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Performance evaluation of small wind turbines for off grid applications in Saudi Arabia

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ABSTRACT

The study evaluated the energy output and plant capacity factor (PCF) of small wind turbines in the category of 1–3 kW, 5–10 kW, 15–20 kW and 50–80 kW rated powers. Furthermore, the effect of hub height on energy output and the PCF has been studied to recommend suitable hub height for different type of applications and load requirements. To achieve the set objectives, hourly average wind speed data measured at 10, 20, 30, and 40 m and wind direction at 30 and 40 m above ground level during July 01, 2006 to July 10, 2008 has been utilized. Highest percentage change in annual energy yield (AEY) was obtained for an increase in hub height of 10 m from 20 to 30 m for both horizontal and vertical wind turbines chosen in the present study. The next best AEY was obtained while increasing hub height from 10 to 15 m. Horizontal axis wind turbines Fortis Passat with PCF of 44.4% at 15 m hub height, Aeolos-H 5 kW with PCF of 20% at 20 m hub height, and CF6e with PCF of 32.5% at 20 m hub height are recommended for different load requirements. Similarly, vertical axis wind turbines UGE Vision 2 kW with PCF of 8.9% at 15 m hub height, Aeolos-V-2 5 kW with PCF of 20.6% at 20 m hub height, and UGE-9M 10 kW with PCF of 14.2% at 30 m hub height are also recommended for various ranges of loads. Horizontal axis wind turbines were found generally more efficient than the vertical axis wind turbines in the present case.

1. Introduction and international practices

The fast technological development and energy intensive life styles have resulted in tremendous increase in power requirements on global, regional and national levels. Besides conventional means of power production to meet the rapidly increasing energy demand, new and renewable sources are being sought to supplement these requirements the conventional sources. Utilization of renewable sources of energy has two fold benefit, one it reduces the dependence on fossil fuels which means reduction in greenhouse gases (GHG) emissions and two to supply energy where there is no national or regional electrical grid. The fast developing and widely used sources of clean energy include the wind, solar thermal, solar photovoltaic (PV), hydro, geothermal, and biomass. Of these sources of clean energy wind energy has been adapted by industries and accommodated by individual users due to its availability, ease of maintenance, low cost of operation. The annual cumulative wind power installed capacity reached 282.587 GW by the end of 2012 compared to 238.050 GW in 2011, an increase of 18.71%, Ref. [1]. With cumulative installed capacity of 75.324 GW, China remained the leader in wind power industry as of end of 2012. United States of America, Germany, Spain and India remained at 2nd, 3rd, 4th, and 5th place with total cumulated wind power installed capacities of 60.007 GW, 31.308 GW, 22.796 GW, and 18.421 GW; respectively by the end of 2012. With respect to new additions, USA remained on top with 13.124 GW and China was at second place with 12.960 GW new wind power installations. However, Germany, India, and Spain remained at 3rd, 4th, and 5th, with new additional capacities of 2.415 GW, 2.336 GW, and 1.122 GW; respectively.

The applications of small wind turbines, include heating greenhouses and residential buildings [2], hydrogen production for upgrading bitumen from oil fields [3], and water lifting goes back to 1997 [4], to name a few. Lara et al. [5] evaluated a 3 kW wind turbine feeding a battery bank of 48 V/880 Ah by means of a non-controlled 6-pulse rectifier. The overall efficiencies showed a maximum of 17% of the wind energy to be available for water pumping. Nagai et al. [6] reported the performance of a 2 kW rated power wind turbine in terms of the functions of wind turbine rotational speed, generated outputs, and its stability for wind speed changes. The expected performance of the machine was confirmed under real wind conditions and the wind turbine showed a power coefficient of 0.257 under the average wind speed of 7.3 m/s. Bekele and Tadesse [7] conducted feasibility of small-scale hydro/pv/

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Nomenclature

AEY	annual energy yield
AGL	above ground level
GHG	greenhouse gases
GW	gigawatt
GW h	gigawatt hour
HAWT	horizontal axis wind turbine
IEC	international electrochemical commission
kW	kilowatt
kW h	kilowatt hour
MW	megawatt
MW h	megawatt hour
PCF	plant capacity factor (%)
PR	barometric pressure (mb)
RH	relative humidity (%)
VAWT	vertical axis wind turbine
TI	turbulence intensity
TM	ambient temperature (°C)
WD	wind direction (°)
WPD	wind power density (W/m^2)
WS	wind speed (m/s)

wind based hybrid electric supply system to the district for six sites. Ozgener [8] presented energy analysis of the 1.5 kW small wind turbine systems with a hub height of 12 m and rotor diameter of 3 m in Turkey. The test results showed that at an average wind speed is 7.5 m/s, the proposed turbine produced 616 W of electricity.

