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ORIGINAL ARTICLE

Application and economic viability of wind turbine installation in Lutak, Iran

Kasra Mohammadi[1] · Ali Mostafaeipour[2] · Ahmad Sedaghat[3] · Shahaboddin Shamshirband[4] · Dalibor Petković[5]

Abstract There is a lack of studies on evaluating the economic feasibility of large-scale wind turbine development in Iran. Thus, this study aims at analyzing the feasibility of large wind turbines installation in Lutak region, situated in the southeast of Iran. For this aim, the 10-min average recorded wind speed data at 40 m height collected from January 2008 to December 2009 in Lutak are analyzed. Based on three reliable statistical indicators, it is found that the Weibull function enjoys excellent capability to analyze the wind data in Lutak. The wind data analysis reveals that the period of May to September is the windiest time of the year for which the wind power classification falls into class 6 or 7. Nevertheless, due to the lower wind potential in the early and late days of year, very high differences are observed between daily mean wind speed as well as wind power values throughout the year. The highest and lowest mean wind speed and wind power occur in July and January. The wind speed lies between 3.85 and 11.26 m/s while the wind power ranges from 78.79 to 1210.32 W/m^2. It is also observed that wind blows predominantly from northwest and north directions in Lutak. The performance and economic feasibility of installing four different types of wind turbines with the rated power of 600–900 kW are examined for installation at 40 m height. The attained results indicate that the EWT 52/900 kW wind turbine is a more appropriate economical option.

Keywords Wind energy · Weibull distribution · Wind turbine · Economic assessment · Lutak · Iran

✉ Shahaboddin Shamshirband
shamshirband@um.edu.my

Kasra Mohammadi
kmohammadi@umass.edu

[1] Department of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003, USA

[2] Industrial Engineering Department, Yazd University, Yazd, Iran

[3] Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran

[4] Department of Computer System and Technology, Faculty of Computer Science and Information Technology, University of Malaya, 50603 Kuala Lumpur, Malaysia

[5] Department for Mechatronics and Control, Faculty of Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Nis, Serbia

Introduction

Nowadays, there are some growing concerns regarding the destructive effects of large-scale exploitations of fossil fuels on the environment. On the other hand, owing to the economical and technological developments as well as the needs to a more comfortable life across the globe, the worldwide energy demand is increasing substantially. Therefore, declining the existing negative environmental issues and enhancing the security of power supply chain is of particular significance. In this regard, developing the renewable energy sources is regarded as a particularly suitable option to conquer the aforementioned problems. Renewable energies are clean, environmentally preferable, ubiquitous, and inexhaustible. In fact, there are favorable reasons to harness renewable energy sources, because renewables can solve climate change, natural resource depletion, and pollution in the world (Dinpashoh et al. 2014). Among various types of renewable and sustainable energy sources, wind energy has rapidly grown in recent

years. The wind industry has shown remarkable progress in terms of installing wind turbines so that the global wind turbines capacity reached close to 370 GW by the end of 2014 (Global Wind Report, Global Wind Energy Council, 2014).

Iranians (known as Persians) are among the first people who used renewable energy over 1000 years ago (Mostafaeipour 2010b). Among renewables, wind has been the most popular in many locations in Iran. In this context, many investigations on different realms of wind energy have been conducted in Iran (Mostafaeipour and Abesi 2010; Mostafaeipour 2011; Pouyan et al. 2011; Kousari et al. 2013; Saeidi et al. 2013; Satkin et al. 2014; Pourrajabian et al. 2014; Sedaghat et al. 2014; Roshan et al. 2015). In Iran, wind energy utilization in terms of modern wind turbines dates back to around two decades ago. First modern wind turbines including only two sets of 500 kW Nordtank model were installed in Manjil and Roodbar in 1994. Wind energy potential of Iran is estimated to be about 6500 MW (Kazemi Karegar et al. 2006); however, Iran's progress in harnessing the wind energy is slow such that by the end of 2013 the installed capacity reported around 100 MW (http://www.thewind power.net/country-datasheet-38-iran.php.). Assessing the wind energy potential is the first step prior to performing any attempt towards wind turbine installation. Moreover, detailed economic evaluation should certainly be conducted to assess the viability of wind electricity production in the studied regions.

Islam et al. (2011) determined the characteristics and potential of wind power for Kudat and Labuan located in Malaysia using measured wind data at 10 m height. They found that the highest monthly mean wind speeds are 4.8 and 4.3 m/s for Kudat and Labuan, respectively, and the maximum wind power densities are 67.40 and 50.81 W/m^2 for Kudat and Labuan, respectively. They concluded that the studied sites are only suitable for small-scale wind energy applications. Adaramola and Oyewola (2011) evaluated the wind energy potential as well as the performance of small to medium commercial wind turbines for installation in three selected locations in Oyo state, Nigeria. They found that the monthly mean wind speed and wind power in Oyo state vary from 2.85 to 5.20 m/s and from 27.08 to 164.48 W/m^2, respectively. In addition, the annual mean power density was reported between 67.28 and 106.60 W/m^2. Abbes and Belhadj (2012) investigated the possibility of constructing a wind farm in the El-Kef region in Tunisia. They analyzed the characteristics of wind speed using Weibull distribution function and found that the capacity factor for different wind turbine configurations is 0.26. They also conducted a techno-economic analysis. Durišić and Mikulović (2012) assessed the wind energy resources in the South Banat region in Serbia using measured wind data at four heights of 10, 40, 50, and 60 m. Based on the statistical analysis of wind data, they found that the region of South Banat has a good potential of wind energy. They concluded that the development of wind turbines projects is promising in the region. Diaf and Notton (2013) investigated the wind energy potential in 13 locations of Algeria using measured wind speed data at 10 m height and found relatively higher wind power for southern regions. They also examined the technical and economic evaluation of electricity generation from six different large-scale wind turbine models. Their results showed that the capacity factor values of considered wind turbines in different sites vary from 6 to 48 %. In terms of energy cost per kWh, the Suzlon S82–1500 wind turbine model was recognized as a better option. Shu et al. (2015) performed a statistical analysis using Weibull function to determine the characteristics and potential of wind energy at five sites located in Hong Kong. The conducted evaluation indicated that among studied stations, the maximum and minimum wind power density belong to Tai Mo Shan and Hong Kong Observatory stations with the average values of 915.53 and 24.20 W/m^2, respectively. They concluded that hilltops and offshore islands are the most appropriate locations for wind energy utilizations in Hong Kong.

Many studies regarding the assessment of the wind energy potential have been recently performed in Iran. The studies can be categorized into two groups. In the first group, the wind energy potential and wind characteristics have been assessed.

Mostafaeipour and Abarghooei (2008), by analyzing the measured wind speed data, determined the potential of harnessing wind energy at six stations in Manjil area located in the north part of Iran. Their analysis showed that all stations have high wind speed and wind power; therefore, Manjil area could be considered as a very favorable region for wind farms construction. Mostafaeipour (2010a) examined the wind speed characteristics of some major cities located in Yazd province in the central part of Iran. The achieved results demonstrated that most of the stations have annual average wind speed of less than 4.5 m/s, which is considered unsuitable for wind turbines installation. Among all cities in Yazd province, only Herat was recognized as a remote area for possible wind energy applications. Alamdari et al. (2012) assessed the potential of wind power generation for 68 sites distributed in different parts of Iran, using 1 year measured wind speed data at three heights of 10, 30, and 40 m. They developed wind power map at 10, 30, and 40 m heights and found that the eastern and northwestern regions of Iran have good potentials for wind turbines installation. Keyhani et al. (2010) assessed the potential of wind energy exploitation in Tehran, the capital city of Iran, using long-term measured

wind speed data at 10 m height. Their results revealed that the annual average values of wind power density in different years are between 74.00 and 122.48 W/m^2. They also found that wind energy potential in Tehran could be suitable only for some applications such as battery charging and water pumping. Saeidi et al. (2011) evaluated the wind energy potentials for four sites of Bojnourd, Esfarayen, Nehbandan, and Fadashk situated in two provinces of North and South Khorasan. They analyzed the measured wind data at three heights and found that except Bojnourd which falls in class 2, other locations stands in class 3 and can be suitable for wind turbine installation. Mostafaeipour et al. (2013) analyzed 4 years measured wind speed data at different heights to determine the potential of wind power generation in Binalood region in the northeast of Iran. They found that the wind speed values in the region are relatively high such that the annual wind speed at 40 m height is 6.938 m/s. They concluded that Binalood region has a great wind energy potential for grid connection systems. Mirhosseini et al. (2011) assessed the potential of wind power generation at five towns in Semnan province by determining the mean wind speed, wind speed distribution function and mean wind power density of the locations. Their results showed that Moalleman possess more potential for wind energy development. The wind powers at 10, 30, and 40 m heights were 172, 257, and 303 W/m^2, respectively. Pishgar-Komleh et al. (2015) performed an investigation to evaluate the wind energy potential in Firouzkooh, Iran. They showed that the annual average of wind speed, wind power, and wind energy densities in Firouzkooh are 5.81 m/s, 203 W/m^2, and 1780 kWh/m^2, respectively. Based upon the conducted examination, they concluded that the selected location is suitable for wind energy development.

