WIND DATA COLLECTION AND ANALYSIS IN KUMASI

by

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DECLARATION

Having acknowledged all materials previously published by other people and materials which have been accepted for the award of any other degree of the university, I hereby humbly declare that this piece of work is mine towards the M.Sc. Mechanical Engineering

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Supervisor's Name **Signature** **Date**

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Head of Dept. Name **Signature** **Date**

DEDICATION

Immortals do not treasure material things at all. As a result, dedicating a materiality like this piece of work to immortals will be a fruitless attempt. However, mortals do treasure or appreciate materialism to some extent so I dedicate this piece of work to them. Specifically, I dedicate this humble piece of work to all up and coming Ghanaian youth especially the youth of my family and families of all well-wishers. It is my fervent hope that this dedication made to them will really motivate them to take inspiration from my aspirations to acquire higher education as a mature student. I however wish to advise them to avoid this situation of mine and rather aspire to acquire higher education as early as practicable.

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ABSTRACT

This research collected wind resource data on the campus of Kwame Nkrumah university of Science and Technology (KNUST) from March 1, 2011 to September 30, 2011 mainly for educational, informational and research purposes. The wind monitoring system which was equipped with an anemometer (an NRG # 40 Maximum cup anemometer), a wind vane (an NRG # 200P wind vane) and a data logging unit (Wind Explorer™) was placed in a building environment (precisely on the rooftop of a 3-storey classroom block belonging to the College of Engineering) to collect wind resource data at 20 m above ground level.

The WAsP Climate Analyst Program was used to handle a three- month time-series wind data stored on a DataPlug. The Stata Software was used to generate bar and line graphs which depict variations in wind speeds and wind directions. The WAsP Climate Analyst program was used to generate time-series graphs of wind direction and wind speed, frequency distributions of wind speeds (wind speed histogram) and a wind rose for the three continuous months of July, August and September, 2011.

An online version of a Speed Calculator developed by Meteotest of Switzerland (for Suisse Eole, also of Switzerland) was used to generate the wind velocity profile of the site. The average wind speed for the seven month period was calculated as 2.2 m/s. The month of August recorded the highest monthly average wind speed of 2.6 m/s with the wind predominantly blowing from North-West due to the nature of the site. Thus, the prevailing wind direction of the selected site was North-West. The months, March and September recorded the lowest monthly average wind speed of 2.0 m/s. The month that recorded the highest gust was April with 24.9 m/s from 200

