International Journal of Green Energy, 7: 410–421, 2010

ISSN: 1543-5075 print / 1543-5083 online
DOI: 10.1080/15435075.2010.493815

DETAILED ANALYSIS OF A 550-MW INSTALLED CAPACITY WIND FARM IN SAUDI ARABIA

Shafiqur Rehman, Aftab Ahmad, and Luai M. Al-Hadhrami
Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

The study presents the wind speed data, frequency distribution, local wind shear exponent, energy yield, air density, and turbulence intensity analysis for a site located in the eastern region of Saudi Arabia. Overall mean wind speed values at 20, 30, and 40 m above ground level were 4.72, 5.34, and 5.74 m/s respectively. The mean local wind shear exponent and air density were found to be 0.302 and 1.126 kg/m^3 respectively. Lower turbulence intensities were noticed at higher altitudes. The proposed wind farm of 550 MW installed capacity could generate 2433.8 GWh of electricity with a plant capacity factor of 50.3% during the year. The study found that during the entire year of operation, the wind turbines remained calm for 3.9% of the time and operated at rated capacity for 9.3% of the time. Overall, noticeable seasonal and diurnal patterns were observed for all the parameters studied in the present scope of the work.

Keywords: ***Wind speed; Wind power density; Wind shear exponent; Plant capacity factor; Turbulence intensity***

INTRODUCTION

The skyrocketing fuel prices; increasing levels of air, water, and soil pollution; and widening gaps between the demands and supplies have become the critical issues to all human beings. There exists a vast majority of population who has not experienced the comfort of grid-connected electricity in this modern and materialistic world. The development of traditional power plants and means of electricity transportation is both time- and finance-intensive. Because of the fast technological development and competitive costs of generation in the fields of wind and solar photovoltaics technologies, these new, clean, and renewable sources of energy are being encouraged these days. The wind farms could be erected within months and lasts at least 20 years and require minimal operation and maintenance cost.

In the present scenario, there are two important issues in the energy sector. First is the energy security and the second is the environmental damage because of the consumption of the conventional sources of energy. On top of it, the need of supplying electricity to remote communities is a critical task in developing and even developed countries. It is now a global fact that the distributed energy resource is the most efficient and economical option for

Address correspondence to Shafiqur Rehman, Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran-31261, Saudi Arabia. E-mail: srehman@kfupm.edu.sa

making electricity available to the billions of people that presently do not have access to it. Long distances and relatively small energy demands in the remote areas make electricity transmission and distribution costs prohibitive.

Becaue of increasing environmental awareness and technological advancement, the renewable electricity generation capacity has reached an estimated 240 GW worldwide in 2007, an increase of 50% over 2004 (World Watch Institute 2008). Renewables represent 5% of global power capacity and 3.4% of global power generation. The largest component of renewables generation capacity is wind power. It is expected, at its current growth rate, that the global installed wind power capacity will top 100,000 MW in March 2008 (Dorn 2008). In 2007, wind power capacity increased by a record-breaking 20,000 MW, bringing the world total to 94,100 MW, which is enough to satisfy the residential electricity needs of 150 million people. The cost of onshore wind power has decreased by more than 80% since the early 1980s to roughly 7¢ per kilowatt-hour at favorable wind sites (World Watch Institute 2008). In some markets, wind is now competitive with even conventional power generation. Driven by concerns regarding climate change and energy security, one in every three countries now generates a portion of its electricity from wind, with 13 countries each exceeding 1000 MW of installed wind electricity-generating capacity (World Watch Institute 2008). With 22,247 MW installed capacity, Germany leads the way while United States, Spain, India, China, and Denmark follow the trends with 16,818, 15,145, 8000, 6050, and 3125 MW installed capacity as of December 2007.

Lewis Dale et al. (2004) studied the additional cost estimates of energy generation from wind power. The study shows that the extra cost from renewable energy as compared with the energy cost by traditional means is just over 0.3 pence/kWh. Bergmann, Hanley, and Wright (2006) carried out a study to estimate the magnitude of external costs and benefits for using the renewable technologies in Scotland.

Herman et al. conducted study on the development of large wind turbine for the design of 500-MW offshore wind farm. The study shows that the project included the design and testing of a 2.75-MW NEG Micon prototype machine, which has been erected at the ECN Wind Turbine Test Farm Wieringermeer in February 2003. Moran and Sherrington (2003) assessed the economic feasibility of a large-scale wind farm project in Scotland. Krokoszinski (2003) carried out study on the efficiency and effectiveness of wind farms development. According to the study, the operation and maintenance cost is the key to the economic viability of large offshore wind farms planned worldwide.

