Analysis of wind speeds based on the Weibull model and data correlation for wind pattern description for a selected site in Juja, Kenya

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as the University supervisors.

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DEDICATION

I dedicate this research thesis to my father Henry Saoke Kisuge, my mother Wilfreda Saoke and my late step mother Salina Were as a symbol of my gratitude, respect and honour for their inspiration and instilling in me values of hard work, self reliance, determination and persistence.

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LIST OF ABBREVIATIONS

BMA	Bayesian Model Averaging
MCP	Measure Correlate and Predict
MEP	Maximum Entropy Principle
MLE	Maximum Likelihood Estimator
PDF	Probability Density Function
WEG	Wind Electric Generator

LIST OF SYMBOLS

V	Wind speed
P	Available wind power
$\mathbf{P_w}$	Wind power density
A	Rotor area
$\mathbf{V_*}$	Frictional velocity
κ	Von Kermann's constant (0.4)
K	Shape parameter (dimensionless)
C	Scale parameter (m/s)
Z	Height above the ground
$\mathbf{C_p}$	Power coefficient
R	Gas constant
T	Temperature
$\mathbf{V_m}$	Mean wind speed
$\mathbf{D_j}$	Median of the j^{th} interval
Γ	The gamma function
ρ	Air density
$\mathbf{Z_o}$	Roughness parameter length
α	Wind shear exponent

$f(V)$	Probability of observing wind speed V

ABSTRACT

There is increasing interest in wind energy investment by both public and private producers in Kenya. However, the biggest challenge is the lack of up-to-date site specific data information on wind energy potential across the country. Hence the need for more studies to establish an updated site specific wind data information. In this research, the wind speeds distribution was investigated for JKUAT-Juja whose altitude is 1416 m above sea level, (1° 10' S, 37° 7' E) in Kiambu county approximately 35 km from Nairobi Kenya. The wind speeds were analyzed and characterized on short term (three months) measured hourly series data of daily wind speeds at 13 m and 20 m heights. Analysis 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 the selected site in 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 150m. Maximum speed obtained at the 150 m height was 8.4 m/s during the month of October. The wind speed distribution was modeled using the Weibull probability function and the power density for Juja site was found to be 131.35 W/m^2.

CHAPTER ONE

1.1 Introduction

Wind is the movement of air masses on the earth surface. The occurrence of these air movements in the atmosphere is due to pressure difference (pressure gradient) that is caused by heterogeneity in the heating of the atmosphere by the sun. Pressure gradient causes air masses to move, as the atmosphere heats up, it warms the air in it causing it to move upwards hence creating areas of low pressure. The air from high pressure areas moves in the direction of low pressure areas, thereby creating a wind (Kargiev *et al*., 2001). Although surface winds are the resource exploited during wind power generation, their flow is highly influenced by the nature of the earth's surface since obstacles and surface roughness slows it. Since the sun is the primary source of air motion occurrences, wind energy can be considered as a form of a solar energy.

The continuing growth in population and the shift of nations to industrialization has lead to the increase in energy demand. However, factors such as energy sustainability and the gradually emerging consciousness about environmental degradation have provoked priority to the use of renewable alternative sources such as solar and wind energies (Demirbas, 2001). Wind energy is one of the key to a clean energy future, first used more than 3,500 years ago in boats to transport goods in Egypt and to grind seeds to produce flour. According to the wind energy outlook report 2007, wind energy is now one of the most cost effective methods for electricity generation available (http://www.ewea.org). The technology is continuously being improved for both cheaper and more productive wind turbines. It can therefore be expected that wind energy will become even more economically competitive in the coming decades (http://www.ewea.org). Its advantages such as cleanliness, abundance of resource, low cost, sustainability, safety and effectiveness in job creation has facilitated its fast growth as an energy source during most of the 1990s, expanding at an annual rate from 25% to 35% (Demirbas, 2001). In Kenya, this expansion rate has not yet been realized despite the fact that Kenya is compatible with current wind technology. The main issue is the limited knowledge on the Kenya wind resource. The meteorological station data are quite inadequate since these stations are only 35 spread all over the country (Marigi, 1999). Information gathered is not adequate to give detailed resolutions due to sparse station network. There is significant potential to use wind energy for grid connected wind farms, isolated grids (through wind-solar hybrid systems) and off-grid community electricity and water pumping.

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 Kenya with some excellent wind regime areas. The North West of the country (Marsabit and Turkana districts) and the edges of the Rift Valley are the two large windiest areas (average wind speeds above 9m/s at 50 m high). The coast is also a place of interest though the wind resource is expected to be lower about 5-7 m/s at 50 m high (Kamau, 2010). Many other local mountain spots offer good wind conditions. Due to monsoon influence, some seasonal variations on wind resource are expected (low winds in the month of May in Southern Kenya). JKUAT in Juja, Kenya where this research work was done is located on the global map at coordinates of latitude; 1° 10' South and longitude; 37° 7' East at an altitude of 1416 m (4648 ft) above sea level and is within Kiambu county approximately 35 km from Kenya's capital city, Nairobi. This area's wind regime is influenced by the presence of the mount Kenya which offers channeling effect on the prevailing winds. In addition, the terrain, the presence of tall buildings and other available small water bodies such the JKUAT dam also influence the local wind regimes through the breezes.

1.1.1 The earth's wind systems

One square meter of the earth's surface on or near the equator receives more solar radiation per year than one square meter at higher latitudes. As a result, the tropics are considerably warmer than the high latitude regions. Since atmospheric pressure is the pressure resulting from the weight of the column of the air that is above a specified surface area, like all other gases, air expands when heated, and contracts when cooled. In the atmosphere, warm air is lighter and less dense than cold air and will rise to high altitudes when strongly heated by solar radiation a low pressure belt is created at the equator due to warm humid air rising in the atmosphere until it reaches the top of the troposphere (approximately 10 km) and will spread to the North and the South. This air gradually cools until it reaches latitudes of about 30 degrees, where it sinks back to the surface, creating a belt of high pressure at these latitudes. The majority of the world's deserts are found in these high pressure regions (Nicolaev *et al*., 2008).

Some of the air that reaches the surface of these latitudes is forced back towards the low-pressure zone at the equator, forming what is known as trade winds. However, not all of the air that sinks at the 30 degree latitudes moves toward the equator. Some of it moves toward the poles until it reaches the 60 degree latitudes, where it meets cold air coming from the poles. The interaction of the two bodies of air causes the warmer air to rise and most of this air cycles back to the 30 degree latitude regions where it sinks to the surface, contributing to high pressure belt.

The remaining air moves towards the poles and sinks to the surface at the poles as it cools. It returns to the 60 degree latitude region. As the earth is rotating, any movement on the Northern hemisphere is diverted to the right. (In the southern hemisphere it is bent to the left). This apparent bending force is known as the Coriolis force. (Named after the French mathematician Gustave Gaspard Coriolis 1792-1843). The apparent motion is according to figure 1.1 (Nicolaev *et al*., 2008).

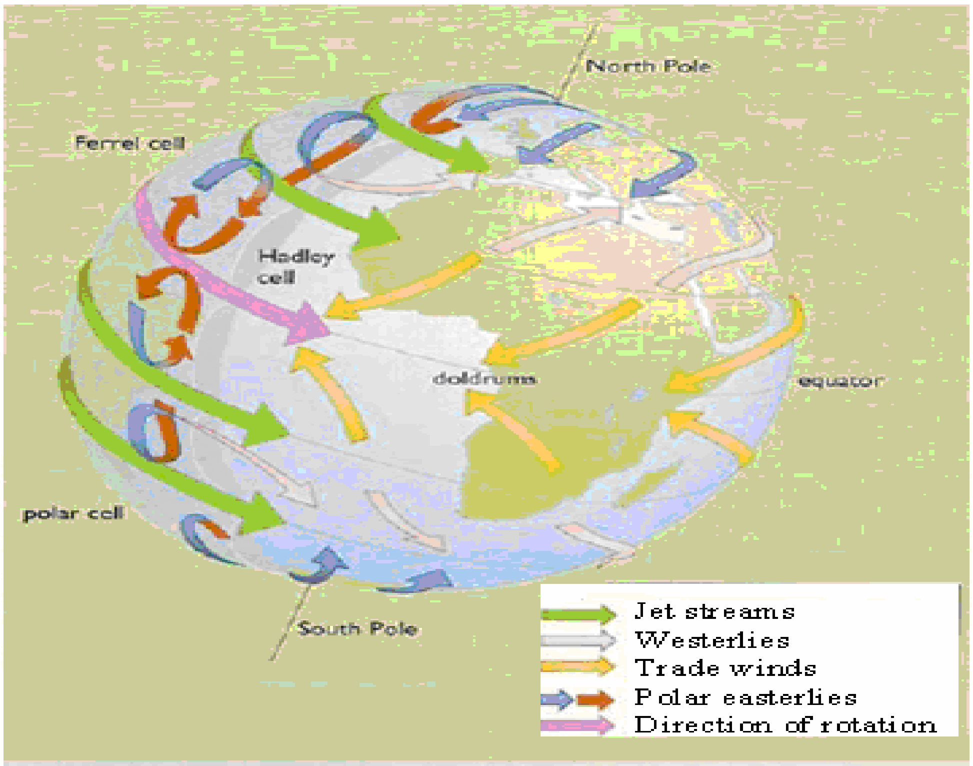

Figure 1.1: The global wind circulation

As a result of the Coriolis bending force, general results for the prevailing wind directions according to the latitude are presented in table 1(Nicolaev *et al*., 2008). These prevailing wind directions are important, since they influence the local wind regime.

Table 1: Prevailing wind directions.

LATITUDE	90-60 N	60-30N	30-0N	0-30S	30-60S	60-90S
DIRECTION	NE	SW	NE	SE	NW	SE

In addition to the main global wind systems, there are also local wind patterns, such as the sea and land breezes as well as the mountain and valley winds. Land masses are heated by the sun more quickly than the sea in the daytime. The air rises from the land and flows out to the sea, and creates a low pressure at ground level which attracts the cool air from the sea. This is called a sea breeze. At nightfall there is often a period of calm when land and sea temperatures are equal. At night the wind blows in the opposite direction. The land breeze at night generally has lower wind speeds, because the temperature difference between land and sea is smaller at night. Mountain and valley winds are created when cool mountain air warms up in the morning, becomes lighter and begins to rise as cool air from the valley below moves up the slope to replace the rising air. During the night the flow reverses, with cool mountain air sinking to the valley.

1.1.2 Wind characteristics

The wind is characterized by two measured parameters, these are: the speed expressed in m/s, km/h, knots (miles/h) and direction, whence it blows. The direction is measured from the north clockwise. Wind speed and wind direction changes frequently owing to turbulence of air flow and under the influence of the external factors caused by spatial and temporal non-uniformity of temperature and pressure in various parts of the atmosphere (Nicolaev *et al*., 2008). In addition it is also caused by the geographical nature of the terrain and surface roughness.

1.1.3 Power from the wind

The major characteristic defining power available in the wind is its speed, (Elistratov, 2008). Power is generated from the wind by converting the force of the wind on the rotor blades into a torque. The amount of energy that is transferred to the rotor by the wind depends on the density of the air, the rotor area and the wind speed. As the wind passes the blades of the turbine it is slowed down and hence its kinetic energy is captured. Thus, the wind moves slower on the downwind side of the turbine than on the upwind side. The amount of wind on each side of the turbine however remains the same, so the wind on the downwind side occupies a larger area as shown in figure 1.2 (Stiebler, 2008)

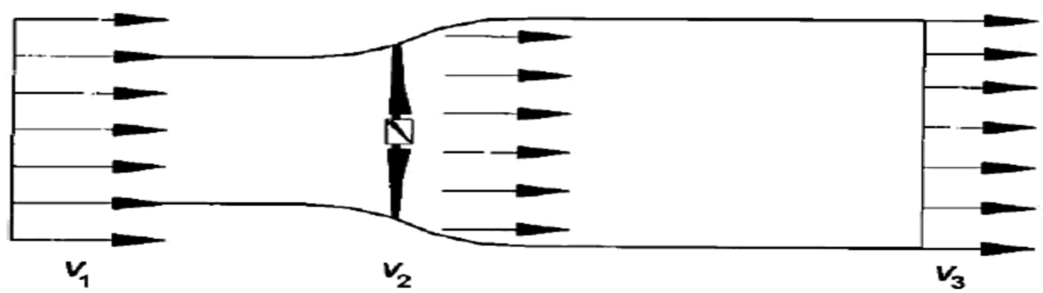

Figure 1.2: Idealized fluid Betz model for a wind rotor

The power of wind is proportional to the cube of wind velocity, the rotor area and the air density. The power available in the wind is given by:

$$P = \frac{1}{2}\rho A V^3 \quad \text{……………………………………………………. (1.1)}$$

Although this is the available power in a given wind, practically it is not possible to extract all of it. The useful mechanical power obtained is expressed by means of the power coefficient. The wind velocity suffers retardation due to the power conversion to a speed V_3 behind the wind turbine, see figure 1.2. The velocity in the plane of the moving blades is of average value of; $V_2 = \frac{V_1 + V_3}{2}$. The calculation of maximum useful power is when $\frac{V_3}{V_1} = \frac{1}{3}$ and power coefficient $C_p \approx 0.59$.

