ANALYSIS OF WIND POWER POTENTIAL FOR WIND PATTERNS IN JUJA AND NAIVASHA BASED ON WEIBULL AND RAYLEIGH MODELS

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(Physics)

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2016

Analysis of wind power potential for wind patterns in Juja and Naivasha based on Weibull and Rayleigh models

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A thesis submitted in fulfilment of the requirements for the degree of Master of Science in Physics in the Jomo Kenyatta University of Agriculture and Technology

2016

DECLARATION

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

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DEDICATION

I dedicate this thesis to the Almighty God for His grace and provision; my dear husband, Samuel M. Mwangi and children, Jude Mwangi and James Ndirangu and my lovely mothers, Hannah Wanjiru and Elishibah Wairimu for their prayers, support and encouragement throughout my study period.

ACKNOWLEDGEMENTS

I express my sincere gratitude to Almighty God, my research supervisors Dr. Kamau J.N. and Dr. Timonah N.S. for their availability and tirelessly guiding me through the research and thesis writing process. Their experimental expertise, discussions, critique and remarks modelled and shaped this work. I am also grateful to the BRIGHT PROJECT for their support and provision of analysis tools in Naivasha site. Great thanks go to Dr. Githiri J. G., Chairperson Physics Department, and Dr. Waweru S. M., postgraduate advisor, for their encouragement, advice and counselling during the course of this work. I sincerely thank JKUAT physics department staff including all the laboratory technicians for their technical support and encouragement. I also thank Professor Nyende who availed JKUAT meteorological data for comparison and JKUAT estate department for allowing me to use some of their facilities. My regards also go to Mr. Ngei Katumo for his guidance in the use of software.

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LIST OF SYMBOLS

A	Area of the turbine blades
E_R	Error due to Rayleigh distribution
E_W	Error due to Weibull distribution
c	Scale parameter for the Weibull distribution.
k	Shape parameter for the Weibull distribution.
v	Wind speed
ρ	Air density
P_R	Wind power density based on Rayleigh probability density function
P_V	Power density at wind speed
P_W	Wind power density based on Weibull probability density function
v_m	Mean value of wind speeds
$f_R(v)$	Weibull probability distribution function.

LIST OF ABBREVIATIONS

FDF	Frequency Distribution Functions
JICA	Japan International Corporation Agency
JKUAT	Jomo Kenyatta University of Agriculture and Technology
Km	Kilometre
KSH	Kenya shilling
MLH	Maximum Likelihood
m	Metres
m/s	Metres per second
MW	Megawatt
PDF	Probability density function

ABSTRACT

The rapidly increasing population and industrialization has led to increased energy demand. Juja, which is about 1416 m above sea level; 1^0 10’ S, 37^0 7’ E and about 35 km from Nairobi, having a rapidly growing population and a major University requires an alternative energy source due to frequent power failure and high power demand. Use of generator backup is an additional cost and also pollutes the environment. Therefore, an accurate analysis on wind speed characteristics which is necessary in determining wind energy potential is critical**.** This study analyzed the wind speed characteristics for purposes of determining wind energy potential in Juja at heights of 10 m and 30 m for a period of three months. The wind data was recorded in hourly intervals and mean diurnal and monthly variations were calculated. Weibull scale and shape parameters were obtained using Weibull-fit, Regression and Maximum Likelihood methods. The wind speed distribution was modelled using the Weibull and Rayleigh probability distribution functions. Power densities for different methods were calculated. Windographer software © and Microsoft Excel were used to determine and generate the Probability Density functions (PDFs) and to analyze wind direction. Results obtained from Juja site were compared with results acquired from Naivasha, St. Xavier site which is at an altitude of 2,086 m; 0° 43' 0'' S, 36° 26' 0'' E. . The wind speed averages for the duration of three months for the 10 m and 30 m heights were 2.54 m/s and 3.04 m/s respectively. The wind shear exponent and roughness parameter were 0.1652 and 0.0374 respectively. The mean wind power densities for Juja (10 m and 30 m) and Naivasha (10 m) were 12.68 W/m², 20.65 W/m² and 39.95 W/m² by Weibull model and 14.51 W/m², 22.43 W/m² and 28.63 W/m² by Rayleigh model respectively. The methods that fitted best Juja and Naivasha sites were Weibull-fit and Maximum Likelihood respectively. The results are expected to be useful in guiding designers on selection of appropriate type of wind turbines for optimum power generation.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Growing global population along with fast depleting reserves of fossil fuels is influencing researchers to search for clean and pollution free sources of energy which are sustainable and cost-effective. These types of energy include; solar, wind, waves, tidal and bio-energies. Wind energy is a never ending natural resource which has shown its great potential in combating climatic change while ensuring clean and efficient energy, yet it is the most under exploited energy. Wind turbine technology has led to significant growth of wind power generation across the world. However, wind energy is more sensitive to variations with topography and wind patterns compared to solar energy. It can be harvested economically if the turbines are installed in a windy area and suitable turbine is properly selected. Wind speed forecasting is a critical factor in assessing wind energy potential and performance of wind energy conversion systems. Wind fluctuation demands a necessary model describing its variation thereby estimating the amount of energy as well as to optimize the design of the wind turbine (Kamau, Kinyua, & Gathua, 2010). The most suitable wind turbine model which needs to be installed in a wind farm is selected by careful wind energy resource evaluation. It is therefore important to choose an accurate distribution model which closely mimics the wind speed distribution at a particular site (Kollu, Rao, Rayapudi, Narasimham, & Pakkurth, 2012). The development and utilization of wind energy in developing countries, particularly Africa, has been hindered by absence of adequate measurements and assessment studies to ascertain its potential viability for power generation (Ajayi, Fagbenle, & Katende, 2011).

Juja, which is 1416 m above sea level (1^0 10' S, 37^0 7' E) and about 35 km from Nairobi, having a rapidly growing population and a major University, Jomo Kenyatta University of Agriculture and Technology (JKUAT) and Naivasha, 2,086m (0° 43' 0" S, 36° 26' 0" E), with agricultural farms require an alternative energy source to supplement existing convectional energy. Use of power generators during power outage leads to air pollution and hence the need for clean, reliable, sustainable and cost effective sources. Wind energy is not fully exploited since the main wind farm is Ngong wind farm of 25.5 MW from the two phases; though there are underway processes of establishing other wind plants in Kenya such as a 300 MW wind farm in Turkana (Mbogo, 2015).

Thorough wind speed analysis in any area is therefore critical. A study based on different methods brings out a better picture of the state of wind in a site. Several methods and Probability Density Functions (PDFs) have been used in literature to describe wind speed characteristics. The methods include Weibull-fit, Regression, Standard deviation, Maximum likelihood, Chi-square among others while PDFs include Weibull, Rayleigh, bimodal Weibull, lognormal, gamma among others (Kollu *et al.*, 2012; Manwell *et al*., 2009 ; Celik, 2003).

This study analyzes wind speed using different methods modeled using Weibull and Rayleigh models for Juja and correlates them with results from Naivasha, St. Xavier site within a period of three months.

1.2 The Study Background

Wind speed forecasting is a critical factor in assessing wind energy potential and performance of wind energy conversion systems. The previous study of wind characteristics in Juja was based on different methods which included straight forward and maximum likelihood, of which none was tested and proven to suit Juja area (Wekesa, 2012; Saoke, 2011).

A study on wind characteristics in Jyvaskyla and Viitasaari sites, Finland, proved that a method that best suits analysis of wind speed data may vary with position or altitude (Paitoon, 2010).

The following are diagrams of results obtained from Paitoon’s findings. Figures 1.1 and 1.2 were probability density graphs obtained from Viitasaari and Jyvaskyla sites respectively. It was noted that Chi-square fitted Viitasaari site best while Weibull-fit and Chi-square fit best Jyvaskyla site.

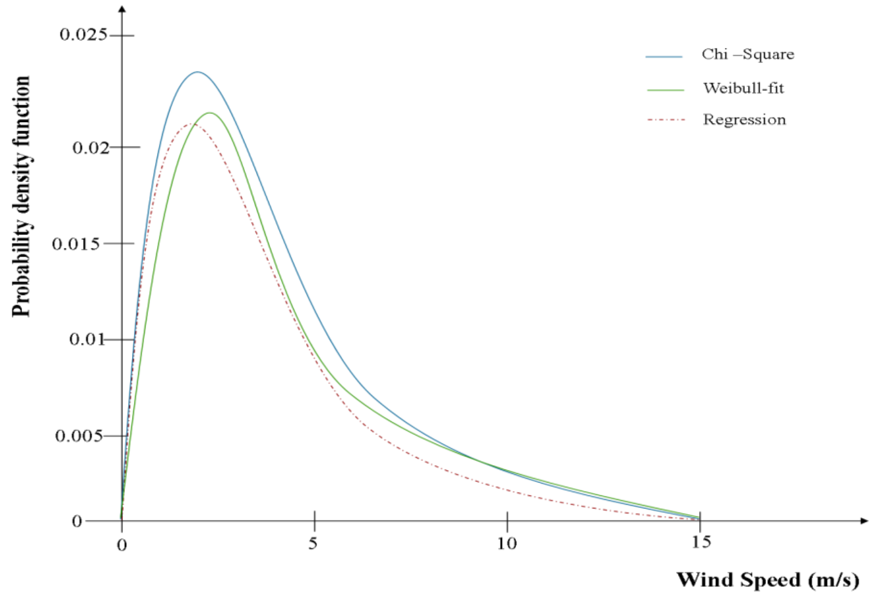

Figure 1.1: Weibull PDF's determined using Weibull-fit, Regression, and Chi-square methods and wind speed data at the Viitasaari site (Paitoon, 2010).

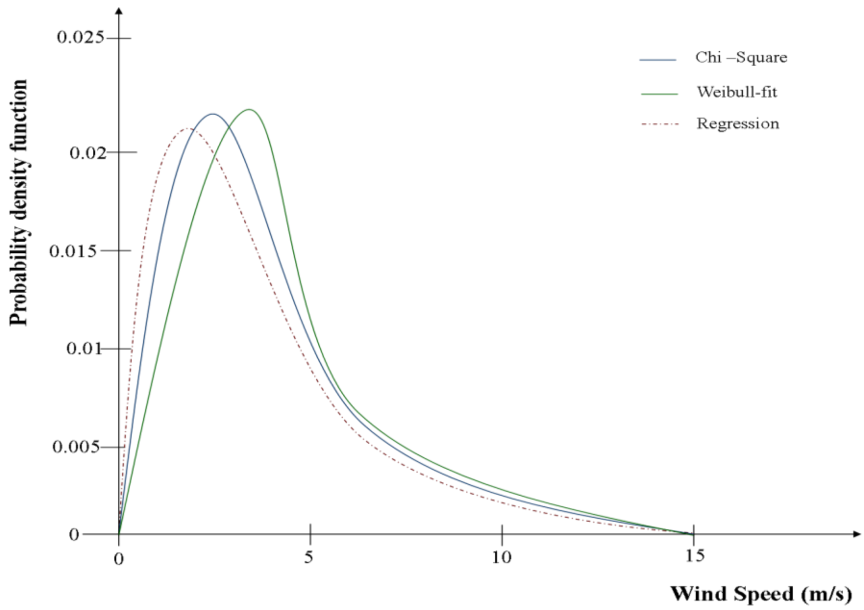

Figure 1.2: Weibull PDF's determined using Weibull-fit, Regression, and Chi-square methods and the wind speed data at the Jyvaskyla site (Paitoon, 2010).

This study by Paitoon, (2010) necessitates a more detailed research using different methods in order to determine the one that suits best the analysis of wind speed data in Juja and Naivasha areas. This will assist in determination of optimum power density which is a key requirement in designing of turbines.

1.3 Cause of Wind

Wind develops as a result of spatial differences in atmospheric pressure. Generally, these differences occur due to uneven absorption of solar radiation at the Earth's surface (Figure 1.3). The greater the difference in pressure the higher the wind speed. Wind speed tends to be at its greatest during daytime when the greatest spatial extremes in atmospheric temperature and pressure exist (Pidwirny, 2006). The wind cycle due to a localized temperature difference is as shown below.

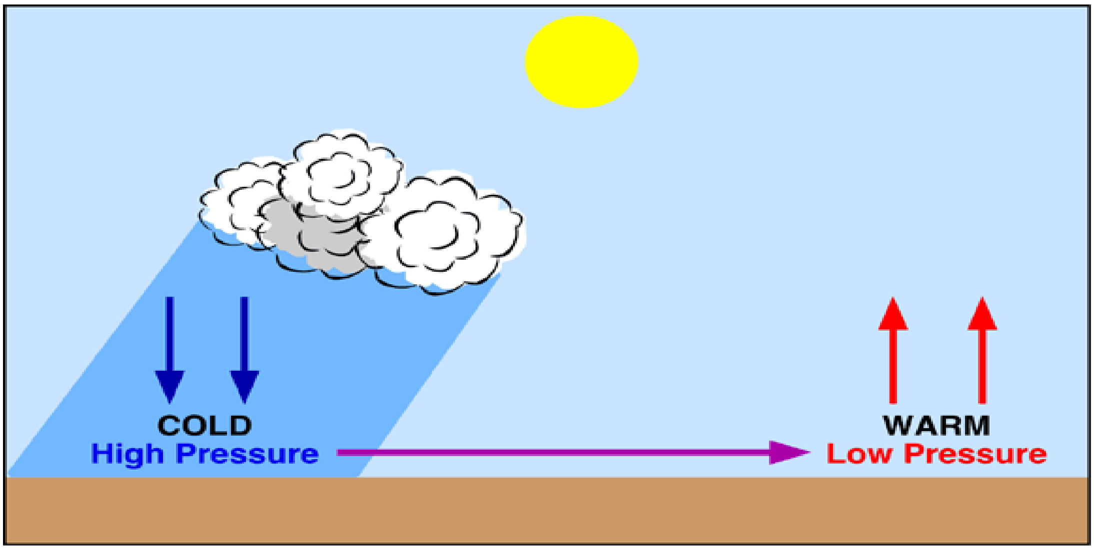

Figure 1.3: Formation of wind as a result of localized temperature differences.

1.4 Types of wind

The wind flow patterns are modified by the earth’s terrain, bodies of water, and vegetative cover because they determine the degree of roughness. Wind is described by both speed and direction (Kargieve, Martirosov, Murugov, Pinov, Sokolsky, & Haritonov, 2001; Rai, 1988).

Winds are commonly classified by their spatial scale, speed and types of forces, as local and global winds. Local winds are those that are caused as a result of scenery such as mountains, vegetation and water bodies. They cover very short distances. These are land/sea breezes and mountain/valley breezes. Global winds are really large air masses that are created mainly as a result of the earth's rotation, the shape and the sun's heating power (Rai, Gopalan, & Naughton, 2015).

1.4.1 Global Wind Systems

Winds can blow in all directions depending on their cause. Prevailing, or global winds, are caused by the sun's uneven heating of large parts of the atmosphere and by the Earth's rotation on its axis. These types of winds are easterly winds, which blow from east to west, and westerly winds which blow from west to east. The easterly surface winds (trade winds) are found in the tropics, within the lower portion of the Earth's atmosphere, in the lower section of the troposphere near the Earth's equator, (Glossary of Meteorology, 2010). They blow predominantly from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere, strengthening during the winter and when the Arctic oscillation is in its warm phase. Historically, these winds have been used by captains of sailing ships to cross the world's oceans for centuries, and enabled European empire expansion into the Americas and trade routes to become established across the Atlantic and Pacific oceans. In meteorology, the trade winds act as the steering flow for tropical storms that form over the Atlantic, Pacific, and southern Indian Oceans and make landfall in North America, Southeast Asia, and Madagascar and eastern Africa, respectively. Trade winds also transport African dust westward across the Atlantic Ocean into the Caribbean Sea, as well as portions of south eastern, North hemisphere. Shallow cumulus clouds are seen within trade wind regimes, and are capped from becoming taller by a trade wind inversion, which is caused by descending air aloft from within the subtropical ridge. The weaker the trade winds become, the more rainfall can be expected in the neighbouring landmasses (Michael, 2008).

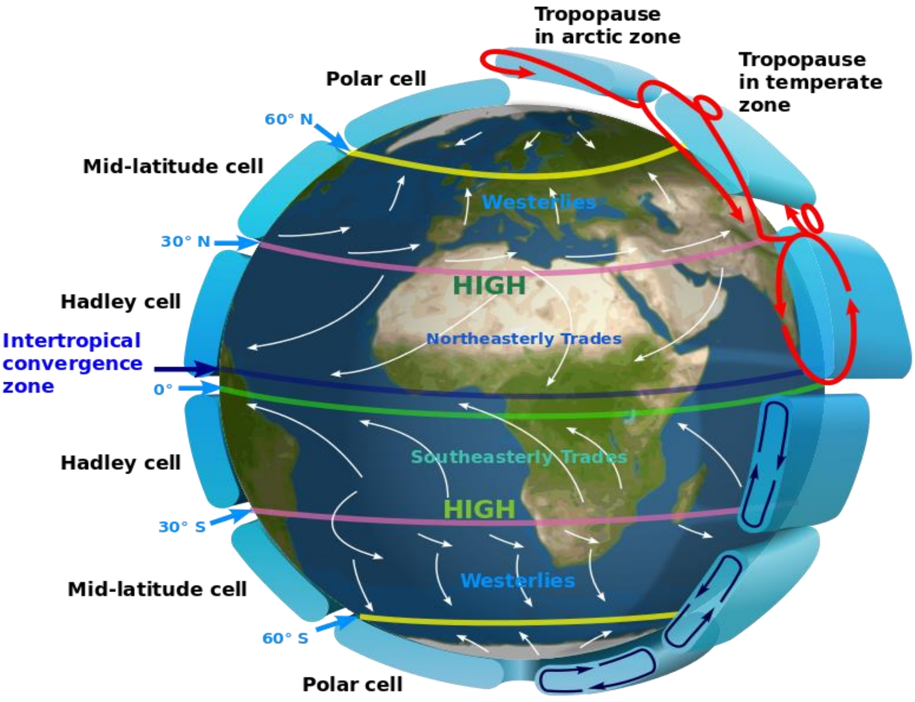

Figure 1.4: Easterlies and Westerlies (Junling and Michael, 2014)

Figure 1.4 shows the westerlies and easterlies (trade winds) of the earth. These are prevailing winds because they flow predominantly from a single general direction, westerlies, from the west and easterlies, from the east. Polar easterlies blow between 60-90 degrees, Prevailing Westerlies, 30-60 degrees, and trade winds between 0-30 degrees. They are subject to coriolis forces due to the earth's rotation. The wind strength changes with seasons as solar input varies (Michael, 2008).

The Hadley cells extend from the equator to between 30 and 40 degrees north and south, and within these cells the trade winds blow towards the equator, and then ascend near the equator as a broken line of thunderstorms, which forms the Inter-Tropical-Convergence Zone (ITCZ). From the tops of these storms, the air flows towards higher latitudes, where it sinks to produce high-pressure regions over the subtropical oceans and the world's hot deserts, such as the Sahara desert in North Africa.

