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Optimal Sizing of Wind Power Systems in Three High Wind Potential Zones in Kuwait for Remote Housing Electrification

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Abstract- this paper presents a technical study for wind power systems in three sites in Kuwait namely Al-Wafra, Um-Omara and Al-Taweel. Hourly wind speed data for three years are used in order to optimally sizing the wind power systems. Firstly, the Wiebull, function is used to model the wind speed data for each sites. After that a numerical method is used to optimize the energy sources in the power system (wind turbine and battery) using MATLAB. After that the MATLAB is used to analyze the performance of these systems. The results show that the sizing ratio of the turbine for Al-Wafra, Um-Omara and Al-Taweel are 17.61, 23.88 and 23.49 respectively. While the sizing ratio of the storage battery for Al-Wafra, Um-Omara and Al-Taweel are 0.724, 1.566 and 1.22 respectively. On the other hand the average cost of energy generated by wind power systems in Kuwait in case of standalone system is 0.282 USD/ kWh while it is 0.15 USD/kWh in case of grid connected system. This research presents worthwhile technical information for those who are interested in wind power systems installation in Kuwait.

Keywords- Wind power systems, sizing of wind power system, wind power, Kuwait.

1. Introduction

Based on the fact that wind systems are clean, environment friendly and secure energy sources, wind system installation has played an important role worldwide. However, the drawback of wind systems is the high capital cost as compared to conventional energy sources. Therefore, many research works are carried out currently focusing on optimization of wind systems [1]. Grid connected wind power systems can be divided into two parts; building integrated wind systems and distribution generatio wind systems. Building integrated wind systems usually supply a specific load and inject the excess energy to the grid. On the other hand the distribution generatio wind systems inject the whole produced energy to the grid without feeding any local load. On the other hand the standalone wind system supply an individual load without connection to the grid [2].

Wind power system size and performance strongly depend on wind speed therefore, to optimize a wind power system, extensive studies related to the wind speed have to be done [3]. The importance of the wind speed in sizing wind systems lies in the fact that the wind turbine output energy strongly depends on the wind speed

However, according to a World Bank report published in 2010, The Electricity production (MWh) in Kuwait was reported at 51749 GWh in 2008 [4]. This energy is totally generated by fossil fuel (64.4% oil sources and 35.7% natural gas), while the alternative energy sources including solar, wind, hydro, nuclear are not used at all [5]. Based on this, the Kuwaiti government has set recently the most ambitious target for using renewable energy in the Gulf region. The new Kuwaiti government renewable energy policy aims to generate 10% of its electricity from sustainable sources by 2020. The Kuwaiti government is trying to free up oil for export and expand its generatio capacity to support increased tourism, manufacturing and home building in a $112-billion development program. However, renewable energy is a new subject for Kuwait, and that's why there's a lack of information regarding the suitability of renewable energy sources for Kuwait’s weather (see figures 1 and 2) [6].

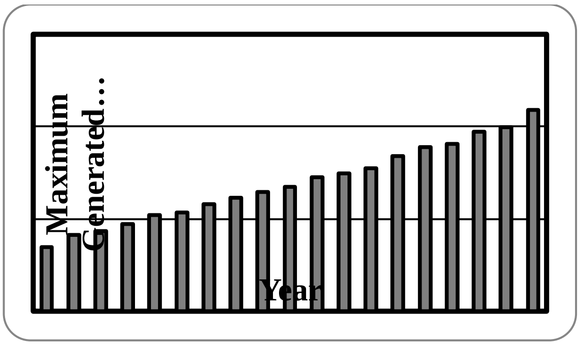

Fig. 1. Maximum generation electricity in Kuwait

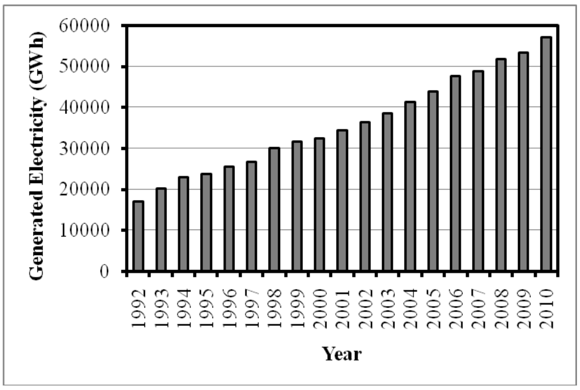

Fig. 2. Generated Electricity in Kuwait.

