ISSN No:-2456-2165

# Analysis of the Wind Energy Characteristics and Potential on the Hilly Terrain of Manga, Nyamira County, Kenya.

Kwamboka, J. O., Kamau, J.N[1]., Saoke, C.O[1]., Ndeda J.O[1]. and Maina A.W.[1]
[1]Department of Physics, Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya.
Corresponding author: cellphone: +254733405509;

**Abstract**:- **This study was carried out at the Manga hill in Nyamira County, Kenya, for a period of three months at the height of 10 m and 15 m. The study sought to determine the wind characteristics and power potential for the site. In addition economic analysis to determine viability of harnessing power for the site was considered. Weibull and Rayleigh distribution methods were compared. Different statistical methods namely; graphical method, moment method, maximum likelihood method and power density method were employed. The mean wind speed for the period of study is 5.1 m/s and wind power flux was estimated to be 142.57 W/m$^2$ by Weibull distribution for 10 m above ground level. The wind characteristics obtained was categorized as wind power flux class II. The shape parameter k values obtained range from 2.22 to 2.26 and the scale parameter c values range from 5.83m/s to 6.21 m/s. The wind shear exponent was found to be 0.233. Installation of a 10 kW rated power horizontal axis wind turbine, at 30 m height would be economically viable for Manga Hill site for domestic power generation.**

***Keywords***:- *Graphical Method, Moment Method, Probability Distribution, Weibull Parameters, Wind Energy, Wind Shear.*

## I. INTRODUCTION

The original source of the renewable energy contained in the earth's wind system is the sun. Global winds are caused by pressure differences across the earth's surface due to uneven heating of the earth by the solar radiation. Spatial variations in heat transfer to the earth's atmosphere create variations in atmospheric pressure field that causes air to move from high to low pressure. Thus atmospheric winds are caused by pressure gradient, gravitational forces, inertia of the air, earth's rotation and friction with the earth's surface [10].

The Equatorial areas are assumed to have poor to medium wind resource. This might be expected to be the general pattern for Kenya. However some topography specifics (channeling and hill effects due to the presence of the Rift Valley and various mountain and highland areas) have endowed some areas in Kenya with excellent wind regimes [7].

Wind power is a clean energy source that can be relied on for the long-term. A wind turbine creates reliable, cost-effective, pollution free energy. It is affordable, clean and sustainable. Because wind is a source of energy which is non-polluting and renewable, wind turbines create power without using fossil fuels, without producing greenhouse gases or toxic wastes and it reduces global warming [11].

Mountains, bodies of water, and vegetation all influence wind flow patterns. Presence of mountains and valleys also produces specialized types of local winds. As the air blows over the mountains and sinks down into the valleys, it creates high pressure. The high pressure, in turn, compresses the air and heats it. For valley and mountain winds, during the day, the warmer air of the mountain slope rises and replaces the heavier cool air above it. The direction reverses at night, as cold air drains down the slopes and stagnates in the valley floor [10].

Kenya's wind installed capacity is 25.5MW, operated by KenGen, at the Ngong site. High capital cost and lack of sufficient wind regime data are some of the barriers affecting the exploitation of wind energy resources. Moreover, potential areas for wind energy generation are far away from the grid and load-centres, requiring high capital investment for the transmission lines [5].

The suitability of the method used to characterize wind may vary with the sample data such as data size, sample data distribution; sample data format and of fit tests (Indumathy *et al*., 2014). In this study, the Weibull distribution, the Rayleigh distribution, the graphical method (GM), the maximum likelihood method (MLM), the energy pattern factor method (EPF) and the method of moments (MM), are explored for Manga hills in Nyamira County.

## II. MATERIALS AND METHODS

Wind speed data over a period of three months for Manga Hill was collected and analyzed. The wind speed data were recorded for a period of three months. Since there is no similar study for this region the study aimed at examining the wind characteristics with a view of determining the wind energy potential by the use of the Distribution methods. A mast was erected to the height of 15 m. Two cup anemometers were placed at the height of 10 m and 15 m with the wind vane placed at the same level with the sensor at 15m but placed at either side to avoid disturbance. The wind sensors were connected to the data logger in which a memory card was inserted to record the site data. The data collected was sorted out according to hourly, daily, and monthly mean wind velocities and the different wind directions noted. The average temperature and the atmospheric pressure of the place were also recorded from an inbuilt temperature and pressure sensor in the data logger. The scale parameter c, the shape parameter k and the wind shear were obtained. The wind power potential was modeled using the distribution functions.

