ASSESSMENT OF WIND CHARACTERISTICS AND POWER POTENTIAL AT KESSES LOCATION - UASIN-GISHU COUNTY, KENYA

BY

WILKINS, KOSGEI CHERUIYOT

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DECLARATION

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Wilkins, Kosgei Cheruiyot Signature ________________________ Date ____________

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

Joel K. Tonui, Signature ________________________ Date ____________

University of Eldoret

Samuel C. Limo, Signature ________________________ Date ____________

University of Eldoret

DEDICATION

To my Parents,

My Wife, Sellah and Daughter, Abigael,

And all whom we share the same dream.

ABSTRACT

Wind energy is increasingly becoming popular all over the world as a green energy source for electricity generation since it is renewable and environmentally friendly. Pioneer wind turbines for electricity generation in Kenya were recently installed at Ngong Hills and Lake Turkana, and more is expected to be initiated in different parts of the country. Wind turbines extract the kinetic energy carried by the flowing wind and this energy is directly proportional to the cube of wind speed. Thus, the wind speed is the most important parameter to consider in designing and selecting an efficient wind energy conversion system. Meteorological Department (MET) and some learning institutions in Kenya have been collecting and storing climatic data for several years, including wind speeds and most of them have not been analyzed. Precise knowledge of availability of wind at any given location is a pre-requisite for the effective planning and implementation and speed analysis is useful for the assessment of wind characteristics and power potential at a location. In this work, analyses of five years (2009-2013) wind speed data collected at a meteorological unit at Moi University, Kesses area, Uasin Gishu County- Kenya, was done. The station measures wind speed at a height of 2 m and were extrapolated to the standard height of measurements of 10 m and typical hub heights of 40 m, 70 m and 100 m for purposes of characterization and determination of energy potential respectively. The extrapolated results revealed that the average annual wind speed at the height of 10 m is 3.86 ms^{-1}, meaning that the location wind speed can be classified as class IV with a maximum wind power density of 100 Wm^{-2}. The average annual wind speed at the hub heights of 40 m, 70 m and 100 m were 5.48ms^{-1}, 6.33ms^{-1} and 6.93ms^{-1}, giving corresponding power densities of 115.563Wm^{-2}, 175.395Wm^{-2}and 228.917 Wm^{-2} respectively. Weibull distribution model was used in the analysis of wind speed distribution. The Weibull scale parameter range from 2.543 ms^{-1} to a maximum of 3.046 ms^{-1}. The Weibull shape parameter was peaked at 5.902 in the year 2012. Both cumulative and probability density function were assessed and graphically presented. Results showed that the site has potential for harnessing wind energy for electricity generation and both small and medium scale wind power turbines are recommended for installation at the site.

TABLE OF CONTENTS

PAGE

LIST OF TABLES

LISTOF FIGURES

FIGURE PAGE

LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

AFREPREN	African Energy Policy Research Network
AWP	Available Wind Power
EWEA	European Wind Energy Association
EWP	Extractable Wind Power
FIT	Feed-in-Tariffs
GHG	Greenhouse Gasses
HAWT	Horizontal Axis Wind Turbine
IPCC	Intergovernmental Panel on Climate Change
KenGen	Kenya Electricity Generating Company
Ltd	Limited
LTWP	Lake Turkana Wind Project
MET	Meteorological Station
NHWP	Ngong Hills Wind Project
RD & D	Research, Development and Demonstration
RER	Renewable Energy Resource
RETs	Renewable Energy Technologies
UN	United Nations
VAWT	Vertical Axis Wind Turbine
WEA	Wind Energy Assessment
WWEA	World wind energy association
$P_{e,ave}$	Average power output of a wind turbine (Wm^{-2})
$F(v)$	Cumulative distribution function (CDF)

v_{in}	Cut-in wind speed (ms^{-1})
v_i	Discrete wind speed (ms^{-1})
Z	Height above ground level (m)
$\bar{v}$	Mean wind speed (ms^{-1})
V_{mp}	Most probable wind speed (ms^{-1})
n	Number of different values of wind speed observed
P	Power of the wind
$f(v)$	Probability distribution function (PDF)
P_{eR}	Rated electrical power (Wm^{-2})
v_r	Rated wind speed (ms^{-1})
A	Rotor swept Area (m^2)
Z_o	Roughness length
N	Total number of observations of a sample
c	Weibull scale parameter (m/s)
k	Weibull shape parameter (dimensionless)
v	Wind speed (ms^{-1})
$U(10)$	Wind speed at 10 m above ground level (m)
$U(z)$	Wind speed at height z (m)
P_D	Mean power density calculated from Weibull function (Wm^{-2})
v_c	Cut-out wind speed (ms^{-1})
v_f	Cut-off wind speed (ms^{-1})

C_f	Capacity factor
C_P	Power coefficient
E_D	Mean energy density
h	Height (m)
K_P	Rated power coefficient
P_A	Available wind power(Wm^{-2})
P_E	extractable power (Wm^{-2})
T	Time
$\mathcal{V}_{\mathrm{max,E}}$	Wind speed carrying maximum energy (ms^{-1})
α	Wind shear exponent
ρ	Air density (kgm^{-3})
Γ	Gamma function
σ	Standard deviation
ξ	Relative deviation

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CHAPTER ONE

INTRODUCTION

1.1. Background

The ever increasing rate of energy consumption poses a great challenge in provision of adequate, reliable and sufficient amount of energy for the ever increasing world population. This challenge has been a major focus for all stakeholders including governments, politicians, scientists, engineers and industrialists among others. However, the level and extend of concerns vary from one nation to another depending on their level of economic development. The developed countries have had great concerns on their energy provision ever since the energy crisis of the 1970s and this prompted them to diversify their energy mix in contrast to the developing countries. The present scenario in energy supply consists of both conventional and non-conventional energy sources, even though the former still constitutes a major source with almost 90% share globally (Ackermann, 2002).

The conventional energy sources, mainly the fossil fuels, have been the major sources of energy all over the world and is utilized in many sectors of our daily lives such as industrial applications (both manufacturing and processing), for electricity generation in steam power plants, for transportation, and also for domestic applications especially in the developing countries. However, because of their finite nature and increasing demand, fossil fuel sources are projected to be unsustainable for the future energy supply. Based on the current reserves and consumption rate of fossil resources, it is projected that the world will sustain 122 years for coal, 42 years for oil and 60 years for natural gas (Lipu *et al.*, 2013). The projected depletion is mainly attributed to the ever rising population and standard of living as well as industrial development especially in the developing countries.

In the utilization of fossil fuels, they are normally burned, either in boilers or internal combustion engines, and these combustions result in emission of large amounts of greenhouse gases (GHG), mainly CO_2, that have given rise to the adverse effect of global warming and environmental pollution. Coupled to this, is the fact that the proportion of consumption of fossil fuels all over the world is skewed in favor of developed Nations but the climate change is global. The huge economic and industrial developments that have been realized in developed nations are attributed to the huge consumption of fossil fuels than in developing countries. The low consumption of fossil fuels in developing countries have made them to trail in economic and industrial development, which is responsible for the social and economic poverty that is prevalent in these nations. This uneven consumption of fossil fuels has been a bone of contention between developed and developing nations when it comes to CO_2 mitigation through reduction of fossil fuel combustion in industries because developing countries need to use more to achieve higher industrialization, hence empowering their citizens economically (Vafaeipour *et al.*, 2013).

The projected depletion of fossil fuel resources and their negative effects on climate and environment has led to a need for alternative or renewable energy sources that are clean and sustainable (Kamau *et al.*, 2010; Soon-Duck Kwon, 2010; Mirhosseini *et al.*, 2011). These alternative energy sources are expected to supplement the conventional energy sources in the provision of energy throughout the world as a short-term mitigation during their developmental stages and probably replace them completely in the future once they are fully developed and become competitive in supply and cost of production. Among the renewable energy sources that are at various stages of investigation, trial and application are solar, wind, geothermal, bio-energy and wave energy sources.

The major challenge of any government today is the provision of affordable and adequate energy to satisfy the ever growing demand and simultaneously satisfy the concern of the Earth’s climate change, a term which is now a common household name. Scientific evidence now exists that show that Earth’s climatic system has changed both in global and regional scale since Industrial Revolution of 1800s, and most of these changes are anthropogenic in nature. The Intergovernmental Panel on Climate Change (IPCC) has held several annual conferences to deliberate on the mitigation measures since its first and famous Kyoto protocol of 1992 (IPCC, 2001; Duic, 2003). Among the recommendations agreed upon was the allocation of quotas for the most industrialized nations to cut on their CO_2 emission by reducing the use of fossil fuels but exempting of the least developed nations by allowing them to burn more fossil fuels so as to bridge the big gap in the levels of industrialization. However, the levels of compliancy by different nations in meeting their quotas have been very minimal as per IPCC report (2013). The Kenyan Government approval and acceptance of the Kyoto Protocol under IPCC of the Doha Amendments which formalized the second commitment period of 2013-2020, guides policy makers to recognize the role of renewable energy resources (RER) in the country’s future electricity generation(Government of Kenya, 2014).

Electrical energy is a superior and high quality form of energy as compared to other forms of energy because of the ease and availability of technologies to convert it to other forms of energy. The development of alternative sources of energy has been mainly for use to generate electricity to replace steam power plants fueled by fossil fuels. Nuclear power plants have been used in various developed countries, for generation of electricity because of its huge potential and zero emission of greenhouse gases (World Nuclear Association report, 2014; Massai, 2011; Lund, 2006). However, use of nuclear energy has serious adverse effects, among them are disposal of highly radioactive waste, accidental leakage of radiation which is hazardous to life for instance the Fukushima and Chernobyl in Japan in 2011 and the more recent accident again in Japan at Fukushima Daiichi nuclear power plant caused by the Earthquake in 2013, (World Nuclear Association, 2014; Royston, 2012 and Massai, 2011). Another disadvantage of nuclear energy is the proliferations of nuclear weapons for instance the ongoing war between Iran and the United Nations (World Nuclear Association, 2014). The government of Kenya has already rolled out plans to develop the first nuclear power plant to meet the rapidly growing electrical energy demand and also to realize its blue-print development goals of Vision 2030 (Kenya, Ministry of Energy, 2012).

Hydropower has been the largest source for electricity generation all over the world, and most of the high potential sites have already been developed and exploited. But in the recent past, there has been resurgence in the development of small hydropower plants mainly by private industries and even individuals to generate their own electricity and hence cut on their extensive use of fossil fuels while simultaneously contributing to climate change mitigation. In Kenya, it is reported that a new wave of development of small scale hydropower projects have been initiated and commissioned mainly by private tea companies, for example Unilever Tea, James Finlay Tea, and Kenya Tea Development Authority (KTDA), among others (Kenya, Ministry of Energy, (2012). The introduction of feed-in-tariffs (FIT) has also boosted the development of more small scale hydropower plants because the excess energy generated can be sold to the main grid and hence acts as a source of income to the investors as well. Geothermal energy is another renewable energy source that has been exploited for electricity generation around the world, including Kenya (Royston, 2012, and AFREPREN, 2002). Geothermal energy is heat energy sourced deep inside Earth’s crust. This form of energy taps the heat in sites with high heat potential and converts it into electricity using suitable technologies. Kenya currently generates about 590 MW of electricity from geothermal power plants, mainly at Olkaria (I, II, III and IV which are operational, and a fifth one under development) and other sites in the Great Rift-Valley region (Kengen, 2015). Other renewable energy sources which have been proven competitive or on trial for electricity generation are solar energy (photovoltaic and solar power plants), biomass (fuel wood, animal and agricultural waste) and ocean waves and tides.

Wind energy is an important renewable energy source that is increasingly becoming attractive for electricity generation all over the world at both large and small scale. In small-scale systems, the energy carried by the wind is tapped using a single wind turbine that harvests energy carried by wind to drive a small generator, and supply a local load. In this type, the electricity generated is used to charge batteries, so as to ensure continuous supply of electricity when there is no wind. For large-scale generation of electricity using wind, a large number of wind turbines are used, usually referred as wind farm or wind parks, and the electricity generated is fed into the local grid.

Application of wind energy for electricity generation in Kenya is still in its infancy stages, though some parts of the country is endowed with substantial potential of wind energy. However, Kenya has recently initiated pioneer projects on wind generated grid-fed electricity. Two such projects are located at Ngong Hills (Ngong wind I and phase II) near Nairobi and Lake Turkana Wind Project. The two projects are being monitored to obtain useful information in order to determine the cost effectiveness, operating schedules and reliability of wind electricity generation in Kenya as well as the return on investment. More sites in Kenya have also been identified to set up more wind farms (Government of Kenya, 2014). However, the reception in some parts of the country, e.g. Kinangop region in Nyandarua County, has been met with public protest citing the potential of huge turbine' interfering with farming activities (KenGen, 2015). Hence, there is a need of creating awareness among the people on the benefits of wind power in mitigating the climate change and reversing adverse effect on rain patterns in the country and hence on their crop yields. They can also be empowered through farmers' co-operative societies or other financial movements to invest on wind power generation, and hence benefit from the proceeds in addition to contributing to climate change mitigation.

The use of wind energy, for whatever application, is suitable in places where there is a prevailing wind regime. Thus, prevailing wind speed profiling at a given site is necessary in order to make an informed decision for adopting wind power generation by any investor. In this regard, assessment of wind energy characteristics and potential at various sites in the world has been an important field of research. In this regard publications exist in journals and conference proceedings. In addition, the technology for generating electricity from wind energy has matured to the point that wind generated electricity is now competitive compared to that produced from conventional sources, even when maintenance and operating costs are factored in. Due to its wide availability and low environmental impact, wind energy is the fastest growing energy resource today (Mathenge and Oliver, 2009; Azad, 2013 and Ohunakin *et al.*, 2012).

The Kenya Meteorological Service (MET) and some institutions of higher learning have been measuring and storing various climatic data in various parts of the country. The data logging date back to more than two decades ago in some stations and much less in others (Kamau, 2010). However, most of the data has not been analyzed, except for some few selected parts, hence not exhaustive. The findings from the existing analysis revealed the potential of using wind to generate electricity both for large and small scale applications. Kamau *et al.,* (2010) carried out analysis on a six year wind data for Marsabit region and found out that the average wind speed is over 14.0 ms^{-1} at a hub height of 100 m. Other analysis includes that done by Kirui (2006) in Nakuru, central rift region and Choge *et al.,* (2013) in Eldoret Town, North Rift region. Moi University Main campus located at Kesses Township of Uasin-Gishu County runs a meteorological station that measures various climatic/weather data, including wind speed. The wind data collected by this station has not been analyzed, and hence the objective of this study was to analyze the available five year wind speed data for the period 2009 to 2013. These analyses are useful for determining the wind characteristics and its technical potential for purposes of recommending the viability of wind electricity generation at the site.

1.2. Statement of the Problem

Wind energy is currently among the renewable energy sources that are being introduced into the energy mix in Kenya, as a source for generating electricity (both for large and small scale applications). Many County Governments, private companies and learning intuitions are also beginning to install hybrid wind/solar street lighting systems as a contingent measure to reduce their expenditure on electricity bills and also as their contribution to energy conservation and climate change mitigation. However, proper analysis of wind data available at the site is beneficial in order to assess its technical potential for purposes of determining wind capacity and hence selection of suitable and efficient wind turbines to install at the site. These analyses are lacking for most wind speed measuring stations and the installed wind turbines in most cases are done without any scientific backup information. This study will provide statistical analyses of wind data collected at Moi University and the findings will be useful for this institution and its environs in selecting optimum wind turbines and operating schedule.

1.3. Objectives of the Study

1.3.1. General Objective

The general objective of this study was to analyze the characteristics and power potential of wind speed data to determine the viability of a wind energy project.

1.3.2. Specific Objectives

The specific objectives of this study were:

1. To analyze wind speed data collected at Moi University weather station.
2. To determine statistical parameters for the assessment of viability of wind energy.
3. To determine wind power potential at the standard height of wind speed measurements of 10 m and typical hub heights of 40 m,70 m and 100 m.
4. To identify suitable wind turbine generators for the region based on the research outcome.

1.4. Justification of the Study

There is a growing interest in renewable energy technologies (RETs) in many parts of the world, and Kenya is not an exception. In addition, there is an increasing awareness among the general public on the need to adopt RETs for electricity generation in their premises as an innovative initiative to cushion the high cost of conventional fuels and also enable them contribute to the climate change mitigation. However, before investing on any RETs, it is necessary to assess the primary energy that drives that technology. With this regard, wind resource assessment, either as pre- or full feasibility studies, is necessary to quantify the characteristics of the wind resource at a location to determine the viability or the non-viability of a wind energy project. The most significant and critical parameter in any wind resource assessment is the wind speed and it is for this reason that this study was undertaken.

1.5. Structure of the Thesis

Chapter one gives general overview on current energy supply scenario for purpose of identifying the statement of the problem and hence constituting the objectives of the study.

Chapter two reviews the background on the wind energy and literature review on the assessment and exploitation of wind energy as a resource for electricity generation.

Chapter three presents methodology used in this study and in particular enumerates various statistical methods used to analyze wind data to determine its characteristic and technical potential.

Chapter four presents the results and discussions on the analysis carried out, while chapter five gives the conclusions drawn from the analyses of the results and recommendations on the probable application of available wind at the site.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

This chapter seeks to address the background information on wind energy regarding its various aspects, characteristics, methods of harnessing, wind distribution in Kenya, and its current status.

