Suitability of utilizing small horizontal axis wind turbines for off grid loads in Eastern Region of Saudi Arabia

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Abstract

Small wind turbines of 1-3kW, 5-10kW, and 15-20kW rated powers are used to find out suitable and efficient turbines for power generation in the eastern region of Saudi Arabia. Additionally, the effect of hub height on energy output and the plant capacity factor is investigated to recommend an optimal hub height to be used in the present case. To achieve the set objectives, hourly mean wind speed data measured at 20, 30, and 40 meter and wind direction at 30 and 40 meter during September 13, 2005 to May 09, 2010 has been utilized. The annual mean wind speed values were 5.73, 5.34, and 4.75 m/s at 40, 30, and 20 m with NNW prevailing wind direction. An increase of about 20.7% was estimated in wind speed measured at 40m compared to that at 20m. Wind turbines Fortis Passat-1.4kW. Fortis Montana-5.8kW, Fortis Alize-10kW, and CF20-20kW with annual energy and plant capacity factor of 7.015MWh and 57.2%, 25.955MWh and 51.08%, 42.603MWh and 48.63% and 54.674MWh and 31.21% were the most efficient turbines for the chosen location; respectively. Highest percentage increase in annual energy yield was obtained for a mere change of 5 m from 15 to 20 m in hub height in the present case study. The next best AEY was obtained while increasing hub height from 20 to 30 m.

Keywords: Small wind turbine; hub height; wind speed; turbulence intensity; wind power density, annual energy yield

1. INTRODUCTION

Globally increasing population, fast technological development, luxurious, and materialistic life styles have resulted in un-proportionate increase in power requirements. Hence new and renewable sources of energy in addition to regular means of power generation are being explored to meet the increasing demands. Exploitation and utilization of clean energy sources reduces the dependence on fossil fuels which means reduction in greenhouse gases (GHG) emissions and facilitates energy supply at places 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 clean sources, wind energy has been accepted commercially due to its availability, ease of maintenance, and low cost of operation. The global cumulative wind power installed capacity reached 369.597 GW by the end of 2014 compared to 318.644 GW in 2013, an increase of 16%, Ref. [GWEC (2015)]. The global annual cumulative wind power growth is shown in Figure 1. With cumulative installed capacity of 91.413 GW, China remained the leader in wind power industry as of December 2014. The USA, Germany, Spain and India remained at 2nd, 3rd, 4th, and 5th place with total cumulated wind power installed capacities of 65.879 GW, 39.165 GW, 22. 987 GW, and 22.465 GW; respectively. With respect to new additions in 2014, China was number one with 23.196 GW (45.1%) and Germany at number two with 5.279 GW (10.2%) new installations. However; USA, Brazil, and India remained 3rd, 4th, and 5th with new capacity additions of 4.854 GW (9.4%), 2.472 GW (4.8%), and 2.315 GW (4.5%); respectively.

Saudi Arabia is a vast country and is well connected with asphalted roads network and with electrical grid. Beside all efforts by the government, there are still some isolated areas and small communities and villages which are not on the national grid due to being un-economical. These villages and communities are being supplied power using diesel generation power plants developed and maintained by the national power utility. This option is very cost and skilled manpower intensive and hence the government is taking initiative to use new and renewable sources of energy like wind, solar thermal and solar photovoltaic to meet partial load requirements of these communities and villages. To investigate the possibility of using small wind turbines for various applications in Rawdat Ben Habbas (RBH), the present study has been initiated.

Small wind turbines applications include heating of greenhouses and residential buildings Ozgener (2010), hydrogen production for upgrading bitumen from oil fields Olateju and Kumar (2011), and water lifting Abed (1997), to name a few. According to Albani et al. (2014), all energy forms or sources have an adverse environmental impact but the wind energy does not, compared to conventional energy sources. Wind energy is one of the cleanest, benign, and environment friendly source of energy and is not going to diminish like fossil fuels having fixed and limited reserves (Al-Qabandi et al., 2014, Bassyouni and Gutub, 2013, and Ozgur and Kose, 2006).

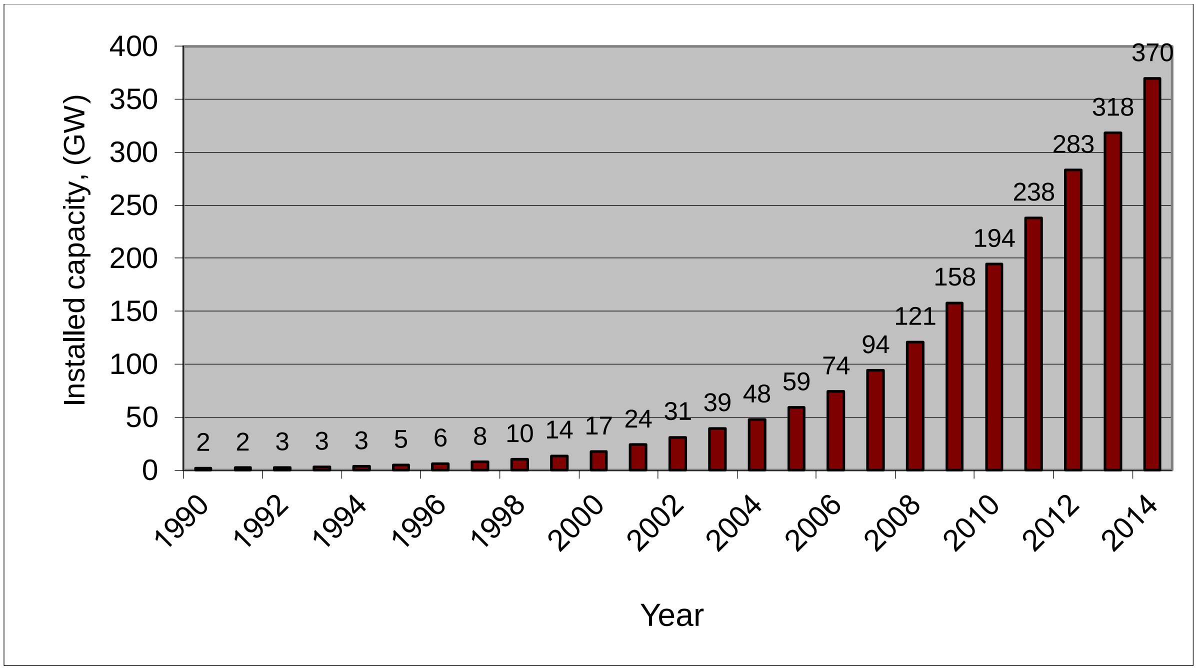

Figure 1. Global cumulative annual wind power installed growth, GWEC (2015)

Lara et al. (2011) evaluated a 3 kW wind turbine for charging a battery bank of 48 V/880 Ah by means of a 6-pulse rectifier. Nagai et al. (2009) 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 turbine was confirmed under actual wind conditions and it showed a power coefficient of 0.257 at an average speed of 7.3 m/s. Bekele and Tadesse (2012) conducted feasibility of small-scale hydro/pv/wind based hybrid system for six sites. Ozgener (2006) presented energy analysis of a 1.5 kW turbine 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 turbine produced 616 W of energy.

Arifujjaman et al. (2008) 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 on the control strategy, wind-speed and the Rayleigh distribution. Jowder (2009) investigated the site matching of wind turbines at 30 m and 60 m heights by estimating the capacity factors of some commercially available wind turbines for its optimal selection. The study conducted by Bishop and Amaratunga (2008) proposed a distributed 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 (2013) 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 300W, 600W and 1kW respectively. 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. (2012).

Etamaly (2013) proposed an accurate procedure to choose the best site and suitable wind turbines. Authors analyzed one hundred turbines to select suitable turbines for chosen best sites at Yanbo, Dhahran, Dhulom, Riyadh and Qaisumah in Saudi Arabia. Bassyouni et al. (2015) used wind data for a period of eleven years (2002–2012) study the wind characteristics of Jeddah in Saudi Arabia. The results showed that maximum and minimum wind power potential was observed in the month of March and February. The study concluded that the wind potential of the region can be used for small scale off-grid applications. Islam et al. (2013) proposed a comprehensive study to highlight the recent and future trends of wind energy technology, and estimated that with in next 2-3 decades the vertical axis wind turbines (VAWT) can dominate the wind-energy technology. Chen et al. (2013) used a statistical method in combination with linear wake model and wind turbine power curve to model the wind speed distribution for wind power assessment for optimal micro-siting. Kishore et al. (2013) proposed the design of a small-scale wind energy portable turbine targeted to operate below 5 m/s wind speed. Simic et al. (2013) performed a detailed study and analysis of small wind turbines with less than 10kW of installed power.

The present study utilizes wind speed measurements made at different heights over a period of around five years at Rawdat Ben Habbas (RBH) meteorological station to evaluate the performance of 13 horizontal axis wind turbines (HAWT) of 3 to 20 kW rated power.

