WIND SPEED DISTRIBUTION, ESTIMATION OF THE WIND SHEAR EXPONENT AND THE ROUGHNESS PARAMETER FOR JUJA-KENYA

Saoke C[*1]., Kamau J.N[1]. and Kinyua R[1]
Department of Physics
Jomo Kenyatta University of Agriculture and Technology, Nairobi-Kenya
E-mail: winsaoke@gmail.com

ABSTRACT

Wind is a source of clean and alternative form of power production. Juja area (1° 10' S, 37° 7' E) in Kenya is growing very fast and being a University town is likely to become one of the economic hubs of Kiambu County and the greater Nairobi metropolis. This area also experiences frequent blackouts due to over reliance on electricity from the nationally connected grid, this despite the fact that it is highly endowed with adequate wind flow which can be locally harnessed to supplement power production and reduce over reliance on generators as backups. In spite of this potential, the lack of adequate site specific data information that enables informed choice on site selection, turbine selection, expected power output and turbine design still remains a challenge to the exploitation of this wind resource. This research paper provides a to study the wind speed variation through statistical data description of the Juja wind speed and the Weibull distribution model developed from the measured wind speeds applied to estimate the wind power density of the site. The wind speeds were analyzed and the wind characterized based on short term (three months) measured hourly series data of daily wind speeds at 13 m and 20 m heights. Analysis of wind data included daily wind data which were calculated to represent; the mean wind speed, diurnal variations, daily variations as well as the monthly variations. The wind speed frequency distribution at the 20 m was determined and the mean wind speed found to be 5.04 m/s with a standard deviation of 2.59. The average wind speeds at the two heights (13 m and 20 m) were used to calculate the wind shear exponent and the roughness parameter for Juja; this was found to be 0.16 and 0.048 m respectively. Using the calculated shear exponent, an extrapolation of the speeds was done to higher heights of up to 150 m. Maximum speed obtained at the 150 m height was 8.4 m/s during the month of October, these results provides a clear understanding of Juja's energy potential and the localized wind parameter characteristics which are necessary for matching the machine characteristics to the local wind regime.

Keywords: Wind speed, wind shear exponent, roughness parameter, wind speed distribution

INTRODUCTION

Wind is a renewable energy source. Wind turbine installations require a careful study of not only the wind speed pattern but also to characterize the vertical wind profile as well as the terrain description. The nature of a terrestrial surface, including various natural and artificial obstacles, such, as hills, trees and buildings have considerable influence on wind speed. As a result, wind moving across the earth surface is slowed by trees, buildings, grass, rocks and any other obstructions in its path. Consequently, wind velocity varies with height above the earth surface, a phenomenon called wind shear. Close to the earth the wind is slowed down at the expense of a friction about a terrestrial surface. Thus, wind is stronger at higher heights in relation to the earth for agricultural fields and deserted territories than areas that are inhabited [6].

Wind shear is a very important factor since it impacts the power available at different wind turbine hub heights and strongly influences the cyclic loading on the turbine blades. Most meteorological instruments measuring wind speeds are placed at a standard height of 10 m however for maximum wind exploitation, wind turbines hub heights operate at higher heights more than 50 m. At such heights it is either expensive or not feasible to measure wind speeds at such heights. To determine how much wind is available at these heights, extrapolation techniques are used to estimate wind speeds at any other heights beyond the standard 10 m. The common methods used is the power law formula [2], given by equation 1.

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\alpha} \quad \text{.......} (1)$$

Where V_1 and V_2 are the mean wind speeds at heights Z_1 and Z_2 respectively, α is the wind shear exponent.

The variation of the wind shear parameter has been investigated by researchers and a table providing the shear exponent for different terrain descriptions is summarized in table 1 [1].

Table 1: Typical shear exponents for varying terrain

TERRAIN DESCRIPTION	SHEAR EXPONENT
Smooth, hard ground, lake or ocean	0.1
Short grass on untilled ground	0.14
Level country with foot-high grass, occasional tree	0.16
Tall row crops, hedges, a few trees	0.2
Many trees and occasional buildings	0.22-0.24
Wooded country-small towns and suburbs	0.28-0.30
Urban areas with tall buildings	0.4

ROUGHNESS PARAMETER LENGTH

The roughness length is a parameter used to characterize shear and is also the height above the ground level where the wind speed is theoretically zero. This value is not constant; it is site specific since it varies according to the terrain of the site. The variation of the roughness parameter has been investigated by researchers and a table providing the roughness parameter lengths for different terrain descriptions is summarized in table 2 [4]. The atmospheric boundary layer also known as the planetary boundary layer is the lowest part of the atmosphere and its characteristics are directly influenced by contact with the earth surface. At this boundary, physical quantities such as speed change rapidly in space and time. [4]. The logarithmic law (equation 2) which is based on the principle of this boundary layer flow is usually used to determine the roughness parameter

$$\bar{V}_z = \bar{V}_r \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)} \quad \text{.......} \quad (2)$$

(Where Z_r and $\bar{V}_r$ are the reference height and the mean velocity of the reference height respectively, Z_0 is the roughness parameter)

This paper examines the wind speeds for Juja (1° 10' S; 37° 7' E), a University town in Kiambu county within central part of Kenya. The specific objectives include:

1. To measure the wind speeds in Juja for three months
2. To characterize the wind speed variations (diurnal, daily and monthly variability)
3. To calculate the wind shear exponent and roughness parameter of the area and extrapolate to determine wind speeds at higher heights.

