wjert, 2020, Vol. 6, Issue 1, 330-345. *Original Article* **ISSN 2454-695X**

World Journal of Engineering Research and Technology

WJERT

www.wjert.org

SJIF Impact Factor: 5.924

ENERGY RATIO ANALYSIS OF THE 5.1MW NGONG WIND FARM, KENYA

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Article Received on 22/12/2019 **Article Revised on 12/01/2020** **Article Accepted on 02/02/2020**

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ABSTRACT

Wind power does not take place under idealized conditions therefore actual energy production regularly deviates from the turbine manufacturer's power curve. The origin for a lower or higher than predicted energy production for a wind farm in operation can be identified only by performance verification. This research has studied performance of the 5.1MW Ngong wind farm in Kenya in relation to the wind energy available. Parameters of analysis were wind characteristics, energy production and system availability. Wind speed and direction data for twelve months was acquired and using Weibull statistics the diurnal and monthly variability were obtained. The mean annual wind speeds on the wind farm ranged between 7.861 m/s and 9.254 m/s, the Weibull shape parameter values ranged between 2.169 and 2.323, while the Weibull scale parameter values ranged between 8.69 m/s and 10.427 m/s. Wind Rose analysis showed that the wind direction was fairly consistent between 90^0 and 135^0. The wind annual energy contents available for conversion ranged from 3317 kWh/m^2/yr to 5351kWh/m^2/yr and overall energy ratio of the wind farm was obtained as 28.09 % against the total energy in the wind. The energy ratio analysis distinguished malfunctioning turbines, improved performance after repair and variance in roughness height due to vegetation cover. The study established that, the wind farm performance could be increased by improving availability of systems and management of vegetation cover on areas adjacent to the wind farm.

KEYWORDS: Ngong wind farm, Diurnal wind speed, Probability Distribution Function, Wind Rose, Wind Power Density, Energy Ratio,

1. INTRODUCTION

Most promising renewable sources of energy with near zero emissions have raised the need to enhance local energy supply. Among the renewable energy technologies, the generation of mechanical and electrical power by wind machines has emerged as a techno-economical viable and cost effective option (Abdeen et *al.,* 2006). Energy yield from a wind turbine installed at a given site depends on strength and distribution of wind spectra, performance characteristics of the wind turbine and more importantly the interaction between the wind spectra and the turbine under fluctuating conditions of the wind regime, (Sathyajith *et al.,* 2011).

A lower than expected wind farm yield may be due to lacking wind potential, non-sufficient technical availability of wind turbines, a non- sufficient wind turbine power curve or a combination of these originates (Albers *et al.*, 1999).

There is a strong demand in the wind industry for understanding, in great detail, the performance of operational wind farms. This can be achieved by collecting sufficient data from the standard SCADA system, careful management of those data and the use of intelligent interrogation techniques, Staffan *et al.*, (2012).This study aimed at establishing the amount of energy in a free wind stream that flows through the turbines at 5.1MW Ngong wind farm over a sampled study period of twelve months and compare against the electrical energy production over the same period of time. The study further characterized the wind regime using Weibull statistics.

2.0 METHODOLOGY

2.1 Study scope

The study was on 5.1MW Ngong wind farm owned and operated by KenGen and which comprises of six (6) Vestas V52-850kW wind turbines. The wind farm which was commissioned in August 2009 is located on Ngong hills approximately 20 km WSW of Nairobi next to the Great Rift Valley in the western direction. The area comprises of a semi complex sloping hill formation with a site elevation between 2180 m and 2390 m above sea level.

The study entailed obtaining a) time series SCADA data averaged on ten (10) minutes for wind speeds and wind directions at 49 m above ground level b) monthly electrical energy production and c) machine and grid availability (to cater for down times) on each of the six turbines for a period of twelve months from September 2014 to August 2015 .The wind speeds and wind direction had been measured by ultrasonic sensors installed on the wind turbine nacelle and the electrical energy production had been measured by energy meters installed on each of the turbines. These were analyzed to give mean values of wind speed, frequency, wind direction variations, wind power densities, wind energy contents and average turbine energy ratios in converting the wind energy to electrical energy.

2.2 Theoretical considerations

Wind is air in motion. Since air has mass, the wind contains kinetic energy. This power can be turned into electric power, heat or mechanical work by Wind Power Plants.

2.2.1 Power density and energy content

The power of the wind at a specific height at a site is usually specified as power density (W/m^2) and the energy content as (kWh/m^2-year); it is the energy in the winds that pass through a vertical area of one square metre during one year. The energy content is a product of the power density and number of hours in a year. The power of the wind is calculated as follows: Use equation editor to write this equation

$$P_{kin} = \frac{1}{2}\rho A v^3 \quad \text{(Eq.1)}$$

Where ρ is the air density which is affected by altitude, atmospheric pressure and temperature, A is the swept area or rotor area and v s the wind speed. The wind velocity at the rotor plane is the average of upstream and downstream wind speeds, (Camilo *et al.*, 2014). The effect of altitude on air density is very significant compared to effect of temperature and atmospheric pressure (Joshua *et al.*, 2011).