*A. Wind power*

The power P, of the wind that flows at speed v, through a blade sweep area A, increases as the cube of its velocity and is given by [2];

$$P = \frac{1}{2}\rho A v^3 \quad (1)$$

Where; ρ is the air density.

Monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows:

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

Setting k equal to 2, the power density for the Rayleigh density function is found to be

$$P_R = \frac{3}{\pi}\rho c^3 \quad (3)$$

*B. Wind Speed Variation With Height*

The wind speed increases with the height above the ground, due to the frictional drag of the ground, vegetation and buildings. Therefore, to calculate the total wind energy potential, the measured surface wind speed must be modified for an altitude different from the normalized height (i.e.10 m) by use of the Power exponent function [12];

$$v_z = v_r\left[\frac{Z}{Z_r}\right]^{\alpha} \quad (4)$$

Where, Z is the height above ground level, $v_r$ is the wind speed at the reference height r, above ground level, $v_z$ is the wind speed at height Z, and $\alpha$ is an exponent which depends on the roughness of the terrain.

*C. Wind speed probability distribution*

The wind probability density functions mainly in use are the Weibull and the Rayleigh distribution models. The variation in wind speed are most often described by the Weibull PDF with two parameters, the dimensionless Weibull shape parameter **k** (dimensionless) and the Weibull scale parameter **c** (m/s). The PDF function is expressed by [6];

$$F(v) = \left(\frac{k}{c}\right).\left(\frac{v}{c}\right)^{(k-1)}.\exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (5)$$

The corresponding cumulative distribution function is given by:

$$F(v) = 1-\exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (6)$$

Where: v is the wind speed; F(v) is the probability of observing v.

The Rayleigh distribution function $F_R$ (v) is a special case of the Weibull model in which the shape parameter, k = 2. This leads to (5) to be given by:

$$F_R(v) = \frac{2v}{c^3}\exp\left[-\left(\frac{v}{c}\right)^2\right] \quad (7)$$

*D. Methods to Estimate Weibull Parameters*

- *Graphical Method*

Wind speed data is given in cumulative frequency distribution format, interpolated by a straight line by use of least square regression. Converting cumulative distribution function (6) into logarithmic form obtaining:

$$\ln\left[-\ln\left(1-F(v)\right)\right] = k\ln(v) - k\ln(c) \quad (8)$$

The parameters c and k are estimated by plotting $\ln(v)$ versus $\ln\left[-\ln\left(1-F(v)\right)\right]$, in which a straight line is determined, the slope of the graph gives the shape parameter k, while the y- intercept is the value of the term $-k\ln(c)$ [9].

- *Maximum Likelihood Method (MLM)*

The MLM method is solved through numerical iterations to determine the parameters *k* and *c* as: [8].

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k . \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n}\ln(v_i)}{n}\right]^{-1} \quad (9)$$

$$c = \left\{\frac{1}{n}\left[\sum_{i=1}^{n} v_i^k\right]\right\}^{1/k} \quad (10)$$

Where: n, number of non-zero data values; i, measurement interval; $v_i$, wind speed measured at the interval i, (m/s).

- *Moment Method (MM)*

The wind speed v, and the standard deviation $\sigma$, of the wind speed so obtained are put into consideration [3].

The standard deviation,

$$\sigma = c.\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]^{1/2} \quad (11)$$

The standard gamma function $\Gamma$ in (11) is given by;

$$\Gamma(x) = \int_0^{\infty} t^{x-1}\exp(-t)dt \quad (12)$$

The shape parameter k is given by:

$$k = \left[ \frac{0.9874}{\frac{\sigma}{v_m}} \right]^{1.0983} \qquad (13)$$

The scale parameter c is evaluated as:

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \qquad (14)$$

- *Power Density Method (PDM)*

The Weibull parameters c and k are estimated by first computing the energy pattern factor, $E_{pf}$ which is later used to obtain parameters, thus [1]:

$$E_{pf} = \frac{(v^3)_m}{(v_m)^3} = \frac{\left[\frac{1}{n}\sum_{i=1}^{n} v_i^3\right]}{\left[\frac{1}{n}\sum_{i=1}^{n} v_i\right]^3} \qquad (15)$$

$$k = 1 + \frac{3.69}{E_{pf}^{\,2}} \qquad (16)$$

The value of c is obtained by using (14).

