the maximum annual value for scale parameter, and wind power density are measured to determine the best location for the wind energy site.

MATHEMATICAL ANALYSIS

The wind speed in a certain region is the most important factor on wind energy potential predication, as well as in determining the effectiveness of wind energy systems. To model the wind speed frequency curve, the probability density functions can be considered. Such as Weibull distribution and Rayleigh probability density (Ucar et al., 2008). The Weibull has two distribution parameters, while the Rayleigh has only one. The Weibull distribution function can be expressed as (Chen et al., 2018):

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

Where (v) is the wind speed, (c) is the Weibull scale parameter, and (k) is the Weibull shape parameter. The cumulative probability function of the Weibull distribution can be expressed as:

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^k} \tag{2}$$

The Weibull shape and scale parameters, (k) and (c), can be determined by many methods. In this research, the average wind speed-standard deviation technique is considered (Jowder, 2009), and the expression for Weibull shape and scale parameters are, respectively:

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad \text{for} \quad (1 \le k \le 10) \tag{3}$$

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

Where (σ) is the standard deviation, ($\bar{v}$) is the average wind velocity, and (Γ) is the gamma function, and they are defined as, respectively (Mostrafaeipour et al., 2011)

$$\sigma = \left(\frac{1}{n-1}\sum_{i-1}^{n}(v_i - \bar{v})^2\right)^{1/2} \tag{4}$$

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{5}$$

$$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt \tag{6}$$

Where (n) is the number of data set in a specific period. The wind power density, the energy of the wind, can be estimated using the average wind velocity, as follows (Boudia et al., 2016):

$$P_w(\bar{v}) = \frac{1}{2}\rho\bar{v}^3 \tag{7}$$

or using the Weibull probability density function, as follows:

$$P_w(\bar{v}) = \frac{1}{2}\rho\bar{v}^3 \frac{\Gamma(1+\frac{3}{k})}{(\Gamma\left(1+\frac{1}{k}\right))^3} \tag{8}$$

To determine wind speed at different elevations, wind speed data can be extrapolated using the following power law formula (Ucar and Balo, 2009):

$$\frac{v_1}{v_2} = \left(\frac{h_1}{h_2}\right)^\alpha \tag{9}$$

Where (α) is the roughness factor, commonly in the range between 0.05 and 0.5 depending on the surface roughness (Li and Yu, 2018). In this research, a value of 1/7 is adopted in the present research because it is for low surface roughness sites (Lashin and Shata, 2012). The rated power is power generated by the turbine based on the rated wind speed. The rates of power can be expressed as (Jangamshtti and Rau, 2001):

$$P_R = \frac{1}{2}\rho\ A\ C_p\ \eta_{me}\ \eta_{el}\ v_R^3 \tag{10}$$

Where (ρ) is air density, (A) is rotor disk area, (C_p) is the coefficient of performance of the turbine. (η_{me}) and (η_{el}) are the efficiencies of the mechanical electrical systems, respectively. (v) is the wind velocity. The actual power output depends on the cut-in, (v_c), rated, (v_R), and cut-out wind speed, (v_f), and can be expressed as (Jangamshtti and Rau, 1999):

$$P_A(v) = \begin{cases} 0 & : \quad v < v_c \\ \frac{1}{2}\rho\ A\ C_p\ \eta_{me}\ \eta_{el}\ v^3 & : v_c \le v \le v_R \\ \frac{1}{2}\rho\ A\ C_p\ \eta_{me}\ \eta_{el}\ v_R^3 & : v_R \le v \le v_f \\ 0 & : \quad v > v_f \end{cases} \tag{11}$$

The average actual power output is obtained by adding the multiplication of the actual power output to the probability of wind speed. overall possible wind speed is obtained by Integrating the average actual power output (Dupont et al., 2018), as follows:

$$P_{A,ave} = \int_0^\infty P_A(v)\cdot f(v)dv \tag{12}$$

The CF is significant in assessing the productivity of a wind turbine. The CF is the ratio of the average actual power output to the rated power output (Chang, 2003), as follows:

$$CF = \frac{P_{A,ave}}{P_R} \tag{13}$$

Substituting equations (10) and (12) in to (13), the (CF) can be determined as follows (Salameh and Safari, 1995)

$$CF = \frac{1}{P_R}\int_{v_c}^{v_R} P_A(v)\cdot f(v)dv + \int_{v_R}^{v_f} f(v)dv \tag{14}$$