The Ferrel cells (mid-latitude cells) are circulation cells that form between 30 degrees and 60 degrees north and south of the equator. In the middle of these cells, air converges at low altitudes and ascends along the boundaries between cool polar air and the warm subtropical air. The circulation within the Ferrel cell is complicated by a return flow of air at high altitudes towards the tropics, where it joins sinking air from the Hadley cell (Junling & Michael, 2014).

1.4.2 Local Winds

Local winds depend on local changes in temperature. They are caused by two mechanisms. The first is differential heating of land and water which results to land and sea breezes. The second mechanism is due to hills and mountain sides which lead to the valley and mountain breezes. Figure 1.5 and figure 1.6 show land and sea breezes, and valley and mountain breezes respectively.

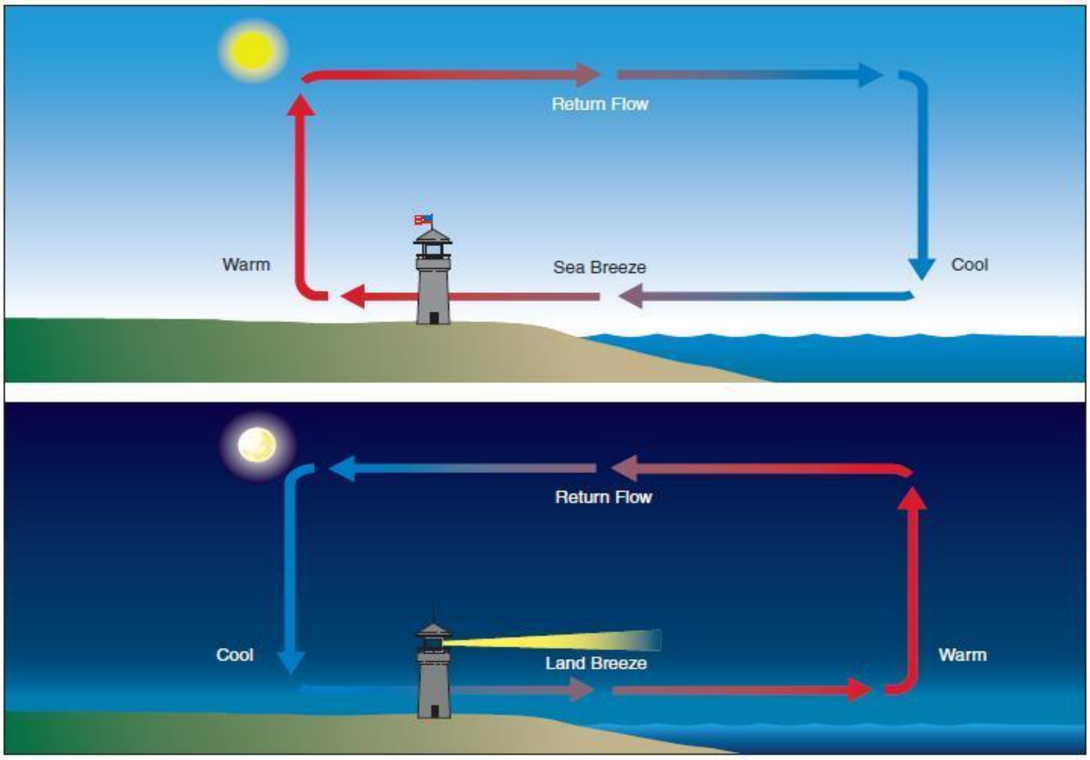

Figure 1.5: Sea and land breezes

A sea breeze usually occurs during the day when air above the land surface is heated by radiation from the sun, thus expanding and rising due to reduction in density.

Cooler air from the sea moves into the land (sea breeze) to replace the warmer rising air. The air from the sea is thermal low (high pressure) while that from the land, due to reduced densities is thermal high (low pressure). On the other hand, a land breeze occurs during the night when air on the land cools more than air on the sea. This causes air on the sea to rise hence being replaced by the more dense air from the land. This movement of wind from the land to the sea is called land breeze, (Michael, 2008).

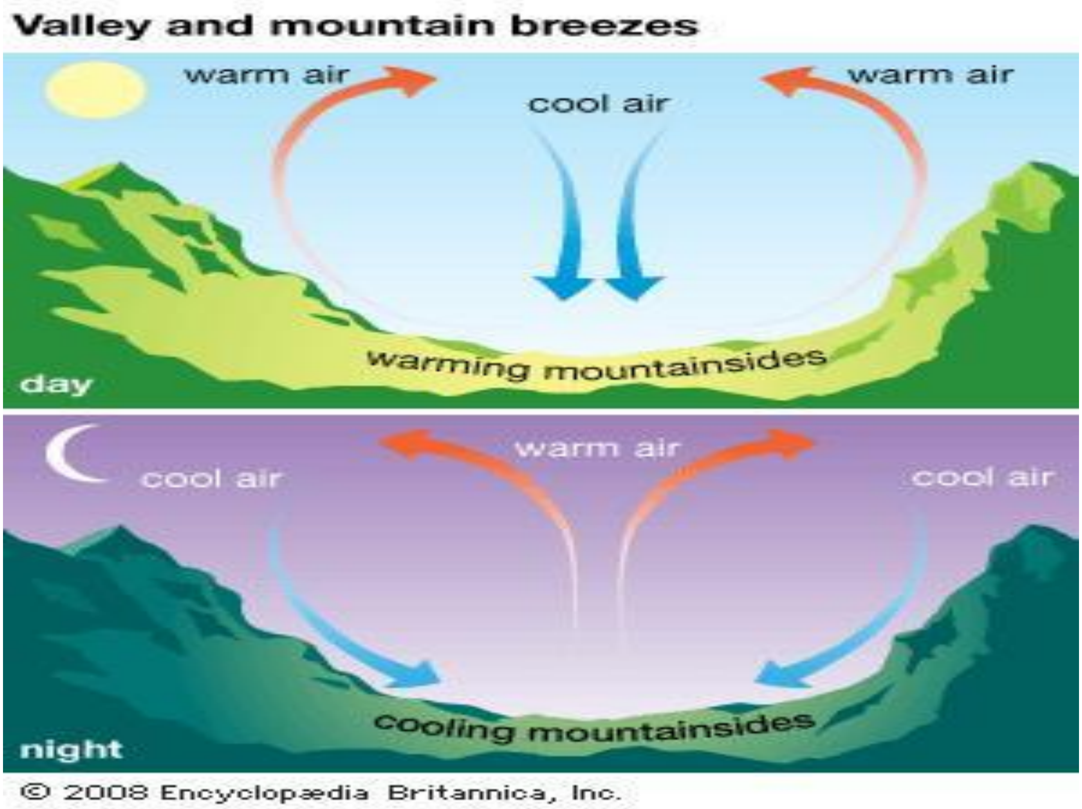

Figure 1.6: Valley and mountain breezes

Mountain and valley breeze occurs as a result of changing in pressure due differential heating rates. During the day, the valley base warms up faster hence causing the wind to move up through the mountain sides. In turn cool air comes vertically downwards to the valley. During the night, the mountain top air is cooler and hence denser. As a result the air comes down the valley while the air in the valley being less dense moves upwards, as it is being replaced hence creating the breeze, Saucier, (2003).

1.5 Wind Characteristics

Wind is characterized by wind speed and direction. These parameters change depending on the state of the atmosphere (this involves weather and climatic changes), surface roughness and nature of terrain (Usta and Kantar, 2008).

Winds are usually named depending on the geometrical compass direction of their source. Thus, wind from the north blowing toward the south is called a northerly wind (Wekesa, 2012).

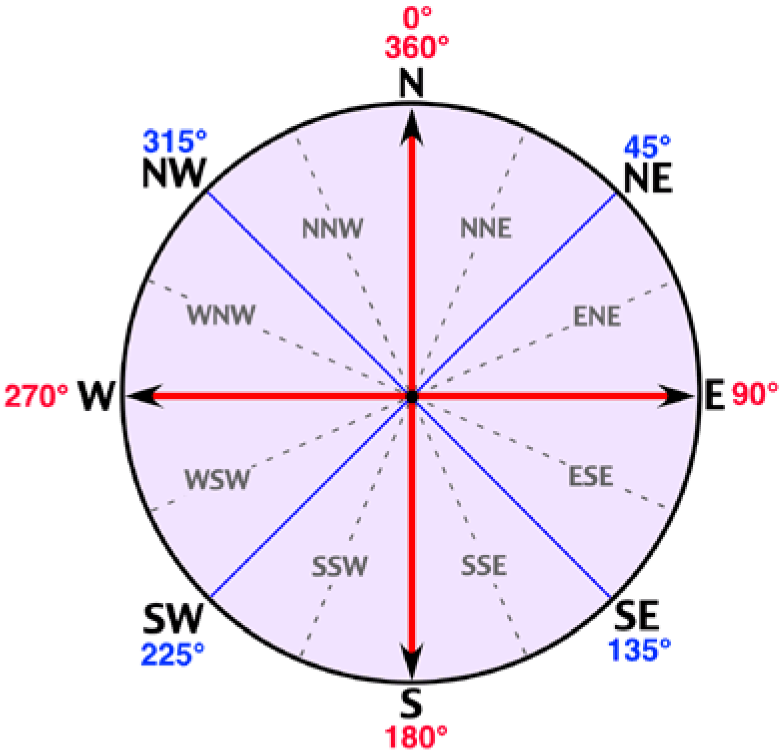

Figure 1.7: Sixteen principal bearings of wind direction

Figure1.7 describes the sixteen principal bearings of wind direction. Most meteorological observations report wind direction using one of these sixteen bearings (Pidwirny, 2006). As observed, the principle bearing cover the whole of the globe and hence despite other winds being given other names such as Monsoons, their main defining concept is their direction which is dictated by the compass bearing.

1.6 Wind Measurements

Winds are measured by their directions and speeds. Anemometers, such as shown in figure 1.8a, are conventionally used for wind speed measurement, (

based on the study of wind characteristics using different methods fitted on Weibull and Rayleigh models in order to determine the one that yields optimum results. The data was obtained at two heights of 10 m and 30 m from the ground of a selected site in Juja for a period of three months. The results were analyzed and wind power densities for various methods were obtained. The results obtained from Juja site were correlated with collected data from a site of different locality (Naivasha site) to find out whether there are any outstanding factor(s) that determine the best applicable wind potential method of analysis in a given area.

1.8 Justification

Renewable energy is a key issue of the 21st century. This is due to high cost of petroleum products, threat of climate change, population increase and the limited potential for expansion of convectional sources. The development and utilization of wind energy in developing countries has been hindered by absence of adequate measurements and assessment studies to ascertain its potential viability for power generation. Juja, which is at an altitude of 1416 m above sea level; 1^0 10’ S, 37^0 7’ E having a rapidly growing population and a major University, JKUAT, and Naivasha, 2,086m (0° 43' 0" S, 36° 26' 0" E), with agricultural farms, require an alternative energy source due to frequent power failure. Use of power generators as power backup pollutes the environment and hence the need for clean, reliable, sustainable and cost effective energy sources. Wind energy is among the least exploited with about 25.5 MW from Ngong wind farm which includes the two phases (Maulidi, 2010). Accurate wind speed modelling/ analysis of wind speed characteristics is critical in estimating wind energy potential for harnessing wind power effectively (Kollu *et al.*, 2012). The quality of wind speed assessment depends on the capability of chosen probability density function to describe the measured wind speed frequency distribution (Hargraves, Mikhail, & Graber, 1978). The results from this research will be important in informing the designers the type of wind turbines that are appropriate to use in Juja and Naivasha in order to harness maximum power. This will lead to development of Juja and Naivasha localities taking care of the environment and also improving the standard of education and agricultural outputs, mainly due to Information Technology (IT), especially in places where there are no backups in case of power failure.

1.9 Objectives

1.9.1 General Objective

To measure and correlate wind characteristics and wind energy potential for selected sites in Juja and Naivasha using different methods fitted in Weibull and Rayleigh models.

1.9.2 Specific Objectives

1. To asses wind characteristics for wind patterns for Juja and Naivasha.
2. To correlate data obtained at selected sites in Juja and Naivasha.
3. To determine wind power potential for Juja and Naivasha wind patterns using the Weibull and Rayleigh distribution models.

CHAPTER TWO

LITERATURE REVIEW

2.1 Wind Patterns Analysis

Saoke, (2011) analyzed wind speeds based on the Weibull model and data correlation for wind pattern description for JKUAT at 13 m and 20 m heights. The data was obtained within a period of three months. The mean wind speed at the two heights was 5.04 m/s with a standard deviation of 2.59. Extrapolation for higher heights was done up to 150 m and a maximum speed of 8.4 m/s was obtained. He recommended further research based on a longer period and different techniques for more accurate wind pattern predictions.

The study by Aguko, Nyaanga, & Onyando, (2014), reported on variation of wind speeds at the shore of Lake Victoria (Kenya) and focused on determination of temporal and spatial wind speeds variation and empirical relationships with height and location within the 2 m height. Wind data was analyzed to determine consistency (diurnal, monthly, seasonal trends, duration and direction) with location and was used to establish direct and indirect relationship in estimating wind speeds at 10 m for installation and utilization of the wind energy. It was established that wind speeds fitted the two parameter Weibull distribution model. The study was confined to the speed of wind of 10 m hence there is need for further research focusing on wind speed beyond 10 m, while taking into account the local location, direction, diurnal and the seasonal variation.

A mathematical model of wind turbine is essential in the understanding of the behaviour of the wind turbine over its region of operation because it allows for the development of comprehensive control algorithms that aid in optimal operation of a wind turbine (Manyonge, Ochieng, Onyango, & Shichikha, 2012**)**. Modelling enables control of wind turbines performance. Model results will be beneficial to designers and researchers of new generation turbines who can utilize the information to optimize the design of turbines and minimize generation costs leading to decrease in cost of wind energy and hence making it an economically viable alternative source of energy.

Rambo, (2013) investigated the renewable energy project financing risks in developing countries with focus on the options for Kenya towards the realization of vision 2030. The paper reports secondary literature on the typical investment risks on developing countries and makes recommendations for Kenya and other African countries to create an environment that is not only safe but also promising to investors. The investment risks identified from the paper include political instability, low-carbon policy and currency value fluctuation, monopolization of energy production, transmission and distribution, as well as community non-involvement. Based on the identified risks, the study recommends the need for the Government to secure a sustainable political stability, strengthen laws and policies promoting foreign investment, establish currency-hedging mechanism, open-up renewable energy market and promote community involvement renewable energy projects.

Yong, Yidong, Johnson, & Jing, (2012) carried out the analysis of wind power potential at multiple heights for North Dakota wind observation sites and observed that wind speed is the most critical factor that determines wind power potential and generation. The wind speed data of multiple years from various observation sites in North Dakota, U.S. was analyzed to assess the wind power potential. The study first applied probability density functions (PDFs) to characterize the wind speed data and fitted the distributions at various heights for each observation site. The fitted distributions were then used to estimate the wind power potential based on the theoretical cubic power relationship between energy potential and wind speed. The numerical integration approach was employed. The findings from this empirical study indicated that Weibull distribution is not always the best function to fit wind speed data. For different height levels at one observation site, the best performing distributions may be different. The estimation accuracies of wind energy potential based on the fitted wind speed distributions range from - 4% to 3.8% (Yong *et al.*, 2012). The rank of energy potential estimation accuracies is not always consistent with that of goodness-of-fit for wind speed distributions. A simplified approach that only relies on the hourly mean wind speed to estimate wind power potential was evaluated. Based on the theoretical cubic relationship for wind power estimation, it was found that the simplified approach may provide significantly lower estimates of wind power potential by 42-54%. As such, this approach will become more practical if this amount of difference is to be compensated. The study was contextual in that it was based in Dakota in United States hence the same study can be replicated in Kenya so as to confirm the findings of the study.

2.2 Theoretical Considerations

2.2.1 Power available in wind

Wind power is extracted from the wind using wind turbines. The power, P, is given by

$$P = \frac{1}{2}\rho A v^3 \quad \text{..1.1}$$

Where;

A is cross-section area of turbine blades, ρ the air density and v the speed in the wind. The air density ρ is also related to air pressure P, gas constant R and, temperature T in degrees Kelvin and is given by $\rho = \frac{P}{RT}$. The wind velocity at the rotor plane is the average of upstream and downstream wind speeds. Maximum useful power is given by Betz's constant ≈ 0.59 of power available in the wind (Rai, 1988).

2.2.2 Power Law Formula, Wind Shear Exponent and Roughness Lengths

Wind speed near the ground changes with height; this involves an equation that forecasts wind speed at different height by using the available wind speed data. Kantar and Usta, (2008) stated that the most commonly used equation for the variation of wind speed with height is the power law;

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \quad \text{..1.2}$$

Where v_1 (m/s) is the actual wind speed recorded at height h_1 (m), and v_2 (m/s) is the wind speed at h_2 (m) and α the shear exponent

Wind shear exponent, also referred to as wind speed gradient, or wind velocity gradient is vertical gradient of the mean horizontal wind speed in the lower atmosphere. It is the rate of increase of wind strength with unit increase in height above the ground level. It is measured in metres per second, per kilometre height (m/s/km) which reduces to inverse seconds (s^{-1}) and depends on the surface roughness and atmospheric stability. Wind shear exponents for various types of terrains by Linacre & Geerts, 1999 values for different terrains are shown in table 2.1.

Table 2.1: **Shear exponent for different terrains** (Linacre & Geerts, 1999)

Type of terrain	Shear Exponent
Smooth, hard ground, lake or ocean	0.10
Short grass on untilled ground	0.14
Level country with foot-high grass, occasional trees	0.16
Tall row crops, hedges, a few trees	0.20
Many trees and occasional buildings	0.22 - 0.24
Wooded country-small towns and suburbs	0.28 - 0.30
Urban areas with tall buildings	0.40

The logarithmic wind profile law is given by;

$$v_a = \frac{v_f}{k} \ln\left(\frac{h}{z_0}\right) \qquad \text{.........1.3}$$

Where v_a is mean wind speed at a height h above the ground, v_f the frictional velocity, z_0 the roughness parameter and k the Von Kerman's constant. Roughness length which is used to characterize shear and the height above the ground is not constant (Manwell *et al*., 2009) and thus equation 1.3 can be modified to yield equation 1.4.

$$v_2 = \frac{v_1 \ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \quad \text{..........1.4}$$

The roughness lengths by Wieringa, (1998), for various terrains are indicated in table 2.2.