2.2.2 Probability distribution function (PDF)

To calculate the power density and energy content of the wind at a site, it is not sufficient to know only the mean wind speed. It is necessary to know all the different wind speeds that occur and their duration i.e. the frequency distribution of the wind speeds has to be found. The power density of the wind at two different sites with exactly the same mean wind speed can differ considerably, (Joshua *et al.*, 2011). It has been found that frequency distribution of wind fits well into Weibull distribution function, (Seguro *et al.*, 2000) and (Akpinar *et al.*, 2004). Weibull distribution function is given by:

$$f\,(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} exp\left[-(\frac{v}{c})^{k}\right] \text{............................ (Eq.2)}$$

Where f(v) is the probability of observing wind speed v, c (m/s) is the Weibull scale parameter related to the long term mean wind speed (windiness) of the site and k is the dimensionless shape factor related to the spatial spread of wind data around the mean. The Weibull shape k parameter indicates the breadth of a distribution of wind speeds. Lower k values mean that winds tend to vary over a large range of speeds while higher k values correspond to wind speeds staying within a narrow range. On the other hand, the Weibull scale c parameter shows how "windy" a location is or in other words, how high the annual mean speed is, (Dieudonne' K.K *et al.*, 2014).

The cumulative probability function of the Weibull distribution is given by:

$$f(v) = 1 - exp\left[-(\frac{v}{c})^{k}\right] \text{.. (Eq.3)}$$

To determine k and c requires a good fit of equation (3) to the recorded cumulative frequency function. Taking the natural log of both sides of equation (3) twice gives:

$$ln\langle -ln[1 - F(v)]\rangle = k\,ln(v) - k\,ln\,c \text{......………………………………… (Eq.4)}$$

If $ln\langle -ln[1 - F(v)]\rangle$ is plotted against $ln(v)$ a straight line would be presented whose gradient is k and y-intercept is $-k\,ln(c)$ from which c is calculated.

2.2.3 Wind direction

A wind Rose is a polar plot that represents the percentage of the time that the wind direction falls within the sector of the compass (Kamau *et al.*, 2010).

2.2.4 Wind power density

According to (Akpinar *et al.*, 2004), monthly or annual wind power density per unit area of a site based on Weibull probability density function P_w, can be expressed as follows:

$$P_w = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \text{.. (Eq.5)}$$

The two significant parameters k and c are related to the mean value (ṽ) of the wind speed, (Ulgen *et al.*, 2002) as follows:

$\tilde{v} = c\Gamma\left(1+\frac{1}{k}\right)$.. (Eq.6)

The maximum extractable power by a system working at optimum efficiency is limited by the power coefficient called Betz limit whose value is 16/27 or 0.593. This power coefficient makes the maximum extractable power approximately 59.3% of the theoretical power density, (Lun *et al.*, 2000).

2.2.5 Machine availability

Maintenance of any equipment is crucial for its effective and efficient functioning, so the same applies to wind turbine as well. Performance and life expectancy of wind Power Plants depend largely on the operation and maintenance functions. Wind turbines have to endure severe mechanical, electrical grid and environmental stresses. Maintenance as a support function has a role in gaining and maintaining competitive advantages. Every wind turbine needs to be reliable so that it may be available all the time. Machine availability is defined as a ratio of total hours machine is available for operation to total number of hours in that time period. The machine will not produce power when it is stopped due to breakdown or maintenance. Thus machine stop hours are the sum of machine fault/breakdown hours, and preventative maintenance hours. According to (Bharat *et al.*, 2013), monthly machine availability is calculated as -:

$$\text{Machine availability} = \frac{\text{Hours in month} - \text{Machine stop hours}}{\text{Hours in month}} \text{........................ (Eq.7)}$$

2.2.6 Grid availability

Grid availability is defined as the ratio of total hours grid is available to evacuate energy generated by wind turbine to the total number of hours in that time period. Grid drop hours are the time for which grid connectivity is not available to wind turbines due to faults in the grid or outages to facilitate preventative maintenance. According to (Bharat *et al.*, 2013), monthly grid availability is calculated as follows:

$$\text{Grid Availability} = \frac{\text{Hours in month} - \text{Grid drop hours}}{\text{Hours in month}} \text{.................................... (Eq.8)}$$

2.2.7 System Availability

According to Bharat *et al.*, (2013), system availability (SA) is the product of machine availability and grid availability and is calculated as follows:

$$System\ Availability = Machine\ availability \times Grid\ availability \ldots\ldots\ldots\ldots \text{(Eq.9)}$$

2.2.8 Energy Ratio

According to (Singh, 2013), Energy ratio is used to review the performance of turbines. It is calculated by dividing the active power produced by the theoretical power available obtained through derivation via the wind frequency distribution. This ratio can be compared between turbines in a wind farm and against other measured operational characteristics such as wind direction, rotor speed, torque, etc. to gain an understanding of whether any particular factor is significant. Over time, thresholds and expected ratios can be determined for each turbine and operational alerts can be triggered if the ratios fall under the expected values.