1.1.3.1 Wind shear

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.

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 more than 20 m. To know 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 are the logarithmic wind profile law and the power law formula.

1.1.3.2 The power law formula

The most common and widely used expression for the variation of wind speed with height is the power law taking the form below.

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\alpha} \quad \text{(1.2)}$$

Where V_1 and V_2 are the mean speeds at the heights Z_1 and Z_2 respectively. The exponent α is the power law exponent (wind shear exponent). This exponent depends on factors such as; surface roughness and atmospheric stability. The most frequently adopted value being 0.14 which is widely assumed for application to low surfaces and well exposed sites. This value (0.14) of the shear exponent is practically not uniform as theoretically assumed due to its dependence on such parameters as elevation, time of the day, season, nature of terrain, wind speed, temperature and various thermal as well as mechanical mixing parameters. The variation of the wind shear parameter has been investigated by researchers and a table providing the shear exponent for different terrain descriptions obtained as summarized in table 2 (Bechrakis *et al*., 2000).

Table 2: Typical shear exponents for various types of terrains

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

1.1.3.3 Logarithmic wind profile law

$$\bar{V} = \frac{V_*}{\kappa} \ln\left(\frac{Z}{Z_0}\right) \quad \text{...} (1.3)$$

where V_* - frictional velocity, κ - Von Kermann's constant, Z - Height above the ground, Z_0 - Roughness parameter $\bar{V}$ - Mean wind speeds at height Z

Due to the complexities associated with the computation of V_*, the logarithmic wind profile law has been modified in equation 1.4;

$$\bar{V}_z = \bar{V}_{10} \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{10}}{z_0}\right)} \quad (1.4)$$

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. (Manwell *et al*., 2009). The logarithmic law which is based on the principle of this boundary layer flow is usually used to determine the roughness parameter

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 3 (Manwell *et al*., 2009).

Table 3: Surface roughness values for various types of terrains.

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

1.1.3.4 Air density

Air density is also as important in determining the power available in the wind, the higher the air density the higher the power in the wind. However, due to the vertical pressure and temperature variations, air density varies with height above the surface. Air density is a function of temperature and pressure both of which vary with height. The density of air can be calculated by applying the ideal gas law which as expressed in equation 1.5;

$$\rho = \frac{P}{R.T} \qquad (1.5)$$

Where: ρ =density (Kg/m^3)

P = pressure, Pascals

R = gas constant, J/ (kg degK) = 287.05 for dry air

T = temperature, deg K = deg C + 273.15

1.1.4 Weibull distribution

It is very important in the wind analysis to be able to describe the variation of wind speeds. Turbine designers need the information to optimize the design of their turbines, so as to minimize generating costs while turbine investors need the information to estimate their income from power generation. A number of studies in the recent years have investigated the fitting of specific distribution to wind speeds for use in practical applications as estimation of wind loads on building and power analysis. Some of the mathematical models that have been used to study wind data and in this work, the wind speeds were modeled using the two-parameter Weibull distribution.

The Weibull distribution model (named after the Swedish physicist W. Weibull, who applied it when studying material strength in tension and fatigue in the 1930s and which provides a close approximation to the probability laws of many natural phenomena) is a probability distribution function used to describe wind speed variations. This method is preferred not only due to its greater flexibility and simplicity but also because it gives a good fit to experimental data. The two-parameter Weibull distribution function can be expressed mathematically as: The probability $f(v)$ of observing wind speed v is given by;

$$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad \text{.. (1.6)}$$

While the corresponding cumulative distribution is

$$F(v)=1-\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad \text{... (1.7)}$$

where;

$v \geq 0$ is the wind speed (m/s for this study), $k > 0$ is a shape parameter (dimensionless), $c > 0$ is a scale parameter (m/s)

It has been found that from Weibull distribution the variance is given by;

$$\delta^2=\bar{v}\left(\frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2\left(1+\frac{2}{k}\right)}-1\right) \quad \text{... (1.8)}$$

A number of other approximations have been found to provide good calculations for the same. Justus, (1978) provided a more straight forward formula for evaluating the shape parameter. This is as below;

$$k = \left(\frac{\delta}{\bar{v}}\right)^{-1.086} \qquad (1.9)$$

The mean wind speed and the two parameters are related through the relationship given in equation 1.10 obtained from the Weibull distribution.

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \qquad (1.10)$$

With this relationship, it is possible to determine the mean wind speed provided the two parameters are available. Equally, it is possible to evaluate the value of the scale parameter from the calculated values of the shape parameter and mean speed. Lysen, (1983) simplified equation 1.10 and obtained a simpler formula for determining the scale parameter, this is as follows;

$$c = \bar{v}\left(0.568 + \frac{0.433}{k}\right)^{-\frac{1}{k}} \qquad (1.11)$$

In the case of the three-parameter Weibull distribution, a third parameter called γ the location parameter is included. Different methods are employed to evaluate the Weibull model parameters (the shape and scale parameters). These include methods such as the maximum likelihood method where the maximum likelihood technique is applied to the wind speed data recorded in the station. Alternatively c and k can be determined by having a good fit for the discrete cumulative frequency. Taking the natural logarithm of both sides of the equation twice gives

$$\ln[-\ln(1-F(v))] = k\ln v - k\ln c \qquad (1.12)$$

Plotting $\ln[-\ln(1-F(v))]$ against $\ln v$ presents a straight line whose gradient is k and y-intercept is $-k\ln c$ from which c can be calculated. Other methods of determining these parameters that are not discussed here although available in literature as in (Rohatgi and Nelson, 1994). Using values of the Weibull scale and shape parameters the wind power density of a given site can be estimated from the wind speed data.

1.1.4.1 The power density

The wind power density per unit area is analyzed based on a Weibull probability density function which can be derived as follows:

$$\text{Power density, } P = \frac{1}{2}\rho v^3 \qquad (1.13)$$

The energy potential per second varies in proportion to the cube (the third power) of the wind speed, and is proportional to the density of the air. (Its weight per unit of volume). Multiplying the power of each wind speed with the probability of each wind speed obtained from the Weibull curve, then the results gives the distribution of wind energy at different wind speeds (the power density).

It is therefore important to determine the expectation $E\left[v^3\right]$ from the Weibull probability density function. This can be derived from the moment generating function.

The moment generating function of the logarithm of a Weibull, distributed wind speed (random variable) is given by;

$$E\left[e^{t\log v}\right] = c^t \Gamma\left(\frac{t}{k} + 1\right) \qquad (1.14)$$

where Γ – the Gamma function.

In particular, the *n*th raw moment of v is given by:

$$M_n = c^n \Gamma\left(1 + \frac{n}{k}\right) \qquad (1.15)$$

The case of interest here is the third moment of v. The average (the expectation) of the cube of velocity ($E\left[v^3\right]$) is given by;

$$M_3 = \left[v^3\right] = c^3 \Gamma\left(1 + \frac{3}{k}\right) \qquad (1.16)$$

Substituting for the third power of velocity, the power density formula becomes;

$$P_w = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \qquad (1.17)$$

where ρ- density, Γ- gamma function k- shape parameter and c- Weibull scale parameter (m/s). The parameters k and c are closely related to the mean value of the wind speed v_m.

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad \text{..........} \quad (1.18)$$

Power output: The power output of a wind turbine varies with wind speed and every wind turbine has a characteristic power performance curve. With such a curve it is possible to predict the energy production of the turbine without considering the technical details of its various components (Manwell *et al.*, 2009). The power curve therefore gives the electrical power output as a function of the hub height wind speed. The performance of any given wind turbine generator can be related to three key points on the velocity scale, these include;

The Cut In Wind Speed: Usually, wind turbines are designed to start running at wind speeds somewhere around 3 to 5 m/s (Manwell *et al.*, 2009). This is called the cut in wind speed. It is the minimum wind speed at which the machine will deliver useful power.

The Cut Out Wind Speed: The wind turbine are usually programmed to stop at high wind speeds above, say 25 m/s, in order to avoid damaging the turbine or its surroundings. This is the maximum wind speed at which the turbine is allowed to deliver power (it is usually limited by engineering design and safety constraints)

Rated wind speed: This is the wind speed at which the rated power (generally the maximum power output of the electrical generator) is reached.

1.1.5 Wind direction

Wind direction is measured as the direction from where the wind blows from, from the north. It is measured in direction sectors where; 0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o and 360^o represent N, NE, E, SE, S, SW, W, NW and N directions respectively. Changes in wind directions are often due to turbulence of wind flow, therefore wind direction variation is also very critical in wind turbine design and siting.

The probability that wind will blow from a given direction interval is given by

$$P(D_j) = \frac{n_j}{N} \qquad (1.19)$$

where; D_j represents the median of the j^{th} interval. The information of wind direction frequency is of critical importance especially when identifying preferred shapes, orientations and optimizing the layout of wind turbine within a wind farm. The wind direction frequency distributions are usually calculated in direction sectors and the results displayed on a wind rose (a radar graph where direction in degrees is plotted on a circular axis). It is a graphic tools used by the meteorologists to give a succinct view of how wind speed and direction are typically distributed at a particular location. It consists of concentric circles which represent the various percentage frequencies of time when wind blows from a given direction

1.1.6 Wind pattern prediction

When assessing the feasibility of a potential wind farm, it is unlikely that any wind data from a relatively long term period will be available. If there is no on-site long-term data available, the measure correlate and predict methods are used to predict the long-term wind speed patterns at the site using reference data from other sites with similar terrain. A number of measure correlate and predict (MCP) methods are applicable in the prediction of the long-term wind resource using short-term measured data, these include ; The Simple linear regression, the variance Ratio method and the Mortimer Method.

The Simple linear regression is the common method for modeling the relationship between wind speeds at two sites and is usually given by the following prediction equation:

$$y = Mx + c \quad \text{(1.20)}$$

where x is wind speed at the reference site, y is predicted wind speed at the target site, and c and M are the estimated intercept and slope of the linear relationship (McLean *et. al.*, 2008).

$$S^2{}_1 = S^2 r^2 \quad \text{(1.21)}$$

where S_1 and S are the predicted and measured variance of wind speed respectively, r^2 is the coefficient of determination from the regression fit or, equivalently in the case of linear regression, the square of the correlation coefficient. This method however, due to the non-linear relationship between wind speed and wind power can result in significant underestimations of the wind resource, particularly for weakly correlated sites.

1.2 Literature Review

Use of probability density function (PDF) models to describe wind speed variations has attracted extensive research interests in recent years, and numerous publications exist in literature. Luna and Church (1974), attempted to use a universal distribution for wind speed, and discovered that lognormal distribution is the most appropriate one. However, it was realized with caution that a universal distribution may not be applicable to different sites due to the differences in climate and topography. This is supported by a recent study by Zhou *et al* (2009), in which the effectiveness of conventional and non-conventional statistical distributions was investigated and compared for characterizing the wind speed characteristics at multiple North Dakota sites. It was discovered that there does not exist a universal distribution function that outperforms the others for all sites. In general, two-parameter Weibull statistical distribution is by far the most widely adopted for representing the wind speed, and a number of publications can be found in literature (Justus 1978, Manwell 2009, Burton *et al.*, 2001). Meanwhile, other conventional probability distribution functions have been proposed for wind speed. They include Rayleigh distribution, which is a special case of Weibull distribution; lognormal distribution, in which the logarithm values of variate follows normal distribution; gamma distribution, which represents the sum of exponentially distributed random variables; as well as inverse Gaussian and generalized extreme value distributions Justus *et al*. (1978). In recent years, the concept of maximum entropy principle (MEP) has been also introduced into this field to derive appropriate PDFs for modeling the wind speed distribution (Li and Shi, 2009). In addition, they applied Bayesian model averaging (BMA) to model the wind speed distribution by combining a number of plausible conventional PDFs. Justus *et al*., (1978) examined the characteristics of the Weibull distribution in relation to the surface wind speed distribution. They found that the Weibull was a good model and adequately describes most wind speed distribution. In addition they also used the model to compute the power output from wind generation in the United States. Van der and Auwera *et al* (1980) successfully fitted the observed wind speed data for Belgium with four statistical distributions, with his results showing that Weibull distribution gives the best fit for wind speed data. They also observed that once the mean of the cube of the wind speed has been determined, it is easier to use Weibull distribution to determine the wind power.