The various studies on wind resource assessment and prospects of wind power plant have been carried out for the Middle East and African countries (Ammari and Maaitah 2003; Buflasa et al. 2008; Buhairi 2006; Elamouri and Amar 2008; El-Osta and Califa 2003; Essa and Mubarak 2006; Marafia and Ashour 2003; Shata and Hanitsch 2005). El-Osta and Califa (2003) carried out feasibility study for a wind farm of 6.0 MW capacity in Zwara, Tripoli, Libya. The results of the study showed that the project is economically feasible. Ammari and Maaitah (2003) presented feasibility study of utilization of wind energy for power generation in Jordan. Their data analysis showed that the annual mean wind speeds at a height of 24 m could reach as high as 7.6 m/s and available wind energy density close to 3 MWh/m^2/year. Marafia and Ashour (2003) carried out an economical feasibility study and assessment of the potential of off-shore/on-shore wind energy as a renewable source of energy in Qatar. The results of the study indicate the suitability of utilizing small- to medium-sized wind turbine machine.

Essa and Mubarak (2006) carried out wind resource assessment for 18 different locations in Egypt, located mainly in Mediterranean, Inland, and Red Sea zones. The study shows that the Hurguda station (Red Sea coast) has 5.8 m/s mean annual wind speed and the largest peak wind speed was 13.8 m/s, with 98% of wind speed records being in the range of 3–10 m/s. Shata and Hanitsch (2005) carried out study on the wind energy potential for electricity generation on the coast of Mediterranean sea in Egypt. The study found out that the best locations are Sidi Barrani, Mersa Matruh, and El Dabaa where the annual mean wind speed was greater than 5.0 m/s.

The studies related to wind resources assessment for Saudi Arabia have been carried out and reported in the literature (Mohandes, Rehman, and Halawani 1998; Naif 2005; Rehman and Ahmad 2004; Rehman et al. 2007; Rehman and Halawani 1994; Rehman, Halawani, and Husain 1994; Rehman, Halawani, and Mohandes 2003). Naif (2005) assessed the wind energy resource for five different locations in Saudi Arabia. He found out that Dhulum and Arar sites have higher wind energy potential with annual wind speed average of 5.7 and 5.4 m/s. Rehman, Halawani, and Husain (1994) carried out work on wind speed data analysis such as Weibull parameter determination and distribution. The results of the study show that the wind speed was well represented by Weibull distribution function. Rehman and Ahmad (2004) carried out detailed wind energy assessment for coastal locations of the Kingdom of Saudi Arabia. The study showed that the Yanbo is the best location, among the sites analyzed, for harnessing wind power. Rehman, Halawani, and Mohandes (2003) calculated the electrical energy cost from the wind using long-term hourly mean wind speed data at 20 locations in the Kingdom of Saudi Arabia. Recently, Rehman et al. (2007) carried out detailed wind data analysis and power resource assessment for Rafha, a city in northern part of Saudi Arabia. In the study, the plant capacity factors and energy yield were determined using the three different sizes of wind machines.

The main objective of the present study is to perform detailed analysis of a wind farm of 550 MW capacity in Saudi Arabia. The specific objectives of the study are to assess the wind power, wind shear exponent (WSE), air density, air turbulence intensity (TI), energy yield, plant capacity factor, and effect of hub height on energy yield and PCF for an isolated site in Saudi Arabia.

DATA AND SITE DESCRIPTION

The meteorological data (wind speeds, wind direction, air temperature, relative humidity, surface station pressure, global solar radiation) were collected at a remote location (Latitude 29°8.282’ N, longitude 44°19.817’ E, and altitude of 443 m above sea level) for a period of about 3 years between September 2005 and November 2008. The data collection site is an open area from all directions except a couple of ware house shades and diesel storage tanks in the far vicinity of wind mast. Data were recorded every 10 min on a removable data card. The wind speed data was collected at 20, 30, and 40 m above the ground. At each height, two sensors were installed (opposite to each other of the mast) and recorded data were tagged as WS1 and WS2 at 20 m, WS3 and WS4 at 30 m, and WS5 and WS6 at 40 m. The wind direction data were recorded at 30 and 40 m as WD1 and WD2 respectively. The surface air temperature (in degree celcius), relative humidity (in percentage), surface station pressure (in inches of mercury), and global solar radiation (in watts per meter square) data were also collected at 2 m above the ground surface. The raw data were transferred from the data acquisition system to the computer using data logger software from NRG, USA.

RESULTS AND DISCUSSION

The wind data analysis provides an idea of the annual, seasonal, and diurnal variability, and the availability of wind speed. The analysis of the data includes data checking for completeness and erroneous values through visual and graphical inspection; calculation of monthly, daily, and hourly mean values of all the parameters; estimation of WSEs using wind speed values at different heights; and calculation of air density using surface temperature and pressure values.