3. RESULTS AND DISCUSSION

In this study wind speed data for Ngong Hills for the twelve months period from September 2014 to August 2015 was analyzed. Based on this data, wind speeds were processed using Windographer© software program to obtain distribution curves and Wind Rose plots. Calculations were then made to obtain Weibull parameters k and c, the mean wind speeds and the mean power density.

3.1. Average diurnal wind speed

Hourly mean wind speeds on each of the six turbines averaged over the study period of twelve months were plotted to give average diurnal wind speed chart as shown on Figure 3.1(a-f). Wind data obtained on all the turbines show a similar profile, with average wind speeds below 8m/s occurring between 0700hrs and 1600hrs. This corresponds to the daytime hours in Kenya. High wind speeds of above 10m/s were prevalent during the late night time hours and early morning hours. According to (Paul, 2004) convective circulation resulting from differential heating or cooling of the earth's surface leads to difference between wind speeds during daylight hours and those at night. Also, wind speed increases near the summit of a long ridge lying across the wind's path.

The diurnal pattern observed at Ngong was as a result of convective circulation due to differential heating during daylight hours between the area to the east of Ngong hills (at higher altitude) and the area on the western side of the hills (which is Rift valley at a lower altitude). The observation at night is as a result of convective circulation due to differential cooling between the two aforementioned areas on either side of Ngong Hills.

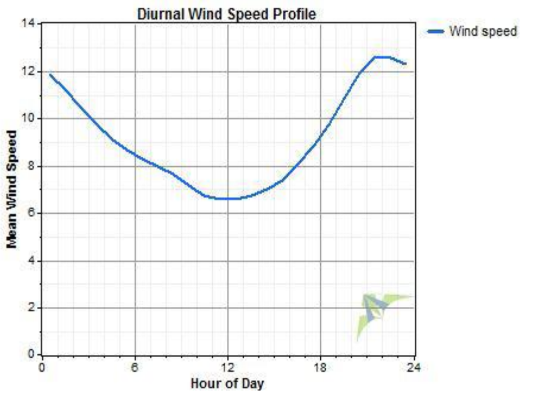

Figure 3.1: (a). Diurnal wind speed profile. Turbine 1.

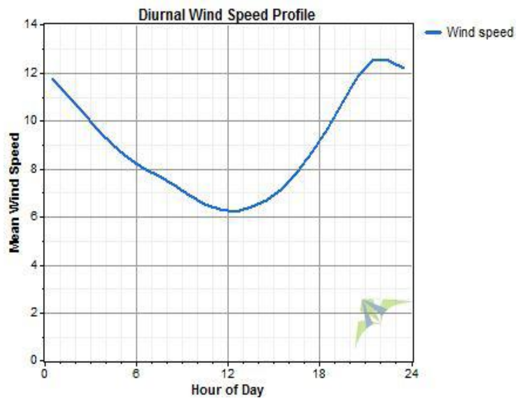

Figure 3.1: (b). Diurnal wind speed profile. Turbine 2.

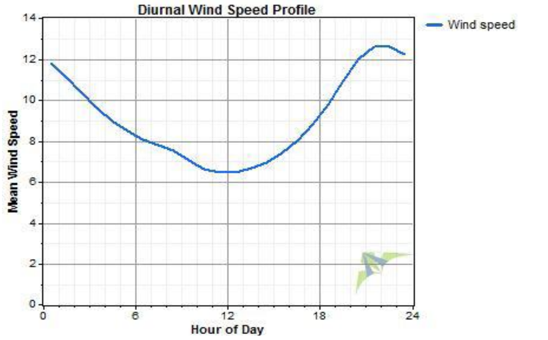

Figure 3.1: (c). Diurnal wind speed profile. Turbine 3.

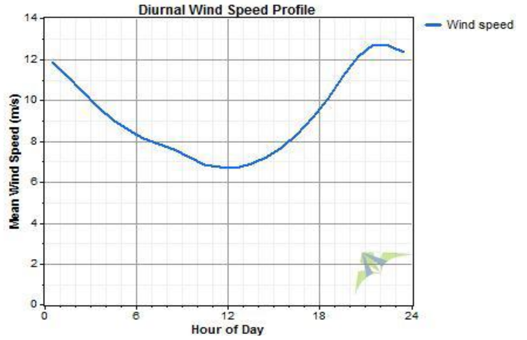

Figure 3.1: (d). Diurnal wind speed profile. Turbine 4.

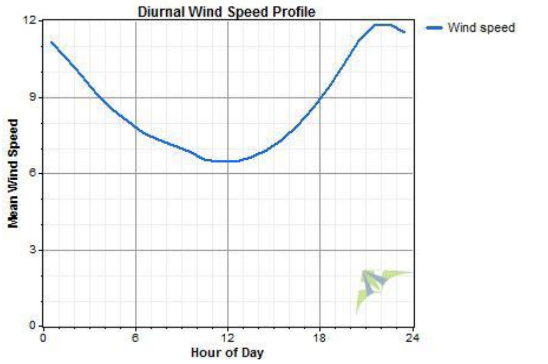

Figure 3.1: (e). Diurnal wind speed profile. Turbine 5.

