REDUCING BLACKOUTS VIA WIND POWER, A SPARSE GRID CASE IN LEBANON

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ABSTRACT

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The statistical analysis of wind speed is an essential requirement in estimating the wind energy potential to generate electrical power by grouping and assessing the yearly observations of a selected site. In our attempt to study the wind energy potential in Lebanon we propose an estimation of wind potential by analyzing the wind characteristics of nine regions where the meteorological stations are located. The Weibull distribution function and its parameters were determined and the energy potential of the wind was assessed in each of the studied sites. The comparison of the resulting power density with the PNL classification scheme in Dahr-El-Baidar, Ksara, Marjayoun and Qlaiat proved that Lebanon posses an important opportunity to generate electric power from wind especially during seasons of peak consumption.

Keywords: wind energy, Weibull distribution, likelihood method, power density distribution, Lebanon.

INTRODUCTION

Investments in wind energy in Lebanon are still limited to individual level despite the importance of energy to socio-economic development and to economic growth to achieve a balanced and sustained development of rural areas. The delay to cope with the implementation of renewable energy technologies at large scale is due to the lack of environmental policies and legislations nationwide. Therefore, the analysis of the potential energy that can be generated from renewable resources is not yet sufficiently triggered in order to assess the potential positive impact on the quality of life in Lebanon in general.

Few studies have been conducted on wind energy in Lebanon but the use of wind energy has not been efficiently adapted to optimize the generation of wind-based electricity. This study was carried out to determine the wind energy potential in several regions of Lebanon to invest in the construction of wind farms for the production of additional electric

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power needed to meet the country energy demand. The selection of these regions was based on the availability of wind speed readings registered at the meteorological stations of "Meteo du Liban".

POWER GENERATION IN LEBANON STATE OF THE ART

Currently the Lebanese production of electrical power is heavily dependent on conventional imported fossil fuel (Fardoun *et al*., 2014). The electricity sector in Lebanon suffers important lack in the production of energy and is unable to supply the reliable electricity needed by homes, offices and industry. Thus, daily power outages are commonly frequent; it is estimated to be on average 133 interruptions of service in Beirut and 300 outside Beirut.

The frequent power interruptions and voltage fluctuations forced locals to act on individual or on community level to generate electricity by installing fuel based generators. This leads to additional 25% in spending on electricity every month; local firms report substantial losses of 7% of its sales value and the economic loss to industry may be as high as US$360 million per year.

Recently, locals in rural areas started investing individually to convert wind energy to electric power by installing small wind turbine on top of habitats. The generated wind-based electricity is stored in back-up batteries kicking-in during power failures. Unfortunately, the installation of those wind turbines is not based on studies estimating wind potential, but people are convinced that wind energy represents a cheap alternative to compensate daily blackouts for power generation compared to individual fuel powered generators.

WIND SPEED DATA COLLECTION

The national wind atlas report of 2011 highlighted an important lack of accuracy in the collected data from the various meteorological stations that are spread over the territory. The uncontrolled modification of the landscape surrounding the meteorological stations throughout the years, the presence of new structures surrounding the stations and/or the relocation/reconfiguration of meteorological masts and material have caused significant data discrepancy in the readings on a monthly basis between stations that are located very close to each other or in similar geographical areas (Garrad *et al.*, 2011). To conclude, the data that was used in the mentioned report was assumed to be valid despite the considerable amount of uncertainty noticed in this assumption.

In this study, and in order to avoid the same problems as above, we have used the data of the previous national wind atlas issued in 1969 since no correlation problem in collected data was reported back then (Service Meteorologique du Liban, 1969).

Over the years of operation of the stations, frequency measurements have been averaged within five wind speed intervals ($v_i<1$, $2< v_i <5$, $6< v_i <10$, $11< v_i <15$, $v_i >16$). In these readings all the speeds are rounded to the nearest integer (i.e. for $1<v_i<2$, v_i is rounded to 2 m/s).

Thus to avoid any gap between the recorded wind speed classes, we have changed the lower limit of the class with the upper limit of the previous class. Hence for this study the adopted five wind speed classes are as follow: 0< vi <1, 1< vi <5, 5< vi <10, 10< vi <15, 15< vi <26.

