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Assessment of wind energy potential for coastal locations of the Kingdom of Saudi Arabia

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Abstract

This paper presents the wind data analysis for five coastal locations of the Kingdom of Saudi Arabia, namely Dhahran, Yanbo, Al-Wajh, Jeddah, and Gizan. The data analysis utilized hourly mean values of wind speed and wind direction covering a period of almost 14 years between 1970 and 1983. The data were validated in terms of completeness, continuity, erroneous values, etc. The analyses include seasonal and diurnal changes in wind speed values. Energy calculations and capacity factors were also determined for wind machines of different sizes between 150 and 2500 kW. It was found that Yanbo is the best location, among the sites analyzed, for harnessing the power of wind, while Dhahran is the next best location. The other three locations were found to have more or less the same results.

1. Introduction

Wind energy is clean, abundant, affordable, inexhaustible, environmentally preferable, and elegant. Wind energy is the fastest growing source of energy of the 1990s and is getting worldwide attention due to the latest technology for harnessing it and its competitive cost of production compared to other traditional means. Wind power utilization is the answer to environmental and climate change problems and also a means of conserving the conventional sources of energy. For example, a single 750 kW wind machine operated for one year at a site

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with an average wind speed of 5.76 m/s at 10 m is expected to displace a total of 1179 tons of CO_2, 6.9 tons of SO_2 and 4.3 tons of NO_2 based on the US average utility fuel mix [1].

The worldwide wind power installed capacity is increasing rapidly due to new projects being commissioned in different parts of the world. As per a literature review [2], Germany is leading the world with a total installed capacity of 12,001 MW by the end of 2002, while Spain, US, Denmark and India rank second, third, fourth and fifth with installed capacities of 4830, 4685, 2880 and 1702 MW, respectively. The Middle East, Iran, Egypt, Morocco and Jordan have a total of 192 MW wind power installed capacity. Saudi Arabia, with vast open flat land and low population density, offers excellent opportunities for harnessing the power of wind and joins the group of wind power producing countries.

For proper and beneficial development of wind power at any location, wind data analysis and accurate wind energy potential assessment are key requirements. Ansari et al. [3] used hourly mean wind speed data and developed a wind atlas in 1986. This atlas provides contours of wind speed, monthly values and information on prevailing wind direction. In Saudi Arabia, more attention was paid to solar energy related work like the establishment of solar radiation and sunshine duration recording stations, a photovoltaic electric generation facility to supply power to a village on the outskirts of the capital city Riyadh, usage of water heaters in housing complexes, photovoltaic cells to supply energy to highway telephones, remote monitoring facilities, and communication towers. Meteorological data collection stations were erected in the year 1970 throughout the kingdom in the vicinity of airports to get weather related information.

In recent years, work on wind speed data analysis such as Weibull parameter determination and distribution, wind speed prediction using different methods such as auto-regression and neural networks, wind power generation cost determination, and so on has been reported in the literature. Rehman et al. [4] calculated the Weibull parameters for 10 anemometer locations in Saudi Arabia and found that the wind speed was well represented by the Weibull distribution function. Rehman and Halawani [5] presented the statistical characteristics of wind speed and diurnal variation. The auto-correlation coefficients were found to match the actual diurnal variation of the hourly mean wind speed for most of the locations used in the study. Mohandes et al. [6] used a neural networks method for the prediction of daily mean values of wind speed ahead of time. They concluded that the performance of the neural network model was much better than the performance of the traditionally used auto-regression model.

Recently, Rehman et al. [7] presented the methodology for the calculation of the cost of each kilowatt hour of electricity produced using long-term hourly mean wind speed data at 20 locations in the Kingdom of Saudi Arabia. The authors developed wind duration curves over the entire period of data collection and used wind power curves for wind machines of 600 kW, 1.3 MW, and 2.5 MW, and all cost elements to calculate the cost of electricity production. Their analysis showed that the minimum cost (US$ 0.0234/kW h) of electricity production was found for Yanbo, while the next best site was Qaisumah, with an electricity production cost of US$ 0.0256/kW h.