Kuwait is a desert country with some sites that has high wind power potentials sun and therefore, the use wind power systems for electricity generatio is promising at this country. Based on this, the main objective of this paper is to assist the electricity generated by wind power systems located at three main sites in Kuwait namely Al-Wafra, Um-Omara and Al-Taweel. This assessment -which is done using technical and economical criteria- provides worthwhile information for those who interested in wind power system installation at Kuwait. This work is done based on real wind speed data for the period 2009-2011. These data are provided by Kuwait National Meteorological Network KNMN at KISR.

2. Wind Speed Situation in Kuwait

In this research we are trying investigate the wind potential in three zones in Kuwait namely Al-Wafra, Al-Taweel and Um-Omara. Wind speed date for 3 years are obtained form (Kuwait National Meteorological Network (KNMN) at KISR). Figure 3 shows monthly averages of the wind speed at these sites. From the figure it is clear that these sites are promising for wind power systems whereas the wind speed average reaches about 7 m/s in the summer time while it not less than 4 m/s in the winter time.

Figures 4 to 6 shows the wind speed distribution histogram for the three sites from these figures it is very clear that the wind speed is in the range of 3-6 m/s most if the time in the year. This to say that a wind turbine is supposed to be rotating most of the time in year since the cut in speed of the most wind turbines is 3 m/s.