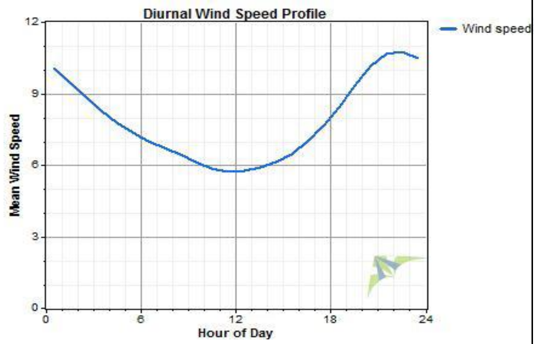

Figure 3.1: (f). Diurnal wind speed profile. Turbine 6.

3.2 Wind speed distribution frequency

The mean annual wind speeds recorded on the wind farm range between 7.861m/s and 9.254 m/s whilst the k values range between 2.169 and 2.322 showing a very small variation. Figures 3.2 (a-f) show the probability distribution function (PDF) for wind speed measurements taken on the Turbines from September 2014 to August 2015. The plots show a similar profile of a near normal distribution around the respective turbine's modal value.

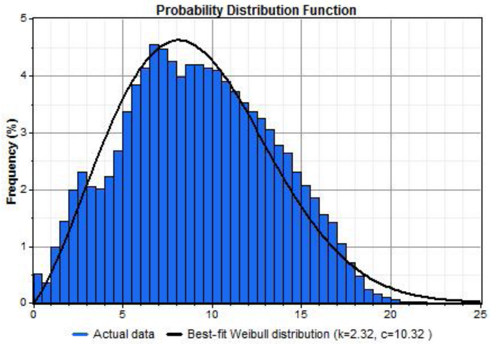

Figure 3.2 (a). Probability Distribution Function. Turbine 1

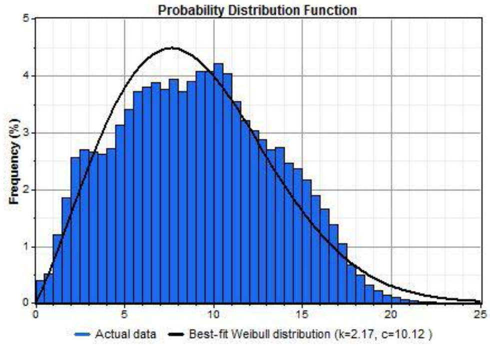

Figure 3.2 (b). Probability Distribution Function. Turbine 2

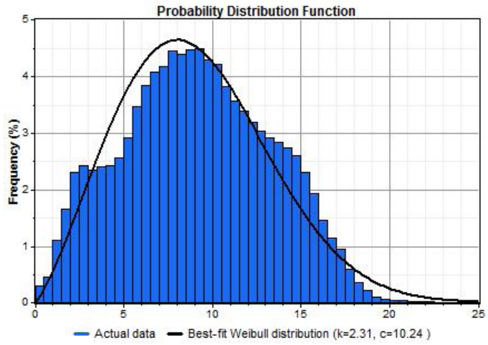

Figure 3.2 (c). Probability Distribution Function. Turbine 3

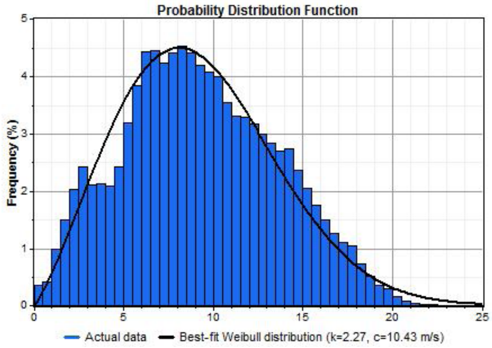

Figure 3.2 (d). Probability Distribution Function. Turbine 4

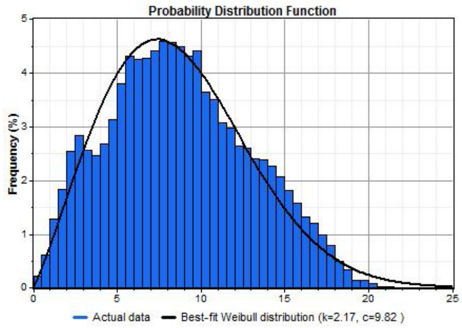

Figure 3.2 (e). Probability Distribution Function. Turbine 5.

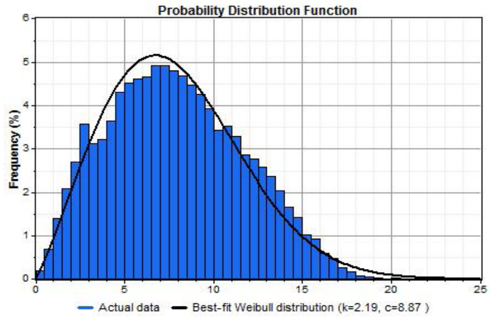

Figure 3.2 (f). Probability Distribution Function. Turbine 6

3.3. Monthly mean wind speed

The study showed that the area experienced higher wind speeds with monthly mean wind speeds above 8m/s in the months of October 2014 to March 2015 while monthly mean wind speeds at 8m/s and below were experienced from April to September (Figure 3.3). The lowest monthly average wind speed of 4.2 m/s was recorded in June on turbine 6 whilst the highest monthly average wind speed of 14.1 m/s was recorded in March on turbine 4. The observations were in line with (Paul, 2004) depiction that the effects of convective circulation are greater during higher temperature seasons than during lower temperature seasons. Higher temperatures lead to increase in pressure gradient, (Kargieve *et al*., 2001).