Hence, the growing need for energy, participation of Middle Eastern countries in wind power generation, global decrease in cost of wind power generation, and growing awareness of the usage of green energy sources are some of the factors which motivated the authors to conduct a detailed wind analysis at relatively windy sites in the Kingdom of Saudi Arabia. The study includes seasonal and diurnal variability, wind availability in different wind speed bins, effect of hub height on energy production, and capacity factor determination.

The objective of the present study is to summarize the seasonal and diurnal variation of wind speed at 10, 40 and 60 m above the ground; wind energy production for wind energy conversion systems of different sizes at 40 and 60 m hub heights; wind energy production from a wind farm of 15 MW installed capacity; and capacity factor for WECS of different sizes.

2. Site and data description

In Saudi Arabia, there are five locations in coastal areas where meteorological data are being collected since 1970. The details of the locations are summarized in Table 1. At all of these locations, the meteorological measurements were made at 10 m height except at Gizan where data were recorded at 8 m height above the ground level. So the data were normalized to 10 m height for Gizan using the 1/7th wind power law. The data used in this analysis cover 14 years of measurements stretching from 1970 to 1983. Data were found to be missing for the year 1976 and for some months of the years and days of the months.

3. Data validation

The data were checked for completeness, ranges, and missing and erroneous values. The following corrective measures were taken in general:

1. Hourly mean wind speeds with zero values for three or more hours were not included in the analysis.
2. During 1970–1972, data were recorded only during 9:00–18:00 h.
3. Records with constant values of hourly mean wind speed for more than three hours continuously were not considered in the analysis.
4. The hourly mean wind speed values were checked for range between 0 and 25 m/s, and values above 25 m/s were not included in the statistical analysis. From our past experience, the hourly mean wind speed does not go beyond 25 m/s except for specific occasions during thunderstorms and unforeseen weather activity.
5. Wind direction values were checked between 0° and 360° and any value greater than 360° was discarded and not included in the analysis.

Table 1
Summary of site related information

Locations	Latitude (N)	Longitude (E)	Altitude (m)	Comments
1. Dhahran	26° 06′	50° 10′	22	Situated on the east coast
2. Gizan	16° 52′	42° 35′	5	Situated on the southwest coast
3. Al-Wajh	26° 14′	36° 26′	22	Situated on the west coast
4. Yanbo	24° 07′	38° 03′	6	Situated on the northwest coast
5. Jeddah	21° 30′	39° 12′	17	Situated on the west coast

6. The hourly mean temperature, pressure and relative humidity values were also checked in the ranges prevalent in Saudi Arabia.

4. Results and discussion

The long-term hourly mean wind speed data at five coastal locations were analyzed statistically and the results are discussed here in the following paragraphs.

