Evaluation of wind energy potential for different regions in Lebanon based on NASA wind speed database

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Abstract. The grid-connected system can be an attractive solution to reduce electricity consumption, dependence on utility power, and increase electricity generation from renewable energy resources like wind energy for residential electricity users. Based on 33-year wind data (1983-2020), this study investigates the potential of wind energy at different locations (Akkar, Baalbek, Beirut, Zahlé, Baabda, Nabatieh, Tripoli, and Sidon) in Lebanon using the Weibull distribution function. Monthly NASA wind speed data during the period (1983-2020) were used to estimate the wind energy potential. The result showed that the averaged wind speeds at the selected regions are varied from 3.695 m/s to 4.457 m/s at the height of 10m. Furthermore, the annual wind power density was estimated at various heights (10m, 30m, and 50m). The results demonstrated that small-scale wind turbines are recommended to be used for generating electricity from wind in the selected regions. Finally, the performance of WRE.060 / 6 kW (vertical axis wind turbine) and Proven WT 6000 (horizontal axis wind turbine) was done based on the monthly NASA wind speed database.

1. Introduction

The energy sector is the most prominent of the economic crisis and the environmental disaster in developing countries including Lebanon. This sector is the biggest waste and the primary cause of budget deficits and debt ballooning, in addition to being the primary cause of air pollution and related deaths. In Lebanon, the growth of population, rising living standards, tourism, and industry sectors have led to an increase in the energy demand and the increased electricity cost associated with fossil fuel-based electrical energy production. Therefore, Lebanon is looking to utilize renewable energy resources instead of fossil fuels to reduce CO₂ emissions and fuel consumption. According to Kinab and Elkhoury [2], Lebanon can generate about 30% of its energy need, which is ten times what it currently produces, from renewable sources. One of the advantages of renewable energy helps to reduce the emission of carbon dioxide (CO₂) or other greenhouse gases (GHG) [3]. It is known that the energy demand in Lebanon exceeds the current generation capacity. While private producers (private generators) are helping to bridge the gap, at the same time, they are seriously increasing the costs and the rates of air pollution [4].

Several scientific researchers have investigated the potential of wind energy in different locations in Lebanon [4-10]. For instance, Kassem et al. [4] investigated the feasibility of 100MW grid-connected wind/solar systems in the Rayak region in Lebanon. The results indicated wind power is considered more efficient than solar power in the selected region. Kassem et al. [5] investigated the potential of
wind energy at three locations in Lebanon. The results indicated that that wind turbines with small capacity can be suitable to generate electricity from wind energy.

Based on the mentioned, the grid-connected system can be an attractive solution to reduce electricity consumption, dependence on utility power, and increase electricity generation from renewable energy resources like wind energy for residential electricity users. Also, the selection of location for the large-scale grid-connected wind project is an important issue due to its direct influence on the performance of the power, economic as well as environmental aspects. Therefore, the present study aims to evaluate the wind energy potential at different locations (Akkar, Baalbek, Beirut, Zahlé, Baabda, Nabatieh, Tripoli, and Sidon) in Lebanon. To achieve this, NASA databases are used to find a suitable region for installing wind systems in the future. Furthermore, the performance of the different types of wind models is estimated based on the monthly NASA wind speed database. In the end, the proposed system can provide valuable inputs for the development of new policies and innovative solutions for the wind market growth in the country.

2. Material and Methods

2.1. Study area and data
Table 1 lists the description of the selected regions including geographical coordinates and altitude. Generally, the climate of Lebanon is the Mediterranean climate (cold to moderate and humid in winter, and hot and dry in summer). The average temperature is varied from 16°C (on the coast) or 10°C (Bekaa Valley) to 32°C. Also, the average precipitation is within the range of 700-1,000mm in coastal areas, 1,500-2,000mm on mountainous elevations, in areas of more than 2,000m, the rains are mainly snowy and help to maintain a basic stock that feeds about 2000 springs during the drought. For analyzing the characteristics of wind energy in the selected location, a monthly NASA database is used in the present study.

| Region  | Latitude [°N] | Longitude [°E] | Altitude [m] |
|---------|----------------|----------------|--------------|
| Akkar   | 34.549         | 36.185         | 479          |
| Baalbek | 34.007         | 36.217         | 1179         |
| Beirut  | 33.896         | 35.507         | 25           |
| Zahlé   | 33.847         | 35.903         | 957          |
| Baabda  | 33.833         | 35.543         | 225          |
| Nabatieh| 33.377         | 35.483         | 424          |
| Tripoli | 34.437         | 35.847         | 24           |
| Sidon   | 33.563         | 35.368         | 16           |