In order to estimate the frequency, we have assumed a randomized uniform distribution of wind speeds according to the number of observations relative to each of the intervals for each area. The resulting average wind speed from this distribution slightly differed from the annual observed average mean speed (Table 1).

TABLE 1

Slight Difference between Measured and Calculated Data

Location	Collected mean speed (m/s)	Calculated mean speed (m/s)
Marjyoun	5.59	5.55
Dahr El-Baidar	5.35	5.86
Qlaiat	5.54	5.90
Ksara	4.78	4.94

The regions subject to the analysis of wind energy potential are spread over the Lebanese territory following the nature of land: littoral, interior and mountain (Table 2).

TABLE 2

Geographical Locations of the Studied Regions

Location	Distance from Beirut (km)	Altitude (m)	Zone	Mast height (m)	Daily readings	Duration (years)	Total readings
Qlaiat	108	7	Littoral	14	3	10	10,519
Ksara	50	918	Interior	13	4	10	10,402
Cedres	130	1915	Mountain	15	8	7	10,414

Dahr El Baydar	40	1512	Mountain	16	4	7	10,504
Marjayoun	85	775	Interior	13	4	10	9,814
Beirut	0	12	Littoral	34	4	7	9,746
Khaldeh	9	7	Littoral	16	4	7	9,480
Tripoli	80	2	Littoral	15	4	7	11,445
Riaq	62	911	Interior	22	4	10	11,993

METHODS AND ANALYSIS

In this work the distribution of wind speed was done using the Weibull distribution method to assess the wind energy potential. The Weibull distribution was proven by previous studies as the most common and reliable distribution function to represent the wind data in the analysis of wind energy potential (Carta *et al*, 2009; Celik *et al.*, 2010; Fyrippis *et al.*, 2010; Ghobadi *et al.*, 2011; He *et al.*, 2010; Keyhani *et al.*, 2010; Safari B., 2011; Zghal *et al.*, 2011). The Weibull distribution with two parameters is given by the following equation:

$$f(v) = \frac{k}{c} \times (\frac{v}{c})^{k-1} \times \exp(-(\frac{v}{c})^{k}) \qquad (1)$$

Where “v” (ms^{-1}) is wind speed, “c” (ms^{-1}) is the scale parameter and “k”, a dimensionless number, is the shape parameter.

The corresponding cumulative probability function of the Weibull distribution is given by:

$$F(v, k, c) = 1 - e^{-(v/c)^{k}} \qquad (2)$$

ESTIMATION OF “k” AND “c”

In the present study, the shape and scale parameters “k” and “c” of the Weibull distribution function for the selected regions are analyzed using the maximum likelihood method and the least square regression method (Akdag *et al.*, 2009; Chang *et al.*, 2011; Garcia *et al.*, 1998; Justus *et al.*, 1978; Morgan *et al.*, 2011; Seguro J.V. and Lambert T.W., 2000; Sopian *et al.*, 1995; Tsurn K. and Hirose H., 2009; Vogiatzis *et al.*, 2004). Even though the maximum likelihood method was ranked in the literature to be the best to determine these parameters [Conradsen *et al.*, 1984; Justus CG. 1980; Seguro *et al.*, 2000; Tsurn *et al.*, 2009), we have chosen to test the degree of accuracy of each of the methods by applying the root mean square error (RMSE) and the mean bias error (MBE) statistical tests. This comparison would allow us to decide on the most accurate correlation to fit the measured data.

MAXIMUM LIKELIHOOD ESTIMATION (MLE) METHOD

$$\hat{k} = \left[\frac{\sum_{i=1}^{n} v_i^{\hat{k}} \ln(v_i)}{\sum_{i=1}^{n} v_i^{\hat{k}}} - \frac{1}{n} \sum_{i=1}^{n} \ln(v_i) \right]^{-1} \quad (3)$$

$$\hat{c} = \left(\frac{1}{n} \sum_{i=1}^{n} v_i^{\hat{k}} \right)^{\frac{1}{\hat{k}}} \quad (4)$$

The non-linear equation of “k” was computed using the successive bisection iterative method. “c” is obtained by replacing the optimal value of ‘k” in equation 3.