The capacity factor can then be expressed as:

$$CF = \frac{1}{v_R{}^3} \int_{v_c}^{v_R} v^3 \cdot f(v) dv + \int_{v_R}^{v_f} f(v) dv \qquad (15)$$

Equation (15) can be analytically integrated and simplified as (Jangamshtti and Rau, 1999):

$$CF = \left(\frac{v_c}{v_R}\right)^3 e^{-\left(\frac{v_c}{c}\right)^k} + \frac{3\,\Gamma\left(\frac{3}{k}\right)}{k\left(\frac{v_R}{c}\right)^3} \left[\gamma\left(\left(\frac{v_R}{c}\right)^k, \frac{3}{k}\right) - \gamma\left(\left(\frac{v_c}{c}\right)^k, \frac{3}{k}\right)\right] - e^{-\left(\frac{v_f}{c}\right)^k} \qquad (16)$$

MONTHLY WIND SPEED DATA

The behavior of wind speed at a site depends on altitude, month, and hours of measurement. The wind speed is hourly measured by Directorate General of Civil Aviation, State of Kuwait, for a period between 2008 and 2017 at four stations. The locations of the stations are illustrated in Fig. 1. All measurements are taken a height of 10 meters above the ground level. The geographical coordinates of the stations are listed in Table 1. The monthly and yearly averages of the wind speed are listed in Table 2.

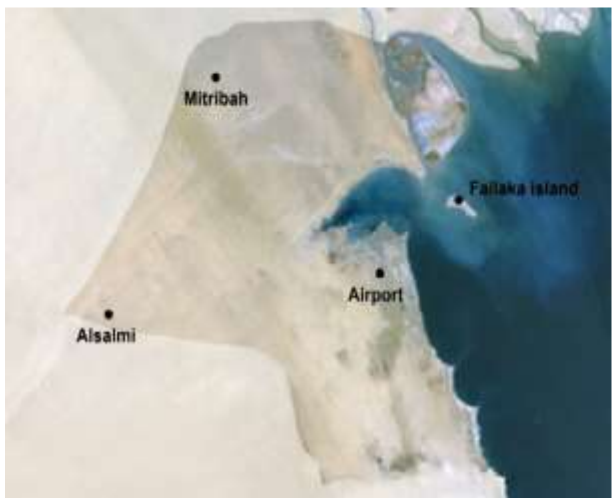


Figure 1. Weather stations selected in this study.

Table 1. Geographical coordinate stations used in the study.

No.	WMO No.	Station	Elevation (m)	Longitude	Latitude
1	40551	Miribah	118.06	47° 21' 35"	29° 36' 35"
2	40570	Alsalmi	288.09	46° 40' 54"	29° 06' 04"
3	40582	Airport	46.2	47° 57' 58"	29° 13' 19"
4	40588	Failaka Island	5.71	48° 19' 58"	29° 26' 56"

The Table 2 also shows the monthly variations of the shape and scale Weibull parameters, k and c. The maximum value of monthly average wind speed is 7.49 m/s at the Miribah station and in June, and a minimum value of monthly average wind speed is 3.32 m/s and at the Airport station in December. As shown in the table, the Weibull shape parameter, k, varies between 1.99 and 4.76. The Weibull scale parameter is varying between 3.74 and 8.35 m/s. The minimum shape and scale parameters occur in the Airport in December. Additionally, the Table indicates that the

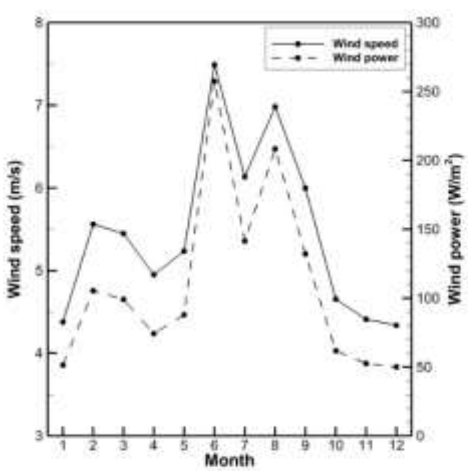
Miribah station shows the highest average wind speed, while the Airport station shows the lowest. Fig. 2 shows the monthly variations of the average wind speed and wind power for the selected four stations. The highest recorded wind power density is 257.36 W/m^2 and it occurs in June at the Miribah station. For other stations, the power density curves have similar changing trends, and the average monthly wind speed and power density are varying insignificantly in the Failaka island.