Oludhe and Ogallo (1989) have carried out studies on wind energy in Kenya and employed the use of several statistical methods to estimate the diurnal and seasonal values of maximum, minimum and mean wind power expectation at various sites. As a result of their work, a map delineating all areas with wind power potential in Kenya has been provided. The investigations have also come up with the optimum rating speeds for wind generation for high and moderate wind potential regions. Kirui (2006) suggests that an approach to renewable energy resource assessment is the investigation of joint solar/wind energy availability. His results show solar and wind availability in central rift valley as well as a study of the relationship between aggregate energy availability and geographical dispersion for wind and solar than the hybrid systems.

The spatial and temporal characteristics of global solar radiation in Kenya has been examined by Marigi (1999) who studied the availability of solar energy resource in Kenya, the study used advanced statistical and empirical techniques. Marigi (1999) went further and did a specific study at Kessess division of Uasin Gishu district where measurements of the global solar radiation, surface winds, air temperature together and atmospheric temperature were carried out and results showed that the mean wind solar energy never exceeded 972 W/m^2. Oludhe (1987) did a space-time analysis of wind resource over the entire country to determine its utilizability. The study provided several classifications of wind speed values and the durations such speeds persist in a given month. The study also shows the country is endowed with adequate wind energy for application in several activities. The handicap the study notes is the intermittent nature of the wind resource. Conclusions made were that from Weibull estimations, the maximum wind power is located around Maralal and Marsabit regions as well as along the coastal strip of Kenya. He goes ahead to recommend that a lot of work needs to be done on the exact wind sites by determining the characteristics of the local factors which influence wind. This is affirmed by the most recent study done by Kamau *et al* (2010) who investigated the wind power parameters (Weibull, wind class, and the return period); the diurnal, monthly and inter-annual variability of the wind speed and direction using empirical methods as the power law and logarithmic law obtaining the shape and scale parameters at a height of 50 meters. Kamau *et al* (2010) consolidated their study in the following sites; Marsabit, Lamu, Garissa, Mombasa, Kisumu, Nyeri and Kericho. Results found out that regions like Marsabit, Lamu, Garissa, Kisumu and Mombasa had wind speeds greater than 3m/s at 50 m while Nyeri and Kericho registered the lowest wind speeds. In addition, the study found out that Marsabit had an available power density of 1800 W/m^2 that is in a wind class of 7. The study finally recommends that more research should be done on more stations and that the use of more than one anemometer is necessary so as to put consideration to the influence of surface roughness and power law constants.

1.3 Statement of the problem

Wind is a source of clean and alternative form of power production. Juja area 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 power outages 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. There is therefore need to carefully study the wind speed variation of this place so as to have a clear understanding of its energy potential, localized wind parameter characteristics necessary for matching the machine characteristics to the local wind regime. This research thesis intended 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.

1.4 Objectives

General objective

The main objective of this thesis is to assess the wind energy potential at JKUAT site in Juja and its localized characteristics.

Specific objectives

1. To measure the wind speeds and direction at different heights above the ground at the selected site.

2. To determine the surface roughness parameter and the power law exponent of the site

3. To calculate the Weibull ***k*** and ***c*** parameters and use them to estimate the localized wind power density of the site.

4. To determine the correlation between the measured wind speeds at JKUAT in Juja and some reference data.

1.5 Significance of the study

It is well known that the amount of the conventional energy sources is limited and they cause fundamental problems with the pollution of the environment during their usage. The renewable sources are therefore being exploited to provide an alternative clean and infinite energy. The effective utilization of wind energy resource in Juja entails having a detailed knowledge of the wind characteristics at this particular location. This research thesis will bring a clear understanding of the area's wind regime in terms of its speed variation, directional probability, terrain description and the expected power output. This understanding will form a basis of understanding the wind energy potential of Juja and requirements for the full exploitation of the wind resource of this area, in that the accurate wind characterization will greatly affect the decisions on site selection for wind farm construction as well as the wind conversion equipment selection for this place. Also, for future wind energy investors and policy makers, the description of the variation of wind speeds of this region will ensure effective optimization of the system designs, so that the energy generating costs can be reduced. Consequently, if wind investors and designers use the information in this research to implement wind energy projects for power generation in this area, there will be:

i. Maximum power production as a result of decisive and informed site-machine selection, matching and design.

ii. Improved power reliability as a result of reduced dependence on the national grid which is subject to the hydrological cycle.

iii. Clean energy future since wind energy has great advantages in that it produces electricity without greenhouse gas emissions such as carbon dioxide (CO_2) and oxides of nitrogen and sulphur.

iv. Energy sustainability since wind energy has no requirement of finite resources such as fossil fuels, or the transportation of fuel and combustion by-products.

CHAPTER TWO

2.1 Materials and methodology

The study was undertaken within Jomo Kenyatta University of Agriculture and Technology (JKUAT) located in a global map coordinates of latitude; 1° 10' South and longitude; 37° 7' East.

In this study, the following materials were used:

a) Two Davis Vantage PRO data loggers
b) Two wind sensors
c) Two transmitting devices
d) Connecting wires
e) Circular metal tubes of different diameters
f) Metal clamps
g) Bolts and Nuts
h) Windographer software

In order to achieve the stated research objectives, the research methodology of this study was carried out in two phases. The first phase involved data collection, which was done by designing, constructing, installing a mast tower and setting up the experimental measurement equipment for data collection and consequently recording the data daily for a period of four months, one month being for instrument testing. The second phase involved organizing the data and employing the use of appropriate softwares to analyze the data.

2.1.1 Mast design and construction

The mast was constructed by cutting circular hollow pipes of different diameters; each of which their ends made such that they could be fitted to each other by bolting. The design was as shown below;

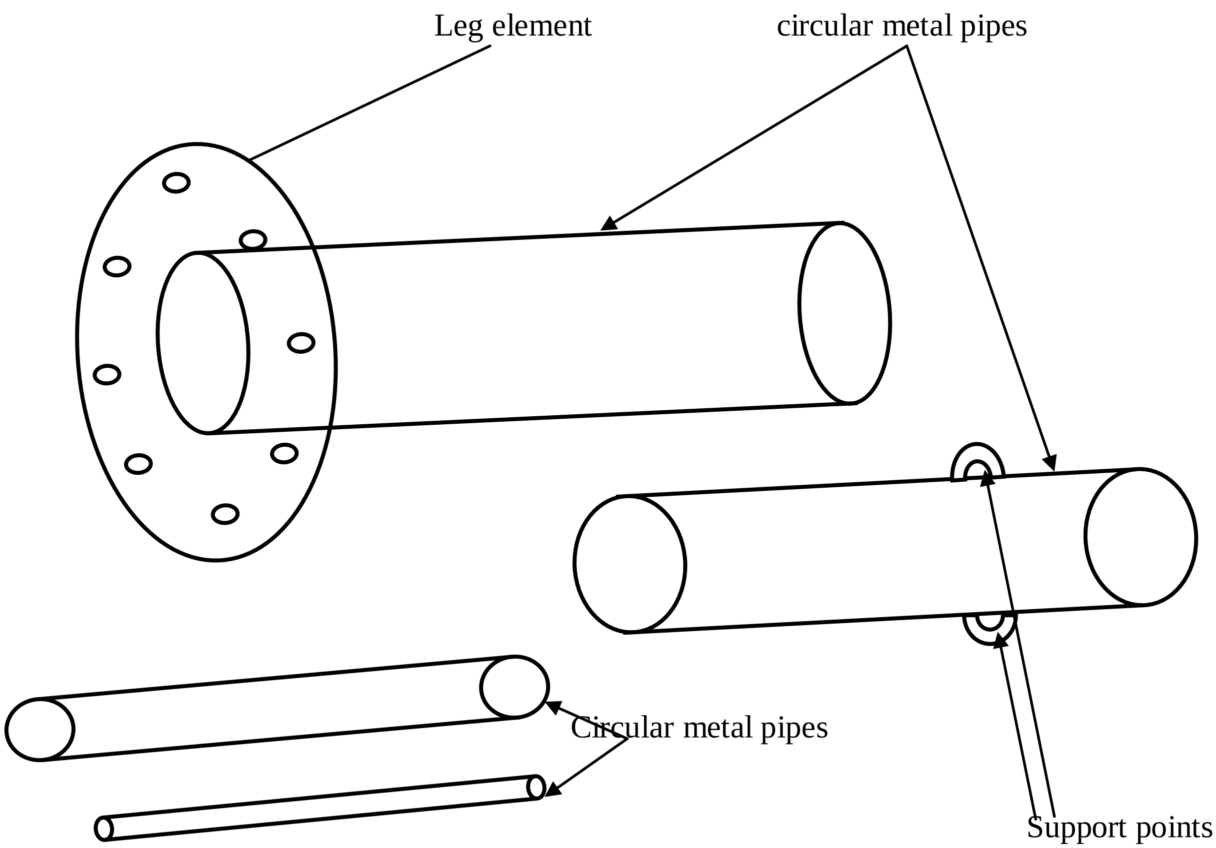

Figure 2.1: Circular tubes used for mast construction

The mast's parts were joined to each other and installed on top of a water tank by clamping its stem onto the safety bars and bolting the circular flanges on the leg element to the floor of the water tank's support base (see appendix, plate 5). In addition guy wires were attached from the middle of the tower to enhance stability by providing support during extreme turbulence and winds. This mast design was preferred to the three face mast because of the construction and installation costs; circular masts are cheap to construct and to install.

2.1.2 Measurement of wind speed and direction

After the mast was designed, constructed, joined and installed, the measuring instruments were set up as follows for data collection;

The two wind sensors (anemometer) were clamped on the mast at 20 m and 13m height above the ground; these sensors were connected using wires to the two transmitting devices, clamped on to the metal safety bars. The two Davis Vontage PRO data devices were programmed so that each one received data remotely only from station one (20 m) while the other from station two (13 m). The following precautions were taken during installation:

i. The anemometer cups and the tower top were separated well enough to avoid the flow disturbance caused by the mast.
ii. The use of many supports was minimized in order to avoid their influence to the wind flow.

iii. The location and orientations was such as to minimize flow disturbance on the anemometers when the wind is in the prevailing direction.

iv. Non corrosive connectors were used while the data loggers were kept inside the building to eliminate disturbances by precipitation and birds while at the same time providing additional protection from people and thieves.

The wind sensors were connected to the transmitting devices by connecting wires while the transmitters relayed data information remotely to the receiving antennas of the data recorders housed in a building. The experimental set up was as illustrated in the diagram in Plate 1; The data logger provided 10 minutes averaged wind speed data, which it further averaged for one hour and stored in the data logger for 24 hours. The wind data for the last 24 hours were retrieved everyday at 9.00 am daily. These retrieved readings were recorded for a period of 3 months. A part from wind speeds and directions other parameters measured were; temperature and air pressure (see appendix 1, 2 and 3).

2.1.3 Data analysis

a) The daily maximum, minimum and mean wind speed values from the site were calculated and recorded.

b) The monthly averages of wind speeds, atmospheric pressure and temperatures were also calculated and presented in the list of appendix.

c) The values of speeds were averaged for every hour for one month so as to find out the average variation of the speeds during a 24 hour cycle and results tabled as in table 4.

d) The daily average wind speeds during each of the three months were calculated and entered in tables 5, 6 and 7.

e) The measured wind speed data of two heights (13 m and 20 m) were averaged into the monthly wind speed averages then used with the power law formula to determine the wind shear exponents. This was done each for the months of September, October and November, thereafter the average wind shear exponent for the three months done and the results were as presented in Table 9.

f) Using the power law formula and the calculated wind shear exponent, an extrapolation of wind speeds at higher hub heights of 50m, 70m 100m, 120m and 150m was done and presented in table 11:

g) The logarithmic law 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. Values obtained are in table 14.

h) The data results were grouped with class width of 1 m/s, the grouped data was used to statistically model a Weibull distribution which was then used to estimate the wind power density of Juja.

i) The wind directions were analysed using the Windographer software to produce the wind rose diagrams as presented in figures 3.11 and 3.12.

j) The simple linear regression technique of the measure correlate and predict methods was employed to establish a correlation between the measured Juja wind data and the Eastleigh wind data as the reference station.