In the second group, in addition to wind energy potential assessment, the performance and economic feasibility of wind turbine installation has also been investigated.

Mostafaeipour et al. (2011) studied the status and potential of wind energy for city of Shahrbabak in Kerman province. Their results showed that, based on wind power classification, the city ranks in class 2 which can be suitable for small-scale wind turbine utilization. They also presented the economic feasibility of a 10-kW wind turbine. According to the results, cost of electricity generation was found as 18 cents per kWh which was 5 cents more than the market price. Nedaei (2012) assessed the wind energy potential for city of Abadan situated in the south-west of Iran. The achieved results showed that monthly wind speed at 80 m height varies between 5.8 and 8.5 m/s with an annual average value of 7.15 m/s. He also estimated the energy production of several wind turbines at different heights and found that Abadan has a good potential for installation of large-scale wind turbines at 80 m height and higher. Mostafaeipour (2013) studied the economic evaluation of installing some small wind turbine models for city of Kerman situated in the southeastern part of Iran. The study results indicated that Kerman has an available wind energy potential to install some small-scale wind turbine models. Mohammadi and Mostafaeipour (2013) utilized different economical approaches to investigate the economic possibility of installing several wind turbine models at 30 m height with different rated powers, ranging from 20 to 150 kW, in city of Aligoodarz located in the west part of Iran. They introduced Aligoodarz as a moderate location for wind energy development. Based upon the economic results, the E-3120 (50 kW) wind turbine was recognized as a better option to generate electricity in Aligoodarz. Mostafaeipour et al. (2014) assessed the wind energy potential in Zahedan located in the southeast part of Iran. They found that the maximum annual wind powers in different years are between 72.777 and 106.525 W/m^2. They also performed an economic evaluation in terms of cost of produced energy by four different types of small-scale wind turbines. They found that the Proven 2.5 kW wind turbine model is a more economical option for installation at Zahedan.

Clearly, the number of studies carried out to evaluate the economic possibility of wind turbine development in Iran is very limited. In addition, no study has been performed in terms of economic possibility of large-scale wind turbine installation in any location of Iran. Thus, this research work aims at evaluating the feasibility of installing large-scale wind turbine systems in Iran. The 10-min average recorded wind speed data in Lutak region at 40 m height collected over the period of 2 years from 2008–2009 are analyzed using Weibull distribution function. The data were recorded at the meteorological mast installed by Renewable Energy Organization of Iran (locally known as SUNA) (http://www.suna.org.ir). The economic feasibility of installing four large-scale wind turbine models with different rated powers ranging from 600 to 900 kW at 40 m hub height is carried in terms of two major economical approaches: energy cost estimation (C) and payback period (PBP) analysis. The wind power potential as well as technical and economical evaluation of installing nominated wind turbines are studied only at 40 m height, since the currently installed large-scale wind turbines in Iran are operating only at this height. In line with increased tendency toward wind energy exploitation in Iran, due to lack of wind turbine installation in Lutak region, results of this survey would provide helpful

information for the purpose of developing wind turbines in the region.

The above review collated the knowledge gained in methodology, regional wind characteristics, and wind turbine utilized in the previous studies to assist the present study goals of using this knowledge to fit most suitable analysis and right decision for installing economically viable wind turbines in Lutak area.

Description of the study region and wind data

Sistan-Baluchestan province, which consists of two regions of Sistan in the north and Baluchestan in the south, is situated in the southeast part of Iran bordering Pakistan and Afghanistan. Sistan-Baluchestan province with the total area of 187,502 km^2, occupying 11 % of the total country area, is the largest province of Iran. The province is located between 25°30′N and 31°27′N and also between 58°50′E and 63°21′E, and is the most sparsely populated province in the country. Sistan-Baluchestan province is one of the driest regions in the country with an increment in the rainfall from north to south, and an obvious increase in relative humidity from north to south in the coastal parts. Based on long-term measurements, the annual average of air temperature varies from around 22 °C in the north part to around 28 °C in the south part of the province. Besides, in the northern parts of the province the air temperature has a much higher fluctuation in different months compared to the southern parts. The annual average of relative humidity varies from around 37 % in the north parts to around 72 % in the south parts. It is clear that the climate conditions change from Sistan part in the north to Baluchestan part in the south. In Sistan region, the rainfall level is very low and the evaporation rate is very high. In fact, the climate of the

region is extremely dry and suffering from extensive and severe successive droughts nowadays.

The Sistan region is subject to seasonal winds known as Sistan 120-day winds chiefly blow from north and northwest directions. In fact, the wind speed in this region follows an obvious annual cycle, which its peak occurs throughout the dry season typically from late spring until early autumn (Alizadeh-Choobari et al. 2014). Basically, Sistan 120-day winds as really powerful regional winds usually begin to below in middle of the May to the middle of September. It is worthwhile to mention that Mesoscale features are indeed important in creating the winds of 120 days (Alizadeh-Choobari et al. 2014). The wind of 120 days is related to the pressure gradient of north–south and is between a cold high-pressure system over the high mountains of the Hindu Kush in north of Afghanistan and a thermal low-pressure system in summer which is common over the desert of eastern Iran and western Afghanistan due to sustained surface warming. It is significant to state that the topographic wind channel effect of Babaei and Hindu Kush Mountains to the northeast and the Palanghan Mountains to the west of the region are the factors that accelerates this wind (Alizadeh-Choobari et al. 2014). More details regarding these 120-day winds can be seen in (Alizadeh-Choobari et al. 2014).

Lutak is a rural area located in the Sistan region in the northeast part of the province at 30°77′N and 61°42′E, and its elevation is 485 m above sea level. The total population of Lutak is estimated to be about 1000. Lutak is situated in plain area and possess warm and dry weather condition, and has one of the lowest levels of rainfall in the province (http://www.wikipedia.com 2014).

Figure 1 shows the location of Lutak and some major cities such as Zahedan, the capital city of Sistan-Baluchestan province, on the map of Iran.

Fig. 1 Location of Lutak and some major cities of Sistan-Baluchestan province on the Iranian map

For this study, the 10-min average recorded data for Lutak region including the wind speed data at 40 m height and wind direction data at 37.5 m height collected over period of 2 years from 1 January 2008 to 31 December 2009 were used. These wind data were measured at the meteorological mast installed by Renewable Energy Organization of Iran locally known as SUNA. The anemometers established in Lutak were constructed by SUNA using the equipment from Germany. According to the SUNA authorities, all the data are accurate and there is a sophisticated computer program, which was purchased from Germany for this purpose. In addition, engineers were monitoring the equipment at all the time. Result of their project was national wind atlas, which is the only accurate source of wind data in Iran.

Analysis methodology

There are several probability distribution functions in the literature for representing the wind speed frequency and evaluating the viability of wind turbines development. Among all, the Weibull distribution function (WDF) is widely used and adopted due to simplicity and satisfactory level of accuracy.