Table 2.2: Terrain classification (Wieringa, 1998)

Class		Roughness length (m)	Landscape features
No.	Name (terrain)		
1	sea	0.0002	Open water, tidal flat, snow with fetch above 3 km
2	smooth	0.005	Featureless land, ice
3	open	0.03	Flat terrain with grass or very low vegetation, airport runway
4	roughly open	0.10	Cultivated area, low crops, obstacles of height H separated by at least 20 H
5	rough	0.25	Open landscape, scattered shelter belts, obstacles separated by 15 H
6	very rough	0.5	Landscape with bushes, young dense forest etc separated by 10 H
7	closed	1.0	Open spaces comparable with mature forest, low-rise built-up area
8	chaotic	over 2.0	Irregular distribution of large elements, such as city centre, large forest with clearings

2.2.3 Wind Probability Distributions

Two of the commonly used functions for fitting a field data probability distribution in a given location over a certain period of time are the Weibull and Rayleigh distribution models (Kantar and Senoglu, 2008; Kantar, & Usta, 2008). The Weibull probability density function, $f_R(v)$ is given as

$$f_R(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \text{.........} 1.5$$

Where k and c are Weibull shape and scale parameters respectively and v is the wind speed in the wind. The Rayleigh $f_R(v)$ distribution is a special case of the Weibull distribution in which the shape parameter k =2. The probability density functions of the Rayleigh distribution is therefore given by;

$$f_R(v) = \frac{2v}{c^3} \exp\left[-\left(\frac{v}{c}\right)^{2}\right] \text{.........} 1.6$$

2.2.4 Methods of Obtaining Weibull Parameter

2.2.4.1 Maximum Likelihood (MLH)

The parameters k and c (m/s) can be estimated by using the Maximum Likelihood Method (Zhang, Xie, & Tang, 2006) as;

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n} \right)^{-1} \text{.........} 1.7$$

$$\left(c = \frac{1}{n} \sum_{i=1}^{n} v_i^k \right)^{\frac{1}{k}} \text{.........} 1.8$$

Where, v_i is wind speed at stage i and n, is the number of data points.

2.2.4.2 Weibull-fit

The shape and scale parameters by Weibull-fit are as follows;

$$v_m = \int_0^\infty v f_R d_v \text{...} 1.9$$

$$= \int_0^\infty v \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] d_v \text{..} 1.10$$

$$= c\Gamma\left(1+\frac{1}{k}\right) \text{..} 1.11$$

Where gamma function, Γ is given by equation 1.12

$$\Gamma = \int_0^\infty v^{k-1} \exp(-v) dv \text{..} 1.12$$

$$k = \left(\frac{\sigma_y}{v_m}\right)^{-1.090} \text{...} 1.13$$

Where σ_y is standard deviation, Γ is the gamma function and v_m is the mean value of wind speed and σ_y is given by equation 1.14

$$\sigma_y = \left[\frac{\sum_{i=1}^{n} f_i (v_i - v_m)^2}{\sum_{i=1}^{n} f_i}\right]^{\frac{1}{2}} \text{...} 1.14$$

Where v_i, is wind speed and f_i is frequency of the wind at stage i.

2.2.4.3 Regression

The cumulative probability function of the Weibull distribution (Akpinar and Akpinar, 2004), is given by;

$$F(v) = 1 - \exp[-(\frac{v}{c})^k] \text{...} 1.15$$

To determine k and c requires a good fit of the equation above to the recorded discrete cumulative frequency function. By taking the natural logarithm of both sides of equation 1.15 twice gives;

$$\ln\langle -\ln[1-F(v)]\rangle = k\ln(v) - k\ln c \qquad 1.16$$

Equation 1.16 is in linear form of y= mx + C. Plotting $\ln\langle -\ln[1-F(v)]\rangle$ against $\ln(v)$ presents a straight line whose gradient (m) is k and the y-intercept(C) is $-k\ln c$ (from which c can be calculated).

2.2.5 Wind Power Density Function

The evaluation of wind power per unit area is of fundamental importance in assessing wind power projects (Zhou, Erdem, Li, & Shi, 2010). The formula for P_v is given by;

$$P_v = \frac{1}{2n}\sum_{i=1}^{n}\rho\left(v_i^3\right) \qquad 1.17$$

Where the wind speed at stage i, is v_i, n, the number of non-zero wind data points and ρ, the air density at standard temperature and pressure and is estimated to be $1.225\,kg/m^3$. The expected monthly or annual wind power density per unit area of a site based on Weibull probability density function P_W (Akpinar and Akpinar, 2004) can be expressed as follows;

$$P_W = \frac{1}{2}\rho c^3\Gamma\left(1+\frac{3}{k}\right) \qquad 1.18$$

Where Γ is the gamma function and c the Weibull scale parameter (m/s) given by equation 1.19 below.

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \qquad 1.19$$

2.2.6 Statistical Analysis of Wind Power Density Based on the Weibull and Rayleigh Models

The two significant parameters k and c are closely related to the mean value of the wind speed v_m. By extracting c from equation 1.18 and setting k = 2, the power density for the Rayleigh model $\left(P_R\right)$ is found to be;

$$P_R = \frac{3}{\pi}\rho v_m{}^3 \qquad 1.20$$

Where;

$\pi = \frac{22}{7}$ and

$$v_m = c\Gamma\left(\frac{3}{2}\right) = 0.88623c \qquad 1.21$$

Power densities using the Weibull and Rayleigh distribution models in comparison to the values of the probability density distributions derived from field data values can be determined using the following formula;

$$Error(\%) = \frac{P_{(W,R)} - P_{(M,R)}}{P_{(M,R)}} \qquad 1.22$$

Where $P_{(W,R)}$ in (W/m^2) is the mean power density calculated from either the Weibull or Rayleigh function used in the calculation of the error and $P_{(M,R)}$ is the wind power density for probability density distribution derived from field data values which serve as the reference mean power density (Ibrahim, 2006).

2.2.7 Wind Turbine Power-output Variation with Wind Speed

Figure 2.1 shows a sketch on how the power output from a wind turbine varies with steady wind speed.

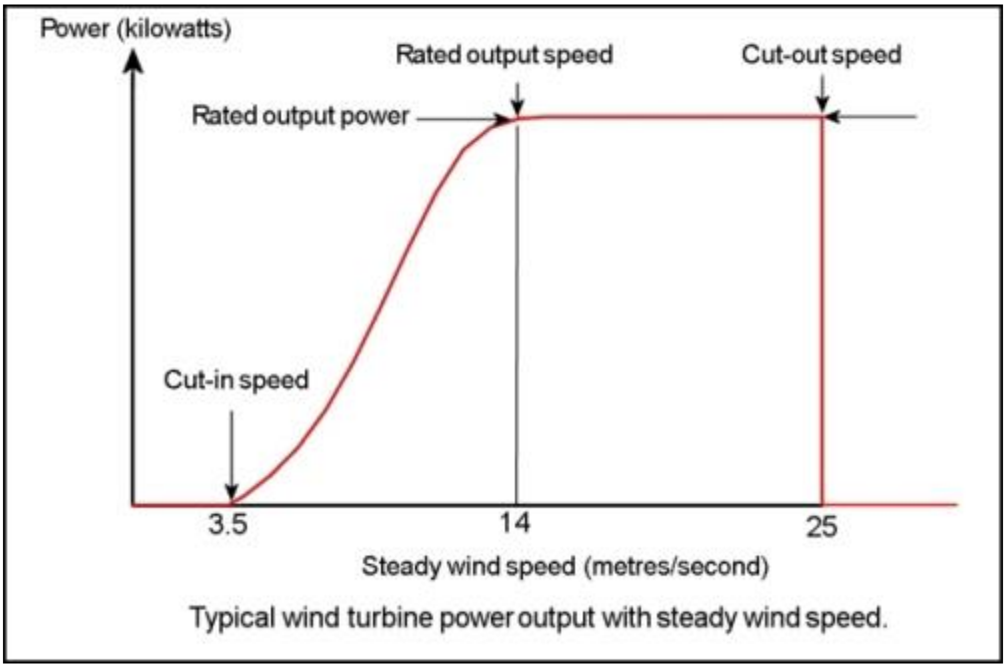

Figure 2.1: Typical wind turbine power-output variation

The minimum speed at which the turbine starts to rotate and generate power is known as cut-in speed (3.5 m/s). This implies that at very low wind speeds**,** the turbine blades cannot rotate and hence no power is generated due to insufficient torque exerted by the wind on the turbine blades. As the speed increases, the wind turbine begins to rotate and generate electrical power. As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly as shown. However, typically somewhere between 12 and 17 ms^{-1}, the power output reaches the limit that the electrical generator is capable of. This limit to the generator output is called the rated power output and the wind speed at which it is reached is called the rated output wind speed. At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. However this varies from design to design but typically with large turbines, it is done by adjusting the blade angles so as to keep the power at the constant level. As the speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the cut-out speed and is usually around 25 ms^{-1}, (Stuart, 2011). A specific example of a power out-put curve was that generated by Vestas turbine, V90-3.0 MW® IEC IA/IIA and is indicated in figure 2.2. Cut-in speed was about 3.5 m/s and cut-out of 25 m/s.

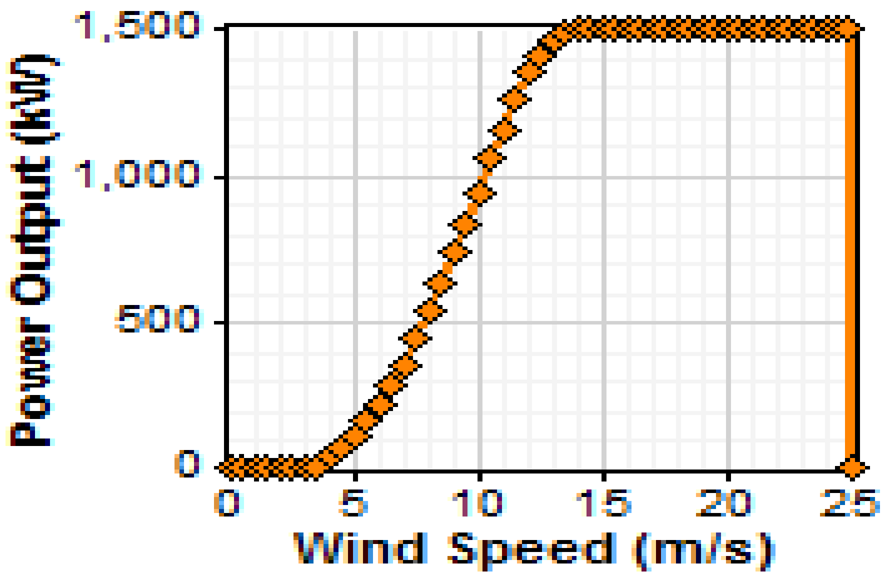

Figure 2.2: Power output wind profile

This type of a turbine is suitable for areas with medium and high wind speeds (Gipe, 2004).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was carried out in Juja, which is about 1416 m above sea level; at latitude 1^{0} 1 0' South and longitude 37^{0} 01’ East, and about 35 km from Nairobi. The area has many tall buildings and trees. The set-up was less than 50 m from nearby obstacles due to limitation of funds required to set up an isolated mast taking into consideration the issue of security. The mast was therefore fixed on a water tank tower in estate department.

The study site map in Juja (yellow torch) is indicated by plate 3.1 (http://www.google.com/earth)

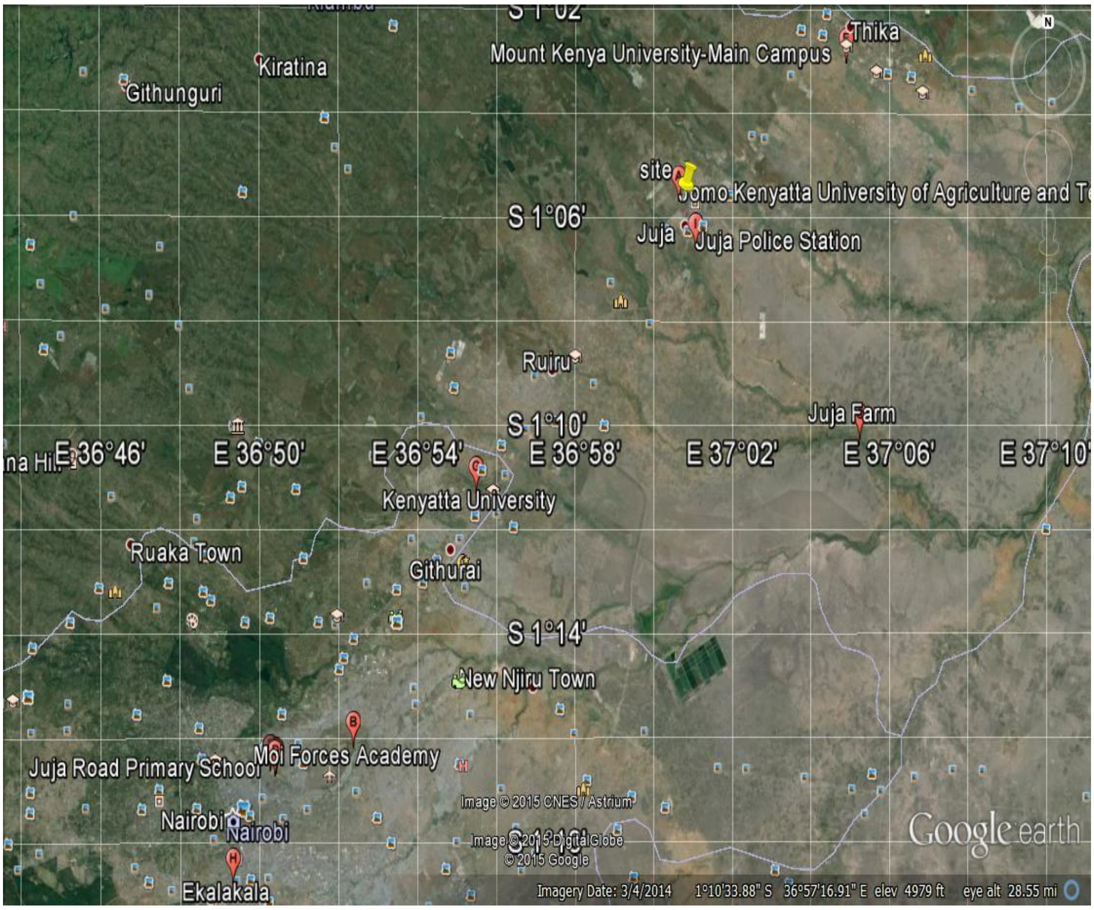

Plate 3.1: Map of study site in Juja

3.2 Assessing Wind Characteristics for Wind Patterns in Juja and Naivasha

3.2.1 Materials/Equipment

The following were the materials used in Juja site and also in Naivasha under BRIGHT PROJECT.

Masts, clamps, nuts, bolts, anemometers (ultrasonic wind sensors), three- cup anemometer, wind vane, transmitting cables (insulated cords), data loggers (Sutron 9210 X-Lite and Davis Vantage PRO), safety boxes, metallic rods, data disc, data cables, Microsoft Excel software, Windographer software and computer.

The following are plates of some of the apparatus used (plates 3.2 and 3.3)

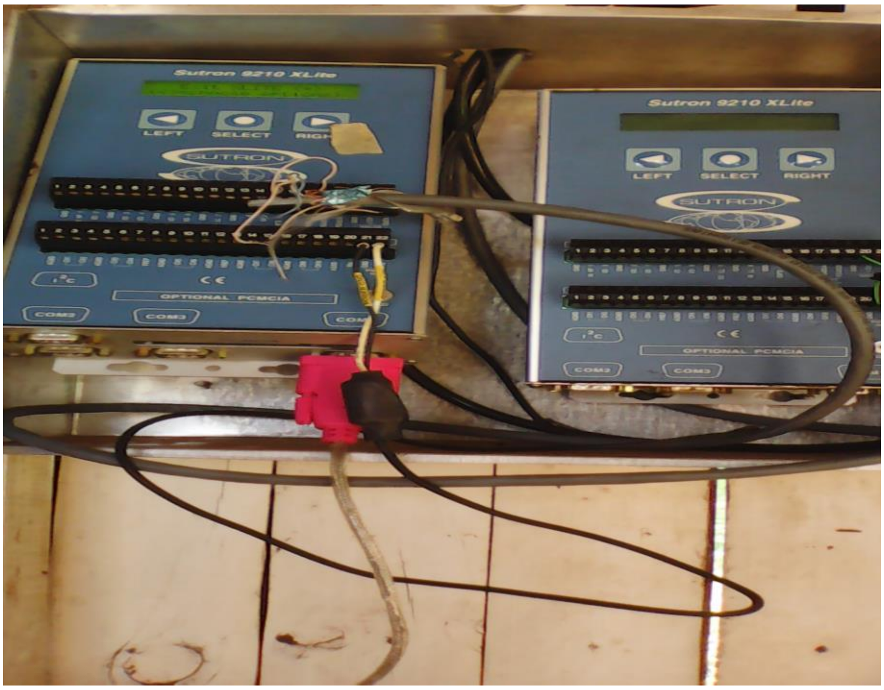

Plate 3.2: Sutron 9210 XLite data loggers

The data loggers recorded both wind speed and direction.

Plate 3.3: Ultrasonic Wind sensors

The wind sensors were conventionally used for wind speed and direction measurements. They were connected to a mast and were aligned North (zero degrees), which acted as a reference point to wind direction.

3.2.2 Data Collection Procedure

A mast of 30 m length was constructed using metallic circular tubes. Anemometers (Ultrasonic wind sensors) were clamped on the mask at 10 m and 30 m in order to measure wind speeds and directions at these heights above the ground, in Juja. The sensors were connected to transmitting devices (clamped on metallic rods) using insulated cords. The transmitters were linked with two Ultrasonic data loggers programmed in such a way that one received data from 10 m and the other from 30 m centers. The data recorded involved wind speed, wind direction and temperature and was stored in computer memory (disc) awaiting processing. The averages of wind parameters were obtained daily for three months. The wind shear exponents, α surface roughness z_0, Weibull scale parameter c, shape parameter k and power densities were determined. Wind power potential was modelled using Weibull and Rayleigh distributions functions.

In case of Naivasha, data was collected from an anemometer height of 10 m for the same months. The results from Juja and Naivasha were compared to determine the correlation.

3.2.3 Research Design

Figure 3.1 shows a schematic flowchart of apparatus setup that were used to measure wind characteristics while figure 3.2 shows methodology flowchart. The results for the daily wind speed averages and direction were tabulated. Analysis of results was done by use of Microsoft Excel and Windographer software ©. Analysis of average power density by direction was carried out using WindRose diagrams.

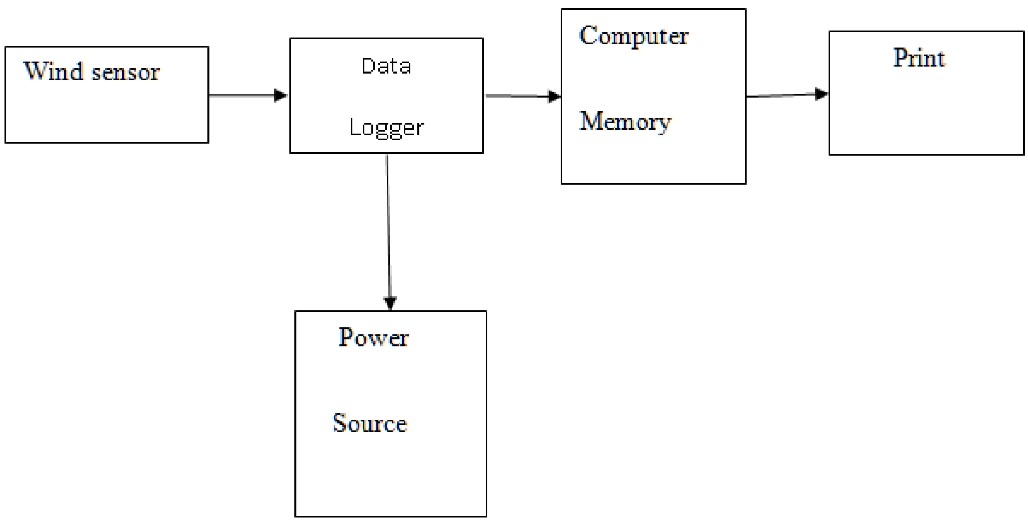

Figure 3.1: Flowchart of wind energy apparatus

The methodology flowchart below shows the steps that were followed to complete resource assessment after installation of wind speed instruments.