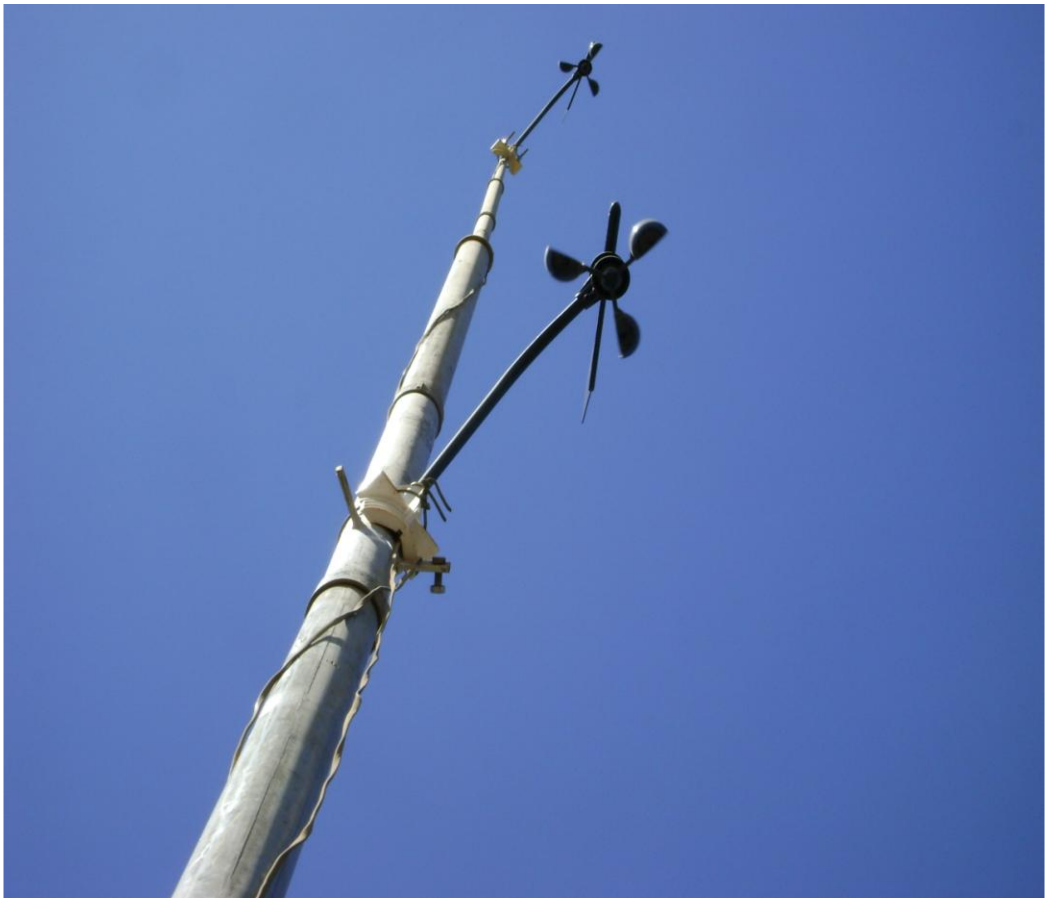

Plate 1: The set up of equipments at the Juja JKUAT site.

CHAPTER THREE

3.1 Results and discussion

3.1.1 Wind speed variation with time

3.1.1.1 Diurnal variations

The results of the wind speed changes occurring over a 24 hour periodic cycle (Diurnal variations) are presented in table 4.

Table 4: Hourly variation of average wind speeds

Time of the day (hrs)	0000	01:00	0200	0300	0400	0500	0600	0700
Av. Speeds (m/s)	**4.76**	**4.66**	**4.14**	**3.72**	**3.21**	**2.86**	**2.75**	**2.95**
Time of the day (hrs)	0800	0900	1000	1100	1200	1300	1400	1500
Av. Speeds (m/s)	**3.03**	**3.55**	**4.32**	**5.27**	**6.32**	**6.85**	**7.65**	**7.87**
Time of the day (hrs)	1600	1700	1800	1900	2000	2100	2200	2300
Av. Speeds (m/s)	**8.14**	**8.29**	**7.74**	**6.80**	**6.02**	**5.94**	**5.57**	**5.55**

A graphical presentation of this hourly average wind speed variation provided a diurnal wind speed distribution pattern as presented in figure 3.1;

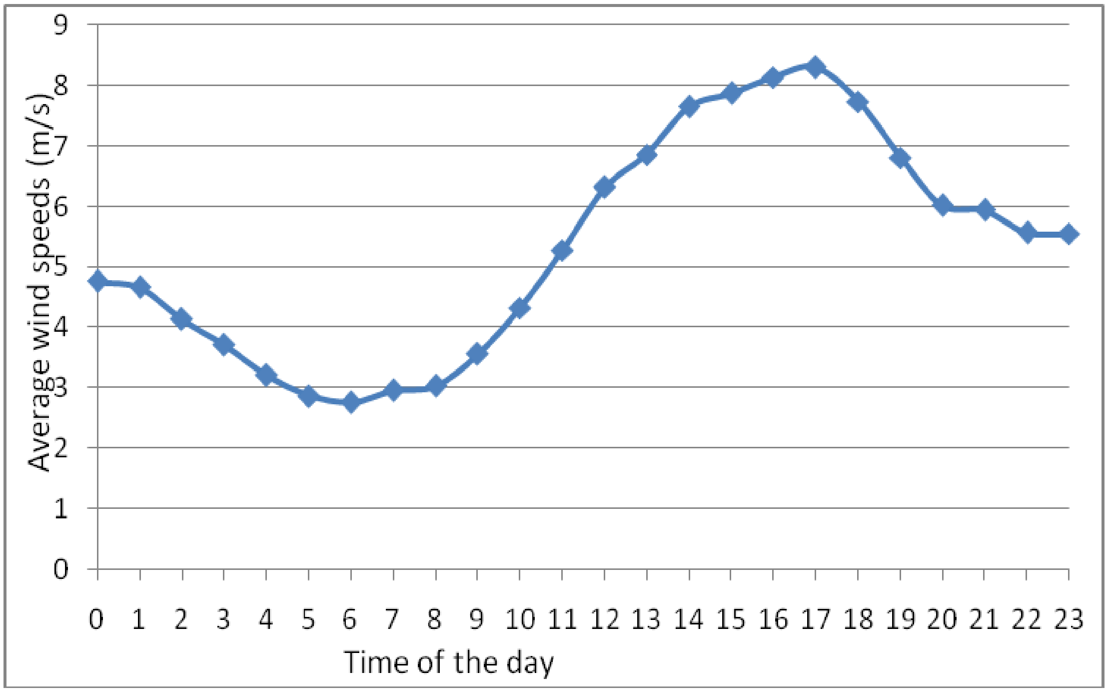

Figure 3.1: Hourly average wind speeds

In figure 3.1, the zero reference value on the horizontal axis represents the time 0000 hours (midnight). The graph demonstrates a smooth and predictable wind speed distribution pattern with high wind speeds prevailing from approximately 1600 hours to 1700 hours, slowing 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 (Manwell *et al.*, 2009)

3.1.1.2 Daily variations

The results for the daily wind speed averages are presented in tables 5, 6 and 7.

Table 5: Daily averages of wind speed, direction and temperature for September 2010

Date September 2010	Speed (m/s) (At 13 m height)	Speed (m/s) (At 20 m height)	Temperature ^{0}C	Direction Degrees
1	3.50	3.60	18	110
2	3.67	3.72	18	115
3	3.42	3.64	20	105
4	4.20	4.26	18	100
5	5.14	5.40	20	130
6	4.42	4.70	20	10
7	5.08	5.48	21	10
8	3.80	4.22	19	5
9	3.99	4.15	18	360
10	4.74	4.84	18	25
11	4.38	4.40	18	25
12	4.42	5.05	18	30
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
18	4.40	4.44	20	40
19	4.38	5.05	19	35
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
26	4.40	5.05	20	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**	
Maximum	**6.47**	**6.76**	**22**	
Minimum	**2.61**	**2.87**	**18**	

Table 6: Daily averages of wind speed, direction and temperature for October 2010

Date October 2010	Speed (m/s) (At 13 m height)	Speed (m/s) (At 20 m height)	Temperature ^0C	Direction Degrees
1	4.37	4.75	20	120
2	4.42	4.86	20	100
3	5.55	5.90	20	30
4	4.83	5.54	21	140
5	5.25	5.47	21	45
6	4.80	5.14	20	30
7	4.62	5.05	19	350
8	4.92	5.16	21	60
9	5.57	6.00	21	45
10	5.11	5.95	22	25
11	5.50	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
16	5.96	6.18	22	40
17	5.60	5.93	22	30
18	6.38	6.75	22	30
19	6.18	6.49	22	55
20	6.10	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
24	5.56	5.74	19	310
25	4.83	5.18	18	320
26	6.10	6.49	19	55

27	6.10	6.49	19	55
28	6.11	6.49	18	85
29	4.58	4.82	19	250
30	5.71	5.90	21	110
Monthly average	**5.58**	**5.96**	**20**	
Maximum	**7.67**	**7.88**	**23**	
Minimum	**4.37**	**4.75**	**18**	

Table 7: Daily averages of wind speed, direction and temperature for November 2010

Date November 2010	Speed (m/s) (At 13 m height) .	Speed (m/s) (At 20 m height)	Temperature ^{0}C	Direction Degrees
1	5.34	6.00	18	115
2	4.09	4.56	18	105
3	4.30	4.82	20	100
4	3.62	4.05	18	130
5	4.09	4.48	20	25
6	3.86	4.30	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	4.30	4.60	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	4.80	4.96	18	15
19	5.44	5.57	19	15
20	5.90	6.05	20	30
21	4.54	4.90	21	30
22	4.39	5.91	22	25
23	5.08	5.36	20	340

24	4.46	4.86	20	310
25	4.50	4.94	20	310
26	4.55	4.94	19	50
27	4.14	5.55	19	60
28	4.72	5.13	18	90
29	4.66	5.05	18	250
30	4.60	5.00	18	120
Monthly average	**4.53**	**4.93**	**19**	
Maximum	**5.90**	**6.05**	**22**	
Minimum	**3.62**	**4.05**	**18**	

The average wind speeds were also found to vary daily during the month, with the month of September, October and November exhibiting the flow represented in figures 3.2, 3.3 and 3.1.6 for both the wind speeds at 20 m and 13 m height. The wind direction is discussed in section 3.1.6 as will be seen.