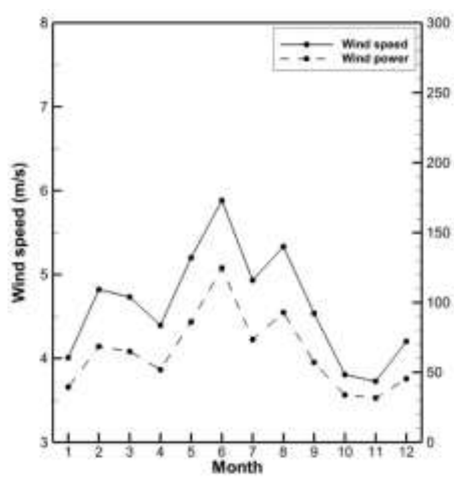
Table 2. Monthly average of the wind speed and Weibull parameters at 10 m elevation.

Month		Miribah	Alsalmi	Airport	Failaka Island
January	Speed (m/s)	4.38	4.01	3.60	4.40
	k	3.67	2.90	2.40	2.86
	c (m/s)	4.85	4.50	4.06	4.93
February	Speed (m/s)	5.56	4.82	4.68	5.38
	k	3.63	3.68	2.55	3.00
	c (m/s)	6.17	5.34	5.28	6.03
March	Speed (m/s)	5.45	4.73	4.71	5.23
	k	3.19	2.92	2.27	2.49
	c (m/s)	6.08	5.31	5.32	5.89
April	Speed (m/s)	4.95	4.39	3.76	4.30
	k	4.47	3.41	3.18	4.76
	c (m/s)	5.43	4.89	4.20	4.70
May	Speed (m/s)	5.24	5.20	4.41	4.45
	k	3.64	3.62	3.21	3.85
	c (m/s)	5.81	5.77	4.92	4.93
June	Speed (m/s)	7.49	5.88	6.08	5.62
	k	3.30	2.97	2.74	2.78
	c (m/s)	8.35	6.59	6.84	6.31
July	Speed (m/s)	6.14	4.93	4.78	4.78
	k	2.57	2.54	2.06	2.78
	c (m/s)	6.91	5.56	5.40	5.37

August	Speed (m/s)	6.98	5.33	5.84	5.36
	k	2.86	2.64	2.57	3.40
	c (m/s)	7.83	6.00	6.57	5.96
September	Speed (m/s)	6.00	4.54	4.45	4.52
	k	3.50	3.11	2.64	3.77
	c (m/s)	6.66	5.07	5.01	5.00
October	Speed (m/s)	4.65	3.81	3.44	4.18
	k	4.17	4.04	3.16	3.42
	c (m/s)	5.12	4.20	3.85	4.65
November	Speed (m/s)	4.41	3.73	3.48	4.74
	k	4.58	3.14	2.86	3.20
	c (m/s)	4.83	4.16	3.91	5.29
December	Speed (m/s)	4.34	4.20	3.32	4.38
	k	3.00	3.25	1.99	2.94
	c (m/s)	4.86	4.69	3.74	4.91

On the other hand, offshore wind power turbine has the potential for solving the major problems associated with climate change (Satir et al, 2018). The wind speed with respect to its direction is required to evaluate the wind energy potential. The relative frequencies of wind directions for the selected four stations are presented in Fig. 3. As shown, the main prevailing wind at all station is north-north-western, and the wind direction in all stations is south only for the month of September.