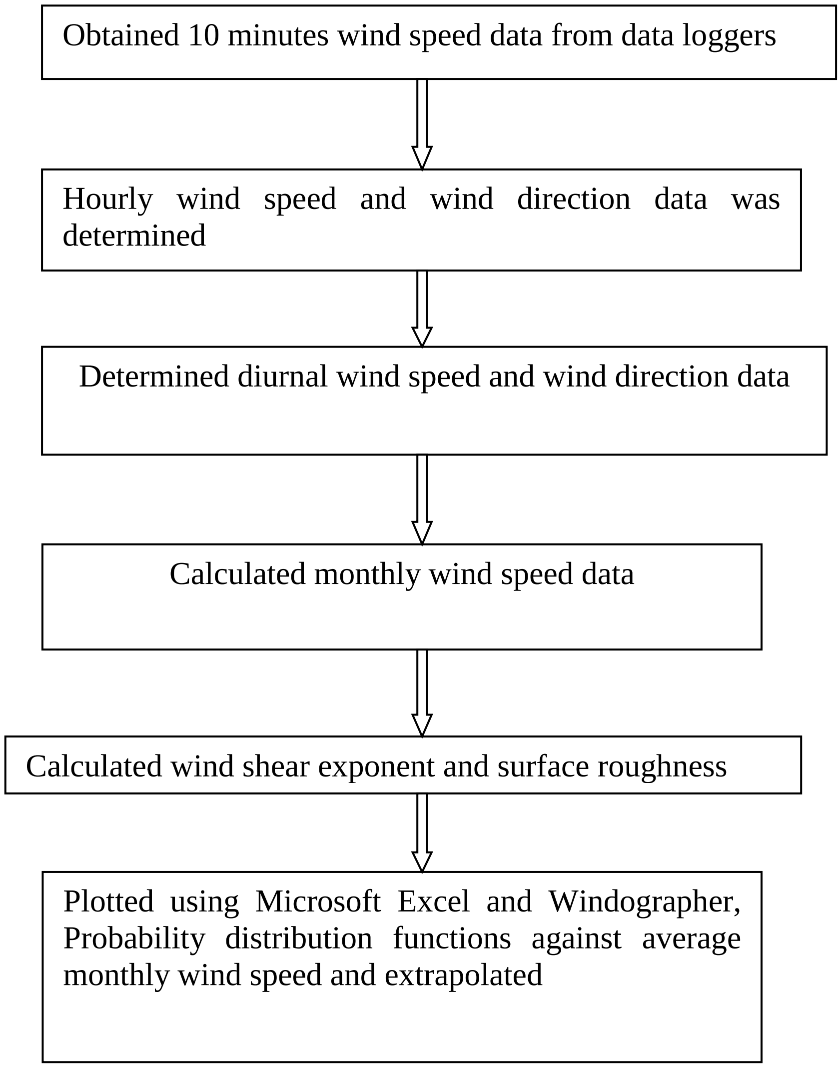

Figure 3.2: Methodology flowchart

3.3 Correlating Wind Data for Selected Sites in Juja and Naivasha

The scale parameters and shape parameters for the two sites were determined using Weibull-fit, Maximum Likelihood, and Regression methods. These parameters were fitted in Weibull and Rayleigh models and power densities for different methods were calculated. Wind directions were analysed using windRose diagrams based on magnitude of power potential per wind direction.

CHAPTER FOUR

RESULTS ANALYSIS AND DISCUSSION

4.1 The Daily Wind Speed and Averages

The daily wind speed, wind direction and temperature averages obtained from Juja for the months of March, April and May, 2015 are shown in tables 4.1, 4.2 and 4.3 respectively.

Table 4.1: Wind characteristics data for the month of March, 2015

DAY	Speed, v_1 (m/s) (10 m height)	Speed, v_2 (m/s) (30 m height)	Wind direction (degrees)	TEMP (^{0}C)
1	3.49	4.13	79.50	**19.94**
2	3.63	4.33	94.50	**20.33**
3	3.27	3.79	88.00	**19.15**
4	2.10	2.52	74.00	**19.56**
5	2.10	2.49	91.50	**19.81**
6	2.24	2.80	104.20	**21.02**
7	2.35	2.95	103.00	**20.29**
8	2.51	3.16	202.30	**20.10**
9	2.27	2.80	116.50	**19.43**
10	2.63	3.14	271.50	**19.77**
11	2.01	2.67	115.00	**20.00**
12	2.91	3.24	282.00	**23.08**
13	2.60	3.10	52.00	**20.48**
14	1.98	2.49	75.00	**19.92**
15	2.19	2.70	262.50	**20.85**
16	2.66	3.27	216.50	**21.10**
17	2.76	3.30	111.00	**21.34**
18	2.43	3.00	112.00	**20.36**
19	4.21	4.80	110.10	**20.92**
20	5.24	5.83	112.60	**22.92**
21	5.17	5.63	65.40	**22.03**
22	3.14	3.70	72.10	**20.98**
23	3.25	3.73	70.30	**19.48**
24	2.37	2.84	97.90	**19.39**
25	2.36	3.57	83.00	**19.80**
26	2.71	3.27	130.78	**17.80**
27	2.28	2.72	334.00	**20.96**
28	2.67	3.12	71.00	**19.50**
29	2.43	2.97	58.00	**20.00**
30	2.59	3.15	11.00	**20.00**
31	2.49	3.07	39.00	**20.47**
Mean	**2.81**	**3.36**	**109.00**	20.35

The maximum wind speeds for March, heights 10 m and 30 m, 2015 were 5.24m/s and 5.83 m/s and the minimum wind speeds were 1.98 m/s and 2.49 m/s and the shear exponent and shape parameters were 0.16 and 0.036 respectively.

Table 4.2: Wind characteristics data for the month of April, 2015

DAY	**Speed, v_1 (m/s) (10 m height)**	**Speed, v_2 (m/s) (30 m height)**	**Wind Direction (degrees)**	**TEMP (^{0}C)**
1	1.71	2.04	2.00	**19.74**
2	2.23	2.37	340.00	**19.52**
3	1.76	2.30	163.50	**17.55**
4	1.52	2.05	193.50	**19.82**
5	1.65	2.12	145.50	**19.65**
6	1.48	1.85	158.90	**18.82**
7	2.70	3.15	157.00	**19.17**
8	2.93	3.28	195.00	**19.26**
9	1.42	1.89	145.00	**18.58**
10	1.48	1.93	141.10	**19.58**
11	2.13	2.65	135.00	**19.35**
12	2.21	2.70	134.50	**19.19**
13	1.81	2.38	142.80	**20.45**
14	1.76	2.27	158.00	**19.24**
15	2.12	2.61	68.50	**19.04**
16	2.56	3.09	131.60	**19.40**
17	1.80	2.35	138.50	**17.91**
18	2.12	2.61	123.10	**18.90**
19	2.08	2.56	110.20	**20.37**
20	2.50	3.03	130.60	**20.17**
21	2.74	3.11	88.60	**19.60**
22	2.25	2.70	165.80	**19.34**
23	2.32	2.73	130.60	**19.24**
24	1.94	2.40	115.90	**19.76**
25	2.03	2.56	168.10	**19.20**
26	2.92	3.30	184.20	**19.60**
27	2.80	3.25	212.20	**16.78**
28	2.42	2.90	144.64	**18.48**
29	2.63	3.15	128.30	**19.67**
30	3.80	4.18	111.50	**20.30**
Mean	**2.19**	**2.65**	**145.47**	19.69

The maximum wind speeds for April, 10 m and 30 m, 2015 were 3.70 m/s and 4.18 m/s the minimum wind speeds were 1.42 m/s and 1.85 m/s and the shear exponent and shape parameters were 0.17 and 0.044 respectively. The wind speeds were fairly low during this month due to attributes of weather such as low hourly temperature differences.

Table 4.3: Wind characteristics data for the month of May, 2015

DAY	**Speed, v_1 (m/s) (10 m height)**	**Speed, v_2 (m/s) (30 m height)**	**Wind direction (degrees)**	**TEMP (^{0}C)**
1	3.72	4.33	109.30	**20.74**
2	5.83	7.30	87.30	**21.13**
3	5.97	6.81	104.50	**21.15**
4	3.66	4.05	163.00	**19.56**
5	3.94	4.37	106.20	**20.10**
6	2.30	2.72	159.60	**19.81**
7	3.40	3.81	180.50	**20.70**
8	3.52	4.09	134.00	**19.67**
9	2.60	3.02	253.00	**20.30**
10	2.59	3.00	207.00	**19.82**
11	2.77	3.05	170.63	**20.11**
12	2.48	2.87	215.00	**19.88**
13	2.50	2.91	167.00	**20.61**
14	2.11	2.53	152.20	**20.64**
15	2.33	2.95	159.00	**19.12**
16	1.59	2.33	167.00	**19.32**
17	1.50	1.91	155.20	**20.72**
18	1.96	2.36	105.90	**19.17**
19	1.97	2.71	74.50	**19.16**
20	2.21	2.80	110.30	**19.62**
21	1.92	2.23	148.10	**18.97**
22	2.39	2.84	171.10	**19.00**
23	1.98	2.53	126.70	**18.80**
24	1.73	2.25	116.10	**19.00**
25	2.22	2.72	84.00	**19.80**
26	2.34	2.76	72.80	**19.73**
27	2.06	2.51	112.90	**20.20**
28	1.80	2.20	151.50	**19.60**
29	1.81	2.20	134.40	**19.30**
30	3.02	03.43	55.90	**19.32**
31	1.73	2.14	74.10	**18.50**
Mean	**2.61**	**3.11**	**139.64**	19.6

The maximum wind speeds for May, 10 m and 30 m, 2015 were 5.97 m/s and 7.3 m/s and the minimum wind speeds were 1.50 m/s and 1.91m/s and the shear exponent and shape parameters were 0.16 and 0.032 respectively. The weather fluctuation led to a big range of wind speed during the month of May.

The monthly wind speed averages' patterns indicated by tables 4.1, 4.2 and 4.3, portray, unpredictable and attribute of weather (Miller, 2005), which led to different temperatures patterns during day and night (Petersen, Mortensen, Landberg, Højstrup & Frank, 1998).

4.2 Monthly Wind Speed Averages

The monthly averages for heights, 10 m and 30 m for Juja were determined. Table 4.4 shows the mean wind speed averages for three months.

Table 4.4: Monthly wind speed averages

Month	March		April		May	
Height (m)	10 m	30 m	10 m	30m	10 m	**30 m**
Average wind speed (m/s)	2.81	3.36	2.19	2.65	2.61	**3.11**

The mean wind speeds (as shown in table 4.4) were fairly low. This implies that the power that can be generated within that duration cannot be for grid connection. Small wind turbines such as modern Vestas turbines would be appropriate for the site (Karekezi and Kithyoma, 2002).

4.3 Wind Shear Exponent and Surface Roughness

The shear exponent and surface roughness were obtained using equations 1.2 and 1.4 respectively in section 2.2 and their values are shown in table 4.5.

Table 4.5: Wind Shear Exponent (α) and Surface Roughness (z_0)

Month	March	April	May	Mean
Shear exponent(α)	0.1627	0.1735	0.1595	**0.1652**
Surface roughness(z_0)	0.0363	0.0441	0.0320	**0.0374**

Wind shear exponent and roughness parameters for Juja were 0.1652 and 0.0374 respectively**.** These parameters are in line by Wieringa, (1998) for a terrain with trees and buildings as indicated in tables 2.1 and 2.2. The average wind shear exponent by

Saoke, (2011) for Juja was 0.16. The deviation of 0.0052 could be due to the presence of a swimming pool near his site since the presence of water bodies influence wind patterns (Kargieve *et al*., (2001).

4.4 Wind Shear Profile

The expected wind speeds at various heights in the three months, extrapolated from the power law and the shear profile are shown in table 4.6 and figure 4.1 respectively.

Table 4.6: **Extrapolated Wind Speeds at Different Heights from the Ground**

Month	10m	30m	50 m	60m	90m	110m	150m
March	2.81	3.36	3.63	3.78	4.04	4.18	**4.40**
April	2.19	2.65	2.82	2.94	3.15	3.25	**3.43**
May	2.61	3.11	3.39	3.51	3.75	3.88	**4.08**

Table 4.6 shows a very gradual increase in wind speed with height between 50 and 150 m. The gradual change in wind speeds above the height of 50 m will result to very small differences in power densities from this height upwards.

Average diurnal wind speeds, wind directions, and temperatures were obtained for the three months. The average wind speeds for Juja at 10 m and 30 m heights were 2.54 m/s and 3.04m/s respectively. Wind shear exponent and roughness parameters for Juja were 0.1652 and 0.0374, with a deviation of 0.0052 and 0.0074 from parameters given by Wieringa, (1998) in table 2.1 and 2.2 respectively. The wind shear profile (figure 4.1) was obtained by use of Windographer software. Hourly and diurnal variation for the whole period of three months is shown by figure 4.1 and 4.2 respectively. The difference between mean wind speeds at a hub height of 50 m and 150 m ranges from 0.64 m/s to 0.81 m/s. This implies that the difference in power densities at 50 m and 150 m will be too small to warrant installation of turbines at 150 m due to cost factor. This is in line with the findings of Saoke, (2011).

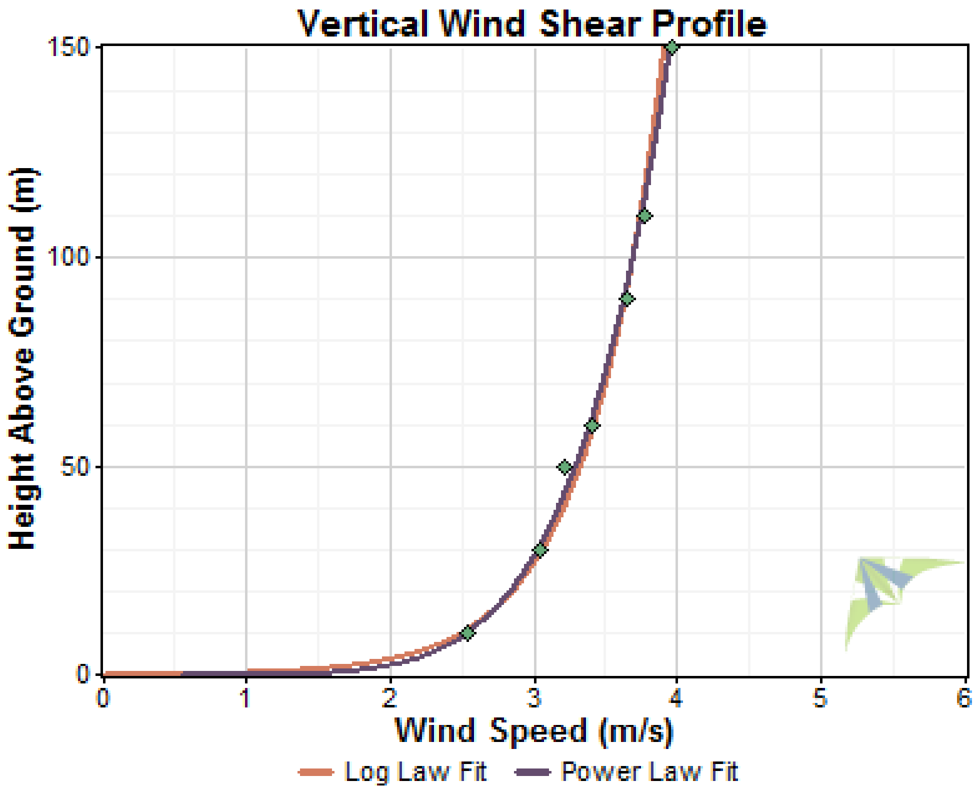

Figure 4.1: Wind Shear Profile (March to May)

The wind profile curves are in line with vertical wind speed profile by Manwell *et al*., 2009. The wind profile power law is a relationship between the wind speeds at two heights while logarithmic wind profile accounts for surface roughness and atmospheric stability. The wind profile power law relationship is often used as a substitute for the logarithmic wind profile when surface roughness or stability information is not available, Robeson & Shein, (1997).

4.5 Variation of Average Wind Speeds

4.5.1 Hourly Variation of Wind Speed

Hourly mean wind speeds were determined from the 10 minutes data and were as indicated in table 4.7

Table 4.7: Hourly wind speed averages (v) in Juja (March-May, 2015)

Hour	00:00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
v (m/s)	2.62	2.33	2.26	1.80	1.58	1.63	1.90	1.75	1.91	2.19	2.31	2.40	3.33	3.11	3.58	4.02	4.72	4.23	3.35	2.95	3.1	2.95	3.10	3.20

A graph of average hourly wind speeds against hour of the day yielded figure 4.2

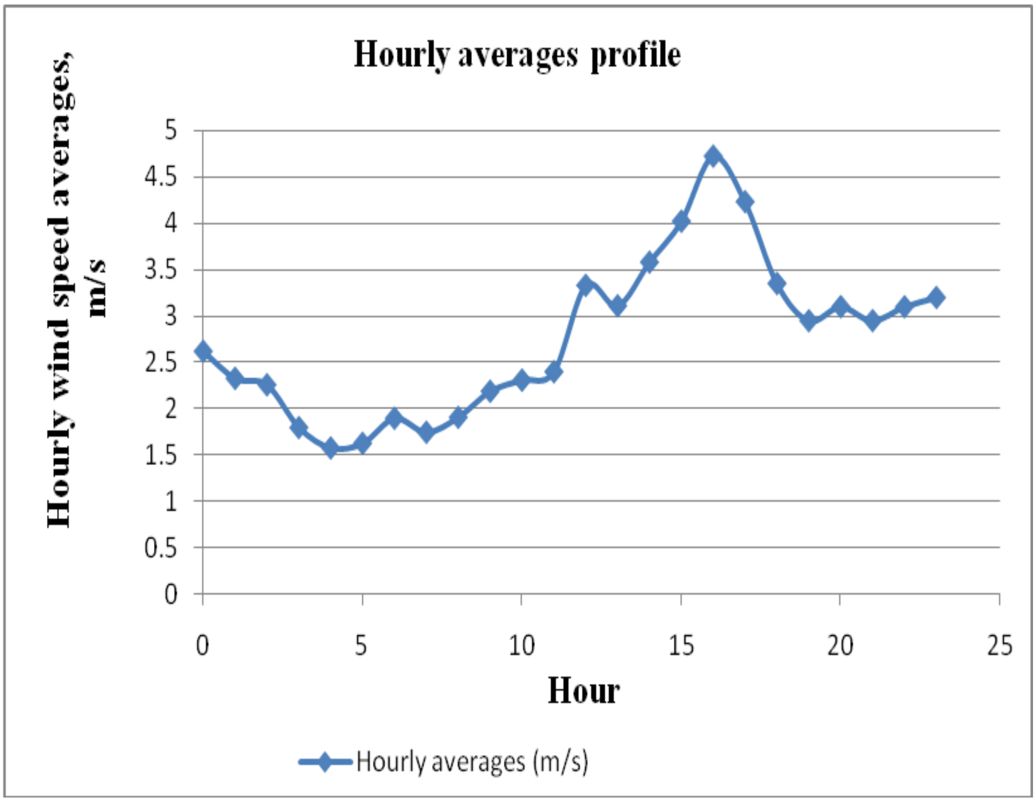

Figure 4.2: Hourly wind speed averages

Figure 4.2 shows that the highest wind speed values were recorded between 3.00 – 6.00 pm. This is as expected because air in the lower atmosphere is heated from the ground upward. The sunlight warms the ground and air above is warmed by conduction, convection and infrared radiation. Since air is a poor thermal conductor, it takes times for layers of air above the ground to be heated up. The temperature gradient /pressure gradient was greatest within this range and hence the stronger winds (Gottfried, 2005).