Weibull distribution function (WDF)

The probability density function of the Weibull distribution is given by (Sulaiman et al. 2002; Liu and Chang 2011; Arslan 2010; Malik and Al-Badi 2009):

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

where $f_w(v)$ is the wind speed probability for speed v, k is shape parameter (dimensionless) and c is scale parameter (m/s). k and c are determined using standard deviation method as (Dabbaghiyan et al. 2016):

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \qquad 1 \le k \le 10 \tag{2}$$

$$c = \frac{\bar{v}}{\Gamma\left(1 + 1/k\right)} \tag{3}$$

where $\bar{v}$ and σ are mean wind speed and standard deviation. In addition, Γ is the gamma function.

Wind power density

The evaluation of the wind power density is an appropriate way to assess the wind potential of any location, since it shows how much energy is accessible at the site for converting to electricity by wind generators. The wind power density per unit area is given by (Mathew 2006):

$$P = \frac{1}{2}\rho v^3 \ (\mathrm{W/m^2}) \tag{4}$$

where ρ is the air density.

The wind power density using Weibull probability density function is obtained by (Mathew 2006):

$$\frac{P}{A} = \frac{1}{2}\rho\int_0^\infty v^3 f_w(v)\,\mathrm{d}v = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{5}$$

Two meaningful wind speed

There are two meaningful wind speeds for wind energy assessment namely the most probable wind speed (v_{mp}) and the optimal wind speed carrying maximum energy (v_{me}) which are calculated in terms of k and c values, respectively, as (Akpinar and Akpinar 2005; Elamouri and Amar 2008):

$$v_{mp} = c\left(1 - \frac{1}{k}\right)^{\frac{1}{k}} \tag{6}$$

$$v_{me} = c\left(1 + \frac{2}{k}\right)^{\frac{1}{k}} \tag{7}$$

Energy generated by wind turbine and capacity factor

One of the key parameters that influence the performance of a wind turbine is the power response to different wind speeds, typically specified by the power curve of the turbine. In fact, each wind turbine has a particular power curve. The typical power curve of a sample wind turbine is shown in Fig. 2.

In Fig. 2, there are two major performance regions that can generate energy, named performance region 1 and performance region 2. For these performance regions, the power curve may be approximated with the following relations (Mathew 2006):

$$P(v) = P_r\left(\frac{v^n - v_i^n}{v_r^n - v_i^n}\right) \qquad v_i \le v \le v_r \tag{8a}$$

$$P(v) = P_r \qquad v_r \le v \le v_o \tag{8b}$$

where v_i, v_r, v_o and P_r are cut-in speed, rated speed, cut-out speed and rated power, respectively. n is the power-speed proportionality. Here, the ideal power-speed proportionality is assumed to be 3. The output-generated energy by wind turbines in the time period of T using Weibull distribution function can be expressed as (Mathew 2006):

$$E_{out} = T\int_{v_i}^{v_o} P(v) f_w(v)\,\mathrm{d}v \tag{9}$$

The total produced energy is the summation of produced energy in the region 1 and region 2. By substituting Eqs. (8a) and (8b) in Eq. (9), after some mathematical manipulation, the produced energy in the region 1, $E_{out,1}$, and the region 2, $E_{out,2}$, can be determined, respectively, as (Mathew 2006; Mohammadi and Mostafaeipour 2013):

$$E_{out,1} = \frac{P_r T c^3}{(v_r^3 - v_i^3)} \int_{x_i}^{x_r} x^{3/k} e^{-x} dx - \frac{P_r T v_i^3}{(v_r^3 - v_i^3)} (e^{-x_i} - e^{-x_r}) \tag{10}$$

$$E_{out,2} = P_r T (e^{-x_r} - e^{-x_o}) \tag{11}$$

where x_i, x_r, and x_o are given, respectively, by (Mathew 2006):

$$x_i = (v_i/c)^k, \quad x_r = (v_r/c)^k \text{ and } x_o = (v_o/c)^k \tag{12}$$

The capacity factor, C_F, as a very important index of wind turbine productivity, is the ratio of the output energy by the wind turbine to the energy which can be generated at the rated power. C_F can be calculated as (Mathew 2006):

$$C_F = \frac{E_{out}}{E_r} = \frac{E_{out}}{P_r T} \tag{13}$$

where E_r is the rated wind turbine energy and P_r is the rated wind turbine power.

Assessing the adequacy of Weibull distribution function

In order to determine the adequacy of Weibull function, its precision should be assessed. For this aim, a statistical comparison is conducted using the reliable indicators of relative percentage error (RPE), mean absolute percentage
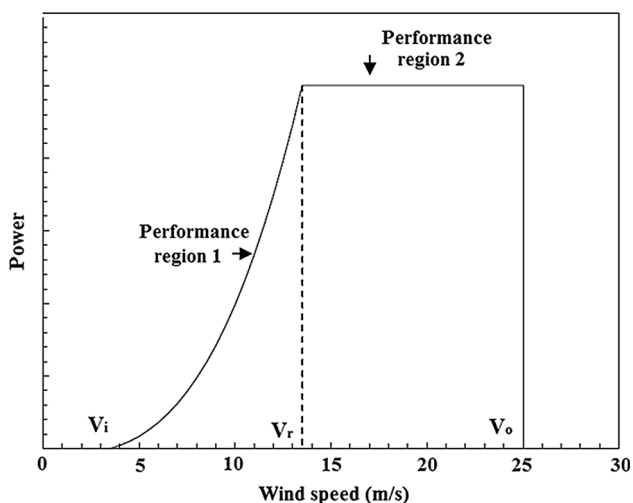
error (MAPE) and correlation coefficient (R) to provide comparison between the daily wind power density calculated using measured data and those obtained by Weibull function. The RPE, MAPE and R are defined, respectively, by Eqs. (14)–(16) as (Celik 2003):

$$RPE = \left(\frac{P_{i,W} - P_{i,M}}{P_{i,M}} \right) \times 100 \tag{14}$$

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{P_{i,W} - P_{i,M}}{P_{i,M}} \right| \times 100 \tag{15}$$

$$R = \frac{\sum_{i=1}^{n} (P_{i,W} - P_{W,avg}) \cdot (P_{i,M} - P_{M,avg})}{\sqrt{\left[\sum_{i=1}^{n} (P_{i,W} - P_{W,avg})^2 \right] \left[\sum_{i=1}^{n} (P_{i,M} - P_{M,avg})^2 \right]}} \tag{16}$$

where $P_{i,W}$ and $P_{i,M}$ are the ith calculated wind power density via Weibull distribution function and the ith calculated wind power density by measured data, respectively. Also, $P_{W,avg}$ and $P_{M,avg}$ are the average of $P_{i,W}$ and $P_{i,M}$ values and n is the total number of observations. It should be noted that the lower values of RPE and MAPE show higher accuracy while the higher R represents more precision.

Results and discussion

In this study, the main objective was evaluating the possibility of wind energy development in Lutak region using 2 years measured wind data for the period of January 2008 to December 2009. For this aim, the Weibull distribution function was used to analyze the wind data. To recognize the suitability of the Weibull distribution function for this study, daily wind power density values calculated by Weibull function were compared with those computed using measured data via the statistical indicators of RPE, MAPE, and R.

Figure 3 shows a comparison between the averages of 2 years wind power density values calculated using Weibull function with those computed via measured data. It is noticed that computed values via Weibull function are in excellent agreements with calculated values by measured data. In terms of RPE, for all days of the year, the RPE values fall within the acceptable range of −10 to 10 % (Menges et al. 2006).