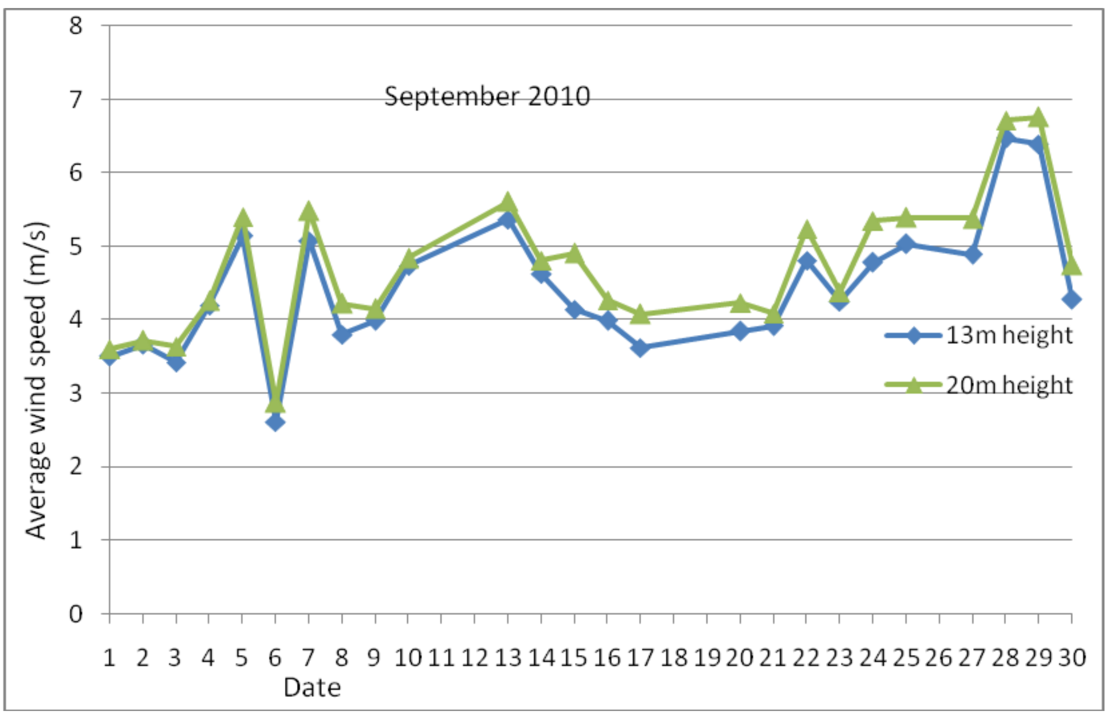

Figure 3.2: Daily average wind speeds during the month of September 2010

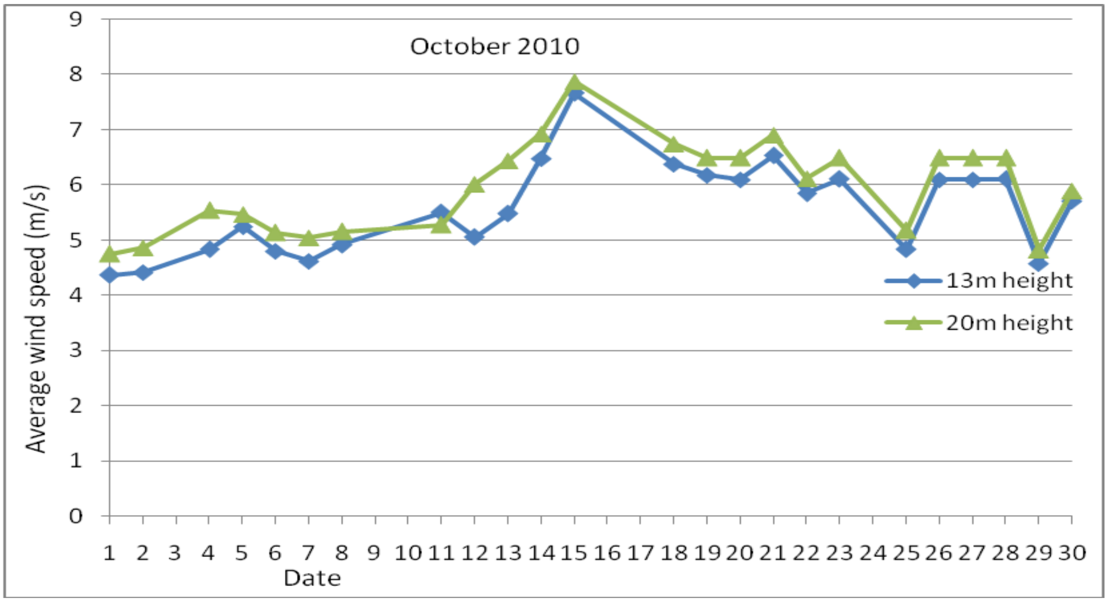

Figure 3.3: Daily average wind speeds during the month of October 2010

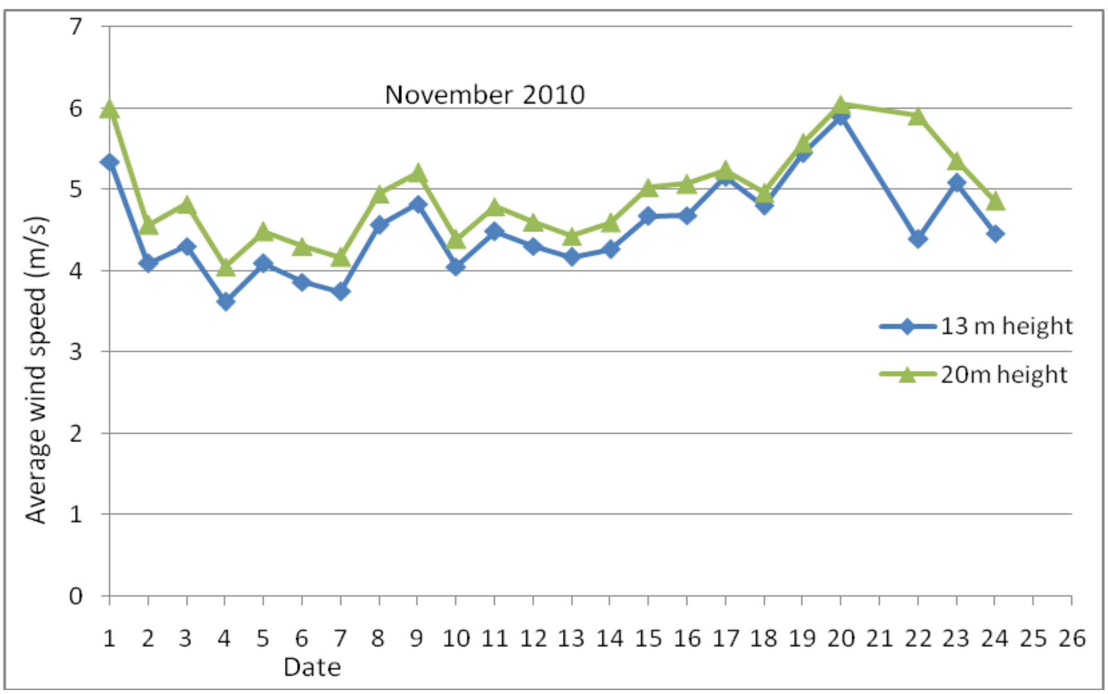

Figure 3.4: Daily average wind speeds during the month of November 2010

From figures 3.2, 3.3 and 3.4 above, it can be seen that as opposed to the diurnal variation (figure 3.1) where the wind speed maxima are expected to be definite and predictable in terms of the peaks and lows, the maxima and the minima for the daily variation apparently do not follow any pattern. This is due to the fact that there is no monthly solar radiation pattern that can render the wind speeds to exhibit a particular pattern; moreover many of the factors that affect wind speeds have a unique daily and not a monthly temporal pattern (Lysen, 1983).

3.1.1.3 Annual variations

The result of the monthly variation of wind speeds at the two heights is presented in table 8.

Table 8: Monthly averages of wind speeds, atmospheric pressure and temperatures

	September		October		November	
Height (m)	13 m	20 m	13 m	20 m	13 m	20 m
Av Speed (m/s)	4.42	4.72	5.58	5.96	4.53	4.93

The month of October gave the highest average wind speed compared to the other months. This variation does not necessarily give the September, October and November pattern throughout all years because the typical behavior of annual variation is not usually defined by a single year's data, hence it may vary year by year. The annual variations are highly influence and attributed to the seasons, in the eastern third of the United States for example, the maximum wind speeds occur during winter and early spring (Manwell *et al*., 2009). These annual variations occurrence are very significant in wind resource exploitation because they have a large effect on long-term wind turbine production.

3.1.2 Wind speed variation with height

The graphical representations of the daily wind speed variations for the months of September, October and November in figures 3.2, 3.3 and 3.4 shows that the average wind speeds for the 20 m height appears to be consistently greater than that of the 13 m height. This portrays the variation of the wind speed with height and therefore confirms that wind speed increases with the height above the ground, a phenomenon known as wind shear (Manwell *et al.*, 2009).

3.1.2.1 wind shear exponent

Table 9 gives the average shear exponents calculated from the average wind speeds while the mean deviations and the standard deviations of the calculated value is provided in table 10.

Table 9: Calculated average Wind shear exponents

	v_1 m/s (13 m)	v_2 m/s (20 m)	v_1/v_2	Shear Exponent 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
			Average α	**0.16**

Table 10: The average and standard deviations of calculated values from the theoretical value.

	Shear Exponent (α)	D = α-0.14	D^2
September	0.15	0.013	0.00018
October	0.15	0.013	0.00018
November	0.19	0.056	0.0031
	Mean deviation	**0.027**	**Variance 0.0011**

From the calculations the average wind shear exponent is 0.16, depicting a mean deviation of 0.027 and a standard deviation of 0.033 from the 0.14 value. Since the value is calculated from measured wind data, it therefore represents the exact wind shear exponent value for this locality. The shear exponent is dependent on such parameters as elevation, nature of terrain, wind speed, temperature and various thermal as well as mechanical mixing parameters. It is an important factor as it has a direct impact on the power available at different wind turbine hub heights and therefore it strongly influences the cyclic loading on the turbine blades. From table 2 and using this calculated value of wind shear exponent the terrain description corresponds to that of a level country with foot- high grass and occasional trees.

The calculated wind shear exponent provided good predictions for the wind speeds at higher hub heights of 50 m, 70 m 100 m, 120 m and 150 m. The results are presented in table 11:

Table 11: Expected wind speeds at various heights extrapolated from the power law

	13 m	**20 m**	**50 m**	**70 m**	**100 m**	**120 m**	**150 m**
SEPT	4.42	4.72	5.45	5.86	6.22	6.42	6.66
OCT	5.58	5.96	6.99	7.40	7.86	8.10	8.41
NOV	4.53	4.93	5.68	6.01	6.38	6.58	6.83

The extrapolated wind speed values when plotted against vertical elevation (height) provides a vertical wind profile graph as shown in figure 3.5.

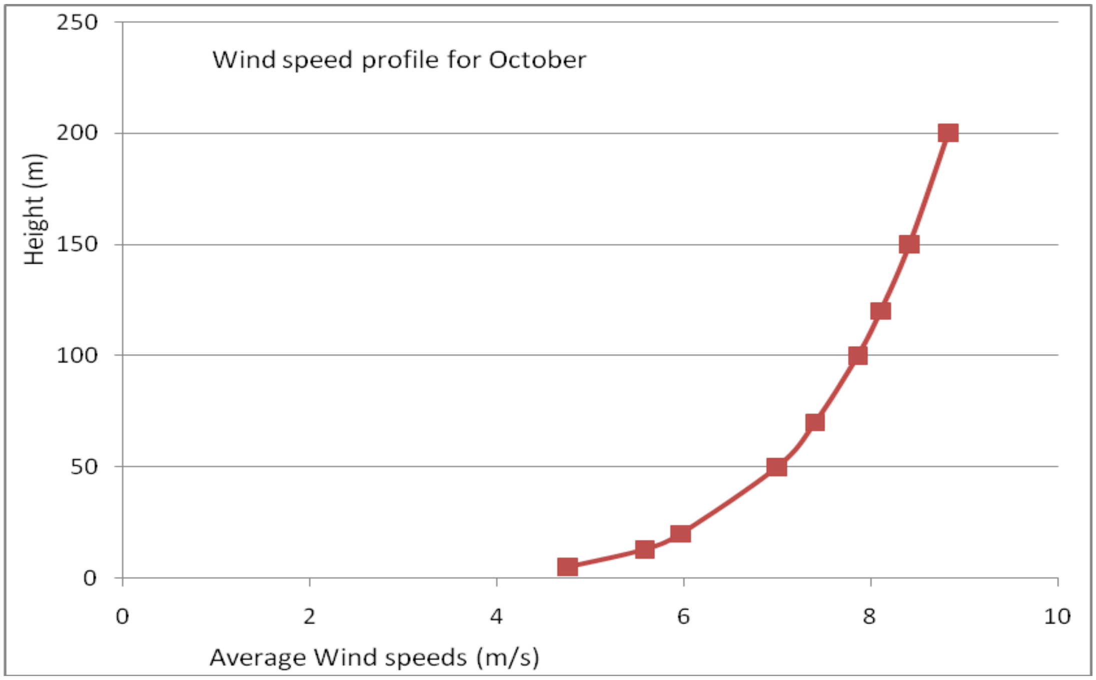

Figure 3.5: Wind speed profile for the month of October 2010

The months of September and November shown in figure 3.6 gives a curve of similar trend. These curves are consistent with a typical vertical wind speed profile curve (Bachrakis *et al.*, Manwell *et al.*, 2009).

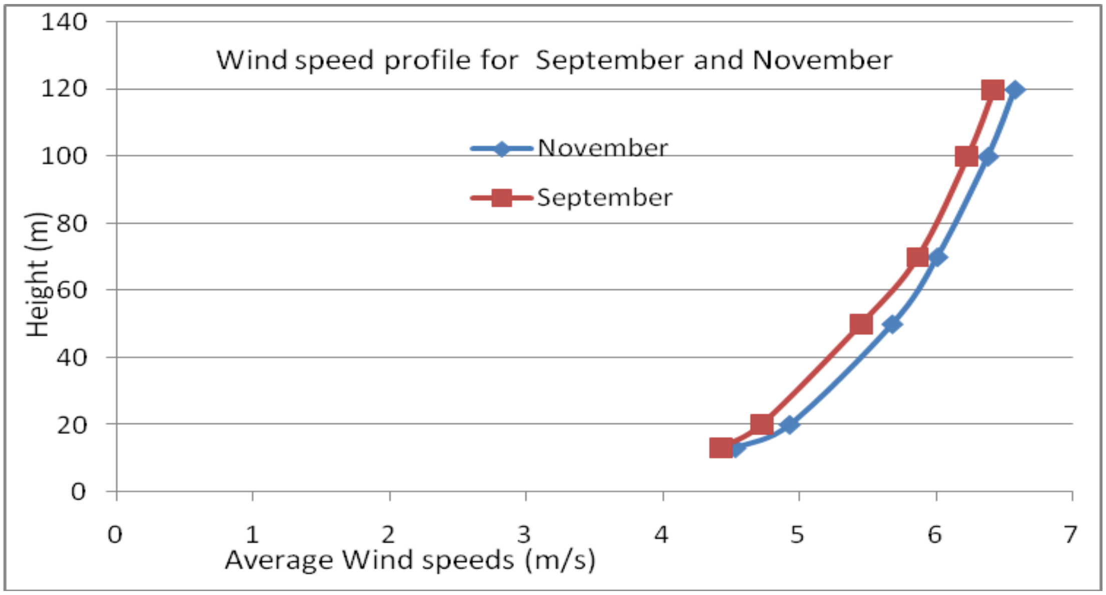

Figure 3.6: Wind speed profile for the months of September and November 2010

3.1.3 Vertical profile for available power in the wind

Wind power is dependent on the wind speed and air density, just like wind speeds air density also varies with height. Table 12 gives the results of the monthly average temperatures, atmospheric pressure and the calculated air density.