4.5.2 WindRose Diagrams (Wind power density Per Wind Direction)

WindRose diagrams were used to analyze wind direction, showing the frequency with which wind blows from the different directions. The monthly windRose diagrams are shown in figures 4.3 to 4.8 and the overall ones by 4.9 (a) and (b). Different colours represent different ranges of wind power densities resulting from different ranges of wind speeds in the two sites. The longer the arm, the higher the percentage of wind blowing from that direction and the more the wind power generated from the indicated direction.

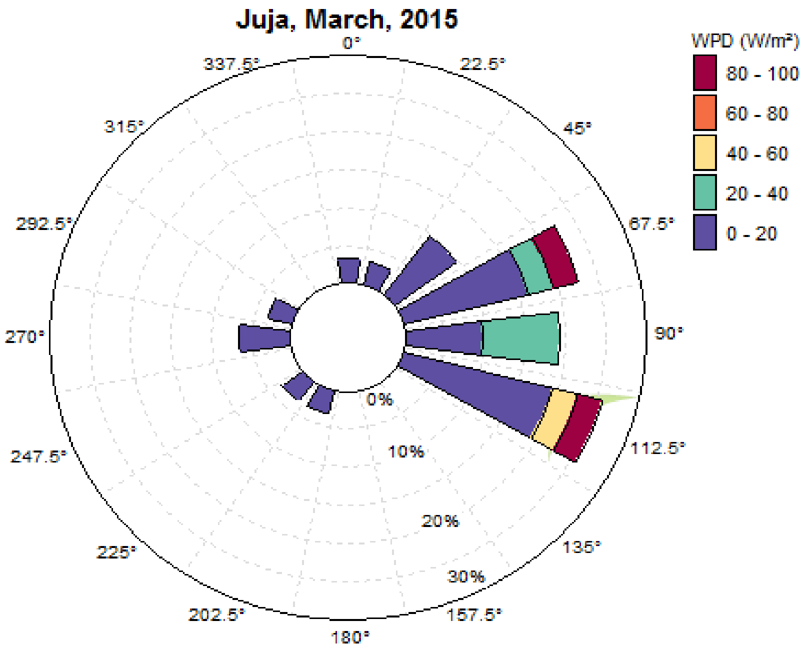

Figure 4.3: WindRose, Juja Site, March, 2015

Figure 4.3 shows the range of most frequent wind is about 50^0– 120^0, (between ENE and ESE directions with modal power density range being 0-20 W/m².

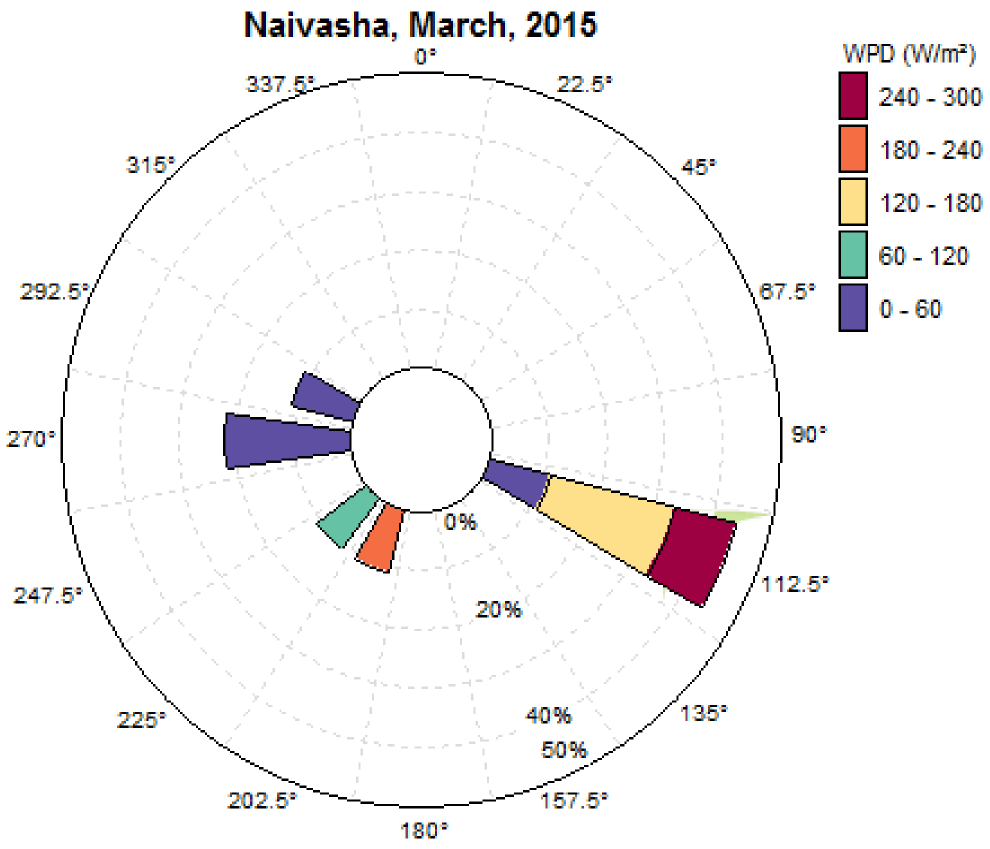

Figure 4.4: WindRose, Naivasha site, March, 2015

Figure 4.4 shows that wind predominantly blew from between ESE and SW with modal power density range being 0-60 W/m². This month had the highest wind power density in the three months of study due to high temperature differences.

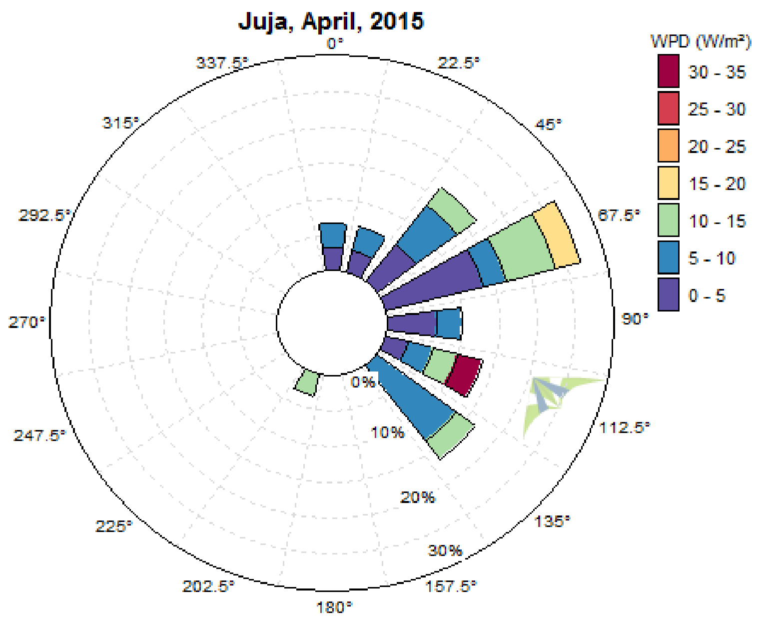

Figure 4.5: WindRose, Juja site, April, 2015

Figure 4.5 shows that wind predominantly blew between NE and SE directions (45-135 degrees) with modal power density range being 5-10 W/m².

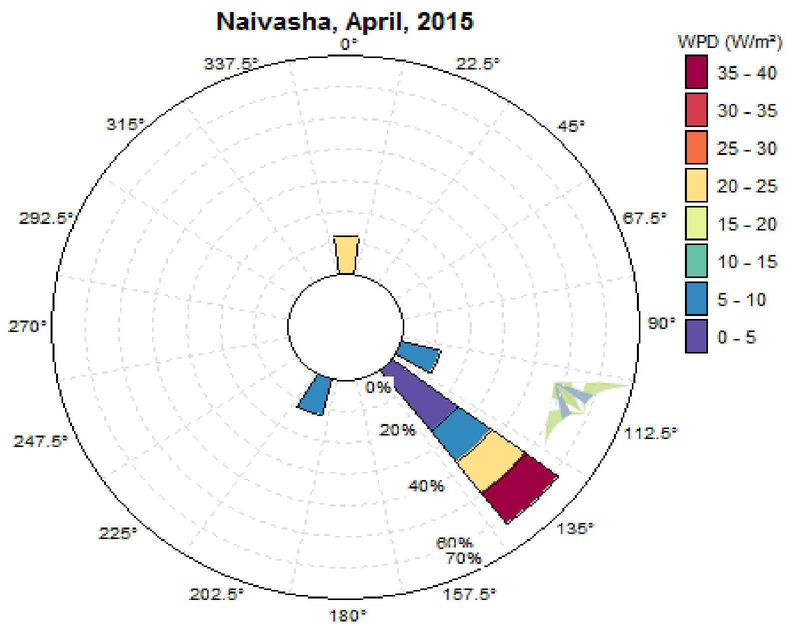

Figure 4.6: WindRose, Naivasha site, April, 2015

Figure 4.6, shows that wind predominantly blew from SE (120-140 degrees) direction with modal power density range being 5-10 W/m².

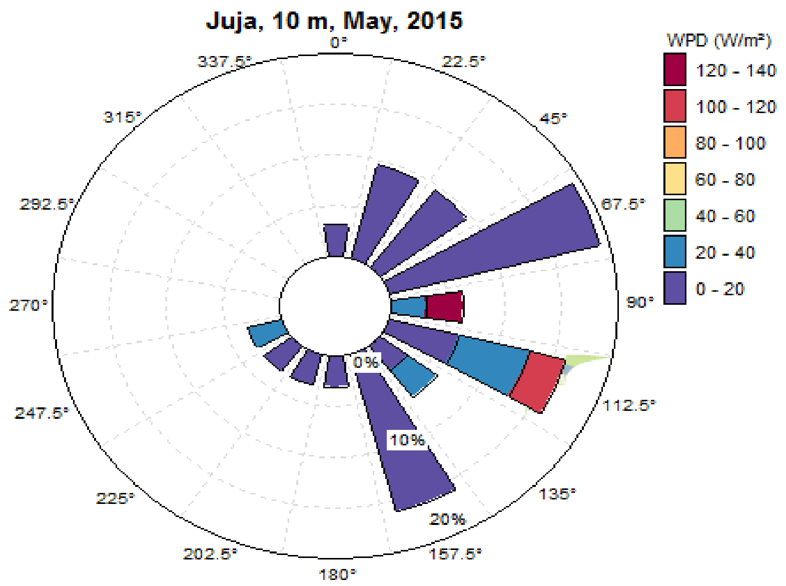

Figure 4.7: WindRose, Juja site, May, 2015

Figure 4.7 shows that wind predominantly blew between NE and SES directions with modal power density range being 0-20 W/m². This month had highest fluctuations in the three months which was caused by change in weather.

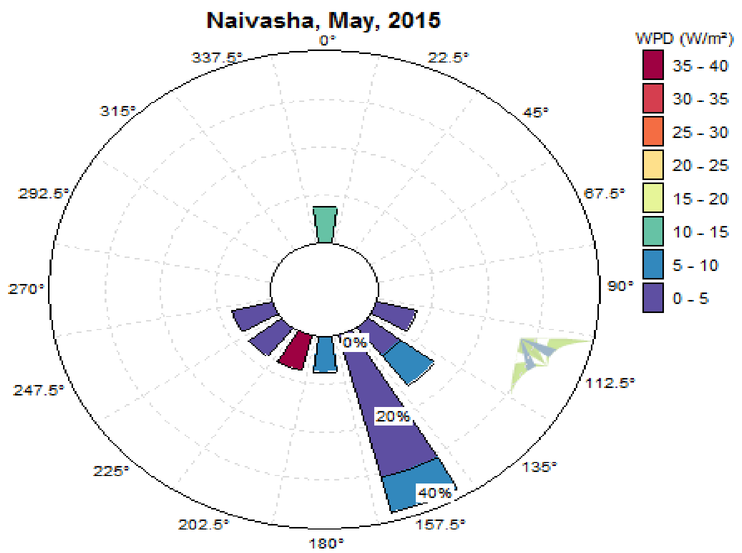

Figure 4.8: WindRose, Naivasha site, May, 2015

Figure 4.8 shows that wind predominantly blew between SE and SW directions (about 140-225 degrees) with modal power density range being 0-5 W/m².

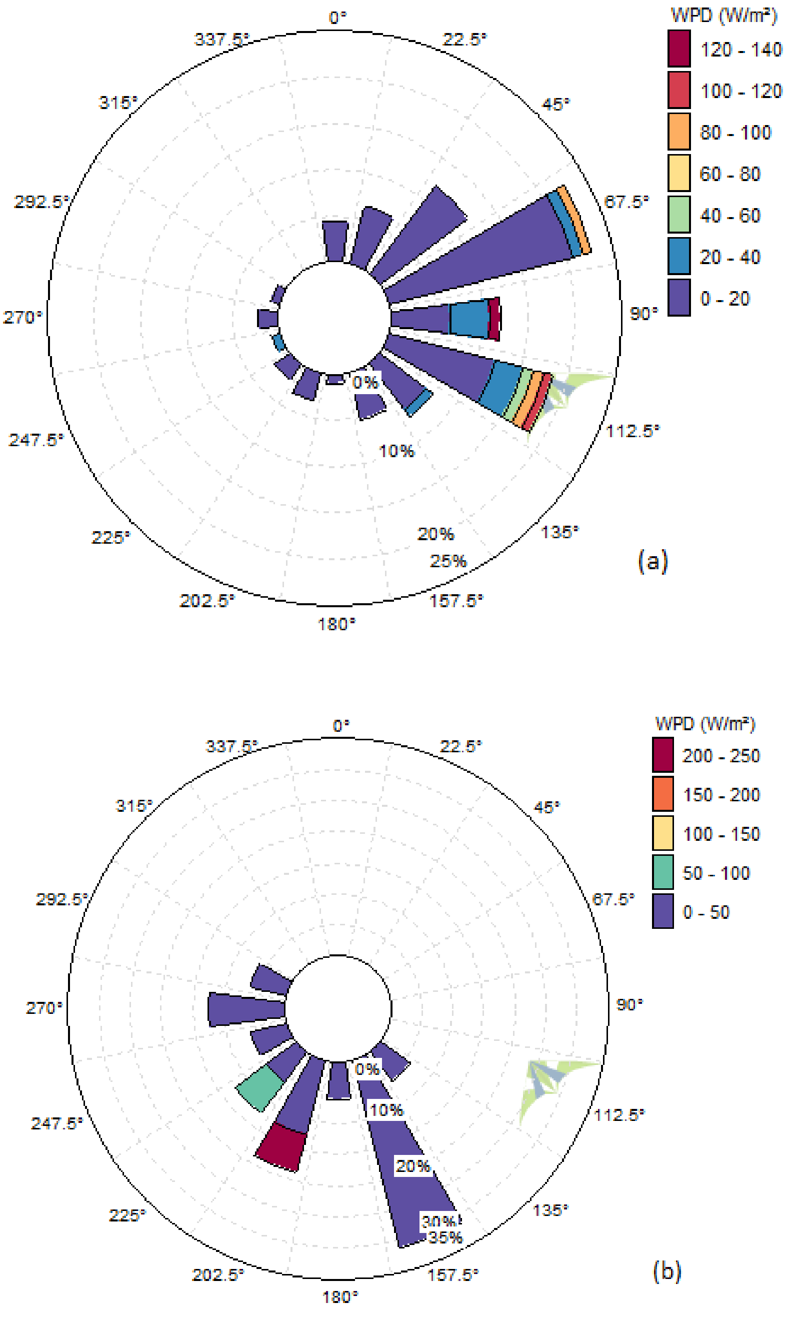

Figure 4.9: Overall WindRose (a) Juja site and (b) Naivasha site

Most Juja wind was between east north east (ENE) and east south east (ESE) while that of Naivasha was between south east (SE) and south west (SW). The windRose diagrams are almost unidirectional which implies that horizontal axis turbines can be recommended for power generation in the two sites. This will minimize cost due to absence of a yaw.

4.5.3 Weibull Parameters, Probability Density Functions and Power Densities

The wind speeds were used to determine Weibull shape parameters (k), scale parameters (c) and wind power densities, for different methods. Windographer software and Microsoft Excel were used to determine and generate the parameters and Probability Distribution Functions (PDFs). The Weibull parameters and wind power densities for different methods are given in table 4.8 and 4.9 respectively.

Table 4.8: Weibull parameters for Different Methods

Method	**At a height of 10 m (Juja site)**		**At a height of 30 m (Juja site)**		**Naivasha (St. Xavier)**	
	c (m/s)	k	c (m/s)	k	c (m/s)	k
Weibull-fit	2.811	2.937	3.646	3.394	4.209	2.390
Regression	2.937	2.773	2.937	2.773	2.718	1.810
MLH	2.394	1.261	2.652	0.943	2.635	0.943

Different methods yielded different values of Weibull scale parameters c and shape parameters k. The values of scale parameter, c and shape parameter k, ranged from 2.394 m/s to 4.209 m/s and 0.943 to 2.937 respectively. The low values of k show the skewing of wind towards lower wind speeds.

4.5.4 Probability Distribution Functions (PDFs)

The Probability Distribution Functions generated from Weibull parameters obtained from different methods are indicated in figures 4.10, 4.11, and 4.12. The areas under PDF curves represent power densities, which were generated using Microsoft excel.