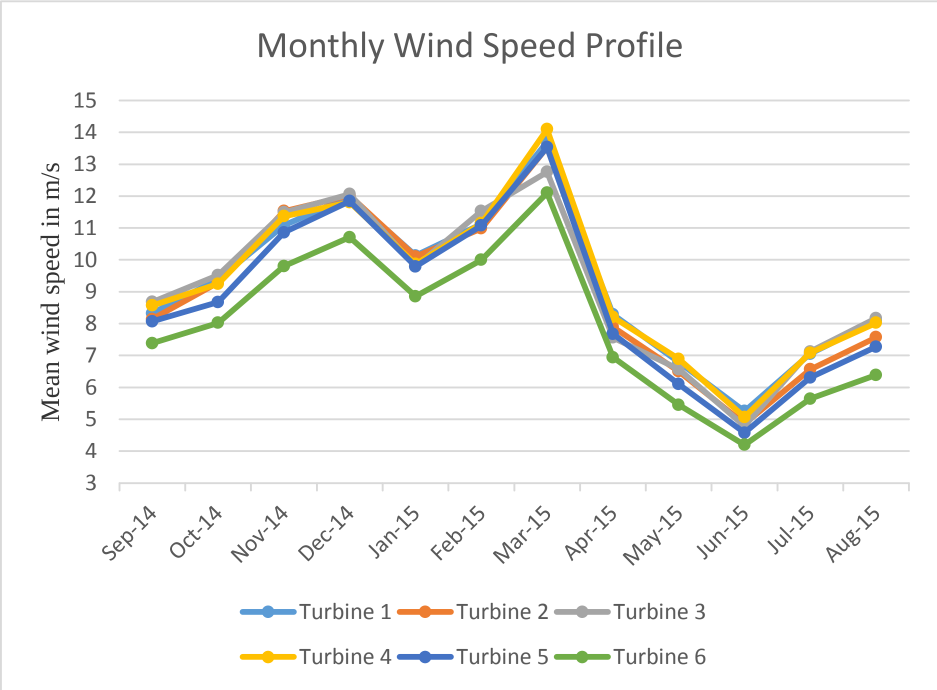

Figure 3.3: Monthly wind speed profiles.

3.4 Wind direction

The data for every month for the study period was interpreted to give the prevalent wind direction and the percentage of wind frequency against sixteen direction sectors. As shown on Figure 3.4, the prevailing winds blew from east and South east direction between 90^0 and 135^0.

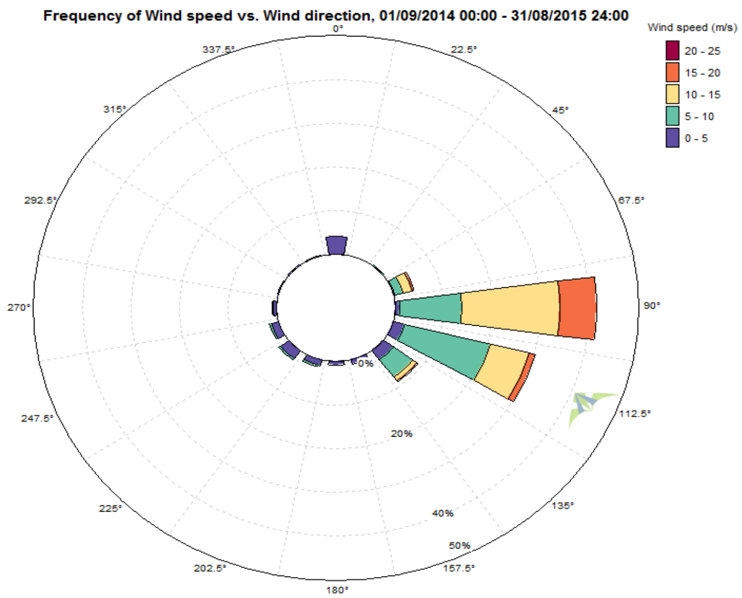

Figure 3.4: Wind Rose Diagram. Frequency of wind speed versus wind direction on Turbine 1.

The frequency of wind which blew from 90^0 and 135^0 directional sector was between 78% and 85% of the entire wind which blew and contributed to the total wind energy over the study period by between 87% and 97%.

3.5 Wind power density (WPD)

The lowest wind power densities were obtained in the month of June whereas the highest wind power densities were obtained in March. The lowest wind power density of 71W/m^2 was obtained on Turbine 6 in June whereas the highest was 1,532W/m^2 obtained on Turbine 4 in March (Figure 3.5).

