Reducing Peak Electricity Demand through 300MW Wind Farm North of Jeddah, Saudi Arabia

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***Abstract*— The drastic increase in electricity demand over the last decade has been putting a huge burden on the Saudi utility company to plan ahead and guarantee continuous power supply to its customers. Private investments in power generation are being solicited and encouraged to contribute significantly to the power grids and alleviate the burden of meeting the surge in power demand. Jeddah, the second largest city in the Kingdom, is located in the western region, which is a major component of the power grid. Power generation plants in Saudi Arabia are conventional fossil-fuel thermal plants; therefore, the addition of a wind farm north of Jeddah would be greener to Earth, have a significant effect on power generation, and relieve the utility company from a considerable chunk of its peak demand obligation.**

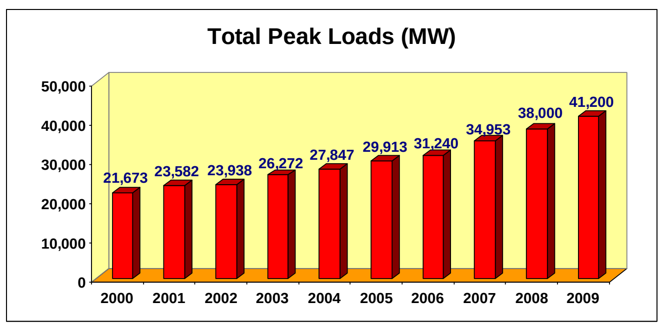
***Index Term*—DSM, Electricity Demand, Renewable Energy, Saudi Arabia, Wind Farms.**

I. Introduction

Electricity demand in Saudi Arabia has been rapidly increasing for the last forty years. In 1975, the total number of power utility customers was only 351,000 and the total peak load was 300MW. Thirty years later, in 2005, the total number of power utility customers rose 14 times to reach 4,728,918; however, the total peak load soared 100 times to reach 29,913MW [1]. Furthermore, over the past decade alone, the total peak load almost doubled from 21GW in the year 2000 to more than 41GW in 2009, and the total available generation capacity doubled from 22GW in 2000 to 44GW in 2009 [2]. Figure 1 shows trends of the total electricity generation data and total peak loads over the last ten years. Compared to last year, the total actual generation capacity was about 38GW, a 10% increase from 2008, and the total available power was 44.5GW in 2009, a 13.4% increase from 2008 [2].

The rapidly increasing population, the increase in number of customer connections, the expansion in industrialization and development projects, and extending electricity to remote villages are all factors playing a substantial role in the increased power demand. In addition, the low tariff also affects the consumer's behavior and increases energy wastefulness, which in turn escalates electricity demand.

Regardless of the reasons causing this rapid increase in electricity demand, the Saudi Electricity Company SEC is bound to meet this demand every year and strives to reach its forecasted loads. However, every year the burden is becoming heavier on the electricity Giant to plan ahead and guarantee continuous power supply to its greedy consumers. Therefore, many actions have been taken by SEC to better meet its anticipated growing electricity demand, such as: launching of nationwide power projects to upgrade and expand existing plants, improving generating units' efficiency, and building new power generation facilities. To benefit from national and regional power grids, huge projects have been taking place



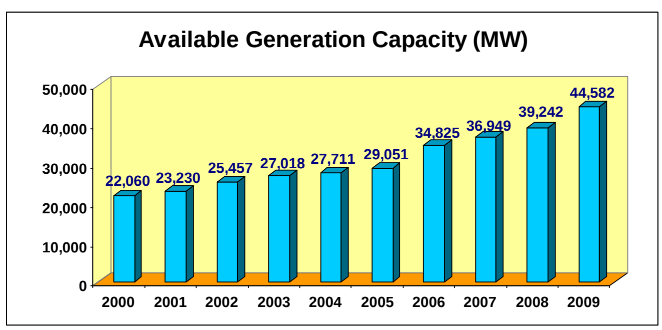


Fig. 1. Electricity demand trends (top) and generation trends (bottom) in Saudi Arabia over the last decade.