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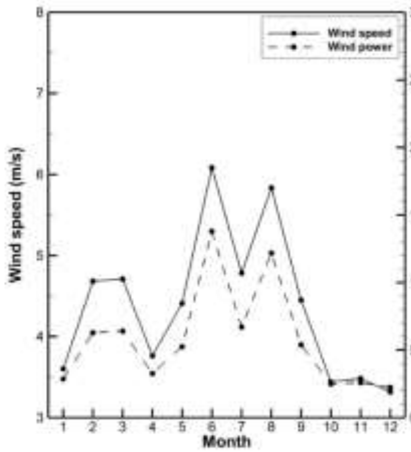

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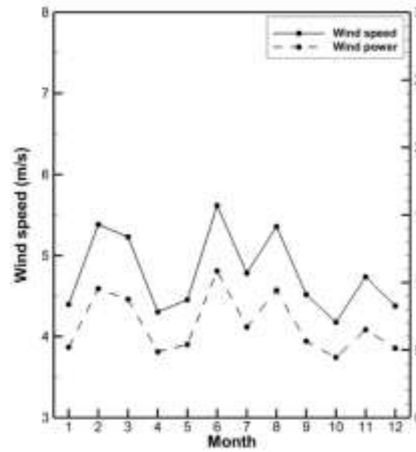


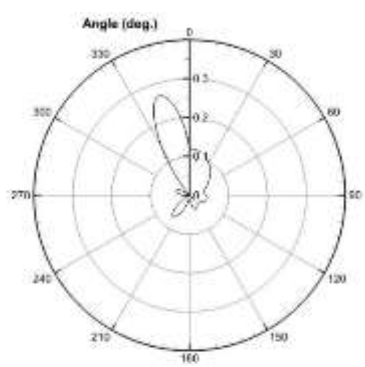
(d)

Figure 2. Monthly variation of average wind speed and wind power density for four stations: a) Miribah, b) Alsalmi, c) Airport, and Failaka island.

PROBABILITY DENSITY FUNCTION

The estimated yearly Weibull frequency distribution of wind speed of the four stations is shown in Fig. 4. In general, the Weibull frequency distribution predicts the actual wind frequency. The mathematical expression of Weibull distribution produces zero probability for zero wind speed, and the highest frequencies are changed toward the greater values of average velocity. For instance, the Miribah station has the maximum annual average wind speed of 5.46 m/s, and peak frequency of 22.9%, while the Airport station has a minimum annual wind speed of 4.38 m/s and peak frequency of 21.3%. Additionally, the figures indicate that at the Miribah station, the wind speed remains above 3.5 m/s for 84.15% of the time, and since the cut-in-speed of a typical wind turbine is around 3.5 m/s, a wind turbine can produce electrical power for this percentage. On the other hand, for the Alsalmi, the percentage is 71.15%, while 72.26% and 59.23% for the Failaka island and the Airport, respectively.

(a)



(b)

(c)

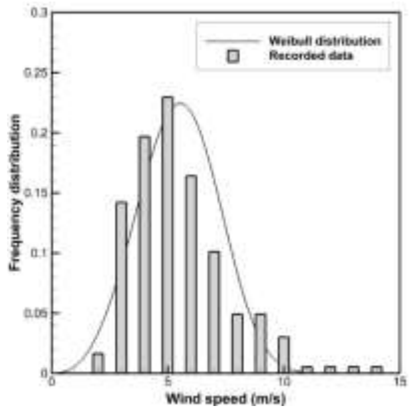
(d)

Figure 3. Frequency of wind direction at station: a) Miribah, b) Alsalmi, c) Airport, and Failaka island.

Table 3. NREL wind power classification for 50 m elevation.

Wind power class	Resource potential	Wind power density (W/m^2)	Wind speed (m/s)
1	Poor	0-200	0.0-6.0
2	Marginal	200-300	6.0-6.8
3	Fair	300-400	6.8-7.5
4	Good	400-500	7.5-8.1
5	Excellent	500-600	8.1-8.6
6	Outstanding	600-800	8.6-9.5
7	Superb	>800	>9.5