The data used in this study consist of averaged series wind speed for the period between September 2010 and November 2010 recorded at mast height of 13 m and 20 m above the ground.

Table 2: Surface roughness values for various types of terrain

Terrain description	**Roughness parameters (Z_0) (m)**
very smooth, ice or mud	0.00001
calm open sea	0.0002
blown sea	0.0005
snow surface	0.003
lawn grass	0.008
rough pasture	0.01
fallow field	0.03
Crops	0.05
Few trees	0.1
Many trees, hedges, few buildings	0.25
Forest and woodlands	0.5
Suburbs	1.5
Centers of cities with tall buildings	3

MATERIALS AND METHODS

In this study the wind data studied was collected using two Davis Vantage PRO weather stations located within Jomo Kenyatta University of Agriculture and Technology (JKUAT) in Juja, located 35 kilometers from the Kenyan capital Nairobi. The experimental set up was as in figure 1; Wind speeds were measured for a period of three months during the months of September, October and November, 2010 during which the data was recorded simultaneously on an hourly basis daily at heights of 13 m and 20 m. The distribution of the wind speeds at 20 meters height was then analysed by grouping the wind speed data in a class interval of 1m/s with their corresponding frequencies. The results obtained are presented in table 3.

The calculated daily averages from the data for the months of September, October and November 2010 were used to determine the monthly average wind speeds and the results presented in tables 4, 5 and 6. To aid in the analysis of wind speed variation through a 24 hour cycle (diurnal variation) an average of the wind speeds of each hour was also calculated and results presented in the table 7. In order to calculate the wind shear exponent, the measured averaged wind speeds for the two heights were used on the power law formula (equation 1). Calculations of the shear exponent was done for each of the three months of September, October and November, thereafter the average wind shear exponent for the three months was determined and the results entered in Table 8. The calculated wind shear exponent was then used to predict the wind speeds at higher hub heights of 50 m, 70 m 100 m, 120 m and 150 m; the results obtained were entered in table 10: The extrapolated wind speed values were plotted against vertical elevation (height) and a vertical wind profile graph was obtained as shown in figures 11 and 12.;

The logarithmic law given by equation 2 was applied to the wind speed averages and used to calculate the roughness parameter length at the site. Values obtained were presented as in table 11:

RESULTS

The statistical distribution of the wind speeds at 20m height is as provided for in table 3. The mean wind speed was calculated and found to be 5.04 m/s while the standard deviation was found to be 2.59. Tables 4, 5 and 6 presents the daily averages of wind speed, direction and temperature for the months of September, October and November 2010 respectively while the diurnal average wind speed is given Table7. The average air pressure was also found to be 1008.75 mb for 13 height and 846.83 mb for the 20 m height.

Table 3: The distribution of wind speeds for statistical analysis

Class (wind speeds m/s)	**V (mid points)**	**Frequency**	**f*v**	**Deviations**	**(D^2)**	**fD^2**
0.0-(	0.45	91	40.95	-4.59	21.06	1917.19
1.0-1.9	1.45	86	124.7	-3.59	12.88	1108.37
2.0-2.9	2.45	282	690.9	-2.59	6.70	1891.68
3.0-3.9	3.45	325	1121.25	-1.59	2.52	821.63
4.0-4.9	4.45	324	1441.8	-0.59	0.34	112.78
5.0-5.9	5.45	194	1057.3	0.41	0.16	32.61
6.0-6.9	6.45	195	1257.75	1.41	1.98	387.67
7.0-7.9	7.45	209	1557.05	2.41	5.80	1213.89
8.0-8.9	8.45	152	1284.4	3.41	11.62	1767.47
9.0-9.9	9.45	90	850.5	4.41	19.44	1750.32
10.0-10.9	10.45	38	397.1	5.41	29.26	1112.18
11.0-11.9	11.45	15	171.75	6.41	41.08	616.32
12.0-12.9	12.45	5	62.25	7.41	54.90	274.54
13.0-13.9	13.45	3	40.35	8.41	70.72	212.18
14.0-14.9	14.45	2	28.9	9.41	88.54	177.09
15.0-15.9	15.45	1	15.45	10.41	108.36	108.36
SUM		2012	10142.4			13504.36

Table 4: Daily averages of wind speed and temperature for September 2010

September 2010	Speed (m/s)	Speed (m/s)	Temperature	Direction
Date	Height (13 m)	Height (20 m)	(^0C)	(Degrees)
1	3.5	3.6	18	110
2	3.67	3.72	18	115
3	3.42	3.64	20	105
4	4.2	4.26	18	100
5	5.14	5.4	20	130
6	2.61	2.87	20	25
7	5.08	5.48	21	10
8	3.8	4.22	19	5
9	3.99	4.15	18	360
10	4.74	4.84	18	25
13	5.37	5.61	18	40
14	4.63	4.81	19	40
15	4.14	4.91	20	40
16	3.99	4.27	20	40
17	3.62	4.08	20	40
20	3.85	4.23	20	35
21	3.92	4.09	19	35
22	4.81	5.24	18	15
23	4.25	4.38	19	15
24	4.78	5.35	20	15
25	5.03	5.39	22	30
27	4.89	5.38	20	25
28	6.47	6.72	20	340
29	6.39	6.76	21	310
30	4.28	4.75	20	315
Monthly average	**4.42**	**4.72**	**19.4**	
Maximum	**6.47**	**6.76**	**22**	
Minimum	**2.61**	**2.87**	**18**	