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over the last five years to create a national interconnection of power networks and interconnection of power networks with neighboring Gulf (GCC) Nations [3]. In addition, the private sector has been solicited to contribute significantly in power generation. In 2007, SEC adopted the "Program for Private Sector Participation in Electricity Projects," [2], where the company would purchase electricity from privately owned generation plants and sells it to its consumers. Independent Power Producer IPP and Independent Water and Power Producer are common terms for such projects.

II. Peak Load Struggle for SEC

For several years, SEC has been struggling with the increased peak load demand in the kingdom [2]. Every year since 2006, the increase in peak loads has been exceeding 3GW steadily, as shown in Figure 1. The total peak loads were 31.2GW, 35GW, 38GW, and 41.2GW in the years 2006 to 2009 respectively. Electricity peak demand times in Saudi Arabia occur yearly on weekdays (Saturday to Wednesday) from 1:00pm to 5:00pm during the months from June to September. In addition, electricity demand increases significantly during the holy lunar months of Ramadan and Dhul-Hijjah. In order to meet the mounting demand during peak times, SEC has taken several actions from launching awareness programs to offering consumer incentives for peak load shifting or shaving. Nevertheless, the utility company has been soliciting private sector participation to pump more power to the grid during peak times. Figure 2 shows the amounts of electricity purchased by SEC from different suppliers to assist in peak load demands in 2008 and 2009. The Figure shows that in 2008 the company was 4.7GW short of its desired production goal, and the deficit was provided by private entities. However, in 2009, the amount needed from the private sector soared 38% to reach 6.5GW. These amounts were needed to maintain the power reserve, which is commonly known in the generation industry to be around 15% to 20% capacity to overcome peaks in demand. Furthermore, in 2009 SEC has announced that the power systems in the Kingdom may become deficient in the event the main generation units are down for hours during the summer season. Therefore, the need is becoming more urgent to add more power generation to the system. Nevertheless, even private sector's generation plants are mainly fossil-fuel based, which have severe negative impact on the environment; hence the need to have renewable energy based sources such as wind farms is critical.

III. Jeddah and the WOA of SEC

Saudi Arabia is divided into four major operating areas in terms of electricity generation, transmission, and distribution networks, namely: Central Operating Area (COA), Eastern (EOA), Western (WOA) and Southern (SOA). These operating areas are not interconnected, except for the EOA, which is connected to the COA by a 230kV double circuit and two 380kV double circuit lines. This means that the WOA would carry alone the responsibility of meeting its own demand since there is no power transfer to it from neighboring networks. The WOA is one of the largest areas in terms of power generation and consumption. Figure 3 shows pie graph distributions of sold energy and number of customers among the four main operating areas. In 2009, about 31% of the electricity was sold in the WOA; and 38% of the total number of electricity customers in the Kingdom was in the WOA. Jeddah is the second largest city in the Kingdom lying on the Red Sea in the western region. It makes up a huge chunk of the power demand and supply for the WOA grid. Therefore, adding more power generation facilities in or around Jeddah would certainly reduce the peak electricity demand and alleviate some of the responsibility from SEC.

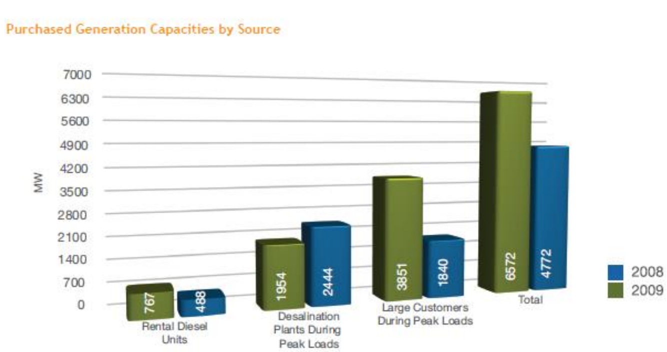


Fig. 2. Electricity purchased by SEC from different suppliers to assist with peak load demand [2].