Wind Speed and Wind Power Density Variation

The hourly variation of wind speed at different heights during entire data collection period is shown in Figure 1. It is evident from this figure that as the height increases, the range of wind speed during 24 h decreases, which is indicative of lesser fluctuations and hence less turbulence at higher altitudes. This implies a continuous operation of the wind turbine wherever diurnal cycle is concerned. Furthermore, higher wind speeds during day time would be advantageous in Saudi Arabia to meet daytime air conditioning loads. The seasonal variation of wind speed, see Figure 2, also provides confidence on the availability of wind throughout the year, and additionally higher winds in summer time, which is critical for Saudi Arabia because of increased energy requirements.

The diurnal and seasonal patterns (Figures 3 and 4) of wind power density values, calculated using local air density values, followed the same trends as the wind speed at different heights depicted in Figures 1 and 2 respectively. At 40 m Above Ground Level (AGL), the wind speed is found to be 15.5% of the times less than or equal to 3.0 m/s, while for 84.5% of the time above it, as can be seen from frequency distribution diagram shown in Figure 5. Most of the modern wind turbines start producing electricity at 3.5–4.0 m/s, hence at the present site of measurements, the wind turbines with 4.0 m/s cut-in speed could produce electricity for 74% of the time during the year.

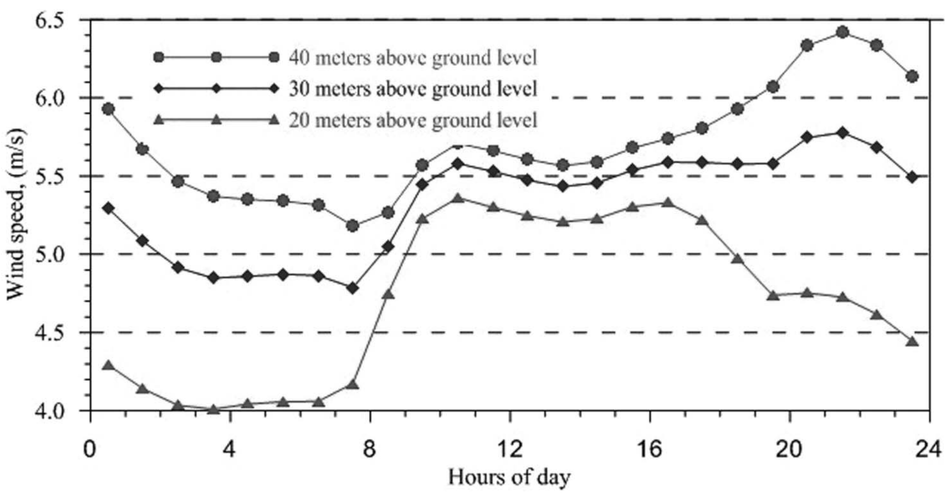

Figure 1 Diurnal variation of wind speed at different heights during the period of September 2005 to November 2008.

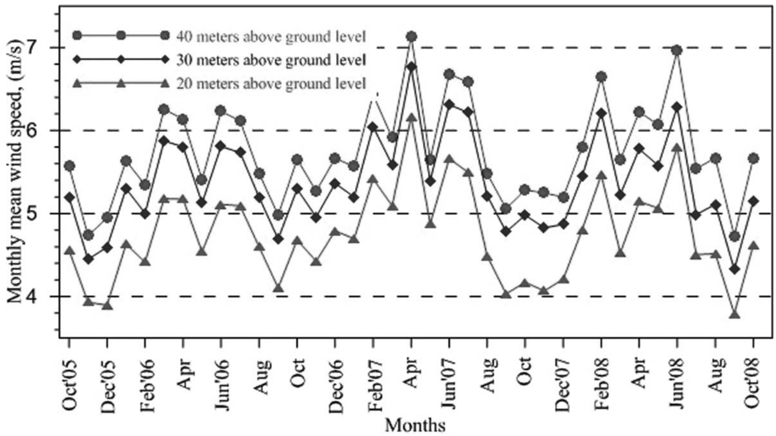

Figure 2 Seasonal variation of monthly mean wind speed at different heights during the period of October 2005 to October 2008.

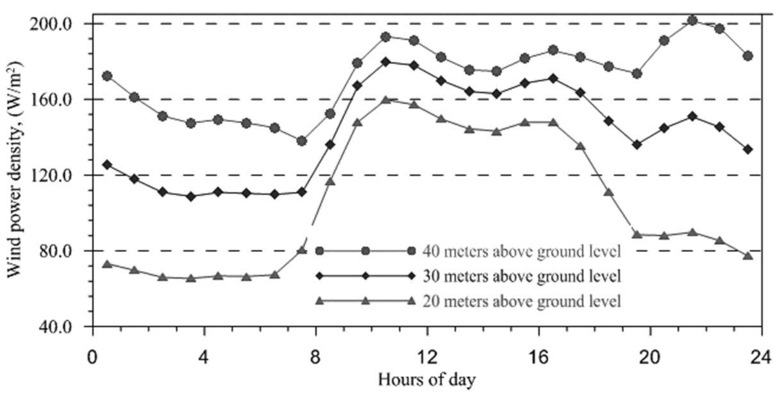

Figure 3 Diurnal variation of wind power density at different heights during the period of September 2005 to November 2008.