2.2. World Energy Scenario

Fossil fuels have driven the world's economic activities since the early part of the 20th century, and have continued to be important in meeting global energy needs to date. The use of petroleum and natural gas as a source of energy is widespread across all economic activities and in addition petrochemical industries that are involved in production of various items are also powered by fossil fuels. Both these fuels have served as key inputs for industrial and technological processes and innovations. However, there has been an emergence of new global threats, such as climate change, water scarcity, and resource constraints. Together with greater public concern about the environmental and health impacts of excessive use of fossil fuels as well as possibility of depletion in the near future, the energy sector is shifting its focus to alternative or renewable sources which are clean and sustainable.

Kenya, as a growing economy, has set up development flagship project duped Vision 2030, which envisages Kenya becoming a middle level economy by the year 2030. One of the necessary ingredients to achieve this goal is provision of adequate and affordable energy supply to spur rapid industrial growth, both manufacturing and processing, in order to achieve sustainable economic growth. The current electrical energy supply in

Kenya is still dependent on the fossil fuel fired steam power plants and hydroelectric power stations and these sources are outstretched due to increasing demand partly as a result of growing population as well as the ambitious government program on rural electrification, especially to all primary and secondary schools. The inability of these conventional electrical power supplies to meet the base load, has prompted the Kenya government, through its generation agency KenGen Ltd, to explore alternative energy sources, among them solar energy, wind energy and nuclear power plant, to supplement its energy supply needs.

2.3. Wind Energy

Since the energy crisis of the 70s, there has been a rising need for alternative and renewable energy sources. This is particularly true in developing countries, Africa included, whose progress and economic growth strongly depends on the development of these sources of energy. Wind energy, together with solar energy, are not only the oldest and widely used forms of energy, but have also shown potential and prospect for efficient utilization in the modern world. Wind energy is a clean, abundant, affordable, inexhaustible and environmentally friendly and coupled to this is availability of inexpensive conversion technologies for electricity generation of varying capacities. Pioneer projects on wind energy exploitation for electricity generation in Kenya begun recently, and the performance is promising. The country is now focusing on the renewable energy sources and nuclear energy to supplement its electricity supply base because of the increasing demand as the country braces itself to achieve the goals contained in its Vision 2030. The country projects to connect 2036 MW of electricity to the national grid generated from wind energy by the year 2030 (Kamau *et al.*, 2010).

Wind energy conversion is a widely exploited renewable energy all over the world, either for stand-alone systems or grid connected systems. Hendry (2009) reported that wind has advanced more quickly into commercialization than any other renewable sources such as solar power, fuel cells and wave power. The stronger growth in installed wind generation capacity worldwide, than other renewable sources, is attributed to the improvement of wind turbine technologies, which have improved conversion efficiency and reduced the cost (Islam *et al*., 2011). In addition, the World Wind Energy Association (WWEA) has reported a boom in wind energy exploitation especially in developed countries such as China and the United States because of the incentives that these nations have put to promote use of this resource and hence help them meet their quotas on CO_2 reduction as spelt out in the various IPCC protocols (IPCC report, 2013).

2.3.1. Origin of Wind Energy

Wind is created by large scale changes in atmospheric pressure and temperature. It is the horizontal movement of air in response to differences in pressure, and is a means by which the atmosphere attempts to balance the uneven distribution of pressure over Earth’s surface. The horizontal variation in pressure is caused by two effects:

1. The temperature difference between the tropics and poles, and
2. The motion of the Earth (both rotation about its axis and orbit around the Sun).

The first effect is also referred as thermal cause and is due to uneven heating of the Earth because of unequal distribution of insolation (solar radiation),differential heating of land and sea, and different albedos of the surfaces. According to the gas laws, pressure and density of a gas varies inversely with temperature, hence as air near Earth’s surface is heated, it expands, become less dense and rises hence reducing surface pressure mostly around the equator. In colder regions, air contracts hence its volume decreases and density increases, this causes the air to sink, hence increase in pressure. This occurs mostly in the polar regions of the Earth. Thus, thermal variation with respect to regions of the Earth makes the pressure at the equator to be constantly low, and the pressure at the poles to be constantly high, which means that pressure increases while temperature decreases gradually from the equator towards the poles, (Akpinar, 2005).

The movement of the Earth also creates wind in the atmosphere because air interacts with the Earth. This is called dynamic effect. Actual measurements of pressure at the Earth’s surface show that the pressure does not rise gradually but in irregular pattern from equator towards the poles. These irregular variations cause the sub-tropic regions to have high pressure and sub-polar regions to have low pressure. These zones or belts of high and low pressures are due to dynamic causes and are more complex than thermal causes. It is to be noted that wind does not move in straight lines but in spiral trajectories because of Coriolis force or effect.

2.3.2. Wind Energy Potential

The origin of all forms of energy, with the exception of tidal, geothermal and nuclear, is the Sun, either directly or indirectly. The wind is an indirect form of solar energy and is created due to uneven heating of Earth’s surface by solar radiation. It is estimated that the amount of energy radiated per hour from the Sun is approximately 10^{13} kWh and it is estimated that 1% to 2% of this energy is converted into wind. This is almost 50 to 100 times more than that converted into biomass by all plants on Earth (Manwell *et al.*, 2002).

The Coriolis effect, land formations, and oceanic circulations further contribute to the strength and direction of wind at a given location. Strong winds have power densities an order of magnitude higher than solar irradiance. Although a gentle breeze of 5 ms^{-1} only has about $0.075kWm^{-2}$, a violent storm can have up to 10 kWm^{-2} of energy in the wind, while solar power only has a maximum power density of 1 kWm^{-2} (Quaschning, 2005). Thus, the concentrated wind energy is what has made it attractive for exploitation all over the world and has made it one of the fastest growing alternatives form of renewable energy source.

Wind energy has several merits associated with its exploitation and include being renewable hence inexhaustible, clean hence environmentally benign, safer as compared to fossil fuels or nuclear power. Wind energy as a resource is also free, has diverse applications and evenly relatively well distributed, Thomas and Sodder, (2000) and Vardar and Alibas, (2008).

Wind energy is not without limitation and one of its demerits is the relatively high capital cost on energy conversion equipment but which is projected to decline due to increasing popularity of this form of energy. Another important limitation associated with its use is the visual and noise pollutions created respectively by the huge and large number of wind turbines in case of wind farms and sound produced due to rotating blades. Coupled with the two demerits are unpredictability and intermittent nature of wind, bird kill and possibility of interfering with communication signals, Ozgeneran and Hepsali, (2002) and Vardar and Alibas, (2008).

2.3.3. The Physics of Wind

There are a number of factors which contribute to the strength of wind which include centripetal/centrifugal force, difference in land mass composition where changes in topography can accelerate or decelerate wind speeds. Also, surface roughness variations; occur as a result of this land mass variation which affects wind speeds and hence wind kinetic energy (Bianchi *et al.,* 2007).

The nature of the 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 Earth's surface is slowed by trees, buildings, grass, rocks and any other obstructions in its path (Carlin, 2005). Consequently, wind velocity varies with height above Earth's surface, a phenomenon called wind sheer. Close to Earth the wind is slowed down due to friction about on the terrestrial surface. Thus, wind is stronger at higher heights in relation to Earth's surface for agricultural fields and desert territories (Fries, 1990).

Most meteorological instruments measuring wind speed are placed at a standard height of 10 m. However, for maximum wind exploitation, wind turbine hub heights can be more than 20 m (Vafaeipour *et al.,* 2013). 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. This requires an equation that predicts the wind speed at one height in terms of the measured speed at another lower height. At a height about 2 km above the ground the change in the wind speed becomes zero (Vafaeipour *et al.*, 2013). The vertical variation of the wind speed (the wind speed profile), can be expressed by different functions. The common methods used are the logarithmic wind profile law and the power law formula (Balouktsis *et al.*, 2002). Wind sheer is an important factor when designing wind turbines for installation at a given specific site.

The variation of the wind sheer parameter has been investigated extensively and typical values for different terrains are given in Table 2.1, (Bechrakis and Sparis, 2000).

Table 2.1: Typical sheer exponents for various types of terrains

Terrain description	Sheer exponent
Smooth, hard ground, lake or ocean	0.1
Short grass on untilled ground	0.14
Level country with foot-high grass, occasional trees	0.16
Tall row crops, hedges and 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

2.3.4. Wind Speed Classification

The wind speed distributions and magnitudes play important roles in the planning of the wind location and selection of wind turbines (Marigi, 1999). Majority of the past research effort has been placed on developing large-scale wind turbines, which has resulted in the rapid reduction of cost of generating electricity from wind in the last 20 years (Hansen *et al.*, 2005).

The wind characteristics are normally based on the wind speeds. The common classification methods of wind characteristics are the EWEA categorization, and the 10 m above the ground categorization given by Table 2.2 and Table 2.3 respectively. The maximum and minimum wind speeds and corresponding wind power density are also given (Mostafaeipour, 2011).

Table 2.2: Wind categories based on EWEA classification

Category	Wind speed (ms^{-1})	Wind power density (Wm^{-2})
Poor	0.0 – 6.0	0 – 300
Fairly good	6.5	300 – 400
Good	7.5	500 – 600
Very good	8.5	700 – 800

Table 2.3: Wind power classification at 10 m (Mostafaeipour, 2011)

Wind class	Min wind speed(ms^{-1})	Max wind speed (ms^{-1})	Min wind power density (Wm^{-2})	Max wind power density (Wm^{-2})
I	0.0	4.4	0	100
II	4.4	5.1	100	150
III	5.1	5.6	150	200
IV	5.6	6.0	200	250
V	6.0	6.4	250	300
VI	6.4	7.0	300	400
VII	7.0	9.4	400	1000

2.4. Wind Energy Exploitation in Kenya

According to Mathenge and Oliver (2009), Kenya is highly dependent on hydroelectricity which is responsible for over 75% of all electrical supply in the national grid. The remaining 25% of electricity supply is met mainly by the steam power generation plants and geothermal power plants. The contribution of renewable energies to national power supply is negligible and these sources are used for isolated power supply for domestic use mainly in rural areas and some agriculturally based industries or mission institution in case of mini-hydropower plants. Thus, there is room for Kenya to incorporate renewable energy sources into their energy mix partly to meet her growing demand for electricity and also promote generation of electricity from green energy.

The Kenyan government has already rolled out measures to promote the use of renewable energy sources for electricity generation by putting in place favorable legislations. In the Energy Act of 2006, and the feed-in-tariff (FIT), there is a commitment to promote electricity generation from renewable energy sources. The government intends to set up a Green Energy Fund Facility under the National Task Force on Accelerated Development of Green Energy, with the purpose to lend funds to viable Renewable Energy projects at concessional rates (Republic of Kenya, 2011) which is currently in progress. The National Renewable Energy Development Strategy, as set in the Least Cost Power Development Plan (LCPDP), Rural Electrification Master Plan, the Kenya National Climate Change Respond Strategy and the Kenya Vision 2030, reiterates the commitment to accelerate the use of renewable energy (Kenya, Ministry of Environment and Mineral resource, 2010). Thus, political will exists in Kenya for the promotion of renewable energy for the generation of electricity and what remains now is action to implement the strategies. An effective implementation strategy is promoting Research, Development and Demonstration (RD&D) projects on various renewable sources throughout the country.

The wind energy exploitation in Kenya is still young and the current installed capacity is a paltry 5.1 MW though the country is endowed with huge potential. However, the amount is bound to increase in the near future because of the government commitment to promote renewable energy and the FIT incentives will see individual or groups of people investing in them. Apart from the government efforts, there is also regional support programs for wind energy that have been rolled out in African countries such as Kenya, Ghana and Ethiopia, among others to study wind characteristics and prepare wind atlas in the continent, (Kamau *et al.*, 2010).

The wind resource assessment carried out by a private company shows that over 73% of the total area of the country experiences annual mean wind-speeds more than 6 ms^{-1} at 100 m above ground (Government of Kenya, 2014). Figure 2.1 shows the wind resource map of Kenya developed by the WinDForce Management Services Private Limited-Kenya 2013. The wind speed for the entire country can be categorized as follows; Class I (>8.5 ms^{-1}), Class II (7.5 - 8.5 ms^{-1}), Class III (6.5 – 7.5 ms^{-1}) and Class IV (6 – 6.5 ms^{-1}) (Kenya, Ministry of Energy, 2012).

The Government of Kenya has estimated that 500 MW of wind capacity will be installed in Kenya by the year 2020 (Kenya, Ministry of Energy, 2013). Two wind projects have been rolled out in Kenya and are currently operating. These projects are the Lake Turkana Wind Project (LTWP) in Marsabit County and the Ngong Hills Wind Project (NHWP) in Kajiado County, near Nairobi. The LTWP will have installed capacity of 310 MW and comprises 365 turbines of capacity 850 KW each. This project is located on a corridor of high and predictable wind streams between the country’s desert hinterland and Lake Turkana (Madeleine *et al.*, 2006).

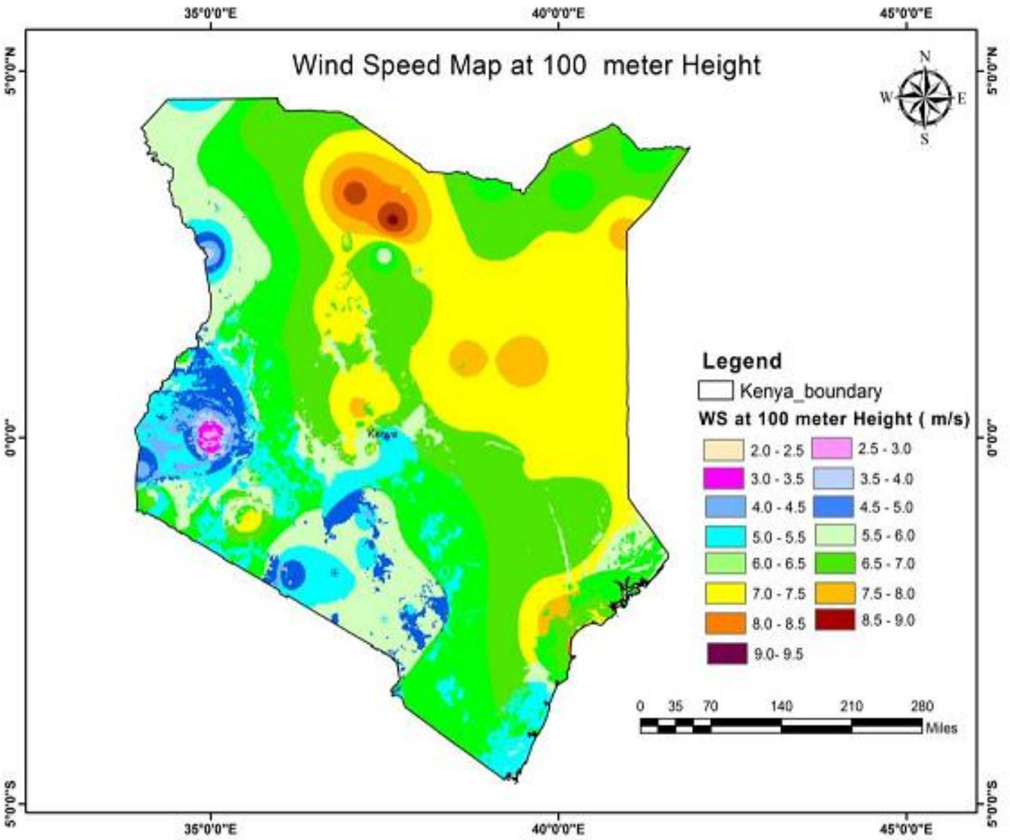


Figure 2.1: Wind Speed Map of Kenya at 100m height

(Source: WinDForce Management Services Private Limited-Kenya, 2013)

2.5. Wind Turbines

A wind turbine or windmill is a device that is used to harness mechanical (kinetic) energy of the wind for either electricity generation or grinding grains or pumping water. In electricity generation, the wind turbine drives an alternator that generates electricity that is either fed to the local utility grid or for individual use (stand-alone system). Since kinetic energy is directly proportional to the square of wind speed, and air mass swept, the energy available for conversion depends on the wind speed and the area swept by the turbine.

Wind turbines are classified based on the orientation of the shaft of the rotor with respect to the ground (Spera, 1994). Based on this criterion, the modern wind turbines are classified into two main configurations which are:

1. Horizontal axis wind turbine (HAWT), and
2. Vertical axis wind turbine (VAWT).

In a VAWT, the shaft is mounted on a vertical axis perpendicular to the ground (like an Eggbeater). Since the VAWT are always aligned (parallel) with the winds, adjustment is not necessary when the wind direction changes (Nigim and Paul, 2007). One major drawback with these turbines is that they cannot self start, but need to be kick started by an electrical system. In addition, the VAWT uses guy wires for support; hence rotor elevation is lower than that of a tower. Due to the low elevation (slower wind due to ground interference) they have lower efficiency. The major advantage of this turbine is that all equipment is at ground level for easy installation and servicing, but that means a larger footprint for the turbine, which is a big negative in farming areas. This design is usually used for small-scale applications.