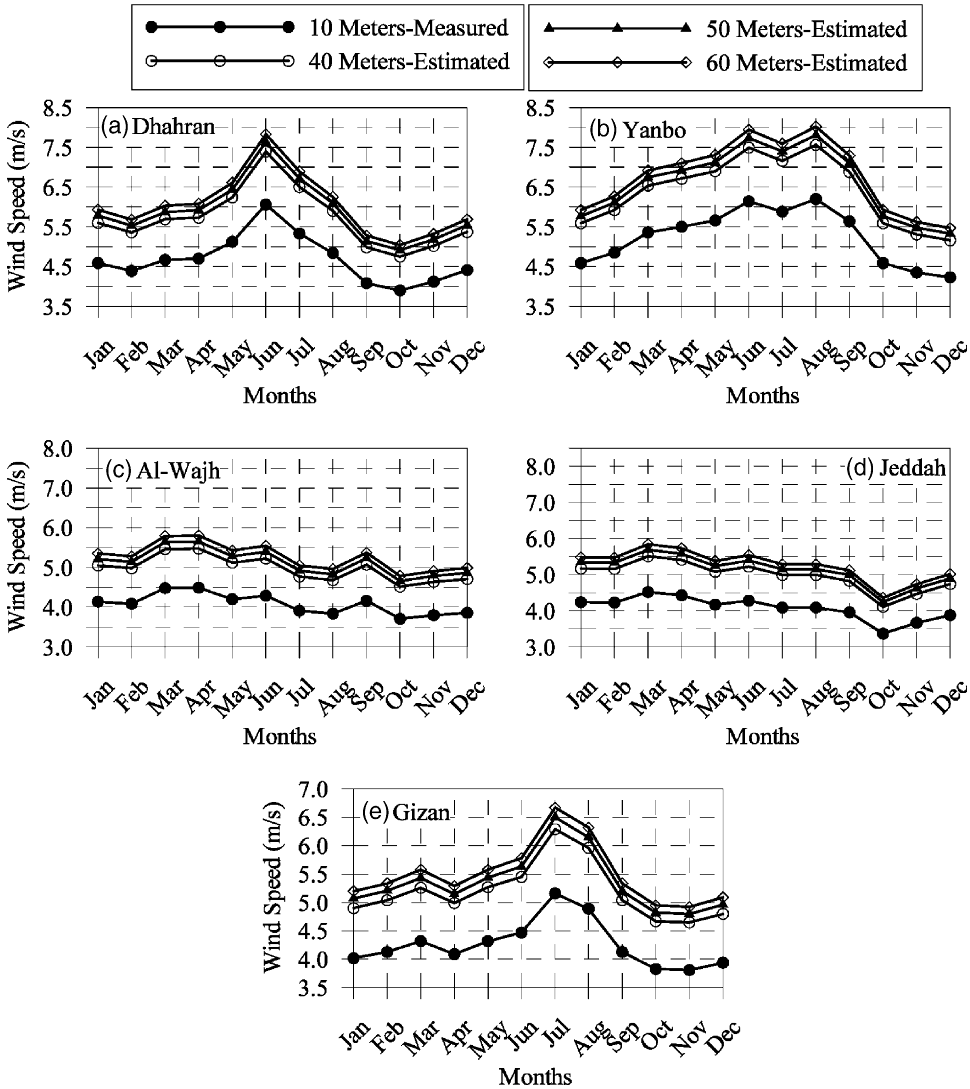

Fig. 1. Monthly mean wind speed at different heights for (a) Dhahran, (b) Yanbo, (c) Al-Wajh, (d) Jeddah and (e) Gizan.

4.1. Seasonal and diurnal behavior of mean wind speed

To compare the seasonal trend of mean wind speed at five locations at different heights, the long-term monthly mean values were calculated at 10, 40, 50 and 60 m above ground level (agl). The hourly mean wind speeds at different heights were estimated using the 1/7th wind power law. The long-term seasonal trends of monthly mean wind speed at all the coastal locations are shown in Fig. 1. As can be seen from Fig. 1(a) for the coastal location of Dhahran, the season's maximum monthly mean wind speed of about 6.0 m/s is observed during June, while the minimum of 4.0 m/s is in October at 10 m above the ground level. Monthly mean wind speeds of the order of 5.0 m/s and above are noticed in the summer months from May to August. At other heights, higher values are observed but follow the same trend as at 10 m.

At Yanbo, the maximum monthly mean wind speed is found in August, i.e. approximately 6.2 m/s, while the minimum is in December, at 10 m height. Higher monthly mean wind speeds of the order of 5.0 m/s or more are observed during March–September. This shows higher monthly mean wind speed at Yanbo as compared to Dhahran. At other heights, the estimated values follow the same trend but with larger magnitudes. At Al-Wajh and Jeddah, the seasonal variation was found to be small and almost constant values of the order of 4 ± 0.5 m/s were observed throughout the year. At Gizan, the highest monthly mean value of 5.2 m/s occurred in the month of July, while the minimum of 3.8 m/s was in November. Higher monthly mean values of the order of 5.0 m/s were observed only during the months of July and August.

Fig. 2 compares the monthly mean wind speeds at 10 m height above the ground level for all the coastal locations. This clearly shows that the highest values of wind speed occur at Yanbo, while second highest occur at Dhahran during all the months. The third highest values of monthly mean wind speeds are observed at Gizan, while at Al-Wajh and Jeddah the values were small and seasonal change was absent.