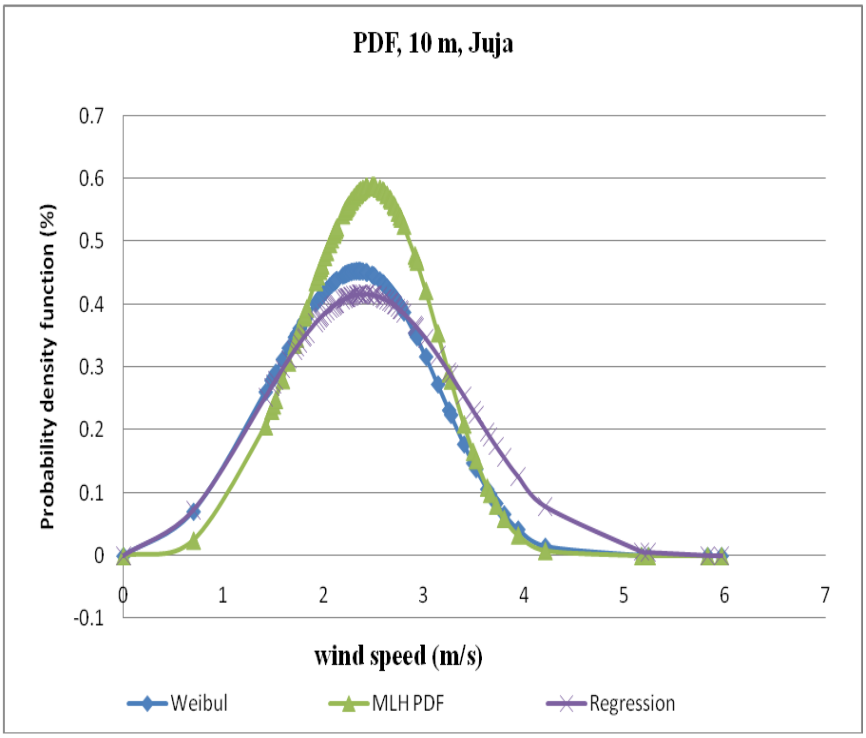

Figure 4.10: Probability Distribution Function (PDF), 10 m, Juja

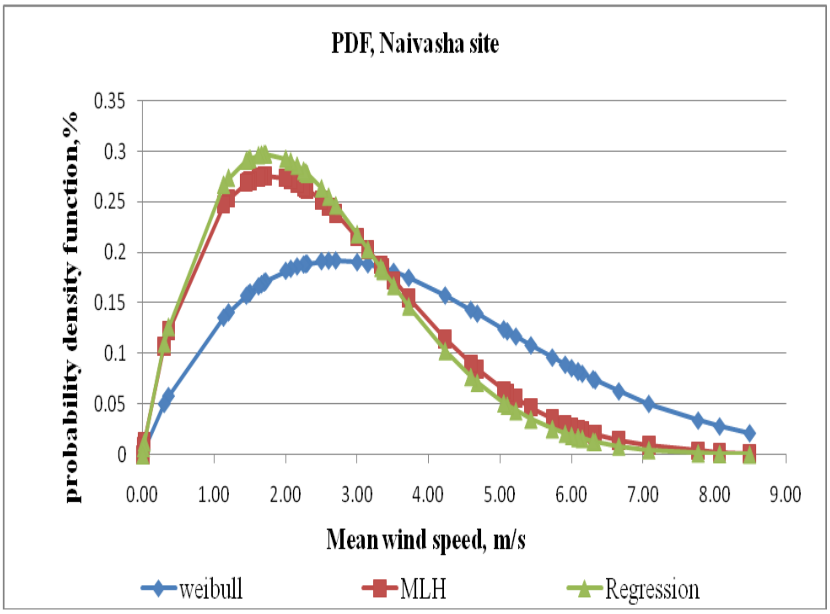

Figure 4.11: Probability Distribution Function (PDF), 10 m, Juja

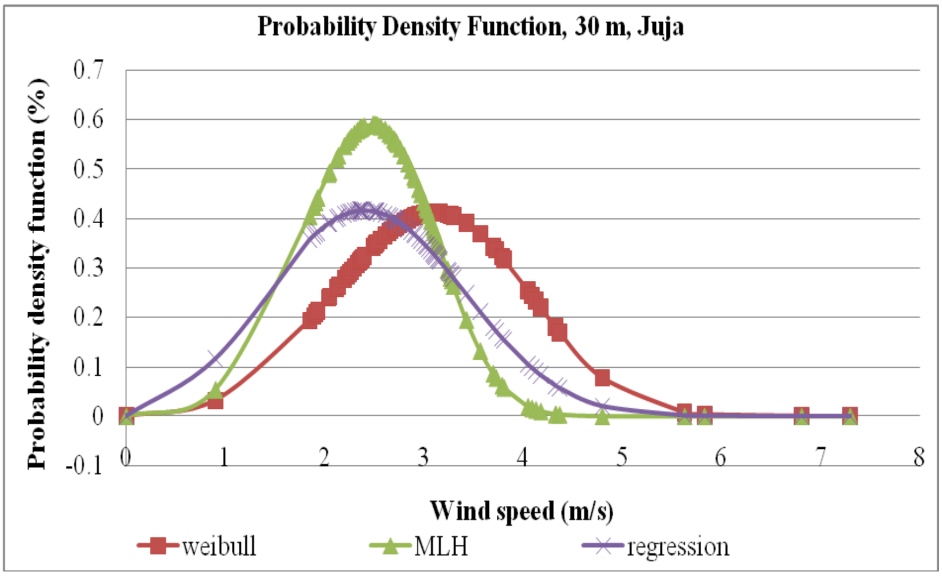

Figure 4.12: Probability Distribution Functions (PDF), 30 m, Juja

The curves show varying wind speed distributions inclined towards the lower wind speeds. This is dependent on prevailing weather conditions of the sites, (Manwell *et al.*, 2009). The wind power densities obtained from different methods are indicated in table 4.9.

Table 4.9: Wind power densities

		Wind Power Density (W/m^2)		
Height	Parameter	Weibull- fit	Regression	MLH
10 m (Juja Site)	W	13.81	13.7	10.5
	E_W	0.09	-0.08	0.17
	R	16.81	16.2	10.4
	E_R	0.17	0.12	-0.28
30 m (Juja Site)	W	22.24	18.81	20.70
	E_W	-0.09	-0.08	0.01
	R	36.85	19.26	14.18
	E_R	0.19	0.18	0.39
10 m (Naivasha site)	W	36.52	18.42	64.90
	E_W	0.17	0.36	0.45
	R	56.70	15.27	13.91
	E_R	0.03	0.46	-0.51

The methods of analysis yielded different values of power densities. This was also portrayed in errors obtained using Weibull (E_W) and Rayleigh (E_R) models of analysis. This can be attributed to conditions or assumptions under which each method was established. The mean wind power densities for Juja (10 m and 30 m) and Naivasha (10 m) were 12.68 W/m², 20.65 W/m² and 39.95 W/m² by Weibull model and 14.51 W/m², 22.43 W/m² and 28.63 W/m² by Rayleigh model respectively. Error analysis was done using equation 1.22.

The results on power density showed Weibull-fit being the method of best fit for Juja and Maximum Likelihood for Naivasha at 10 m by Weibull distribution model while Regression fits Juja best and Weibull-fit Naivasha by Rayleigh model respectively. This implies that power density for any selected site should be obtained using different methods in order determine the actual state of the wind in the site.

4.5.5 Frequency Distribution Functions (FDFs)

Generated Frequency Distribution Functions are indicated in 4.13, 4.14, and 4.15. These were plots of frequencies against wind speeds. These distribution curves show how many instances there are of each value of wind speed.

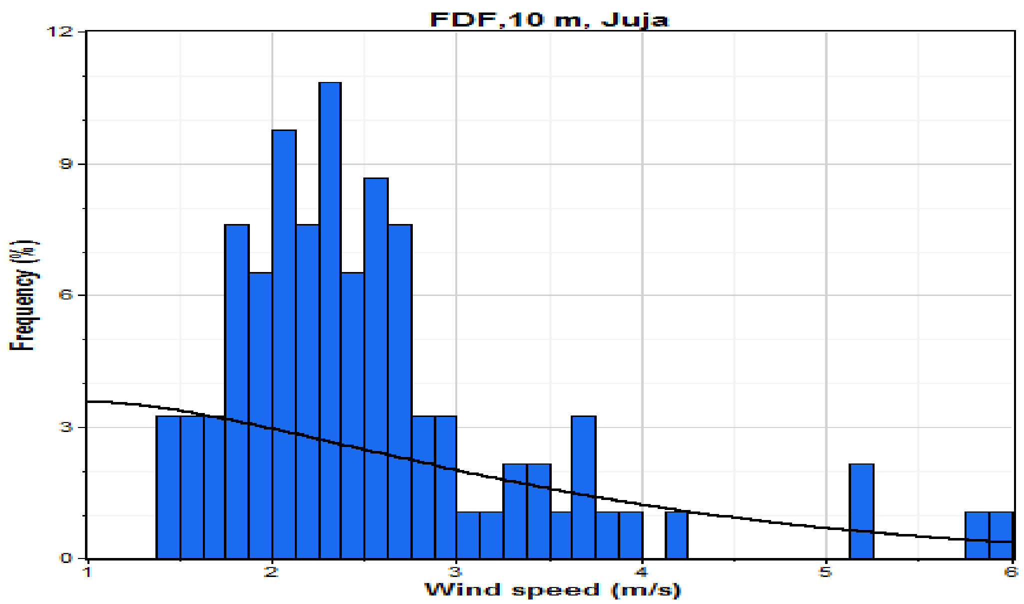

Figure 4.13: Frequency Distribution Function (FDF), 10 m, Juja

Figure 4.13 shows a modal frequency of about 2.2 m/s and decrease in frequency towards higher winds. This implies that 10 m height in Juja is not appropriate for wind power generation for gid connection.

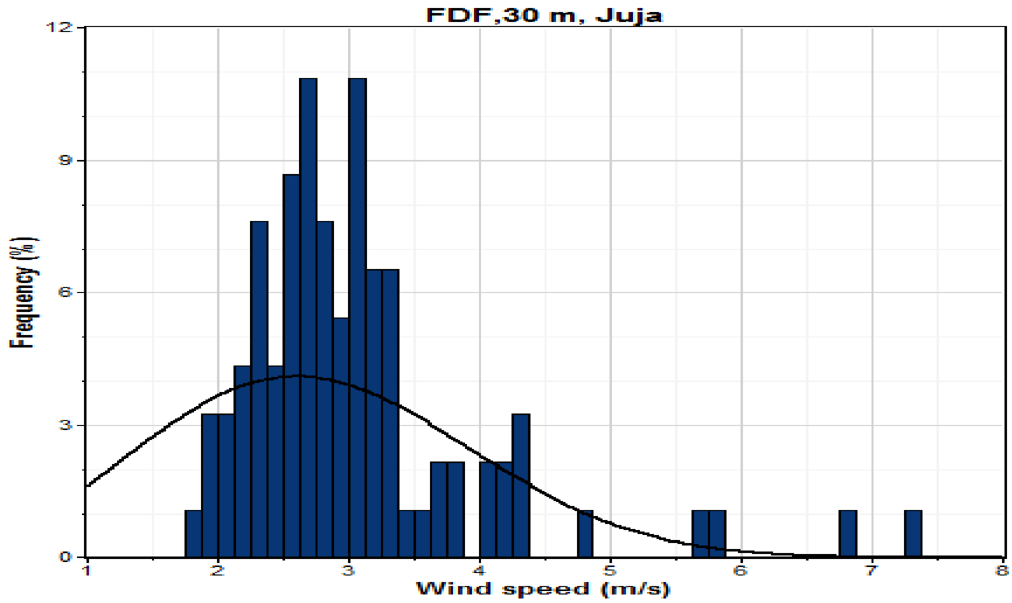

Figure 4.14: Frequency Distribution Function (FDF), 30 m, Juja

Figure 4.14 shows a modal frequency of about 2.6 m/s and a best-fit Weibull frequency distribution curve that is skewed towards lower wind speeds.

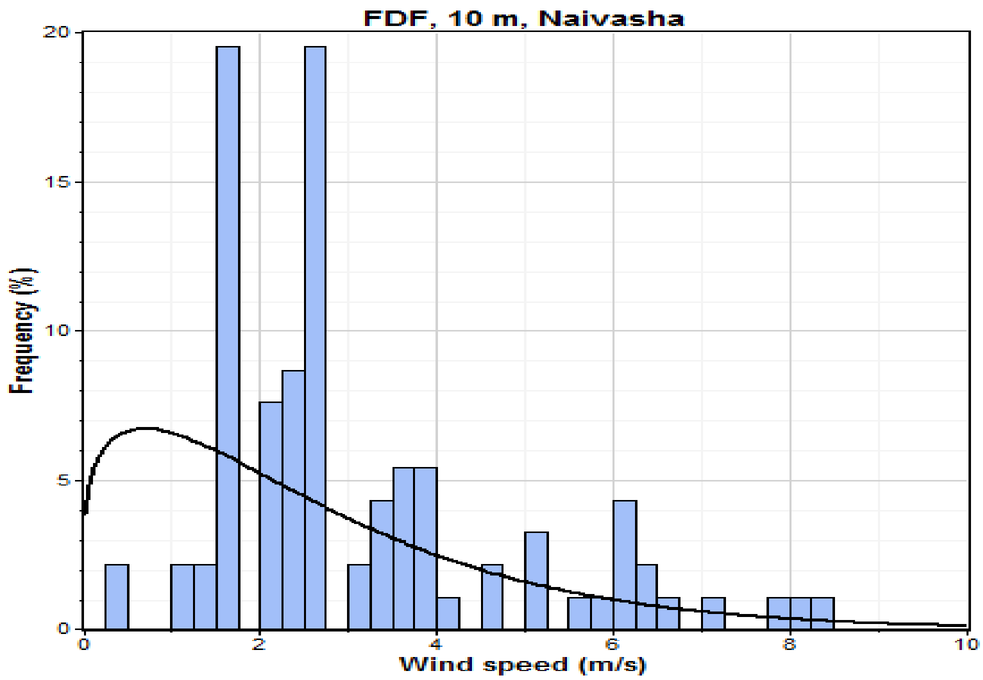

Figure 4.15: Frequency Distribution Function (FDF), Naivasha

Figure 4.15 shows a modal frequency of about 2.5 m/s, though with higher wind speeds than Juja site. This implies that more wind power can be generated from Naivasha site than Juja, at a height of 10 m.

In general, figures 4.13, 4.14 and 4.15 show best-fit Weibull curves that are positively skewed. This in implies that the wind speeds in the two sites are skewed towards lower wind speeds and therefore the wind power that can be generated from the two sites can only be applied in stand-alone systems but not for grid connection (Forsyth, 2009).

4.6 Recommended Turbine's Specifications

Juja and Naivasha sites, having low wind speeds, require a wind turbine with minimal cut-in speed. The specification of a turbine recommended is a HAWT upwind turbine (for micro-production) by Karekezi and Kithyoma, (2002), with specifications indicated in table 4.10.

Table 4.10: Specifications of recommended wind turbine for Juja site

cut-in speed	Rated power	Rated power wind speed	MAX power	MAX power wind speed	Cut-out wind speed	Rotor diameter	Swept area,	Number of rotor blades
1.3 m/s	600 W	11 m/s	1100 W	16 m/s	25 m/s	1.7 m	2.27 m^2	3

This type of a turbine can generate and feed power to stand-alone systems. This is because it will be able to capture a long range wind speeds and convert it into useful power. It can be installed on a roof and be used in battery charging, (Forsyth, 2009; Karekezi and Kithyoma, 2002).

4.7 Number of Hours when Wind Speed was above Cut-in Speed for March, 2015

The daily number of hours and monthly percentages above cut-in speed (of 3.5 m/s) analysis' based on 10 minutes intervals was done and results obtained are indicated in table 4.11

Table 4.11: Daily number of hours above cut-in speed of 3.5 m/s

Date	Number of hours above cut-in speed at 10 m		
	March	April	May
1	10.54	4.50	6.50
2	17.80	6.67	23.17
3	14.50	5.53	20.50
4	5.00	5.00	18.67
5	3.00	4.25	10.49
6	4.00	2.17	15.23
7	6.72	4.25	10.67
8	6.33	2.17	8.23
9	6.00	4.25	6.23
10	6.62	4.50	5.87
11	7.27	2.85	4.67
12	4.92	3.33	4.39
13	3.73	3.33	4.00
14	6.40	2.00	5.16
15	6.60	7.25	3.29
16	7.30	4.93	3.11
17	6.40	10.00	3.40
18	6.00	7.50	5.00
19	4.00	3.17	1.67
20	3.98	3.83	2.13
21	6.00	4.50	6.17
22	10.00	6.17	4.67
23	6.33	4.40	2.17
25	6.00	4.67	4.00
26	9.57	5.50	4.17
27	8.33	3.96	3.50
28	8.40	4.21	3.50
29	8.83	2.96	3.17
30	5.00	3.15	4.17
31	7.00	-	2.00
Total	705.36	132.05	210.57
Mean	7.024	4.553	6.793
Mean- monthly percentages, %	**29.39**	**18.97**	**28.30**

Statistics showed that 29.39%, 18.87% and 28.30% of daily number of hours had wind speed above 3.5 m/s, which is sufficient for power generation using variety of wind turbines in the market such as the V90-3.0 MW® IEC IA/IIA which is a great choice for high and medium wind sites with high turbulence and is designed for easy transportation and installation while reducing foundation costs (Karekezi and Kithyoma, 2002). The percentages of number of hours when mean wind speeds are greater than cut-in speed of 3.5 m/s based on 10 minutes intervals give a better state of wind than daily averages.

4.8 Data Correlation for Juja and Naivasha, 10 m

The results from Juja, 10 m, site were correlated with results from Naivasha during the same months. This was to investigate wheather altitude has any effect on method of analysis. This invoved correlation between mean daily wind speeds and probability density functions for the two sites.