Local Wind Shear Exponent, Air Density, and Turbulence Intensity

Local WSE is extremely important to extrapolate the wind speed at higher altitudes to estimate energy yields from modern high hub height wind turbines. The measured values of wind speeds at 20, 30, and 40 m were used to obtain the local WSE and its seasonal variation along with extreme values is shown in Figure 6. A mean minimum value of WSE of 0.258 was observed in April, while a maximum of 0.347 was observed in October with the overall mean remained as 0.302. The wind power density is directly proportional to air density and hence is important from energy generation point of view. The higher the air density, the larger the wind power and vice versa. Higher values of air density were observed during winter season and lower in the summer months, as can be seen from Figure 7. The highest mean, maximum, and minimum values were found in the month of January (1.198 kg/m^3), while the lowest in August (1.078 kg/m^3). The air density is directly affected by the temperature, the higher the temperature, the lower the air density and vice

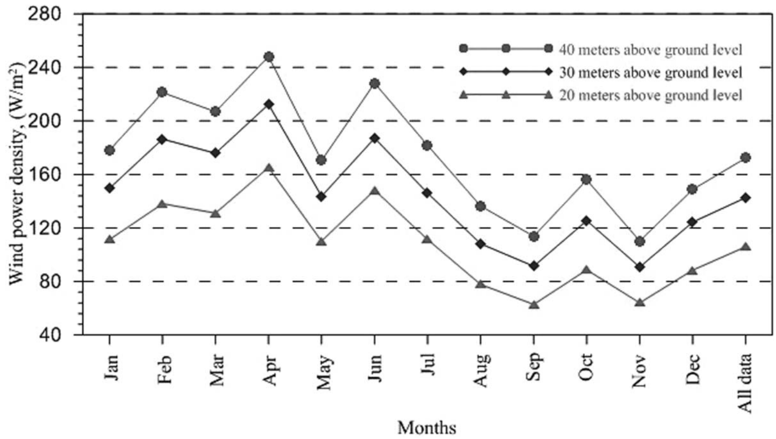

Figure 4 Seasonal variation of wind power density at different heights during the period of September 2005 to November 2008.

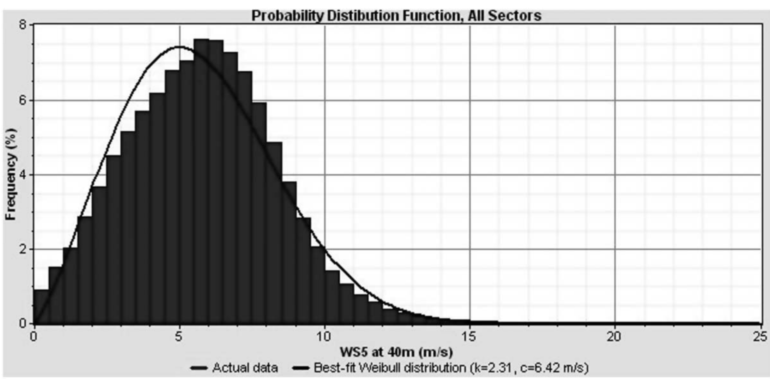

Figure 5 Frequency distribution of wind speed at 40 meters above ground level during the period of October 2005 to October 2008.

versa. The highest value of mean air density was observed at 06:00 h, while the lowest at 15:00 h, as can be seen from Figure 8. This behavior is indicative of the possibility of the low wind power density during the day time and higher during the night time.

An accurate and quantitative knowledge of TI is critical from working life of wind turbine. The greater the turbulence, the lesser the life of wind turbine will be. Today's modern wind turbines have hub heights of more than 100 m with a rotor diameter of the same magnitude and had to carry tons of loads of nacelle unit under dynamic load conditions. The monthly mean values of TI were calculated at different heights over entire period of data collection, and it was found that TI decreases with increasing height, as can be seen from Figure 9. Furthermore, higher TI's were observed during the summer time and lower during the winter period. Similarly, higher TI's were reported during the day time and lower during the nighttime, as shown in Figure 10.