The diurnal behavior of hourly mean wind speeds at different heights and locations is shown in Fig. 3. At 10 m height above the ground level, the higher values of hourly mean wind speed of the order of 4.5 m/s and greater are observed between 8:00 and 18:00 h at Dhahran, 12:00 and 21:00 h at Yanbo, 12:00 and 20:00 h at Al-Wajh, and 11:00 and 19:00 h at Jeddah and Gizan. This diurnal trend is compatible with load requirement in Saudi Arabia in general. Simi-

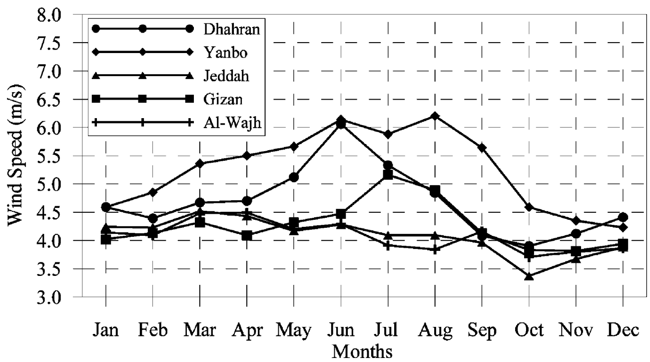

Fig. 2. Comparison of monthly mean wind speed at 10 m above the ground.

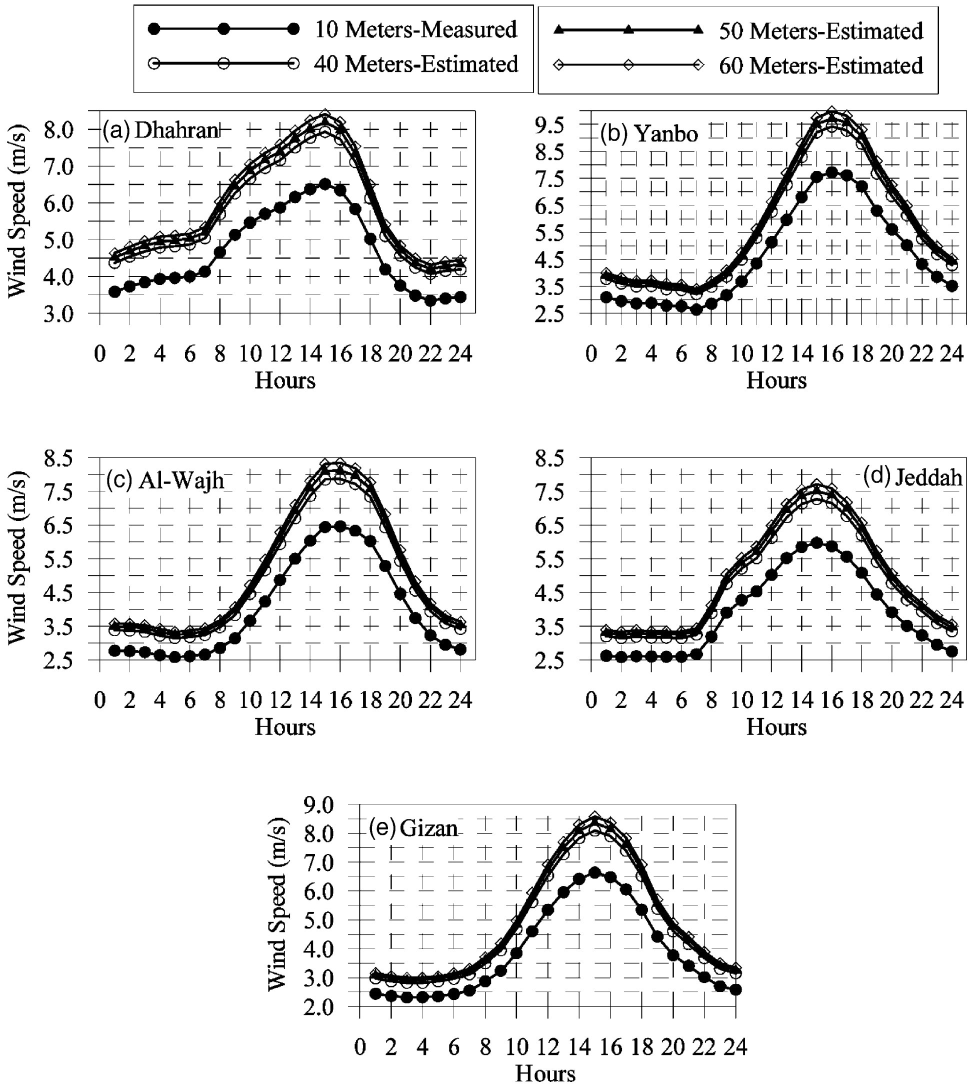

Fig. 3. Diurnal variation of wind speed at different heights for (a) Dhahran, (b) Yanbo, (c) Al-Wajh, (d) Jeddah and (e) Gizan.

lar trends, but with larger magnitudes, are observed at other heights as well. Diurnal change at 10 m agl is compared in Fig. 4 for all the locations. The diurnal change follows almost the same trend at all locations except Dhahran.