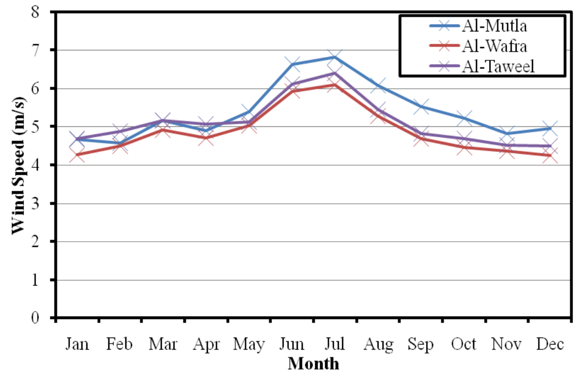

Fig. 3. Monthly averages of wind speed for the selected sites

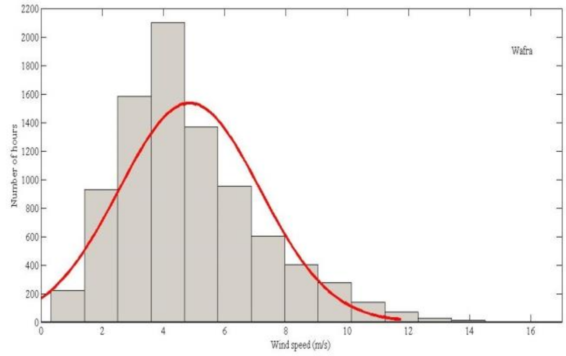

Fig. 4. Wind speed distribution histogram for Al-Wafra

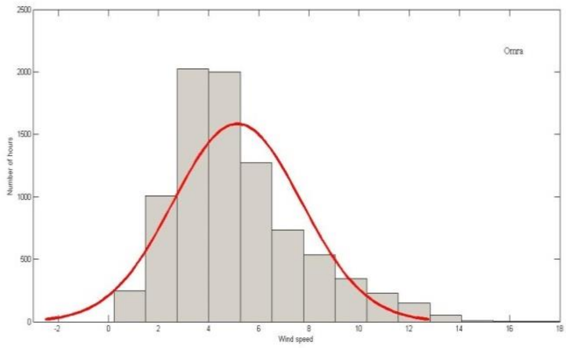

Fig. 5. Wind speed distribution histogram for Um-Omara

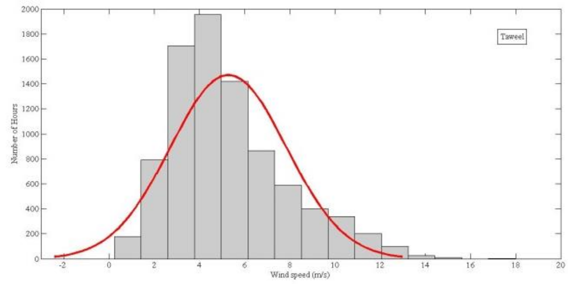

Fig. 6. Wind speed distribution histogram for Al-Taweel

However, in order model these profiles and to generalize the obtain results of other sites in Kuwait and nearby countries, Weibull distribution function is used. The weibull distribution function is given by

$$y = ab^{-b}x^{b-1}e^{-\left(x/b\right)^{b}} \tag{1}$$

where y is the number of hours , x is the wind speed while a and b are coefficients [7]. Matlab fitting tool is used to find these coefficients. Table 1 shows the calculated coefficients for each sites as well as the average value.

Table 1. Weibull function coofeicents

Site	a	b
Al-Wafra	5.4914	2.2438
Al-Taweel	5.9919	2.1921
Um-Omara	5.8223	2.1426
Av.	5.769	2.193

Based on the hourly data provided and illustrated in figures 5 to 7. The average values of the hourly wind speed for Al-Wafra, Al-Taweel, and Um-Omara are 4.85 m/s, 5.29 m/s and 5.14 m/s respectively. Meanwhile the maximum wind speed value was 16.67 m/s for Um-Omara site, 17.98 for Al-Taweel site and 19.2 m/s for Um-Omara site. Based on this, assume that we have a HUMMER 5 kW wind turbine that generates 790 Watt at 5 m/s. this means that this wind turbine will generates 6.92 MWh per year which means that the yield factor (energy generated to the rated capacity) of this power source is 1384 kWh/1 kWp. This roughly calculated number shows that the wind power systems can be a feasible solution for remote electrification in these sites. And therefore, optimal sizing recommendation must be provided for future projects.

3. Sizing of Wind Power System

Figure 7 shows a typical wind power system consisting of wind generator(s), block of storage batteries, DC-DC converters, AC-DC converters and loads. The storage battery supplies the load in the case that the wind generator is not able to cover the demanded energy. On other hand it is charged by the excess energy in case of any.

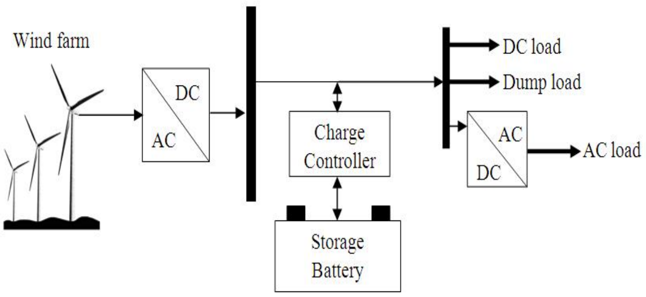

Fig. 7. Typical wind power system

The output energy of the wind generator of a wind system as a function of wind speed is illustrated in figure 8.

From Figure 8, the characteristic of a wind turbine, from the figure the output power of a wind turbine can be described as follows (Dursun, 2011, Orosa, 2012, Emami, 2012),

$$\begin{Bmatrix} 0, & V_{cut\ out} < V < V_{cut\ in} \\ P_{rated}, & V = V_{rated} \\ P = c_1 e^{c_2 V} + c_3 e^{c_4 V}, & V_{cut\ in} < V < V_{rated} \end{Bmatrix} \quad (2)$$