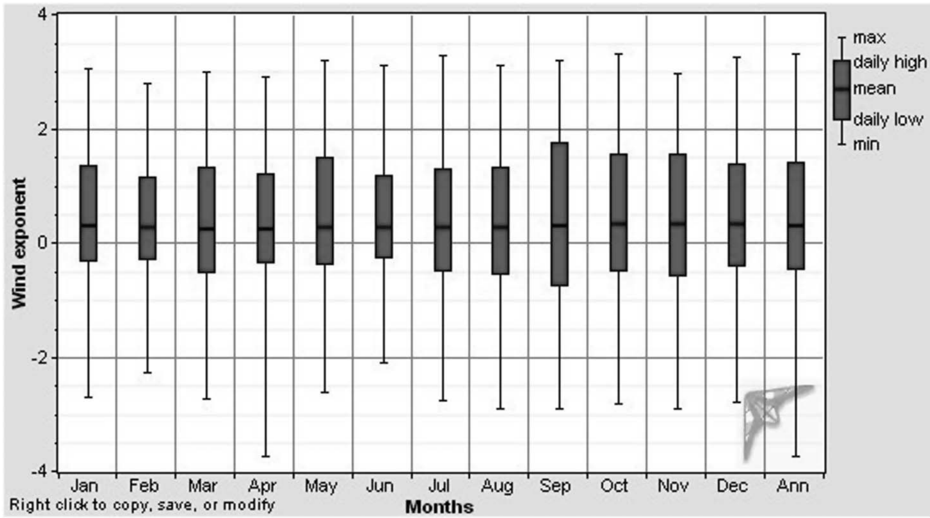

Figure 6 Monthly variation of wind shear exponent.

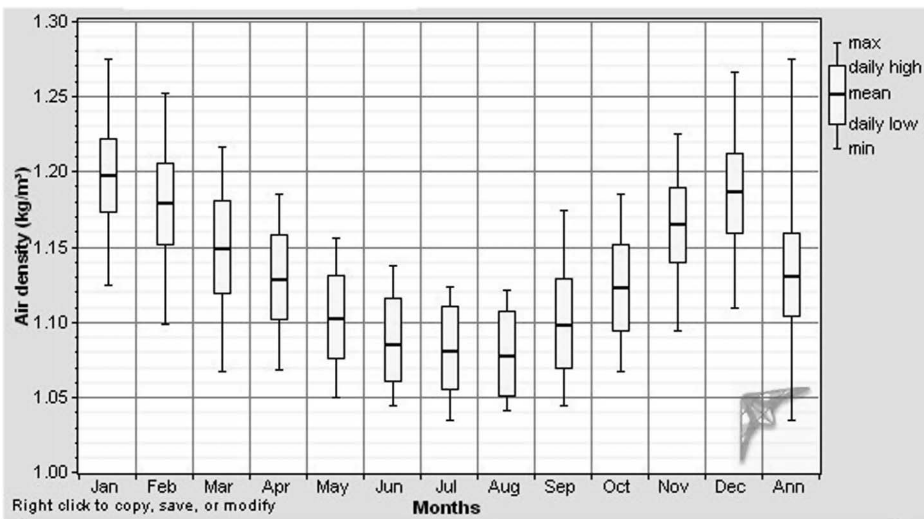

Figure 7 Monthly mean variation of air density.

Energy Yield Estimation

The wind data collected during the aforementioned period at 20, 30, and 40 m above ground level was used to estimate the energy yield from a grid-connected wind farm of 550 MW installed capacity at the site of measurements. For energy yield estimation, 200 wind turbines, type V100, each of 2.75 MW rated power from Vestas were considered. The rotor diameter of V100 was 100 m and a hub height of 100 m was considered for the present application. The cut-in speed of V100 was 2.0 m/s, while the rated and cut-out speeds were 11.5 and 25 m/s respectively. The wind energy yield was estimated using Windographer software (Mistaya

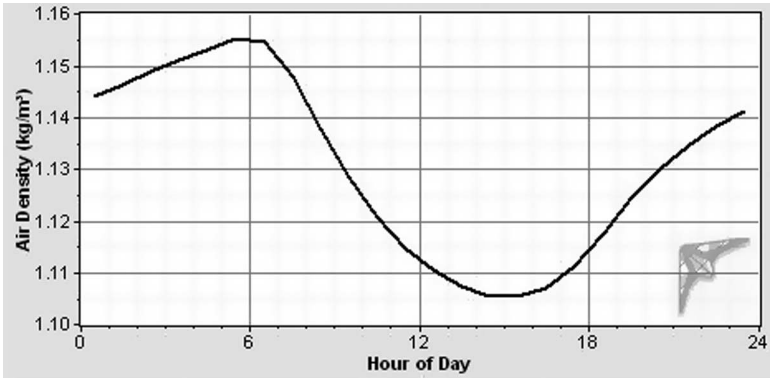

Figure 8 Diurnal variation air density.