4.2. Wind availability analysis

The wind availability analysis is performed in terms of the frequency (or number of hours) for which wind remained in a certain wind speed interval or bin. The frequency is obtained by

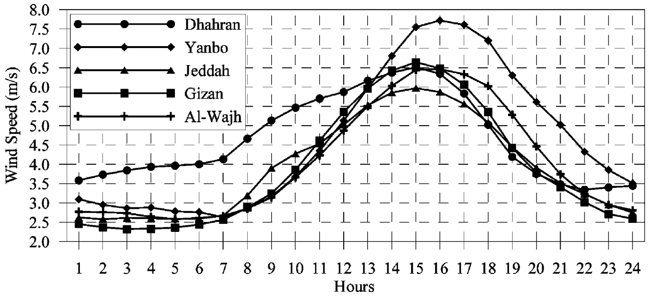

Fig. 4. Comparison of diurnal change in mean wind speed at 10 m above the ground.

constructing a wind rose diagram using the hourly wind speed and corresponding wind direction data of the entire data collection period. Generally, modern wind energy conversion systems have cut-in speeds of the order of 3.0 m/s, so that the first bin is taken as 0–2.9 m/s, the second as 2.9–4, and so on.

The resulting percentage frequency distribution at 10 m height above the ground level and in different bins for all the locations is shown in Fig. 5. At Dhahran, Fig. 5(a), the hourly mean wind speed remains above 2.9 m/s for about 74% of the time during the entire data collection period. It is also observed that hourly mean wind speed remained above 6 m/s for 29% of the time at Dhahran. This shows that the power of the wind can be harnessed for 74% of the time at Dhahran. At Yanbo, Fig. 5(b), the hourly mean wind speed remained below 2.9 m/s for 23% of the time or above 2.9 m/s for 77% of the time. This shows that a WECS with a cut-in speed of 3.0 m/s can produce energy for almost 77% of the time during the entire year. It is also observed that the hourly mean wind speed remained above 6.0 m/s for 36% of the time at Yanbo, which indicates high energy production for 36% of the time.

At Al-Wajh, Jeddah and Gizan, the hourly mean wind speed remained above 2.9 m/s for 67%, 68% and 66% of the time during the entire year, respectively. This shows that these three locations behave more or less in a similar way from a wind energy generation point of view. It is also observed that the hourly mean wind speed remained above 6.0 m/s for only 21% of the time at these three locations. So, from the wind availability point of view, Yanbo is the best location followed by Dhahran, while the remaining three locations behave similarly and can be placed third from the energy generation point of view.

4.3. Capacity factor analysis for WECS of different sizes

To calculate the capacity factors of wind machines, nine wind machines from Nordex of sizes 2500, 2300, 1500, 1300, 1000, 800, 600, 250 and 150 kW were considered. The energy output from each wind machine at all locations under present investigation was obtained using the wind power curve of each WECS and frequency in terms of number of hours during which wind remained in different wind speed intervals. These energy output calculations were performed using wind speed data at 10 and 50 m agl. The resulting energy output in megawatt