Table 5: Daily averages of wind speed and temperature for October 2010

October 2010	Speed (m/s)	Speed (m/s)	Temperature	Direction
Date	. Height (13 m)	Height (20 m)	(^0C)	(Degrees)
1	4.37	4.75	20	120
2	4.42	4.86	20	100
4	4.83	5.54	21	140
5	5.25	5.47	21	45
6	4.8	5.14	20	30
7	4.62	5.05	19	350
8	4.92	5.16	21	60
11	5.5	5.28	22	10
12	5.06	6.02	23	5
13	5.48	6.44	22	350
14	6.48	6.93	23	345
15	7.67	7.88	22	45
18	6.38	6.75	22	30
19	6.18	6.49	22	55
20	6.1	6.49	21	35
21	6.53	6.91	19	60
22	5.85	6.12	18	40
23	6.11	6.49	20	15
25	4.83	5.18	18	320
26	6.1	6.49	19	55
27	6.1	6.49	19	55
28	6.11	6.49	18	85
29	4.58	4.82	19	250
30	5.71	5.9	21	110
Monthly average	**5.58**	**5.96**	**20.4**	
Maximum	**7.67**	**7.88**	**23**	
Minimum	**4.37**	**4.75**	**18**	

Table 6: Daily averages of wind speed and temperature for November 2010

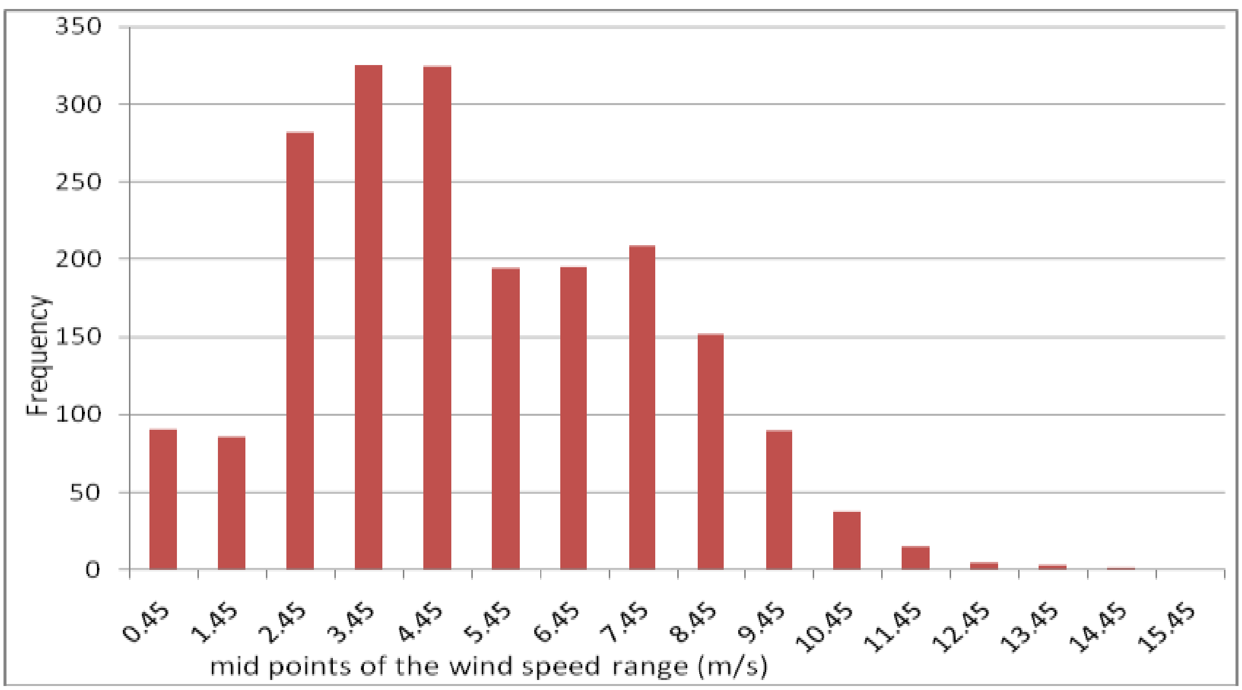
November 2010	Height (13 m)	Height (20 m)	Temperature	Direction
Date	Speed (m/s) .	Speed (m/s)	(^0C)	(Degrees)
1	5.34	6	18	115
2	4.09	4.56	18	105
3	4.3	4.82	20	100
4	3.62	4.05	18	130
5	4.09	4.48	20	25
6	3.86	4.3	20	10
7	3.74	4.17	21	5
8	4.56	4.95	19	360
9	4.82	5.21	18	25
10	4.05	4.39	18	40
11	4.48	4.79	18	40
12	4.3	4.6	19	40
13	4.17	4.43	20	40
14	4.26	4.59	20	40
15	4.67	5.03	20	35
16	4.68	5.07	20	35
17	5.15	5.24	19	15
18	4.8	4.96	18	15
19	5.44	5.57	19	15
20	5.9	6.05	20	30
22	4.39	5.91	22	25
23	5.08	5.36	20	340
24	4.46	4.86	20	310
Monthly average	**4.53**	**4.93**	**19.3**	
Maximum	**5.9**	**6.05**	**22**	
Minimum	**3.62**	**4.05**	**18**	