LEAST SQUARE ESTIMATION (LSE) METHOD

$$\ln[-\ln\{1 - F(v)\}] = k \ln(v) - k \ln(c) \quad (5)$$

To perform the linear regression, the Weibull cumulative function was transformed into the form of a straight line $Y = aX + b$ by applying twice the natural algorithm, where $Y = \ln(-\ln(1 - F(v)))$ and $X = \ln(v)$. Once Y is plotted against X, "k" will be equal to the slope of the plotted line and "c" can be calculated as follow: $c = \exp(-a/k)$.

WIND SPEED VARIATION WITH HEIGHT ABOVE THE SURFACE

In general, wind speed increases with height above the ground under near-neutral conditions. Since the existing stations don’t record wind speed at different heights it is important to estimate the variation of wind speed with elevation. The power law equation for height projection of wind profiles is given by:

$$v = v_a \left(\frac{z}{z_a} \right)^{\alpha} \quad (6)$$

Where "v_a" is the speed of wind at anemometer height "z_a" and "v" is the required speed at “z” height. The Hellman coefficient “α” depends upon the coastal location and the shape of the terrain, it varies from 0.06 to 0.60; since the studied sites are generally characterized by an unstable air we have chosen α=0.27.

ESTIMATION OF THE POWER DENSITY DISTRIBUTION

The available power in a stream of wind that flows perpendicularly to a cross-section is defined as the flow of kinetic energy. Wind power, expressed in "W", is function of the air density "ρ", the cross-section of the swept area "A" and the wind velocity. The wind power density distribution, expressed in watts per square meter (W/m^2), is function of kinetic energy and the frequency distribution function f(v) of each wind speed. It is obtained as follow (Jamil *et al.*, 1995; Jaramillo *et al.*, 2004):

$$\frac{P(v)}{A} f(v) = \frac{1}{2} \bar{\rho} v^3 f(v) \quad \left[W\, m^{-3}\, s \right] \tag{7}$$

The mean wind power density available over a period T is expressed by integrating equation:

$$\bar{P} = \frac{1}{2} \bar{\rho} \int_0^\infty v^3 f(v) dv \quad \left[W\, m^{-2} \right] \tag{8}$$

As for the calculation of the variation of wind power density with height, the Weibull parameters "k_z" and "c_z" for an altitude "z" above the anemometer level are estimated using the following equations:

$$k_z = \frac{k_a \left[1 - 0.088 \ln\left(z_a / 10 \right) \right]}{\left[1 - 0.088 \ln\left(z / 10 \right) \right]} \tag{9}$$

$$c_z = c_a \left(\frac{z}{z_a} \right)^n \tag{10}$$

Where "k" and "c" are Weibull parameters (at the anemometer height) and the exponent "n" is given by:

$$n = \frac{\left[0.37 - 0.088 \ln c_a \right]}{\left[1 - 0.088 \ln\left(z_a / 10 \right) \right]} \tag{11}$$

RESULTS AND DISCUSSION

Regarding the nine analyzed sites, the stations in Marjyoun, Qlaiat, Dahr-El-Baydar, and Ksara scored respectively the highest average frequency 58.1%, 53.4%, 52.8% and 47.3% for wind speeds ranging from 4 to 16 m/s. The remaining other stations recorded frequencies from ranging between 38% in Cedre and 46% in Tripoli for the same speed interval.

In Qlaiat the frequent and powerful Eurasian continental winds blow from the NE and NNE directions (Figure 1) from October till March. These winds are nearing calm from April till September due to the low pressure that dominates the region. While the SW and WSW winds that are deviated from to the East of the Mediterranean are active all year long. Figure 2 shows that monthly mean wind speed ranges between 5 and 6.9 m/s from October till March and varies between 4.3 to 5 m/s from April till September.