Moreover, the achieved MAPE and R between the computed values by Weibull function and measured data are 0.97168 % and 0.99994 which indicates very high precision of Weibull function for wind data analysis in Lutak. Therefore, Weibull function is applied in this study for all wind data analysis.
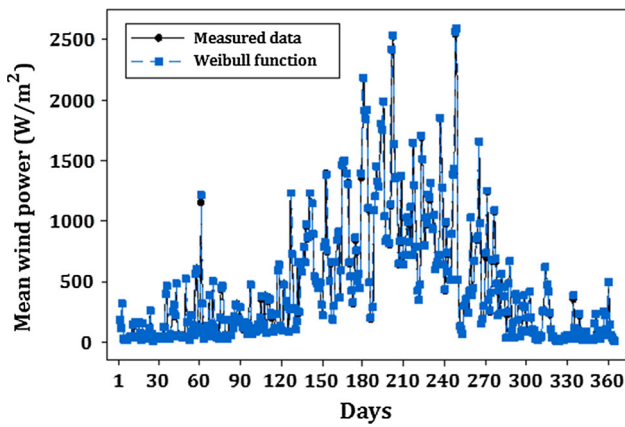

Fig. 2 Typical power curve of a sample pitch controlled wind turbine (Mathew 2006)

Fig. 3 Comparison between averaged daily wind power density values computed using Weibull function and those obtained using measured data

Figures 4 and 5 illustrate the daily variation of wind speed and wind power at 40 m height for both the years of 2008 and 2009. It can be seen that the period of May to September is the windiest time of the year with higher wind speed and wind power. Obviously, during this period the daily wind speeds and power values are very high in some days, which even reach to the values of 18 m/s and 4000 W/m^2, respectively. However, since the wind blows lower in early and late days of year, very high difference between daily mean wind speed as well as wind power values is observed throughout the year. Consequently, in case of installing wind turbines in Lutak, the generated energy is subjected to a significant change from windiest period (May to September) to other periods. It should be mentioned that since the windiest period occurs within the hot period of the year, the high electricity demands of
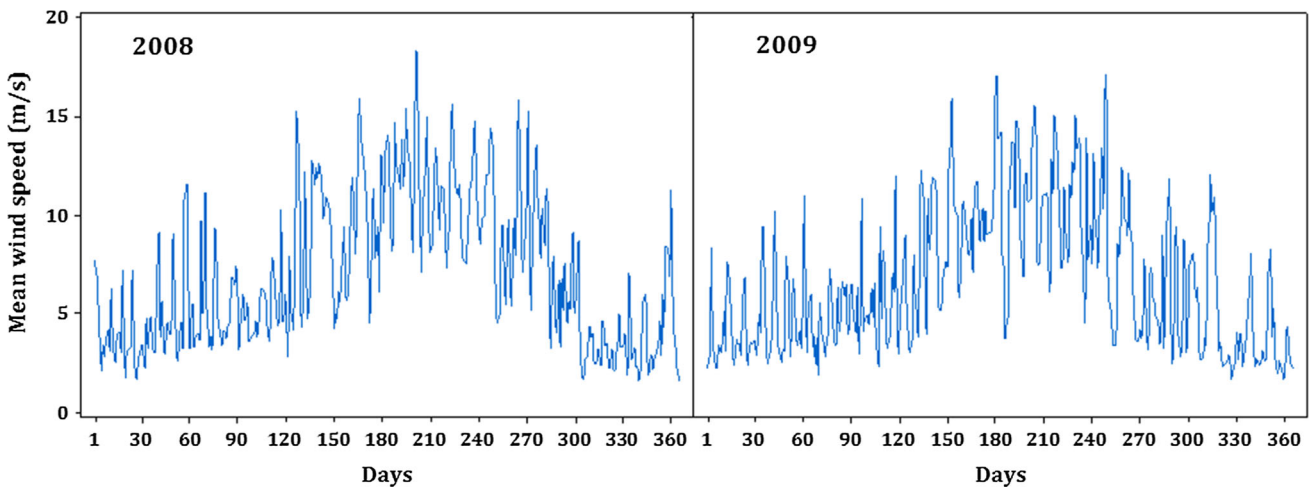

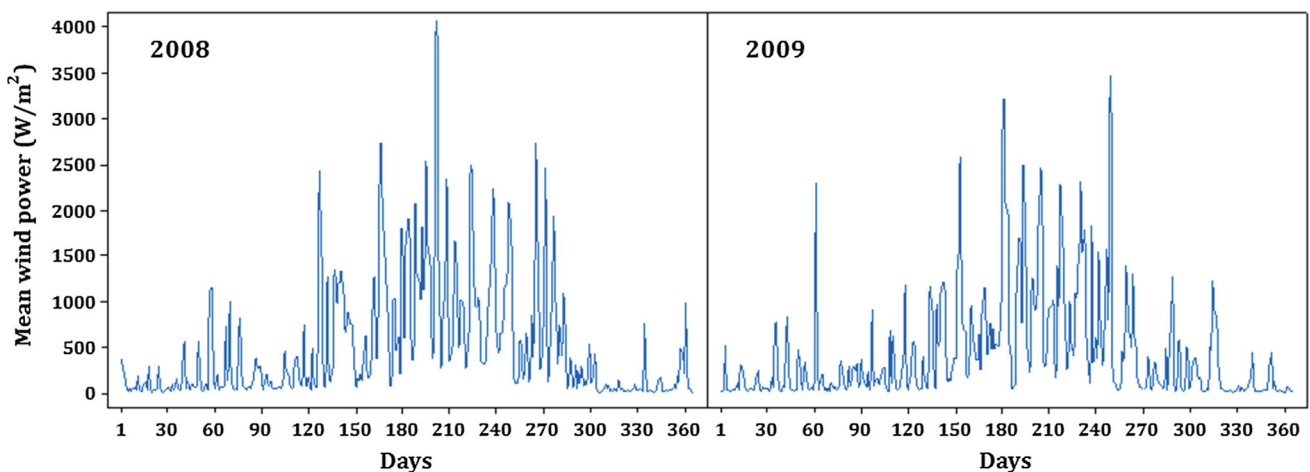**Fig. 4** Daily mean wind speed at 40 m for 2 years of 2008 and 2009

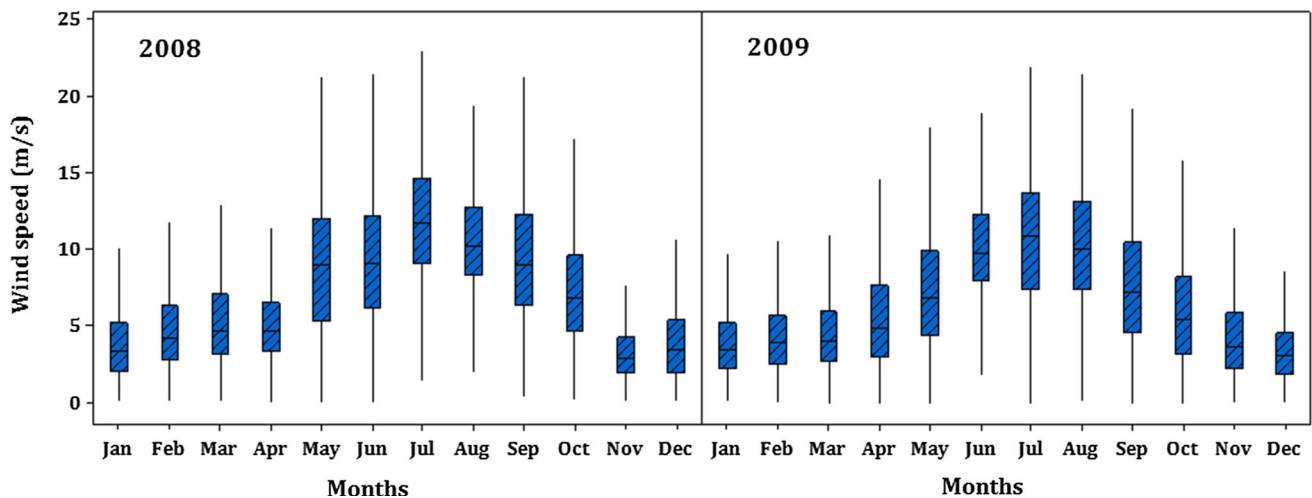**Fig. 5** Daily mean wind power at 40 m for 2 years of 2008 and 2009

Fig. 6 Box plots of measured wind speed data at 40 m in different months for 2 years of 2008 and 2009

households for cooling systems can be provided by using wind turbines.

Figure 6 illustrates the box plots of the measured wind speed data at 40 m height in different months for both years of 2008 and 2009. It is worth mentioning that a box plot shows the inference of variances. The bottom and top of every box are the first and third quartiles and the line inside every box is the second quartile. According to the Fig. 6, the first, second, and third quartiles show 25th, 50th, and 75th percentile of the distribution of the measured wind speed in different months, respectively.