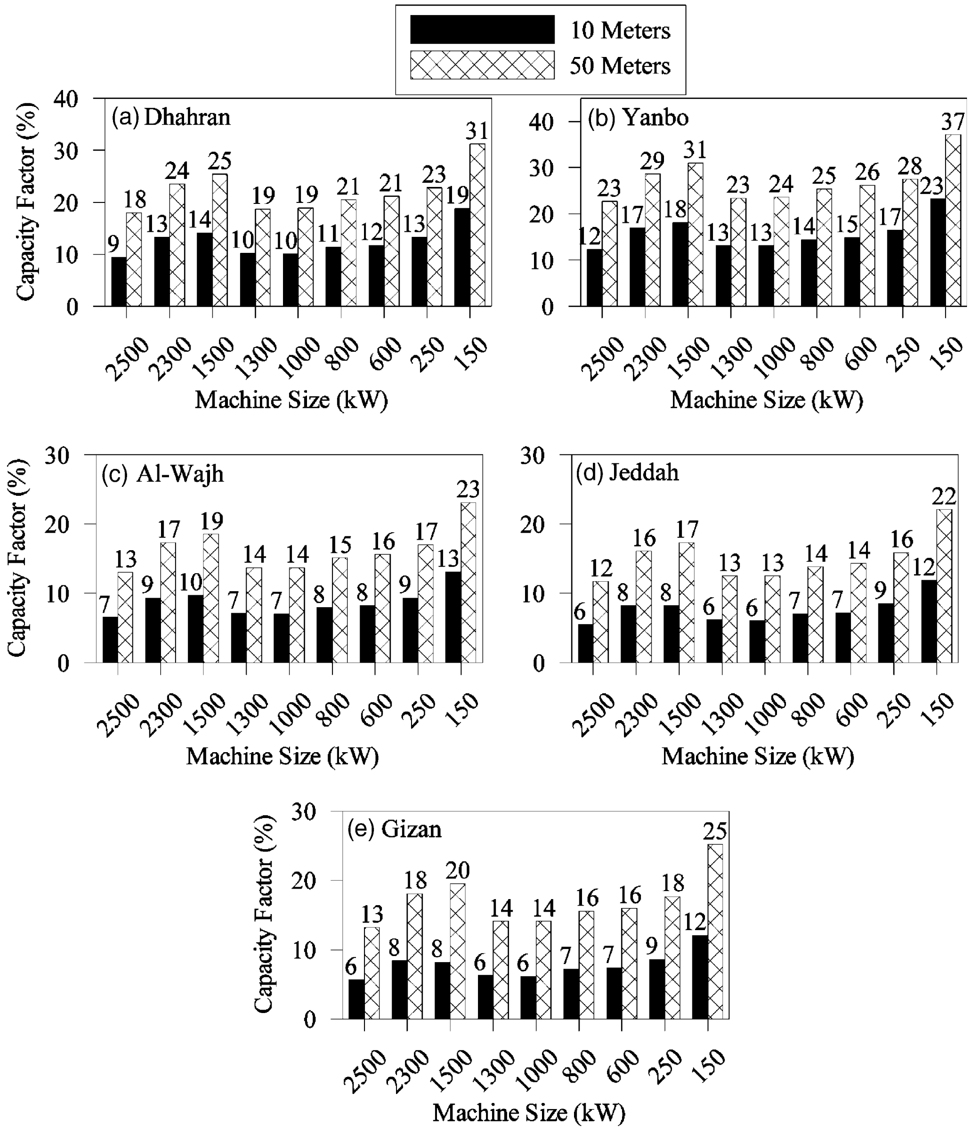

Fig. 5. Percent distribution of hourly mean wind speed in different bins for (a) Dhahran, (b) Yanbo, (c) Al-Wajh, (d) Jeddah and (e) Gizan at 10 m above ground level.

hours from all the WECS at each site is shown in Fig. 6. It is clear from this figure that the maximum energy output is obtained from WECS of size 2300 kW at all the locations and at both the heights. The maximum energy output is obtained at Yanbo, while the next highest is at Dhahran. Gizan is placed at number three and Al-Wajh at number four, while Jeddah is in the fifth place from the energy generation output point of view.