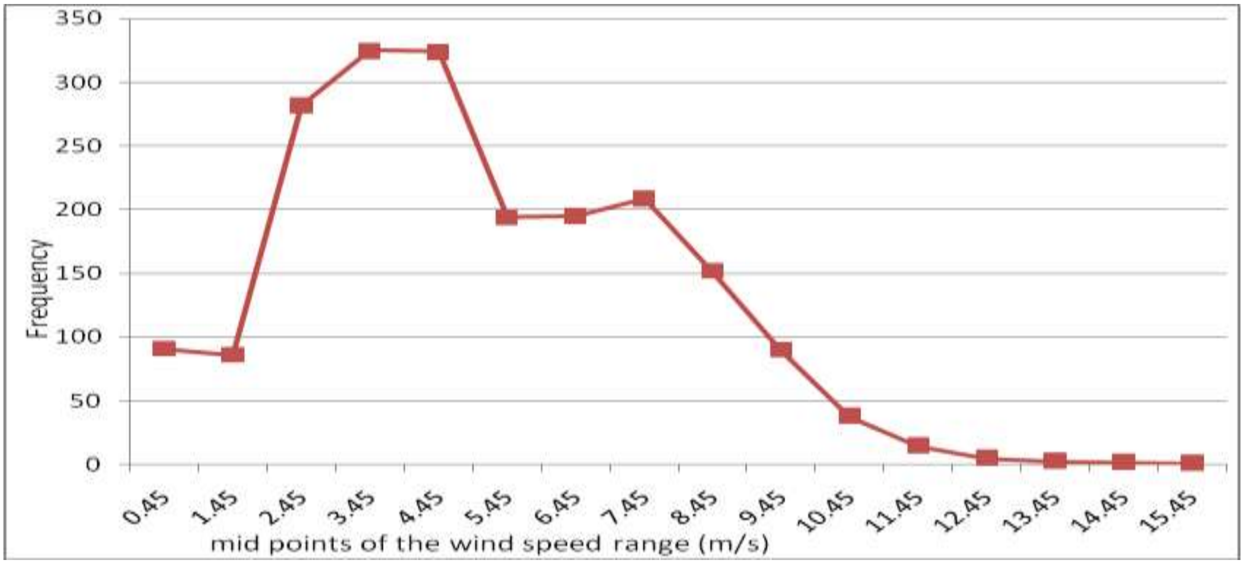
Table 7: The diurnal average wind speed

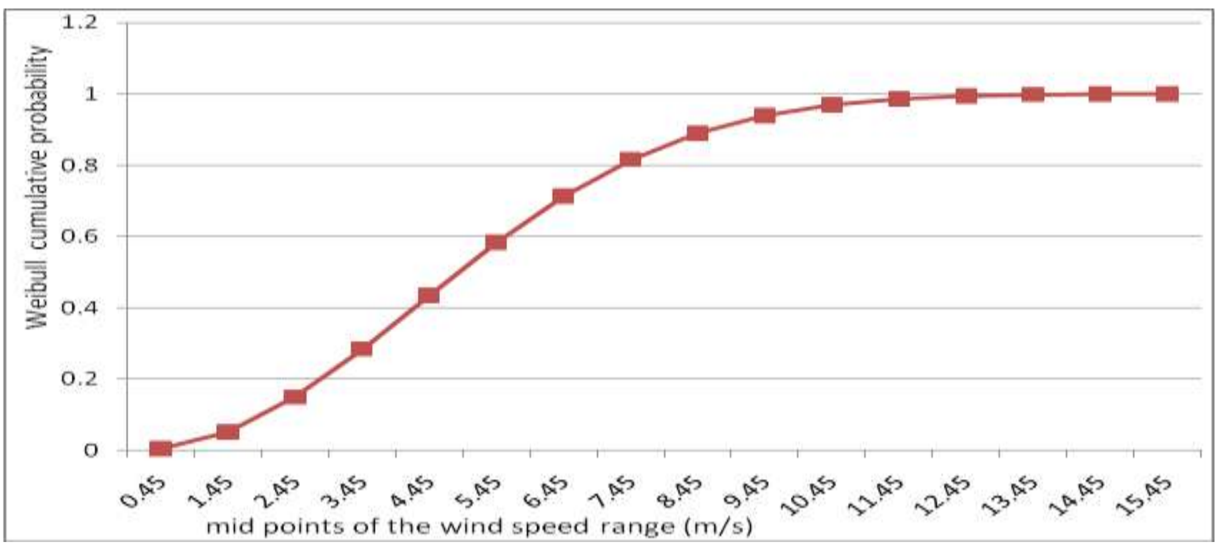
Time of the day	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Av. Speeds (m/s)	**4.32**	**5.27**	**6.32**	**6.85**	**7.65**	**7.87**	**8.14**	**8.29**
Time of the day	18:00	19:00	20:00	21:00	22:00	23:00	0:00	1:00
Av. Speeds (m/s)	**7.74**	**6.80**	**6.02**	**5.94**	**5.57**	**5.55**	**4.76**	**4.66**
Time of the day	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00
Av. Speeds (m/s)	**4.14**	**3.72**	**3.21**	**2.86**	**2.75**	**2.95**	**3.03**	**3.55**

DISCUSSION

Figures 2 and 3 gives the wind speed distribution for the data recorded during the three months period at the 20 m height. From the distribution graphs in figure 2 and 3, the modal wind speed class is 3.0-3.9 m/s. While the lowest number of recorded wind speed values lie within the range of 15m/s and above. During the period of the research the maximum wind speed recorded was 15.7m/s. The cumulative distribution curve (Figure 4) which represents the time fraction or probability that the wind speed is smaller than or equal to a given wind speed. From the Weibull probability graph in figure 4, 40% of the wind speeds recorded was above the wind speed class interval of 5.05-6.05 m/s.