4.8.1 Correlation of Mean daily Wind Speeds

Daily wind speeds averages for Juja were compared with results from Naivasha sites and were as shown in figures 4.16, 4.17 and 4.18

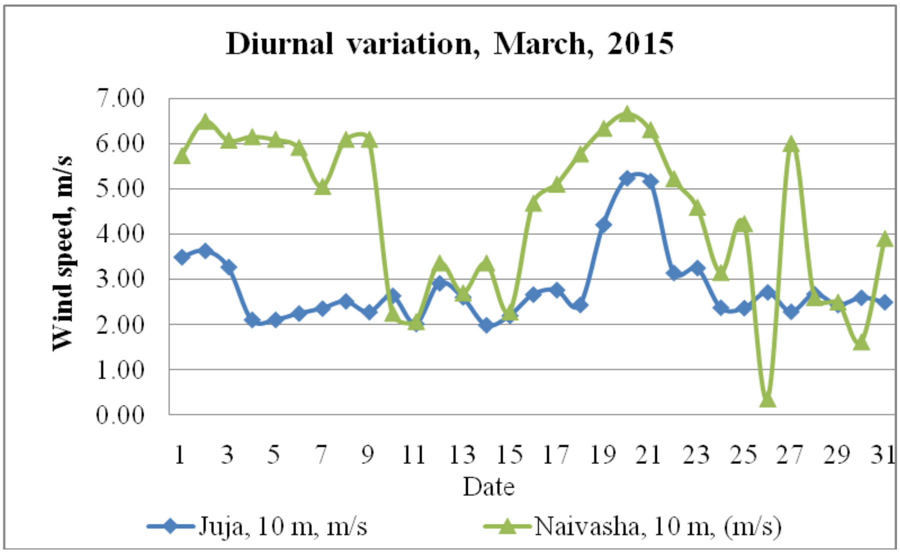

Figure 4.16: Diurnal profiles March, 2015

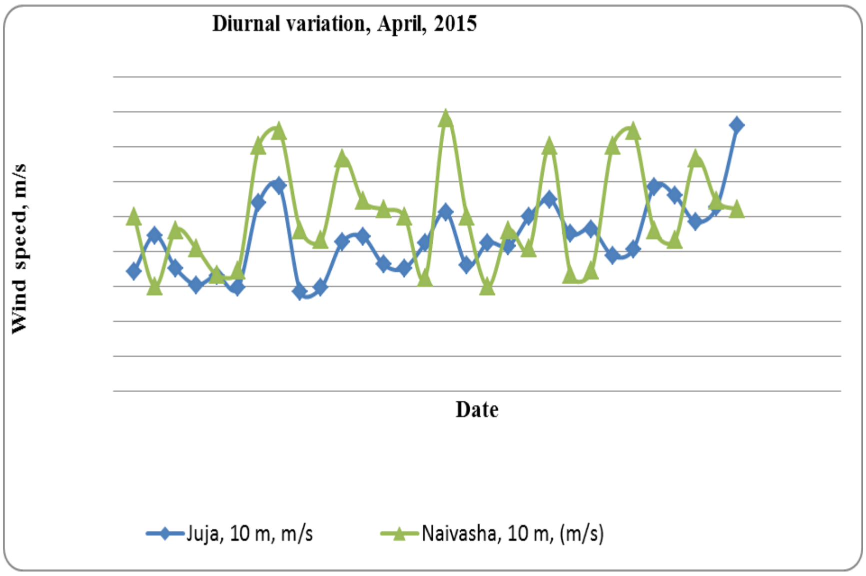

Figure 4.17: Diurnal profiles April, 2015

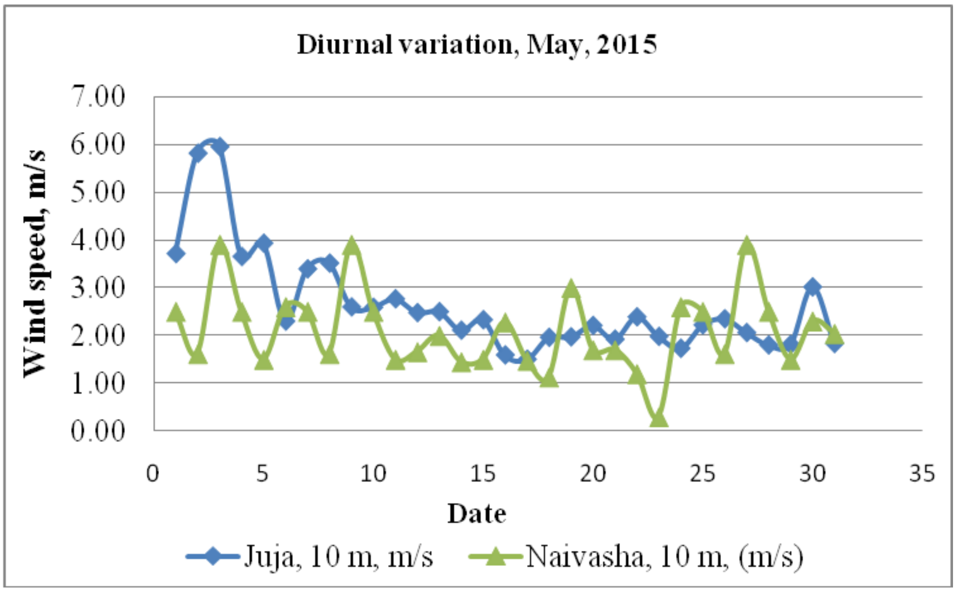

Figure 4.18: **Diurnal profiles May, 2015**

The two sites had low wind speeds of wind class 1, though wind speeds in March and at the beginning of May, were slightly higher due to higher daily temperatures. Diurnal profile portrays higher wind speeds in Naivasha than Juja site for the three months. Since the wind flow patterns are modified by the earth's terrain, bodies of water and vegetative cover which determine the degree of roughness (Saoke, (2011;

Kargieve *et al*., 2001), higher wind speeds in Naivasha can be attributed to the effect of the lake Naivasha and channelling effect of the Rift valley and the nearby hills.

4.8.2 Correlation of Wind Power Density

The wind power density correlation-regression for Juja and Naivasha sites is shown in figure 4.19.

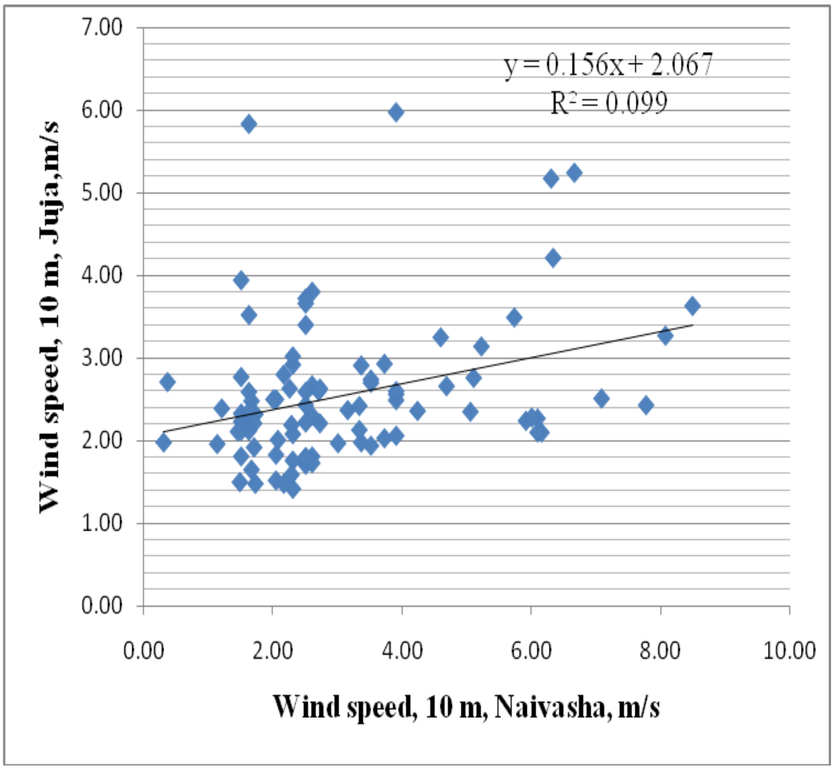

Figure 4.19: The WPD regression

Wind power density for Juja site (y-axis) was plotted against that of Naivasha (x-axis). The average linear regression equation is y = 0156x + 2.067. The correlation coefficient, 0.099, is greater than common level of 0.05 and is therefore not statistically significant which implies that the regression equation is not reliable for future predictions (Clogg, Petkova, & Haritou, 1995). The diurnal profile and linear regression equation portray higher wind speeds in Naivasha than Juja site for the three months. Since the wind flow patterns are modified by the earth's terrain, bodies of water and vegetative cover which determine the degree of roughness, (Akpinar & Akpinar, 2004; Kargieve *et al*., 2001; Wieringa, 1993), higher wind speeds in

Naivasha can be attributed to the effect of the lake Naivasha and channelling effect of the Rift valley and the nearby hills such as Longonot. Wind also tends to have higher velocities at a higher attitude (Rai, 1988) of which is the case of Naivasha site as compared to Juja site.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Wind energy analysis for Juja in the month of March to May, 2015 showed low wind speed averages ranging from 0.3 m/s to 3.54 m/s which resulted to low power density, rated as wind class 1. The wind speed averages for heights 10 m and 30 m were 2.54 m/s and 3.04 m/s respectively. The percentages of number of hours above cut-in speed of 3.5 m/s for March, April and May were 29.39%, 18.87% and 28.30% respectively. Weibull scale and shape parameters were obtained using Weibull-fit, Regression and Maximum LikeliHood. The wind speed distribution was modeled using the Weibull function. Results obtained from Juja site were compared with results acquired from Naivasha. The mean wind power densities for Juja (10 m and 30 m) and Naivasha (10 m) were 12.68 W/m², 20.65 W/m² and 39.95 W/m² by Weibull model and 14.51 W/m², 22.43 W/m² and 28.63 W/m² by Rayleigh model respectively. The Weibull-fit and Maximum Likelihood fitted best Juja site and Naivasha site respectively.

5.2 Conclusions

The following conclusions were made from wind data obtained from the two sites:

- Mean wind speed was highest in March and lowest in April. The variation was due to change in monthly weather conditions (fluctuations in temperature and hence pressure gradient).

- The Weibull scale parameters c and shape parameters k ranged from 2.394 m/s to 4.209 m/s and 0.943 to 2.937 respectively. These parameters portray low wind speeds in the two sites.

- The mean wind power densities for Juja (10 m and 30 m) and Naivasha (10 m) were 12.68 W/m², 20.65 W/m² and 39.95 W/m² by Weibull model and 14.51 W/m², 22.43 W/m² and 28.63 W/m² by Rayleigh model respectively. The two sites had wind class 1.

- Power density is dependent on locality/altitude.

- Wind power generated during the three months can only be used in stand-alone systems such as water pumping machines for household use, irrigation and for livestock, but not electricity for grid connection.

5.3 Recommendations

It is recommended that wind energy analysis for different altitude sites be done in future. In addition, the variation of shear exponent with atmospheric stability and surface roughness should be obtained for longer periods, probably a year or more. This would help in eliminating seasonal bias in the information about wind characteristics. Analysis of power densities at different hub heights should be carried out using different methods. Since it was found that wind speeds were of class 1 in the two sites, we recommend design of small wind driven systems such as ventilation systems to supplement grid’s power.

REFERENCES

Aguko, K. P., Nyaanga, D. M., & Onyando, J. O. (2014). Variation of Wind Speeds at the Shore of Lake Victoria (Kenya). *International Journal of Pure and Applied Sciences and Technology*, *20*(1), 36.

Ajayi, O. O., Fagbenle, O. R., & Katende, J. (2011). Wind profile characteristics and econometrics analysis of wind power generation of a site in Sokoto State, Nigeria. *Energy science and technology*, *1*(2), 54-66.

Akpinar, E. K., & Akpinar, S. (2004). Statistical analysis of wind energy potential on the basis of the Weibull and Rayleigh distributions for Agin-Elazig, Turkey. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *218*(8), 557-565.

Celik, A. N. (2004). A statistical analysis of wind power density based on the Weibull and Rayleigh models at the southern region of Turkey. *Renewable energy*, *29*(4), 593-604.

Clogg, C. C., Petkova, E., & Haritou, A. (1995). Statistical methods for comparing regression coefficients between models. *American Journal of Sociology*, 1261-1293.

Forsyth T. (2009). "Small Wind Technology". National Renewable Energy Laboratory available at: http:// www.google.com/small wind energy.

Gipe, P. (2004). *Wind power: renewable energy for home, farm, and business*. Chelsea Green Publishing.

Glossary of Meteorology, (2010). Trade winds. American Meteorological Society. Available at: http://glossary,ametsoc.org

Google Earth. (n.d). Google Earth Map for Juja and Naivasha. Available at: http://www.google.com/earth/.

Huang, J., & McElroy, M. B. (2014). Contributions of the Hadley and Ferrel Circulations to the Energetics of the Atmosphere over the Past 32 Years*.*Journal of Climate*, *27*(7), 2656-2666.

Ibrahim M.Z., (2006). *Renewable Energy*. University Malaysia Terengganu. Kuala Terengganu; Malaysia.

Justus, C. G., Hargraves, W. R., Mikhail, A., & Graber, D. (1978). Methods for estimating wind speed frequency distributions. *Journal of applied meteorology*, *17*(3), 350-353.

Kamau J.N., Kinyua R., and Gathua J.K., (2009). Determination of the wind power parameters by statistical analysis, the case of Garissa; the Second scientific conference proceedings *2*(1): 44-55

Kamau, J. N., Kinyua, R., & Gathua, J. K. (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*, *35*(6), 1298-1302.

Kantar, Y. M., & Şenoğlu, B. (2008). A comparative study for the location and scale parameters of the Weibull distribution with given shape parameter. *Computers & Geosciences*, *34*(12), 1900-1909.

Kantar, Y. M., & Usta, I. (2008). Analysis of wind speed distributions: Wind distribution function derived from minimum cross entropy principles as better alternative to Weibull function. *Energy Conversion and Management*, *49*(5), 962-973.

Karekezi, S. and Kithyoma, W., 2002. Renewable Energy in Africa. Available at: www.afrepren.org/Energy.

Kargieve V.M., Martirosov S.N., Murugov V.P., Pinov A.B., Sokolsky A.K., and Haritonov V.P., (2001*). Wind power engineering, an application guide for wind mills of small and average power*. Intresolar Centre, Moscow.

Kollu R., Rao S., Rayapudi M., Narasimham S. and Pakkurthi K.M. (2012). Mixture probability distribution functions to model wind speed distributions. *International Journal of Energy and Environmental Engineering*, 27 (3), 2251-6832

Linacre E. and Geerts B. (1999). *Roughness length*. Available at: http://www-das.uwyo.edu/~geerts/cwx/notes/chap14/roughness.html

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind energy explained: theory, design and application*. John Wiley & Sons.

Manyonge, A. W., Ochieng, R. M., Onyango, F. N., & Shichikha, J. M. (2012). Mathematical modelling of wind turbine in a wind energy conversion system: Power coefficient analysis. *Applied mathematical sciences*, *6*(91), 4527-4536.

Maulidi B. (2010). Wind Regime Analysis and Reserve Estimation (Case study-Kenya). *M.Sc. thesis.* University of Nairobi, Nairobi, Kenya.

Mbogo S. (2015). 'Works On 3000MW Wind Farm Start' The East African (Nairobi): Retrieved 25 April 2015.

Michael E. R., (2008). "*The Physical Environment: Global scale circulation.*" University of Wisconsin-Stevens, America.

Miller, M. (2005). *Weird, wild & unpredictable: An illustrated history of East Tennessee weather*. Lincoln, NE: iUniverse.

Paitoon S. (2010). Demonstrating Measure-Correlate-predict algorithms for Estimation of Wind Resources in Central Finland; *MSc. thesis*, University of Jyvaskyla, Finland.

Petersen N. G., Mortensen L. Landberg J., Højstrup and Frank H. (1998). Siting of wind farms: Basic aspects. *Wind Energy*, *1*(51), 25-45

Pidwirny M., (2006). "Forces Acting to Create Wind". Fundamentals of Physical Geography, 2nd Edition, University of British Columbia- Okanagan, USA.

Rai G.D., (1988). *Non- Convectional Energy Sources.* Khanna Publishers, Nai Sarak, Delhi.

Rai, R. K., Gopalan, H., & Naughton, J. W. (2015). Effects of spatial and temporal resolution of the turbulent inflow on wind turbine performance estimation. *Wind Energy*. DOI:10.1002/we.1888

Rambo, C. M. (2013). Renewable energy project financing risks in developing countries: Options for Kenya towards the realization of vision 2030.*International Journal of Business and Finance Management*, *1*, 1-10.

Robeson, S. M., & Shein, K. A. (1997). Spatial coherence and decay of wind speed and power in the north-central United States. *Physical Geography*, *18*(6), 479-495.

Sachs, G. (2005). Minimum shear wind strength required for dynamic soaring of albatrosses. *Ibis*, *147*(1), 1-10.

Saoke C.O., (2011). Analysis of wind speeds on Weibull and data correlation for wind pattern description for a selected site in Juja; *M.Sc. thesis*, Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya.

Saucier, W. J. (2003). *Principles of meteorological analysis*. Mineola, N.Y: Dover Publications.

Stuart Y., (2011). *Analysis of United Kingdom wind power generation.* Stuart Young Consulting.

Wekesa D.W., (2012), Microcontroller based on the instrumentation system for wind speed and direction; *M.Sc. thesis*; JKUAT, Kenya.

Wieringa, J. (1998). How far can Agro meteorological station observations be considered representative? Preprint to 23rd American Meteorological Social Conference on Agriculture and Forest Meteorology (Albuquerque).

Williams, B. (2013). *New applications of remote sensing technology for offshore wind power* (Doctoral dissertation, University of Delaware).

Woelfle, G. (2013). *The Wind at Work: An Activity Guide to Windmills*. Chicago Review Press.

Yong, H. O. U., Yidong, P. E. N. G., Johnson, A. L., & Jing, S. H. I. (2012). Empirical analysis of wind power potential at multiple heights for North Dakota wind observation sites. *Energy Science and Technology*, *4*(1), 1-9.

Zhang, L. F., Xie, M., & Tang, L. C. (2006). Robust regression using probability plots for estimating the Weibull shape parameter. *Quality and Reliability Engineering International*, *22*(8), 905-917.

Zhou, J., Erdem, E., Li, G., & Shi, J. (2010). Comprehensive evaluation of wind speed distribution models: A case study for North Dakota sites. *Energy Conversion and Management*, *51*(7), 1449-1458.

APPENDICES

Appendix 1: Plates on experimental process

Plate 4.1: Collecting data from Juja site.