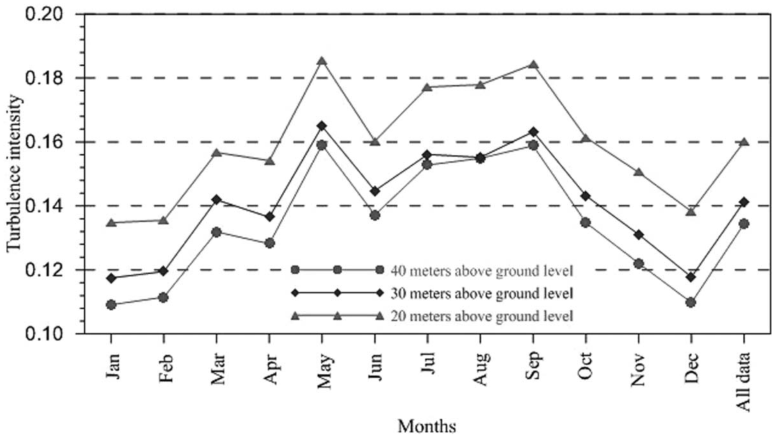

Figure 9 Seasonal variation of mean turbulence intensity at different heights.

Engineering Year). The wind power curve, shown in Figure 11, of the wind turbine was used from the built in library of Windographer software. The wind farm energy losses like array, icing, down time, and miscellaneous were taken as 2%, 5%, 2%, and 3% respectively.

A maximum of 236.8 GWh of electricity was produced in the month of June (as shown in Figure 12) by the proposed 200 wind turbines in the area of the wind measurements reported in this study. A minimum of 170.7 GWh of electricity was generated in the month of November. With existing wind intensities, a total of 2433.8 GWh of electricity could be produced with an overall mean plant capacity factor of 50.3% from the proposed hypothetical wind farm of 550 MW installed capacity in the area of wind speed measurements. The seasonal variation of achievable plant capacity factors is shown in Figure 13. The plant capacity factor was found to vary between a minimum of 43.1% and a maximum of 59.8% corresponding to November and June months of the year, respectively. Furthermore, it was noticed that plant capacity factor remained above 47% during most of the months during the year. The present analysis also estimated the percentage of times the wind turbines remained calm and the duration during which rated output was obtained.

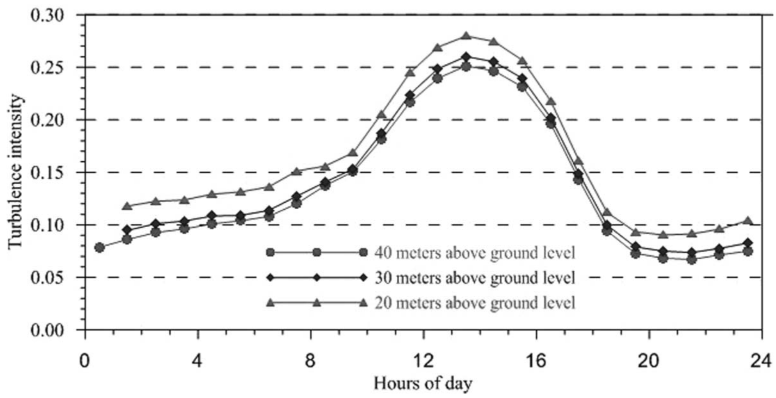

Figure 10 Diurnal variation of mean turbulence intensity at different heights.

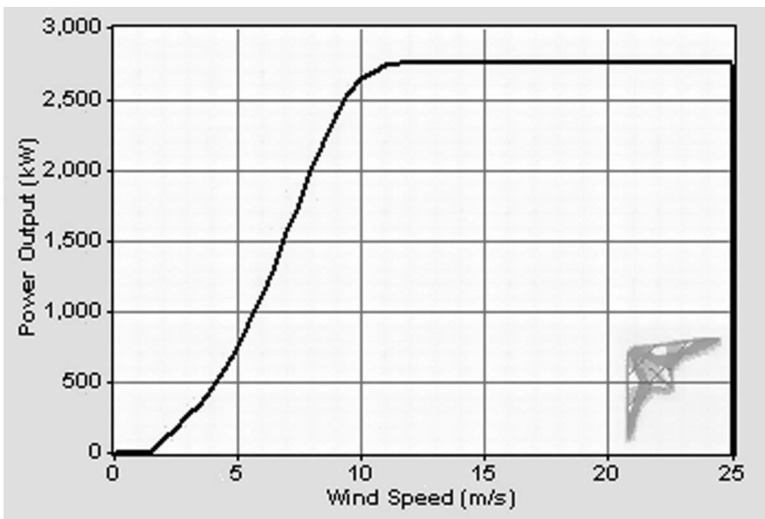

Figure 11 Wind power curve of V100 wind turbine from Vestas [24].

A maximum of 6.1% of the times wind turbines could be found calm at the location of interest during whole year in the month of September and a minimum of 2.1% of times in the month of June. On the other hand, it was found that the wind turbines could generate energy at rated capacity for a maximum of 12.4% of times in the month of April and a minimum of 5.2% in November, as depicted in Figure 14. Overall, the zero and rated capacities were found to be 3.9% and 9.3% during the entire year. This shows that the proposed wind farm could not produce energy only for a mere 3.9% of the time during the entire year of operation.