There are also lines extending vertically from the boxes, which illustrate the variability outside the upper and lower quartile. Moreover, for each month, end of the lines indicate the minimum and maximum of wind speed data. From Fig. 6, it is clear that the monthly distributions of wind speed in both years are relatively similar. Similar to Fig. 4, it is found that from May to October wind speeds are very higher than other periods. In addition, in both years, July is the windiest month of the year for which most of wind speed values are higher than 8 m/s.

Wind direction is an important parameter in wind energy analysis. In fact, hawing knowledge on wind direction is of indispensable significance to identify the optimum positioning for wind turbine installations in a wind farm. In this regard, the frequency for which the wind direction falls within different sectors should be determined.

For Lutak, only measured wind direction was available for the height of 37.5 m without the measured wind speed at this height. Figure 7 shows the wind direction frequencies based on 10-min recorded wind directions at the height of 37.5 m for 2 years of 2008 and 2009. As it is clear, the wind directions show very similar behavior in both years. From Fig. 7, it is observed that wind blows predominantly from northwest and north directions. In fact, the highest

frequencies of wind directions are obtained within 326.25° and 12.5°.

In order to provide more evaluation on wind energy potential in Lutak, the main monthly wind characteristics and Weibull parameters at height of 40 m are presented in Table 1. These values were obtained using the average of 2 years measured data. It is found that the highest and the lowest mean wind speed ($\bar{v}$) occur in July and January with the values of 11.26 and 3.85 m/s, respectively. The standard deviation (σ) varies between 2.34 in January and 4.28 in September. The most probable wind speed (v_{mp}) and the wind speed carrying maximum energy (v_{me}) are in the range of 2.04–11.08 and 6.76–14.82 m/s, respectively. Moreover, the shape parameter (k) varies between 1.49 and 3.22, while the scale parameter (c) lies between 4.22 and 12.59 m/s. The minimum and the maximum values of monthly mean wind power (P) are equal to 78.79 and 1210.32 W/m^2, which occur in January and July, respectively.

To identify the suitability of a location for developing the wind energy, the wind power classification proposed by Elliot and Schwartz from Pacific Northwest Laboratory (PNL) can be used (Elliott and Schwartz 1993). Table 2 presents this classification based on different ranges of power density for three heights of 10, 30, and 50 m. Classification of wind resource at height of 40 m can be obtained by interpolation of PNL wind power classification at 30 and 50 m. The last column of Table 1 presents the classifications of wind power at 40 m height in different months of the year based upon PNL wind power classification. Usually each class represents the suitability level of locations for developing wind power. Table 3 offers the definitions of each class for the height of 50 m (Yu and Qu 2010). In this regard, based on Tables 2 and 3, it is found that during 5 months from May to September, Lutak has an
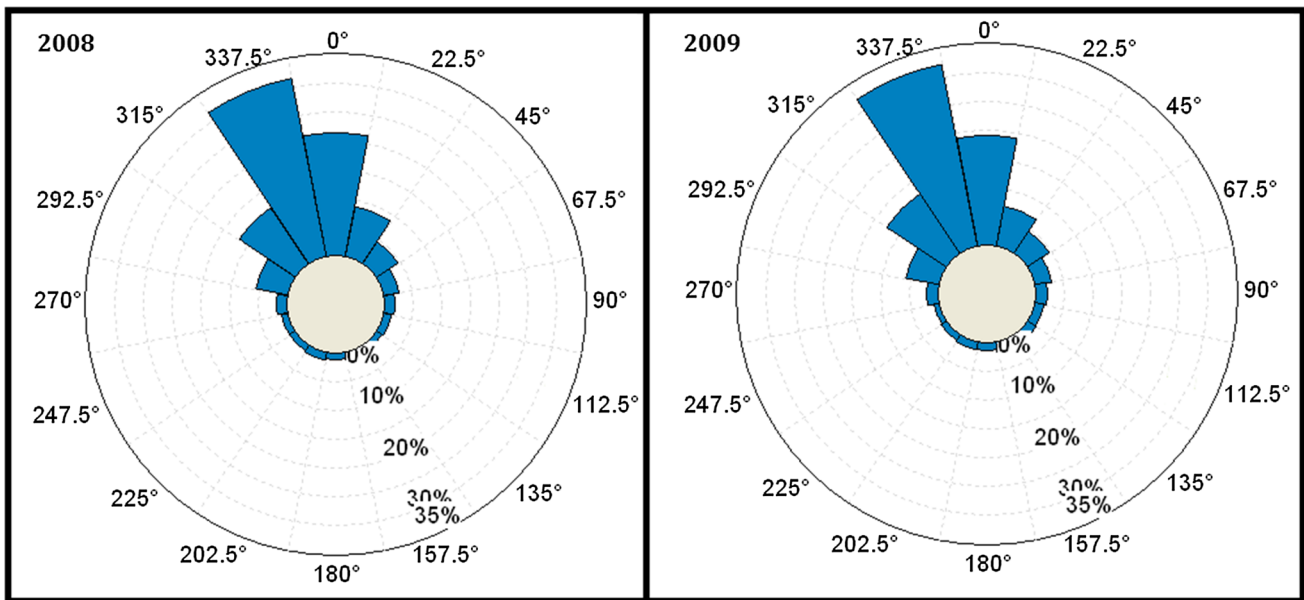
Fig. 7 Wind direction frequencies at the height of 37.5 m for 2 years of 2008 and 2009

Table 1 Monthly wind characteristics and Weibull factors at 40 m

Months	$\bar{v}$ (m/s)	σ	v_{mp} (m/s)	v_{me} (m/s)	k (–)	c (m/s)	P (W/m^2)	Wind power class
January	3.85	2.34	2.59	6.76	1.72	4.31	78.79	1
February	4.82	3.20	2.79	9.10	1.56	5.37	176.45	1
March	5.06	3.21	3.19	9.19	1.64	5.65	190.14	2
April	5.36	3.04	3.97	8.95	1.85	6.03	194.96	2
May	8.03	3.91	6.86	12.21	2.18	9.07	558.25	6
June	9.80	3.81	9.39	13.36	2.79	11.01	845.62	7
July	11.26	4.00	11.08	14.82	3.08	12.59	1210.32	7
August	10.44	3.55	10.38	13.54	3.22	11.65	943.01	7
September	8.66	4.28	7.30	13.28	2.15	9.78	709.63	7
October	6.54	3.43	5.25	10.38	2.02	7.38	324.36	3
November	3.91	2.68	2.04	7.58	1.49	4.29	97.44	1
December	3.87	2.57	2.12	7.29	1.53	4.22	88.93	1

excellent potential for utilizing wind turbines since its wind power stands in classes 6 and 7.

Capacity factor and energy output of wind turbines

In order to determine the amount of energy that can be harnessed from wind turbines in Lutak area, the performances of four different wind turbines with the rated power ranging from 600 to 900 kW with hub height of 40 m are analyzed. The technical information of the selected wind turbines for this study is given in Table 4.