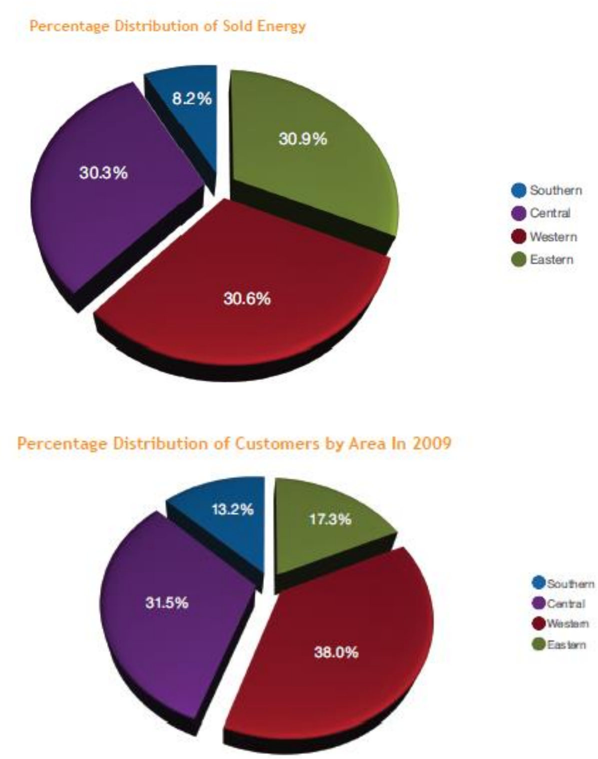


Fig. 3. Percentage distribution of sold energy (top) and customers (bottom) among the four power operating areas in Saudi Arabia in 2009 [2].

IV. Wind Power Generation in Saudi Arabia

Since the mid 1970s, extensive research and development in Saudi Arabia has been focused on solar energy. More than thirty years ago, two major international joint research and development programs were funded by the Saudi government in cooperation with the USA and Germany [4, 5]. The $100M joint ventures aimed at developing solar energy technology by conducting large scale projects associated with solar power generation, such as the Solar Village near Riyadh. Since then, and for the last thirty years, numerous other solar related projects have been designed and installed at universities and research centers throughout the Kingdom.

Unlike solar energy, wind energy did not get as much attention from researchers or large scale investments from the government. Nevertheless, several research works have been conducted by university professors and research centers for wind energy assessment in the kingdom, but most of the conducted research work was without implementation [6-8]. Large funding budgets are required in order to implement and build a wind farm for research purposes. Since that is still not of interest to funding sources in the Kingdom, most research work, like the one presented here, will continue to be merely studies and analysis without implementation. The literature is rich of studies on wind speeds and wind energy potentials in Saudi Arabia. Most of these studies depended on the available meteorological data, which have been collected over many years from stations erected in the year 1970 throughout the Kingdom in the vicinity of airports to get weather related information. Studies have shown feasibility of building wind farms at several sites in the Kingdom, especially at cities on the east and west coasts, such as Yanbu and Dhahran [9]. However, most of the studies do not relate the power generated by the wind turbines to the electricity demand and peak loads, which are the major concern of the utility company.

Compared to other forms of renewable energy, such as photovolataics and fuel cells, wind turbines are more appealing at remote sites, or locations far from urban areas. While one can install a rooftop covered with solar cells on his home, it would be inconvenient to install a wind turbine on the roof. Noise, safety, and aesthetic issues are all factors that limit such implementation of wind generators in or around residential areas. However wind power generation is green and environmentally friendly. Also, most wind generators are rugged and require minimal maintenance throughout their life span, which is more than 20 years on average. Over the last few years, wind power generation has become very popular, and more countries are installing wind farms as a major source of electricity. For example, in 2006 Germany has topped the world in wind power generation, where 21GW out of the Country's 80GW total power came from wind farms [10].