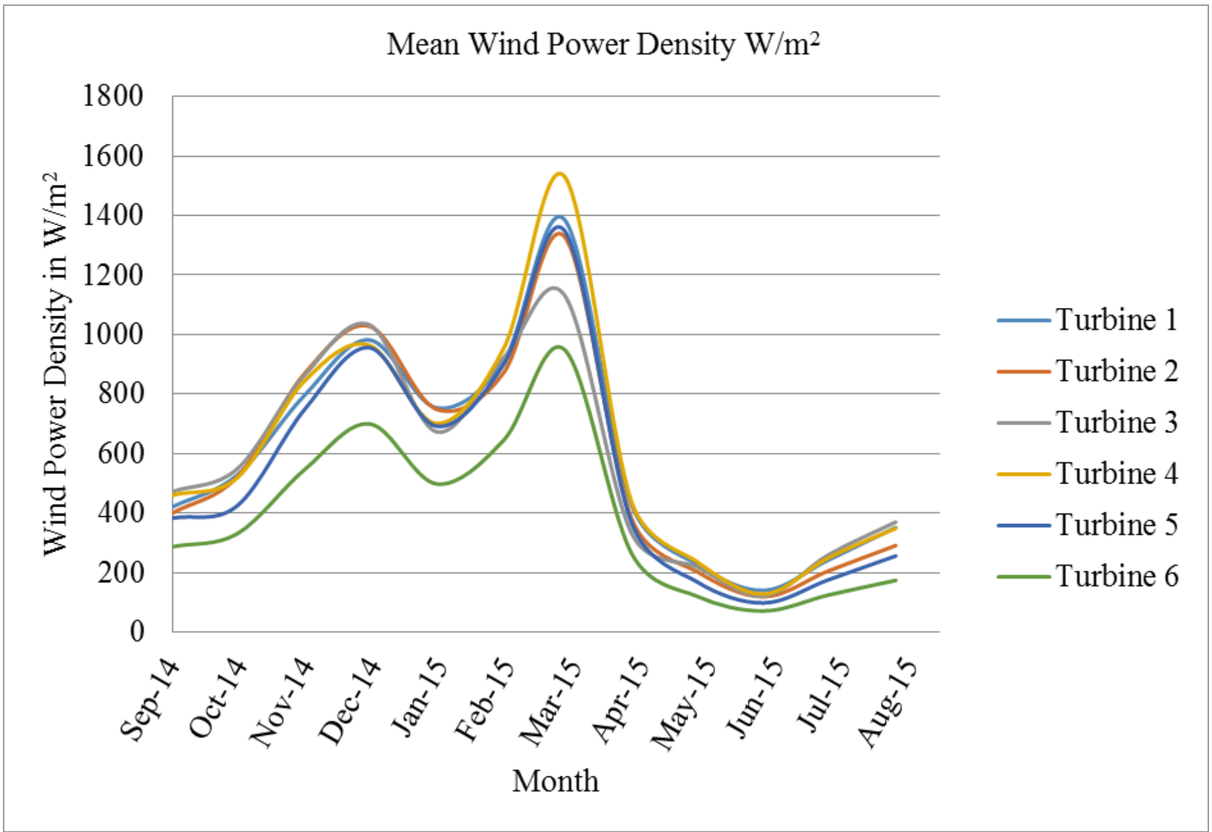

Figure 3.5: Variation of mean Wind power densities versus month.

It was also observed that wind power density varied from turbine to turbine and it was consistently low on Turbine 6. It was observed that the foreground to the turbine had trees and shrubs hence a higher roughness height leading to lower wind speeds compared to the other turbines.

3.6 Energy ratio of wind turbines-individual and combined

Using the wind power densities shown on Figure 3.5 above and the number of hours for each respective month, the wind energy contents available for conversion on each turbine in every month were obtained. Then by factoring turbine swept area, monthly mean system availability (Eq. 7, Eq.8 and Eq.9) and comparing with turbine monthly energy production the average energy ratios of the wind turbines were obtained as shown on Table 3.6.

Table 3.6: Wind turbine energy ratio in percentage.

Month	Turbine 1	Turbine 2	Turbine 3	Turbine 4	Turbine 5	Turbine 6	**Average**
Sep-14	20.52%	18.33%	18.44%	20.83%	22.00%	27.44%	21.26%
Oct-14	16.44%	16.62%	10.82%	24.04%	26.99%	25.42%	20.06%
Nov-14	14.59%	13.67%	12.72%	13.99%	14.99%	19.56%	14.92%
Dec-14	13.11%	12.67%	10.61%	13.81%	13.18%	15.14%	13.09%
Jan-15	28.30%	26.82%	12.01%	28.41%	27.62%	41.20%	27.39%
Feb-15	25.34%	23.92%		25.86%	24.14%	31.32%	26.12%
Mar-15	22.21%	12.14%		21.33%	22.68%	29.80%	21.63%
Apr-15	29.83%	19.06%		32.36%	32.20%	36.08%	29.91%
May-15	40.15%	28.64%		40.56%	41.50%	44.50%	39.07%
Jun-15	38.04%	29.14%	45.05%	39.53%	36.26%	34.75%	37.13%
Jul-15	40.00%	32.70%	36.76%	39.22%	39.90%	42.18%	38.46%
Aug-15	40.08%	28.73%	39.47%	40.72%	40.46%	45.82%	39.21%
Average	27.38%	21.87%	23.24%	28.39%	28.49%	32.77%	**27.02%**

From Table 3.6, it was observed that the turbine energy ratio ranged between 10.61% and 45.82%. Statistical tests on the monthly turbine energy ratio values indicated that energy ratio values for Turbine 2 and 3 were out of the range compared to the energy ratio results of Turbines 1, 4, 5 and 6 as shown on Figure 3.6.1.