In a HAWT, the shaft is mounted horizontally, parallel to the ground. The HAWTs need to constantly align themselves with the direction of the wind. This type of turbine uses a tower as a base and the components are at an optimum elevation for wind speed. As such, each tower takes up very little space since almost all of the components are up in the air. The horizontal axis turbines collect the maximum amount of wind energy for the time of day and season and adjust their blades to avoid high wind storms; they are considered more common than vertical-axis turbines (Lynette, 1990).

(a) (b)

Figure 2.2: Horizontal (a) and Vertical (b) Axis Wind Turbines

(Source; Windterra Corporation)

Most large modern wind turbines are horizontal-axis turbines, and are the predominant configuration for large grid-connected wind turbines. The common configuration of the HAWT turbine is a 3-blade turbine on a free-standing tubular tower as shown on Figure 2.2. The wind turbines have the same basic design but can vary considerably in terms of height, blade length and generating capacity.

A wind turbine is comprised of four major components:

1. Rotor,
2. Nacelle,
3. Tower and
4. Blades.

In many countries, these components are shipped from the countries where they are manufactured. The rotor is also called the hub and is used to connect the blades to the gear box and power generation train within the nacelle. The nacelle is an enclosure which contains the electrical and mechanical components, such as gear box, the brake, the speed and direction monitor, the yaw mechanism and the generator. The tower is usually a tubular tall structure of about 80 m high, and is used to support the rotor and nacelle. It also raises the rotor high in the air where the blades are exposed to stronger winds. The tower sits on reinforced concrete foundation, so that it is well fixed onto the ground. The modern rotor blades are made of composite materials, making them light but durable. Blades are often made of fiberglass, reinforced with polyester or wood epoxy. Most wind turbines have three blades, with length varying from 30 m to 50 m, with the most common size around 40 m. Blades typically represent approximately 22% of the value of a wind turbine (Yun and Deng, 2008). Wind turbines are classified as small, medium and large and their characteristics are presented in Table 2.4. Selected wind turbine characteristics at a hub height of 40 m are presented in Table 2.5.

Table 2.4: Typical wind turbine characteristic

Description	Small	Medium	Large
Rated power (MW)	0.5	1.0	>1.3
Cut-in wind speed (ms^{-1})	>0.5	1.0	2.22
Rated wind speed (ms^{-1})	8.5	12	15
Cut-out wind speed (ms^{-1})	11	18.25	26.94
Rotor diameter (m)	2.5	22.5	62
Hub height (m)	10	40	50

(Source: www.darlingwindfarm.co.za /projectfactsheet.htm)

Table 2.5: Wind turbine data for altitude of 40 m

Wind turbine	Rated power (kW)	Rotor diameter (m)	Hub height (m)	Cut-in speed (ms^{-1})	Cut-out speed (ms^{-1})	Rated speed (ms^{-1})
WINDWORKER	750	47	40-65	4	25	14.5
SUPERWIND	660	47	40-55	4	25	15
WFD	600	48	40-70	3	22	11.5
Westwind	600	43	38.5-48.5	3.8	14.5	25
ML1500	900	52	40	2	25	11.5

(Source: Wind Engineering)

2.6. Wind Power

The relationship between wind speed data and energy performance of a wind turbine rely heavily on the quality and quantity of site wind observations. Wind data of shorter periods less than 30 years, may use variations borrowed from the long term wind speed average for accurate resource assessments. Many developing nations do not possess accurate long term wind speed data and as a result data of shorter recording periods have to be used for wind resource assessment (Lun and Lam, 2000).

The power output of a wind turbine depends on the wind speed, and the amount of air mass swept by the turbine blades. Since the wind speeds have both temporal and spatial variations due to variation in the local weather patterns and landscape, the output power from wind will also be variable. The power of the wind that flows at speed v through a blade sweep area A of a wind turbine increases as the cube of its velocity (Akpinar, 2005).

The relationship between the wind power P (W) and the wind speed v (ms^{-1}) can be derived easily using basic physics (Carlin, 2005) as:

$$P = \frac{1}{2}\rho A \upsilon^3 \tag{2.1}$$

Here ρ is the air density (kgm^{-3}) and depends on the air temperature and pressure. From this equation, it can be seen that power varies as the cube of wind velocity. Hence, for any given wind speed, a correspondingly large power can be realized.

By dividing both sides of equation (2.1) by swept area A the wind power density Equation is obtained and is given by:

$$P_{D=}\frac{1}{2}\rho v^3 \tag{2.2}$$

2.6.1. Betz Limit

Betz limit is the theoretical limit assigned to efficiency of a wind turbine. It states that no turbine can convert more than 59.3 % of wind kinetic energy into shaft mechanical energy. It is derived from linear momentum theory. Thus the power coefficient, *Cp* is limited to Betz limit and for a well-designed turbine the efficiency lies in the range of 35-45 %. The ratio of the maximum power to the incoming potential power defines the maximum theoretical rated power (Wagner *et al.*, 2008). This ratio is given as:

$$C_P = \frac{0.5\ K_P\ \rho\ A\ {v_1}^3}{0.5\ \rho\ A\ {v_1}^3} \tag{2.3}$$

Where K_P is the rated power coefficient, ρ is the air density and A is the area swept by wind turbine. This factor limits the amount of wind energy that the turbine can convert into useful energy. Betz estimated the power coefficient of an ideal propeller type of a wind turbine to be 16/27 giving C_P=0.593 (Hemke, 1946).

The wind power extractable from any wind machine is limited by the Betz relation (Betz, 1966) i.e. the wind machine cannot use 100% of the energy given by equation (2.1) and the maximum extractable power P_{max} is given by:

$$P_{\max} = \frac{1}{2} \rho A C_P \upsilon^3 \tag{2.4}$$

2.7. Theoretical Wind Energy Analysis

To develop the wind speed frequency curves, a continuous mathematical function is convenient rather than discrete values. Therefore the probability value $P(\upsilon_i)$ becomes a density function $f(\upsilon)$ known as probability density function (PDF). If v is a continuous random variable at the range (0, α), its PDF $f(\upsilon)$ must satisfy $f(\upsilon) \geq 0, \quad 0 < v < \alpha$.

$$\int_0^{\propto} f(v) dv = 1 \tag{2.5}$$

Another important probability measure is the cumulative density function (CDF). For continuous data, f(υ) represents CDF for continuous random variable $0 < v < \alpha$ given as;

$$\mathrm{F}(v) = \int_0^v f(v) dv \tag{2.6}$$

When the wind speed is considered as a continuous random variable then the $\mathrm{F}(v)$ has properties F(α)=0 and F(α)=1. The quantity F(α) is not necessarily zero in the discrete case because there are calm speeds with normally zero wind speed measured and included in F(α). In the continuous case, F(α) is the integral with the integration limits (Lun and Lam, 2000).

The variation in wind speed is characterized by two parameter functions, the probability density function and the cumulative distribution function. Determination of k and c is by graphical method where the cumulative distribution function is transformed into a linear form, adopting logarithmic scales. The prediction of the time for which an installed turbine could be potentially functional is determined through the use of cumulative distribution function. This is because cumulative distribution function of the velocity (v) indicates the fraction of time the wind speed is equal or lower than speed (v) by taking the difference of its values and it is possible to estimate the functional time of the wind turbine installed at a specific site (Reddy *et al.*, 2014).

2.8. Wind Energy Status

Recently, many governments all over the world started investigating the wind as an energy resource together with other renewable resources in order to reduce their geopolitical dependency, enhance their energy security, limit the environmental implication of fossil fuels and control oil price fluctuations. As a result, many experimental and theoretical assessments of wind energy potential have been undertaken at various locations all over the world and reported in peer reviewed energy related journals and conference proceedings. The research campaigns on wind energy exploration spans several decades and available literature on present status are enormous to be reviewed in one thesis.

Several theoretical models have been proposed and used to assess wind energy characteristics and potential at different sites in the world. Use of probability density function (PDF) models to describe wind speed variations has received extensive research acceptance in recent years, and numerous studies on its application are in the literature Rivkin and Silk (2013) and Mouangue *et al.*, (2014). Luna and Church (1974) used a universal distribution for wind speed at California and discovered that lognormal distribution is the most appropriate. However, the authors cautioned that the universal distribution may not be applicable to different sites due to the differences in climate and topography. This was also later supported by a study carried out by Zhou *et al.*, (2009), at several sites in North Dakota, who found that there is no universal distribution function that performs well for all sites.

Much research work regarding the evaluation of wind energy potential for different regions by using the various probability distribution functions have been carried out by some researchers. Most of the researches have indicated that the Weibull wind speed distribution is accurate for wind energy estimation and has been used widely to represent wind speed distribution for application in wind energy studies (Lima, 2012). Justus *et al*. (1978) presented an elaborate discussion on Weibull function, mainly on how to determine the two-parameters (scale factor, c and shape factor, k) and also compared with the then newly developed "square-root-normal" distribution. They found that the model was a good theoretical model that adequately describes most of the wind speed distribution than the new method. Auwera *et al,*(1980) successfully fitted the measured wind speed data for Belgium using four statistical distributions, and their results showed that Weibull distribution gave the best fit for wind speed data and is easier using it in determination of wind power by use of Equation (2.2).

In general, two-parameter Weibull statistical distribution is by far the most widely adopted for representing the wind speed, and several studies have used it in literature (Manwell *et al.,* 2002, Islam *et al.*, 2011; Albadi *et al.*, 2012, among others). Ramachandra *et al*., (2005) addressed a statistical model and monogram method to investigate wind turbine characteristics for various wind turbine generators by using the same sets of wind data at Kappadgudda wind power station, India. Analysis by use of Weibull and Rayleigh models have been carried out by Gupta and Biswas, (2010) who analyzed Wind data of Silchar (Assam, India) and Mathew, (2006) who presented an analytical approach to study the wind energy density, energy available in the wind spectra, and the energy received by turbine. Estimation of wind energy density and other wind characteristics based on the two-parameter Weibull wind speed distribution have been developed and evaluated by Jamil *et al.*, (1995) in Iran, Bekdemir *et al.*, (2007) in two windy sites located in the coastal region of Red Sea and Meishen Li and Xianguo, (2005) in Hong Kong. In this study, the two-parameter Weibull statistical distribution was applied in analysis of the wind speed data, wind energy density, wind power potential and wind turbine characteristics.

Wind speed profile analysis and investigation have been carried out by Wagner *et al.*, (2008) on flat terrain up to a height of 160 m. The study was done to identify the influence of wind sheer and turbulence on wind turbine performance at varying hub heights. The profile's shapes were found to extend from no sheer to a high wind sheer, and on many occasions, local maxima within the profiles were also observed. The results from the study showed that wind profiles do not follow the logarithmic law; instead, their behavior heavily depends upon the atmospheric conditions of the region.

Several assessment of wind energy potential in various parts of the world have been done and reported. Ahmed *et al.*, (2006) carried out assessment of wind energy potential on the coastal area of Pakistan, Mahyoub and Buhairi (2006) carried out an investigation of wind energy potential in Taiz, Yemen; Fagbenle *et al.*, (2011) performed analytical assessment of wind energy potential in North-Eastern region of Nigeria; Hoogwijk *et al.*, (2004) reported on the assessment of global and regional onshore wind energy; Ajayi (2011) carried out assessment of wind energy potential for electricity generation in Shaki region of Nigeria; Nguyen (2006) undertook a study on the wind resource and implementation status in Vietnam; AL-Yahyai *et al.*,(2010) assessed wind energy potential in Oman from an existing five year hourly wind data; Chang *et al.*, (2003) carried out both wind and turbine characteristics assessment potential in Taiwan; Celik(2004) carried out statistical analysis of wind speed data for five different regions of Turkey fitted to Weibull distribution and examined using Chi-Square and Kolmogorov-Smirnov tests; Bhuiyan and Yazdani (2011) used web based tool called Wing Energy Assessment (WEA) tool to analyze wind data of Kuakta, Bangladesh; Al-Buhairi and Al-Haydari (2012) reported on monthly and seasonal assessment for wind data in Al-Mokhan, Yemen; CumaliIlkilic (2012) carried out wind energy analysis in turkey; Rosen *et al.*, (1999) reported on wind potential assessment of sparse wind data at the costal Eritrea; Youm *et al.*, (2005) analyzed wind potential along the northern coast of Senegal. Diab and Garstang (1984) used a two-dimensional numerical model to predict surface wind velocities and then wind power for contracting east and west coast of South Africa.

On more recent work, Mukhopadhyay and Panigrahi (2013) analyzed wind speed data for various seasons for one decade in Kolkata using wavelet and S-transform; Ahmet Yucekaya (2015) used a simulation approach to evaluate operational economics of wind power investment in Turkey; Mert and Karakus (2015) carried out a statistical analysis of wind speed data using Burr, generalized gamma, and Weibull distributions in Antakya, Turkey; Essandoh(2013) presented a preview of wind data collection and analysis in Kumasi, Ghana; Reddy *et al.*, (2014) carried our analysis of wind power density for micro-scale wind turbines in Gadanki, India using Weibull distribution function.

On the local scene, among the first reported studies on wind energy in Kenya is the work done by Oludhe (1987) and Oludhe and Ogallo (1989), where they tried several statistical methods to estimate the diurnal and seasonal values of maximum, minimum and mean wind power expectation at various sites. Their results were used to map out and delineate all areas with wind power potential in Kenya and to specify the optimum rating speeds for wind power generation for high and moderate wind potential regions. Kirui (2006) carried out investigation on the correlation between the wind and solar radiation in the Nakuru region. Kamau *et al.,* (2010) used Weibull distribution function to characterize wind speed profile in Maralal and Marsabit regions and investigated the wind power parameters using empirical methods as the power law and logarithmic law obtaining the shape and scale parameters at a height of 50 m above the ground level. They concluded that Marsabit has a power density of 1800 Wm^{-2} that is in a wind class of 7 as presented in Table 2.3. They recommended that more work needed to be done on the exact wind sites by determining its characteristics and the local factors which influence wind. Choge *et al.,* (2013) carried out a correlation analysis of wind and solar energy at Eldoret by use of both Reyleigh and Weibull models. Their conclusion showed that wind energy can be combined with solar energy in isolated villages and areas which are not electrified for relatively small amount of power applications.

CHAPTER THREE

METHODOLOGY

3.1. Introduction

This chapter presents materials and analytical methods employed for wind energy assessment in this study. The wind speed data used for this research work was collected by the meteorological station at the main campus of Moi University at Kesses region. Various statistical methods were employed to characterize the wind speed data and will be discussed in subsequent sections.

3.2. Site of Wind-data Measurement and Recording

The available data at Moi University meteorological station are daily records of wind speed measured at a height of 2 m above the ground level. Figure 3.1 is the picture showing the rotating cup anemometer used for wind speed measurement at the station.

Figure 3.1: Picture of Moi University MET station showing a rotating cup anemometer used to measure wind speed
(Source: Author , 2015)

The site is located at 0.28333^0 N and 35.29444^0 E with an average altitude of 1311 m above sea level. The region experiences two rainy seasons with an annual rainfall ranging from 900 mm to 1200 mm, and occur between the months of April and November. The driest season comes between the months of December and March. The annual average ambient temperature experienced in the region range from 8.5 ^{0}C and 27 ^{0}C.

The station measures wind speed on hourly basis and average them to get the daily average wind speed, which is then recorded as raw data at the station. The wind speed data need to be analyzed in order to get useful wind characteristics that are necessary for the assessment of the site's potential as a source of energy for various applications. Various statistical analyses are available in literature for evaluating useful wind parameters that are necessary for wind energy potential assessment. Among the statistical analyses are the mean wind speed (daily, monthly and annually), standard deviations and the Weibull two-parameters.

3.3. Mean Wind Speed and Standard Deviation

The wind speed varies in both magnitude and direction as a function of time. As such, it is necessary to determine average value over a specified period of time, e.g. hourly, daily, monthly or yearly. The general average wind speed is evaluated by the equation (Diab *et al.*, 1984):

$$\overline{V} = \frac{1}{n}\sum_{i=1}^{N} v_i \tag{3.1}$$

Where v_i is the wind speed measured at any instant of time, i and N is the total number of observations.

The standard deviation σ is a variable that describes the deviation of a measurement from the mean values and is given by the following equation (Reddy *et al.*, 2014):

$$\sigma = \left[\frac{1}{n-1} \sum_{i=1}^{N} (v_i - \bar{v})^2 \right]^{0.5} \tag{3.2}$$

Where $\bar{v}$ is the mean wind speed. Note that Equations (3.1) and (3.2) apply to all types of evaluations regardless of the duration.

3.4. Weibull Scale and Shape Parameters

The Weibull two-parameters are the shape (*k*) and scale parameter (*c*). The *k*-parameter is a dimensionless quantity and it indicates how wind speed is peaked at the site. The *c*-parameter, on the other hand, has the units of wind speed (i.e. ms^{-1}) and it shows how windy the site is (Justus *et al*., (1978).

The Weibull *k*-factor is defined by the following equation:

$$k = \left(\frac{\sigma}{\bar{v}} \right)^{-1.086} \tag{3.3}$$

Where σ is the standard deviation and $\bar{v}$ is the average wind speed.

The Weibull *k*- and *c*- factors are closely related to the mean wind speed $\bar{v}$ as per the following equation (Jamil *et al.*, 1995);

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{3.4}$$

Where Γ is the gamma function and is defined by the following integral equation;

$$\Gamma(x) = \int_0^\infty t^{x-1} \exp(-t)dt \tag{3.5}$$

Equation (3.5) can be solved by standard methods for solving gamma functions, while the *k*- and *c* factors can be determined using Equations (3.3) and (3.4) respectively when the mean wind speed and standard deviation are evaluated from the measured data. The Weibull *k*- and *c* parameters are useful in several statistical analyses of wind speed data, when assessing the wind energy potential. The useful distribution functions used in this study are discussed below.