Arifujjaman et al. [9] modeled a small wind-turbine with furling mechanism and its resulting dynamics using Matlab/Simulink platform. The results indicated that the energy capture of a wind-turbine depends not only on the control strategy but on the wind-speed and Rayleigh distribution. Jowder [10] investigated the site matching of wind turbine generators at 30 m and 60 m heights by estimating the capacity factors of various commercially available wind turbines. The authors estimated monthly and annual variation of capacity factors to ensure optimum selection of wind turbines. The study conducted by Bishop and Amaratunga [11] proposed a 10 MW distributed wind energy system using micro wind turbines of horizontal and vertical axis configurations of less than 500 W rated power. The study illustrated great potential of small wind turbines to be competitive with conventional wind farms. Mostafaeipour [12] statistically analyzed the three hourly measured long term wind speed data (1991–2004) of Kerman, Iran. Mean wind power based on measured data and Weibull distribution function as well as the relative percentage error (RPE) between estimated values of wind power based on two methods have been studied and reported results for three small wind turbine having rated powers of 300 W, 600 W and 1 kW respectively. In an earlier study Mohammadi and Mostafaeipour [13] reported that small wind turbines could be used effectively and economically in Zarrineh area in Iran for power generation for small loads and off-grid applications. By scaling down the wind turbines to investigate their characteristics using open jet wind generating facilities to gauge the effect of turbulence on small wind turbines have been discussed by Sedaghat et al. [14]. The operating principles as well as the main characteristics of several storage technologies along with a summary of potential energy storage systems (ESS) applications in wind power have been defined and discussed by Rabiee et al. [15].

Zaccheus and Komla [16] performed a case study for Darling site where they deployed 2–3 acquisition systems on hub heights of 50, 60, and 70 m to determine the actual wind characteristics. They [16] empirically concluded that the analysis of the energy output of wind turbines based on the site power curve is an accurate technique for wind energy analysis as compared to the actual turbine power curve. Numerical simulation as applied to wind energy is proposed by Miller et al. [17]. Eltamaly [18] proposed an accurate procedure to choose the best site from many sites and suitable wind turbines for these sites. For that matter, one hundred wind turbines have been chosen for the sites of Yanbo, Dhahran, Dhulom, Riyadh and Qaisumah. Islam et al. [19] proposed a comprehensive study to highlight the recent and future trends of wind energy technology, and estimated that within next 2–3 decades the vertical axis wind turbines (VAWT) can dominate the wind-energy technology due to their land space. Chen et al. [20] proposed a statistical method that combines the linear wake model and wind turbine power curve to model the wind speed distribution for wind power assessment in wind turbine positioning optimization.

Sainz et al. [21] adapted statistical technique of the Least Median of Squares combined with a random search to carry out the characterization of the turbines in a wind farm. The results were tested with long term real data from wind farms in Spain. Chen et al. [22] investigated the effect of using different hub height wind turbines in a small wind farm on power output and analyzed three different wind conditions by nested genetic algorithm. The results showed that power output of the wind farm using different hub height wind turbines will be increased even when the total numbers of wind turbines were same. Suomalainen et al. [23] proposed a new methodology that includes diurnal wind characteristics along with their relevant stochastic effects and seasonality in order to simulate a possible chain of events that conveys valuable information on temporal wind speed. Peng et al. [24] used artificial neural networks (ANN) and hybrid strategy based on the physical and statistical methods to predict short term power. It is shown that ANN based prediction achieves results quickly as compared to hybrid strategy. However, the accuracy of ANN was lower as compared to hybrid method. Mirghaed and Roshandel [25] optimized the sizing parameters and farm layout of wind turbines according to the wind resource and economic aspects and calculated the optimal cost of energy for one turbine of about 46.7, 54.5 and 46.6 dollars per MW h at the studied sites, respectively.

Sheen et al. [26] used Particle Swarm Optimization (PSO) with a power flow algorithm to analyze the long-term benefits of Wind Turbine (WT) allocation at the demand side of a power distribution system. The study found that the simulation results could help decision makers in selecting the proper installation sites for WTs, as well as in determining the tradeoff between optimal investment and environmental policy for future electricity and carbon markets. Tu et al. [27] used the wind data of first-10 days of each month in 2006 for training the ANN to estimate the power generation for next 20 days of the same month. They showed that with adequate number of neuron the wind data of first-10 days can estimate energy outputs except for the months where wind regime is weak (May, June, and July). In yet other paper [28] neural computation techniques, such as, support vector regression was used as prediction method for wind energy time series, along with self-organizing Maps Kohonen et al. [29] for monitoring high-dimensional wind time-series data. Kishore et al. [30] proposed the design of a small-scale wind energy portable turbine targeted to operate below 5 m/s wind speed. Simic et al. [31] performed a detailed study and analysis of small wind turbines with less than 10 kW of installed power.