2.2. Weibull distribution function
Analyzing the characteristics of wind speed is considered the first step to determine the wind energy potential at a given location. Several scientific studies have studied wind speed characteristics using various distribution functions [4, 5]. In the literature, the Weibull distribution is widely used to study the statistical analysis of wind data. The probability density function (PDF) and Cumulative Distribution Function (CDF) of the Weibull distribution function can be expressed as in Eqs. (1) and (2), respectively [4, 5].

\[
PDF = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \exp \left(-\left(\frac{v}{c}\right)^k\right) \quad (1)
\]

\[
CDF = 1 - \exp \left(-\left(\frac{v}{c}\right)^k\right) \quad (2)
\]

The shape parameter \((k)\) and scale parameter \((c)\) of the Weibull distribution can be estimated by utilizing Eqs. (3) and (4), respectively.
$$k = \left( \frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n} \right)^{-1}$$

$$c = \left( \frac{1}{n} \sum_{i=1}^{n} v_i^k \right)^{1/k}$$

Where $v$ is the mean wind speed in m/s.

Several methods such as the method of moments, maximum likelihood estimation, and least-squares are used to estimate the Weibull parameters. However, it was stated that the maximum likelihood estimation is the most effective method in determining the parameters of the Weibull distribution function [4, 5]. In this study, the method of maximum-likelihood is utilized to determine the Weibull parameters.

2.3. Wind power density

The wind power density (WPD) indicates how much energy is available in the region that needs for converting it to electricity by using a wind turbine. It is the ratio between the wind power ($P$) and area ($A$) and it can be estimated for the Weibull distribution function using Eq. (5) [4, 5].

$$\left( \frac{P}{A} \right)_W = \frac{1}{2} \rho c^3 \Gamma \left( 1 + \frac{3}{k} \right)$$

In general, the measurement of the wind speed is carried out at 10m height. To obtain the wind energy from the wind turbine, it is necessary to determine the wind speed at the hub height of the wind turbine, which can be calculated by using Eq. (6) [4, 5].

$$\frac{v}{v_{10}} = \left( \frac{z}{z_{10}} \right)^{\alpha}$$

where $v_{10}$ is the wind speed at the original height $z_{10}$, and $\alpha$ is the surface roughness coefficient (Eq. (7)).

$$\alpha = \frac{0.37 - 0.088 \ln(v_{10})}{1 - 0.088 \ln(z_{10}/10)}$$

2.4. Energy production and Capacity factor

In general, the amount of generating electricity from the wind turbine is dependent on wind speed. Thus, the measurement of wind speed and the power curve of the wind turbine is essential to develop a wind project in a specific region. Consequently, the power output ($P_{wt}$) and total energy ($E_{wt}$) of the wind turbine over the period ($t$) can be expressed as [11].

$$P_{wt(i)} = \begin{cases} P_r \frac{v_i^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} & v_{ci} \leq v_i \leq v_r \\ \frac{1}{2} \rho A C_p v_r^2 & v_r \leq v_i \leq v_{co} \\ 0 & v_i \leq v_{ci} and v_i \geq v_{co} \end{cases}$$

$$E_{wt} = \sum_{i=1}^{n} P_{wt(i)} \times t$$

where $C_p$ is the coefficient of performance, which can be determined using Eq. (10).

$$C_p = 2 \frac{P_r}{\rho A v_r^2}$$

Finally, the capacity factor (CF) of the wind turbine can be calculated using Eq. (11) [11].

$$CF = \frac{E_{wt}}{P_r \cdot t}$$
3. Results and discussion

3.1. Wind energy characteristics at the height of 10m

Figure 1 shows the average monthly wind speed for all chosen regions. During the investigation period, the highest and lowest values of wind speed are recorded in February and August with a value of 4.457 m/s and 2.665 m/s, respectively. The highest and lowest values of wind speed are occurred at Sidon and Zahlé/Beirut, respectively.

Furthermore, the monthly wind speed NASA database (1983-2020) was utilized to identify the characteristics of wind speed of each selected region using the Weibull distribution function. Matlab 2015 was used to estimate the parameter of the Weibull distribution function. The value of shape (k) and scale (c) parameters for various heights (10 and 30) are listed in Table 2. Also, the mean and variance of the Weibull distribution function are tabulated in Table 2 for all regions.

For the height of 10m, it is found that the maximum and minimum mean wind speeds are occurred at Tripoli and Beirut/Zahlé with a value of 3.565 m/s and 3.030 m/s, respectively. Additionally, the highest value of shape (k) is recorded in Akkara and the lowest one is obtained in Sidon. It is should be noted that the parameter of the Weibull distribution functions is determined at the height of 30m and 50m based on wind power classification (10m and 30m).