Nevertheless, reports of wind turbine and generator prices have been ambiguous over the last three years. While some economic reports show significant increase in wind turbine prices in light of the increased demand on wind energy, other reports show signs of price drop due to the global financial crisis [11]. Overall, the prices are expected to go up over the coming years as more power generation worldwide is shifting towards wind energy.

V. Wind Farm Site Location

Several studies have been conducted by other researchers to assess the feasibility of installing wind turbines in different locations in the Kingdom. Studies have shown feasibility of building wind farms at several cities, especially in the vicinity of Yanbu on the west coast [12-14]. Yanbu is about 260km north of Jeddah. Studies have also shown that installing wind turbines in or around Jeddah is not very promising. However, since Jeddah is the second largest city in the Kingdom in terms of electricity consumption, and its peak load demands are of major concern to SEC, it is important to reduce its demand. Figure 4 shows a map of the geographical location of the site chosen to build the wind farm in the vicinity of Jeddah [15]. Although Yanbu seemed more productive to other researchers than Jeddah; this paper will show that the location chosen in the suburbs of Jeddah has more potential for wind power generation. In addition, installing the wind farm near Jeddah is more efficient and effective to its network than installing it far away and transmitting the power to Jeddah.

In general, coastal locations usually have stronger winds than non-coastal locations. Therefore, when searching for a location near Jeddah, the focus was on locations along the northwestern coastal line. An initial choice was north of Obhur, the recreational and beaches area of Jeddah. However, since the city is rapidly expanding towards the north and

Fig. 4. Geographical location of the selected site to build the wind farm 56km northwest of Jeddah on the west coast [15].

northwest, it was decided to look farther north for the prospective site. Premature data pointed at a location about 8km northwest of Dahaban, a small village around 48km north of Jeddah. Figure 5 shows a detailed map of the site location. The selected area is open plains having the shape of a quarter-circle, where the largest span is towards the northwest facing the strongest wind direction. The total area is 122 square km (more than 30,000 acres), and each radius is approximately 12.5km long.

VI. Wind Characteristics of the Selected Site

Available wind data has shown an average wind speed of 6.35 m/s at the selected site near Dahaban. Wind directions were shown to be strongest at NW, N, and N-NW. This wind data were collected from the worldweatheronline website [16], which has been posted since July 2008. On daily average, wind speeds show significant increase between 12:00 noon and 6:00pm, as shown in Figure 6. In general, higher values are observed during daytime, and lower values are observed during the evening and night hours. During an entire given day, the mean wind speed is shown to vary between a minimum of 5.0 m/s between midnight and 03:00h and a maximum of 8.4 m/s between 15:00 and 18:00h.

On monthly average, winds are shown to be strongest in the months of May to September, and weakest in the months of November to January, as shown in Figure 7. In general, higher wind speeds are observed during the summertime and lower speeds are observed during wintertime. In Most of the western-region coastal cities in Saudi Arabia, only two seasons: summer and winter are prevalent. The summer usually stretches from March or April till September, and winter starts in October and continues till February or March.

Wind turbines are usually installed at high altitudes due to their long blades. In order to assess the performance of wind turbines, the available wind speeds of the selected site are normalized at three altitudes using the $1/7^{th}$ wind power law [17]. The collected data, which is shown in Figures 6 and 7 are taken at an altitude of 10m. For the purpose of this work, the wind speeds at 10m altitude are normalized to 60m, 80m, and 100m altitudes, as shown in Figure 8.

The results show that mean wind speeds vary between 7 m/s and 11.7 m/s at 100m altitude and between 6.8 m/s and 11.3 m/s at 80m altitude.