2. DATA, SITE, and MATERIAL DESCRIPTION

The meteorological data (wind speeds, wind direction, ambient temperature, relative humidity, surface pressure, global solar radiation) were measured at Rawdat Ben Habbas (RBH) station for a period of approximately 56 months from September 13, 2005 to May 09, 2010. The data was scanned every 3 seconds and 10 minutes averaged values along with mean, standard deviation, minimum and maximum were recorded. The data collection was done through on-site visits and remotely using Al-Jawal GSM data services. The latitude, longitude and altitude of the measurements site were 29° 8’ N, 44˚ 20’ E and 443.0 meter. The data collection site at RBH is an open area from all directions except a number of transmission line poles, cables and shades for housing the generators and other inventory items. The site is located inside the RBH diesel power plant and is fenced from all sides. The wind speed data were collected at 20, 30, and 40 meters height above the ground. At al measurement heights, two wind speed sensors were installed. The wind direction data were recorded at 30 and 40 meters. The ambient temperature (˚C) and global solar radiation (W/m^2) data were recorded at 2 meters above the ground level. A schematic of the meteorological sensors installed on 40 meter tall tower is shown in Figure 2 and an actual photo of the mast taken at the site is shown in Figure 3. The technical specifications of all the sensors used in this measurement campaign are given in Table 1.

The energy pattern factor (K_e) also known as the cube factor is calculated for each wind speed using the following equation:

$$K_e = \frac{1}{N\overline{U}^3}\sum_{i=1}^{N} U_i^3 \tag{1}$$

Where N is the number of time steps, U_i is the wind speed at time step I, U is the mean wind speed. For constant air density, the energy pattern factor is calculated as the ratio of the actual mean wind power density to the wind power density calculated based on only the mean wind speed as follows:

$$\frac{\overline{P}}{A} = \frac{1}{2}\rho\,\overline{U}^3 K_e \tag{2}$$

Where $\frac{\bar{P}}{A}$ the mean wind power density in W/m3, ρ is the air density in kg/m^3, U is the mean wind speed in m/s, and K_e is the energy pattern factor. The average wind energy content for each wind speed in the data set is estimated using the following equation:

$$\frac{\overline{E}}{A} = \frac{\overline{P}}{A}\cdot\frac{8760\,\mathrm{hr}}{\mathrm{yr}} \div \frac{1000\,\mathrm{W}}{\mathrm{kW}} \tag{3}$$

Where $\frac{\bar{E}}{A}$ is the average wind energy content in kWh/m^2/yr and $\frac{\bar{P}}{A}$ is the average wind power density in W/m^2.

A total of 13 commercially available small horizontal axis wind turbines (HAWT) were selected and the required technical specifications are given in Tables 2. The wind power curves of chosen HAWT were obtained from different internet sources (web links are given in Appendix-A). The rated power of HAWT varied from 1.4 kW to 20 kW. The wind power curves used for energy yield estimation are given in Figures 4(a) and 4(b).

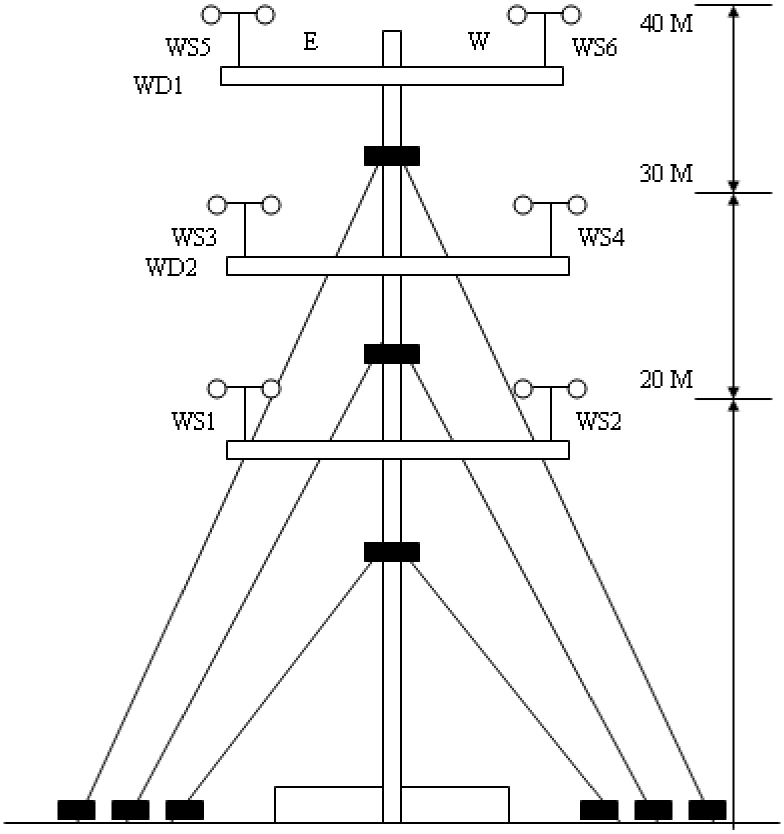

Figure 2. Schematic diagram of meteorological measurement tower at RBH

Table 1. Operating ranges and accuracies of various sensors used for data collection.

Item Description	Technical Information
Wind speed sensor, NRG#40 Three cup anemometer	AC sine wave, Accuracy: 0.1m/s, Range: 1-96 m/s Output: 0-125 HZ, Threshold: 0.78 m/s
Wind direction vane, NRG#200P Potentiometer	Accuracy: 1%, Range: 360^{o} Mechanical, Output: 0-Exc. Voltage, Threshold: 1m/s, Dead band: Max -8^{o} and Typical 4^{o}
Temperature sensor #110S Integrated circuit	Accuracy: ±1.1^{o}C, Range: -40^{o}C to 52.5^{o}C, Output: 0–2.5 volts DC, Operating temperature range: -40^{o}C to 52.5^{o}C
Barometric pressure sensor BP20	Accuracy: ±15 mb, Range: 150–1150 mb, Output: Linear voltage
Relative humidity sensor RH-5 Polymer resistor	Accuracy: ±5%, Range: 0–95% Output: 0–5volts, Operating temperature range: -40^{o}C to 54^{o}C
Pyranometer Li-Cor #LI-200SA Global solar radiation	Accuracy: 1%, Range: 0–3000W/m^{2} , Output: Voltage DC, Operating temperature range: -40^{o}C to 65^{o}C

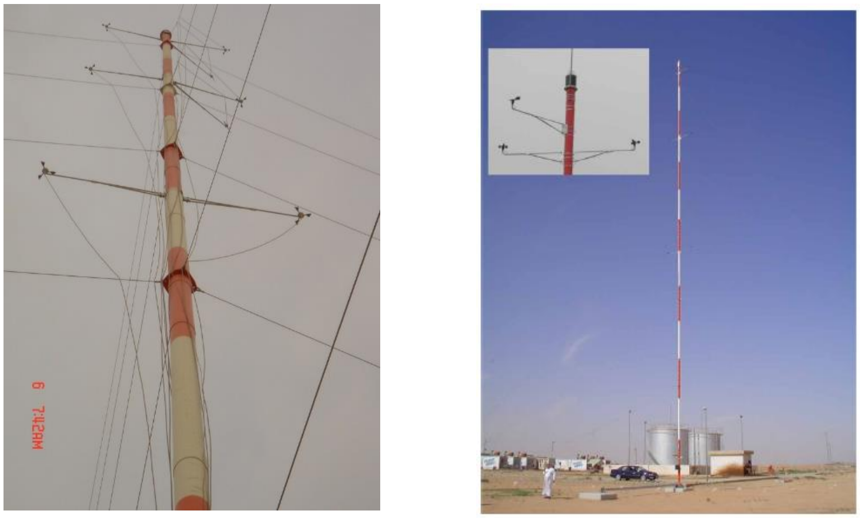

Figure 3. Meteorological measurement mast at RBH

Table 2. Horizontal axis small wind turbine specifications

S. N.	Model	Rated Power (kW)	Cut-in-speed (m/s)	Rated Speed (m/s)	Rotor Diameter (m)
1	Aeolos 3kW	3	3	11	5
2	Aeolos 5kW	5	3	10	6.4
3	Aeolos 10kW	10	3	10	8
4	Aeolos 20kW	20	3	10	10
5	Bergey Excel-10	10	2.2	11	7
6	CF6e	6	1.2	8	8
7	CF11	11	1.2	9	9
8	CF15	15	1.5	9	11.1
9	CF20	20	1.5	9	13.1
10	Evance R9000	5	3	12	5.5
11	Fortis Passat 1.4kW	1.4	4	15	3.12
12	Fortis Montana	5.8	3	17	5
13	Fortis Alize 10kW	10	4	13	7