As it is seen, two wind turbine models of EWT Direct wind 52/900 and AWE 54/900 have the same rated power of 900 KW, but they have different operating speeds. It should be mentioned that these four wind turbines were

selected among many wind turbine models based on two criteria. First, these turbines were chosen from an inventory of available turbines in the market with the hub height of 40 m. Second, since the efficiency of a wind turbine is closely related to wind speed carrying maximum energy, the wind turbines were selected which their rated wind speed were close to the wind speed carrying maximum energy in the windiest time of the year. Generally, different losses can influence the performance of wind turbines in each location. The main sources of losses are turbine performance losses, electrical losses, and environmental losses (Jain 2011). The examples of turbine performance losses are a decrement in the generated energy owing to soiling of blades, deterioration in performance of gearbox, generator, as well as other

Table 2 Classification for wind power density by Elliott and Schwartz (1993)

Wind power class	Power density (W/m^2) at 10 m	Power density (W/m^2) at 30 m	Power density (W/m^2) at 50 m
1	$0 < P_{10} \leq 100$	$0 < P_{30} \leq 160$	$0 < P_{50} \leq 200$
2	$100 < P_{10} \leq 150$	$160 < P_{30} \leq 240$	$200 < P_{50} \leq 300$
3	$150 < P_{10} \leq 200$	$240 < P_{30} \leq 320$	$300 < P_{50} \leq 400$
4	$200 < P_{10} \leq 250$	$320 < P_{30} \leq 400$	$400 < P_{50} \leq 500$
5	$250 < P_{10} \leq 300$	$400 < P_{30} \leq 480$	$500 < P_{50} \leq 600$
6	$300 < P_{10} \leq 400$	$480 < P_{30} \leq 640$	$600 < P_{50} \leq 800$
7	$400 < P_{10} \leq 1000$	$640 < P_{30} \leq 1600$	$800 < P_{50} \leq 2000$

Table 3 Wind power density classification for 50 m height by Yu and Qu (2010)

Wind power class	Potential	Power density (W/m^2) at 50 m
1	Poor	$P_{50} \leq 200$
2	Marginal	$P_{50} \leq 300$
3	Moderate	$P_{50} \leq 400$
4	Good	$P_{50} \leq 500$
5	Excellent	$P_{50} \leq 600$
6	Excellent	$P_{50} \leq 800$
7	Excellent	$P_{50} \leq 2000$

mechanical components. Electrical losses occur due to difference between the produced energy at the generator and the energy delivered to the grid. The examples are transformer losses and transmission losses from generator to grid. Finally, environmental losses typically include (1) shut down and degradation of the performance due to icing, and (2) extreme weather conditions which are outside the operating range of wind turbine (Jain 2011). In this study, the amount of energy output from considered wind turbines is estimated under the assumption of ideal performance with neglecting such power losses.

Figure 8 illustrates the daily energy output from selected wind turbines throughout the year for 2 years of 2008 and 2009. As seen, the energy output values are very low for some early and late days of the year. In contrast, in mid days of the years the energy output values are really high.

Obviously, the wind energy production during the windiest months does not compensate the other less windy periods of the year. Nevertheless, it should be stated that since the windiest period occurs within the hottest period of the year, the high electricity demands of households for cooling systems can be provided by using wind turbines. It is seen from Fig. 8 that EWT 52/900 wind turbine produces the maximum energy output in different days. On the other hand, the lowest energy output values are obtained using HW 43/600 kW model which has the lowest rated power.

The amounts of capacity factor and energy output of considered wind turbines in different months of the year are listed in Table 5. It should be mentioned that these values were computed by utilizing the average of 2 years data. The obtained results show that the highest and the lowest values of capacity factors as well as energy output of the wind turbines are obtained in July and January, respectively. The best performance in terms of capacity factor and the amount of energy output in all months of the year is obtained using EWT 52/900 kW wind turbine model. For EWT 52/900 kW model, the amounts of monthly capacity factor values and energy output are in the range of 0.053–0.587 and 35.338–393.126 MWh, respectively. According to the Table 5, the AWE 52/750 model has the lowest capacity factor ranging between 0.033 and 0.480 in different months. In addition, the HW 43/600 kW turbine produces the lowest amount of energy output ranging between 14.853 MWh and 226.585 MWh in different months.

Table 4 Technical data of selected wind turbines with hub height of 40 m (http://www.hewind.com; http://www.ewtdirectwind.com; http://www.awe-wind.com)

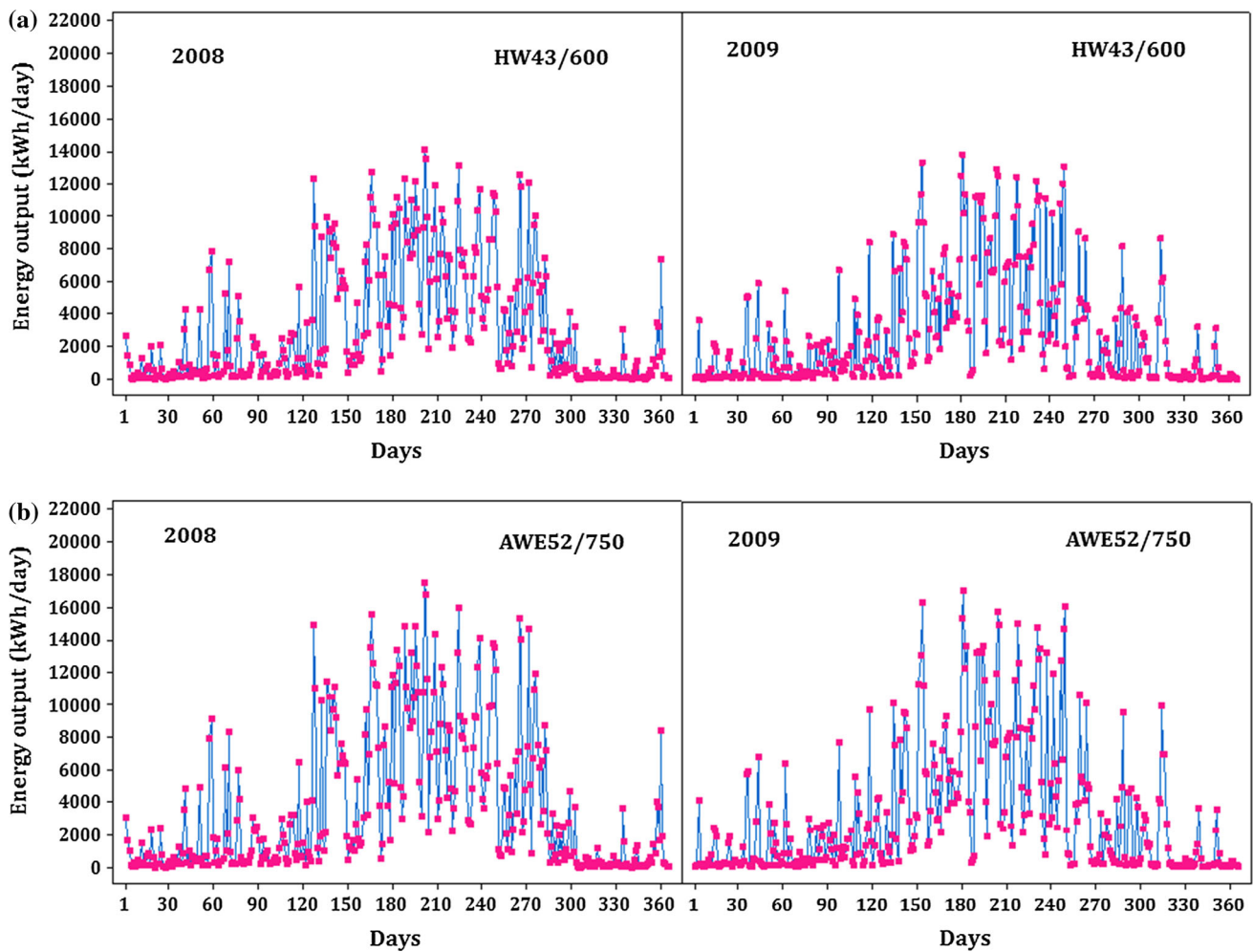| Wind turbine model	Rated power (KW)	Cut-in speed (m/s)	Rated speed (m/s)	Cut-out speed (m/s)	Rotor diameter (m)	Swept area (m^2)
Hewind HW 43/600	600	3.5	14.5	25	43	1452.2
AWE 52/750	750	3	15	25	52	2082
EWT Direct wind 52/900	900	2.5	13	25	52	2083.1
AWE 54/900	900	3	14	25	54	2290

Fig. 8 Daily energy output of nominated wind turbines for 2 years of 2008 and 2009

Economic assessment

Economic feasibility of wind turbine projects is usually dependent on the cost of generated energy by wind turbines. Therefore, the project should be optimized for the lowest possible cost per kWh energy generated. In this study, the present worth method (PWM) is used to calculate the cost of energy (C) produced by four selected wind turbines. In addition, the payback period (PBP) of the nominated wind turbines is calculated in order to make a better decision for selection of a more appropriate wind turbine for the region.