CONCLUSIONS

It is concluded that site-specific wind speed measurements are a must before going for any real-time wind power generation development to make real assessment of energy

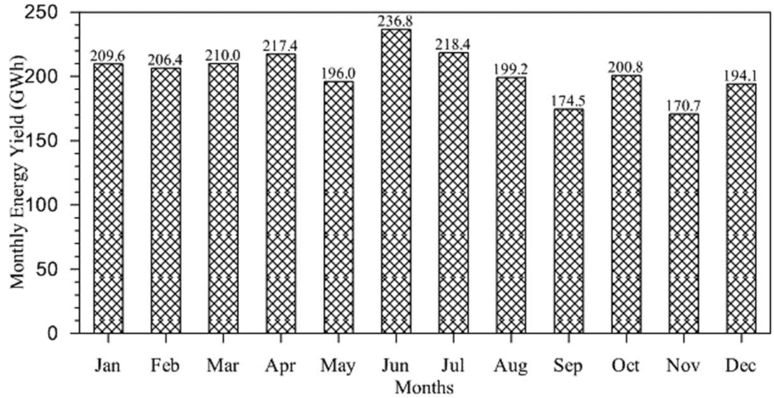

Figure 12 Variation of monthly total energy yield from the wind farm.

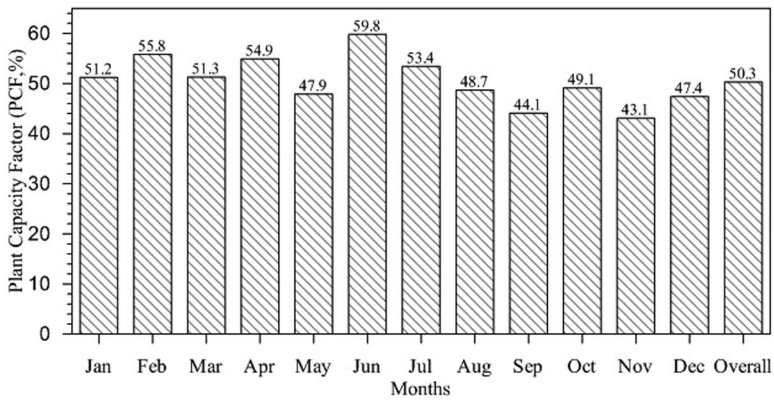

Figure 13 Seasonal variation of plant capacity factor of the wind farm.

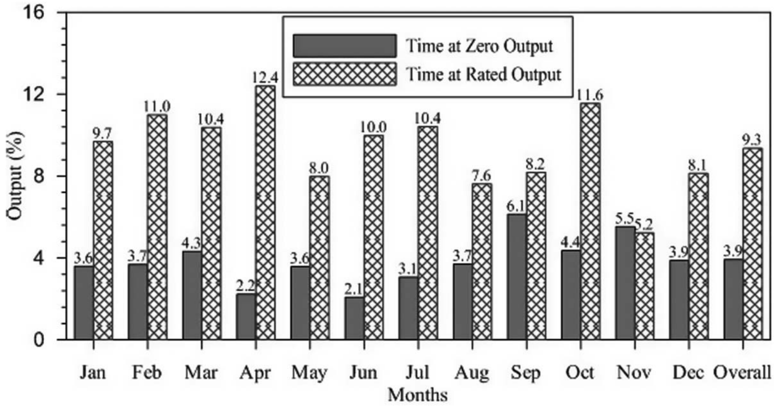

Figure 14 Zero and rated output during the entire year.

yield from today's modern wind turbines of multimegawatt rated capacities and hub heights of around 100 m. The present study utilized wind speed, ambient temperature, and barometric pressure data measured for a period of around 3 years between September 2005 and November 2008 at a remotely located power plant. The wind speed measurements were made at three heights, namely 20, 30, and 40 m above ground level, to obtain the local WSE for wind speed extrapolation up to hub heights of 100 m. Specifically, following points are needed to be specified for further utilization and if needed investigation.

- The overall wind speed was found to be 4.72, 5.34, and 5.74 m/s at 20, 30, and 40 m above ground level. Higher values were observed during day time and summer months and lower during nighttime and winter months. The wind power density values also followed the same trend as that of wind speeds.
- An overall WSE of 0.302 is suggested to be used at this sight and in the surrounding area up to 200 km radius because the area is almost flat with gentle topographical features. Higher values of the exponent were observed during winter and lower in the summer time. Similarly, lower values were observed during daytime and higher during nighttime.
- The local air density values calculated using ambient air temperature and barometric pressure were found to be between 1.078 kg/m^3 in August and 1.198 kg/m^3 in June with an overall mean of 1.126 kg/m^3.
- The proposed 550-MW installed capacity wind farm (200 wind turbines V100 each of 2.75 MW rated power from Vestas) could generated a net 2433.8 GWh of electricity at a plant capacity factor of 50.3% with a hub height of 100 m at the site of interest. Maximum net energy of 236.8 GWh could be obtained from the proposed wind farm at a plant capacity factor of 59.8% in June, while a minimum of 170.7 GWh with plant capacity factor of 43.1% in November.