3.4.1. Most Probable Wind Speed

The most probable wind speed denotes the most frequent wind speed, V_{MP} and is defined in terms of the Weibull two-parameter by the following equation (Carlin, 2005):

$$v_{MP} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{3.6}$$

3.4.2. Wind Speed Carrying Maximum Energy

The wind speed carrying maximum energy, $V_{\mathrm{max,E}}$ can be determined also by using the Weibull two-parameter given by the following equation:

$$v_{\max E} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{3.7}$$

3.4.3. Weibull Distribution Functions

The wind speed data measured experimentally have wide ranges of values and if analyzed directly will require a lot of time, expense and the results obtained may not be considered sufficient for obtaining a clear view of the available wind potential. For this reason, statistical functions have been introduced in the literature to reduce the analysis. Two of these functions are Weibull wind speed Probability Distribution Function (PDF) and Weibull Cumulative Distribution Function (CDF).

The wind speed Weibull PDF indicates the fraction of time for which a wind speed possibly prevails at the area, and can be calculated by the following equation Zhou *et al.*, (2009);

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \tag{3.8}$$

Note that in Equation (3.8), the values of *k*, *c* and *v* are non-negative.

The wind speed Weibull CDF is used to predict the fraction of time when the wind speed is equal or lower than speed (v) by taking the difference of its values, and can be evaluated using the following equation (Lun and Lam, 2000):

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^{k}} \tag{3.9}$$

Notice that Weibull CDF in Equation (3.9) is the integral of the Weibull PDF in Equation (3.8).

3.4.4. Wind Power Density

The monthly or annual wind power density per unit area swept by turbine rotor is also important for wind energy potential assessment at the site and is given by the following expression;

$$\mathrm{P}_{\mathrm{D}} = \frac{1}{2}\rho c^{3}\left(1+\frac{3}{k}\right) \tag{3.10}$$

It is evident from this equation that the wind power density varies directly with the cube of Weibull scale parameter (Lima, 2012).

The mean energy density (E_D) over a period of time T is the product of the mean power density and the time T, and it is expressed as;

$$E_{\mathrm{D}} = \frac{1}{2}\rho c^{3}\Gamma\left(1+\frac{3}{k}\right)T \tag{3.11}$$

From Equation (3.11) the available wind energy for any specific period of time when the wind speed frequency distributions are different can be calculated.

3.5. Actual Wind Power

The amount of energy available from wind varies with season and time of the day. The common terminologies used to characterize wind resource are Available Wind Power (AWP) given by Equation (2.1) which represents the maximum realizable power.

The extractable wind power (EWP) represents the amount of power that can actually be produced by wind energy conversion systems based on the assumed performance characteristics. An estimation of the EWP, using an average Equation (2.3) with an assumed average power coefficient is given by the relation (Yun and Deng, 2008);

$$\overline{\mathrm{P}_{\mathrm{E}}} = \frac{1}{2}\overline{C_P}\rho\overline{v}^{3}A \tag{3.12}$$

The actual power output of a wind turbine is simulated using the following equation;

$$P_e = \begin{cases} 0 & v < v_{in} \\ P_{eR}\dfrac{v^k - v_{in}^k}{v_R^k - v_{in}^k} & v_{in} \le v \le v_R \\ P_{eR} & v_R \le v \le v_c \\ 0 & v > v_c \end{cases} \tag{3.13}$$

Where P_{eR} is the rated electrical power; v_{in} is the cut in wind speed; V_R is the rated wind speed; and v_c is the cut out wind speed. However, the average power output ($P_{e,ave}$) of a turbine is a very important parameter of a wind energy conversion system since it determines the total energy production and the total income (Rene, 2003).

3.5. Wind Speed at Various Heights

The wind speed varies with height above the ground and the wind speed profile as a function of height can be determined by mounting wind speed sensors at different heights and measuring actual speeds. However, several empirical methods have been derived that correlate wind speeds with height, and some of these expressions are discussed in the subsections below.

3.5.1. The Power Law

The power law that correlates wind speeds with height fairly accurately is expressed by the equation below:

$$\frac{v_2}{v_1} = \left(\frac{\mathrm{h}_2}{\mathrm{h}_1}\right)^{\alpha} \tag{3.14}$$

Where $v_2$and $v_1$are the mean wind speeds at respective heights $h_2$and h_1. The exponent or power coefficient, α is normally called the wind sheer, and varies with height, time of the day, season of the year, nature of the terrain, wind speed and temperature (Hendry, 2009). When α is taken as the surface roughness coefficient, it is assumed to be 0.143 (or 1/7) in most cases. The surface roughness coefficient α can be determined from the following expression:

$$\alpha = \left[0.37 - 0.088 \ln (v_1)\right] / \left\{1 - 0.088 \ln \left(\frac{h_1}{10}\right)\right\} \tag{3.15}$$

Alternatively, the Weibull probability density function can be used to obtain the extrapolated values of wind speed at different heights above the ground level. Since the boundary layer development and the effect of the ground are non-linear with respect to wind speed, the Weibull *c*- and *k*- parameters will change as a function of height as per the following expressions:

$$\mathrm{c}(\mathrm{h}_1) = \mathrm{c}_0 \left(\frac{\mathrm{h}_1}{\mathrm{h}_0}\right)^{\mathrm{n}} \tag{3.16}$$

And

$$\mathrm{k}(\mathrm{h}_1) = \mathrm{k}_0 \left[1 - 0.088 \ln \left(\frac{\mathrm{h}_0}{10}\right)\right] / \left[1 - 0.088 \ln \left(\frac{\mathrm{h}_1}{10}\right)\right] \tag{3.17}$$

Where c_0 and k_0 are the scale and shape parameters respectively at the reference measurement height h_0 above the ground level. The exponent n is defined as:

$$\mathrm{n} = \left[0.37 - 0.088 \ln (\mathrm{c}_0)\right] / \left\{1 - 0.088 \ln \left(\frac{\mathrm{h}_1}{10}\right)\right\} \tag{3.18}$$

The expression (3.16) is valid for surface roughness values in the range of 0.05 to 0.5 (VuXuan, 2011).

3.5.2. The Logarithmic Law

The logarithmic law relating wind speed with height under stable conditions is given by;

$$\frac{\mathrm{U}_{(\mathrm{z})}}{\mathrm{U}_{(10)}} = \frac{\ln\left(\frac{\mathrm{Z}}{\mathrm{Z}_0}\right)}{\ln\left(\frac{10}{\mathrm{Z}_0}\right)} \tag{3.19}$$

Here $\mathrm{u}_{(10)}$ is the wind speed at 10 m above the ground level, Z_0 is the roughness length at reference level ground and$\mathrm{U}_{(\mathrm{z})}$ is the wind speed at height *z* (Sodder, 2000).

Both functions can be used for calculation of the mean wind velocity at a certain height, if the wind velocity is known at the reference height of 10 m.

3.6. Wind Power Resource Assessment

For determination of annual energy output corresponding to a rated speed of wind turbine, the equation below is used;

$$v_{in} = (0.15)^{\frac{1}{3}} * v_r \approx 0.5313 v_r \tag{3.20}$$

Some of the parameters regarding the wind turbine optimum rated wind speed are discussed below.

At very low wind speeds, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. However, as the speed increases, the wind turbine starts to rotate and generate electrical power at a wind speed known as the cut-in wind speed (v_{in}).

As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly till it reaches the rated power output and the wind speed at which it is reached is the rated wind speed (v_r).

Wind speed increases above the rated wind speed with time and the forces on the turbine structure continue to rise and at some point, there is a risk of damage to the rotor. Wind speed at which the turbine is shut down to avoid damage due to high wind speeds is the cut-off wind speed (v_f).

The wind speed at which the turbine reaches rated capacity and maintains constant electrical output for subsequently higher wind speeds is known as full load while the wind speed that the turbine is designed to withstand without falling over is known as the survival wind speed.

3.7. Energy Output and Capacity Factor of a Wind Turbine

A wind turbine is a wind energy conversion system that can operate at its maximum efficiency only if it is designed for a particular site because the rated power, cut-in and cut-off wind speeds must be defined based on the site wind characteristics (Akpinar, 2005). It is essential that these parameters are selected so that energy output from the conversion system is maximized. The performance of a wind turbine installed in a given site can be examined by the amount of mean power output ($P_{e,ave}$) over a period of time and the conversion efficiency or capacity factor of the turbine (Wagner *et al.*, 2008).

The mean power output $P_{e,ave}$ of a wind turbine can be estimated using the following expressions based on Weibull distribution functions;

$$P_{e,ave} = P_{eR}\left(\frac{e^{-\left(\frac{v_{in}}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k}\right) \tag{3.21}$$

Wherev_c, v_r and v_f are the cut-in wind speed, rated wind speed and cut-off wind speed, respectively.

Capacity factor C_f defined as the ratio of the mean power output $P_{e,ave}$ to the rated electrical power P_{eR} is used to compare how much electricity a wind turbine actually produces over a given period of time with the amount of power output for the wind turbine running at full capacity for the same amount of time and is given by:

$$C_f = \frac{P_{e,ave}}{P_{eR}} \tag{3.22}$$

For an investment in wind power to be cost effective, it is suggested that the capacity factor should always be greater than 0.25 (Mayhoub, 1997).

3.8. Relative Deviation of the Mean Wind Speed

The annual mean wind speed can be analyzed with the relative deviation ξ of each year by using the relation given as (Azad, 2013);

$$\xi = \frac{\overline{v_i} - \bar{v}}{\bar{v}} \times 100\% \tag{3.23}$$

Where $\overline{v_i}$ the annual mean wind speed of the year concerned and $\bar{v}$ is the mean wind speed of all the years for which data is available.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

In this chapter, analytical results and discussions on various wind speed characteristics are presented. The data from the station was analyzed and presented in either tabular or graphical form wherever applicable. MathCAD software was used for the calculations and computer spread sheets OriginPro and Microsoft excel were used in the analysis of the data acquired.

4.2. Wind Speed Characteristics Results

The daily mean wind speeds recorded at the station are tabulated in appendix I, II, III, IV and V for each respective year.

4.2.1. Monthly Mean Wind Speed

The mean monthly wind speeds were calculated from the raw data using Equation (3.1) for all the years and are presented in Figure 4.1.

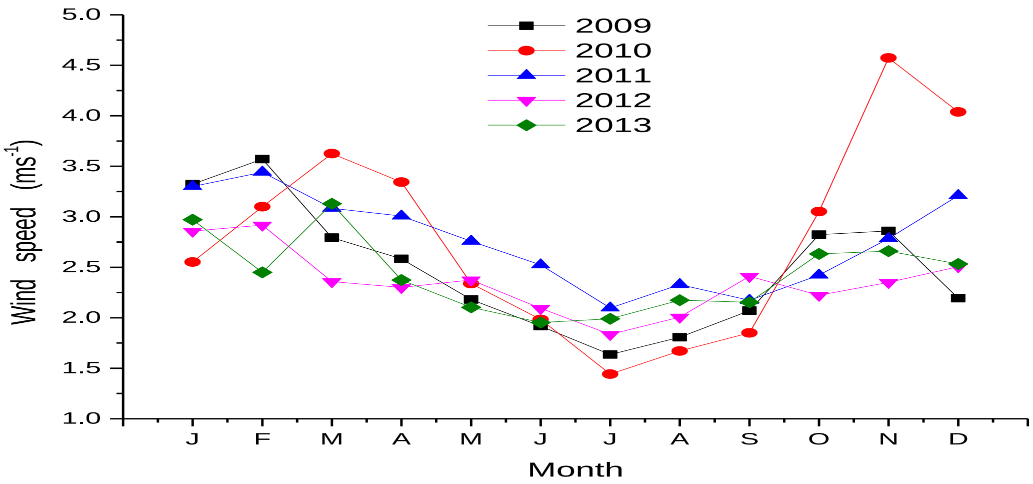


Figure 4.1: Monthly mean wind speed for the five year period at a height of 2 m.

From the results in Figure 4.1, there are two seasons of the year of relatively high speeds namely in the first and last three months of the year while midyear experiences low wind speeds. The highest recorded wind speed is 4.57 ms^{-1} and was observed in the month of November 2010 though it seems to deviate a lot from the other years. Similarly the lowest recorded wind speed is 1.44 ms^{-1} observed in the month of July 2010. Apparently, the year 2010 presented both the highest and the lowest values of wind speeds, while the rest of the years presented a relatively uniform variation of mean wind speeds across all the months. The year 2011 was observed to present relatively highest mean wind speeds across all the months.

4.2.2. Deviations of Mean Wind Speed

Figure 4.2 presents the yearly maximum and minimum deviations from the mean of wind speeds.

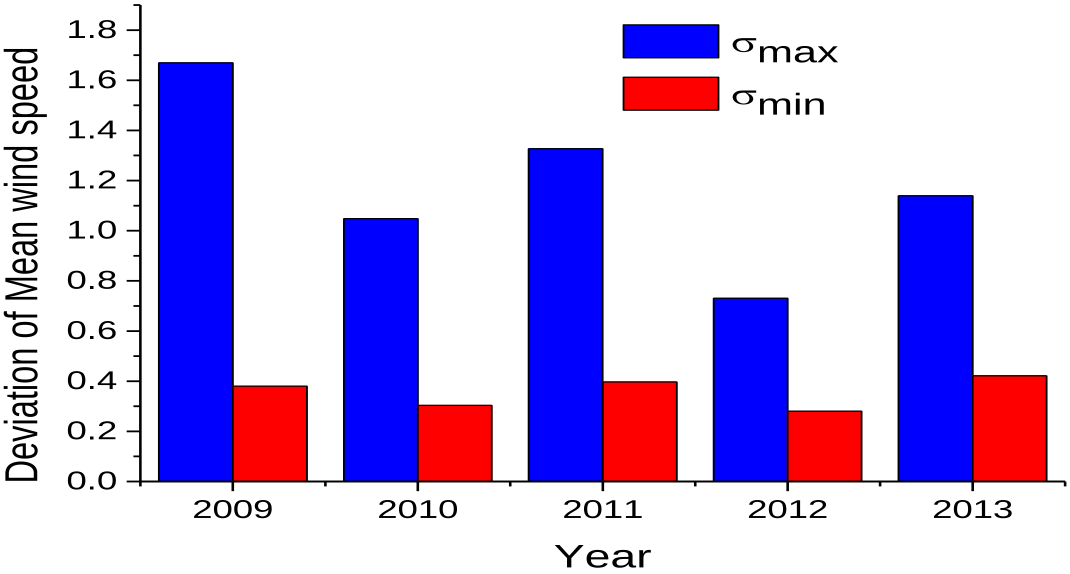


Figure 4.2: Annual deviations of mean wind speed at 2 m

The deviation describe the amount of variability or dispersion around mean wind speed which states how windy a site is for prediction of the best year yielding maximum wind power. The deviations for each month were calculated for the five years and the results showed that the monthly deviation was variable. Figure 4.2, presents the lowest and the highest yearly deviation respectively. These results show that the annual deviation had the lowest value of 0.281 in the year 2010 and the highest value of 1.669 in the year 2009. From these results, the year 2012 had the least difference between the highest and the lowest values hence represent the year with more uniform wind speed.

4.3 Weibull Parameters

The Weibull parameters k and c of the station at a height of 2 m were calculated by using Equations (3.3) and (3.4) and the results obtained are tabulated in Table 4.1.

Table 4.1: Monthly Weibull scale parameter, c (ms^{-1}) and shape parameter, k at 2 m

Y/M		J	F	M	A	M	J	J	A	S	O	N	D
2009	c	3.71	4.03	3.00	2.88	2.41	2.08	1.81	1.96	2.27	3.16	3.21	2.41
	k	3.22	2.28	6.29	3.34	3.92	5.33	3.98	5.43	4.31	3.09	2.88	4.31
2010	c	2.84	3.44	4.01	3.67	2.51	2.11	1.60	1.82	1.98	3.38	4.87	4.33
	k	3.42	3.55	3.85	4.39	6.44	7.63	3.54	5.17	7.12	3.71	7.65	6.54
2011	c	3.49	3.86	3.40	3.33	3.00	2.77	2.27	2.49	2.34	2.61	3.04	3.47
	k	8.49	2.82	4.02	3.66	5.00	4.31	5.78	6.83	6.14	6.01	4.90	5.83
2012	c	3.09	3.11	2.54	2.42	2.54	2.26	1.99	2.19	2.64	2.39	2.56	2.77
	k	5.60	7.27	6.06	9.83	6.78	5.69	5.29	4.88	4.49	6.19	4.94	3.81
2013	c	3.25	2.70	3.50	2.59	2.33	2.13	2.19	2.39	2.36	2.88	2.84	2.83
	k	4.58	4.05	2.99	4.67	3.66	4.93	4.04	4.15	4.44	4.72	7.39	3.22

From Table 4.1, the lowest and the highest values of *c* occurred respectively in the months of July and November 2010 with values of 1.60 ms^{-1} and 4.87 ms^{-1}. The *c*-parameter shows how windy a site is where higher value indicates highest steady wind speed, hence November, 2010 was steady month with the highest wind speed.