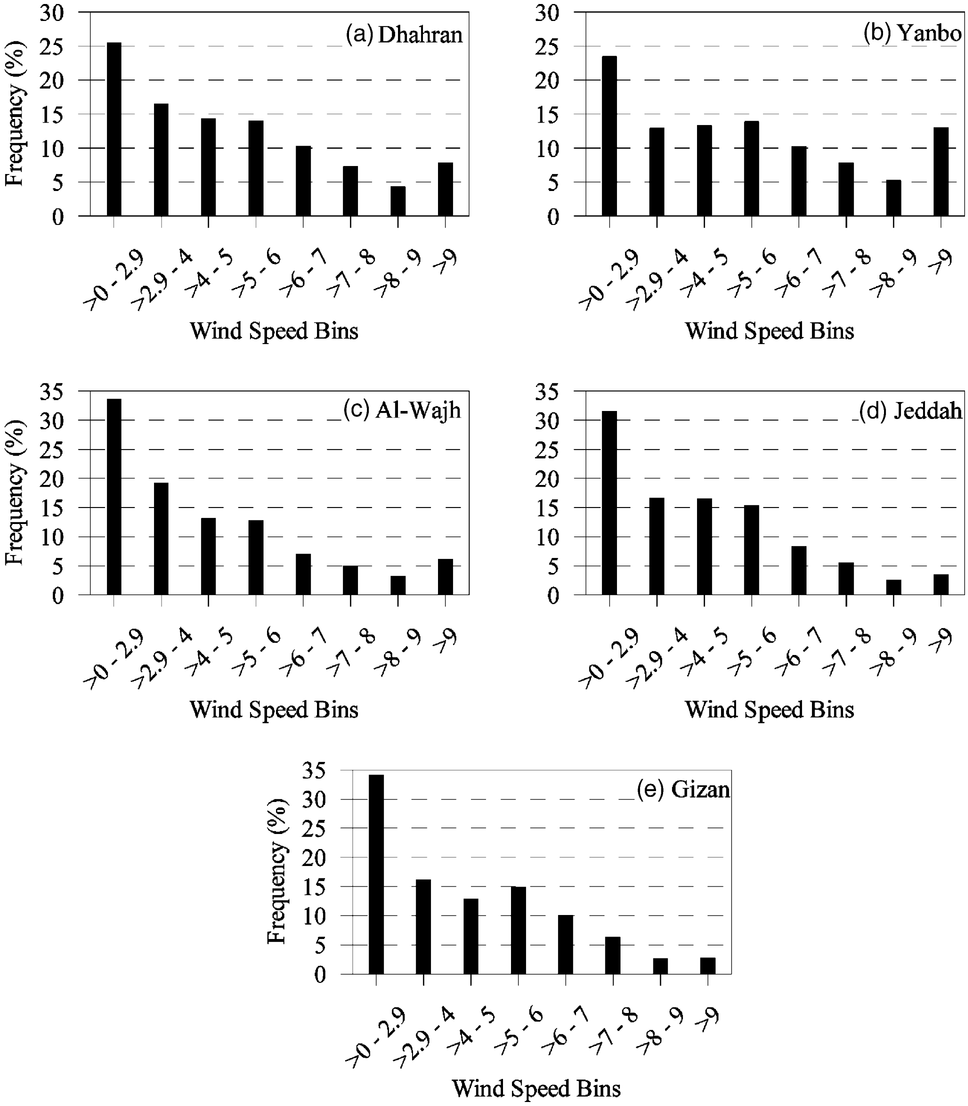

Fig. 6. Energy output for wind machines of different sizes at 10 and 50 m.

The energy output data along with the rated capacity of each WECS is used to calculate the capacity factor of the wind machines. The capacity factor, reported in Fig. 7, was calculated as:

$$\text{C.F. } (\%) = \frac{\text{actual energy output}}{\text{rated capacity} \times 8760} \times 100 \qquad (1)$$

In general, it is observed that the capacity factor increases as the size of the WEC decreases. At Dhahran, the highest capacity factor of 31% was obtained for the 150 kW machine, while 24% and 25% were obtained for the 2300 and 1500 kW machines, respectively, at 50 m agl. The capacity factors for WECS of size 2500, 1300, 1000, 800 and 600 kW were found to vary