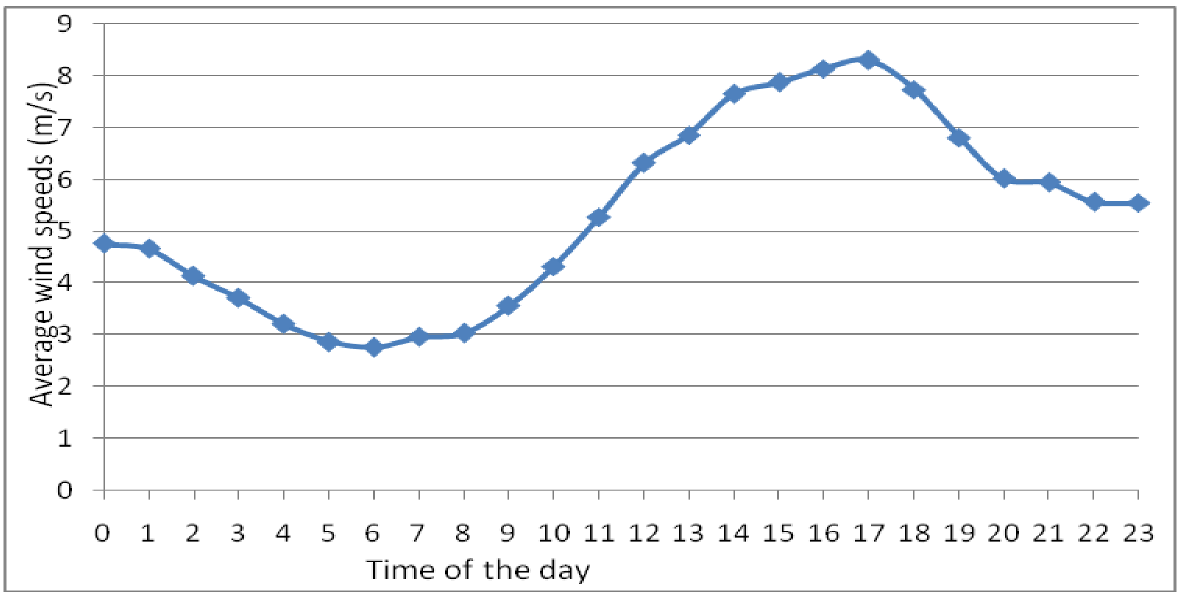


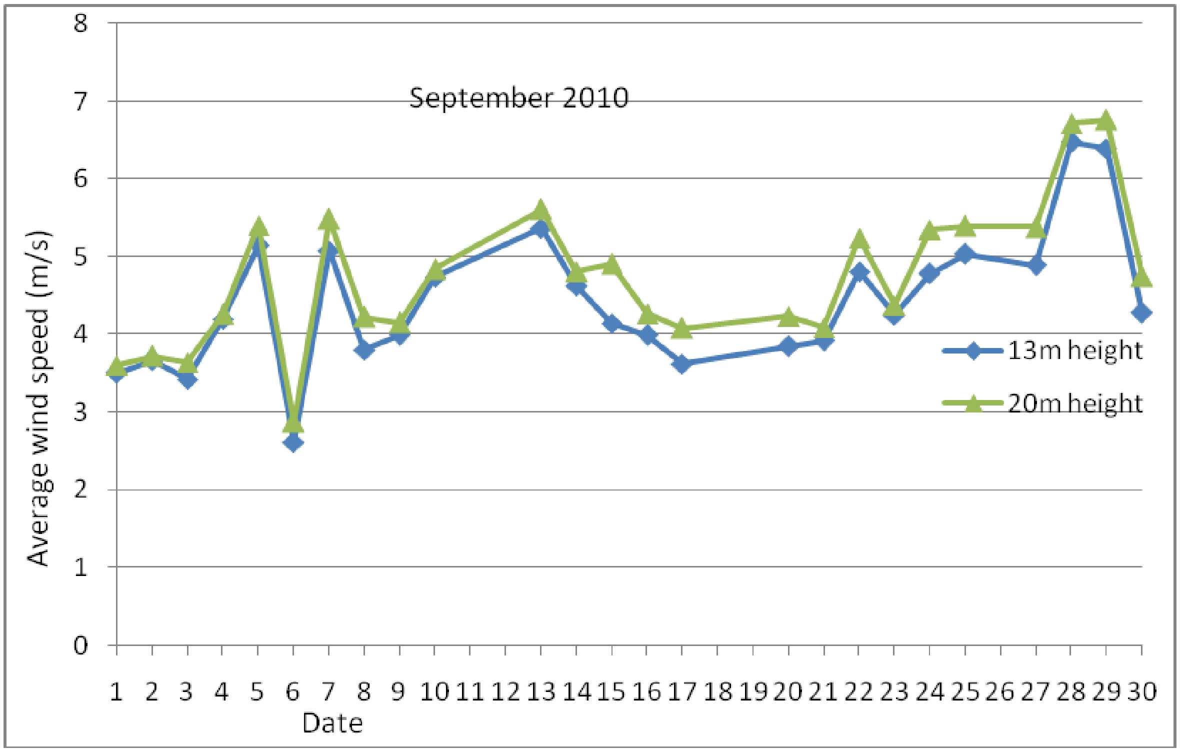
DIURNAL VARIATIONS

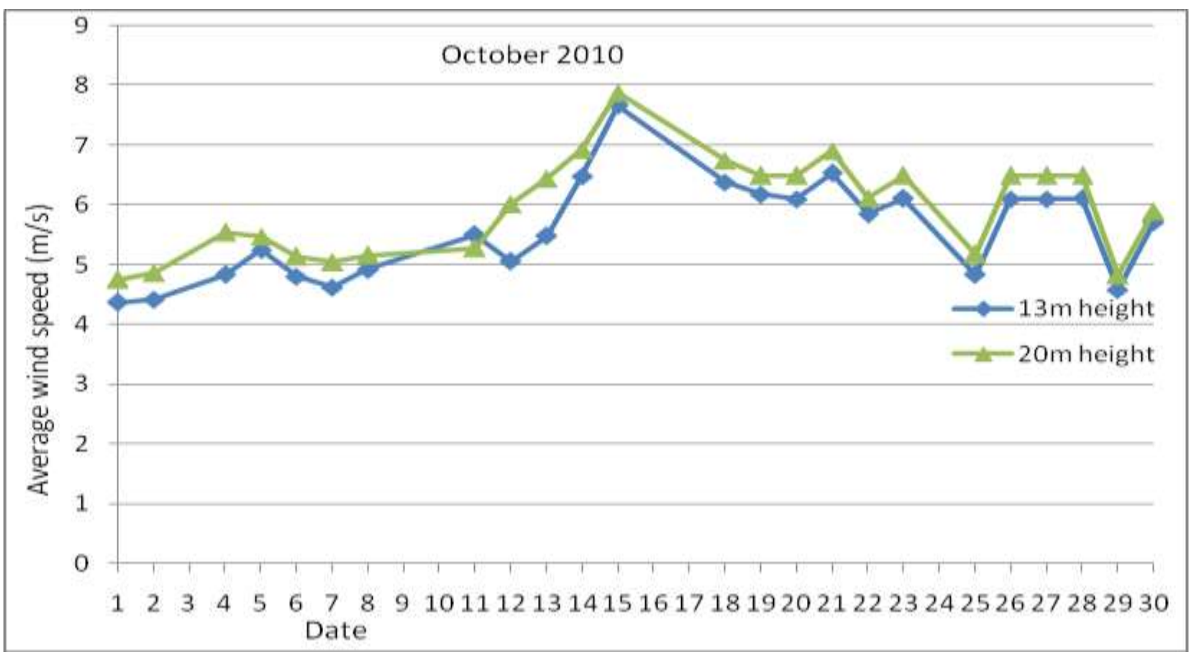
A graphical presentation of this hourly average wind speed variation provided a diurnal wind speed distribution pattern as presented in figure 5; In figure 5, the zero reference value on the horizontal axis represents the time 0.00 hours (midnight). The graph demonstrates a smooth and predictable wind speed distribution pattern with high winds prevailing from approximately 16.00 hours to 17.00 hours and slows down during the night hours. This diurnal wind speed variation pattern occurs due to the differential heating of the earth's surface during the daily radiation cycle. This is typical of diurnal pattern where wind speeds increase during the day with wind speeds lowest