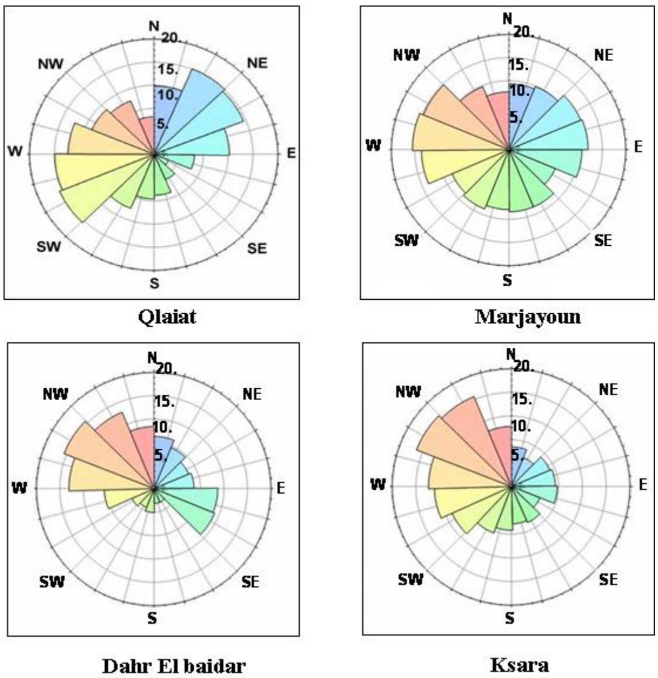

Figure 1. Polar diagram – wind roses of the four sites.

Marjayoun is influenced all year long by maritime winds that come from the West. During summer (from May till September), these winds are at their peak due to the WNW winds that blow there after bypassing Cyprus. From October on, these winds become weaker but then it's the NE winds that are remarkably active in addition to the maritime winds that come from the South, through the Jordan valley, that blow from December till February. The comparison of monthly winds (figure 2) shows that speeds vary between 5-6.8 m/s from May till September and between 4.8-5.5 m/s from October till April.

In Dahr-El-Baidar, the topographic nature of the land directs winds to blow from the E and WNW directions during all the year reaching peak during winter season (December till April). The exception is that the NW winds become predominant during summer due to the Eurasian wind mass that is routed SE over the sea before reaching Cyprus because of low pressure. The monthly wind speeds profile shows that wind speeds varies between 5-6.8 m/s from December till April and between 4.3-5.5 m/s from May till November.

Ksara is hit by the maritime winds blowing from SW-NNW directions all year long. During summer, wind is at peak due to the frequent and powerful NW winds coming from Dahr-El-Baidar. The representation of average monthly wind speeds shows maximum speeds ranging from 4.5-5.6 m/s from February till September (spring and summer seasons) and between 3.5-4.5 m/s from October till January.

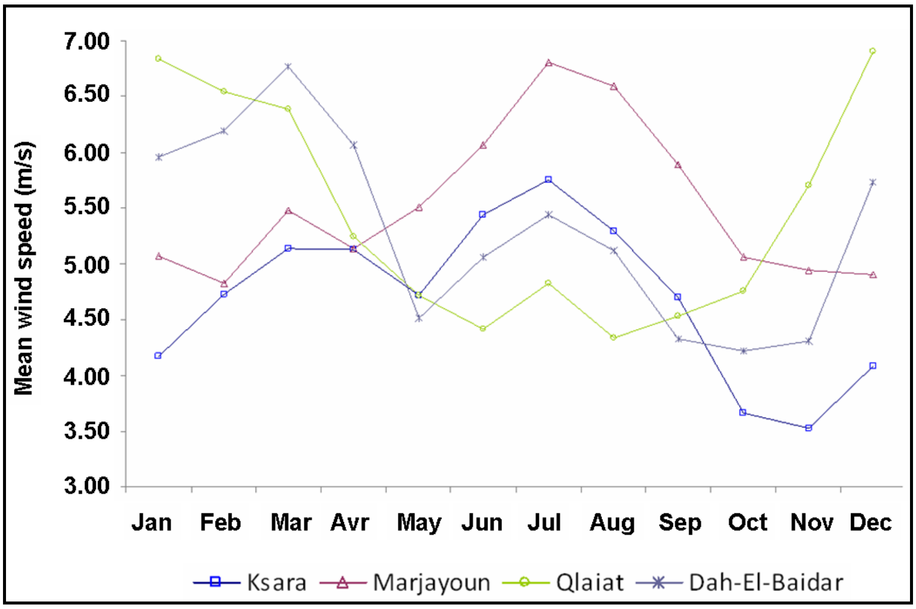

Figure 2. Monthly mean wind speed of the four sites.