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LIST OF ABBREVIATIONS

agl: Above Ground Level

asl: above sea level

AEP: Annual Energy Production

ASCII: American Standard Code for Information Interface

AWS: Automatic Weather Station

COE: College of Engineering

CSIR: Council for Scientific and Industrial Research

DTU: Denmark Technical University

E: East

EC: Energy Commission

ENE: East-Northeast

EPA: Environmental Protection Agency

ESE: East-Southeast

EWEA: European Wind Energy Association

GBC: Ghana Broadcasting Corporation

GEF: Global Energy Fund

GMA: Ghana Meteorological Agency

GNA: Ghana News Agency

GUI: Graphical User Interface

IEA: International Energy Agency

JMA: Japan Meteorological Agency

KNUST: Kwame Nkrumah University of Science and Technology

LASER: Light Amplification by Simulated Emission of Radiation

LIDAR: Light Detection and Ranging

MET/Met: Meteorological

METU: Middle East Technical University

N: North

N/A: Not Applicable

NASA: National Aeronautic and Space Administration

NE: Northeast

NEED: National Energy Education Development

NGDC: National Geophysical Data Center

NGO: Non-Governmental Organization

N/meas.: Not Measured

NNE: North-Northeast

NNW: North-Northwest

NOAA: National Oceanic and Atmospheric Administration

NREL: National Renewable Energy Laboratory

NW: Northwest

RCEER: Resource Center for Energy Economics and Regulation

S: South

SE: Southeast

SEAL: Solar Energy Application Laboratory

SODAR: Sonic Detection and Ranging

SSE: South-Southeast

SSW: South-Southwest

SW: Southwest

SWERA: Solar Wind Energy Renewable Assessment

TEABAG: The Education and Book Appeal Ghana

TEC: The Energy Center

USA: United States of America

W: West

WAsP: Wind Atlas Analysis and Application Program

WEC: World Energy Council

WSW: West-Southwest

WNW: West-North-West

WWEA: World Wind Energy Association

LIST OF SYMBOLS

A: Area

E: Energy

GW: Gigawatt

km: kilometer

km /h: kilometer per hour

ln: Natural logarithm

m/s; ms^{-1}: meter per second

MW: Megawatt

P: Total Wind Power

v: Speed/velocity

v(z): Wind speed at height, z

v(r): Wind speed at reference height

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The need to reduce the use of conventional or traditional fuels (fossil fuels) has been established globally for some time now. This need became an issue when it was realized that fossil fuel is a finite resource, a major contributor to global warming and a potential expensive resource. The above need has now become a policy for most countries as well as a global concern. With this established concern, there is the need to research and develop appropriate and attractive alternative energy sources to offset the shortfall in power generation as a result of the reduction in the use of fossil fuels which are used extensively worldwide in power generation. Ghana as a nation started power generation in the then Gold coast using diesel oil in generating sets. These generating sets were concentrated in the national capital, Accra. Ghana switched from the use of generating sets to its first hydroelectric power plant (Akosombo hydroelectric power plant) in 1966 (**Resource Centre for Energy Economics and Regulation (RCEER) Team, 2005**) for the whole country in order to increase its installed electric power capacity and to reduce the cost of power generation. However, due to droughts experienced by the country over the years coupled with the nation's rising energy demand trends, Ghana reverted to the use of significant quantity of fossil fuels for power generation in the late 90's.This reversion occurred when the first trench of Takoradi thermal power plant was commissioned in 1999 **(RCEER Team, 2005)** to augment the hydroelectric power plants (Akosombo and Kpong hydroelectric power plants). These hydroelectric plants operate at reduced capacities due to low water levels in the dams as a result of long periods of droughts.

Since energy crisis is now a global issue, Ghana cannot isolate itself from the efforts being made by countries all over the world to develop new renewable energy resources for power generation. Wind energy for some time now has contributed significantly to the world energy supply and in addition, its technology is well advanced. However, Ghana is not recognized as a contributor to the world pool of wind energy since there is no data on the wind power production of Ghana and in fact Ghana does not produce any significant amount of wind power presently. This implies that the wind energy supply of Ghana hardly plays a role in its power or energy economics. It is therefore imperative to raise awareness among students, researchers, industrialists and the general public about the need to devote attention to the development and deployment of wind power technologies across the nation to harness the wind energy in Ghana. This thesis indirectly seeks to do that. The principal focus of this thesis is to measure wind data for small-scale or residential power generation in Kumasi. This thesis is specifically designed to collect primary or firsthand wind data and analyze it to provide good quality wind data summary for an interior part of Ghana and to be precise, on KNUST campus in Kumasi. Thus, this collection of primary wind data was carried out to determine whether areas far away from the coastal lines of the country can be used as suitable sites for small-scale/micro-scale power generation. Spots or sites endowed with topographical features (Natural and/or Manmade) may have the tendency to speed up the local wind (**Ragheb, 2011 and Better Generation Ltd., 2009**) and as a result make these spots suitable for at least small-scale or micro-scale wind power generation. This thesis is therefore carried out to verify whether the monthly average wind speeds at the selected wind recording site on KNUST campus at a height of 20 m would be better than the predicted wind speed at the given height. This thesis also provides the number of hours and percentage of time the wind blows at a specific speed and from a specific direction on KNUST campus for the period of measurements. This research work was also carried out to determine whether the wind speeds of Kumasi confirm the assertion that regions close to the equator are endowed with trade winds which blow steadily or constantly **(NEED, 2011**).

This thesis recorded real wind data at a reasonable height with the intent to provide wind speed measurements relatively free from the earth's surface friction. Measurement of laminar flow of air in Kumasi would provide a strong and credible basis for performing accurate and reliable wind resource assessment of Kumasi and its environs.

1.2 OBJECTIVES OF THE STUDY

1.2.1 MAIN OBJECTIVE

The main objective of this thesis is to revive and rebuild the capacity to collect and analyze wind data on KNUST campus and thereby establish a platform for future research work on wind energy at KNUST.

1.2.2 SPECIFIC OBJECTIVES

The specific objectives of this thesis are enumerated as follows;

(1) To collect and analyze wind data at a height of 20 meters.

(2) To use wind data to calculate wind power potential for the selected site at KNUST.

(3) To compare the wind speeds obtained during the period of measurement with existing data sets for Kumasi/ KNUST

1.3 RATIONALE OF THE STUDY

Before the discovery of oil in commercial quantities in Ghana, the Government of Ghana has been nursing the desire and the need to consider a policy to increase its energy capacity by using renewable energy resources. This desire was sustained because of the fact that the cost of fossil fuel was becoming relatively expensive coupled with the fact that world reserves of the fossil fuels are under the threat of being depleted. Though, Ghana is currently an oil producing country, its desire to increase its energy capacity using renewable energy resources has not been abandoned since crude oil is a finite resource and the fact that it is essential for the country to broaden its energy or power mix. The hitherto implicit desire of Ghana has been explicitly revealed by the enactment of Ghana Renewable Energy Act, 2011(Act 832). The use of fossil fuels leaves in its trail considerable amount of greenhouse gases which cause global warming, an international household name because of the regular concerns expressed by international Communities about the devastating effects of global warming. The introduction of wind power would reduce the use of fossil fuel for power generation thus conserving energy obtained from fossil fuel. Energy conservation is simply the reduction in the use of available energy or the deferment of the use of available energy. In everyday life, energy conservation is simply using energy when it is really needed.