Table 12: Values of air densities at different temperatures and atmospheric pressures

	Av. Temp ^0C	**Av. Atm pressure (Pa)**		**Air density (kg/m^3)**	
		13 m	20 m	13 m	20 m
Sept	19.44	1009.54	847.04	1.20078	1.0075
Oct	20.42	1009.41	846.61	1.20063	1.0069
Nov	19.35	1009.31	846.84	1.20051	1.0072
			Average densities	**1.20064**	**1.0072**

The results show that air density decreases with height due to the vertical drop of air pressure in higher altitudes.

Table 13 shows the power available in the wind at different heights as calculated from the extrapolated wind speed values and using the average air density of 1.103 kg/m^3. These values depict the power available in the wind stream that rotates the rotor blades. The power values in table 13 however cannot be fully extracted since maximum extractable power by a system operating at its optimum efficiency is limited by the power coefficient called the Beltz limit whose value is 0.593 as demonstrated in figure 1.2, meaning the power coefficient makes the maximum extractable power approximately 59.3% of the theoretical power density (Stiebler, 2008).

Table 13: The variation of the power available in the wind with height

		13 m	20 m	50 m	70 m	100 m	120 m	150 m
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**

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 cost 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 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.

3.1.4 The roughness parameter length

The results of the calculated roughness parameter length for the site are presented in table 14.

Table 14: Calculated average Roughness parameter lengths, Z_o (m)

	V_1 m/s at 13 m	**V_2 m/s at 20 m**	**lnZ_o**	**Z_o (m)**
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
Average Z_o				**0.048 m**

In JKUAT-Juja therefore, 0.048 m represents the height above the ground level where the wind speed is theoretically zero. From table 3, the calculated Z_o value represents a terrain covered by crops. Comparing both tables 2 and 3 with 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 trees.

3.1.5 Describing the wind speed variations

Wind speed being variable in both time and space, describing the wind speed variation for the site is very necessary so as to aid the development of a model that describes the wind regime of this area at any point in time. Since from equations 1.9 and 1.10, both the scale and the shape parameters are functions of the mean wind speed and the standard deviation of the wind speed data, fitting the measured wind speed data require the calculation of the standard deviation, mean wind speed and the parameters.

3.1.5.1 Frequency distribution of wind speeds

The frequency distribution of the grouped data is presented in table 15 and the corresponding distribution curves are shown in figures 3.7 and 3.8.

Table 15: The distribution of wind speeds for statistical analysis

Class	V(m/s)	F	Fv	D	(D^2)	fD^2
0.0-0.9	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
		$\sum$f= 2012	$\sum$fv=10142.4			$\sum fD^2$=13504.36

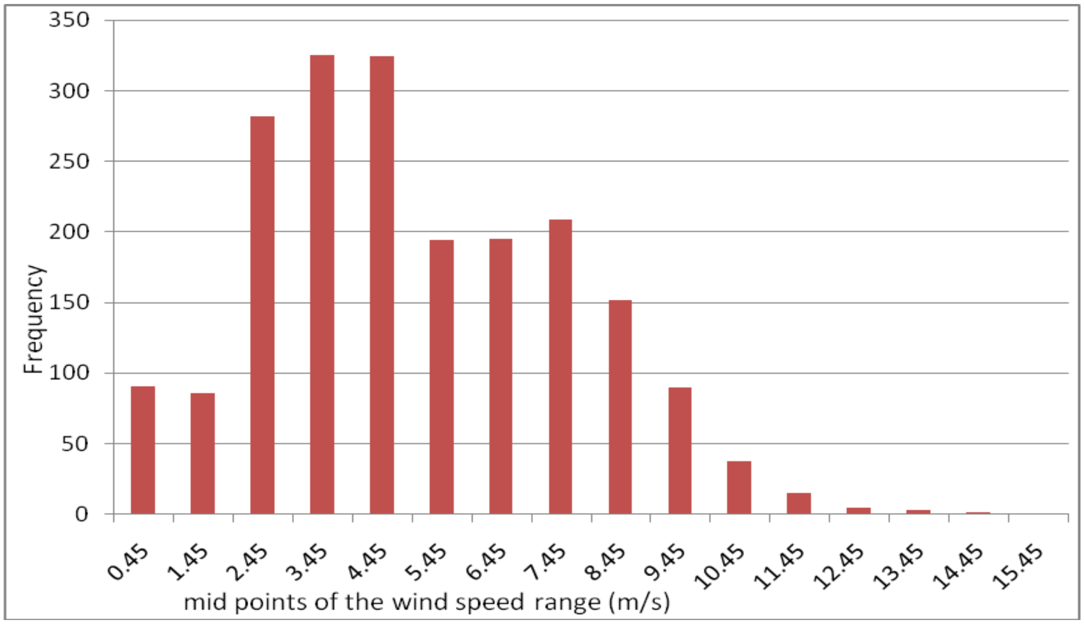

Figure 3.7: The distribution of wind speeds at the site

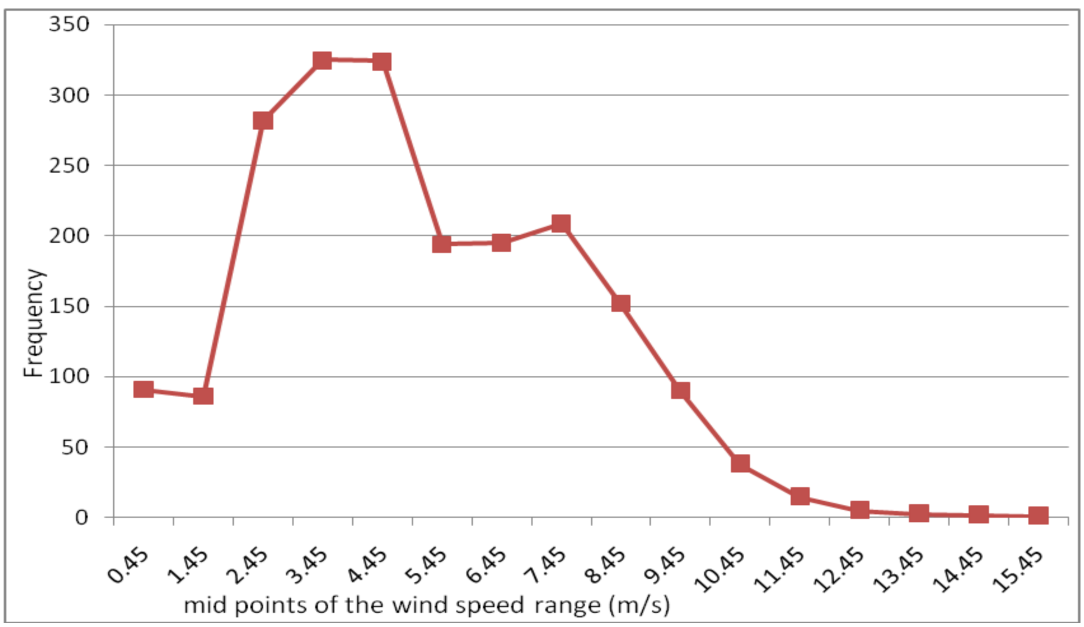

Figure 3.8: Frequency curve for the observed wind speeds

The frequency distribution graph of wind speed is unevenly distributed and shows that the highest number of recorded wind speed values lie within the wind speed range of 3.0-3.9 m/s while the lowest number of recorded wind speed values lie within the range of 15 m/s and above; with 15.7 m/s being the maximum wind speed recorded.

3.1.5.2 The mean wind speed

$$\bar{v} = \frac{\sum f_i v_i}{\sum f_i} = \frac{10142.4}{2012} = 5.04 \text{ m/s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

The standard deviation is given by:

$$\delta^2 = \frac{\sum f_i D_i^2}{\sum f_i} = \frac{13504.36}{2012} = 6.71$$ where D is the deviation from the mean wind speed.

Hence the standard deviation is

$$\delta = \sqrt{\delta^2} = \sqrt{6.71} = 2.59 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... \text{(3.2)}$$

Because of the flactuative/intemitent nature of wind speeds to assume and use the mean wind speed only to predict the wind energy potential generally gives very rough estimates. Consequently, for effective energy prediction the wind speed data is fitted in to Weibull distribution model (which is characterised by Weibull scale factor (*c*) and the shape parameter (*k*) for much better predictions.

3.1.5.3 The weibull (shape) *k*-parameter

This is the Shape parameter, a very important parameter in wind energy prediction. Its value normally lies within the range of 1.5 and 3.0. Using equation 1.9, the shape parameter was calculated as follows;

$$k = \left(\frac{\delta}{\bar{v}}\right)^{-1.086} = \left(\frac{2.59}{5.04}\right)^{-1.086} = 2.06 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.3)}$$

From the calculations, the value of the shape parameter was found to be 2.06. This parameter is very important in wind energy prediction since it tells how peaked the distribution is, meaning it determines the shape of the Weibull distribution and hence it determines the wind speed variation. The value obtained indicates a peaked distribution i.e, the wind speeds tend to be very close an indication of less speed variation. This is evident in the Weibull distribution curve in figure 3.9.

3.1.5.4 The weibull (scale) *c*-parameter

The simplified empirical formula in equation 1.11 gave the scale parameter as follows;

$$c = \bar{v}\left(0.568 + \frac{0.433}{k}\right)^{\frac{-1}{k}} = 5.04\left(0.568 + \frac{0.433}{2.06}\right)^{\frac{-1}{2.06}} = 5.69\,\text{m/s} \ldots\ldots\ldots\ldots \text{(3.4)}$$

The mean wind speed, the scale parameter, is used to indicate how windy the site is, on average. The values obtained shows the site as having very good winds. The calculated

Weibull shape and scale parameters give a Weibull probability curve as shown in figure 3.9.

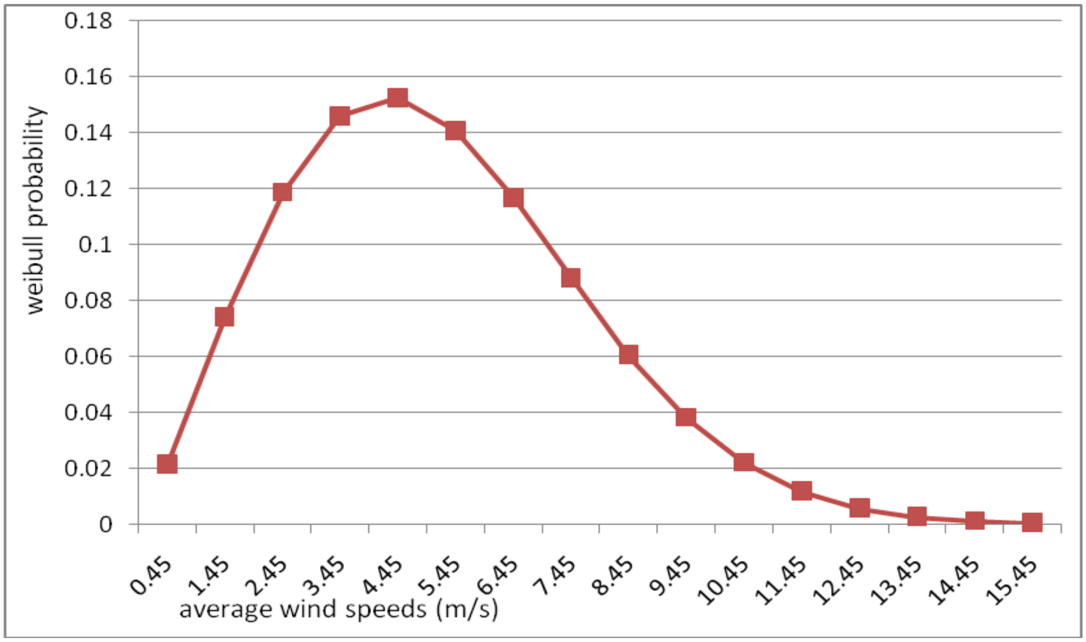

Figure 3.9: Weibull probability distribution of the wind speeds

Compared to the actual frequency distribution graph in figure 3.8, the Weibull probability curve in figure 3.9 gives a good fit for this experimental data and therefore provides the probability of obtaining a given wind speed at this site any given time.