The maximum and minimum values of k were 9.83 and 2.28 and occurred in April 2012 and February 2009 respectively. The *k*-parameter is used to describe the PDF curves of wind speed distribution. High values of *k* give high peaks and narrow PDF curves while the low values gives lower peaks and wider PDF curves. From the results obtained in this study, the month of April 2012 presents high peak and narrow PDF curve hence high wind speeds were observed in this month but over a short period. On the other hand, the month of February presents a low peak and a wide PDF curve hence low wind speed was observed in this month but over a longer period.

The annual mean values of *c* and *k* were evaluated from the results in Table 4.1, and presented in Table 4.2.

Table 4.2: Yearly mean Weibull scale parameter, *c* and the shape parameter, *k* at 2 m

Year	Weibull parameter	
	c (ms^{-1})	k
2009	2.743	4.032
2010	3.046	5.251
2011	3.006	5.316
2012	2.543	5.902
2013	2.666	4.404

It is observed from Table 4.2 that the highest annual mean of the Weibull *c*-parameter is 3.046 ms^{-1} in 2010 and the lowest value is 2.543 ms^{-1} in 2012. Thus, the year 2010 has highest steady wind speed and the calmest year is 2012 over the five years period. The average annual values of the Weibull *k*-factor are relatively high ranging from 4.032 to 5.902 hence the site is peaked across all the years. Based on the values of *c* and *k* obtained, the site has high wind energy potential that can be harnessed for electricity generation.

4.4. Wind Speed Frequency Distribution

The yearly PDF and CDF distributions were respectively evaluated using Equation (3.8) and (3.9) and the results are presented in sections 4.4.1 and 4.4.2. From distributions obtained, it is observed that a similar trend of the wind speeds is evident for both the PDF and the CDF.

4.4.1. Weibull Probability Density Distribution (PDF)

Figure 4.3 presents the results obtained from Weibull PDF analysis of the wind speed data.

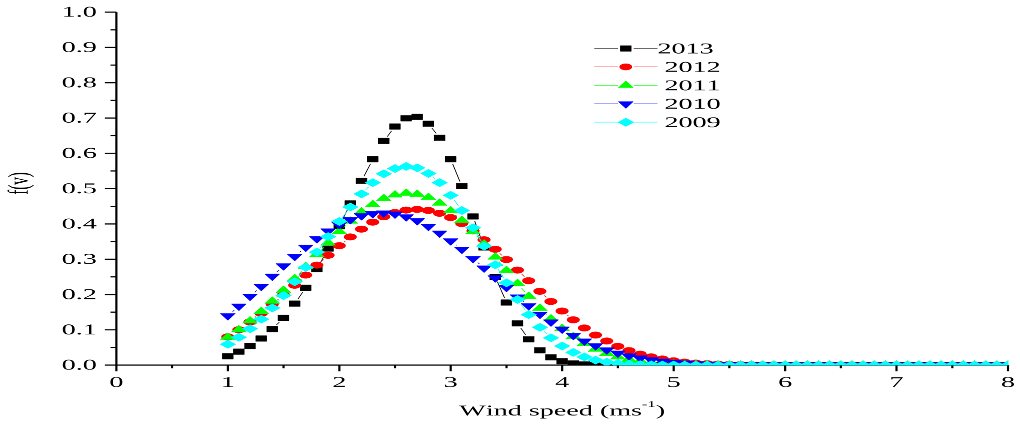


Figure 4.3: Yearly Weibull probability density distributions.

It is observed from Figure 4.3 that these results have normal distributions for all the years and centered at wind speed of about 2.823 ms^{-1}. The years 2013 and 2009 have the highest and second highest peaks respectively giving the highest probabilities of observing high wind speeds but with narrow distribution while the years 2010 and 2012 have equal peaks and wider distribution with low probabilities of observing high wind speeds. The year 2011 is intermediate the two extremes. These results show that the Weibull PDF fits the wind speed distribution at the site reasonably well in the range of 1 ms^{-1} to 4 ms^{-1}. In addition, the most probable wind speed at the site is 2.823 ms^{-1} which correspond to the peak value.

4.4.2. Weibull Cumulative Distribution (CDF)

Figure 4.4 presents the results obtained from the CDF analysis of the wind speed data of the station.

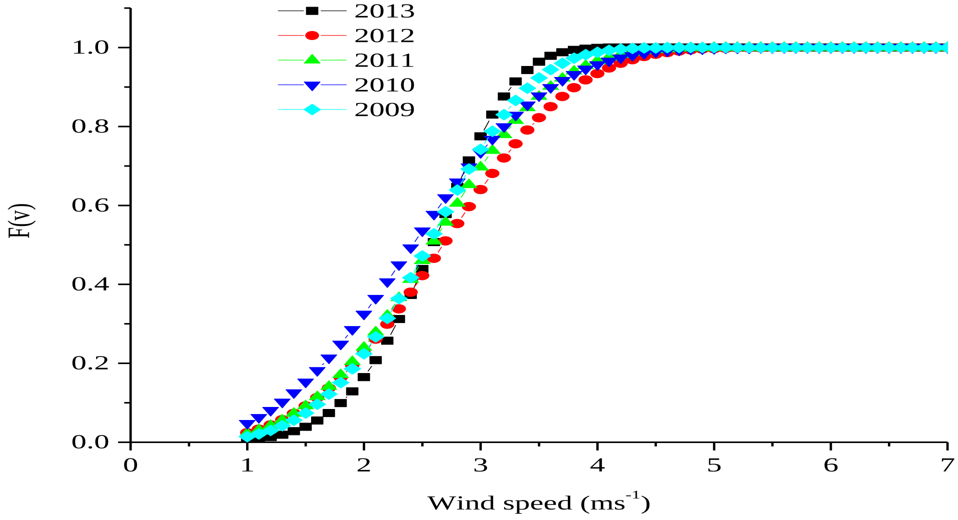


Figure 4.4: Yearly wind speed Weibull cumulative probability distribution

From the results in Figure 4.4, it is observed that the CDF of all the years have similar trends of the wind speeds. The Weibull CDF of wind speed is normally used to estimate the time for which the wind speeds lie within a certain speed interval. CDF curves are used in estimating the cut-in wind speeds frequency of site wind turbines selection. Commercial wind turbines have typical cut-in wind speeds of between 2.5 ms^{-1} to 3.5 ms^{-1} specified by the manufacturer. With a cut-in wind speed of 2.5 ms^{-1}, it is observed from the graph that the site has frequencies of about 35-50%; with a cut-in wind speed of 3.0 ms^{-1} have frequencies of about 65-75% and at a cut-in wind speed of 3.5 ms^{-1}, the site has frequencies of about 80-95%. Therefore, a wind turbine with a cut-in wind speed of about 3.0 ms^{-1} is recommended for the site.

4.5. Characterization of Wind Speed Data at Different Heights

The standard recommended height at which wind speed is measured is 10 m. Since the wind speed data at the station was measured at 2 m height, it was extrapolated to standard 10 m height and typical hub heights of 40 m, 70 m and 100 m and their respective wind energies were calculated.

4.5.1. Wind Sheer

The average yearly values of wind sheer exponent were evaluated using Equation (3.15) from the average wind speeds and tabulated in Table 4.3.

Table 4.3: Yearly average wind sheer exponent

YEAR	WIND SHEER EXPONENT(α)
2009	0.249
2010	0.251
2011	0.246
2012	0.258
2013	0.255
AVERAGE	0.252

These results show that the yearly values of sheer exponent is relatively a constant, and has an average value of 0.252. This value corresponds to a level ground terrain with occasional buildings and many trees which is a true case of the locality in which the data was collected from. The monthly wind speeds and important characteristics at different heights were evaluated and their results were tabulated in Appendix VII to Appendix IX.

4.5.2. Wind Speed Variation with Height

The monthly wind speeds at heights of 10 m, 40 m, 70 m and 100 m were extrapolated by using the power law Equation (3.14). Figure 4.5 presents the monthly mean variations of wind speeds at varying heights. The results show that the wind speed increases with increase in height as expected and got similar trend.

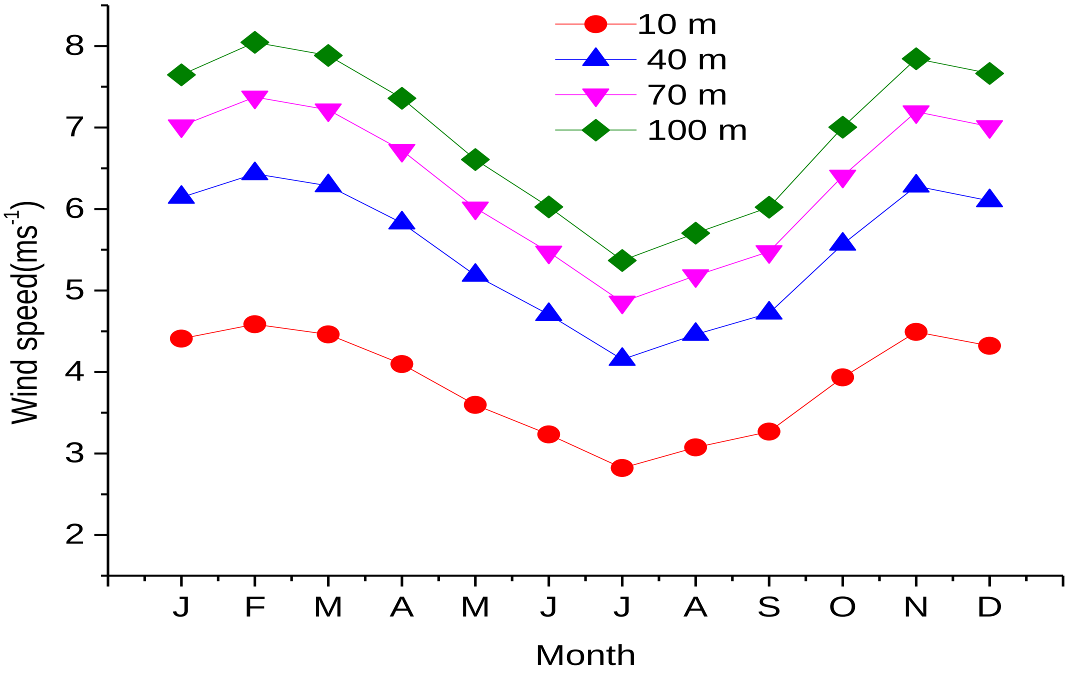


Figure 4.5: Monthly mean wind speed variation with Height

4.6. Variation of Power Density and Extractable Power with Speed

The maximum power extractable from the wind was calculated after factoring in the Betz's limit. Figure 4.6 shows representative results on power density and extractable wind power variations with wind speed at a height of 10 m above the ground level.

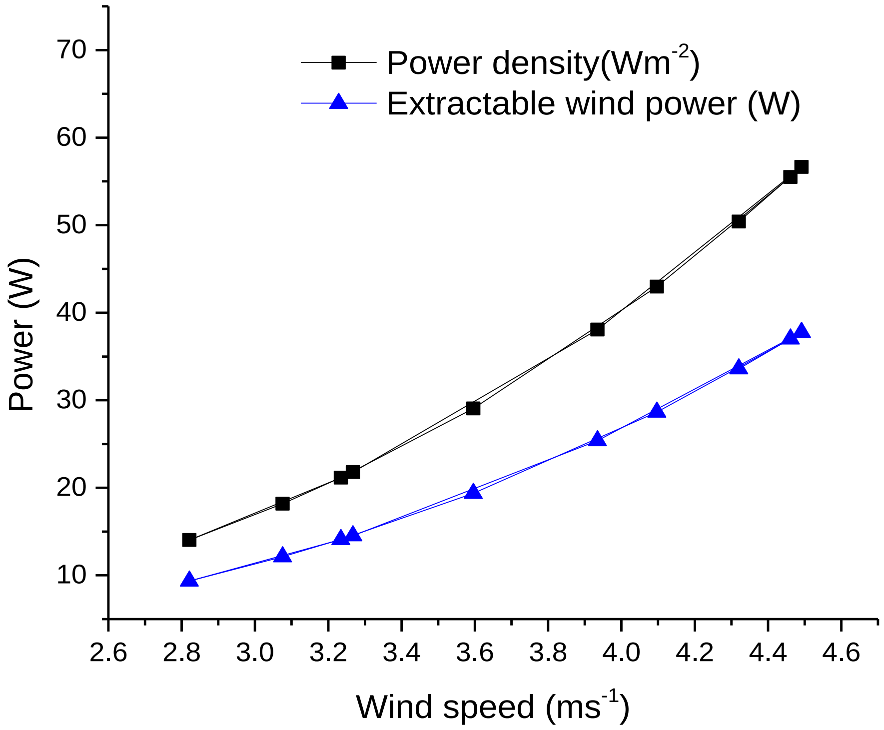


Figure 4.6: Power density and extractable wind power variation with wind speed at 10 m height.

The results in Figure 4.6show that the extractable wind power is always lower than the power density for all the wind speeds. It is further determined that the efficiency at a lower speed of 2.8 ms^{-1} is 40.34% while at a higher speed of 4.5 ms^{-1} is 36.59%. It is notable that a small change in wind speed produces a large change in wind power density because of the power cubic law.

4.6.1. Variation of Monthly Power Density at Selected Heights

The monthly power density for the selected heights of 40 m, 70 m and 100 m were evaluated and are presented in Figure 4.7.

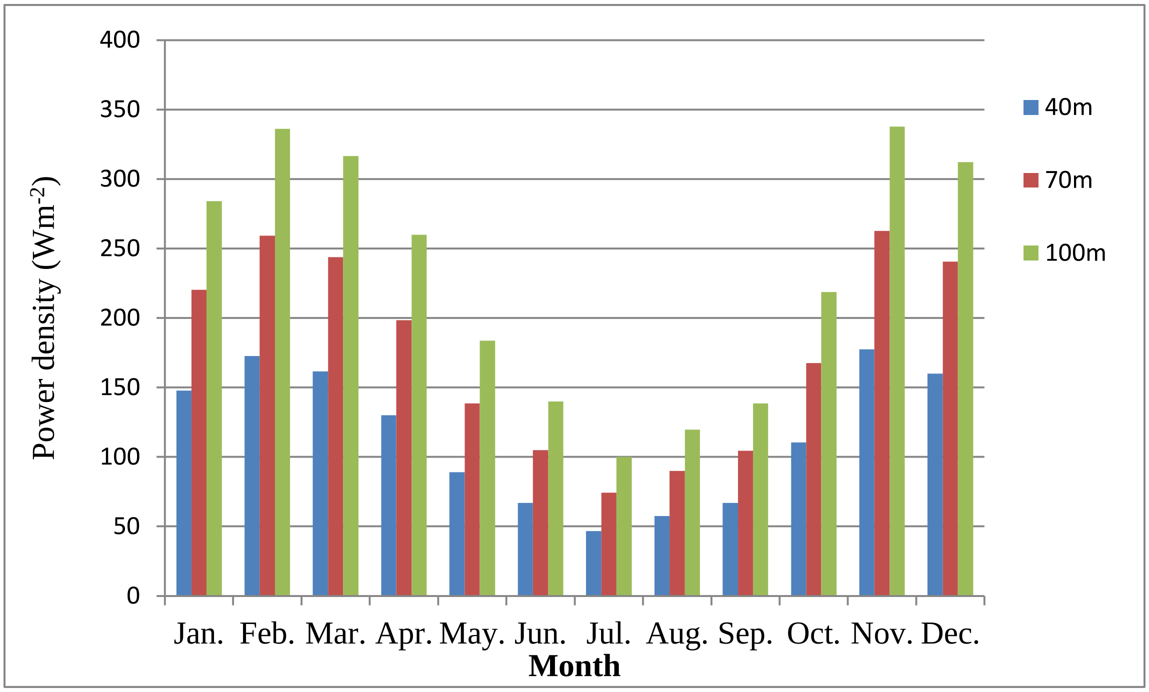


Figure 4.7: Monthly wind power density at 40 m, 70 m and 100 m

From the results obtained in Figure 4.7, there exist two levels of high (November to April) and low (May to October) wind power density across the year and that wind power density increases with increase in height.

4.7. Site Classification

Site classification is based on the wind speed characteristics at given hub height. The monthly maximum and minimum wind speeds are presented in Appendix K. Table 4.4 presents maximum and minimum wind speeds and average power density at a standard height of 10 m and the selected heights of 40 m, 70 m, and 100 m.