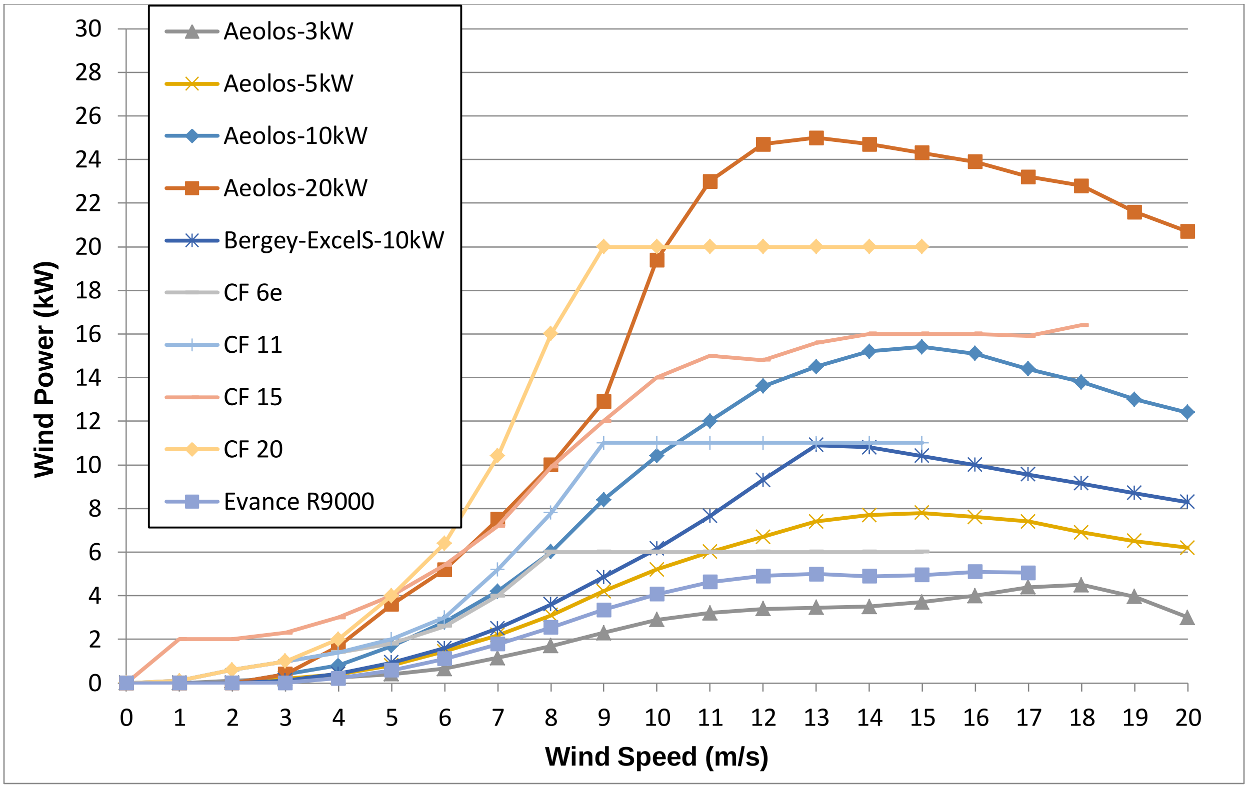

Figure 4(a). Wind power curves of selected HAWT's

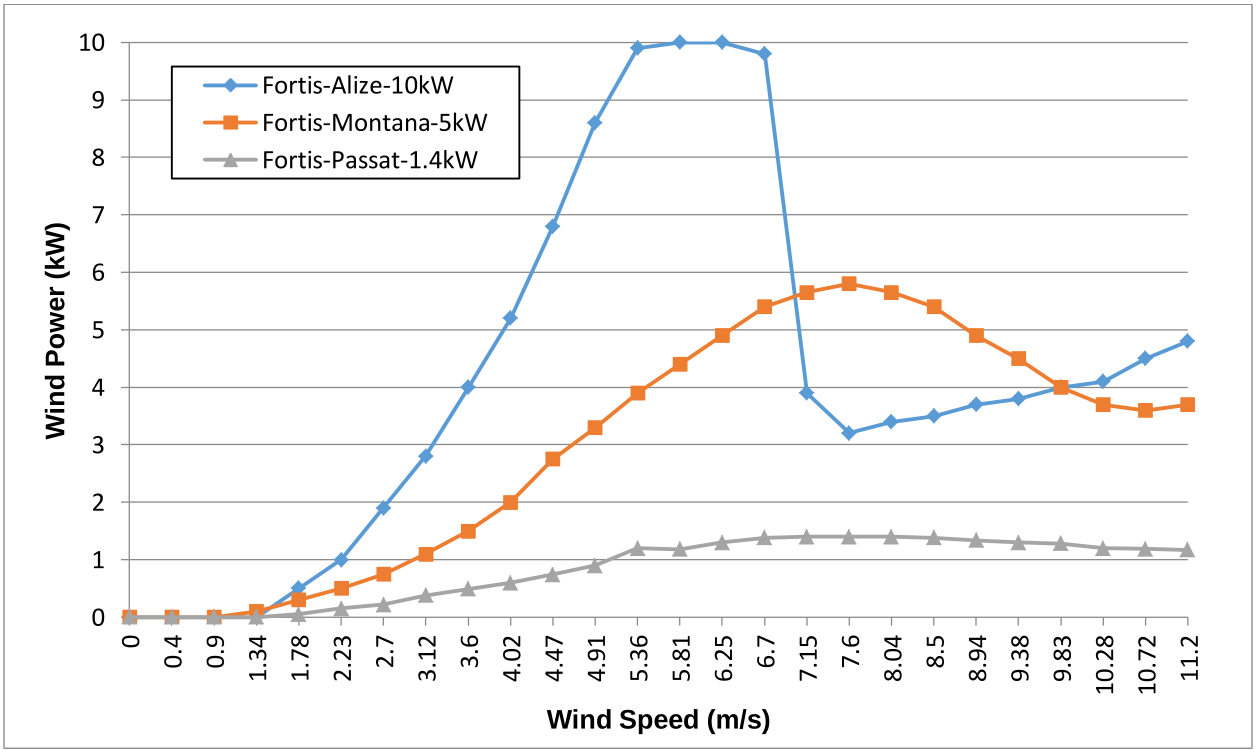

Figure 4(b). Wind power curves of selected HAWT's

3. RESULTS AND DISCUSSION

The theoretical computation results are presented as overall meteorological summaries, energy yield and plant capacity factor (PCF), annual and monthly energy yield and PCF variation. To estimate the net power or energy yield, the availability, wake effect, turbine performance, electrical losses are assumed as 3%, 4%, 3%, and 2% respectively with an overall loss of 11.48%. The PCF values were obtained by dividing the actual energy yield by the maximum possible yield in a given period of time.

3.1. Meteorological summaries at RBH (September 13, 2005 to May 09, 2010)

The mean, mean of monthly means (MoMM), minimum, and maximum values along with the median of measured wind speeds (WS1, WS2, WS3, WS4, WS5, and WS6), wind directions (WD1 and WD2), ambient temperature, global solar radiation, pressure, and relative humidity and derived parameters (like air density, turbulence intensity-TI, and wind power density-WPD) are summarized in Table 3. The mean WS increased by around 7.1 and 12.7% at 30 and 40 m above ground level (AGL) compared to its value at previous height, respectively. An overall increase of about 20.7% was observed in wind speed measured at 40m compared to that at 20m. The MoMM gives a better estimate of mean wind speed values because the seasonality effects are minimized by taking the average of monthly men values. In the present case, the MoMM were almost the same as the mean wind speed values as seen from the data given in Table 3. The mean WD was predominantly from NNW with an average value of 339° at 40 m and 327° at 30 m. The ambient temperature at the site varied from a minimum of -6.1°C to a maximum of 49.1°C with an overall average of 24.7°C. The mean values of global solar radiation, pressure, and relative humidity were 231 W/m^2, 931.4 mbar, and 21.4%; respectively. The air density was calculated using ambient pressure and temperature and was found to vary from 0.72 to 1.27 kg/m^3 with an overall mean of 1.09 kg/m^3. The local value of air density was used for the estimation of wind power density (WPD) and energy yield from the chosen wind turbines.

The mean air turbulence intensities were calculated using the mean wind speed and standard deviation values and were found to be 0.14, 0.14, and 0.16 at 40, 30, and 20 m AGL which were always less than the critical TI value of 0.18 as the permissible value recommended in IEC 61400-1 standard (2005). Furthermore, the mean TI values were found to be decreasing with height which indicates that wind turbines will be safe to operate even at further higher hub heights if needed. Finally, the mean WPD was found to vary from 102 W/m^2 to 165 W/m^2 corresponding 20 and 40m heights. The mean WPD at 30 m height was 135 W/m^2 as can be seen from Table 3. In case wind power density, the MoMM of WPD and simple WPD values were almost the same in magnitude. The WPD density was also found to increase with increasing heights. The mean energy content or the wind speed cube factor was observed to be decreasing with increasing wind measurement height. For an increase of height of 10 m from 20 to 30, the energy content changed by around 25% while for the same height change from 30 to 40 m it changed only by 18%. This simply implies that the energy content or the wind cube factor effect decreases with height. The energy pattern factors were found to be decreasing with increasing height with highest values at 20 m height and lowest at 40 m.