In this study, the value of air density is assumed to be constant ($\rho = 1.23 \text{ kg/m}^3$). The estimated and actual value of the average WPD for each selected region is tabulated in Table 2. It is found that the highest value of WPD is observed in Sidon for all heights. According to the average power density values classification, the wind energy generation potential of all regions is classified as class 1 (poor) [12]. Thus, it can be concluded that the high-scale wind turbines are not suitable to generate electricity from wind energy in the selected regions. However, the low cut-in wind turbine is considered a good option to be utilized to produce electricity in the selected regions, which can be installed on the rooftop of a building.

3.2. Assessment of wind turbines performance

As mentioned previously, the low cut-in wind turbines are being considered as one of the most attractive solutions to reduce the electricity crises and can be installed on the rooftop of the building. In this study, WRE.060 / 6 kW (Vertical axis wind turbine) and Proven WT 6000 (Horizontal axis wind turbine) were selected and the main characteristics of these turbines are available in Ref. [12]. In Lebanon, the average household area is varied from 78m² to 200m² and the average number of floor buildings is within the range of 2-6 floors. Therefore, it is assumed that the number of the floor in the selected building is 2 floors, i.e. the height of the household is about 10m. Figure 2 illustrates the annual energy output for the selected wind turbines at various heights. It is found that the maximum annual energy output is about 4,390 kWh obtained from the Proven WT 6000 model. Also, it is found that the highest
energy output is recorded in Sidon and Tripoli with the value of 4,390 kWh and 4,395 kWh, respectively as shown in Figure 2. Besides, it is observed that the maximum monthly capacity factor is about 73% kWh obtained from the Proven WT 6000 model and recorded in Sidon and Tripoli as shown in Figure 2. These observations can be supported by other scientific researchers who analyzed the wind potential energy in Lebanon. For instance, Kassem et al. [5] found that the CF of the proposed PV system in Oman was within the range of 10-100%.

In general, estimating the cost of energy ($/kWh) is essential to select the best wind turbine between the different models. In fact, due to the problem of lack of information about the price of wind turbines in the country, this section was unsuccessful, which can be considered as another aim of this study.

Table 2. Mean, variance, and Weibull parameters for all regions at 10m height

| Height | Parameter | Akkar | Baalbek | Beirut | Nabatieh | Sidon | Tripoli | Zahlé |
|--------|-----------|-------|---------|--------|----------|-------|---------|-------|
| 10 m   | Mean [m/s]| 3.193 | 3.228   | 3.030  | 3.161    | 3.564 | 3.565   | 3.030 |
|        | Variance  | 0.125 | 0.167   | 0.164  | 0.212    | 0.337 | 0.229   | 0.164 |
|        | c [m/s]   | 3.344 | 3.401   | 3.201  | 3.353    | 3.803 | 3.766   | 3.201 |
|        | k         | 10.939| 9.477   | 8.937  | 8.157    | 7.236 | 8.906   | 8.937 |
|        | WPD [W/m²]| 20.742| 21.659  | 18.001 | 20.621   | 29.995| 29.322  | 18.001|
| 30 m   | Mean [m/s]| 4.285 | 4.328   | 4.086  | 4.245    | 4.731 | 4.732   | 4.086 |
|        | Variance  | 0.224 | 0.300   | 0.299  | 0.383    | 0.594 | 0.403   | 0.299 |
|        | c [m/s]   | 4.488 | 4.560   | 4.316  | 4.503    | 5.049 | 5.000   | 4.316 |
|        | k         | 10.941| 9.477   | 8.935  | 8.156    | 7.237 | 8.912   | 8.935 |
|        | WPD [W/m²]| 50.129| 52.204  | 44.151 | 49.953   | 70.188| 68.604  | 44.151|

Figure 2. Annual energy output and capacity factor produced by wind turbines (energy output: solid line; capacity factor: dashed line)

4. Conclusions
In this study, a 33-year NASA database of seven selection regions in Lebanon has been used to evaluate the potential of wind energy as a power source for producing electricity. To this aim, the Weibull distribution function was utilized to study the distribution of the wind speed characteristics at different locations in Lebanon. The results showed that the maximum wind speed of 4.457 m/s was found in Sidon and the minimum one was found in Beirut and Zahlé with a value of 3.695 m/s. The mean values of WPD were found within the range of 29.995-18.001 W/m². Based on the WPD classifications, it is
observed that a small-scale wind turbine is recommended to be used in the selected regions for generating electricity from wind. From the results of the analysis of the performance of the different types of wind turbines, it is found that Proven WT 6000 (horizontal axis wind turbine) had the highest capacity and energy output compared to the vertical axis wind turbine

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