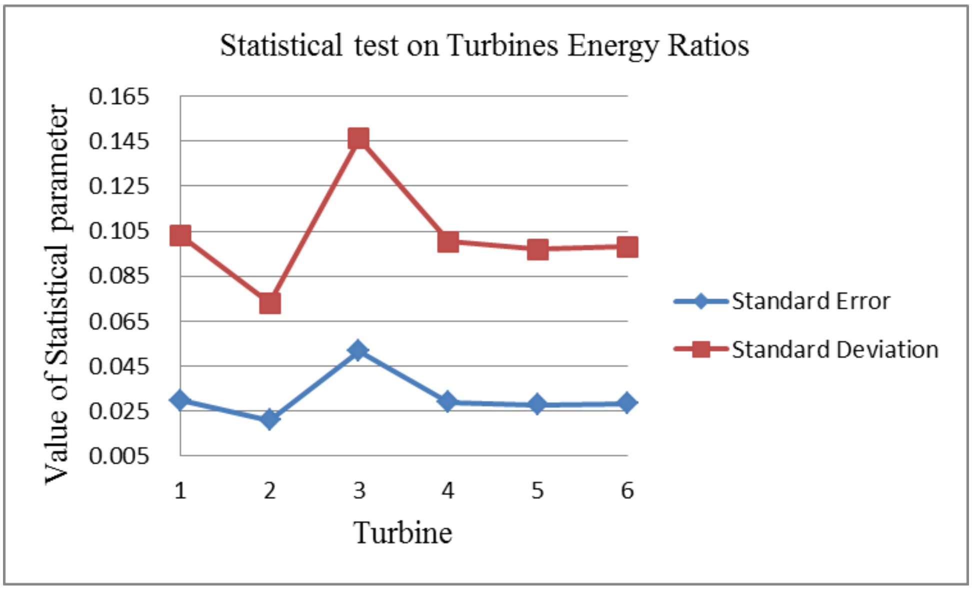

Figure 3.6.1: Standard Error and Standard Deviation on Turbine Energy Ratios.

That observation was as a result of the following:

- Turbine 2 was operating under faulty condition during the study period.
- Turbine 3 operated under faulty condition which led to a breakdown and downtime of four months during the study period.

Owing to the discrepancy on Turbine 2 and 3, further analysis on monthly wind speeds versus energy ratio was only done on results for Turbines 1, 4, 5 and 6. Correlation analysis on wind speed and turbine energy ratio done on results for Turbine 1, 4, 5 and 6 indicated that correlation of wind speed and turbine energy ratio was negative and relatively consistent on Turbine 1,4 and 5 compared to Turbine 6 as shown on Figure 3.6.2.