Ghana as a nation has ratified several conventions (e.g. Rio De Janeiro, Kyoto and Copenhagen conventions) on global warming sending signals that Ghana is ever ready to launch a full flight into the generation of both heat (or thermal energy) and electricity via the use of renewable energy resources if local and foreign investors lay bare their interest in such a venture.

Among the energy sources which produce “green” or clean energy, it has been found that wind energy is very competitive especially in terms of relative cost to the conventional modes of generating power (i.e. generating power using fossil fuels). This factor in addition to others gives the wind turbine an edge over solar panel modules.

The establishment of the fact that wind energy is the least expensive of all renewable energy technologies coupled to the fact that the cost for generating electricity with the wind has fallen over 80 % since the early 1980s in USA **(NRG System Inc, 2008**) and the successful stories of Denmark, China and other countries across the World lend credence to the effort being made to harness the wind energy in Ghana for electric power generation. Perhaps, another motivational fact that lends credence to the efforts being made to harness Ghana's wind energy is the revelation that the wind energy is world's fastest growing source of renewable energy (**Zobaa, 2011**).

Presently, the advantages of the wind energy technology should provide a strong basis and make it the first option to anyone who is interested in researching into the application of renewable energy resources for electric power generation in a developing country like Ghana. Taking cognizance of the number of identified potential wind sites and the number of solar potential sites in Ghana the author of this thesis is of a strong conviction that the utility wind power potential of Ghana is higher than its utility solar power potential.

It is justifiable to undertake this academic task following the fact that before any wind power project is implemented there is the need to do wind measurements and analyses which is all that this thesis is about. This thesis afforded the author the opportunity to study how to measure wind data using a cup anemometer, a vane and a data logger. This thesis would make available real wind data collected on KNUST campus (or Kumasi) for wind engineers and other users of wind data to do useful analyses. For example, this wind data collected at KNUST may be used for wind power assessment, site classifications in terms of vegetation growth and wind hazard.

1.4 SCOPE OF WORK

This research work was planned to cover:

- the design and implementation of a wind monitoring system
- The collection of wind data (wind speeds and directions) which are sampled every two (2) seconds and averaged every (10) ten minutes.
- The analysis of both internally binned wind data stored in a Wind Explorer™ and time-series wind data stored on a DataPlug that is plugged in the Wind Explorer™.
- Comparison of observed wind speeds at a site on KNUST campus with other sources of wind data (RETScreen and Weather Underground Inc. wind data).
- The calculation of the wind power density and the plotting of the wind speed histogram and wind rose of KNUST Site 0001 through the analysis of time-series wind data
- The estimation of the output power of two selected wind turbine models from the library of an online Wind Power Calculator designed and developed by Meteotest of Switzerland based on size (the two smallest turbines in the library of the Power Calculator were selected).

This research work measured wind speed and wind direction using a proprietary wind monitoring equipment leaving out air temperature, density, pressure and humidity. The measurement of icing frequency was not an issue because the site does not experience snowfall. Each of the two wind sensors used for the measurement was mounted on a lateral boom attached to a 5.8 m tall galvanized steel tubular tower supported in a concrete base on the rooftop of a 15 m three-storey building.

The wind monitoring system was placed on the rooftop in the vicinity of a satellite dish and a communication tower which increased the turbulent structure or zone of the wind flow around the wind monitoring system.

The height of the anemometer was 5 m above the rooftop and 20 m above the ground while the wind vane was about 4.90 m above the rooftop and about 19.90 m above the ground. The height of the wind instruments above the rooftop of the building was specifically chosen and was not up to the standard meteorological height of 10 m due to infrastructural constraints. As a result of this the anemometer and the vane used for the measurement were engulfed by turbulent wind flow which affects the sensitivity of the wind instruments. Seven months internally binned wind speeds and directions (Captured on the display pages of a Wind Explorer™) were organized and made available for analysis while only the last three months time-series wind data (stored on 128 KByte DataPlug) was made available for analysis due to accidental loss of the data for the first four months of the measurement period. Stata software was used for the analysis of the internally binned wind data while the Wind climate Analyst component of WAsP and the Microsoft Excel Software were separately used for the analysis of the three month time-series wind data. The full WAsP software could not be used for the analysis of the three month wind data because the wind data was limited in size (minimum recommended size of wind data for analysis by the full WAsP software is one year). No climate-adjustment was done. The wind measurement campaign for this research work could not be carried out even for one year because of time constraints or better put because this thesis was time bound.

1.5 THESIS STRUCTURE

This thesis is organized under five main headings namely, Introduction, Literature Review, Method, Results and Discussions and Conclusions and Recommendations. Chapter one contains the introduction which is subdivided into Background, Objectives of Study, Rationale of the Study, Scope of work and this very section. The next chapter (i.e. Chapter Two) reviews literature which should provide the theoretical foundation on which the thesis is developed. In addition, Chapter Two has been prepared in a way that gives an overview of wind and some of its related phenomena.