## III. RESULTS AND DISCUSSIONS

### *A. Hourly Wind Variations*

The hourly mean wind speeds for the study period were calculated and a graph for the variation is shown in Fig. 1. The graph shows the wind speeds increasing gradually from midmorning to late afternoon and in the evening which continues to early night and through midnight and starts to decrease and records lowest wind speeds after sunrise in the hours between 0600 hours to 1000 hours.

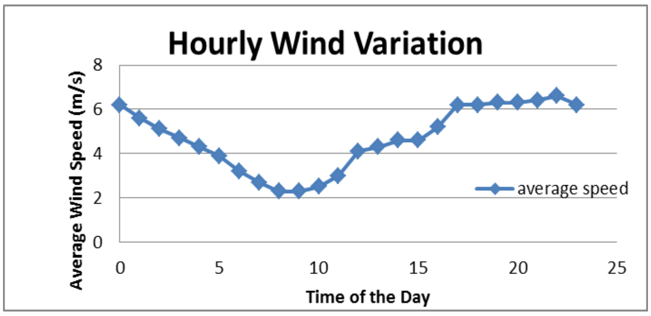


Fig 1:- Hourly mean wind variation

This suggests that there is an experience of both slope and valley winds in the Manga Hill. The transition from up valley to down valley flow takes place early in the night. The transition is gradual, first the down slope winds, then a pooling of cool and heavy air in the valley bottoms, the cool air in the higher valley bottoms will flow in the lower elevations and increase in velocity as the pool of air deepens. This continues through the night and diminishes at sunrise [4]. According to the diurnal variation of the wind speed, it can be concluded that in case of installation of wind turbines in Manga Hill, the electricity generation between 0600 hours and 1100 hours is very low.

### *B. Daily Wind Speed Variation*

Graphs representing the variations of the daily mean wind speed for the 10 m and 15 m height above ground level, for the months of June, July and August are shown in Fig. 2, 3 and 4.