Table 4.4: Minimum and maximum wind speed with varying heights

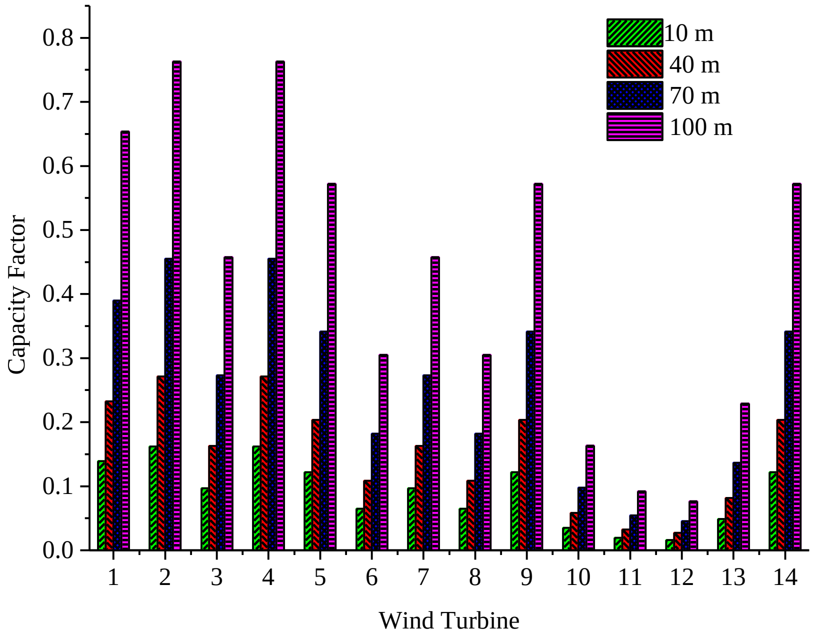
Height (m)	V_{max} (ms^{-1})	V_{min} (ms^{-1})	Average (ms^{-1})	Power density (Wm^{-2})
10	6.45	2.32	4.385	41.247
40	8.68	3.49	6.085	115.563
70	9.78	4.12	6.950	175.394
100	10.56	4.58	7.570	228.917

At a height of 10 m, the results obtained show that the wind speed is of class I with a maximum wind speed of 6.45 ms^{-1} and a mean of 4.385 ms^{-1}. Wind speed at 100 m is classified as of class IV with average wind speed of 7.570 ms^{-1}. The wind speeds are under fairly good category for this height with a mean of 7.570 ms^{-1} and an average power density of 228.917 Wm^{-2}.

4.8. Performance of Selected Wind Turbines

Fourteen small to medium-size commercial wind turbine models with rated power range from 300 to 2500 W were selected from the commercially available wind turbines to simulate their performance at the site of the study. The selected wind turbine models and their characteristic properties are presented in Appendix L. For each wind turbine, the annual average power output and capacity factor based on Weibull distribution function parameters at their respective hub height were determined using Equations (3.21) and (3.22) respectively. The selection of commercial wind turbines was based on the recommendation made in the CDF analysis (section 4.4.2) on the cut-in wind speed.

From the results the capacity factor of each of the selected wind turbine were evaluated for each respective height and are presented in Figure 4.8.



Wind turbines	
1	AC-120
2	SUPERWIND
3	WINDWORKER-300
4	WINDWORKER-500
5	ML1500
6	SOMA
7	VK240
8	WFD500W
9	WFD750W
10	Windtalker
11	Passaat
12	Tulipo
13	Westwind
14	WINDWORKER-1000

Figure 4.8: Capacity factor with varying heights of selected wind turbines.

The results obtained in Figure 4.8 shows that the capacity factor of a wind turbine increases with increase in height. This is due to increased wind speeds at these high hub heights.

In order to meet the minimum recommended capacity factor of 25% for electricity generation, the following design parameters are suggested: wind turbine model with a minimum hub height of 10 m, cut-in wind speed of less than 3.5 ms^{-1}, rated wind speed of around 10 ms^{-1} and cut-out wind speed of 30 ms^{-1} are recommended for height of 10 m and this fits the AC-120 (Aerocraft, Germany) wind turbine model. For a hub height of

70 m, wind turbine with a cut-in wind speed of less than 3.5 ms^{-1}, rated wind speed of around 11 ms^{-1} and cut-out wind speed of 35 ms^{-1} are recommended fitting nearly all the selected wind turbines except for turbines 10-13 for this site.

4.9. Relative Deviations

The relative deviations of the average wind speeds, wind power density and energy density of a given month for the five year period with reference to their averages are presented in Figure 4.9.

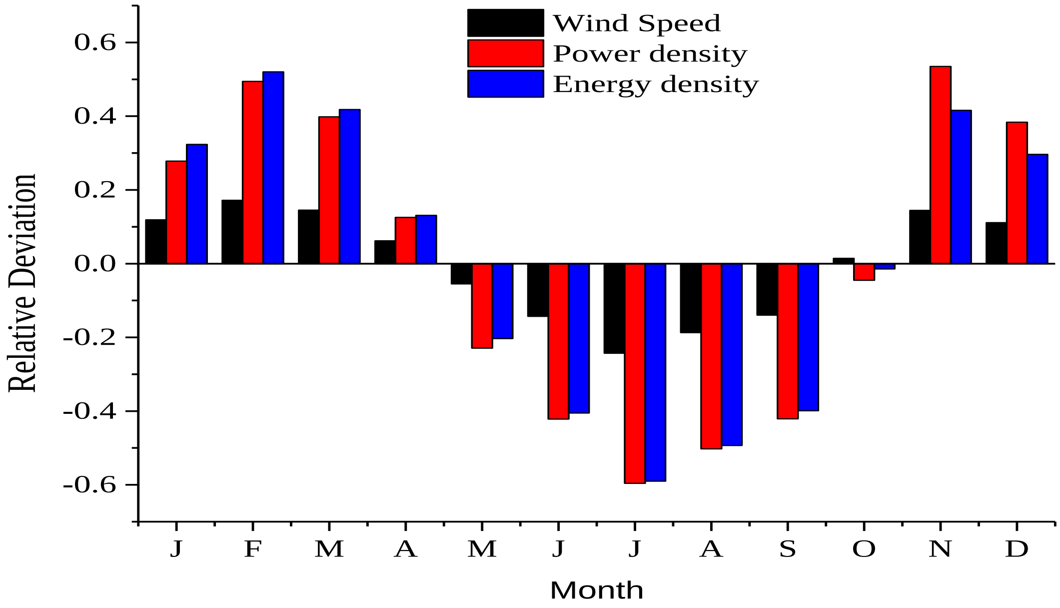


Figure 4.9: Average monthly Wind speed, wind power density and energy density relative deviation

It is obtained from the results that wind speed deviation from their mean may not be more than 2.5% meaning that its monthly average do not vary much hence more stable across the years. Power density and energy density deviations may not be more than 6% representing a stable state of power supply from the wind.

Furthermore, it is determined that there is a negative deviation for the months from May to October, while the rest of the months present a positive deviation across the years. The negative deviations occur during the months that low wind speeds are experienced across all the years.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In today's world, where a greener source of energy is the need of the hour, wind energy is a promising resource, waiting to be harnessed to its true potential. Wind speed data collected for a period of five years (2009–2013) were subjected to two-Weibull parameter model which fitted well to the measured probability distributions on a yearly basis. The average scale parameter (c) was found to be 2.801 ms^{-1} showing the site as being moderately windy. The shape parameter (k) is 4.98 showing that the wind speeds of the site are a bit variable and would give a peaked Weibull probability distribution at about 2.823 ms^{-1}.

The wind power density for the site was found to be 15.045 Wm^{-2} which is a power class of I at 2 m. The wind shear exponent for the site was found to be 0.252 and extrapolation of wind speeds using this value gave mean speeds at a hub height of 10 m, 40 m, 70 m and 100 m as 3.857 ms^{-1}, 5.49 ms^{-1}, 6.33 ms^{-1} and 6.93 ms^{-1} respectively. The mean respective power densities at these heights were found to be 41.23, 115.56, 175.39 and 228.92 Wm^{-2}. According to amount of mean wind power density and energy density, it is found that this area is a suitable location to install both small and medium wind turbine. Moreover, status of wind power density at both elevations of 70 m and 100 m are suitable conditions for wind turbine usage to generate power.

5.2. Recommendations

There should be considerable strategies for the development of the energy sector in Kenya if a certain share of renewable energy in the energy supply mix is desired. Both the small and large (at higher hub heights) wind turbines are recommended in this study as fit for installation to provide for domestic needs and grid connection electrical supply in Kesses.

The highest annual capacity factor with values of 0.637, 0.389, 0.454, 0.356 and 0.341 were determined at 70 m for the AC-120, SUPERWIND, ML1500, WFD750 and WINDWORKER wind turbines, respectively. These wind turbines are recommended to be installed in the Kesses area.

More studies should be carried out at this site by actual observations and measurements of wind speed for a longer period of time more than 30 years to provide more precise predictions of wind power potential. It is further recommended that wind data collection should be automated by using a digital data-logger system capable of measuring wind speed at specified times. The information can then be relayed to a computer for analysis.

The wind pattern should be studied alongside other forms of energy sources so as to ascertain the feasibility of designing hybrid systems in the region. In addition, it is recommended that studies in other neighboring sites should be done to create a site integration model that can enhance wind power reliability by reducing the wind resource intermittency. Moreover, more aspects need to be introduced in the assessment such as economic aspect of wind energy, environmental and geographical aspects (i.e. using Geographical Information System) in the future studies.

REFERENCES

Ackermann, T. and Sodder, L. (2002).An Overview of Wind Energy-Status 2002.*InRenewable and Sustainable Energy Reviews,* Vol. 6:67-128.

AFREPREN. (2002). The Socio-Economic and Environmental Impact of Geothermal Energy on the Rural Poor in Kenya.*Occasional Paper,* Vol. 12. Nairobi, Kenya.

Ahmed, S. and Hanitsch, A. S. (2006).Evaluation of wind energy potential and electricity generation on the coast of Mediterranean Sea in Egypt. *Renewable Energy,*Vol.2:1–20.

Ahmet, Y. (2015). A survey of wind energy potential in Turkey.*Solar and Wind Technology,* Vol. 7: 155–67.

Ajayi, O. O.(2011). Assessment of utilization of wind energy resources in Nigeria.*Energy Policy*, Vol.37:750-753.

Akpinar, E. K. and Akpinar, S. (2005). An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics.*Energy conversion and management,*Vol. 46:515-532.

Albadi, M. H., El-Saadany, E. F. and Albadi, H. A.(2012). Wind to power a new city in Oman. *Wind Energy*, Vol.34(10):1579-1586.

Ani, S.O., Polinder, H. and Ferreira, J.A. (2012). Performance of axial flux permanent magnet generator for human power application. *IET Conference on Power Electronics and Drives (PEMD),* Bristol, UK, 27-29 March.

Azad, A.(2013).Statistical Weibull distribution analysis for wind power of the two dimensional ridge Areas.*International Journal for Advanced Renewable Energy Resources*. Vol.1: 8–14.

Balouktsis, A., Chassapis, D. and Karapantsios, T.D. (2002). A nomogram method for estimating the energy Produced by wind turbine generators. *Solar Energy,* Vol.72: 251–259.

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

Bekdemir, S., Gökçek, M. and Bayülken, A. (2007). Investigation of wind characteristics and wind energypotential in Kirklareli, Turkey.*Renewable Energy*, Vol.32(10):1739-52.

Betz, A. (1966). Introduction to the Theory of Flow Machines,(D. G. Randall, Trans.) Oxford; Pergamon Press.

Bhuiyan, F.A. and Yazdani, A. (2011). Multimode Control of a DFIG-Based Wind-Power Unit for Remote Applications. *IEEE Trans. on Power Delivery*, Vol. 24(4): 2079-2089.

Bianchi, F.D., Battista, H. and Mantz, R.J. (2007). Wind turbine control systems principles, Modeling and gain scheduling design. *Wind Engineering,* Vol.15: 207-215.

Buhari, A. M. H.(2006). A statistical analysis of wind speed data and an assessment of wind energy potentialin Taiz-Yemen.*AUCES*, Vol.9(2):21-33.

Carlin, P.(2005). A Suggested Modification to a Common Expression for the Energy Content of a Wind Data Sample.*Wind Energy*,Vol.8: 477-480.

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*,Vol. 29: 593–604.

Chang, T.J., Wu, Y.T., Hsu, H.Y., Chu, C.R. and Liao, C.M. (2003). Assessment of Wind Characteristics and Wind Turbine Characteristics in Taiwan. *Renewable Energy*, Vol.28:851 - 871.

Choge, D.K., Rotich, S.K., and Tonui, J.K.(2013). Small Wind Turbines: A Simulation for Optimal Selection in Uasin-Gishu, Kenya. *Pacific Journal of Science and Technology*, Vol.14 (2):102-108.

CumaliIlkilic, J. (2012). A Survey on Variable-Speed Wind Turbine System in Turkey. *Electronics of Power,* Vol.2:732-738.

Duic, N., Alves, L.M., Chen, F. and da Graca Carvalho, M.(2003). Potential of Kyoto protocol clean development mechanism in transfer of clean energy technologies to small Island developing states: case study of Cape Verde.*Renewable and Sustainable Energy Reviews,* Vol.7:83–98.

Essandoh, D. A, (2013). The application of artificial neural networks to mapping of wind speed profile for energy application in Kumsi, Ghana. *Applied Energy*, Vol.87(3):934-942.

Fagbenle, R.O., Katende, J., Ajayi, O.O. and Okeniyi, J.O. (2011). Assessment of wind energy potential of two sites in North-East, Nigeria. *Renewable Energy*,Vol.36: 1277–1293.

Fries, L.L., Ed.(1990). Wind Energy Conversion Systems, Englewood Cliffs, New Jersey: Prentice Hall.

GOK(Government of Kenya).(2014). Scaling-Up Renewable Energy Program (SREP). *Investment Plan for Kenya*. Government Printers, Nairobi Kenya.

Gupta, R. and Biswas, A. (2010). Wind Data Analysis of Silchar (Assam, India) by Rayleigh and Weibull Methods.*Journal of Mechanical Engineering Research,* Vol.2: 10-24.

Hansen, L.H. (2001). Generators and Power Electronics for Wind Turbines. *In Proceedings of The IEEE Industrial Electronics Conference*,Vol.3:2000-2005.

Hemke, P.E. (1946). Elementary Applied Aerodynamics, New York: Prentice Hall, Inc.

Hendry, C. andHarborne, P.(2009). Pathways to commercial wind power in the US, Europe and Japan: the role of demonstration projects and field trials in the innovation process. *Energ Policy*, Vol.37(9):3580-95.

Hoogwijk, M., de Vries, B.,Winkel, J. and Turkenburg,W.(2003). Assessment of the potential of wind and photovoltaic energy.*Energy Economics* (submitted for publication).

http://cleantechnica.com/2011/04/18/projected-wind-energy-growth. Accessed on 15th Jan 2015

IPCC. (2013). Special Report on Emission Scenarios, Cambridge Univ. Press, Cambridge.

Islam, K., Walker, J.F. and Jenkins, N. (2011). Wind Energy technology, New York: John Wiley.

Jamil, M., Parsa, S. and Majidi, M.(1995). Wind power statistics and evaluation of wind energy density.*Renew Energy*, Vol.6(5-6):623-628.

Justus, C.G., Hargraves, W.R., Mikhail, A., and Graber, D.(1978).Methods for estimating wind Speed frequency Distributions. *Journal of Applied Meteorology*, Vol. 17:350–353.

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

Kamau, J. N., Kinyua, R. and Gathua, J. K. (2010). 6 years of wind data for Marsabit, Kenya average over 14 ms^{-1} at 100 m hub height; an analysis of the wind energy potential. *Renewable Energy*, Vol. 35: 1298-1302.

KenGen. (2015). State of renewable development in Kenya *assessment reports, Government printers.*

Kenya, Ministry of energy.(2008). Feed-in-Tariffs policy on wind, biomass and small hydros.*Government printers*.

Kenya, Ministry of Energy. (2012). *National Energy Policy*. 3rd Draft. Nairobi.

Kenya, Ministry of Environment and Natural Resource. (2010). Potential natural resources in Kenya. *Government printers.*

Kirui, W.H. (2006). Assessment of the wind and solar energy potential in the central rift valley of Kenya, MSc. Thesis. Egerton University, Nakuru, Kenya.

Lima, L. (2012). Wind resource evaluation in Sao Joao do Cariri (SJC)-Paraiba Brazil.*Energy Converence Management*,Vol.16:474-480.

Lipu, M. S. H., Uddin, M. S., and Miah, M. A. R. (2013). A Feasibility Study of Solar-Wind-Diesel Hybrid System in Rural and Remote Areas of Bangladesh. *International Journal of Renewable Energy Research (IJRER),* Vol. 3:892-900.

Lun, I. and Lam, J.C. (2000). A study of Weibull pparameters using long term wind observations *Renewable Energy*, Vol. 20(2):289-295.

Luna, H. and Church, N.(1974). Wind energy bibiliography, Mukwonago Wisconsin.*Windworks*, Vol 2(2):14-15.

Lund, H.(2006). The Kyoto mechanisms and technological innovation.*Energy,* Vol.31:2325–2332.

Lynette, A. and Robert, H.(1990). Status and Potential of Wind Energy Technology. *Windpower'90 Proceedings, American Wind Energy Association Conference*, Washington, D.C., September 24–28.

Manwell, J.F., McGowan, J.G. and Rogers, A.L. (2002). Wind Energy Explained: Theory, Design and Applications, Chic ester; New York: Wiley.

Marigi, S.N. (1999). Assessment of solar energy resources in Kenya,Ph.D. Thesis, Moi University, Eldoret, Kenya.

Massai, L. (2011). The kyoto protocal in the EU and member state under international law, The Hague: T.M.C. Asser Press.

Mathenge, O.(2009). Kenya set to tap much more power from renewable energy in new plan, Newspaper. Nairobi: daily nation,Tuesday 7th July.

Mathew, S. (2006). Wind Energy: Fundamentals, Resource Analysis and Economics, Springer, Heidelberg.

Mayhoub, A. B. and Azzam, A. (1997). A survey on the assessment of wind energy potential in Egypt.*Renewable energy*,Vol.11:235-247.