Wind energy in a site is classified according to the wind power density in that site at a particular height, and there are several classifications proposed by wind power agencies. The European Wind Energy Association, EWEA (Annual report, 2017), classifies wind power into three categories, fairly good, good, and very good. National Renewable Energy Laboratory, NREL (Wind Research, 2017), proposes a wider range of wind power classification into seven categories from poor (class 1) to superb (class 7). Table 3 shows the NREL wind power classification for 50 m elevation. Fig. 5 shows the changes in monthly average wind power at heights 25, 50, and 100 m at the four selected stations, respectively. For instance, at the Miribah station at a height of 100 m, the monthly average wind power is 690.43 W/m^2. Additionally, the yearly average wind power is 295.45 W/m^2 at 100 m height. According to EWEA classification, the Alsalmi, the Airport, and the Failaka island are not a favorable location for wind turbine location, while the Miribah is fairly good. Based on NREL classification, Miribah is categorized as good/excellent location, while other three locations are almost marginal. Clearly, the Alsalmi, Airport, and Failaka island are not suitable locations to establish a large-scale wind farm. However, for a small-scale wind farm, these locations are acceptable.



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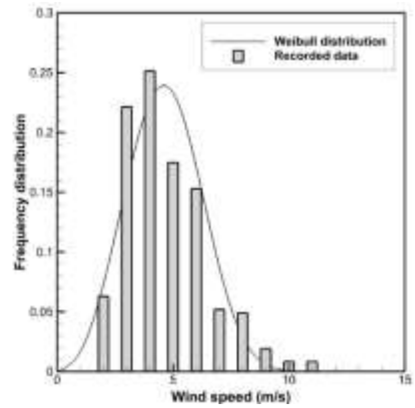

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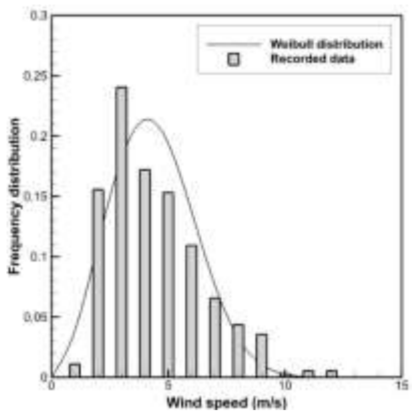

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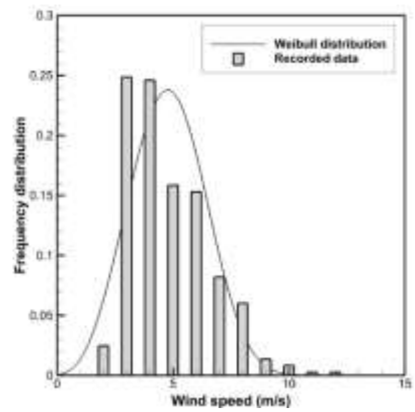

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Figure 4. Annual frequency distributions of wind speed using Weibull and recorded data for station: a) Miribah, b) Alsalmi, c) Airport, and Failaka island.

CAPACITY FACTOR

The monthly and yearly variations of a capacity factor are calculated to obtain the optimum selection of the wind turbine. The CF is obtained using equation (13), where (ρ) is air density and equal to 1.225 kg/m^3. The cut-in, rated, and cut-out, velocity is obtained from five difference turbines for each of the six rated powers: 0.5, 0.75, 1.0, 1.5, 2.0, and 3.0 MW. The manufactured are Neg Micin, NedWind, Wind World, Ventis, Nordtank, Emergya, Lagerwey, Seawind, Sudwind, AAER, AN Bonus, Nordic, WinWinD, Dewind, Nordex, Repower, Tacke, United Power, and Vensys. The wind turbine characteristics are obtained from (www.wind-turbine-models.com). The objective of the following analyses is to determine the most efficient rated power turbine for each site. In general, the capacity factor is increased as the rated power increases in all sites. For example, in the Alsalmi site, the 0.5 MW turbine provides the capacity factor of around 0.1, while the 3.0 MW turbine provides the capacity factor of around 0.25. Additionally, characteristics of the wind turbine have a significant effect on the capacity factor.