WIND SPEED PROBABILITY DENSITY DISTRIBUTION FUNCTION

For consistency purpose, accuracy tests of RMSE and MBE (%) of proposed correlations, were calculated and are shown in Table 3 along with the corresponding computed “k” and “c” values.

TABLE 3

Calculated "k" and "c" Parameters of the Weibull Function and the Corresponding Accuracy Test

Location	k (LSE)	c (LSE)	RMSE	MBE	k (MLE)	c (MLE)	RMSE	MBE
Dahr El Baydar	1.39	5.84	0.034	-0.723%	1.37	5.86	0.036	-0.745%
Ksara	1.32	5.12	0.080	-1.234%	1.30	5.15	0.084	-1.268%
Marjayoun	1.45	6.20	0.020	-0.513%	1.52	6.15	0.016	-0.461%
Qlaiat	1.37	5.92	0.032	-0.677%	1.31	5.97	0.038	-0.733%

These % values are very low indicating fairly good agreement with measured data. As for the regions of Dahr-El-Baidar, Ksara and Qlaiat the linear regression method gave higher degree of accuracy while in Marjayoun "k" and "c" were best estimated with the maximum likelihood method.

The best fitted wind speed distribution probability parameters were set according to the carried tests where "k" and "c" are respectively: 1) 1.39 and 5.84 for the site of Dahr-El-Baidar; 2) 1.32 and 5.12 for the site of Ksara; 3) 1.52 and 6.15 for the site of Marjayoun; and 4) 1.37 and 5.92 for the site of Qlaiat. The comparison of the four graphics illustrated in Figure 6 proves that the four sites are experiencing very good opportunities of wind speeds exceeding 4.5 m/s. The median speed is peak at Marjayoun with 4.8 m/s, and minimum in Ksara with 3.88 m/s. In Dahr-El-Baidar and Qlaiat wind speed conditions are significantly comparable except that the median wind speed in Qlaiat (4.53 m/s) is slightly greater than in Dah-El-baidar (4.49 m/s) due to the important frequency in lower speeds.

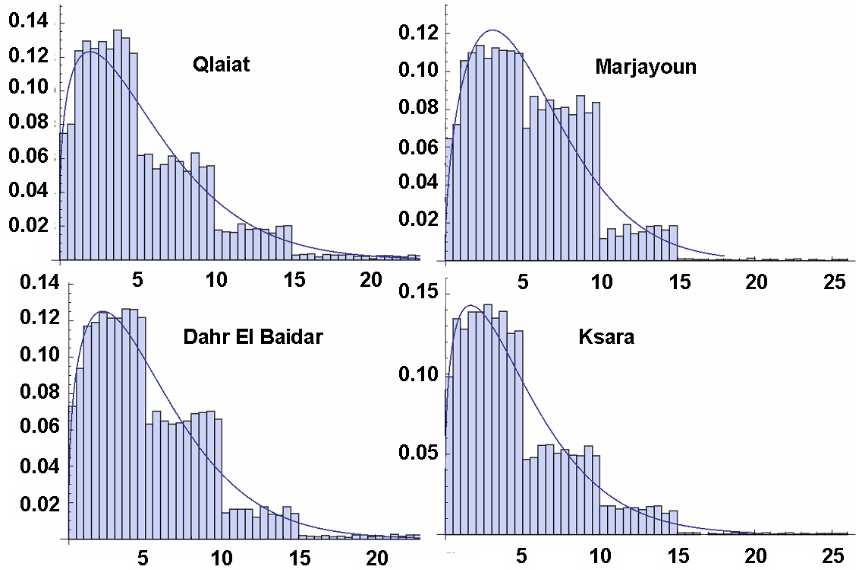

Figure 3. Yearly Weibull probability density distribution for the four sites.

The comparison of the cumulative distributed function graphics of the four sites with the classification of the PNL shows that all of the four sites fall within the category of areas suitable for year-round energy production (Table 4). At 50 m above surface, wind power in Qlaiat, Marjayoun and Dahr-El-Baidar are class 5 while Ksara is class 4. For wind speeds ranging from 4 to 16 m/s we have more than 5200 hrs/year in each of the four sites with a maximum of 6200 hrs/year in Marjayoun.