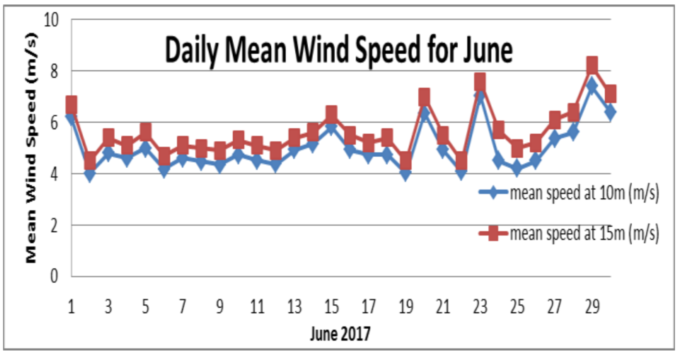


Fig 2:- Daily meanwind speed for June

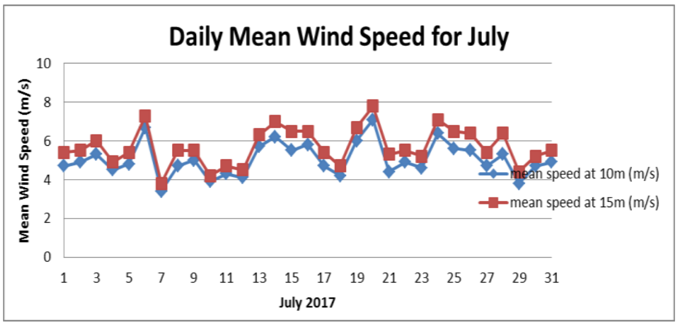


Fig 3:- Daily mean wind speed for July

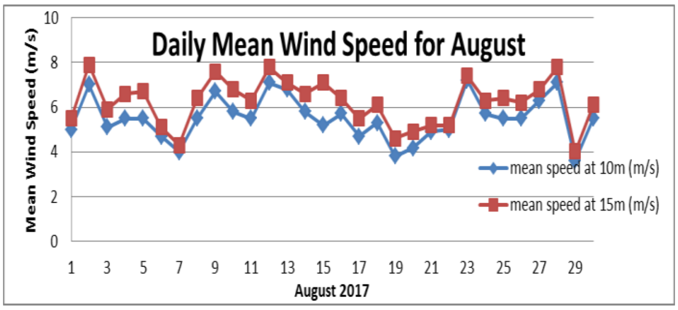


Fig 4:- Daily mean wind speed for August

From the Fig. 2, 3 and 4 the daily variation for 15 m height data was consistently high as compared to the mean wind speed for 10 m height for all the three months implying that wind speed increase with height. The mean speed averages for each of the three months however follow no particular pattern. The daily averages for the month of June are lower, followed by July and August has the highest value, however this doesn't imply that this pattern is applicable for all years for the site.

### C. Wind Power Density

The wind power densities ware obtained as 142.57 W/m$^2$ and 147.54 W /m$^2$ for Weibull and Rayleigh respectively at 10 m above ground level. The calculated power density using the two distribution functions are different since the shape parameter applied for the Rayleigh is a rough estimate whilst the value used for the Weibull has been estimated for the particular site. The Rayleigh distribution uses the shape parameter k=2, since the calculated shape parameter for the site has been found to be higher than 2, the Rayleigh distribution has been considered unsuitable for estimating the power density for the site.

### D. Probability Density Functions

The distribution functions have been used for modeling the variation of the wind speed for the site and the distribution curves obtained represented in Fig.5, which illustrates curves for Weibull and Rayleigh and Fig.6, which shows the frequency distribution for the MLM, GM, MM and PDM distributions.

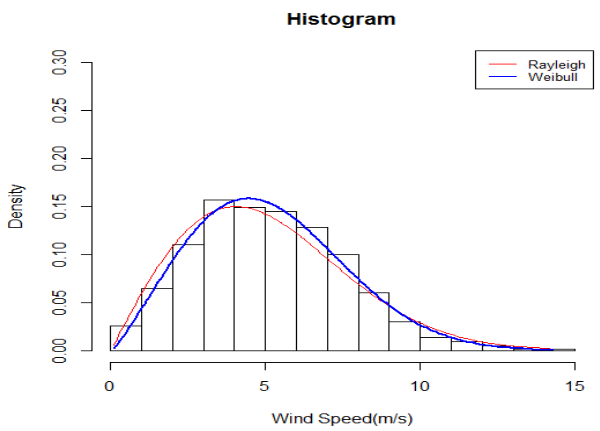


Fig 5:- Histogram of wind speed fitted with Rayleigh and Weibull curves

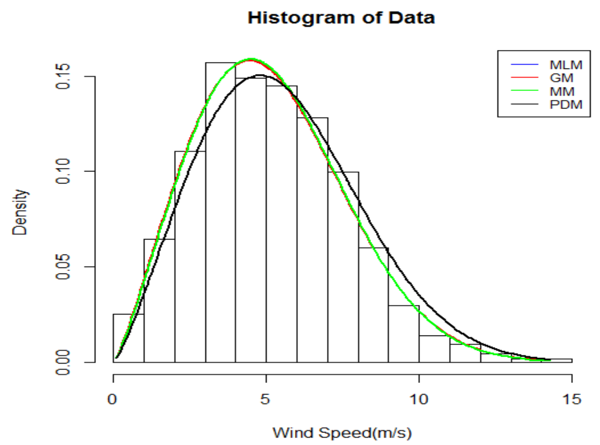


Fig 6:- Histogram of wind speed fitted with distribution methods

The Fig. 5 shows Weibull and Rayleigh curves superimposed on a histogram of the wind speed of the site fitted with Weibull and Rayleigh curves and Fig. 6 shows PDM, MM, GM and MLM PDF curves superimposed on the histogram. All the methods under study give nearly same and fairly accurate results. The MLM, GM and MM give similar results and show a fair fit. The Weibull gives the best fit. The Rayleigh and PDM gives a poor fit.