during the hours from midnight to sunrise. Although the daily variations in solar radiation are responsible for these diurnal wind speed changes, the diurnal changes also vary with seasons (large diurnal changes in spring and summer), location and altitude above the sea level [4].

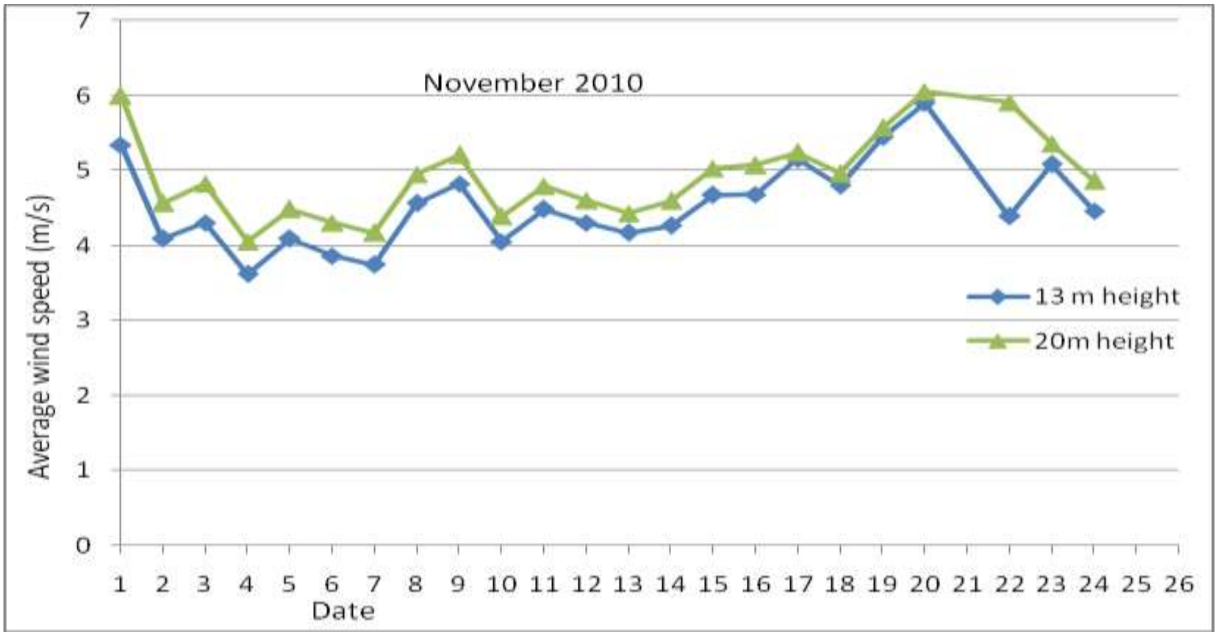
DAILY WIND SPEED VARIATIONS

The daily wind speeds averages calculated for both the two heights plotted against the dates of the month gives graphical representations in figure 6, 7 and 8 for the months of September, October and November respectively. This is consistent with other studies that have shown that the months of June to November as being periods of high wind averages and is usually attributed to the north-easterly wind currents that arise due to the northern hemisphere summer [3].