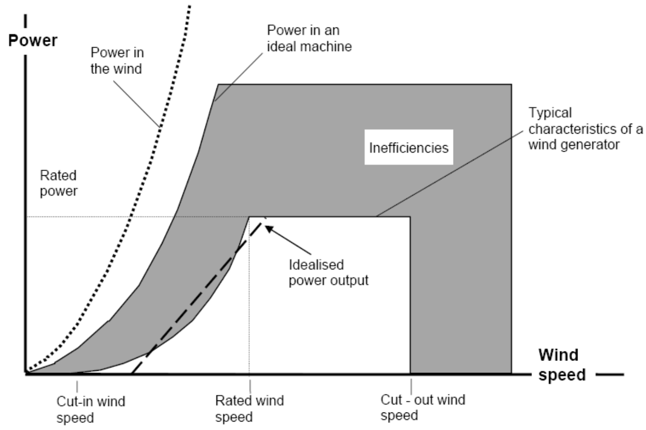

Fig. 8. A wind turbine characteristic

The coefficients (C1-C4) can be calculated by fitting tool such as MATLAB fitting tool. However, the energy at the front end of a wind power system or at the load side is given by,

$$E_D(t) = \sum_{i=1}^{8670} (E_W(t) - E_L(t)) \quad (3)$$

where E_L is the load energy demand.

The result of equation.3 is that it may be either positive $(E_W > E_L)$ or negative $(E_W < E_L)$. If energy difference is positive then there is an excess in energy (EE), while if it is negative then there will be an energy deficit (ED). The excess energy is stored in batteries in order to be used in case of energy deficit. Meanwhile, energy deficit can be defined as the disability of the wind turbine to provide power to the load at a specific time. Therefore, the energy flow across the battery can be expressed by,

$$E_{Battery}(t) = \begin{Bmatrix} E_{Battery}(t-1) * \eta_{inv} * \eta_{wire} * \eta_{discharging} - E_L(t) & E_D < 0 \\ E_{Battery}(t-1) * \eta_{charging} + E_W(t) & E_D > 0 \\ E_{Battery}(t-1) & E_D = 0 \end{Bmatrix} \quad (4)$$

The proposed sizing process starts by defining the specification of a wind turbine, storage battery, location, and load demand. Then hourly wind speed for the selected location is obtained. Here a range of wind turbine capacity is set and the developed model of the wind turbine described in equation (1) is used to predict the generated power through a year time. At this point the energy balance is calculated using equation 2 as well as the excess energy. Here the battery size (C_B) is estimated using the excess energy as follows

$$C_B = \frac{\sum_{i=0}^{8750} Excess\ energy\ g_i * \eta_B}{V_B} \quad (5)$$

Where η_B and V_B are the charging efficiency and the battery voltage respectively.

After defining the values of the wind turbine and the battery, the defined wind turbine model, the obtained hourly wind speed data, the assumed hourly load demand and the battery model described in equation 3, a simulation of the system is performed in order to calculate it is reliability by calculating the loss of load probability which given by,

$$LLP = \frac{\sum_{i=1}^{366} Energy\ deficits_i}{\sum_{j=1}^{366} Energy\ demand_j} \quad (6)$$

This iterative loop is repeated until reaching the maximum range of the wind turbine capacity. After that the pairs (wind turbine capacity, battery capacity) which investigate the desired LLP are listed in array. Finally, the cost of the system for each possible configuratio is calculated and based on the minimum cost, the optimum system is selected [8].

4. Results and Discussion

In this section, an hourly load demand occurring in 24 hours is used. The average daily load demand is 6.130 kWh/day while the maximum peak power is 520 kW as illustrated in Figure 9.

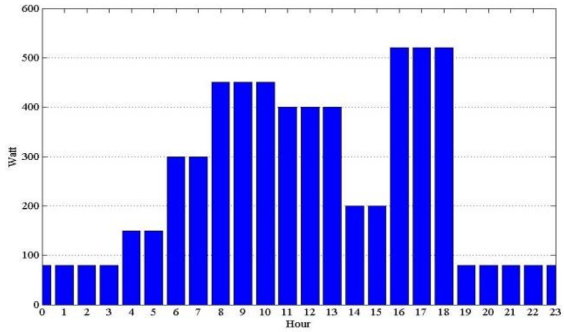

Fig. 9. Simulated load demand

The optimum size of the wind power system which supposed to supply the assumed load is calculated considering the wind speed profile of the selected sites. Here the calculated variables are wind farm capacity (CW) and batteries capacity (CB). After that each system is simulated using the hourly load demand and the provided hourly wind speed to calculate the energy produced by the wind farm, damped energy (ED) and energy deficits (EN). Finally the loss of load probability and the cost of energy (CoE) of each system is calculated.