TABLE 4

Classification of Wind Potential at 50 m above Surface

Location	**Power (W/m^2)**	**PNL Class**	**Commercial Viability**
Dahr-El-Baidar	541	5	Very Good
Ksara	417	4	Good
Marjayoun	536	5	Very Good
Qlaiat	576	5	Very Good

To evaluate the variation of wind speed with height, the power law exponent is set to be 0.27 due to the rough nature of surface of the selected areas. Therefore, for the heights above forty meters the regions of Dahr-El-Baidar, Marjayoun and Qlaiat are exposed to wind speeds greater than 7 m/s. In Ksara we need to go as high as sixty meters above surface to reach 7 m/s. The comparison of wind speed at 50 and 65 m (Table 5) with the wind power classification schemes of: 1) the US Department of Energy (DOE) (7 classes) (U.S. Army Corps of Engineers, 2004); 2) the Massachusetts Technology Collaborative (MTC) (9 classes) (U.S. Army, 2004); 3) and the European Wind Energy Association (EWEA) (3 classes) (Dundar *et al.*, 2002) proves that the resulting wind power in the four sites is economically feasible.

TABLE 5

Comparison with DOE and MTC Classification

	DOE (50 m)	**MTC (65 m)**
Dahr-El-Baidar	5	6
Ksara	3	4
Marjayoun	6	7
Qlaiat	5	6

A CASE STUDY: THE CONTRIBUTION OF POTENTIAL WIND ENERGY TO REDUCE BLACKOUTS

In this paragraph, the wind energy output was compared in the four studied areas to determine the best location to install wind farm. At this stage, the economic study and feasibility analysis of the wind farm are not taken into consideration in the decision process. Hence only the technical evaluation of the wind turbine is considered.

Since the design characteristic of the wind turbine affects the wind energy electrical output, three different rated power turbines were considered (Table 6). The power curves of the selected wind turbines are shown in Figure 4.

TABLE 6

Technical Specifications of Selected Turbines

	Fuhrlander		
Specification	**FL 30**	**FL 100**	**FL 250**
Rated power (kW)	30	100	250
Hub height (m)	27	35	50
Rotor diameter (m)	13	21	29.5
Swept area (m2)	133	346	683.49
Cut-in wind speed (m/s)	3	3	2.5
Rated wind speed (m/s)	12	12	15
Cut-out wind speed (m/s)	25	25	25
Maximum hub height (m)	27	35	50

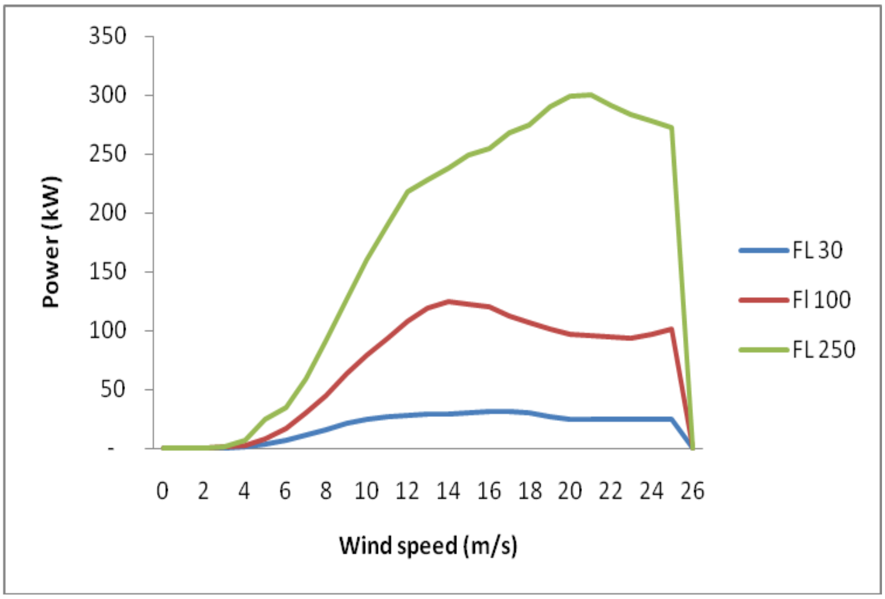

Figure 4. Power curves of the selected turbines.