September 2010
Average wind speed (m/s)
Date
13m height
20m height


October 2010
Average wind speed (m/s)
Date
13m height
20m height



WIND SHEAR

From figures 6, 7 and 8, it is evident that the average wind speeds for the 20m height is consistently greater than that of the 13m height. This potrays the variation of the wind speed with height and therefore confirms that wind speed increases with the height above the ground. The factor that estimates this vertical wind profile is called the wind shear exponent which as explained earlier can be determined from the power law formula (equation 1). The monthly wind speed averages at heights of 13m and 20m was determined and used to calculate the wind shear exponents. Table 8 summarizes the results of the wind shear exponents values obtained.

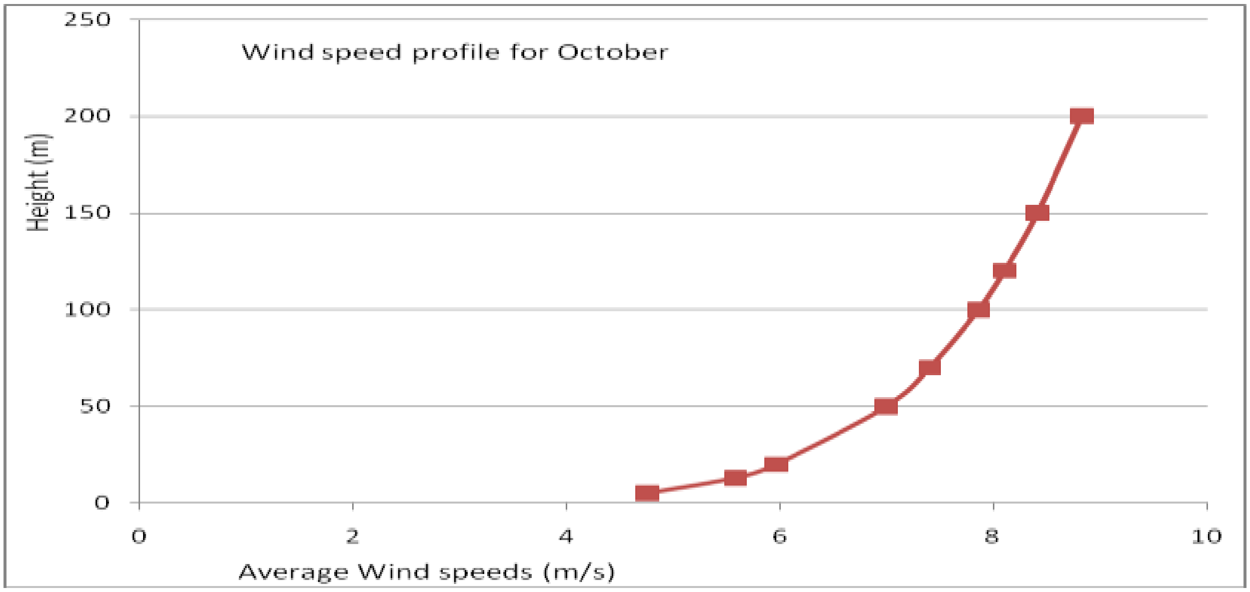
From the calculations in table 8, the range of values of the wind shear exponent ranges from 0.15 to 0.19, this is consistent with terrain of the study area as shown in figure 1 [1]. The calculated wind shear exponent gives extrapolated wind speeds at higher hub heights of 50m, 70m 100m, 120m and 150m as in table 10. The extrapolated wind speed values when plotted against vertical elevation (height) provides a vertical wind profile graph as shown in figure 9; A graph of similar trend was obtained for the other two months of September and November as shown in the graph of figure 10; Although the wind speeds at hub height of 150 m is higher, the difference of the speed values between the 50 m height and 150 m height is merely an average of 1.9 m/s. This difference is small and therefore it would be uneconomical to incur the expensive costs of exploiting the winds at 150 m whose speeds is only 1.9 m/s higher than at 50 m. Based on this argument and considering turbine installation costs, the optimum height for wind power generation in Juja is 50 m (it would be uneconomical to build turbine 150 m tall instead of one that is 50 m just to tap an additional 1.9 m/s at 150 m.) It would therefore be necessary to extract Juja winds at 50 m hub height and select a more efficient turbine design whose technical specifications would optimize the power generation.