Table 2 shows the wind farm rating, the storage batteries capacity, the LLP and the CoE of each system. In calculating the CoE the life time of the wind generators is supposed to be 20 years while it is supposed that the life cycle of the storage battery is 5 years. Table 2 shows the optimum site of the wind system. To power the assumed load at 99% availability rate (1 % loss of load probability) in Al-Wafra 4.5 kWp wind a 370 Ah/12 batter is required. Meanwhile a 6.1 kWp and 800 Ah/12 battery are required to power such a load in Um-Omara. As for The Al-Taweel site, the situation was close to the Um-Omara site whereas the required system specifications are 6 kWp and 700 Ah/12 storage unit.

From these results, it is clear that Al-Wafra site has the most wind power potential as compared to the other selected sites. However, to generalize these sizing results, assume that a S_W is the ratio of the maximum daily energy that can be generated at full rated operatio to the daily energy demanded On the other hand, SB is the capacity of the battery in kWh to the daily demanded energy. Based on these assumptions the sizing ratios described on table 3 can be derived.

Table 2. Designed systems specifications

Site name	C_W (kWp)	C_B (kAh)	LLP	E_D (MWh)	E_N (kWh)
Al-Wafra	4.5	0.37	1.43%	6.86	31.9
Um-Omara	6.1	0.8	1.17%	11.7	26.1
Tawell	6	0.7	1.16%	12.3	25.9

Table 3. Systems sizing ratios

Site name	S_W	S_B
Al-Wafra	17.61	0.724
Um-Omara	23.88	1.566
Tawell	23.49	1.370
Av.	21,66	1.220

As Al-Wafra site is the most promising site among these sites. A full analysis is done for the recommended system. Figure 10 shows the generated power by the wind turbine and the load power. From the figure it is clear that most of the time the power generated by the wind turbine is higher than the load power which interprets the high value of the energy excess of damped energy mentioned in Table 2.

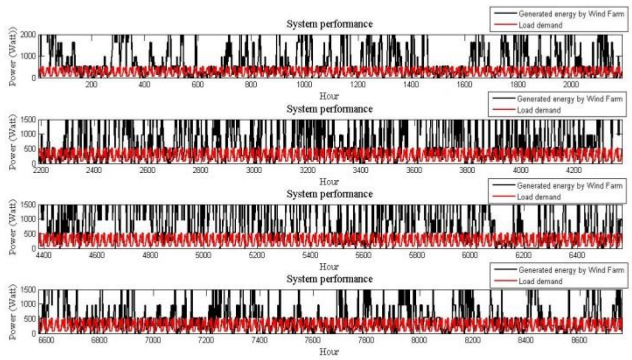

Fig. 10. Generated power by the system and the load power profile

Meanwhile figure 11 shows the batter role through a year time. From the figure, the battery is intensively used in the first and fourth quarters of the year specially in the period of November to February whereas low wind speed averages are observed in this period. However, in the middle of the year the battery is mainly used to cover some minor shortages happen due to instantaneous low wind speed value. However, Figure 12 shows the shortages time in the year. According to this figure the loss of the load probability is 1.43% which means that the availability rate is about 98.5 %. Finally Figure 13 shows the excess energy generated by the system. This amount of energy must be damped in case of a standalone system. However, such amount of energy can be well harnessed in case of building integrated system whereas in these system all this energy amount is supposed to be fed back to the grid.