Chapter Three captures the Method which describes the experimental set-up and how wind data in the form of wind speeds and directions on KNUST campus is measured. Chapter Four presents and discusses the actual results obtained over the period of wind measurements. The final Chapter which is Chapter five draws conclusions and makes some recommendations that may go a long way to improve on wind data collection and analysis on KNUST campus and thereby enhance future research work on wind energy studies.

CHAPTER TWO

LITERATURE REVIEW

2.1 DATA GATHERING / INFORMATION SEARCH

Information gathering began before the equipment were received. Information was largely sought from the internet and from some personnel in the telecommunication industry and the Energy Commission of Ghana. Several versions of NRG System Incorporated Tall Tower and Wind Explorer™ as well as Power Predictor User Manuals were read. Field visits were made to several mast/tower sites belonging to some telecommunication operators such as Vodafone, MTN and Air-Tel as well as some FM Stations in Ghana. After the acquisition of the equipment a visit was paid to a mini-wind measurement site at Mankoadze, a coastal town in the central region of Ghana whose geographical coordinates are 5.19

1. Identification of potential wind development sites
2. Ranking and inspection of candidate sites
3. Selection of tower and other monitoring location(s) within the candidate sites

The site selection process should be planned efficiently to focus on the most suitable areas (**Brower, et al., 2010**).

2.3 WIND POWER GENERATION CAPACITY OF AFRICA

The potential of wind energy in Africa is very high and it is noted to be better than that of Europe (**Van kooteng and Wong, 2009**). The best world wind sites are found in North and South Africa (**WWEA, 2009)**. Also, the availability of wind on the Western coast of Africa has been found to be substantial however, the wind resources of central Africa is found to be lower than average. Though, Africa is noted to be endowed with substantial amount of wind resources, wind energy still plays a marginal role on the continent with regards to World total wind power Capacity (**WWEA, 2009).** Considering Africa's current wind power capacity, it can be asserted that little effort has so far been made to exploit this energy resource on commercial bases. This setback may be attributed to several reasons including lack of attractive renewable policy instruments and measures, limited financial resources of African governments, low participation of the private sector, lack of capacity building and low international co-operation **(WEC, 2007**)

The emerging economies of Africa which may be endowed with strong and sufficient winds are attractive locations for the utilization of wind energy technology.

All Wind turbines installed in Africa in 2009 had a capacity of 770 MW (0.5 % of the total worldwide capacity). 169 MW out of the 770 MW was added in Egypt and Morocco. As of 2009, new wind projects were ongoing in the above mentioned leading countries notably Egypt and morocco but also new markets like Cape Verde, Ethiopia, Kenya, Namibia, South Africa and Tunisia emerged (**WWEA, 2011**).

Certainly, the completion of some of the previous year's ongoing wind projects in the continent might have contributed to the increase in the Continent's total wind turbines installed in 2010. All Wind turbines installed in Africa in 2010 had a capacity of 906 MW (0.5 % of the total World-wide capacity), out of which 155 MW were added in three countries, Egypt, Morocco and South Africa in 2010 (**WWEA, 2011).**

According to World Wind Energy Association's total installed capacity rankings for the year, 2010, Egypt was ranked 24th in the World with a total capacity of 550 MW after 435 MW in 2009 and 390 MW in 2008 followed by 310 MW in 2007 and 230 MW in 2006. Egypt is currently the top ranked African country in the wind power industry. The second ranked country in Africa is Morocco which happens to be ranked 32nd in the year 2010 according to World Wind Energy Association. The entire rankings of countries per their total installed capacity in the year, 2010 are shown from page 12 up to page 15 in Tables 2.1a, 2.1b, 2.1c and 2.1d. These tables also provide country's total installed capacity for previous years (i.e. from 2009 up to 2006). The continental Share of total installed capacity from 2007 to 2010 is also shown in Figure 2.1 on page 16. Figures 2.2 and 2.3 are shown on pages 16 and 17 respectively. They specifically show the new wind capacity and total wind capacity for the year 2009 respectively with the aid of pie charts.

It is encouraging to learn that industrial activities in manufacturing of wind turbines have also started on the continent, mainly in Egypt **(WWEA, 2010**).