Fig. 5. Detailed map of the suggested site location to build the wind farm [Source: Google Maps.]

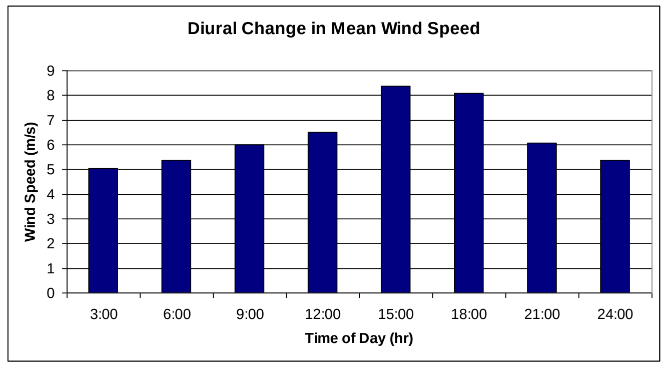


Fig. 6. Mean wind speeds throughout the 24hrs with 3 hrs increments.

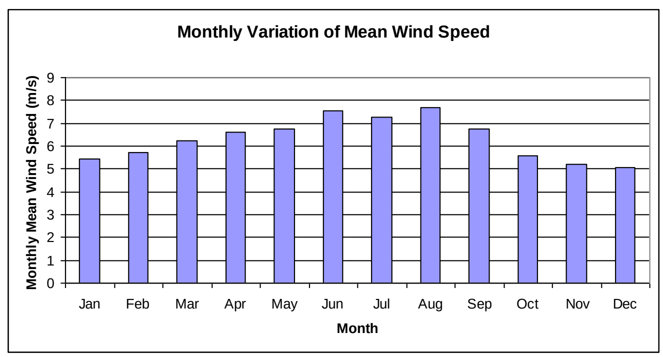


Fig. 7. Mean wind speeds of each month of the year for the selected site.

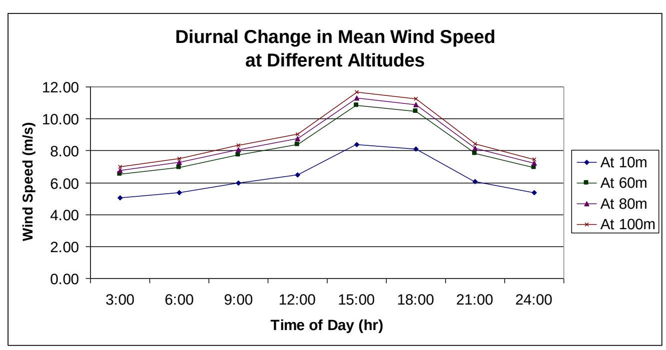


Fig. 8. Mean wind speeds at 10m (collected), and 60m, 80m, and 100m (normalized).

VII. Wind Turbine Selection

Of the many available types of wind turbines, the turbine of choice for the wind farm is the GE Energy brand. It has two lines of high capacity wind turbines, namely 1.5MW and 2.5MW. Recently, GE Energy has improved the performance of its 1.5MW turbine to reach 1.6MW at enhanced reliability and capacity factor [18]. The 2.5MW turbine has a rotor diameter of 100m, while the 1.6MW has a rotor diameter of 82.5m. Both turbines require hub heights of 85-100m. Figure 9 shows power curves for each turbine as provided by GE.

In order to compare the two, the hub height needs to be selected for both turbines first. Choosing 100m hub height is convenient since the wind speeds are already normalized for this height. At 100m altitude, the daily average wind speed is estimated to be 8.68m/s, ranging between 7m/s and 11.7m/s during the 24 hour period. According to the charts of Figure 9, if running at the average wind speed, the 2.5MW turbine would generate roughly 1.515MW, which would correspond to a capacity factor of 60.6% if assumed constant. On the other hand, the 1.6MW turbine would generate 1.095MW, which would correspond to a capacity factor of 68.4% if assumed constant. If running at the average low speed of 7m/s, the 2.5MW turbine would generate 0.75MW and the 1.6MW turbine would generate 0.55MW. If running at the average high speed of 11.7m/s, the 2.5MW turbine would generate 2.44MW and the 1.6MW turbine would generate its rated 1.6MW.