Table 3. Meteorological data summary (September 13, 2005 to May 09, 2010)

Variable	**WS5**	**WS6**	**WS3**	**WS4**	**WS1**	**WS2**
Measurement height (m)	40	40	30	30	20	20
Mean wind speed (m/s)	5.72	5.68	5.34	5.21	4.74	4.52
MoMM wind speed (m/s)	5.73	5.69	5.34	5.22	4.75	4.54
Median wind speed (m/s)	5.7	5.7	5.3	5.1	4.5	4.3
Min wind speed (m/s)	0.4	0.4	0.4	0.4	0.4	0.4
Max wind speed (m/s)	18.6	18.7	18.3	18.2	17.4	17.3
Weibull k	2.39	2.35	2.37	2.22	2.20	1.91
Weibull c (m/s)	6.44	6.40	6.01	5.87	5.35	5.07
Prevailing wind direction (Deg)	339.1		327.8			
Mean power density (W/m^2)	165	163	135	132	102	99
MoMM power density (W/m^2)	164	163	135	131	102	99
Mean energy content (kWh/m^2/yr)	1,444	1,428	1,185	1,155	895	864
MoMM energy content (kWh/m^2/yr)	1,440	1,424	1,181	1,151	893	865
Energy pattern factor	1.617	1.635	1.632	1.71	1.754	1.944
Frequency of calms (%)	0.32	0.36	0.39	0.95	0.62	2.19
	Mean	**Min**	**Max**			
Ambient temperature (°C)	24.7	-6.1	49.1			
Surface pressure (mb)	931.4	650.8	986.6			
Relative humidity (%)	21.4	0.0	100.0			
Air density (kg/m^3)	1.09	0.72	1.27			
Turbulence intensity at 40 m	0.14	0.0	1.00			
Turbulence intensity at 30 m	0.14	0.0	0.88			
Turbulence intensity at 20 m	0.16	0.0	1.17			

3.2. Energy yield and plant capacity factor analysis (July 01, 2006 to July 10 2008)

The annual energy yield and the PCF corresponding to all wind turbines at 10, 15, 20, 30, and 40 m heights are summarized in Table 4. For a small load of 700W or less Fortis Passat WT with 1.4 kW rated capacity could be used. The annual energy yield (AEY) of this turbine is 4.847 MWh with a PCF of 39.5% at 10 m hub height. The same WT could produce 7.084 MWh of electricity with a PCF of 57.8% at 40 m hub height. Among 5 kW rated power turbines, Aeolos-5kW was found to be most efficient with an AEY of 12.017 MWh and PCF of 27.44% corresponding to 40 m hub height. From 10 kW rated power WT's, Fortis Alize-10k was found to be most efficient with AEY of 43.901 MWh and PCF of 50.12% at 30 m hub height. The 20 kW rated power WT CF20 produced 54.674 MWh electricity annually with a PCF of 31.21% while Aeolos-20kW turbine produced 42.141 MWh of energy with a PCF of 24.05% corresponding to 40 hub height. The performance of other WT's of 3 kW, 6 kW, 11 kW, and 15 kW are also included in Table 4 and a particular WT with suitable hub height can be selected for meeting the required electrical loads.

The effect of hub height on the percent change in energy yield from chosen WT's is shown in Figure 5. As seen from this figure, maximum percentage increase in AEY was observed for all the chosen WT's while changing the hub height from 15 to 20 m i.e. an increase of only 5 m. Next best percentage increase in AEY was obtained for hub height change of 5 m i.e. from 10 to 15 m. An interesting observation is made from this figure that almost all the WT's showed same percentage change in AEY for an increase of hub height of 5 m (from 10 to 15m) and an increase of hub height of 10 m (from 20 to 30 m). Furthermore, highest percentage increase in AEY of about 45% was observed for Bergey Excel-10 and Evance R9000 wind turbines. For example in case of Evance R9000, the AEY changed from 2.869 MWh to 3.882 MWh to 5.657 MWh to 7.603 MWh to 9.186 MWh corresponding to change in hub height from 10 to 15, 15 to 20, 20 to 30, and 30 to 40 m; respectively.

For practical applications at RBH and its surroundings and areas with similar or better wind resources, following wind turbines are recommended:

- For small loads of < 0.7 kW, Fortis Passat with PCF of 41.76% at 15 m hub height
- For medium loads of up to 1.5 kW, Aeolos-5kW with PCF of 17.61% at 20 m hub height
- For larger loads of up to 2.5 kW, CF6e with PCF of 29.78% at 20 m hub height

- For further higher loads, suitable wind turbines could be chosen from the performance data given in Table 4.

Table 4. Annual energy yield and plant capacity factor obtained from HAWT's

S. No.	**Wind Turbine Model**	**Hub Height (m)**									
		10		**15**		**20**		**30**		**40**	
		Energy (kWh)	**PCF (%)**	**Energy (kWh)**	**PCF (%)**	**Energy (kWh)**	**PCF (%)**	**Energy (kWh)**	**PCF (%)**	**Energy (kWh)**	**PCF (%)**
1	Fortis Passat	3,996	32.58	5,122	41.76	5,654	46.1	6,625	54.02	7,015	57.20
2	Aeolos-3kW	2,513	9.56	3,065	11.66	4,237	16.12	5,391	20.51	6,428	24.46
3	Aeolos-5kW	4,219	9.63	5,494	12.54	7,714	17.61	10,077	23.01	12,017	27.44
4	Evance 5kW	2,869	6.55	3,882	8.86	5,657	12.92	7,603	17.36	9,186	20.97
5	Fortis Montana	14,171	27.89	18,328	36.07	20,381	40.11	24,280	47.79	25,955	51.08
6	CF6e	10,767	20.49	12,869	24.49	15,652	29.78	18,835	35.83	21,387	40.69
7	Aeolos-10kW	8,387	9.57	10,921	12.47	15,298	17.46	19,888	22.7	23,674	27.03
8	Bergey Excel-10	4,600	5.25	6,083	6.94	8,776	10.02	11,589	13.23	13,936	15.91
9	Fortis Alize-10	30,148	34.42	39,315	44.88	39,761	45.39	43,901	50.12	42,603	48.63
10	CF11	12,393	12.86	14,933	15.5	19,680	20.42	24,486	25.41	28,764	29.85
11	CF15	24,854	18.91	28,371	21.59	33,535	25.52	39,154	29.8	43,715	33.27
12	Aeolos-20kW	15,271	8.72	20,288	11.58	27,808	15.87	35,865	20.47	42,141	24.05
13	CF20	21,006	11.99	26,778	15.28	35,988	20.54	46,241	26.39	54,674	31.21

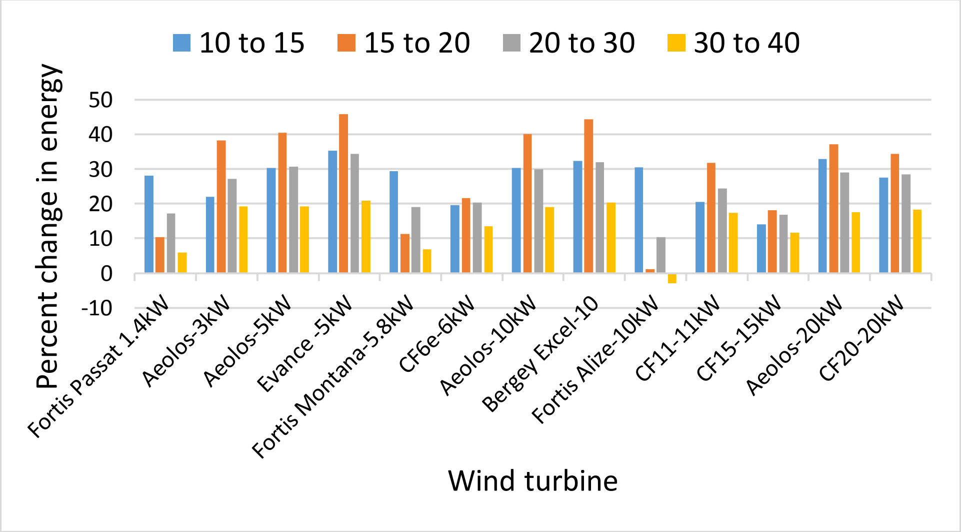

Figure 5. Percentage increase in AEY of wind turbine with change in hub height

Figures 6 and 7 provide the performance of all the WT's at a glance based on AEY and PCF and could be used for the selection of an efficient wind turbine for a particular load requirement and application. Furthermore, these figures could also be helpful in choosing the hub height of the chosen wind turbine based on AEY or PCF or combination. The long term performance in terms of actual energy produced in different years (from 2006 to 2009) of all the WT's corresponding to hub heights of 10, 15, 20, 30, and 40 m is displayed in Figures 8 to 12, respectively.