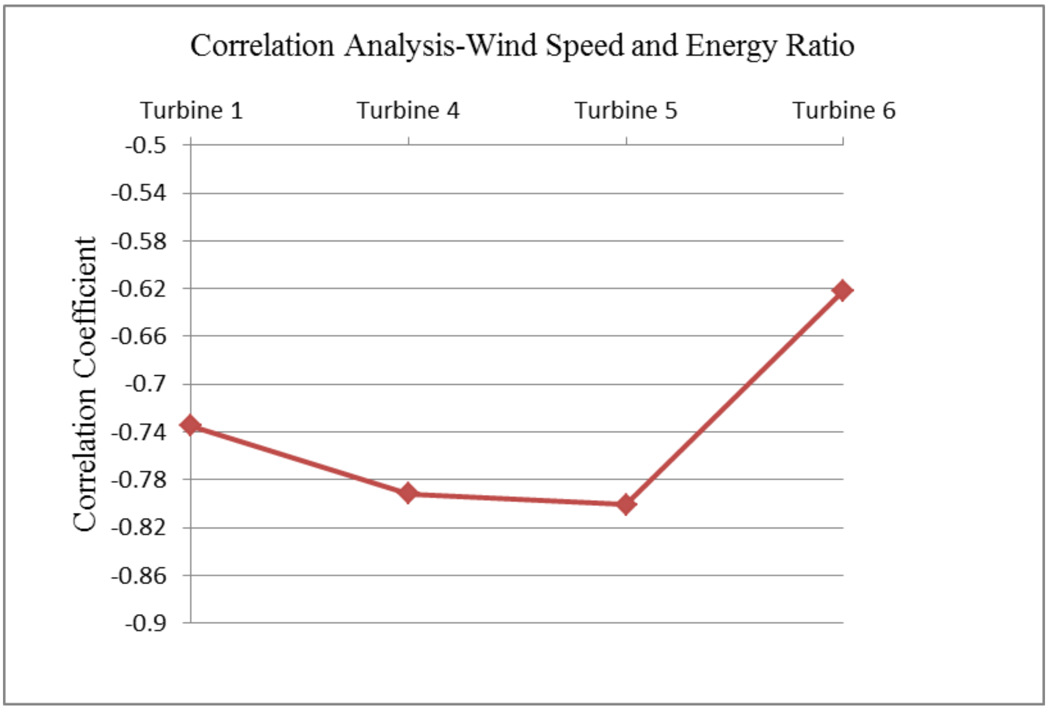

Figure 3.6.2: Correlation Analysis of wind speed and Energy Ratio on Turbine 1, 4, 5 and 6.

The discrepancy is attributed to the effect of unique vegetation cover, on the South East forefront leading to Turbine 6, to the wind speed.

On basis of above statistical analysis, results for Turbine 1, 4 and 5 were articulated to have a better representative on wind farm energy ratio. Further analysis of wind speed versus turbine energy ratio indicated that the overall average wind farm energy ratio over the study period was 28.09 % as shown on Table 3.7.

Table 3.7: Sampled Wind turbine energy ratio in percentage.

	Average of monthly mean wind speeds (m/s)	Energy Ratio in %			
		Turbine 1	Turbine 4	Turbine 5	Average
Sep 14 to April 15	8.1-13.8	21.29%	22.58%	22.98%	22.28%
May 15 to August 15	5.0-7.8	39.57%	40.01%	39.53%	39.70%
Difference		18.28%	17.43%	16.56%	17.42%
Overall		27.38%	28.39%	28.49%	28.09%

It was observed that the months with monthly mean wind speeds above 8m/s had a low average energy ratio of 22.28%, whereas the months with monthly mean wind speeds below 8m/s had a relatively high average energy ratio.This was due to the occurrences of wind whose speed was above the rated wind speed of 16m/s. A high frequency of wind speeds above 16m/s resulted to an apparent low energy ratio while a low frequency of wind speeds above 16m/s results to a relative apparent higher energy ratio. This observation made on energy ratio whereby it was low during months with high wind speeds is supported by (Thomas, 2005) who explained that modern wind turbines are variable-speed machines which have a control mechanism to regulate maximum power through dynamic blade pitch control. When the wind speed is below rated, generator torque is used to control the rotor speed in order to capture as much power as possible. The most power is captured when the tip speed ratio is held constant at its optimum value .As wind speed increases, rotor speed should increase proportionally. The difference between the aerodynamic torque captured by the blades and the applied generator torque controls the rotor speed. If the generator torque is lower, the rotor accelerates, and if the generator torque is higher, the rotor slows down. Below rated wind speed, the generator torque control is active while the blade pitch is typically held at the constant angle that captures the most power, fairly flat to the wind. Above rated wind speed, the generator torque is typically held constant while the blade pitch is active.

The overall average energy ratio of the wind farm over the study period was 28.09%, which translated to 48.7 % against the maximum extractable wind power. This compare well with report by (New South Wales Government- Department of Environment, Climate Change and Water, 2010), which state that wind turbines convert around 45% of the wind passing through the blades into electricity and almost 50% at peak energy ratio.

4.0 CONCLUSIONS

The following main conclusions were drawn from the research study:

4.1 The average wind speeds at Ngong Wind farm of below 8m/s occurred during daytime hours (0700hrs and 1600hrs) and high wind speeds of above 10m/s were prevalent during the late night time hours and early morning hours. Mean wind speeds of above 8m/s occurred from October to March while monthly mean wind speeds of 8m/s and below were experienced from April to September.

4.2 Average wind speed for the study area ranged from 7.861m/s to 9.254m/s, , the Weibull shape parameter values ranged between 2.169 and 2.323, while the Weibull scale parameter values ranged between 8.69m/s and 10.427 m/s. Wind direction was fairly consistent between 90^0 and 135^0 which is generally from east and South east direction.

4.3 The lowest wind power density of 71W/m^2 was obtained in the month of June whereas the highest wind power density of 1,532 W/m^2 was obtained in March. Also, the wind annual energy contents available for conversion ranged from 3317 kWh/m^2/yr to 5351kWh/m^2/yr which correspond to maximum extractable energy content of 1967 kWh/m^2/yr to 3173 kWh/m^2/yr respectively.

4.4 The turbine energy ratios in percentage ranged between 10.61% and 45.82% against the total energy in the wind, which translate to 17.89% and 77.27% against the maximum extractable wind energy. Low energy ratios were observed in the months with good wind speed averages whereas high energy ratios were observed in the months with low wind speed averages. The overall average energy ratio of the wind farm over the study period was 28.09%, which translated to 48.7 % against the maximum extractable wind power.

ACKNOWLEDGEMENT

The Author thanks Kenya Power and Lighting Company and Kenya Electricity Generating Company, both in the republic of Kenya for making necessary data available for this study.

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