ACKNOWLEDGMENT

The authors wish to acknowledge the support of The Research Institute of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

REFERENCES

Bergmann, A., N. Hanley, and R. Wright. 2006. Valuing the attributes of renewable energy investments. *Energy Policy* 34: 1004–1014.

Ammari, H.D., and A.A. Maaitah. 2003. Assessment of wind-generation potentiality in Jordan using the site effectiveness approach. *Energy* 28: 1579–1592.

Buflasa, H.A., D. Infield, S. Watson, and M. Thomson. 2008. Wind resource assessment for the Kingdom of Bahrain. *Wind Engineering* 32(5): 439–448.

Buhairi, M.H.A. 2006. A statistical analysis of wind speed data and an assessment of wind energy potential in Taiz-Yemen. *Ass. Univ. Bull. Environ. Res.* 9(2) 13–21.

Dale, L., D. Milborrow, R. Slark, and G. Strbac. 2004. Total cost estimates for large-scale wind scenarios in UK. *Energy Policy* 32: 1949–1956.

Dorn, J.G. 2008. Global wind power capacity reaches 100,000 megawatts. http://www.earthpolicy.org/Indicators/Wind/2008.htm, Accessed on November 29, 2008.

Elamouri, M., and F.B. Amar. 2008. Wind energy potential in Tunisia. *Renewable Energy* 33: 758–768.

El-Osta, W., and Y. Califa. 2003. Prospects of wind power plants in Libya: A case study. *Renewable Energy* 28: 363–371.

Essa, K.S.M., and F. Mubarak. 2006. Survey and assessment of wind-speed and wind-power in Egypt including air density variation. *Wind Engineering* 30(2): 95–106.

Herman, S.A., H.J.T. Kooijman, H.B. Hendriks, M. Zaaijer, E.V.D. Drug, W.O.D. Velde, A. Winnemuller, and R.V.D. Berg 1999. Variations on a 500 MW offshore wind farm design, report. Netherland.

Krokoszinski, H.J. 2003. Efficiency and effectiveness of wind farms—keys to cost optimized operation and maintenance. *Renewable Energy* 28: 2165–2178.

Lempp, P. Renewables 2007 Global Status Report. 2008. Paris: REN21 Secretariat and Washington, DC: World watch Institute, Renewable Energy Policy Network for the 21st Century. REN21. http://www.ren21.net

Marafia, A.H., and H.A. Ashour. 2003. Economics of off-shore/on-shore wind energy systems in Qatar. *Renewable Energy* 28: 1953–1963.

Mohandes, M.A., S. Rehman, and T.O. Halawani. 1998. A neural network approach for wind speed prediction. *Renewable Energy* 13(3): 345–354.

Moran, D., and C. Sherrington. 2003. An economic assessment of wind farm power generation in Scotland including externalities. *Energy Policy* 35: 2811–2825.

Naif, M.A.A. 2005. Wind energy resource assessment for five locations in Saudi Arabia. *Renewable Energy* 30: 1489–1499.

Rehman, S., and A. Ahmad. 2004. Assessment of wind energy potential for coastal locations of the Kingdom of Saudi Arabia. *Energy* 29: 1105–1115.

Rehman, S., I. El-Amin, F. Ahmad, S.M. Shaahid, A.M. Al-Shehri, and J.M. Bakhashwain. 2007. Wind power resource assessment for Rafha, Saudi Arabia. *Renewable and Sustainable Energy Reviews* 11: 937–950.

Rehman, S., and T.O. Halawani. 1994. Statistical characteristics of wind in Saudi Arabia. *Renewable Energy* 4(8): 949–956.

Rehman, S., T.O. Halawani, and T. Husain. 1994. Weibull parameters for wind speed distribution in Saudi Arabia. *Solar Energy* 53(6): 473–479.

Rehman, S., T.O. Halawani, and M. Mohandes. 2003. Wind power cost assessment at twenty locations in the Kingdom of Saudi Arabia. *Renewable Energy* 28: 573–583.

Shata, A.S.A., and R. Hanitsch. 2005. Evaluation of wind energy potential and electricity generation on the coast of Mediterranean. *Renewable Energy* 31(8): 1183–1202.

Mistaya Engineering. 2008. Windographer, A state of the art wind data analyzing tool. http://www.mistaya.ca/.