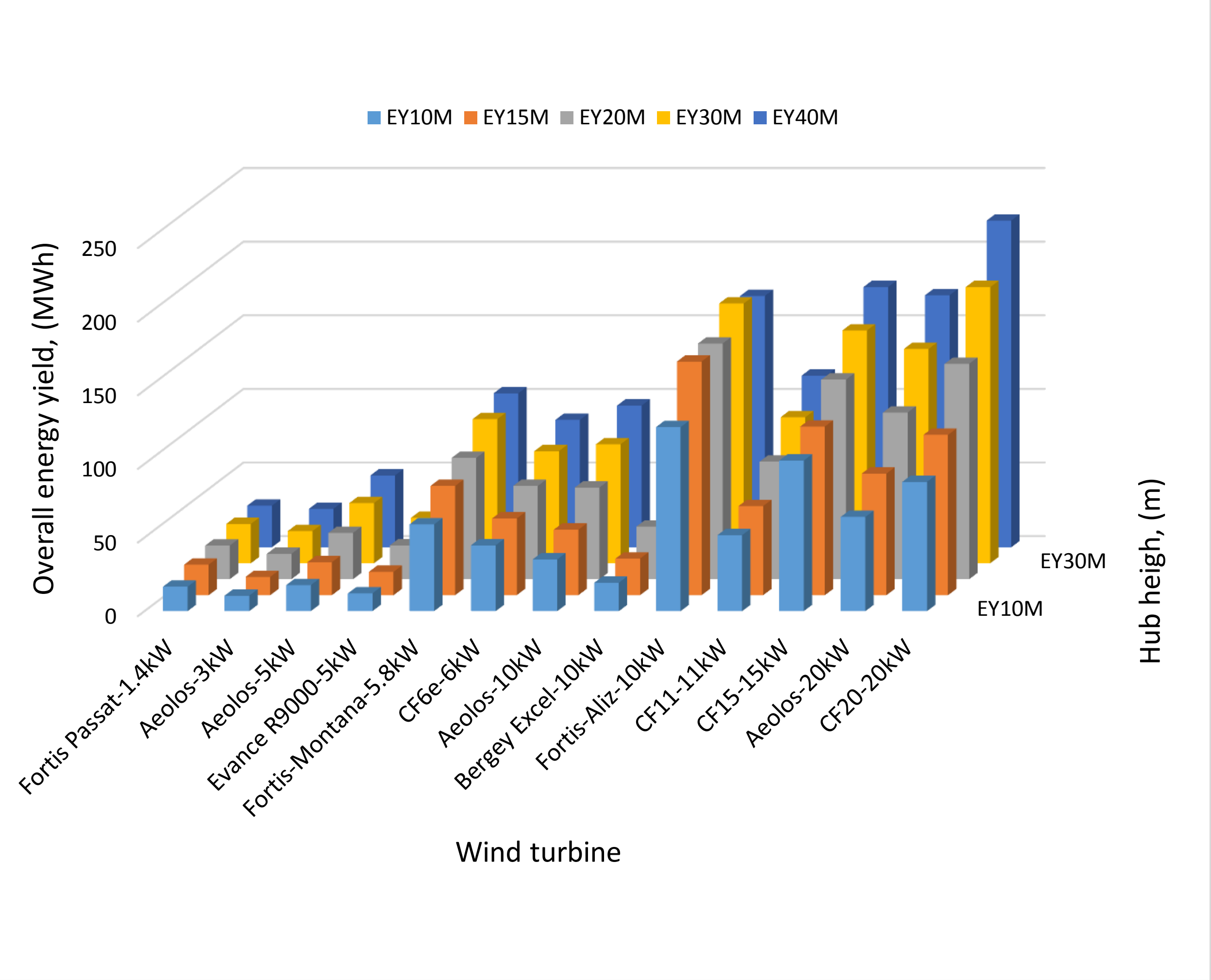

Figure 6. Variation of overall energy yield from chosen wind turbines with hub height

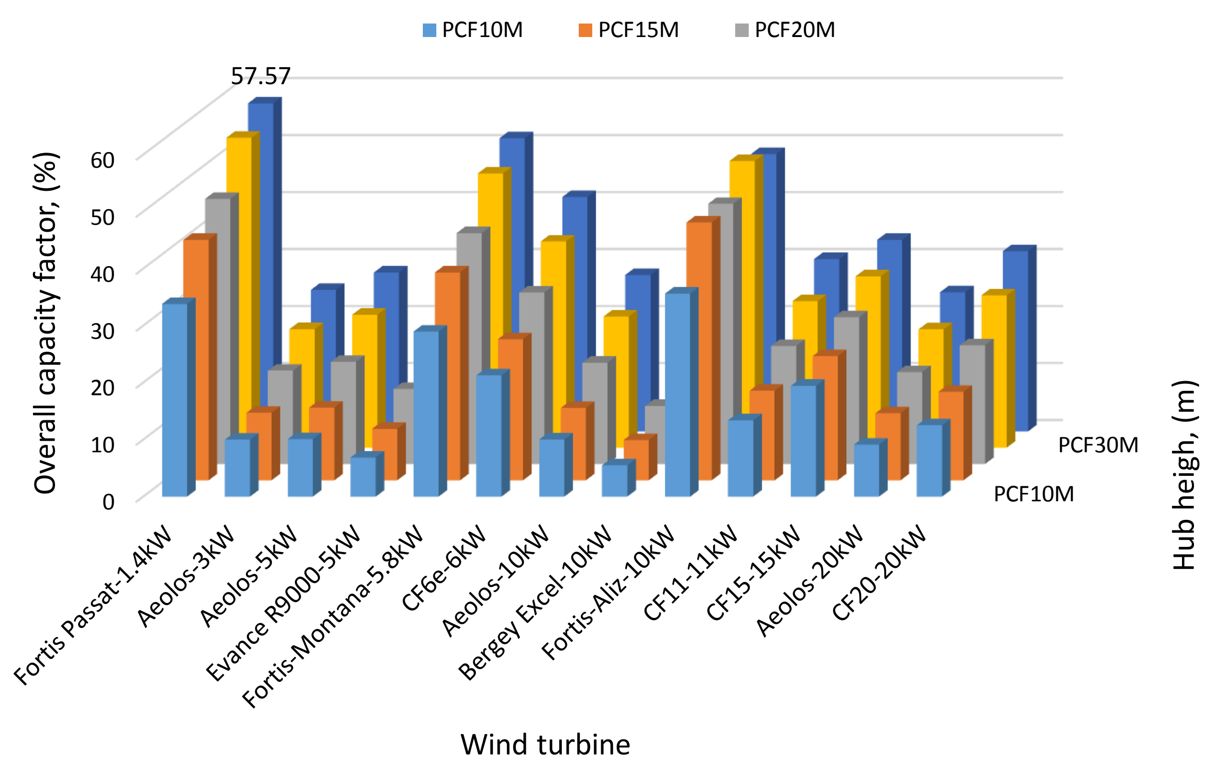

Figure 7. Variation of overall plant capacity factors of chosen wind turbines with hub height