Plate 4.2: Power house at Naivasha

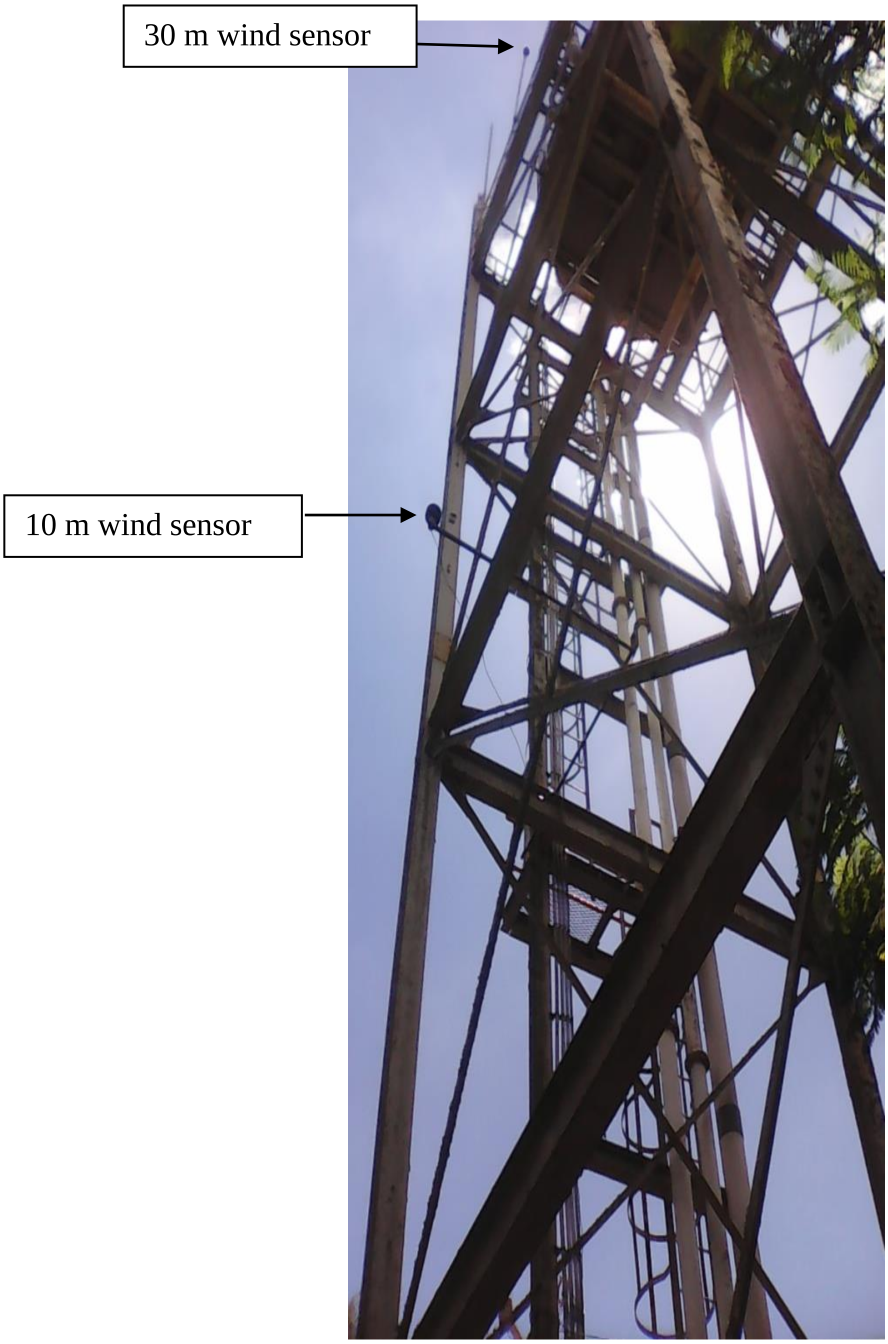

Plate 4.3: Experimental setup in Juja

Appendix 2: Daily Wind Speed Averages Profiles for Juja Site

Daily wind speed profiles generated using MS Excel were as per plates 2.1, 2.2 and 2.3

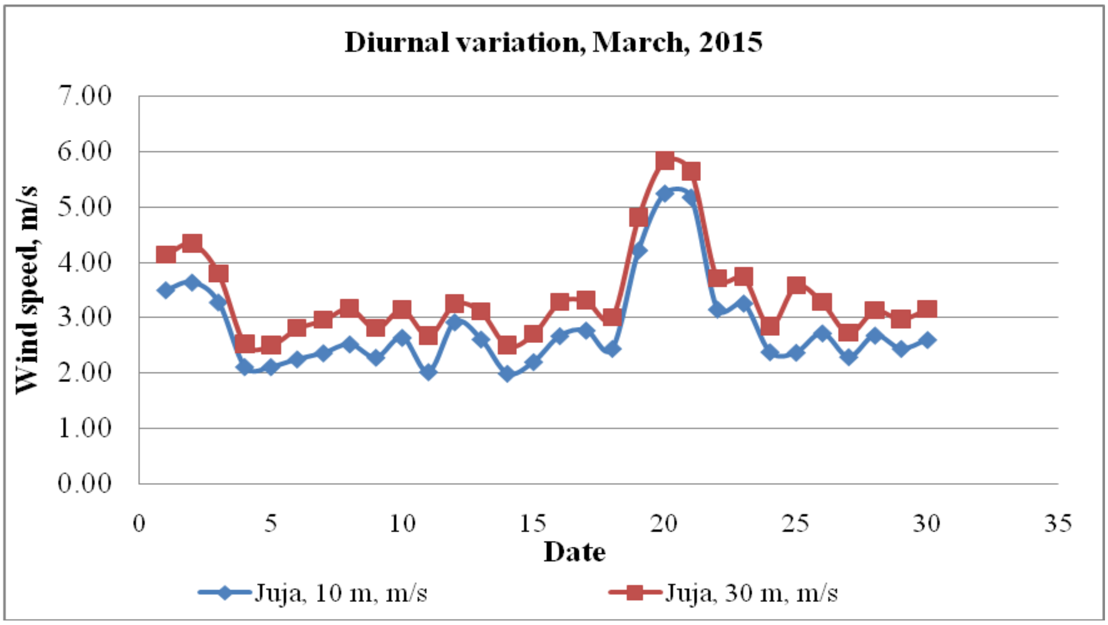

Plate 4.4: Diurnal wind profile for March, 2015, Juja site

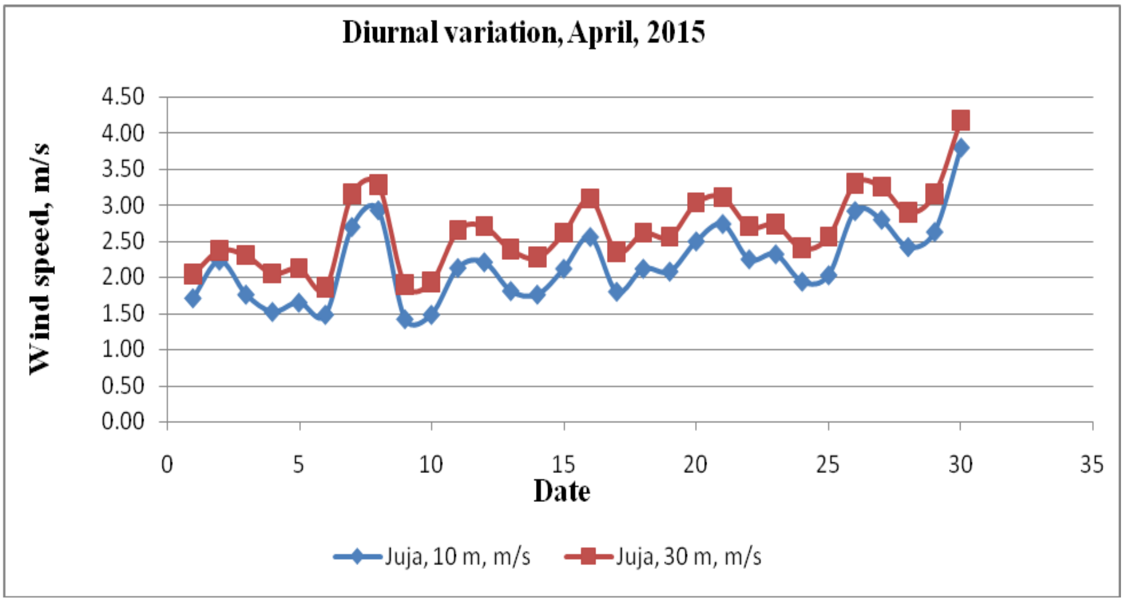

Plate 4.5: Diurnal Wind Profile for April, 2015, Juja site

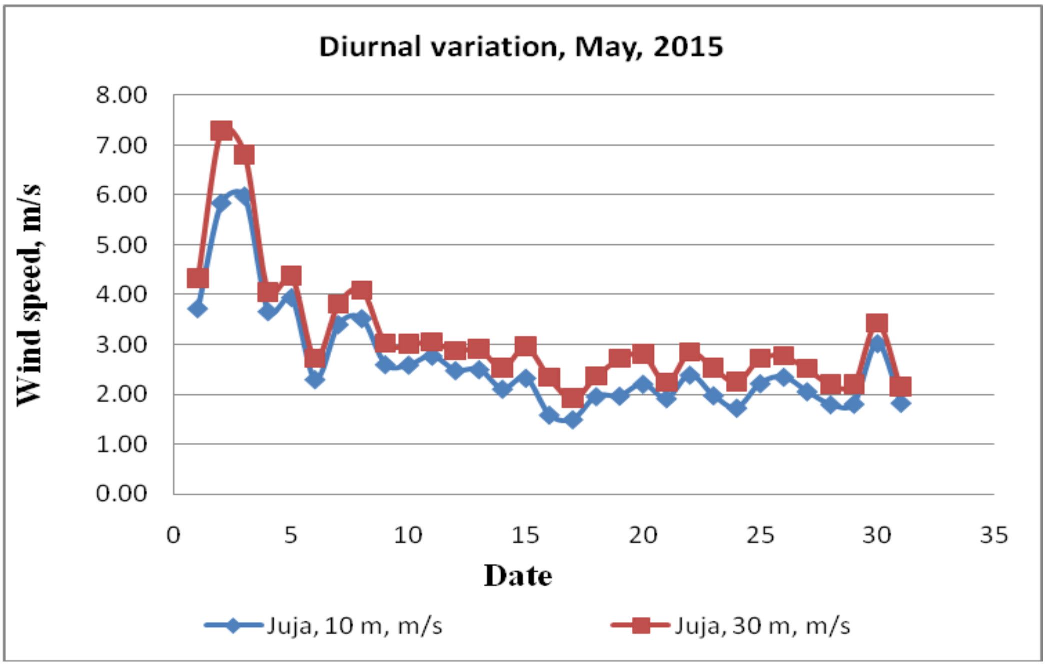

Plate 4.6: Wind Profile for May, 2015, Juja Site

Appendix 3: Figure of overall diurnal variations for Juja and Naivasha sites

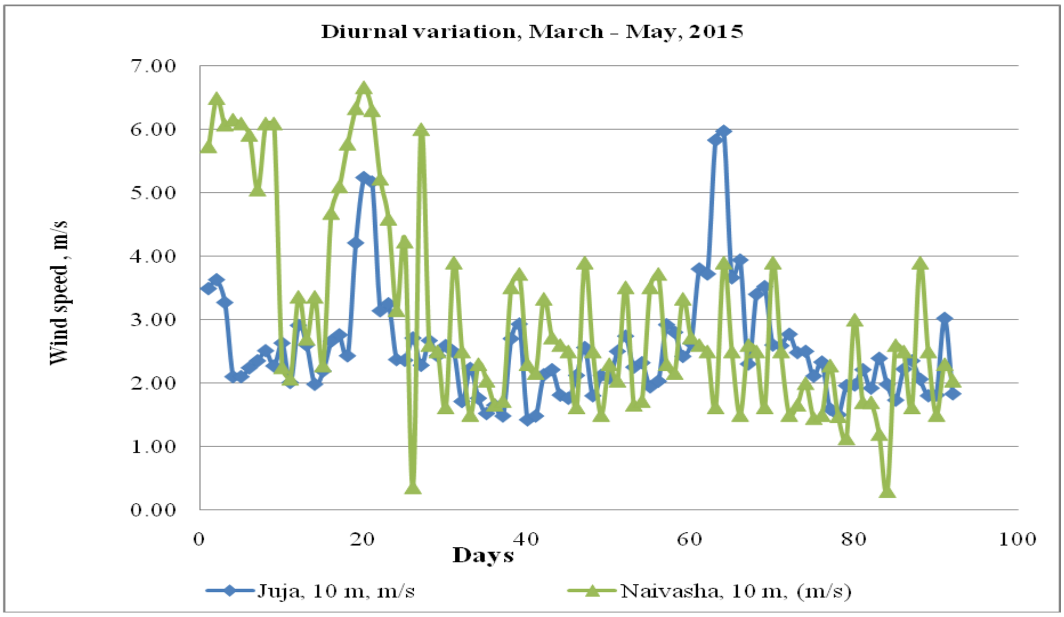

Figure A1: Diurnal wind variation for Juja and Naivasha

Appendix 4: Table of online wind prediction for Naivasha site

Table A1: Naivasha annual averages, 2015

	ANNUAL AVG	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Km/h	10.7	10.8	11.2	11.5	10.8	10.1	9.4	9.7	9.7	11.2	11.9	11.5	11.2
M/s	2.97	3.00	3.11	3.19	3.00	2.81	2.61	2.69	2.69	3.11	3.31	3.19	3.11

Appendix 5: Figures of cumulative frequency curves

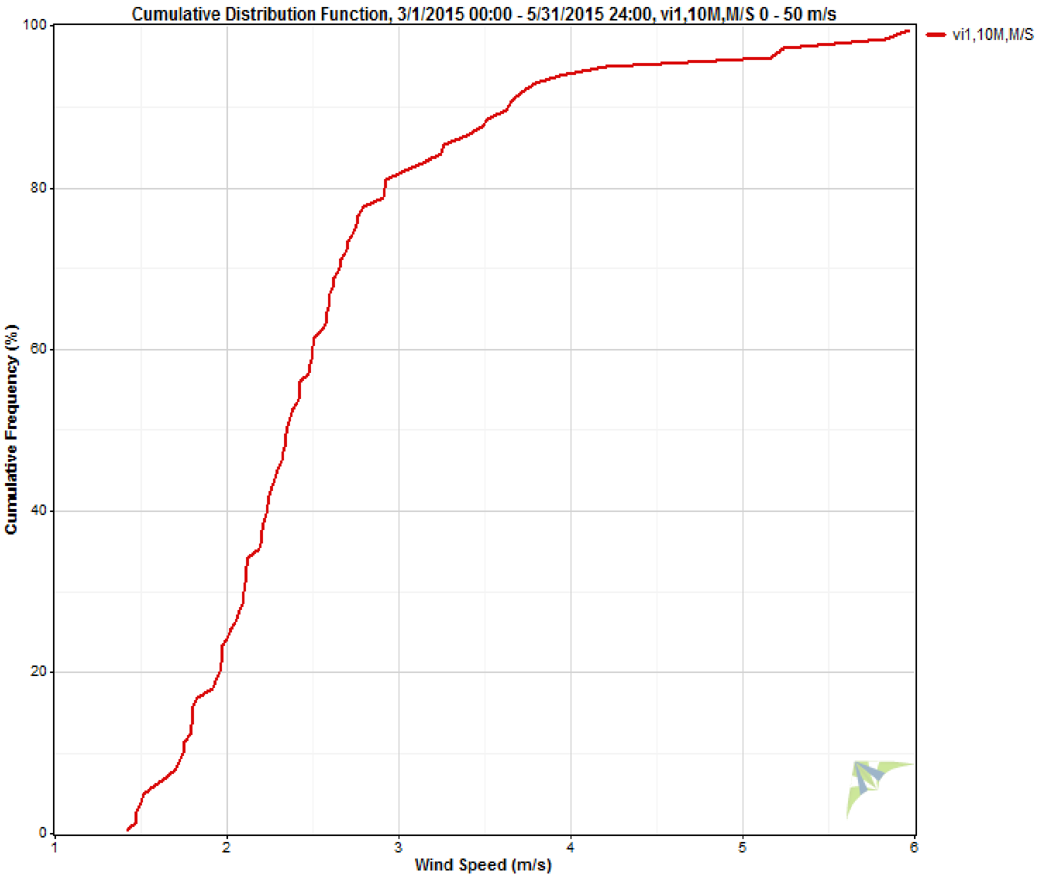

Figure A2: Cumulative Distribution Function at 10 m, Juja

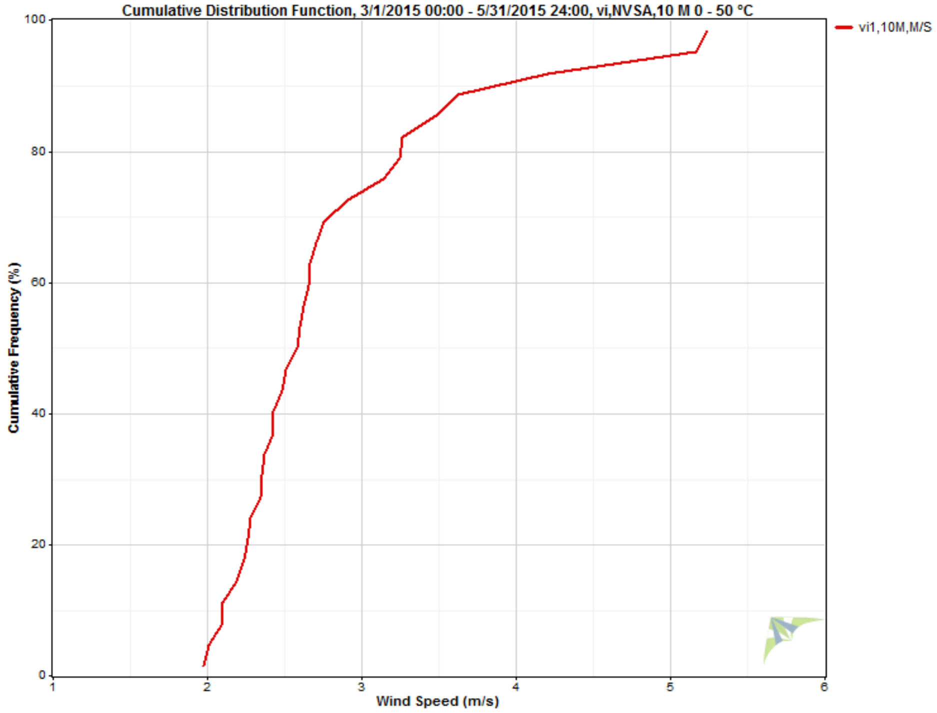

Figure A3: Cumulative Distribution Function at 10 m, Naivasha

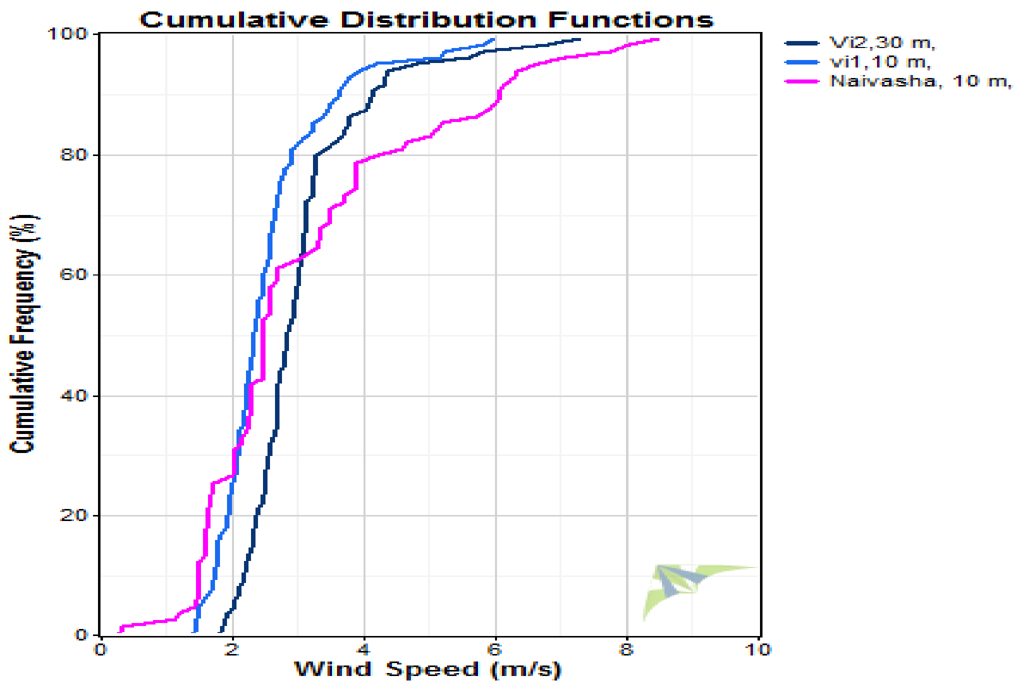

Figure A4: Cumulative distribution functions curves

(Comparison for Juja, heights 30 m and 10 m and at height, 10 m, Naivasha)