Table 2.1a: World Total Installed Capacity of Wind Power

Position 2010	Country/ Region	Total Capacity end 2010 (MW)	Added Capacity 2010 (MW)	Growth Rate 2010 (%)	Position 2009	Total Capacity end 2009 (MW)	Total Capacity end 2008 (MW)	Total Capacity end 2007 (MW)	Total Capacity end 2006 (MW)
1	China	44733.0	18928.0	73.3	2	25810.0	12210.0	5912.0	2599.0
2	USA	40180.0	5600.0	15.9	1	35159.0	25237.0	16823.0	11575.0
3	Germany	27215.0	1551.0	6.0	3	25777.0	23897.0	22247.4	20622.0
4	Spain	20676.0	1527.2	8.0	4	19149.0	16689.0	15145.1	11630.0
5	India	13065.8	1258.8	10.7	5	11807.0	9587.0	7850.0	6270.0
6	Italy	5797.0	950.0	19.6	6	4850.0	3736.0	2726.1	2123.4
7	France	5660.0	1086.0	23.7	7	4574.0	3404.0	2455.0	1567.0
8	United Kingdom	5203.8	1111.8	27.2	8	4092.0	3195.0	2389.0	1962.9
9	Canada	4008.0	690.0	20.8	11	3319.0	2369.0	1846.0	1460.0
10	Denmark	3734.0	309.0	8.9	10	3465.0	3163.0	3125.0	3136.0
11	Portugal	3702.0	345.0	10.3	9	3357.0	2862.0	2130.0	1716.0
12	Japan	2304.0	211.0	10.1	13	2083.0	1880.0	1528.0	1309.0
13	The Nether-lands	2237.0	15.0	0.7	12	2223.0	2235.0	1747.0	1559.0
14	Sweden	2052.0	603.8	41.7	15	1448.2	1066.9	831.0	571.2
15	Australia	1880.0	3.0	0.2	14	1877.0	1494.0	817.3	817.3
16	Ireland	1428.0	118.0	9.0	16	1310.0	1027.0	805.0	746.0
17	Turkey	1274.0	477.5	59.9	19	796.5	333.4	206.8	64.6
18	Greece	1208.0	123.0	11.3	17	1086.0	989.7	873.3	757.6
19	Poland	1107.0	382.0	52.7	20	725.0	472.0	276.0	153.0
20	Austria	1010.6	16.0	1.6	18	995.0	994.9	981.5	964.5

Source: WWEA, 2011.

Table 2.1b: World Total Installed Capacity of wind Power (continued)

Position 2010	Country/ Region	Total Capacity end 2010 (MW)	Added Capacity 2010 (MW)	Growth Rate 2010 (%)	Position 2009	Total Capacity end 2009 (MW)	Total Capacity end 2008 (MW	Total Capacity end 2007 (MW)	Total Capacity end 2006 (MW)
21	Brazil	920.0	320.0	53.3	21	600.0	338.5	247.1	236.9
22	Belgium	886.0	340.0	62.0	22	548.0	383.6	286.9	194.3
23	Romania	591.0	577.0	4121.4	55	14.0	7.0	7.8	2.8
24	Egypt	550.0	120.0	27.6	26	435.0	390.0	310.0	230.0
25	Mexico	521.0	104.5	25.1	27	416.8	85.0	85.0	84.0
26	Chinese Taipeh	518.7	82.6	18.9	24	436.0	358.2	279.9	187.7
27	New Zealand	506.0	8.8	1.8	23	497.0	325.3	321.8	171.0
28	Norway	434.6	18.4	4.3	25	431.0	429.0	333.0	325.0
29	Korea (South)	379.3	48.9	14.0	28	348.4	278.0	192.1	176.3
30	Bulgaria	374.5	198.0	112.2	30	176.5	157.5	56.9	36.0
31	Hungary	295.0	94.0	46.8	31	201.0	127.0	65.0	60.9
32	Morocco	286.0	33.0	13.2	29	253.0	124.0	125.2	64.0
33	Czech Republic	215.0	24.0	12.6	32	191.0	150.0	116.0	56.5
34	Finland	197.0	52.0	35.4	33	147.0	143.0	110.0	86.0
35	Chile	170.0	2.6	1.5	39	167.6	20.1	20.1	2.0
36	Lithuania	154.0	63.0	69.2	36	91.0	54.4	52.3	55.0
37	Estonia	149.0	6.9	4.8	34	142.3	78.3	58.6	33.0
38	Costa Rica	123.0	0.0	0.0	35	123.0	74.0	74.0	74.0
39	Iran	100.0	18.0	22.0	38	82.0	82.0	66.5	47.4
40	Ukraine	87.4	0.6	0.7	37	90.0	90.0	89.0	85.6

Table 2.1c: World Total Installed Capacity of wind Power (continued)