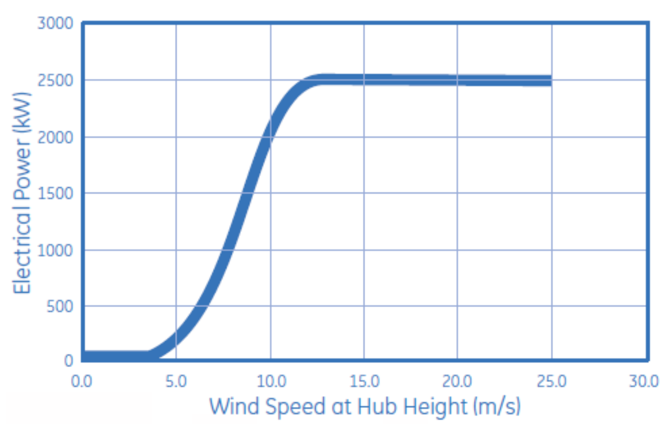
Even though the 2.5MW turbine seems more productive at the selected site; it would be difficult to conclusively determine this fact without accurate and long term wind data. Wind duration availability (in terms of number of hours the wind remained in a particular speed bin) is an important factor to be considered for accurate comparison between wind turbines' output power calculations. Nevertheless, the available wind data show that both turbines would be sufficient for the purpose of this wind farm as both would generate their rated power values at the high wind speeds.

Another important factor to consider, when determining which turbine is more appropriate, is the total land area. Researchers differ in determining the minimum required spacing between wind turbines horizontally and vertically when arranged in a wind farm. Some require a distance of 3 times the turbine rotor diameter (3d) for horizontal spacing and 10 times the rotor diameter (10d) for vertical spacing [19]. Other researchers suggest the distance to be 15 times the rotor diameter for horizontal as well as vertical spacing, [20]. In this work, the spacing between turbines is set to 10d for vertical and horizontal spacing, which is sufficient to assure less wind interference between turbines. This means that each 1.6MW turbine would acquire an area of 0.68 square km, and each 2.5MW turbine would acquire 1 square km of land. In other words, while 2.5MW turbines generate 56% more power than the 1.6MW ones, they require only 47% more land. Therefore, if installed on the same area, the total power generated by the 2.5MW turbines would be about 9% more than the total power generated by the 1.6MW turbines.

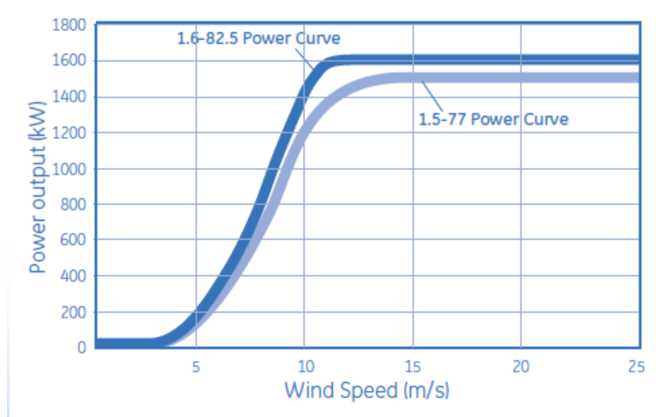
Cost comparison between the two turbines is very difficult, on the other hand, as many factors affect the purchase price. Based on current worldwide wind farm projects, a rough estimate would be that 2.5MW turbines cost about 60% more than the 1.6MW ones. The weight and dimensions of the two turbine types are different; therefore, the costs of shipping, transportation, installation, and maintenance would all vary significantly between the two types. If the land area had no restriction and the purchase price was affordable, the 2.5MW turbine would be ideal for this farm.