### E. Use of Statistical Tools to Assess the Distribution Methods

The performance of the PDFs for assessing the wind energy potential of the site was also analyzed and the results summarized in the Table 1, which shows the Weibull parameters obtained from the different distribution methods and an evaluation done using three statistical tools namely the chi-square ($\chi^2$), correlation coefficient ($R^2$) and the Root Mean Square Error (RMSE).

| Distribution Method | Parameter Evaluation | | | | |
|---|---|---|---|---|---|
| | c | k | $\chi^2$ | $R^2$ | RMSE |
| GM | 5.83 | 2.22 | 27.17 | 0.995 | 3.492 |
| MM | 5.84 | 2.24 | 34.16 | 0.9952 | 3.445 |
| MLM | 5.83 | 2.22 | 32.87 | 0.9923 | 3.527 |
| PDM | 6.21 | 2.26 | 74.36 | 0.987 | 3.578 |

Table 1. Comparison of the distribution methods

In evaluation using the statistical tools, for the chi-square test, the method with a lowest value will be considered as the one yielding the best results. For the RMSE, the parameter with lowest value will indicate successful forecasts while high value shows deviations. A higher value of the correlation coefficient ($R^2$) represents a better fit and highest obtainable value is 1[9]. It can be seen that the statistical tools give similar results in all cases, since the values are close to each other with an exception of the PDM. The correlation coefficient and RMSE rank the distribution methods as MM, GM, MLE and lastly PDM. The chi- square test however ranks the distribution method as GM, MLE, MM and lastly PDM. The proposed three distribution methods are effective in evaluating the parameters of the Weibull distribution for the available data since the values of RMSE, and $R^2$ have magnitudes very close to each other for the data collected in the Manga Hill. This shows that the PDM gives a less accurate approximation for the available set of data values. The MM and GM gives the best fitting distribution method and therefore will be used to evaluate the wind power resource for the site.

### F. Representation of Wind Direction

A wind rose gives a succinct view of how wind speed and direction are typically distributed to help visualize wind patterns at the site. The Fig. 6 and Fig.7 illustrate the wind roses for 10 m and 15 m above ground level respectively for the site.

ISSN No:-2456-2165

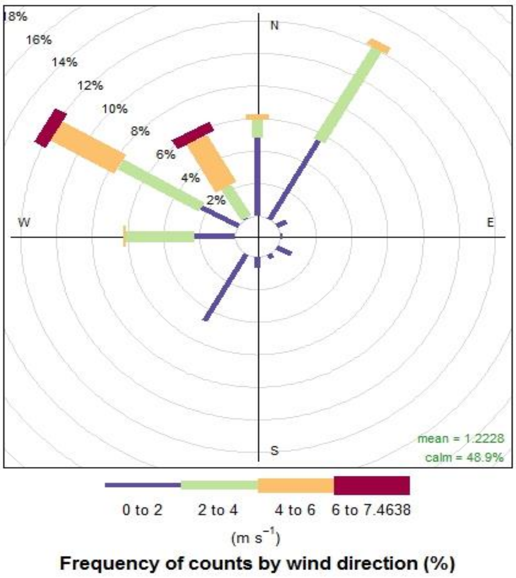


Fig 7:- Wind rose for 10 m

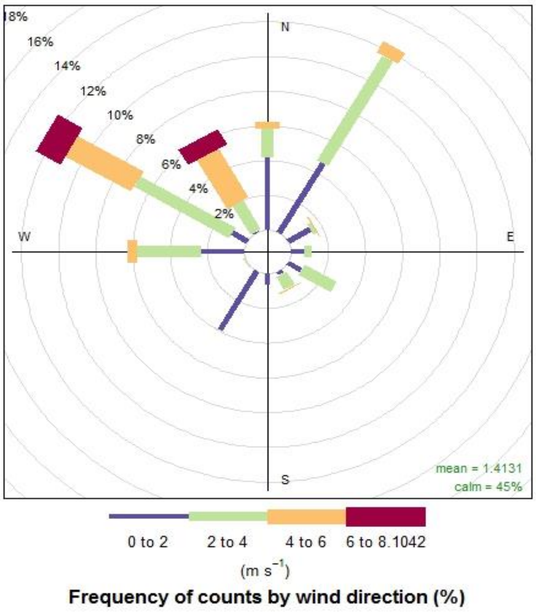


Fig 8:- Wind rose for 15 m

The prevailing winds are in the NW and NNW direction of magnitude above 6 m/s and occasionally wind speeds between 0 m/s to 2 m/s , wind speeds below 6 m/s are observed in the N an NE directions. However, it is observed that minimum wind speeds below 4m/s are recorded from the SE directions and speeds below 2 m/s were recorded in the SW direction. Both wind roses show that the prevailing direction i.e. NW and NNW comprise 48% of all hourly wind directions, implying that the other 14 directions account for the 52%. A horizontal axis turbine will be recommended for the site which has the ability to turn in the horizontal plane to face the wind.