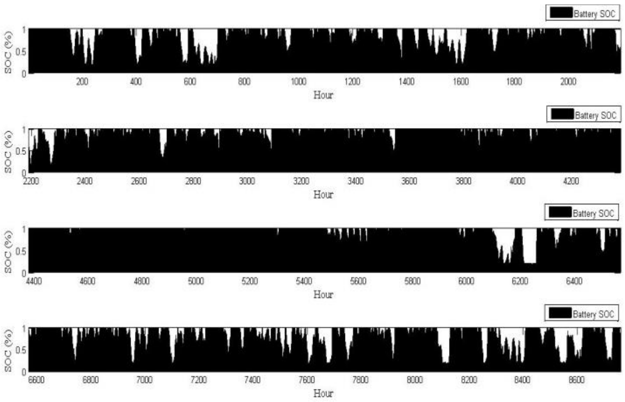

Fig.11. Battery role through the year time

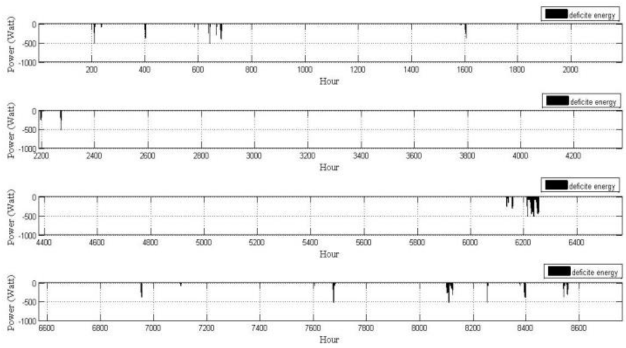

Fig. 12. Energy shortages during a year time

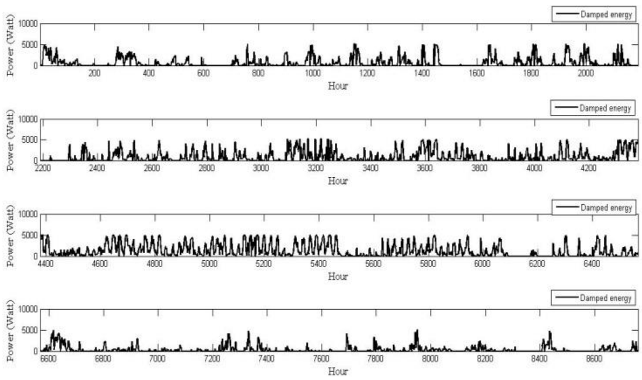

Fig. 13. Excess Energy by the system

To calculate the cost of the energy, the natural of the system must be defined first. In case of standalone systems, all the excess energy illustrated in figure 14 will be damped and therefore, only the harnessed energy must be included in the calculation of the cost of the energy. However, in case of building integrated system the excess energy can be encountered and absolutely the cost of energy will be much lower than the one calculated for standalone system. Table 4 shows the cost of energy generated by wind power systems in the selected sites.

Table 4. Cost of energy generated by the systems

Site name	Standalone system (USD/kWh)	Building integrated system (USD/kWh)
Al-Wafra	0.227	0.056
Um-Omara	0.342	0.225
Tawell	0.278	0.179
Av.	0.282	0.15

The calculation of the system cost is done assuming that the system life cycle time is 20 years, the cost of the wind turbine is 1.2 USD/ Wp, the cost of battery is 2.5 USD/Ah and additional costs 2000 USD.

5. Conclusion

In this research, an investigation of the feasibility of wind power systems in Kuwait was done for three sites. Analysis and modeling of hourly wind speed series was done firstly. After that system sizes and sizes ratio were done using a proposed sizing procedure. Finally an analysis was done for the three systems in order to find out the technical and economical features of these systems. The results showed that the sizing ratio of the turbine for Al-Wafra, Um-Omara and Al-Taweel are 17.61, 23.88 and 23.49 respectively. While the sizing ratio of the storage battery for Al-Wafra, Um-Omara and Al-Taweel are 0.724, 1.566 and 1.22 respectively. On the other hand the average cost of energy generated by wind power systems in Kuwait in case of standalone system is 0.282 USD/ kWh while it is 0.15 USD/kWh in case of grid connected system. Such a research is helpful for those who are interested in wind power system investment in Kuwait and nearby countries.

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