The area under the Weibull curve in figure 3.9 is exactly one, since the probability that the wind will be blowing at some wind speed including zero must be 100 per cent.

As can be seen from the graph, the distribution of wind speeds is skewed, i.e. it is not symmetrical. Sometimes there are very high wind speeds, although the probability is low hence high speeds being rare. The curve peaks at wind speeds of 3.5 m/s meaning 3.5

m/s depicts the most probable speeds at this site. If each of the tiny wind speed interval is multiplied by the probability of getting that particular wind speed, and added up, the mean wind speed value is obtained.

The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface. The Weibull distribution may thus vary, both in its shape, and in its mean value (Manwell *et al.*, 2009).

Figure 3.10 gives the cumulative distribution function of the wind speeds. The curve represents the time fraction or probability that the wind speed is smaller than or equal to a given wind speed. From the figure 3.10, 30% of the wind speeds recorded will be below the wind speed 3 m/s. The curve is very significant especially when analyzing the percentage wind speed distribution for this site.

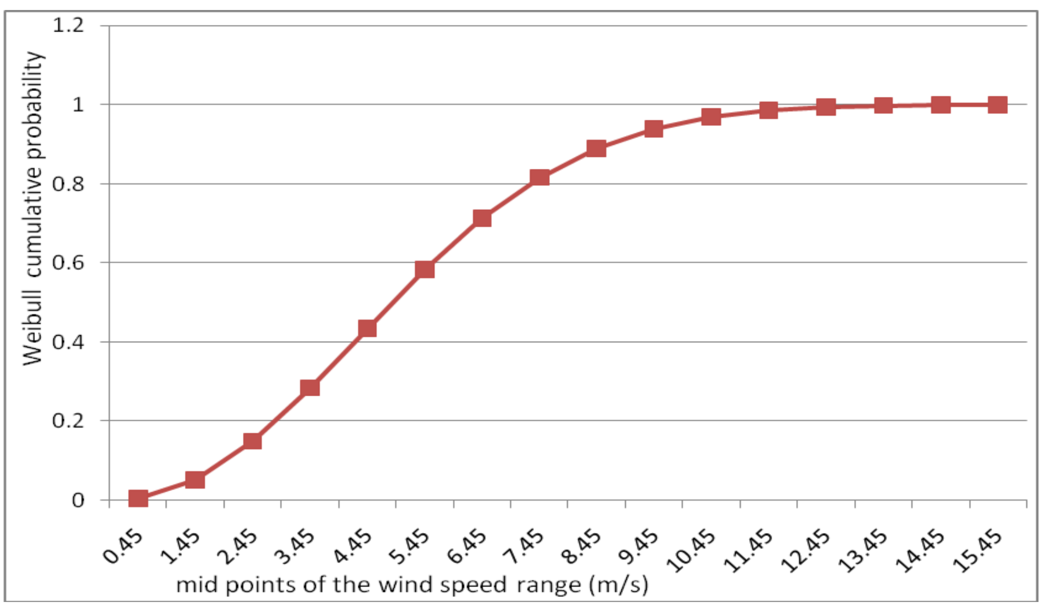

Figure 3.10: The Weibull cumulative frequency curve

3.1.5.5 Estimation of the mean wind power density

From the formula in equation 1.17, and using Weibull shape parameter (*k)* =2.06, Weibull scale parameter (*c*) = 5.69 m/s and air density of 1.1 kg/m^3, the power density was calculated as follows

$$P_w = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) = \frac{1}{2} \times 1.1 \times 5.69^3 \Gamma\left(1+\frac{3}{2.06}\right) \text{.................................(3.5)}$$

$$P_w = \left[0.55 \times 184.56 \times \Gamma(2.45)\right]$$
$$= 101.87\Gamma(2.45)$$

Power density = 131.35 W/m^2

A power density of 131.35 W/m ^{2} is obtained. It is noticeable that the power density is almost twice as much power as the wind would have if it were blowing constantly at the mean wind speed of 5.04 m/s. this is because the power density is obtained from the contribution of every speed with which the wind flows during the fluctuations, while the power available in the wind assumes that the wind constantly blows at a constant speed. It is not practical to use the mean speed to calculate wind power because sometimes the wind will be extremely high while other times it will be lower. For a height of between 10 m and 30 m at this research was done, the estimated wind power density lies in the wind power density class 2

Considering the effect of the Beltz limit whose value is 0.593, the maximum extractable power approximately 59.3% of the theoretical power density. For this site, the maximum extractable power by a system of unit area operating at its optimum efficiency is given by;

$$0.593 \times 131.35 = 77.89 \text{ W/m}^2$$

By considering a typical wind turbine design for Ngong, the Vestas V52-850 KW wind turbine with specifications presented in table 16 (www.thewindpower.net).

Table 16: Technical characteristics of Vestas V52 wind turbine

Cut in Wind speed (m/s)	3
Cut out wind speed (m/s)	25
Rated Power (kW)	850
Rotor diameter (m)	25
Rotor swept area (m^2)	2,123.72
Number of blades	3
Material	Glass fibre reinforced plastic, epoxy resin

If a wind turbine of the above specifications is installed in Juja and operates at optimum efficiency, then from the maximum extractable wind power density for Juja (77.89 W/m^2); the amount of power that can be produced is 165 kW. This value is about a fifth of one turbine capacity in Ngong station. JKUAT in Juja therefore has a potential for not only wind power utility for local community consumption but also has the capacity to feed considerable amount of power to the national grid if fully harnessed.

3.1.6 Wind direction analysis

The site's wind rose diagram for the heights of 13 m and 20 m are presented in figures 3.11 and 3.12 respectively.

Figure 3.11: Wind Rose diagram for the site at 13 m height

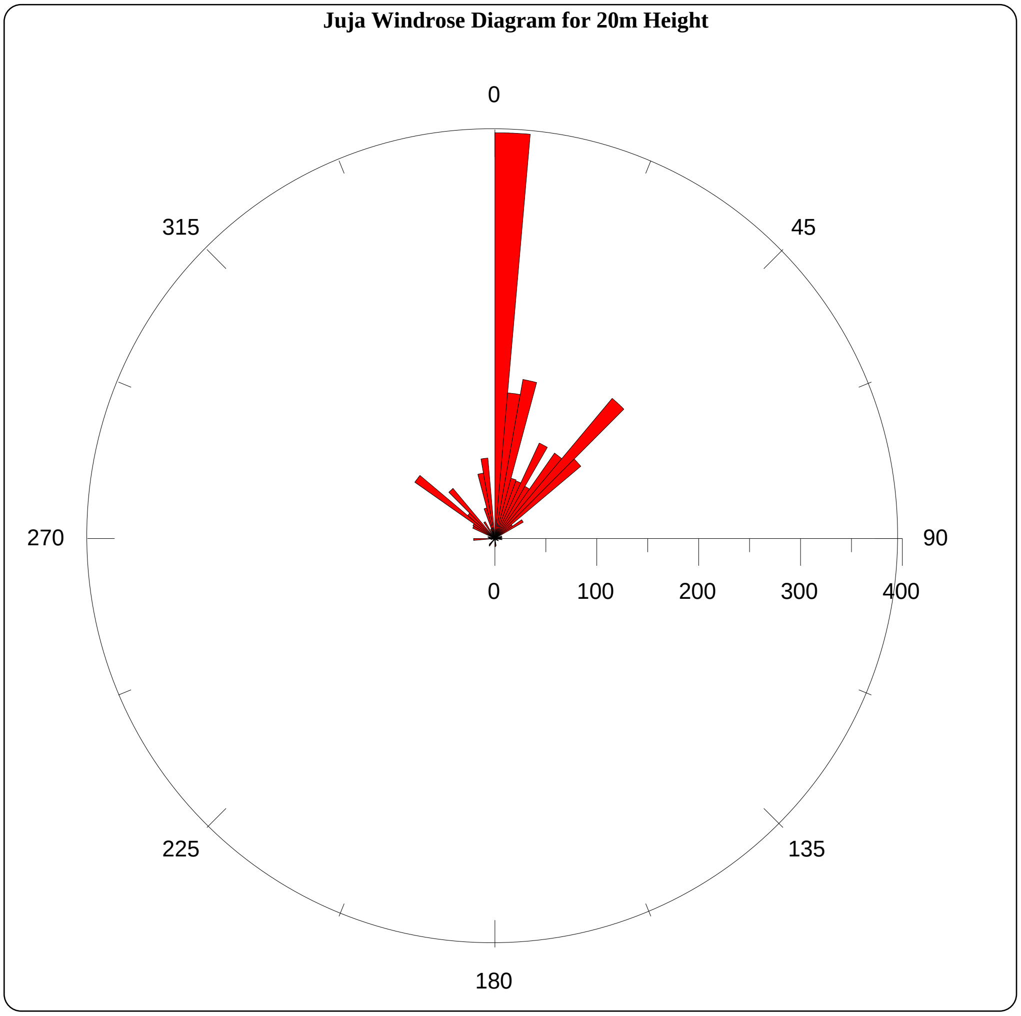

Figure 3.12: Wind Rose diagram for the site at 20 m height

The wind rose diagrams shows the frequency with which wind blows from the different directions; the innermost central origin of the circle represents the percentage few or no occurrence of wind speed at that direction. The various arms radiate from the innermost circle and the length of each arm represents the total percentage frequency of time the wind blows from the direction concerned.

From the diagrams, it is evident that a large frequency of wind at this site blows from the North , north east. On the other hand the frequency of wind is lowest from the south and south east directions; while the rest of the direction the frequency is generaly low too. There is a large calm condition in the wind system of the station such that the maximum bulge of wind blows from the north to north east diretion. The station is therefore in the monsoon wind system although there could have also been the influence of the buildings that were closer especially on the southern direction this could have influence the wind direction, moreover, the presence of the dam on the north north east direction could also have influence the regime of wind direction through the breezes.

Some of the four major potential markets for wind power in the Juja include; Individual domestic utilities, village/community utility through localized grid systems. Some specific aspects that need to be considered to enhance utilization of wind power include among others; right selection of wind electric generator (WEG) ratings that are based on cost effectiveness and standardization of equipment ratings to fit the wind regime.

3.1.7 Data correlation

The reference data was obtained from Eastleigh (1° 16° S, 36° 51' E) based on site measured hourly series data for the year 2001. Although the altitude of Eastleigh (1687 m) is slightly higher than that of Juja (1416 m) other geographical elements such as the temperatures, air pressure as well as the terrain descriptions remain the same. A correlation of data for wind speeds of these two sites (Juja and Eastleigh as the reference site) was done to establish how strong the correlation of the two sites are, so that measure correlate and predict methods (dicsussed in section 1.1.6) could be used in future to predict the long term of the wind pattern of either of the sites given enough measured data of the other site at any instance of time. The scatter diagram for the correlation between the JKUAT site in Juja and the reference site (Eastleigh) is presented in Figure 3.13.

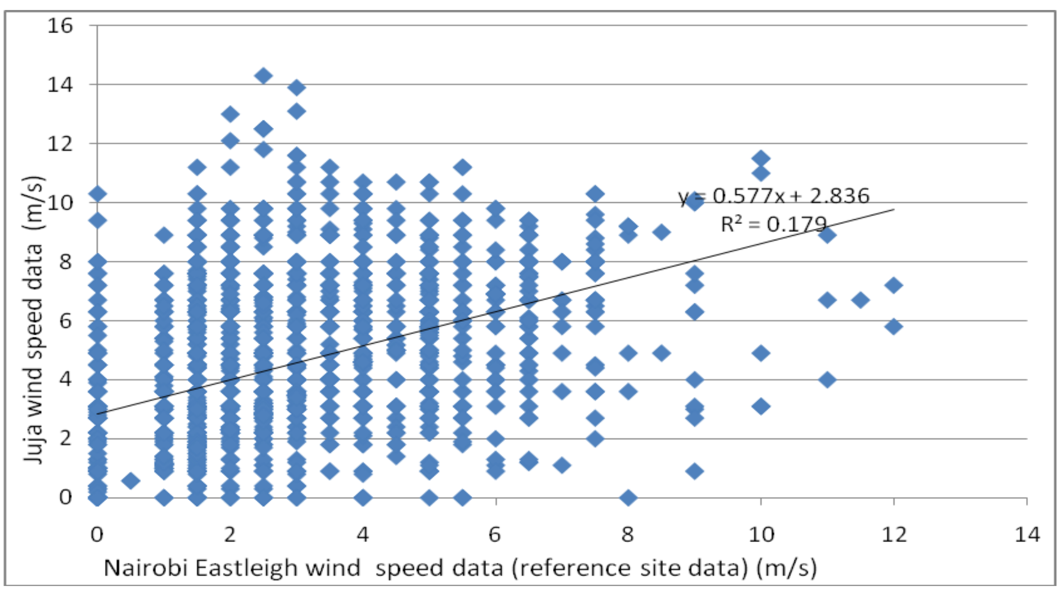

Figure 3.13: The scatter diagam of the wind speeds of the two sites

From the value of R^2 (0.179) there is low correlation of wind speeds between the two sites, although a general equation of best fit can be extracted from the scatter diagram as in equation 3.6. This equation however may not provide acurate prediction for Juja's long term wind speeds due to the low correlation between the two sites and therefore if used it can give highly underestimated results.

$$y = 0.57x + 2.84 \qquad (3.6)$$

Where: y – Juja wind speeds (Predicted speed)

wind speed, x – Eastleigh wind speed.