## IV. CONCLUSION

The analysis of the measured data showed that the monthly average wind speeds were 4.96m/s and 5.45 m/s for June, 5.11 m/s and 5.61 m/s for July and 5.496 m/s and 6.068 m/s for August at 10 m and 15 m respectively. The prevailing wind direction was found to be NNW and NW during the measurement period. The average wind power density values at 10 m and 15 m above ground level were 71.29 W/m$^2$ and 94.21 W/m$^2$ for June, 77.4W/m$^2$ and 102.43W/m$^2$ for July and 96.52W/m$^2$ and 129.9 W/m$^2$ respectively. The Wind Shear Exponent obtained using all the data values is 0.233. A hub height of 30 m is suitable for turbine installation for the site. Given the average wind speeds for the three months at 10 m height as 5.1 m/s and the wind power density of 142.57 W/m$^2$ and 147.54 W/m$^2$ for Weibull and Rayleigh respectively, the site was categorized as wind power flux class II. The shape parameter **k** values obtained range from 2.22 to 2.26 and the scale parameter **c** values range from 5.83m/s to 6.21 m/s. The site was found to be economically viable for domestic power generation since it has moderate characteristics. Installation of a 10 kW rated power, up wind horizontal axis wind turbine, with three blades, 7 m rotor diameter, at 30 m height, without a yaw will be recommended.

## V. ACKNOWLEDGMENT

The authors would like to thank the INSTOL Company limited for their technical support and the congregation of the Sisters of the Blessed Virgin for funding the project.

## REFERENCES

[1]. S.A. Akdag, and D.A. Ali, " New method to estimate weibull parameters for wind energy applications," Energy Conversion and Management, vol 50, 2009, pp.1761-1766.

[2]. E.K. Akpinar and S. Akpinar, "An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics," Energy Conversion and Management, vol. 46, 2005, pp. 515-532.

[3]. K.Azad, M.G.Rasul, and T.Yusaf, "Statistical diagnosis of the best weibull methods for wind power assessment for agricultural applications,'' Energies, vol.7, 2014, pp. 3057 -3085.

[4]. F. Defant, "Local winds in Compendium of meteorology," American Meteorological Society, Boston, MA, 1951, pp. 655-672.

[5]. Energy Regulatory Commission, *201-2015 Annual Report*, Nairobi, Kenya, 2016.

[6]. D.Indhumathy, C.V. Sheshaiah, and K. Sukkiramathi, "Estimation of weibull parameters for wind speed calculation at kanyakumari in India," International Journal of Innovative Research in Engineering Science and Technology, vol.3, 2014, pp. 2319-8758.

[7]. J.N. Kamau, "Determination of the wind power parameters for the assessment of the wind energy potential for some selected sites in Kenya*,"* Ph.D. Thesis, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya,2010.

[8]. D.K. Kidmo, R.Danwe, S.Y. Doka, and N.Djongyan, “Comparison of numerical methods for estimating weibull parameters for wind energy applications, Kousseri, Cameroon,” Asian Journal of Natural and Applied Sciences, vol. 3, 2014, pp. 72-87.

[9]. D.K. Kidmo, R. Danwe, S.Y. Doka, and N. Djongyan, ”Statistical analysis of wind speed distribution based on six Weibull methods for wind power evaluation: Garoua, Cameroon,” *Revue des Energies Renouvables*, vol.18, 2015, pp.105- 125.

[10]. J.F. Manwell, J.G McGowan and A.L.Rogers, Wind Energy Explained Theory:Design and Application. John Wiley and sons Ltd. West Sussex, United Kingdom. 2009.

[11]. B. Maulidi, “Wind regime analysis and reserve estimation (Case study- Kenya*)*.M.Sc. thesis, University of Nairobi, Nairobi, Kenya,2010.

[12]. K. Rokenes and K. Per-Age, “Wind tunnel simulation of terrain effects on a wind farm siting,“ Wind Energy, vol 12, 2009, pp. 391-410.