Cost of energy (C)

The cost of energy produced by wind turbines is contingent upon many factors such as wind speed, tax, installation, operation, and maintenance. Except the price of wind turbines, other factors are site dependent (Adaramola et al. 2011).

The cost of wind turbines depends on the manufactures. Nevertheless, the average specific cost of wind turbines for the rated powers of more than 200 kW can be considered equal to 1150 \$/kW (Adaramola et al. 2011; Diaf and Notton 2013).

To estimate the cost of energy, C_I is considered as the initial investment of the wind turbine project and C_{OM} as the operation and maintenance cost including salary, insurance, tax, rent, and salvage value. C_{OM} can be expressed as a percentage m of C_I (Mathew 2006; Saeidi et al. 2013):

$$C_{OM} = mC_I \tag{17}$$

Present worth of operation and maintenance cost, for useful life of n years, can be determined by:

$$PW(C_{OM})_{1-n} = mC_I \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \tag{18}$$
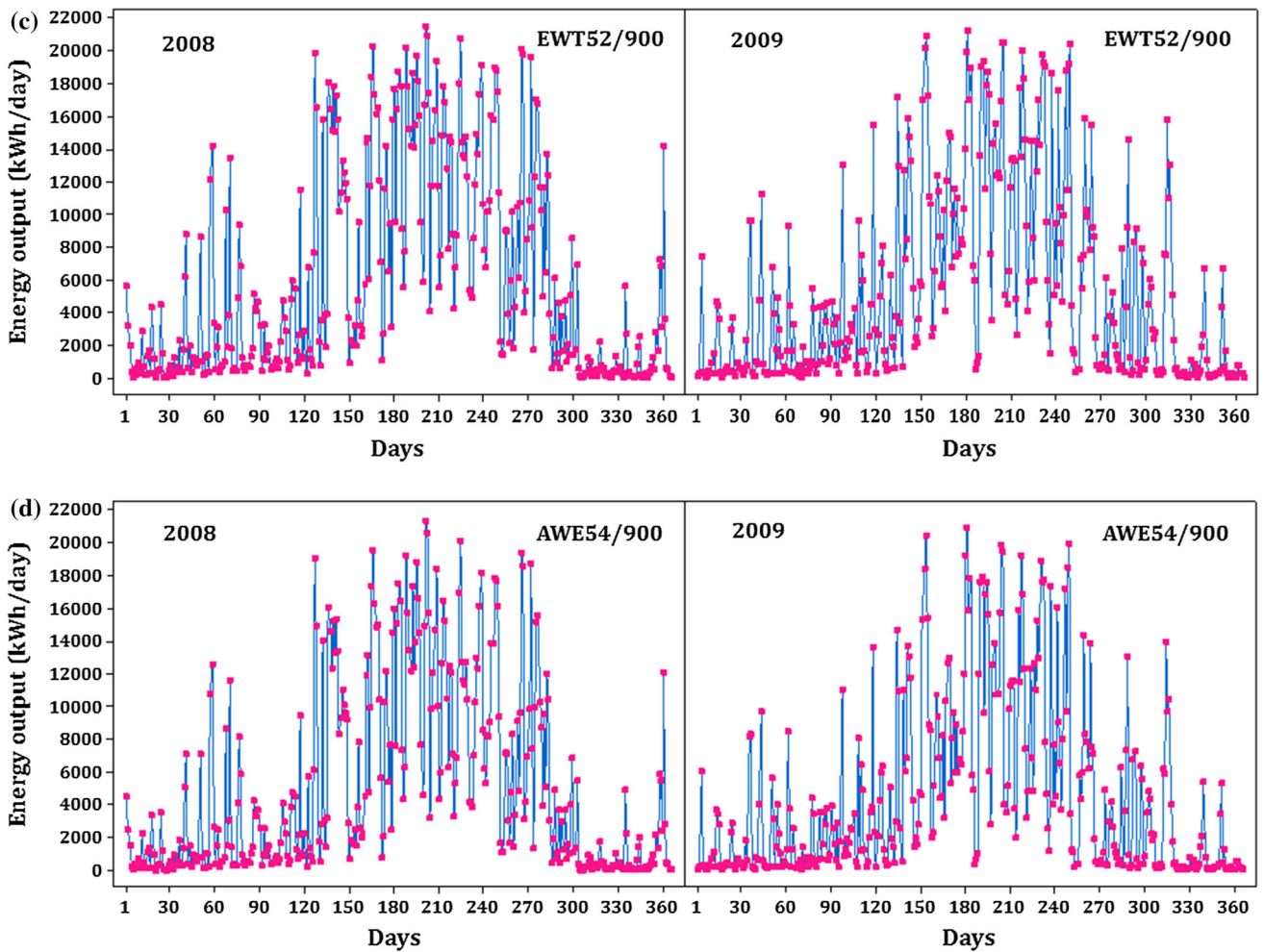
where I is the real rate of discount.

Fig. 8 continued

Table 5 Monthly capacity factor and energy output of nominated wind turbines for Lutak

Months	Hewind HW 43/600 kW		AWE 52/750 kW		EWT direct wind 52/900 kW		AWE 54/900 kW	
	C_F	E_{out} (MWh)	C_F	E_{out} (MWh)	C_F	E_{out} (MWh)	C_F	E_{out} (MWh)
Jan	0.033	14.853	0.033	18.185	0.053	35.338	0.040	26.839
Feb	0.081	32.806	0.077	38.621	0.115	69.684	0.092	55.850
Mar	0.088	39.360	0.083	46.441	0.125	83.584	0.100	67.236
Apr	0.092	39.874	0.087	46.846	0.133	85.906	0.105	68.326
May	0.256	114.088	0.239	133.390	0.331	221.476	0.280	187.658
Jun	0.385	166.351	0.361	194.715	0.482	312.347	0.417	270.490
Jul	0.508	226.585	0.480	267.581	0.587	393.126	0.541	362.526
Aug	0.437	195.269	0.409	228.326	0.544	364.431	0.473	317.029
Sep	0.304	131.424	0.286	154.378	0.382	247.666	0.330	213.736
Oct	0.155	69.126	0.145	80.786	0.212	142.102	0.174	116.312
Nov	0.044	18.796	0.041	22.388	0.065	42.399	0.051	32.787
Dec	0.039	17.392	0.038	20.957	0.060	39.896	0.046	30.777

The accumulated present worth of all costs (PWC) including initial investment cost of the turbine C_I is calculated by (Mathew 2006; Saeidi et al. 2013):

$$PWC|_{1-n} = C_I \left\{ 1 + m \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \right\} \quad (19)$$

Consequently, the yearly operation cost of the wind turbine project can be obtained as (Mathew 2006; Saeidi et al. 2013):

$$PWC = \frac{PWC|_{1-n}}{n} = \frac{C_I}{n} \left\{ 1 + m \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \right\} \quad (20)$$

The output energy (E_{out}) produced by the wind turbine in 1 year is estimated as:

$$E_{out} = 8760 P_r C_F \quad (21)$$

where P_r and C_F are rated power and capacity factor of the wind turbine.

Therefore, cost of electricity generated by the wind turbine in terms of money/kWh is calculated by (Mathew 2006; Saeidi et al. 2013; Fazelpour et al. 2015):

$$C = \frac{PWC}{E_{out}} = \frac{C_I}{8760\,n} \left(\frac{1}{P_r C_F} \right) \left\{ 1 + m \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \right\} \quad (22)$$

The following assumptions are made for economic evaluation:

1. The other initial costs including installation, transportation, custom fee and grid integration are taken 40 % of the wind turbine price (Habibi 2013; Saeidi et al. 2013).
2. The real discount rate, I, can approximately be taken as the difference between interest rate and inflation rate. Interest rate and inflation rate are considered 20 and 16 %, respectively. Thus, the real discount rate is equal to 4 % (Saeidi et al. 2013).
3. Annual operation and maintenance costs plus the land rent, m, is taken to be 4 % of the wind turbine cost (Habibi 2013).
4. Expected useful life, n, of the wind turbines is assumed 20 years (Diaf and Notton 2013; Quan and Leephakpreeda 2015).