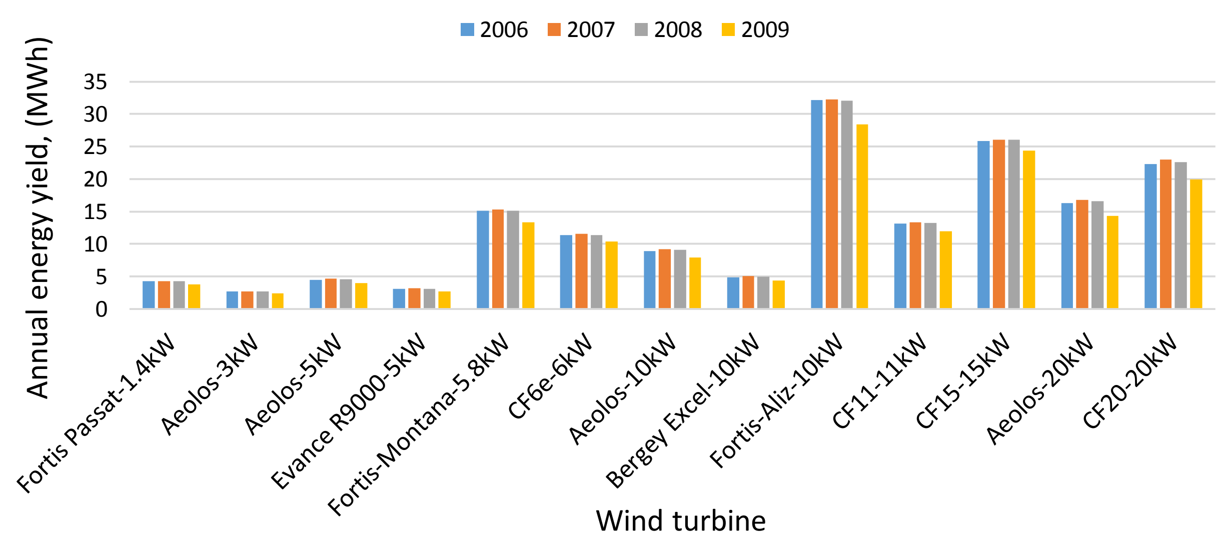

Figure 8. Annual variation of energy yield of wind turbines with 10 m hub height

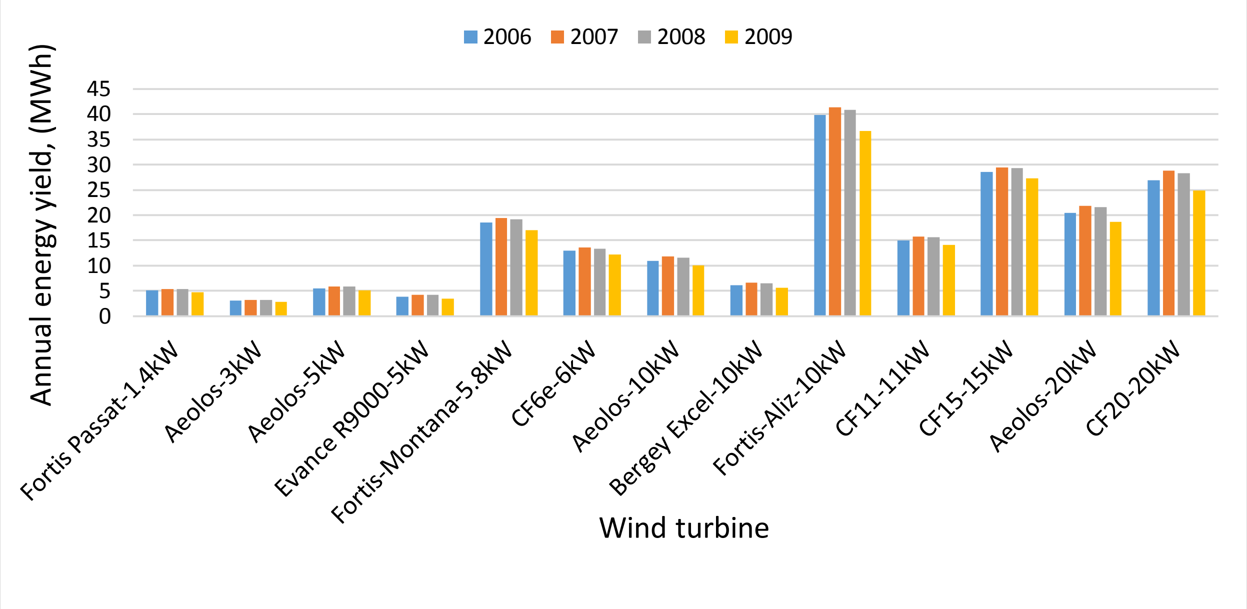

Figure 9. Annual variation of energy yield of wind turbines with 15 m hub height

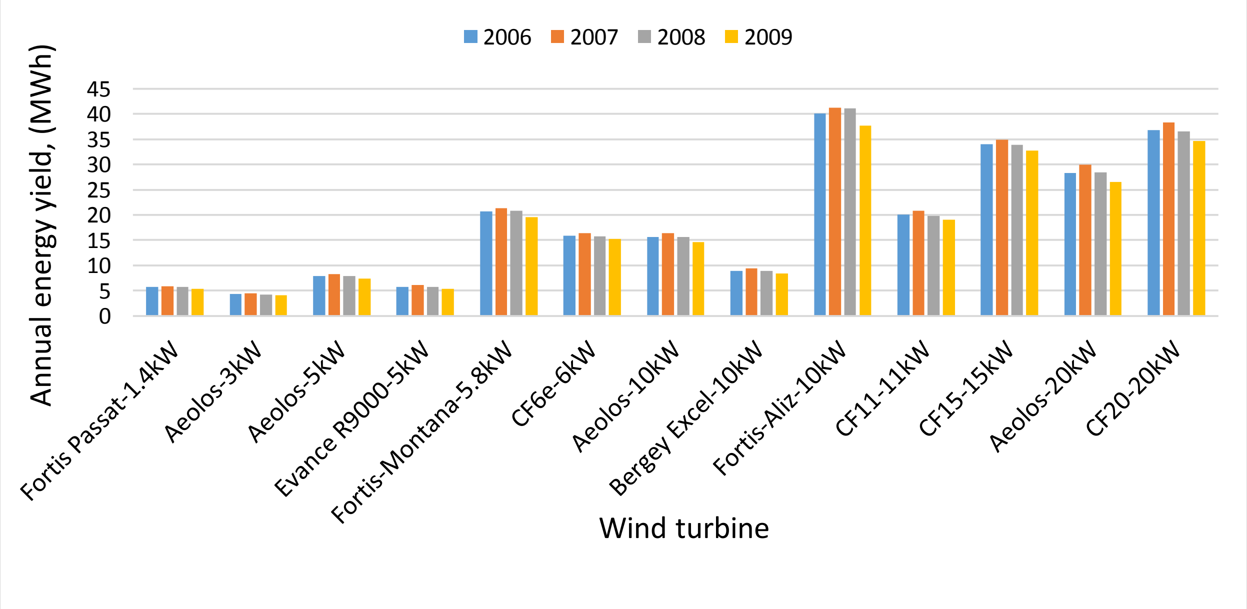

Figure 10. Annual variation of energy yield of wind turbines with 20 m hub height

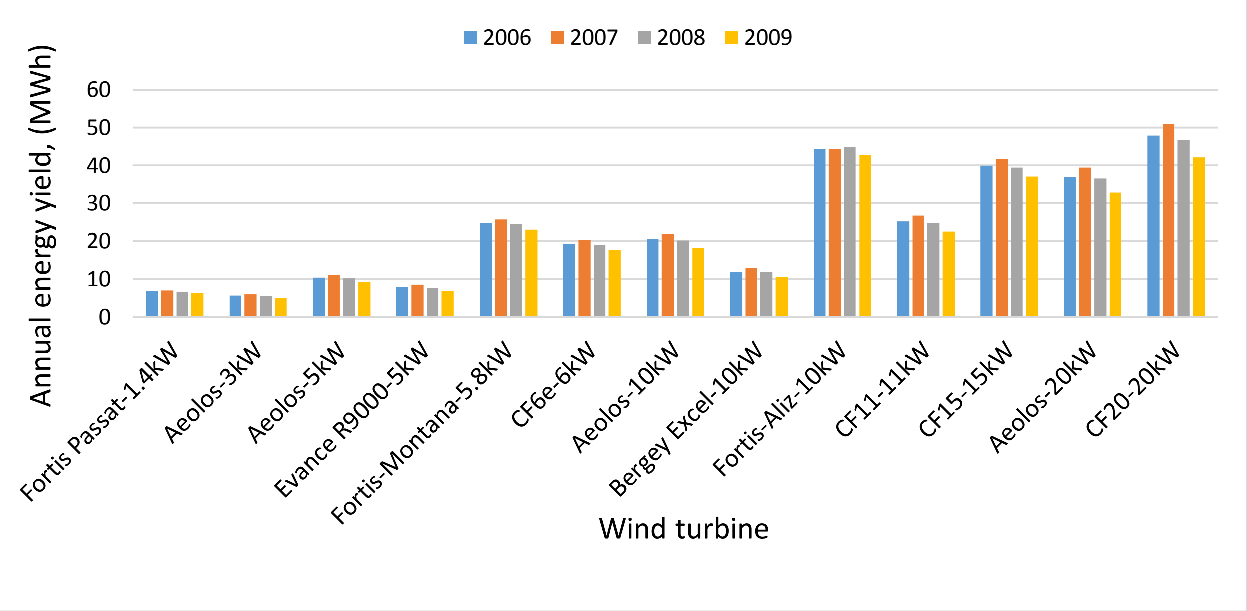

Figure 11. Annual variation of energy yield of wind turbines with 30 m hub height

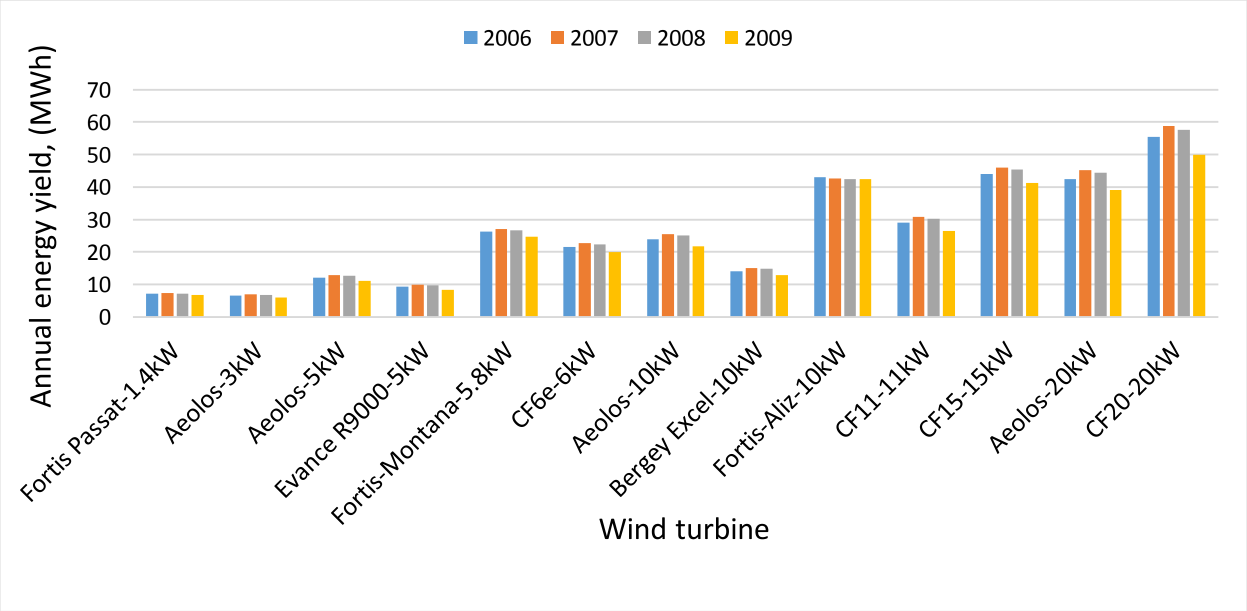

Figure 12. Annual variation of energy yield of wind turbines with 40 m hub height