Position 2010	Country/ Region	Total Capacity end 2010 (MW)	Added Capacity 2010 (MW)	Growth Rate 2010 (%)	Position 2009	Total Capacity end 2009 (MW)	Total Capacity end 2008 (MW)	Total Capacity end 2007 (MW)	Total Capacity end 2006 (MW)
41	Cyprus	82.0	82.0	∞	0	0.0	0.0	0.0	0.0
42	Croatia	69.8	43.0	161.0	46	26.7	18.2	17.2	17.2
43	Argentina	54.0	25.3	88.2	43	28.7	29.8	29.8	27.8
44	Tunisia	54.0	0.0	0.0	44	29.7	20.7	20.7	20.7
45	Luxem-bourg	42.0	7.0	19.8	41	35.3	35.3	35.3	35.3
46	Switzer-land	42.0	24.4	138.6	53	17.6	13.8	11.6	11.6
47	Nicaragua	40.0	0.0	0.0	40	40.0	0.0	0.0	0.0
48	Philip-pines	33.0	0.0	0.0	42	33.0	25.2	25.2	25.2
49	Latvia	31.0	2.0	7.0	45	28.5	26.9	27.4	27.4
50	Vietnam	31.0	22.3	254.3	57	8.8	1.3	0.0	0.0
51	Uruguay	30.5	10.0	48.8	50	20.5	20.5	0.6	0.2
52	Jamaica	29.7	0.0	0.0	52	54.0	20.0	20.0	20.0
53	Nether-lands Antiles	24.3	0.0	0.0	47	24.3	12.3	12.3	12.0
54	Guade-luape	20.5	0.0	0.0	49	20.5	20.5	20.5	20.5
55	Colombia	20.0	0.0	0.0	51	20.0	19.5	19.5	19.5
56	Russia	15.4	1.2	8.6	54	14.0	16.5	16.5	15.5
57	Guyana	13.5	0.0	0.0	56	13.5	13.5	13.5	13.5
58	Cuba	11.7	4.5	62.5	58	7.2	7.2	2.1	0.5
59	South Africa	10.0	2.0	25.0	48	8.0	21.8	16.6	16.6
60	Israel	6.0	0.0	0.0	59	6.0	6.0	6.0	7.0

Table 2.1d: World Total Installed Capacity of wind Power (Concluding Part)

Position 2010	Country/ Region	Total Capacity end 2010 (MW)	Added Capacity 2010 (MW)	Growth Rate 2010 (%)	Position 2009	Total Capacity end 2009 (MW)	Total Capacity end 2008 (MW	Total Capacity end 2007 (MW)	Total Capacity end 2006 (MW)
61	Slovakia	6.0	0.0	0.0	60	6.0	6.0	5.0	5.0
62	Pakistan	6.0	0.0	0.0	61	6.0	6.0	0.0	0.0
63	Faroe Islands	4.0	0.0	0.0	62	4.0	4.1	4.1	4.1
64	Cape Verde	2.8	0.0	0.0	63	2.8	2.8	2.8	2.8
65	Ecuador	2.5	0.0	0.0	64	2.5	4.0	3.1	0.0
66	Nigeria	2.2	0.0	0.0	66	2.2	2.2	2.2	2.2
67	Belarus	1.9	0.0	0.0	67	1.;9	1.1	1.1	1.1
68	Antarctica	1.6	0.0	0.0	68	1.6	0.6	0.0	0.0
69	Jordan	1.5	0.0	0.0	69	1.5	1.5	1.5	1.5
70	Indonesia	1.4	0.0	0.0	70	1.4	1.2	1.0	0.8
71	Mongolia	1.3	0.0	0.0	65	1.3	2.4	0.0	0.0
72	Martin-ique	1.1	0.0	0.0	71	1.1	1.1	1.1	1.1
73	Falkland Island	1.0	0.0	0.0	72	1.0	1.0	1.0	1.0
74	Eritrea	0.8	0.0	0.0	73	0.8	0.8	0.8	0.8
75	Peru	0.7	0.0	0.0	74	0.7	0.7	0.7	0.7
76	Kazakh-stan	0.5	0.0	0.0	75	0.5	0.5	0.5	0.5
77	Syria	0.4	0.0	0.0	77	0.4	0.4	0.3	0.3
78	Namibia	0.2	0.0	0.0	76	0.5	0.5	0.5	0.3
79	Domini-can Republic	0.2	0.0	0.0	78	0.2	0.2	0.0	0.0
80	Dominica	0.2	0.0	0.0	79	0.2	0.2	0.0	0.0
81	North Korea	0.2	0.0	0.0	80	0.2	0.2	0.0	0.0
82	Algeria	0.1	0.0	0.0	81	0.1	0.1	0.0	0.0
83	Bolivia	0.01	0.0	0.0	82	0.01	0.01	0.01	0.01
Total	World	196629.7	37642.0	23.56		159766.4	120903.0	93926.8	74122.0

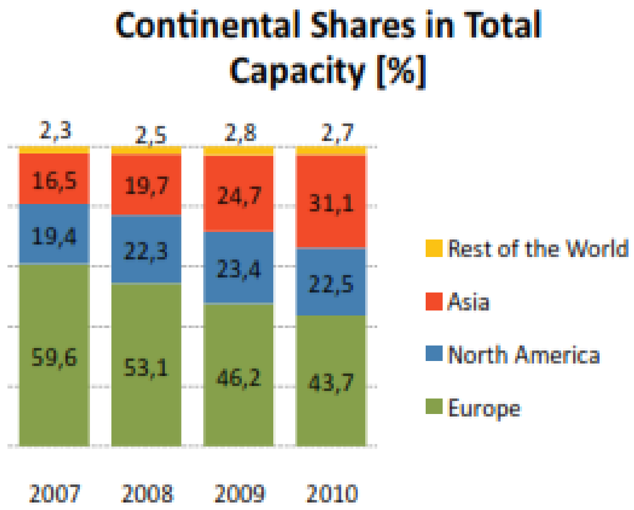

Figure 2.1: Continental Share in Total Wind Power Capacity.