The obtained results for cost of energy per kWh for selected wind turbines are shown in Fig. 9. It is observed that the highest cost of unit energy per kWh is obtained by AWE 52/750 kW wind turbine which is equal to 0.0751 $/kWh while the lowest value is attained using EWT 52/900 kW wind turbine which is equal to 0.0572 $/kWh. Thus, it can be concluded that in terms of energy cost, the EWT 52/900 kW model is a more economical option.

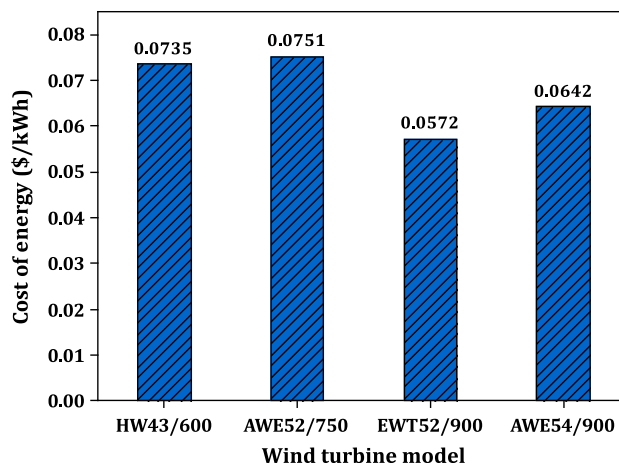The Iranian government has recently approved to increase the purchase tariff for electricity generated by

Fig. 9 Cost of energy output for nominated wind turbines

renewable energies from 0.063 to 0.13 $/kWh, a hundred percent increase (Saeidi et al. 2013). Currently, private wind turbine owners at Manjil and Binalood areas are selling electricity at the rate of about 0.13 $/kWh to the government (Saeidi et al. 2013). According to the Fig. 9, the electricity cost of selected wind turbines are lower than the market price.

Payback period (PBP) analysis

PBP shows the period of time that the investor would recover the initial investment. Therefore, the shorter payback period is more favorable. At payback period, the PWB are equal to PWC, which means (Mathew 2006; Saeidi et al. 2013):

$$EUAB \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] = C_I \left\{ 1 + m \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \right\} \quad (23)$$

EUAB is the Equivalent Uniform Annual Benefit which is the product of the annual electricity produced by the wind turbine and the selling price of energy. The selling price is considered 0.13 $/kWh. Also, PWC is calculated using Eq. (19) (Mathew 2006; Saeidi et al. 2013).

After some mathematical manipulation, PBP can be computed from the following relation as (Mathew 2006; Mohammadi and Mostafaeipour 2013):

$$PBP = -\frac{\ln\left(1 - \frac{IC_I}{EUAB - mC_I}\right)}{\ln(1+I)} \quad (24)$$

Figure 10 shows the results of PBP for nominated wind turbines. It is evident that the PBP values are less than the expected life (20 years) of the wind turbines. The lowest value of 8.91 years is obtained for EWT 52/900 kW wind turbine. Therefore, it should be stated that based on the energy cost and payback period analysis, the EWT
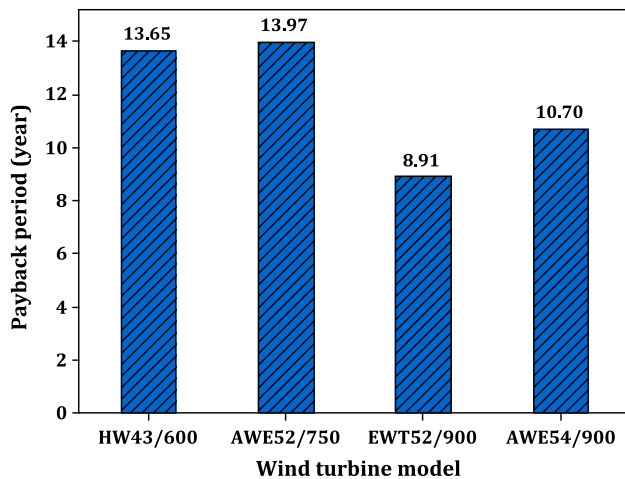
Fig. 10 Payback period (PBP) for nominated wind turbines

52/900 kW wind turbine model can be introduced as a more appropriate option for installation in Lutak area.

Economic evaluation results demonstrate that although the nominated wind turbines for this study were examined for operation at 40 m height, which is generally the lowest hub height for large-scale wind turbine installation, any investment by private market in Lutak area for wind farm construction would be very attractive. Undoubtedly, wind turbines installations at higher heights would be more profitable.

Conclusions

In this study, the major objective was evaluating the possibility of installing wind turbines in Lutak situated in the southeast part of Iran. For this aim, the measured wind speed data at 40 m height for the period of 2 years from 2008 to 2009 were utilized and then Weibull distribution function was employed for wind data analysis. The wind energy potential and wind characteristic for Lutak was investigated. Furthermore, the performance and economic viability of four different commercial wind turbines were evaluated. The main findings from this study can be summarized as:

- The suitability of the Weibull distribution function was assessed via three widely used statistical indicators of RPE, MAPE and R. For this aim, daily wind power density values computed by Weibull function were compared with those calculated using measured data. It was found that Weibull function has an excellent efficiency for wind data analysis in Lutak.
- Analyzing both years wind data revealed that the period of May to September is the windiest time of the year with higher wind speed and wind power so that these values

were very high in some days. Nevertheless, because the wind blows lower in early and late days of year, a very high difference between wind potential was observed throughout the year. In fact, in case of installing wind turbines in Lutak, the generated energy is subjected to a significant change from windiest period (May to September) to other periods. Clearly, the wind power production during the windiest months does not compensate the other less windy periods of the year. However, it should be mentioned that since the windiest period occurs within the hottest period of the year, the high electricity demands of households for cooling systems can be provided by using wind turbines.

- By determining the frequency of wind direction for the height of 37.5 m, it was observed that the wind direction has very identical behavior in both studied years. It was found that wind blows predominantly from northwest and north directions in Lutak. In fact, the highest frequencies of wind directions were attained within the interval of 326.25° and 12.5°.
- Monthly analysis of wind data showed that the highest and the lowest mean wind speed occur in July and January with the values of 11.26 and 3.85 m/s, respectively; moreover, the maximum and minimum monthly mean wind power happen exactly at the same time which the values are 1210.32 and 78.79 W/m^2, respectively.
- Based upon the PNL wind power classification, it was found that during the five windiest months (i.e. May to September), except May for which wind resource in Lutak stands in class 6, in the remaining 4 months wind resource ranks in class 7. This indicated that Lutak has an excellent potential for wind turbines utilization in these months.

From the performance and economic evaluation, it is observed that:

- The conducted analysis based on average data of both years revealed that the highest performance in terms of both capacity factor and electricity production is obtained using EWT 52/900 kW wind turbine. For this turbine, the capacity factor in different months was between 0.053 and 0.587 while the output energy was between 35.338 MWh and 393.126 MWh. Furthermore, it was found that the total amount of energy generated by this wind turbine in the whole year is 1955.649 MWh.
- The obtained costs of energy per kWh using all selected wind turbines were obtained less than the current purchase tariff of renewable energy in Iran (0.13 $/kWh). The minimum cost of unit energy per kWh was attained by using EWT 52/900 kW equal to 0.0572 $/kWh. Moreover, the payback period (PBP) values for

all wind turbines were obtained less than the expected life (20 years) of the wind turbines. The best result is obtained again for EWT 52/900 wind turbine equal to 8.91 years. In fact, the achieved results specified that the EWT 52/900 wind turbine is a more proper economical option among all studied wind turbines for installation in Lutak.

The results of this study encouraged the utilization of wind turbines in Lutak for generating electricity in an environmentally friendly manner, particularly to meet the cooling demands in Lutak and its neighboring. Follow up of this study would be interesting if to use more wind turbines for providing a more complete evaluation and selecting the most economically feasible wind turbine for Lutak. Wind turbines with higher hub heights should be analyzed too. The influence of different losses such as turbine performance, electrical and environmental losses on the performance of each nominated wind turbine should also be investigated in the future for this region.

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