The durations during which the chosen wind turbines did not produce any energy are compared in Figure 13. It is very clear from this representation that all the wind turbines had highest percentages of zero out for hub height of 10 m. This simply meant that the wind has more fluctuations near the ground level due to high roughness value. As the hub height of the turbine increased, the percentages of the zero output energy were noticed to decrease, as depicted in Figure 13. In case of wind turbines Fortis Passat, Aeolos-H-3kW, Fortis Montana-H5.8kW, and Fortis Alize-H-10kW; the decrease in zero output percentages was insignificant while in case of rest of the turbines it was noticeable. It is however established that maximum decrease in zero output power was achieved for a mere increase in hub height of 5 m from 10 to 15. On the other hand almost no change or decrease was seen in percent time duration of zero power output.

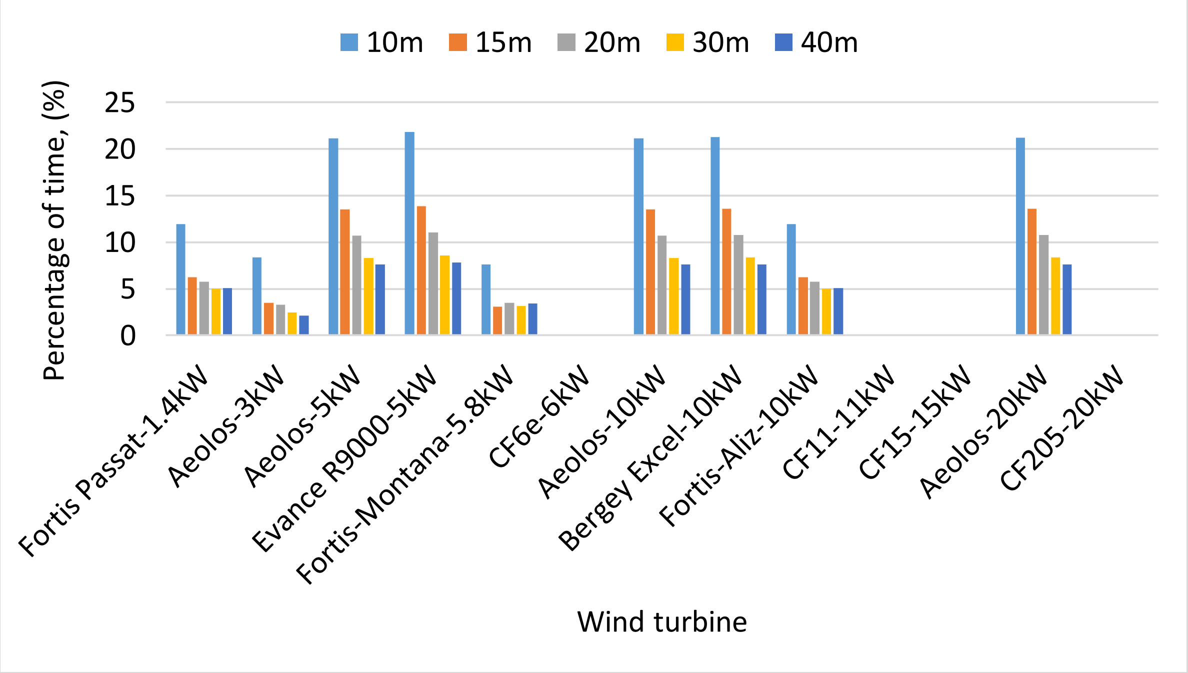

Figure 13. Zero output power duration during entire data collection period

The percent duration of time during which the wind turbines produced the rated power at different hub heights is shown in Figure 14. In general the rated power generation duration was found to increasing with increasing hub height due to the fact that wind speed intensity increases with height above the ground level due to minimal effect of ground activities and additional contribution of regional wind speed. At 10 and 15 m hub heights none of the wind turbine except Fortis Passat, CF6e, and Fortis Alize produced the rated power. The data provided in Figures 13 and 14 can also provide a guide line for the selection of an efficient wind turbine for a particular site for wind power development.

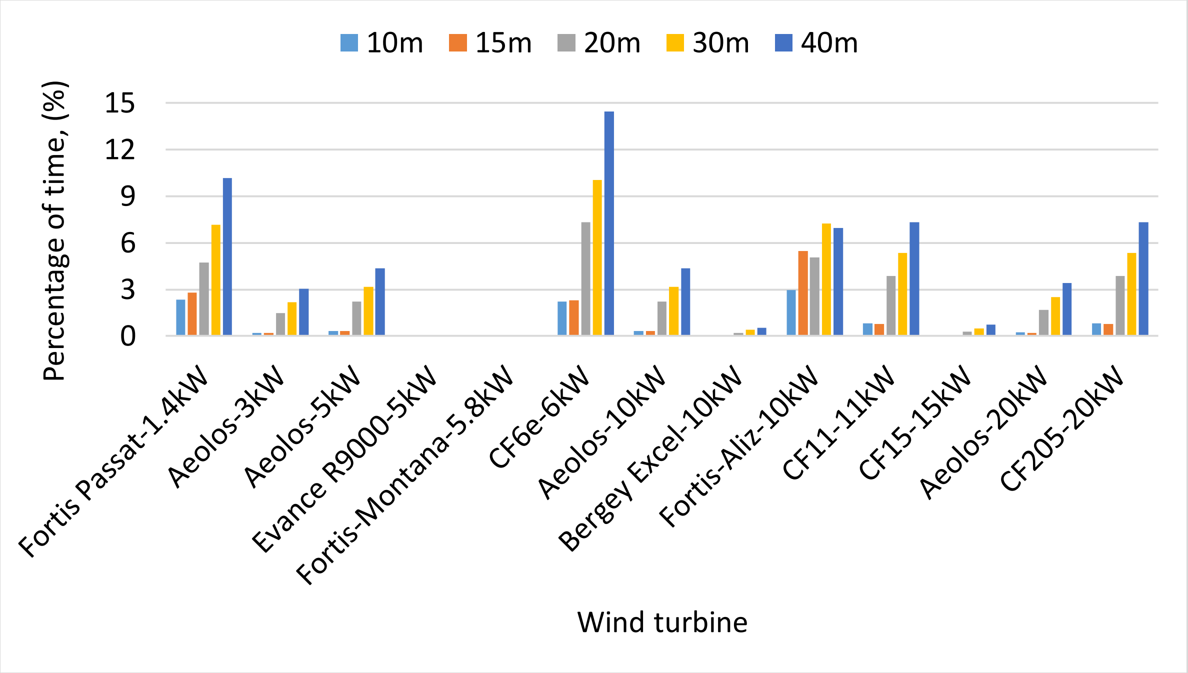

Figure 14. Rated output power duration during entire data collection period

3.3. Monthly variation of energy yield and plant capacity factor

Based on optimal annual energy yield, the PCF, and hub height; wind turbines with higher values have been chosen here for further analysis on monthly basis. The selected wind turbines are Fortis Passat of 1.4 kW, Fortis Montana of 5.8 kW, Fortis Alize of 10 kW, and CF20 of 20kW rated powers. The respective plant capacity factors (PCF) of these turbines are of 41.76%, 4011%, 50.12% and 31.21% corresponding to hub heights of 15 m, 20 m, 30 m, and 40 m; respectively.

Under RBH wind conditions, the 1.4 kW wind turbine is expected to produce a maximum of 497 kWh of energy in July while a minimum of 324 kWh in the month of September with respective PCF’s of 47.7% and 32.2%. Furthermore, during entire year, a net energy of about 400 kW could be available from this small wind turbine of 1.4 kW and hence can be used comfortably for small energy needs as seen from the data summarized in Table 5. The duration during which the energy output was zero remained always < 10%. The duration during which the turbine produced rated power was >2% during most of the months and around 5% during February to June. The net PCF values were mostly around 35%, as can be seen from the last column of Table 5.