Source: World Wind Energy Association, 2011.

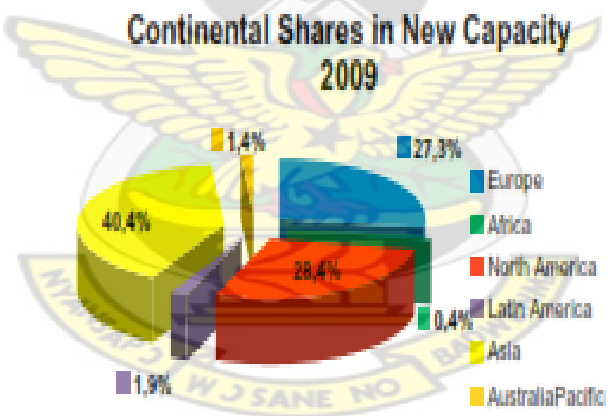

Figure 2.2: Continental Share in New Wind Capacity for 2009.

Source: WWEA, 2010.

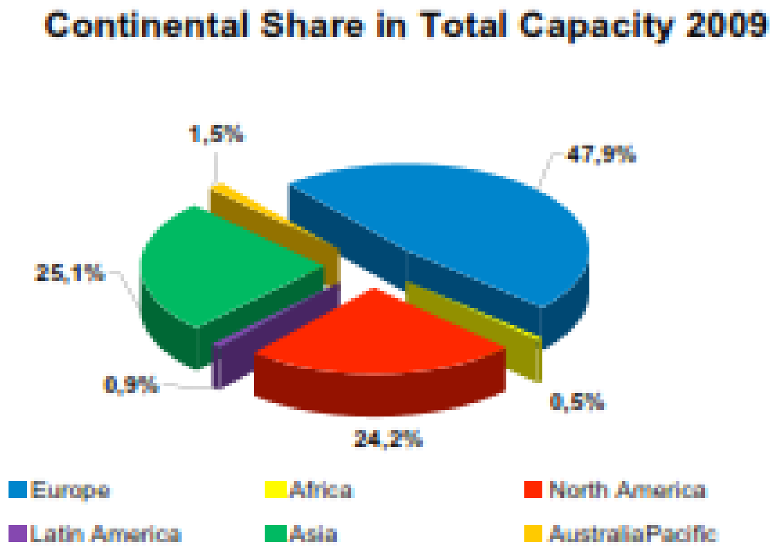

Figure 2.3: Continental Share in Total Wind Capacity for 2009

Source: WWEA, 2010.

2.4 HISTORICAL PERSPECTIVE OF WIND MEASUREMENTS IN GHANA

Weather conditions were measured in Accra, the national capital of Ghana as far back as 1921**.** This was the year that the agency which was responsible for meteorological data collection in the then Gold Coast measured wind direction at a site in Accra using a wind vane. In 1936, the above agency now, Ghana Meteorological Agency (GMA) installed a cup counter anemometer and William H. Dine‘s pressure tube anemometer to measure instantaneous wind speed and direction in Accra. They have since been recording wind speed and direction data at 2m above ground level (agl) at all the 22 synoptic stations sited within every latitude (between 4

Studies on wind measurements conducted under the supervision of Professor F.O. Akuffo of Kwame Nkrumah University of Science and Technology using historical data from the GMA and captured in Akuffo ,1991 (as cited by Nkrumah, 2002) suggest that the monthly average wind speed across the country is 1.7 m/s. The study also indicated that a maximum monthly average wind speed of about 3.4 m/s came from the Eastern coastline of the Accra plains (**Nkrumah, 2002**). These measurements were taken at a height of 2 m above ground level. The coastlines of the country have a monthly average wind speed of 5.6 m/s at a height of 12 m (**Agbeve, et al., 2011**). Monthly average wind speed along the coastlines of Ghana is about 6.8 m/s at 50 m agl (**Appiah F. & Donkor R., 2011**).

NEK UMWELTTECHNIK GmbH of Switzerland in March, 1999 in collaboration with Future Energy of Koblenz, Germany as client and service provider respectively installed a 10 m and 40 m high masts (i.e. two masts) in each of the following three selected sites: Prampram, Ningo and Ada. These three towns are all located in the Accra plains along the eastern coastline. This project undertaken by NEK UMWELTTECHNIK GmbH received support from DEG- Deustsch Investitons-Und Entwicklungsgellchaft GmbH of Cologne, Germany after obtaining project execution permit from the then Ministry of Mines and Energy, now Ministry of Energy (the mining functions are in another ministry). Wind measurements taken at the above-mentioned sites lasted for about a year spanning from May, 1999 to June, 2000. An annual average wind speed of 5.8 m/s for these three sites was recorded at a height of 10 m by NEK UMWELTTECHNIK GmbH **(Nkrumah, 2002**).