VIII. Feasibility Analysis

The selected site has an overall area of 122 km^2, which is equivalent to more than 30,000 acres. Using the area per turbine calculation for proper spacing stated above, such land area would be suitable to install a total of 175 1.6MW turbines or 120 2.5MW turbines. This corresponds to a total wind farm rated output power of 280MW and 300MW for the 1.6MW and 2.5MW turbines respectively. The proposed calculations for the number of wind turbines of each type allow for at least 2km^2 of free area dedicated to control-rooms and facility and



(a) 2.5MW Turbine



(b) 1.6/1.5 MW Turbine

Fig. 9. Power curves for GE Energy Turbines [18].

management buildings.

Assuming no restriction on the available funds, the following analysis will be based on building the wind farm with 2.5MW turbines for maximum output power. For better assessment of the wind farm performance, the average output power needs to be calculated at different times of the day and different months of the year. The daily and monthly average wind speeds of Figures 6 and 7 are first normalized at 100m altitude for that purpose as shown in Figure 10. The charts show monthly average wind speeds of more than 10m/s for the months of May, June, and July. They also show hourly average wind speeds of more than 11m/s between 1:00pm and 7:00pm. This means that for one fourth of the year, on average, the wind speed is above 10m/s. Figure 11 shows the expected mean power generation of the wind farm for each month of the year. It shows that the highest average power output is 267MW in August, and the lowest average power output is 92MW in December. The Figure also shows that for approximately one fourth of the year, on average, the farm would be generating at least 250MW of power, and for all the months except December, the farm would generate at least 100MW of power. The average monthly power output is 184MW corresponding to 60% capacity factor.

On an hourly basis, Figure 12 shows the expected mean power generation of the wind farm in a 24hr period with increments of 3hrs. The Figure depicts that the output power is highest between the hours of 1:00pm and 7:00pm, where the farm generates more than 200MW. This means that for approximately one fourth of the day, on average, the farm would be generating at least 200MW of electricity. On the other hand, the output power drops below 100MW only for a short time around 3:00am.

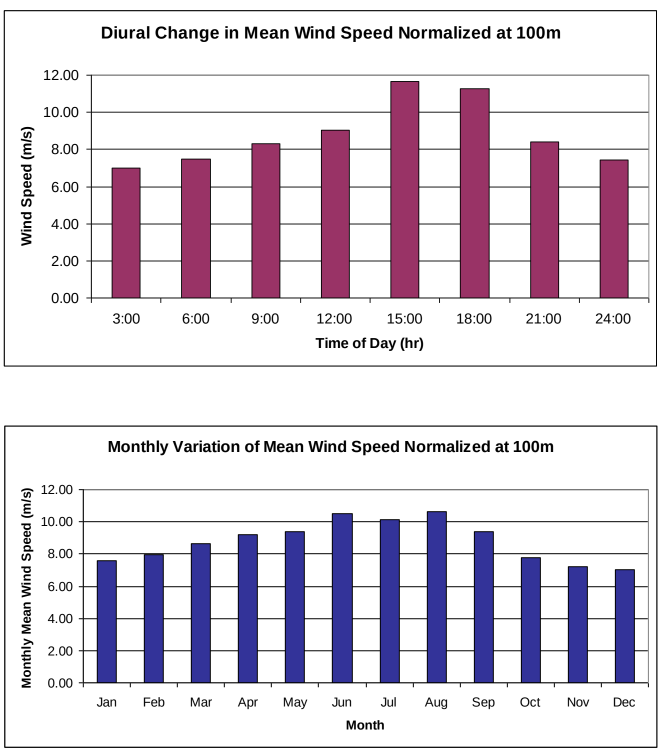


Fig. 10. Mean wind speeds normalized at 100m for the selected site.