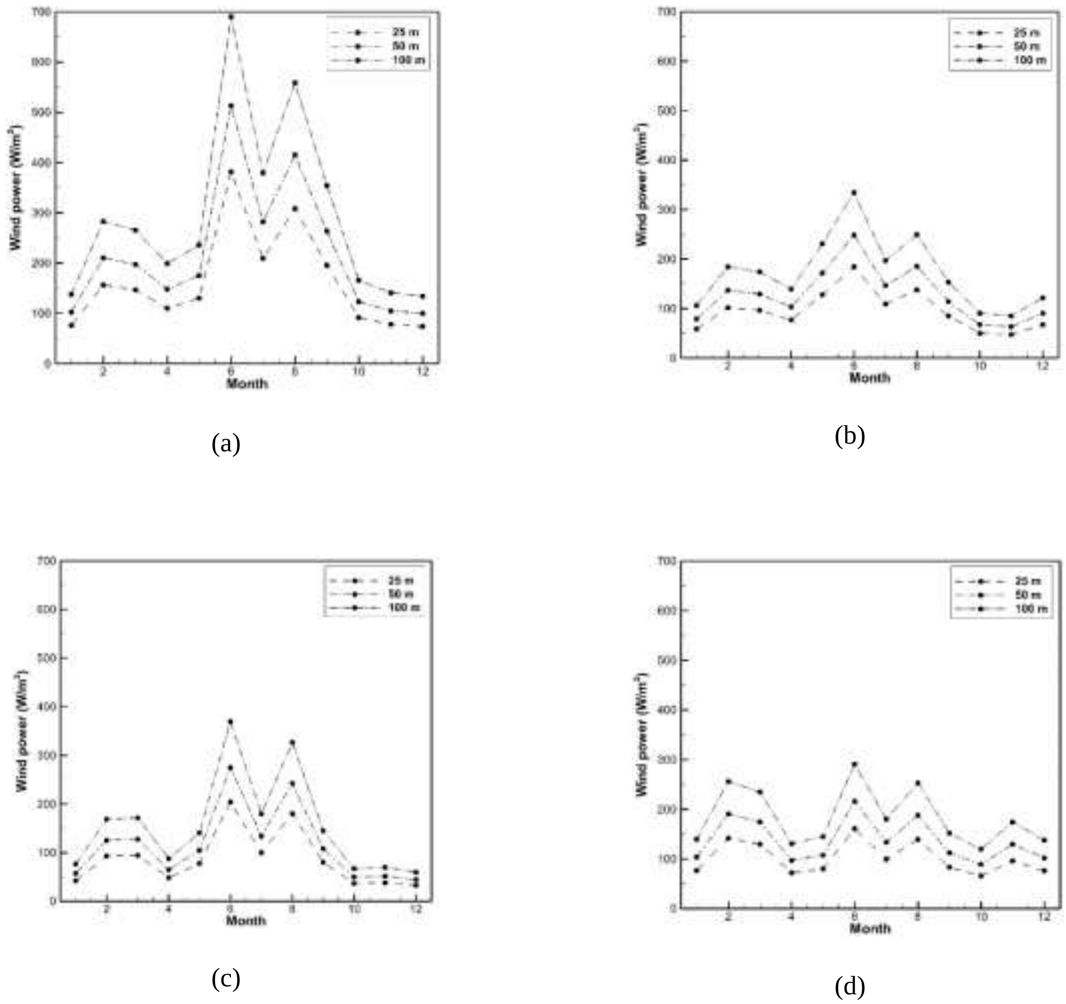

Figure 5. Monthly average wind power at height 25, 50, and 100 m at station: a) Miribah, b) Alsalmi, c) Airport, and Failaka island.

A turbine with high rotor height, low cut-in, and rated speed would definitely produce a higher capacity factor. For example, in the Filaka island and using 1.0 MW turbine, the A-1000/S turbine by AAER has a capacity factor of just 0.106, while the D6/62-1000 turbine from Dewind has a capacity factor of 0.25. The Miribah site shows highest capacity factor for all rated turbine powers, while the Airport site shows the lowest. Additionally, the maximum possible capacity factor is 0.44 and obtained in Miribah site using either 1.5 MW rated power turbine, United Power UP1500-86, or 3.0 MW rated power turbine, Swiss electric YZ115/3.0. For any turbine rated power, the Miribah site provides the highest capacity factor, and therefore it is the best site for a wind farm.