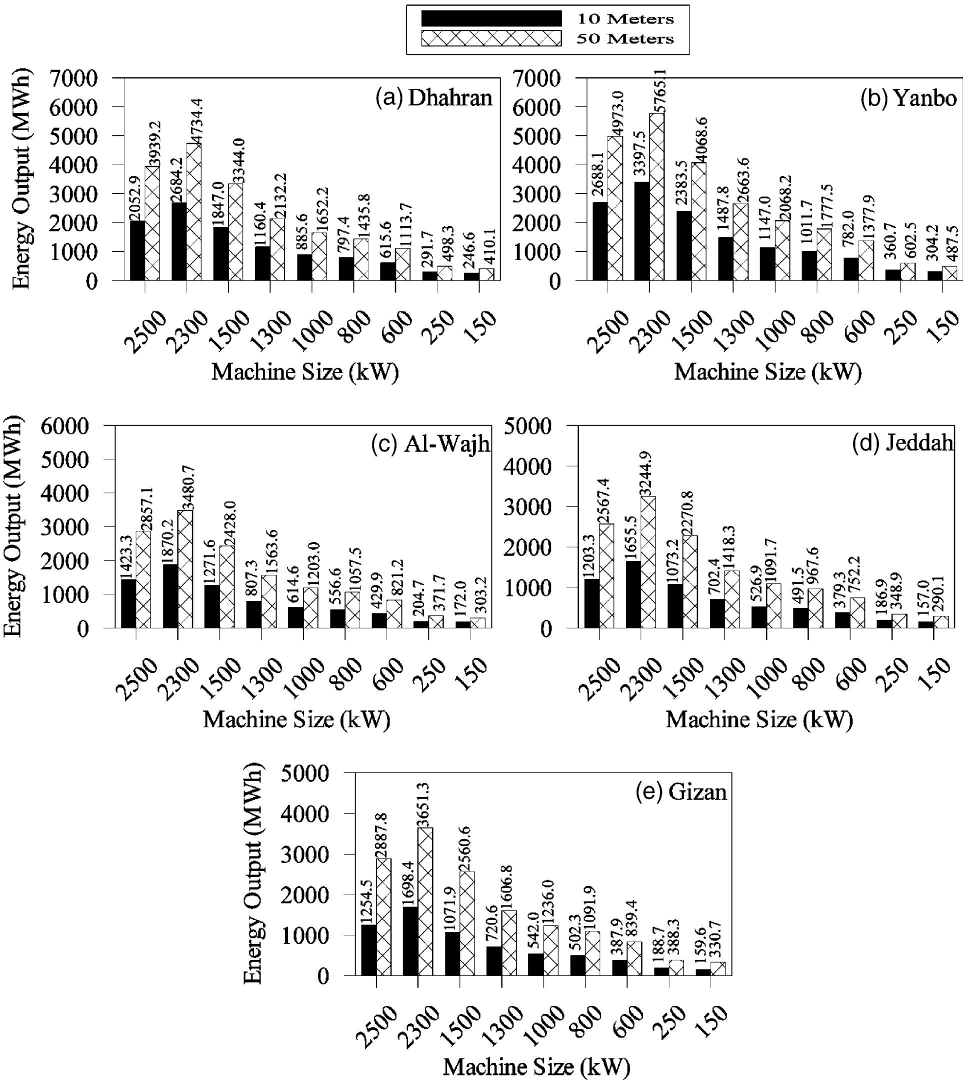

Fig. 7. Capacity factor for wind machines of different sizes at 10 and 50 m.

between 18% and 21%, i.e. not a significant change compared to the change in rated capacity. This type of behavior, for these sizes, is also observed at all the other locations as well. At Yanbo, as shown in Fig. 7, the highest capacity factor of 37%, which is also the highest value compared to all locations, is obtained for the WECS of 150 kW at 50 m agl. Overall, highest capacity factors were obtained for all WECS at Yanbo, while the next highest values were found at Dhahran. Gizan, Al-Wajh and Jeddah were placed third, fourth and fifth while comparing the capacity factors at different locations.

5. Conclusions

The seasonal analysis of monthly mean wind data showed the availability of higher winds during the summer months at Dhahran, Yanbo and Gizan, while the effect of season was insignificant at Al-Wajh and Jeddah. The higher values of monthly mean wind speed in summer months show higher availability of wind energy, which matches with the larger electrical load requirements during the summer months in Saudi Arabia. The diurnal variation of hourly mean wind speed at all the locations was quite visible, matching the daily load requirements of the locations.

The energy production analysis shows that Yanbo is the best location for harnessing the power of wind to generate energy followed by Dhahran in comparison with all the locations studied here. The highest capacity factors were obtained at Yanbo for all the WECS considered. The next highest values of capacity factors were obtained at Dhahran, while Gizan was placed third.

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