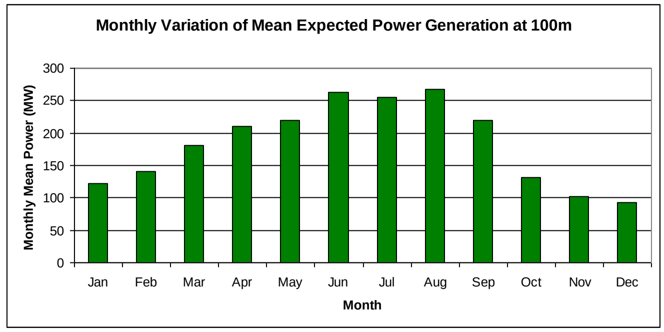


Fig. 11. Mean expected monthly power generation of the wind farm.

These preliminary results show that building the farm at the selected site is promising and would be feasible based on the available data. However, accurate and long term wind data would allow for proper assessment of the site and assure more confidence in the results obtained. In addition, overall wind farm installation costs need to be considered.

IX. Feasibility Analysis for SEC

Electricity peak demand times in Jeddah occur yearly on weekdays (Saturday to Wednesday) from 1:00pm to 5:00pm during the months from June to September. During these times, SEC struggles to meet the hiking electricity demand, which causes forced shut-downs of generators due to overloading and complete system blackouts or brownouts. This study shows that the seasonal trend of the average monthly and hourly wind speeds at the selected farm site matches the electricity load trend in Jeddah. This study shows that the proposed wind farm would generate more power when the electricity is most demanded in Jeddah, and it generates less power when the electricity is least demanded. This would be of great benefit to SEC from two points: relieving it from a considerable chunk of its peak demand obligation, and allowing it for better generation planning during high electricity demand periods.

X. Conclusion

The average wind speed of 6.4 m/s at the selected site near Dahaban indicates a great potential for building a wind farm

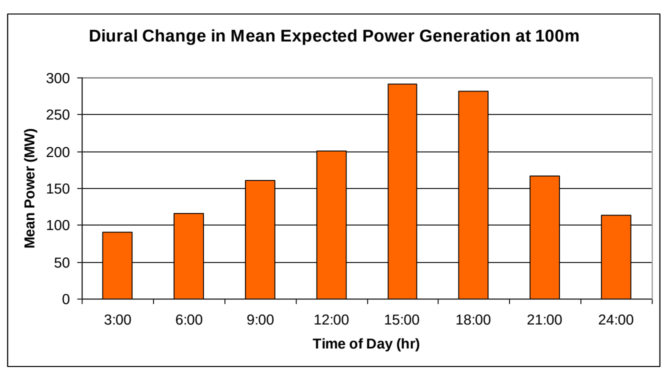


Fig. 12. Mean expected hourly power generation of the wind farm.

there with GE's 2.5MW turbines. The proposed farm would have 300MW capacity. Normalized average wind speeds at the turbine's altitude of 100m were shown to reach as high as 11.7m/s. Results have shown that for one fourth of the time, the farm could be generating at least 200MW of electricity. Furthermore, analysis of wind speeds and the corresponding output power has shown that the trend of the farm's average electricity generation matches the trend of electricity demand in Jeddah. The farm would be of great benefit to SEC in terms of aiding it with a considerable chunk of its peak demand obligation. The results obtained are promising; however, more accurate and long term wind data would allow for better assessment of the site and assure more confidence in the results. Wind speed readings are already being collected at the proposed site for future evaluation. At least 18 months of continuous readings would be needed for more accurate turbine output power calculations.

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Dr. Obaid's other research interests include motor diagnostics, renewable energy, and nanotechnology applications in photovoltaics. His focus is more on DSM and electrical energy generation problems. He has two patents registered with the USPTO and numerous publications in these fields.