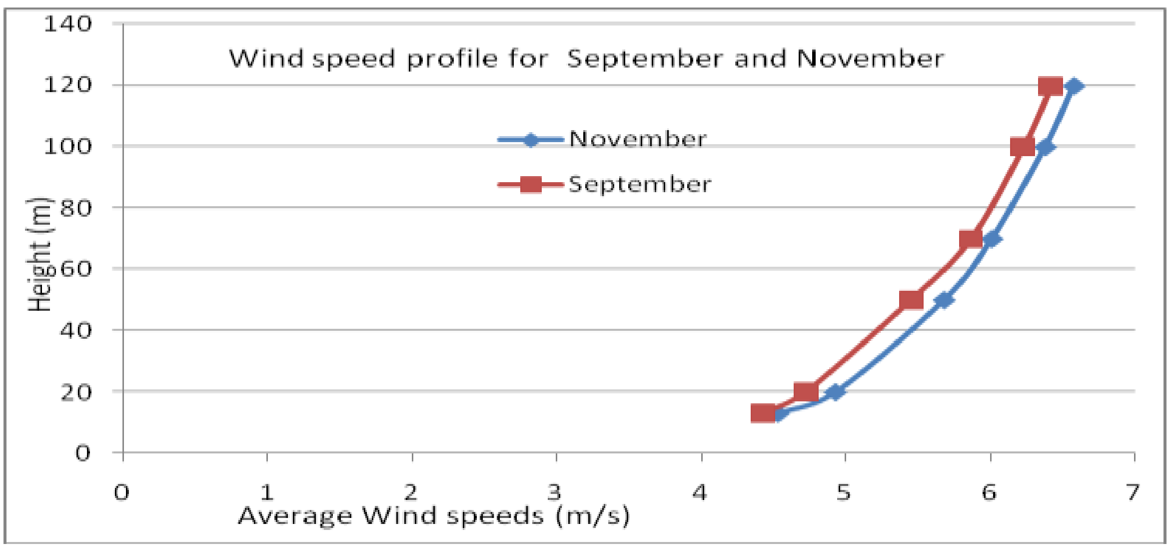
Table 8: Calculated average shear exponents

Month	**13 m**	**20 m**		**Shear Exponent**
Height	**V_1 (m/s)**	**V_2 (m/s)**	**V_1/V_2**	α
September	4.42	4.72	0.93	0.15
October	5.58	5.96	0.93	0.15
November	4.53	4.93	0.91	0.19

Table 10: Expected wind speeds at various heights extrapolated from the power law

Month		**13m**	**20m**	**50m**	**70m**	**100m**	**120m**	**150m**
Sept	Speeds (m/s)	4.42	4.72	5.45	5.86	6.22	6.42	6.66
	Power W/m^2	**47.75**	**58.26**	**89.50**	**111.50**	**133.45**	**146.29**	**163.69**
Oct	Speeds (m/s)	5.58	5.96	6.99	7.40	7.86	8.10	8.41
	Power W/m^2	**96.03**	**117.09**	**189.27**	**224.26**	**268.36**	**294.17**	**329.17**
Nov	Speeds (m/s)	4.53	4.93	5.68	6.01	6.38	6.58	6.83
	Power W/m^2	**51.40**	**51.31**	**101.30**	**120.02**	**143.64**	**157.45**	**176.19**





ROUGHNESS LENGTH

The atmospheric boundary layer also known as the planetary boundary layer is the lowest part of the atmosphere and its characteristics are directly influenced by contact with the earth surface. At this boundary, physical quantities such as speed change rapidly in space and time [2]. The logarithmic formula (equation 2) which is based on the principle of this boundary layer flow was applied to the wind speed averages and used to calculate the roughness parameter length at the site. The values obtained were entered in table 11:

Roughness length is a parameter used to characterize shear and is also the height above the ground level where the wind speed is theoretically zero [4]. This value is not constant; it is site specific since it varies according to the terrain of the site. Table 2 gives a summary of the roughness parameters for different terrain descriptions. From table 1 and table 2, the calculated values of wind shear exponent and roughness parameter obtained actually describes the terrain where this research was done which comprised of crops, hedges, a level country with foot-high grass and occasional tree.

Table 11: Calculated average Roughness parameter lengths

	V_1 (m/s)	V_2 (m/s)	$\ln Z_o$	Z_o (m)
	13 m	***20 m***	***c/d***	
September	4.42	4.72	-3.71	0.024
October	5.58	5.96	-3.73	0.023
November	4.53	4.93	-2.33	0.097

REFERENCES

1. Bechrakis, D.A., and Sparis P.D. (2000). Simulation of the wind speeds at different heights using artificial neural networks. *Wind energy.* Vol. 24 (2), 127-136.

2. Celik A. N. (2004). Statistical analysis of wind power density based on the Weibull and Rayleigh models at the southern region of Turkey. *Renewable Energy* Vol **29**.

3. Kamau J. N., Kinyua R., Gathua R. (2010). 6 years of wind data for Marsabit, Kenya average over 14m/s at 100m hub height; an analysis of the wind energy potential, *Renewable Energy, Vol.* ***35*** *(6)*

4. Manwell J.F., McGowan J.G., Rogers A.L. (2009) *Wind energy explained Theory; design and application*, John Wiley & sons Ltd. West Sussex, UK.

5. Oludhe C. and Ogallo L. J. (1989). Statistical characteristics of surface winds over Kenya. *Journal of applied statistics,* Vol 16, No. 3, pp 331-343.

6. Rai, G. *D.* (1994) *Non conventional energy sources*, Khanna Publishers, Delhi

FIGURE LEGENDS

Figure 1: The experimental set up
Figure 2: Wind speed distribution (bar chart)
Figure 3: Histogram of the distribution of wind speeds
Figure 4: Weibull cumulative probability distribution curve
Figure 5: Diurnal wind speed distribution
Figure 6: Daily wind speed variation for September 2010
Figure 7: Daily wind speed variation for October 2010
Figure 8: Daily wind speed variation for November 2010
Figure 9: Graph of the vertical wind profile for October 2010
Figure 10: Graph of the vertical wind profile for September and November 2010