If the correlation between the two sites was high i.e R^2 being greater than 0.6 then such an equation can be used with at least one year site measured data to predict a general long-term pattern of the wind regime. Such a method however should not replace on-site measurements for more formal wind farm energy assessments since due to the non-linear relationship between wind speed and wind power, use of such equations can result in significant underestimations that can lead to wrong conclusions on the wind resource, particularly if the sites are weakly correlated.

CHAPTER FOUR

4.1 Conclusions

i. The wind shear exponent for JKUAT site was found to be 0.16 and extrapolation of wind speeds using this value gave mean speeds at a hub height of 50 m as 5.45 m/s, 6.99 m/s and 5.68 m/s for the months of September, October and November 2010 respectively. These speeds are particularly significant especially considering that this is the hub height for Ngong siteas discussed in section 3.1.5.5.

ii. The roughness parameter for JKUAT site was found to be 0.048 m this value gives the height above the ground where the viscousity is highest and the wind speed has been slowed down to 0 m/s. Based on the value and using the tables of roughness parameters for various terrains, the terrain for the site can be described as generally comprising of crops, hedges, a level country with foot-high grass and occasional trees and buildings

iii. The mean wind speed was found to be 5.04 m/s at 20 m hub height. The Weibull distribution parameters were found to be; scale parameter (c) = 5.69 m/s showing the site as being very windy. The shape parameter (k) = 2.06 showing that the wind speeds of the site are less variable and would give a peaked Weibull probability distribution. The wind power density for the site was found to be 131.35 W/m^2 which is a power class 2.

4.2 Recommendations

The following recommendations are made; that

i. More studies should be done at this site by taking wind speed measurements for a much longer period (i.e more than one year).

ii. Actual measurements should be taken at a higher hub height of 50 m and the use of three or more anemometers at different heights will give a better estimation of the shear exponent and the roughness length.

iii. Further research should emphasize on wind turbine design/selection that fits the wind regime of the site, this should focus on micro power generation for localized grid connections and individual backup systems.

iv. Other measure correlate techniques should be employed for much accurate long term wind pattern predictions

v. The wind pattern should be studied with other forms of energy sources so as to ascertain the feasibility of designing hybrid systems. In addition studies in other sites should be done to create a site integration model that can enhance wind power reliability by reducing the wind resource intermittency.

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APPENDICES

Appendix 1: Daily averages of wind speed, air pressure, direction and temperature for September 2010

Date during Sept 2010	Height (13 m)		Height (20 m)		Temperature (^oC)	Direction degrees
	Speed (m/s)	Air pressure (mb)	Speed (m/s)	Air pressure (mb)		
1	3.50	1007.20	3.60	848.60	18	110
2	3.67	1007.00	3.72	848.10	18	115
3	3.42	1006.90	3.64	847.20	20	105
4	4.20	1007.10	4.26	846.00	18	100
5	5.14	1007.70	5.40	845.00	20	130
6	4.42	1007.70	4.70	845.00	20	10
7	5.08	1007.80	5.48	844.10	21	10
8	3.80	1008.30	4.22	844.60	19	5
9	3.99	1008.60	4.15	844.90	18	360
10	4.74	1008.50	4.84	845.60	18	25
11	4.43	1008.70	4.40	845.60	18	25
12	4.42	1008.80	5.05	846.40	18	30
13	5.37	1008.90	5.61	846.30	18	40
14	4.63	1009.10	4.81	847.10	19	40
15	4.14	1009.30	4.91	847.90	20	40
16	3.99	1009.60	4.27	848.30	20	40
17	3.62	1009.80	4.08	848.10	20	40
18	4.40	1009.50	4.44	848.00	20	40
19	4.38	1010.50	5.05	848.10	19	35
20	3.85	1010.60	4.23	847.60	20	35
21	3.92	1010.80	4.09	847.10	19	35
22	4.81	1011.10	5.24	846.90	18	15
23	4.25	1011.30	4.38	846.70	19	15
24	4.78	1011.70	5.35	847.20	20	15
25	5.03	1011.60	5.39	847.90	22	30
26	4.40	1011.50	5.05	848.50	20	30
27	4.89	1011.70	5.38	848.60	20	25
28	6.47	1011.80	6.72	849.20	20	340

29	6.39	1012.10	6.76	849.40	21	310
30	4.28	1012.20	4.75	849.40	20	315
Monthly average	**4.42**	**1009.54**	**4.72**	**847.04**	**19**	
Monthly maximum	**6.47**	**1012.20**	**6.76**	**849.40**	**22**	
Monthly minimum	**2.61**	**1006.90**	**2.87**	**844.10**	**18**	

Appendix 2: Daily averages of wind speed, air pressure, direction and temperature for October 2010

Date during Oct 2010	**Height (13 m)**		**Height (20 m)**		**Temperature (^oC)**	**Direction degrees**
	Speed (m/s)	Air pressure (mb)	Speed (m/s)	Air pressure (mb)		
1	4.37	1006.30	4.75	848.50	20	120
2	4.42	1006.10	4.86	847.70	20	100
3	5.55	1006.10	5.90	846.50	20	120
4	4.83	1006.10	5.54	846.70	21	140
5	5.25	1006.10	5.47	845.40	21	45
6	4.80	1006.60	5.14	844.40	20	30
7	4.62	1006.50	5.05	844.00	19	350
8	4.92	1006.50	5.16	844.00	21	60
9	5.57	1006.50	6.00	844.00	21	45
10	5.11	1006.40	5.95	844.10	22	25
11	5.50	1006.40	5.28	844.20	22	10
12	5.06	1006.90	6.02	844.70	23	5
13	5.48	1007.20	6.44	845.20	22	350
14	6.48	1007.30	6.93	846.20	23	345
15	7.67	1007.00	7.88	847.10	22	45
16	5.96	1007.10	6.18	847.20	22	40
17	5.60	1007.20	5.93	847.50	22	30
18	6.38	1007.30	6.75	847.80	22	30
19	6.18	1007.30	6.49	848.20	22	55
20	6.10	1007.80	6.49	848.20	21	35

21	6.53	1007.60	6.91	847.70	19	60
22	5.85	1008.70	6.12	847.10	18	40
23	6.11	1008.90	6.49	846.80	20	15
24	5.56	1008.90	5.74	846.80	19	310
25	4.83	1008.80	5.18	846.80	18	320
26	6.10	1008.40	6.49	846.80	19	55
27	6.10	1008.50	6.49	847.20	19	55
28	6.11	1008.30	6.49	847.60	18	85
29	4.58	1008.50	4.82	848.10	19	250
30	5.71	1008.70	5.90	848.30	21	110
Monthly average	**5.58**	**1007.41**	**5.96**	**846.61**	**20**	
Monthly maximum	**7.67**	**1008.90**	**7.88**	**848.50**	**23**	
Monthly minimum	**4.37**	**1006.10**	**4.75**	**844.00**	**18**	

Appendix 3: Daily averages of wind speed, air pressure, direction and temperature for November 2010

Date during Nov 2010	**Height (13 m)**		**Height (20 m)**		**Temperature (^{o}C)**	**Direction degrees**
	Speed (m/s)	Air pressure (mb)	Speed (m/s)	Air pressure (mb)		
1	5.34	1007.20	6.00	848.60	18	115
2	4.09	1007.00	4.56	848.10	18	105
3	4.30	1006.90	4.82	847.20	20	100
4	3.62	1007.10	4.05	846.00	18	130
5	4.09	1007.70	4.48	845.00	20	25
6	3.86	1007.90	4.30	844.40	20	10
7	3.74	1007.80	4.17	844.10	21	5
8	4.56	1008.30	4.95	844.60	19	360
9	4.82	1008.60	5.21	844.90	18	25
10	4.05	1008.50	4.39	845.60	18	40
11	4.48	1008.70	4.79	846.30	18	40
12	4.30	1009.10	4.60	847.10	19	40

13	4.17	1009.30	4.43	847.90	20	40
14	4.26	1009.60	4.59	848.30	20	40
15	4.67	1009.80	5.03	848.10	20	35
16	4.68	1010.60	5.07	847.60	20	35
17	5.15	1010.80	5.24	847.10	19	15
18	4.80	1011.10	4.96	846.90	18	15
19	5.44	1011.30	5.57	846.70	19	15
20	5.90	1011.70	6.05	847.20	20	30
21	4.54	1011.70	4.94	847.50	21	30
22	4.39	1011.60	5.91	847.90	22	25
23	5.08	1011.70	5.36	848.10	20	340
24	4.46	1011.80	4.86	848.20	20	310
25	4.50	1011.80	4.94	848.30	20	305
26	4.55	1011.90	4.94	848.50	19	310
27	4.14	1011.90	5.55	848.70	19	50
28	4.72	1011.80	5.13	848.70	18	60
29	4.66	1011.70	5.05	848.80	18	90
30	4.60	1011.80	5.10	949.20	18	250
Monthly average	**4.53**	**1009.31**	**4.93**	**846.84**	**19**	
Monthly maximum	**5.90**	**1011.90**	**6.05**	**849.20**	**22**	
Monthly minimum	**3.62**	**1006.90**	**4.05**	**844.10**	**18**	

Appendix 4: Photographs of the experimental set up

Plate 2: Tuning the transmitting device

Plate 3: The wind sensors clamped on a mast

Plate 4: The Vontage PRO data receiver and recorder

Plate 5: Mast clamped on to the supports

Plate 6: Collecting data

Plate 7: Clamping the transmitting device

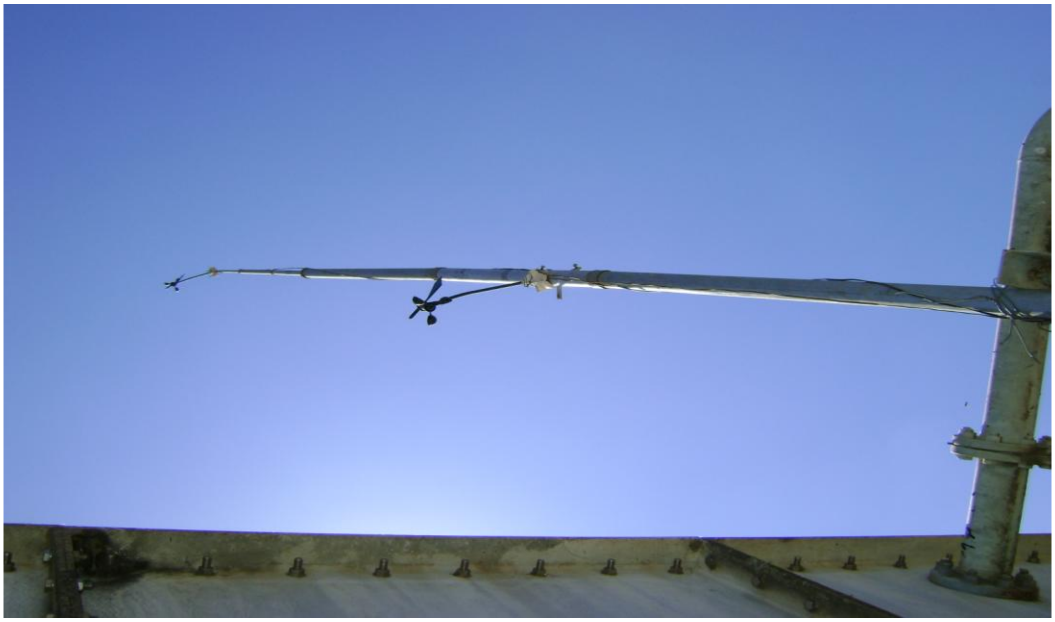

Plate 8: Cord connecting the sensors to the transmitting device

Plate 9: View of the experimental set up