Meishen Li and Xianguo Li. (2005). MEP-type distribution function: a better alternative to Weibull function for wind speed distributions. *Renewable Energy*; Vol. 30:1221–1240.

Mert, K. S. and Karakus, M.A. (2015). Investigation of wind characteristics and assessment of wind generation potentiality in Antakya, Turkey.*Applied Energ*, Vol.86(3):333-339.

Mirhosseini, M.(2011). Assessing the Wind Energy Potential Locations in Province of Semnan in Iran.*Renewable and Sustainable Energy Reviews*, Vol. 15(1): 449-459.

Mostafaeipour, A. Sedaghat, A. A., Dehghan, N., and Kalantar, V. (2011). Wind energy feasibility studyfor city of Shahrbabak in Iran.*Renewable and Sustainable Energy Reviews*, Vol.15:2545-2556.

Mouangue, R.M., Kazet, M.Y., Kuitche, A. and Ndjaka, J.M. (2014). Influence of the Determination Methods of K and C Parameters on the Ability of Weibull Distribution to Suitably Estimate Wind Potential and Electric Energy. *International. Journal of Renewable Energy Development*, Vol. 3(2), 145-154.

Mukhopadhyay, N. M. and Panigrahi, S.K. (2013). An assessment of wind energy potential as a power generation source in Kolkata.*Energy*, Vol. 35(1):188-201.

Nguyen, Q.K. (2006). Simulation of the power output for single wind turbines within a wind farm, Master thesis, Faculty of Physics. University of Oldenburg, Germany.

Nigim, K. A. and Paul, P. (2007). Heuristic and probabilistic wind power procedures.*Renewable energy*, Vol.32:638-648.

Ohunakin, O.S. and Akinnawonu, O.O.(2012). Assessment of wind energy potential and the economics ofwind power generation in Jos, Plateau State, Nigeria.*Energy Sustainability for Development*,Vol.16:78–83.

Oludhe, C. (1987). Statistical characteristics of surface wind power in Kenya, MSc. Thesis. University of Nairobi, Nairobi, Kenya.

Oludhe, C. and Ogallo, L. J. (1989). Statistical characteristics of surface winds over Kenya. *Journal of applied statistics*, Vol.16: 331-343.

Ozgener, O. and Hepsali, A. (2002). Current status and future directions of wind energy applications inTurkey.*Energy sources*, Vol.24: 1117-1129.

Quaschning, V. (2005). Understanding Renewable Energy Systems, Earthscan. *Renewable energy*, Vol.3: 224-228.

Ramachandra, T.V., Rajeev, K.J., Krishna, S.V. and Shruthi, B.V. (2005). Wind energy potential assessment spatial decision support system.*Energy Education Science and Technology*, Vol.14 (2):61-80.

Reddy, H., Johansson, A.K.N., Kelly, T.B. and Williams, R.H.(2014). Renewable fuels and electricity for a growing world economy—defining and achieving the potential. *Renewable Energy: Sources for Fuels and Electricity*. Island Press, Washington, DC, Vol.2.

Rene, T. and Ernest, K. (2003). Wind energy in Adamaoua and north Cameroon provinces. *Energy conversion and management,*Vol.44:845-857.

Rivkin, D. and Silk, L. (2013). Wind energy, Jones and Bartlett Learning publishers, Burlington.

Rosen, K. R., Van Buskirk, R. and Garbesi, K. (1999). Wind energy potential of coastal Eritrea: an analysis of sparse wind data. *Solar Energy*, Vol.66 (3):201–213.

Royston, A. (2012). Nuclear accident, Arcturus Publishers, Mankato, Minnesota.

Spera, D.A. Ed. (1994). Wind Turbine Technology, New York: ASME Press.

Soon-Duck, K. (2010). Uncertainty analysis of wind energy potential assessment.*Applied Energy,* Vol.87:856-865.

The IPCC Third Assessment Report. (IPCC, 2001)

Thomas Ackermann, and Lennart Sodder, (2000). Wind energy technology and current status. *Renewable and Sustainable Energy Reviews,*Vol.4:315-374.

Vafaeipour, m., Rahbari, O.,Rosen,M. A., Fazelpour, F. and Ansarirad, P. (2013). An artificial neural Network approach to predict wind velocity time-series in Tehran. *In The 5th International Congress of Energy and Environment Engineering and Management,* Lisbon.

Van der Auwera,L., Meyer, F. D. and Malet, L. M. (1980). The use of the Weibull three-parameter model for estimating mean wind power densities.*Journal of Applied Meteorology,* Vol.19: 200-220

Vardar, A. and Alibas, I.(2008). Application of Weibull model in win assessment. *Renewable Energy*, Vol. 33:1721–1732.

VuXuan, H., Lahaye, D., Ani, S.O., Polinder, H. and Ferreira, J. A. (2011). Effect of design parameters electromagnetic torque of PM machines with concentrated windings using nonlinear dynamic FEM. *IEEE International Electric Machines & Drives Conference, Niagara*, 15-18 May: 390-395.

Wagner, R., Ioannis, A., Pedersen, S.M., Courtney, M.S. and Hans, E.J. (2008). The Influence of the Wind Speed Profile on Wind Turbine Performance Measurements.*Wind Energy,* Vol.12:348-362.

Wind Engineering SPA. Available from: http://www.wind-engineering.it/turbines.html. Accessed on 12th Jan 2015

World Nuclear Association. (2011). Fukushima Accident December 22- 2011, citing the *Japanese Nuclear and Industrial Safety Agency (NISA)*,http://world nuclear.org/info/fukushima_accident_inf129.html.

World Nuclear Association.(2014). World Nuclear Status December 22- 2014, citing the *UN An IndustrialSafetyAgency(NISA).*

Youm, J.,Sarr, M.,Sall, D. and Kane, M.M.(2005). Renewable Energy Activities in Senegal Review. *Renewable and Sustainable Energy Reviews*, Vol.4:75 - 89.

Yun, D. (2008). Design Optimization of a Micro Wind Turbine using Computational Fluid Dynamics, Unpublished Masters Thesis. University of Hong Kong.

Zhou, W. (2008). Simulation and optimum design of hybrid solar-wind and solar-wind-diesel power generation systems, Hong Kong: Hong Kong Polytechnic University,:218-222.

APPENDICES

Appendix I: Daily Wind Speeds for the Year 2013

KESSES MET 2013 WIND SPEEDS (ms^{-1})												
DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1	2.5	2.1	2.7	2.8	1.5	1.8	1.7	2	2.2	2.2	3.2	1.8
2	2.2	1.5	3	2	2.5	1.7	1.8	2.3	1.3	1.8	3.7	2.2
3	2.8	2	2.5	2.5	2.5	2.2	1.2	1.8	2.3	3	2.8	3.3
4	2	1.8	3.8	3.5	1.2	1.8	1.7	1.2	1.3	2.8	2.8	2.2
5	2.5	1.8	2.7	2.3	1.5	1.5	1.7	1.7	2	2.8	2.8	1.7
6	2.7	2.3	3	2.3	2.2	1	1.8	2.2	1.7	2.2	2.8	1.8
7	2	1.8	3	3	1.7	2.2	2.2	2.2	1.8	2.5	2.8	1.8
8	2.8	1.7	3.3	2.5	1.8	2.3	1.6	1.7	1.7	1.8	2.5	1.7
9	2	2.8	6	3.7	1.7	1.5	2.2	3	1.5	2.5	2.5	2.7
10	2.3	2.7	5	2	2.3	2	1.8	2.8	2.5	2.3	3	3
11	3	2.7	6.2	2	1.2	2.7	1.3	1.7	2.2	2.5	2.3	4.7
12	3.2	2.7	3.7	2	1.8	1.8	2.5	2.3	1.7	2.8	3.5	2
13	3.3	4	2.7	3.7	1.5	2.7	3.3	3.3	2	4.2	2.7	3
14	4	3.7	3.7	2	3	2.2	2.2	1.7	2.3	3.7	2.7	2.2
15	2.2	2.5	5	1.7	1.7	1.2	1.8	2	2.2	4.2	2.5	4.7
16	2.3	2.7	2.2	1.7	1.8	2.2	1.8	1.7	2.8	3.5	2.2	3.2
17	4.3	1.7	3.3	2.2	1.5	2.2	1.5	2.3	2.2	2.3	2.2	2.7
18	4.3	3.2	4	2.3	1.3	1.2	2.2	1.5	1.7	2.3	2.7	2.2
19	3	2.2	2.3	1.8	1.7	1.8	2.2	1.5	2.2	3	2.2	2.7
20	3.7	2.8	2.3	2.8	3.2	2	2.2	1.5	2	2	2.5	2
21	3	2.7	3.2	2.7	3.7	2.2	1.2	3.7	2.7	2.2	2.5	2.5
22	2.8	3.8	3.2	1.8	2.3	1.7	2.7	2.5	2	2.7	2.5	2
23	2.5	2.5	3	1.8	2.7	1.8	2.2	2.5	2.5	2.2	3	1.8
24	4.3	2.8	1.8	1.7	2	2	1.5	2.7	1.8	2	2.2	1.8
25	3.3	2.7	2.7	1.8	2.2	2	1.7	2.7	1.8	2.5	2.7	2.3
26	2	1.5	2.3	2.2	3.5	1.7	1.3	2.8	2.2	2.8	3.3	2.7
27	2.7	2.2	2.5	2.7	2.2	1.8	1.8	2	2.7	3.2	3	4.2
28	3.7	1.7	2.7	2.8	2.2	2.8	2.8	2	3	3.2	2	2.5
29	4		1.7	2.2	2	2.8	2.7	1.7	4	2.2	2	1.5
30	3.7		1.8	2.7	2.5	1.8	3.3	2.7	2.3	2	2.2	1.8
31	3		1.7		2.3		1.8	1.7		2.2		3.8

Appendix II: Daily Wind Speeds for the Year 2012

KESSES MET 2012 WIND SPEEDS (ms^{-1})												
DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1	4.5	3	2.2	2.8	2.5	1.5	2.2	2.2	2	2.2	2	4.2
2	2.5	2.3	2.3	2.5	2.2	2	1.8	2	1.5	2	2	3.8
3	2.8	2.3	2.2	2.2	2.2	2	1.5	1.8	1.5	2.3	1.8	2
4	2.8	3.2	2	2.5	3.5	2.2	1.8	1.8	2.2	2	3.2	4.3
5	2.8	3	2.3	2.8	3	2	1.5	1.5	2.2	2.3	2.8	4
6	3.3	3	2.5	2.5	2.5	2.8	1.5	2	2.7	2.2	2.2	3
7	3	2.3	2.7	2	2.8	1.5	2	2.5	2	1.8	2.3	2.7
8	3.3	2.8	3.5	2.3	2.8	2.7	1.5	3	2.7	2.7	2	2
9	2.5	2.5	2.5	1.8	2.5	1.5	2	2.7	2.2	2	2	2
10	2.7	4.2	1.8	2.3	2.7	2.2	2	2.2	3.5	2.5	1.7	1.7
11	3	2.8	1.8	2.5	1.8	1.7	2.2	1.8	1.5	2.3	1.7	1.5
12	2.7	3.2	2.3	2.8	2.5	2.7	1.5	2.3	2.5	2.3	1.8	1.8
13	2.5	3.3	1.7	2	2.7	2.3	1.5	1.8	2.2	1.8	2.2	2.5
14	2.7	3.7	2	2.2	2.7	2.5	1.8	0.8	3.3	2.2	2.5	2.3
15	3.3	2.8	2.5	2.5	2.3	2	1	2.3	3.2	1.8	2.5	1.7
16	3.5	2.7	2.3	2.5	2	1.2	1.8	1.5	4	1.8	1.5	2.2
17	4.2	2.8	3	2	2	2	2.5	1.5	2.7	2.7	2	1.7
18	3	3	2.8	2.2	1.7	2	2.5	1.8	2.2	1.5	2	2.5
19	3.8	3.2	2	2.5	2	2	1.5	1.8	3	2	2.6	2.2
20	3.2	3.3	2.3	2.5	2	2.5	1.2	1.5	3	3	2.8	2.5
21	2.5	3.2	2.3	2.3	2.3	1.8	2	2.7	2.7	3.2	3.2	2.2
22	2	3.2	1.8	2.2	3	2.2	1.5	2.2	2	2	2.5	2.8
23	2.5	2	1.8	2.5	2.2	2.8	1.5	2	2.2	2.7	1.7	2.7
24	2.8	2.5	2.8	1.8	2.3	2.7	2.5	2	2.7	2.2	1.7	1.7
25	2	2.3	2.3	2	2	1.8	2.5	2	2.5	2.3	3	2.7
26	2.8	2.8	2.5	2.2	2.3	1.8	1.5	1.8	2.5	2.2	2.8	2.5
27	2.3	3.3	1.7	1.8	2.7	2.2	2	2	2	2.3	3.3	3
28	2	3	2.5	2.3	2.3	2	2.2	2.7	2	1.5	2.7	2.5
29	2.3		3.2	2.3	2.3	1.7	2.2	2.7	1.8	1.8	2.7	2.5
30	2.8		3	2.2	2	2.5	1.7	1.8	1.8	2.3	3.3	2.2
31	2.5		2.5		1.8		2	1.5		3		2.3

Appendix III: Daily Wind Speeds for the Year 2011

KESSES MET 2011 WIND SPEEDS (ms^{-1})												
DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1	3.7	3.5	2.8	3.2	2.7	2	2.8	2.2	2	2.2	2.5	3
2	4.2	3.3	3	2	3	2	2.7	3	2.8	2.7	2	3.8
3	3.5	3	3	3.2	3.5	2.2	2.8	2	3	2.7	2	2.7
4	2.8	3.3	2	3.8	4	2.2	2.3	2.3	2.8	2.2	2	3.7
5	2.8	3	3	4.2	4	2	1.7	1.7	2.8	2.2	2.5	2.8
6	2.8	3	4.7	4.2	3	3	2	2.3	3	2.2	1.8	3.5
7	2.8	3	3.2	2.3	3.2	1.8	2	2.2	3	2.8	3.2	3.5
8	2.7	2.2	4	2.5	2.7	2.2	2.5	2.2	2	2.8	3	3.3
9	3.2	2	3	2.7	2.7	2	2.3	1.8	1.8	2	1.8	2.7
10	3	1.7	4.5	1.3	2	2.5	2.3	1.7	1.5	2.2	3.2	3
11	3	4	4.2	2.3	1.7	1.8	2.8	2.5	1.8	2.7	2.8	2.8
12	3.5	1.5	4.3	2.3	3	2.7	1.3	2.8	1.7	2.3	3	3
13	4	2	3.5	2.3	2.8	3.7	2	3	2.3	2	3.2	3.3
14	4	2	3.7	2.7	2.7	3.7	2	2.4	2	2.8	1.8	2.7
15	4	1.5	3.7	1.5	4	4.3	2.3	1.8	2	2.8	3	3
16	3	1.5	4	2.8	2.7	3.3	2	2.5	2	2.5	3.2	3
17	3.5	2.7	4	2.8	2.7	3	2	1.8	2	3.7	2.8	3
18	3.5	4	2	3	2	2.5	1.8	2	2.2	2.5	2.3	3.2
19	3.5	5	2	3.3	3	2	2.7	2	2	2.8	3.3	2.7
20	4.3	4.2	3	2.7	3	2	1.8	2.5	2.2	2	3.7	2.5
21	3.2	4.2	2.3	2.3	2	1.8	1.8	2	2	2	3.3	2.7
22	3	6.8	4	1.8	2.7	3	2	2	2.2	2.5	2	4.8
23	3	4.7	2.3	4	3	3	2.2	2.3	2	1.5	3.3	2.3
24	3.3	4	3.3	3.3	2	2	1	2.5	2.2	2.8	3	2.3
25	3.8	4.8	3	5	2.4	3	2.3	2.5	2	2.5	3.5	3
26	3.3	4.7	2	4.3	2.5	2	2.2	2.3	2	1.5	4.3	3.2
27	3	4.7	1.8	4.3	2.8	3.2	2	2.6	2	3.3	3.5	4.8
28	3.2	4.7	2.2	2.7	3	2	1.8	2.5	1.8	2.2	2.5	3.7
29	2.7	4.8	2.8	3.7	2	2.5	1.8	3	1.8	2.2	2.2	3.5
30	3		2	3.7	3.2	2.3	2	2.8	2.3	2	2.8	4.5
31	3		2.3		1.5		1.8	3		2.5		3.5