Table 5. Monthly variation of energy yield and plant capacity factor for a 1.4 kW (Fortis Passat) wind turbine at 15 m hub height

Month	Hub Height Wind Speed (m/s)	Time At Zero Output (%)	Time At Rated Output (%)	Mean Net Energy (kWh)	Net PCF (%)
Jan	4.21	6.18	3.31	432	41.5
Feb	4.61	6.77	5.47	427	45.4
Mar	4.48	7.45	4.49	449	43.1
Apr	4.38	6.47	4.78	420	41.7
May	4.15	6.67	3.34	406	39.0
Jun	4.74	4.03	4.93	478	47.4
Jul	4.72	3.36	3.56	497	47.7
Aug	3.97	5.81	1.51	379	36.4
Sep	3.69	7.97	1.24	324	32.2
Oct	4.02	6.59	2.12	390	37.5
Nov	3.69	8.28	1.44	335	33.2
Dec	3.91	7.58	2.50	380	36.5
Overall	4.20	6.52	3.22	4,903	40.0

A 5.8 kW (Fortis Montana) wind turbine could produce maximum energy of 2001 kWh in the month of July while a minimum of 1308 kWh in September with respective PCF's of 40.6% and 31.3% with a hub height of 20m, as given in Table 6. On an average, during entire year, the net energy output was > 1500kWh. The duration during which the energy output was zero remained mostly < 4%. This turbine was never able to produce the rated power under wind conditions of RBH, as it is evident from the data given in Table 6. The net PCF values were mostly around 40% with a minimum of 31.3% in the month of September, as can be seen from the last column of Table 6.

Table 6. Monthly variation of energy yield and plant capacity factor for a 5.8 kW (Fortis Montana) wind turbine at 20 m hub height

Month	Hub Height Wind Speed (m/s)	Time At Zero Output (%)	Time At Rated Output (%)	Mean Net Energy (kWh)	Net PCF (%)
Jan	4.64	3.47	0.00	1,722	39.9
Feb	5.08	3.90	0.00	1,654	42.4
Mar	4.95	4.19	0.03	1,752	40.6
Apr	4.89	3.33	0.06	1,660	39.7
May	4.63	3.40	0.00	1,663	38.5
Jun	5.26	2.92	0.00	1,863	44.6
Jul	5.22	1.81	0.00	2,001	46.4
Aug	4.36	2.45	0.00	1,551	35.9
Sep	4.02	3.79	0.00	1,308	31.3
Oct	4.40	2.98	0.03	1,568	36.3
Nov	4.03	4.06	0.00	1,363	32.6

Dec	4.27	3.71	0.00	1,514	35.1
Overall	4.63	3.37	0.01	19,546	38.5

The 10 kW wind turbine (Fortis Alize) was the most efficient turbine among 10 kW rated power machines studied in the present work. This turbine with 30 m hub height was able to produce a maximum of 4,030 kWh of energy in July with a PCF of 54.2% and a minimum of 3,254 kWh in February with a PCF of 48.4% as shown in Table 7. Furthermore this turbine produced more energy during summer time compared to wintertime as dictated by numbers given in the 5th column of Table 7. The zero output duration was always < 7%. However, the rated energy output was almost always > 6% which is an indication of good performance of this turbine at the test site. The net PCF was always > 47% with a minimum of 47.2% in March and a maximum of 50.3% in October, as can be seen from the last column of Table 7.

Table 7. Monthly variation of energy yield and plant capacity factor for a 10 kW (Fortis Alize) wind turbine at 30 m hub height

Month	Hub Height Wind Speed (m/s)	Time At Zero Output (%)	Time At Rated Output (%)	Mean Net Energy (kWh)	Net PCF (%)
Jan	5.27	5.40	6.45	3,679	49.5
Feb	5.73	7.00	6.03	3,254	48.4
Mar	5.63	6.96	6.16	3,508	47.2
Apr	5.76	5.11	6.89	3,443	47.8
May	5.30	4.63	6.54	3,677	49.4
Jun	5.83	3.89	7.67	3,717	51.6
Jul	5.75	2.52	7.76	4,030	54.2
Aug	4.89	4.03	7.39	3,813	51.2
Sep	4.60	6.19	6.79	3,406	47.3
Oct	5.08	5.16	7.42	3,740	50.3
Nov	4.64	5.78	6.83	3,486	48.4
Dec	4.94	5.86	7.37	3,685	49.5
Overall	5.28	5.29	6.92	43,324	49.5

The 20 kW rated power (CF20) turbine never had zero output during entire operation period as can be seen from column 3 of Table 8. On the other hand the rated output duration was relatively on the higher side varying from 2% to 13%. The energy output from this turbine was found to be increasing from January till July and then decreasing towards September and then a recovery towards the end of the year. The maximum energy of 5,318 kWh with a PCF of 36.9% could be received in June while a minimum of 3,321 kWh in September with a PCF of 23.1% at a hub height of 40 m. Furthermore this turbine produced more energy during summer time compared to wintertime as shown in 5th column of Table 8. This energy pattern matches with the larger load requirement during summer time and lower during rest of the period. The net PCF was always > 23%, as seen from the last column of Table 8.

Table 8. Monthly variation of energy yield and plant capacity factor for a 20 kW (CF20) wind turbine at 40 m hub height

Month	Hub Height Wind Speed (m/s)	Time At Zero Output (%)	Time At Rated Output (%)	Mean Net Energy (kWh)	Net PCF (%)
Jan	5.67	0.03	7.77	4,756	32.0
Feb	6.19	0.30	13.56	4,991	37.1
Mar	6.11	0.40	11.77	5,280	35.5
Apr	6.24	0.11	12.94	5,294	36.8
May	5.67	0.09	6.20	4,503	30.3
Jun	6.27	0.00	10.63	5,318	36.9
Jul	6.22	0.00	6.96	5,310	35.7
Aug	5.30	0.00	2.22	3,765	25.3
Sep	5.01	0.00	2.43	3,321	23.1
Oct	5.52	0.00	5.59	4,269	28.7
Nov	5.03	0.00	2.50	3,419	23.7
Dec	5.32	0.05	5.22	4,115	27.7
Overall	5.70	0.09	7.36	54,320	31.0

4. Conclusions

A total of 13 wind turbines have been analyzed in terms of annual energy yield and plant capacity factor by using wind speed data measured at 20, 30 and 40 m above ground level at RBH meteorological station in Saudi Arabia for a period of 55 months and 25 days. To estimate the net power or energy yield, the down time, array, icing, and other losses were assumed as 5%, 4%, 1%, and 2% respectively. Following are the findings of the present study:

- The long term mean WS varied from 4.74 to 5.34 to 5.72 m/s corresponding to measurement heights of 20, 30, and 40 m. An increase of about 20.7% was found in wind speed measured at 40m compared to that at 20m. In the present case, the mean of monthly mean (MoMM) wind speed were almost the same as the normal mean values. The mean WD was predominantly from NNW with an average value of 339° at 40 m and 327° at 30 m.
- The ambient temperature varied from a minimum of -6.1°C to a maximum of 49.1°C with an overall average of 24.7°C. The mean values of global solar radiation, pressure, and relative humidity were 231 W/m^2, 931.4 mbar, and 21.4%; respectively.

- The mean air turbulence intensities were 0.14, 0.14, and 0.16 at 40, 30, and 20 m AGL which were always less than the critical TI value of 0.18 as the permissible value recommended in IEC 61400-1 standard.
- The mean wind power density values were 102 W/m^2, 135 W/m^2, and 165 W/m^2 at 20, 30, and 40m heights.
- The mean energy content or the wind speed cube factor was observed to be decreasing with increasing wind measurement height. For an increase of measurement height of 10 m from 20 to 30, the energy content changed by around 25% while for the same height change from 30 to 40 m it changed only by 18%. This simply implies that the energy content or the wind cube factor effect decreases with height.
- The energy pattern factors were found to be decreasing with increasing height with highest values at 20 m height and lowest at 40 m.
- Maximum percentage increase in AEY was observed for all the chosen WT's while changing the hub height from 15 to 20 m i.e. an increase of only 5 m. Next best percentage increase in AEY was obtained for hub height change of 5 m i.e. from 10 to 15 m. An interesting observation is made that almost all the WT's showed same percentage change in AEY for an increase of hub height of 5 m (from 10 to 15m) and an increase of hub height of 10 m (from 20 to 30 m).
- In general the rated power generation duration was found to increasing with increasing hub height due to the fact that wind speed intensity increases with height above the ground level due to minimal effect of ground activities and additional contribution of regional wind speed.
- For small loads of < 0.7 kW, Fortis Passat with PCF of 41.76% at 15 m hub height can be used while for medium loads of up to 1.5 kW, Aeolos-5kW with PCF of 17.61% at 20 m hub height is recommended. For larger loads of up to 2.5 kW, CF6e with PCF of 29.78% at 20 m hub height is suggested.

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Appendix-A

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