YEARLY WIND OUTPUT ENERGY

Wind energy estimations are calculated using six wind turbines with a rated power of 0.5, 0.75, 1.0, 1.5, 2.0, and 3.0 MW. The site and supplier selections for each rated power are based on the capacity factor analysis in the previous section. The site is the Miribah, and the suppliers and models are Micin M 1500-500 for 0.5 MW, LW Lagerwey 50/750 for 0.75 MW, Dewind D6/62-1000 for 1.0 MW, United Power UP1500-86 for 1.5 MW, Dewind D9.0 for 2.0 MW, and Swiss Electric YZ115/3.0 for 3.0 MW. The Miribah site is the best, and these turbines performed the best on their corresponding rated power. The rotor height varies between 56.5 and 115 m, cut-in speed varies between 1.8 and 3.0 m/s, and the rated speed varies between 10 and 13.5 m/s. The output energy is calculated and presented in Figure 6. As wind turbine rated power increases, the yearly output power is increased, but the relation is not linearly proportional. It is noticeable that the maximum yearly output energy of 11.71 GW-h can be produced by a 3.0 MW wind turbine (Swiss Electric YZ115/3.0), while the minimum yearly output energy of 1.003 GW-h can be produced by a wind turbine with a rated power of 0.5 MW (Micin M 1500-500). One can observe that the 2.0 MW wind turbine (Dewind D9.0) can produce slightly more power than the 1.5 MW turbine (United Power UP1500-86), just 6.9% more. Although the rotor height of the 2.0 MW turbine is higher than the 1.5 MW turbine by 20 m, the rated speed of the 1.5 MW turbine is less than the 2.0 MW, which makes the capacity factor close to each other. Changing the rated power from 2 MW to 3 MW, almost double the yearly output power from 6.22 GW-h to 11.71 GW-h.

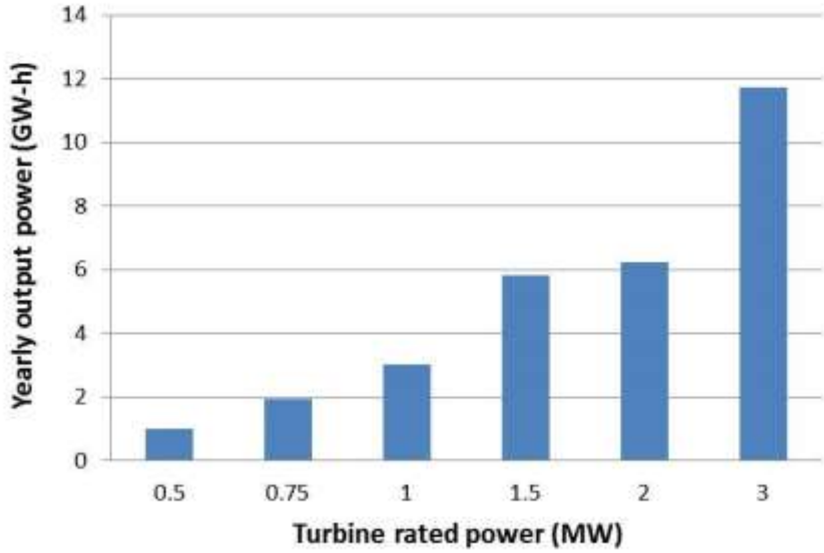

Figure 6. The yearly output power for site of Miribah for different wind turbine rated power.

CONCLUSIONS

A predication of wind energy generated in four sites in Kuwait is statically investigated. The average wind speed from four weather stations in the one-hour interval from 2009 to 2017 is adopted in the investigation. The numerical value of the dimensionless Weibull shape and scale parameters is determined, and the maximum annual value for shape parameter is 4.76, and the maximum annual value for scale parameter is 8.35 m/s. The highest recorded monthly wind power density is 257.36 W/m^2. Changing the rated power from 2 MW to 3 MW, almost double the yearly output power from 6.22 GW-h to 11.71 GW-h. The maximum yearly output energy of 11.71 GW-h can be produced by a wind turbine with a rated power of 3.0 MW. According to EWEA classification, the Alsalmi, the Airport, and the Failaka island are not a favorable location for wind turbine location, while the Miribah is fairly good.

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