Appendix IV: Daily Wind Speeds for the Year 2010

KESSES MET 2010 WIND SPEEDS (ms^{-1})												
DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	1.5	2.3	1.5	5.7	2.7	2.3	2.2	1.5	1.8	3.3	5	4.7
2	2	3.2	3.3	6	3	2.2	2	1.7	1.5	1.7	3.2	5.2
3	3.2	2.8	3.8	3.3	2	2	1.8	2.2	1.8	2.5	4.3	5
4	3.2	2.5	5.3	3.2	2.3	2.3	1	2.3	1.5	2.5	4	4
5	2.5	3.5	3.5	3	2.3	2	1	1.5	1.5	2.4	4	5
6	2	3	3	3	2.2	2	1.2	1.3	1.7	2.1	4	4.3
7	1.5	3	3	3.2	2.8	1.5	0.7	1.5	2.2	2.5	4	5
8	2.2	2.5	2.8	3.7	1.8	2	1	2	2.2	2.3	5	4.2
9	3.3	2.3	3.5	3.3	2	1.8	2	1.5	1.8	3.2	4.3	3.8
10	2.3	2.5	2.7	3	2	2.2	2.7	1.8	1.8	2.8	4.2	3.5
11	1.7	1.5	3	3	2.1	2	1.5	2	1.8	2.3	4.7	4
12	2.3	2.3	4	3.2	2.5	2	1.5	1.8	1.7	3.2	4.8	2.5
13	2.5	2.8	4	2.5	2.2	2.2	1.7	1.5	1.7	2	5.3	3.7
14	2.5	2.8	3.8	2.8	2.3	2	1.7	1.8	1.5	2	5.3	4.2
15	2.3	2.8	4.2	3.2	2.7	2.2	2	1.5	1.8	3	4.7	5.7
16	1.8	3	2	1.8	2.8	1.8	1.5	1.8	1.2	2.8	5.7	5
17	2.2	4.7	2.7	2.5	2.8	2.2	1.8	1	2.2	4	5.7	4
18	2.2	5	3	3	1.7	2.2	1	1.6	2.2	2.5	5	4.2
19	1.7	4.5	2	3.2	2.3	1.8	1.5	2	2	1.8	4.2	3
20	1.8	5	3.2	3.2	2.3	2.2	0.8	2.5	1.5	3	5.3	4
21	3.2	5	4.2	3	3.2	1.5	1.5	1.7	2.2	3.2	3.8	4
22	4	3.5	3	3.2	3.2	1.8	1.5	1.7	1.8	2.8	4.5	4.3
23	2.8	3.3	3.8	3.2	2.8	1.8	1.5	2	1.5	2.7	4.7	4.2
24	3.7	3	2.8	4.3	2.3	2.3	1.2	1.2	2	3.5	3.3	3.7
25	4.3	3.5	4	4.5	2.3	2.8	1	1	1.8	5	4.2	3.5
26	4.5	2.7	5	3.3	1.8	1.8	1.2	1	1.8	4.3	4.5	3.7
27	3.2	2.3	4.3	3.7	1.8	1.5	1.2	1.8	2	3.2	5	3.5
28	2.2	1.5	5	3.5	2.3	2	1.5	2	2.5	4.7	6	3.5
29	3		5.3	3.5	2	1.3	1	1.5	2.3	4.6	5	3.5
30	1.5		4.7	2.3	2.3	1.8	1	1.8	2.2	4	3.5	3
31	2		6		1.7		1.5	1.3		4.7		3.3

Appendix V: Daily Wind Speeds for the Year 2009

KESSES MET 2009 WIND SPEEDS (ms^{-1})												
DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	4.7	3.5	2.2	2.3	3.2	2.3	1	1.7	2.7	2	4	3.8
2	5.7	5.7	2.3	3.8	3.2	2	1.7	1.2	1.2	1.2	5	2.2
3	3.7	6.3	2.5	2.3	1.5	1.8	0.8	1.7	2.5	1.2	3.5	2.2
4	5.5	7	2.4	1.3	1.3	2.1	1.7	1.8	3.5	2.2	3.8	2.2
5	4.2	6.3	2.8	1.2	2.3	2.5	2	1.8	2.8	1.5	4	2.5
6	3.3	4.3	2.7	1.5	1.8	2	1.7	1.8	1.5	3	4.3	2.5
7	3.7	2.5	3.2	1.8	2.3	2.3	0.7	1.5	1.8	4.7	4.3	3.2
8	3.3	3.2	3	1.8	1.7	2.3	2.2	2.3	2.5	3.2	2.2	2.8
9	3.7	2.5	3.2	2.7	2.8	2.3	2	2.2	2.2	3	2.2	2.5
10	2.5	3.4	2.7	2.7	3	1.8	2.1	1.7	2.5	3.7	2.8	2.5
11	1.3	2.2	3.7	3.5	2.3	1.2	1.7	1.3	1.8	3.2	2.7	2.5
12	1.4	2	2.8	4	3.5	1.7	2	1	1.5	3.7	2.2	2.2
13	2.5	2.8	2.6	4	2.5	2.5	1.2	1.2	1.8	2.3	2.3	2.3
14	2.5	1.6	2.7	4	1.5	1.5	1.5	1.8	2	3.2	4.3	2.3
15	1.7	1.7	2.8	2.5	1.7	1.7	1.3	2	1.8	3.7	4	2.5
16	1.8	1.3	2.8	2.3	1.7	2	1.7	1.7	1.8	2.7	4	2.2
17	1.8	2.1	2.7	1.8	1.8	2.3	2	1.7	1.5	2.2	3.8	3.2
18	2.5	2.8	2.7	2	1.8	1.2	2.1	2	2.3	2.3	2.5	2.5
19	4	2	3	3	1.8	1.3	2	2	1.8	3.5	2.2	1.5
20	2.8	5.2	1.8	1.7	2.8	1.7	1.8	1.7	2.2	4.7	2	1.2
21	3	4.2	2	2.8	3	2	2	2	1.7	4.3	1.8	1.2
22	2.5	6	2.2	2.5	2.5	1.7	1	2.3	2	4	1.8	1.7
23	3.2	6	2.8	2.3	2.5	1.7	1.2	1.5	1.2	1.5	1.5	1.7
24	3	4.2	2.7	1.7	1.8	2	2.3	2.8	1.7	2.3	3.3	1.8
25	3.5	3.5	2.7	2	2	3	1.3	2	1.8	2.3	1.8	1.7
26	4	2.5	3.8	3.3	1.8	2	1.8	1.3	2	1.8	1	1.8
27	5	2.8	4	2.5	1.8	1.5	2.5	2	2.3	2	2.5	1.7
28	4.5	2.4	3.8	2.7	1	1.5	1.2	2	3.2	2.2	1	2
29	3.7		2.7	3.7	2.2	1.8	1.3	2	2	2.3	2.5	2
30	4.2		3	3.8	2.7	1.8	1.7	1.7	2.5	3.4	2.5	1.8
31	3.8		2.3		1.8		1.2	2.3		4.2		1.8

Appendix VI: Calculated Monthly most Probable Wind Speed V_{MP}, Wind Speed Carrying Maximum Energy $V_{MAX.E}$, Power Density P_D, Maximum Extractable Power P_{MAX} and Energy Density E_D at 2m

Y/ M		J	F	M	A	M	J	J	A	S	O	N	D
2009	V_{MP}	3.301	3.132	2.922	2.587	2.224	2.001	1.678	1.886	2.138	2.782	2.766	2.266
	$v_{max.E}$	2.735	1.617	2.826	2.189	2.007	1.904	1.514	1.799	1.961	2.257	2.124	2.085
	P_D	31.07	48.18	14.99	14.32	8.06	5.00	3.38	4.171	6.67	19.40	21.02	7.94
	P_{max}	15.28	18.98	9.08	7.18	4.32	2.93	1.82	2.456	3.69	9.36	9.74	4.39
	E_D	932.3	1445.3	449.92	429.6	241.7	150.0	101.4	125.1	200.1	582.0	630.77	238.13
2010	V_{MP}	2.566	3.136	3.707	3.45	2.446	2.072	1.458	1.742	1.934	3.106	4.778	4.224
	$V_{max.e}$	2.196	2.724	3.313	3.19	2.370	2.028	1.266	1.652	1.886	2.745	4.677	4.097
	P_D	13.64	24.08	37.29	27.94	8.76	5.21	2.42	3.34	4.27	22.54	63.96	45.03
	P_{max}	6.92	12.41	19.86	15.57	5.32	3.25	1.24	1.94	2.63	11.84	39.85	27.44
	E_D	409.4	722.62	1118	838.3	262.9	156.5	72.77	100.1	128.2	676.3	1918	1350
2011	V_{MP}	3.443	3.306	3.167	3.06	2.872	2.607	2.192	2.435	2.272	2.533	2.896	3.355
	$V_{max.e}$	3.582	4.675	3.761	3.751	3.213	3.029	2.384	2.588	2.450	2.738	3.254	3.644
	P_D	23.75	37.12	22.58	21.65	15.13	12.09	6.44	8.57	7.09	9.85	15.63	23.06
	P_{max}	14.97	16.98	12.22	11.32	8.74	6.69	3.84	5.26	4.27	5.92	8.98	13.77
	E_D	712.5	1113	677.6	649.6	454.0	362.7	193.2	257.3	212.8	295.7	469.0	691.8
2012	V_{MP}	2.985	3.050	2.465	2.39	2.483	2.187	1.915	2.087	2.497	2.322	2.446	2.560
	$V_{max.e}$	3.265	3.219	2.662	2.46	2.641	2.386	2.112	2.347	2.867	2.502	2.743	3.096
	P_D	16.41	16.72	9.07	7.93	9.09	6.43	4.40	5.86	10.40	7.57	9.39	12.36
	P_{max}	9.727	10.35	5.46	5.06	5.57	3.82	2.57	3.36	5.83	4.57	5.41	6.56
	E_D	492.3	501.6	272.3	238	272.8	192.9	132.0	175.9	312.0	227.1	281.7	370.8
2013	V_{MP}	3.082	2.518	3.060	2.464	2.137	2.033	2.045	2.239	2.229	2.734	2.780	2.517
	$V_{max.e}$	3.519	2.982	4.156	2.801	2.627	2.281	2.424	2.631	2.567	3.100	2.928	3.285
	P_D	19.36	11.29	26.91	9.82	7.42	5.39	6.06	7.82	7.44	13.36	12.63	13.74
	P_{max}	10.92	6.127	12.76	5.57	3.87	3.10	3.28	4.28	4.16	7.59	7.84	6.76
	E_D	580.9	338.8	807.2	294.5	222.7	161.8	181.8	234.7	223.2	400.8	379.1	412.2

Appendix VII: The Calculated Wind Parameters at a Height of 10 m.

Month	$\bar{v}$ (ms^{-1})	σ	*k*	***C*** (ms^{-1})	V_{mp} (ms^{-1})	$V_{max, E}$ (ms^{-1})	E_D (Wh m^{-1} month^{-1})
J	4.41	0.416	12.978	4.59	4.56	4.53	1648.40
F	4.59	0.586	9.327	4.83	4.78	4.71	1895.08
M	4.46	0.605	8.743	4.72	4.65	4.58	1755.706
A	4.09	0.597	8.085	4.35	4.28	4.19	1370.509
M	3.59	0.346	12.674	3.75	3.72	3.69	895.497
J	3.23	0.345	11.349	3.38	3.36	3.33	655.671
J	2.82	0.372	9.019	2.98	2.94	2.89	442.618
A	3.08	0.375	9.818	3.24	3.19	3.16	569.261
S	3.27	0.279	14.434	3.39	3.37	3.35	667.826
O	3.93	0.415	11.491	4.11	4.08	4.04	1179.243
N	4.49	1.127	4.485	4.92	4.65	4.32	2020.325
D	4.32	0.988	4.959	4.71	4.49	4.24	1748.993

Appendix VII: The Calculated Wind Speed Parameters for Years 2009–2013 at 40 m.

Month	$\bar{v}$ (ms^{-1})	σ	*k*	***C*** (ms^{-1})	V_{mp} (ms^{-1})	$V_{max, E}$ (ms^{-1})
J	6.142	0.510	14.912	6.361	6.332	6.300
F	6.432	0.733	10.569	6.746	6.682	6.613
M	6.284	0.747	10.102	6.603	6.535	6.460
A	5.828	0.765	9.060	6.153	6.074	5.985
M	5.186	0.451	14.184	5.380	5.352	5.323
J	4.704	0.454	12.660	4.899	4.867	4.833
J	4.155	0.493	10.111	4.365	4.320	4.271
A	4.460	0.500	10.759	4.674	4.632	4.585
S	4.721	0.368	15.973	4.879	4.859	4.838
O	5.567	0.500	13.682	5.782	5.750	5.712
N	6.281	1.387	5.170	6.828	6.550	6.212
D	6.099	1.259	5.546	6.604	6.371	6.092
Mean	5.488	0.681	11.062	5.773	5.694	5.603

Appendix IX: The Calculated Wind Speed Parameters for Years 2009–2013 at 70 m.

Month	$\bar{v}$ (ms^{-1})	σ	k	C (ms^{-1})	V_{mp} (ms^{-1})	$V_{max, E}$ (ms^{-1})
J	7.021	0.550	15.862	7.259	7.229	7.197
F	7.374	0.799	11.168	7.717	7.652	7.581
M	7.217	0.809	10.767	7.563	7.495	7.420
A	6.720	0.843	9.518	7.078	6.996	6.905
M	6.012	0.500	14.875	6.228	6.198	6.167
J	5.472	0.505	13.282	5.690	5.656	5.620
J	4.858	0.551	10.628	5.093	5.046	4.995
A	5.182	0.560	11.189	5.423	5.377	5.328
S	5.477	0.410	16.672	5.654	5.633	5.610
O	6.404	0.535	14.812	6.635	6.603	6.570
N	7.193	1.496	5.501	7.792	7.513	7.177
D	7.012	1.384	5.822	7.570	7.329	7.043
Mean	6.329	0.746	11.675	6.642	6.561	6.468

Appendix X: The Calculated Wind Speed Parameters for Years 2009–2013 at 100 m.

Month	$\bar{v}$ (ms^{-1})	σ	k	C (ms^{-1})	V_{mp} (ms^{-1})	$V_{max, E}$ (ms^{-1})
J	7.647	0.577	16.531	7.896	7.866	7.834
F	8.046	0.843	11.585	8.407	8.342	8.271
M	7.883	0.849	11.234	8.247	8.179	8.104
A	7.358	0.896	9.832	7.740	7.656	7.563
M	6.606	0.534	15.342	6.836	6.806	6.774
J	6.026	0.541	13.702	6.259	6.224	6.187
J	5.367	0.590	10.985	5.620	5.571	5.518
A	5.703	0.602	11.481	5.961	5.914	5.863
S	6.021	0.439	17.145	6.210	6.188	6.165
O	7.003	0.557	15.630	7.243	7.212	7.179
N	7.843	1.571	5.732	8.476	8.197	7.865
D	7.663	1.469	6.012	8.259	8.013	7.722
Mean	6.931	0.789	12.102	7.263	7.181	7.087

Appendix XI: .Minimum and Maximum Wind Speed with Varying Heights.

Height	V(ms^{1})	J	F	M	A	M	J	J	A	S	O	N	D
10 m	V_{min}	3.82	3.74	3.62	3.51	3.25	2.98	2.32	2.61	2.87	3.41	3.57	3.39
	V_{max}	4.82	5.22	5.27	4.94	4.15	3.83	3.48	3.54	3.64	4.46	6.45	5.86
40 m	V_{min}	5.43	5.39	5.23	5.06	4.73	4.38	3.49	3.84	4.19	4.94	5.13	4.94
	V_{max}	6.65	7.23	7.28	6.91	5.90	5.49	4.74	5.07	5.19	6.20	8.68	8.07
70 m	V_{min}	6.25	6.24	6.07	5.86	5.49	5.11	4.12	4.48	4.88	5.73	5.93	5.75
	V_{max}	7.57	8.24	8.29	7.91	6.80	6.34	5.51	5.87	5.99	7.08	9.78	9.19
100 m	V_{min}	6.84	6.86	6.67	6.44	6.06	5.64	4.58	4.95	5.38	6.30	6.51	6.33
	V_{max}	8.22	8.96	9.01	8.62	7.45	6.96	6.07	6.44	6.57	7.70	10.56	9.98

Appendix XII: Capacity Factor and Pe,ave for Various Chosen Wind Turbines at Varying Heights

	Turbine	10 m		40 m		70 m		100 m	
S/R NO.		Pe,ave	C_f	Pe,ave	C_f	Pe,ave	C_f	Pe,ave	C_f
1	AC-120 (Aerocraft, Germany)	126.07	0.343	120.08	0.678	119.99	0.637	119.94	0.707
2	SUPERWIND 350	437.51	0.139	351.38	0.232	350.13	0.389	350.04	0.654
3	WINDWORKER-300H	302.49	0.162	299.73	0.999	298.42	0.454	292.72	0.763
4	WINDWORKER-500H	525.32	0.097	500.31	0.162	499.82	0.272	498.96	0.457
5	ML1500 (Moratec, Germany)	545.33	0.162	538.44	0.271	331.34	0.454	310.54	0.763
6	SOMA 400 (SOMA Power)	911.71	0.121	406.96	0.203	400.81	0.341	400.28	0.572
7	VK240 (SVIAB, Sweden)	756.25	0.064	750.06	0.108	749.98	0.182	749.92	0.305
8	WFD500W	525.32	0.097	500.34	0.108	499.98	0.272	499.75	0.457
9	WFD750W	787.98	0.121	750.53	0.203	750.02	0.182	749.91	0.305
10	Windtalker 400 (China)	420.26	0.034	400.28	0.058	400.02	0.341	400.00	0.163
11	Passaat (The Netherlands)	1470.91	0.050	1401.01	0.032	1400.08	0.097	1400.02	0.092
12	Tulipo (The Netherlands)	2626.626	0.016	2501.773	0.027	2500.083	0.045	2499.704	0.076
13	Westwind (Australia)	3750.082	0.048	3011.849	0.081	3001.182	0.136	3000.434	0.228
14	WINDWORKER-1000H	1050.65	0.121	1000.693	0.203	999.963	0.341	999.518	0.572