In order to calculate wind speeds at any hub height, log law was used in this study. Table 7 shows the form (k) and scale (c) Weibull parameters calculated relatively to each of the heights. Thus, based on the computed c & k the performance of the different wind turbines in Marjayoun, Dahr-el-Baidar , Ksara and Qlaiat was estimated as shown in Table 8.

TABLE 7

Weibull Parameters (c, k) at Different Heights

	Marjayoun		**Dahr-El-Baidar**		**Ksara**		**Qlaiat**	
Height	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**
@ 27 m	7.19	1.63	6.59	1.43	6.10	1.39	6.90	1.39
@ 35 m	7.60	1.67	6.98	1.47	6.48	1.42	7.30	1.42
@ 50 m	8.21	1.74	7.56	1.52	7.04	1.47	7.89	1.48

Of the four sites, Marjayoun recorded the best wind energy output with a capacity factor exceeding 31% for the three turbines. As it is shown in Table X, the maximum electricity generation is in Marjayoun and the minimum is in Ksara.

TABLE 8

Weibull Parameters (c, k) at Different Heights

Location		**FL 30 @ 27 m**	**FL 100 @ 35 m**	**FL 250 @ 50 m**
Marjayoun	E (kWh)	86,325	282,041	684,301
	Cf	33%	32%	31%
Dahr-El-Baidar	E (kWh)	76,058	248,742	606,764
	Cf	29%	28%	28%
Ksara	E (kWh)	67,885	222,640	545,231
	Cf	26%	25%	25%
Qlaiat	E (kWh)	81,668	266,181	646,261
	Cf	31%	30%	30%

Therefore, the Marjayoun site is selected to install a wind farm to feed the city of Nabatieh with wind generated electricity. The city of Nabatieh is located in the south of Lebanon, 10 km to the west of Marjayoun. In this city the electricity supply is restricted to 12 hrs per day. By choosing the FL 250 wind turbine rated 250 kW at 50 m hub height, 91 turbines are required to provide electricity during blackout periods for the 40,000 city inhabitants. This estimate is based on the consumption rate per capita of 3,120 kWh/year defined by the Electricity of Lebanon administration.

Taking into consideration the important technical losses of electricity during transmission and distribution, estimated to 15% of the production (Akkaya *et al*, 2009), Seventeen additional turbines will be required to cope with these losses. In total, a wind farm of a capacity of 27MW (108 FL 250 turbines) is required to reduce blackout duration to zero for the city of Nabatieh should the winds blow 24h per day all year long, which is not realistic. Therefore, along with the wind farm, a power backup system should be put in place to store the generated electricity to be used when needed.

CONCLUSION

The results of the present study can be regarded as preliminary results, due to the fact that the data used in the analysis is forty three years old. However, these results prove that in Lebanon the potential of wind energy is highly rewarding if capitalized on both in terms of capacity usage and energy quality.

The use of the widely used Weibul distribution function in our analysis allowed us to determine the characteristics of wind energy of nine sites spread over the Lebanese territory. The shortlisted four sites presented important wind energy potential to build wind farms generating electric power for more than 5200 hrs/year. Three of the balance sites proved to be suitable for the installation of small/medium wind turbine.

In this study, the comparison of monthly mean wind speed shows that the windiest season in: 1) Dahr-El-Baidar and Qlaiat is during the rainy/cold season; 2) during the semi-dry and the dry/hot seasons in Marjayoun; and 3) and during dry/hot season in Ksara. Knowing that the electricity sector in Lebanon experiences the peak electricity loads during the abovementioned seasons due to the additional consumption of electricity to heat up water and habitats (cold season) or to chill habitats (hot season).

The results show that the obtained values are sufficient to build high power wind farms in Dahr-El-Baidar, Marjayoun and Qlaiat since at 10 m above surface the power density exceeds 250W/m^2 (Onat N. and Ersoz S., 2010). In four of the remaining six sites, medium power wind farms are commercially viable.

Our results proved that the wind energy in Lebanon is a reliable source of energy to reduce power intermittency. The improvement of the quality of distribution grid network will optimize the power transmission to the end user and reduce the size of wind farms.

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