In June, 1999 the Energy Commission of Ghana began to take wind measurements at eleven (11) coastal sites east and west of the Greenwich Meridian (around Accra). These measurements were taken at a height of 12 meters above ground level yielding a range of monthly average wind speed of 4.8 to 5.5 m/s. The eleven sites are Lolonya, Tema, Adafoah, Pute, Kpone, Bortianor, Aplaku, Warabeba, Mankoadze, Gomoa Fetteh and Asemkow. The annual average wind speed at a height of 12 m agl for the above eleven (11) sites according to their other of arrangement as given just above are: Lolonya (5.4 m/s), Tema (5.0 m/s), Adafoah (5.3 m/s), Pute (5.5 m/s), Kpone (4.9 m/s), Bortiano (4.8 m/s – 5.5), Aplaku (5.2 m/s), Warabeba (3.9 m/s), Mankoadze (6.1 m/s), Gomoa Fetteh (4.8-5.5 m/s) and Asemkow (3.7 m/s) - (**Appiah and Donkoh, 2011, Nkrumah, 2002**).

Tema, Adafoah, Pute, Kpone, Bortianor and Aplaku are all in Greater Accra region. Lolonya is in Volta region. Warabeba (a suburb of Winneba), Mankoadze and Gomoa Fetteh are in Central region whilst Asemkow is in the Ahanta West District of Western region. These sites may be geographically grouped into two, namely, east of the Meridian Sites and west of the Meridian Sites. Tema, Adafoah, Lolonya , Pute and Kpone are categorized as East of the Meridian Sites while Aplaku, Bortianor, Warabeba, Mankoadze, Gomoa fetteh and Asemkow fall under the West of the Meridian Sites. In fact the Energy Commission in June, 1999 started the wind speed measurements at the sites located in the east of the Meridian on a pilot basis with the assistance of the Folk centre of Denmark and later in the same year extended it to the west of the Meridian Sites. In the same year, some individuals also undertook studies on wind energy at six coastal sites within Tema with the view of generating wind power subsequently. However, their dreams did not materialize hence detail information about them were not documented. The year 1999 witnessed several wind measurement projects in Ghana since in this same year CINERGY GLOBAL POWER INC, USA in August, 1999 measured wind speeds at Sege in the Accra plains adding to the list of entities that carried out wind measurements in the year, 1999 in Ghana. The average wind speed for Sege was given by CINERGY as 5 m/s at a height of 10 m (**Nkrumah, 2002**).

In August, 2002, the Solar Wind Energy Resource Assessment (SWERA) program in collaboration with the Energy Commission and the GMA began a nationwide wind resource assessment in Ghana

As part of the SWERA project, a wind resource map of Ghana with a resolution of 1 km^2 (shown in Figure 2.4) was developed by NREL of USA. This wind energy resource map of Ghana shows that there is a class 2 wind resource (i.e. wind resource with speeds ranging from 6.2 m/s to 7.1 m/s) at a height of 50 m along the Coast and away from Accra in the Southeast part of Ghana. It also indicates that there is a good to excellent wind resource - class 5 to class 7 (8.4 – 9 m/s at 50 m) in the higher regions northwest of Accra and along the border with Togo. Studies have also revealed that a land area of about 1128 km^2 which is about 0.5 % of Ghana's total land area is endowed with a class 3 wind resource or higher **(Park, et al., 2009**). The total surface area of Ghana is about 238533 km^2 while the land and water areas are 227, 533 km^2 and 11,000 km^2 respectively (**Index Mundi, 2011**).

In a bid to confirm or invalidate the satellite data developed by NREL of USA under the UNEP/ GEF SWERA project, the Energy Commission (EC) of Ghana in May, 2006 installed wind measuring systems which were manufactured by NRG of USA to take ground wind measurements at the following locations: Anloga, Areeba-Nkwanta, Kue-Nkwanta, and Amedzofe all in the Volta Region. The anemometer installed at Anloga was mounted on a mast (guyed-tower) at a height of 20 m agl and it recorded an annual mean wind speed of 5.5 m/s. The anemometer installed at Areeba-Nkwanta was mounted on a pylon belonging to the telecommunication network company which was then called Areeba but now MTN. This anemometer recorded an annual mean speed of about 3.3 m/s. An annual mean wind speed of 3.0 m/s was recorded by the anemometer installed at Kue Nkwanta. This anemometer was mounted on a mast at a height of 30 m. The Amedzofe wind measurement was done by an anemometer which was installed at a height of 20 m on a pylon belonging to Ghana Broadcasting Corporation (GBC). The Amedzofe anemometer recorded an annual average wind speed of 3.5 m/s (**Appiah, 2007**).

In August 2010, Eleqtra West Africa Limited started taking wind measurements at Ada in the Greater Accra region of Ghana at a height of 60m. The monthly average wind speed recorded at this site was 4.95 m/s (**Arthur, 2012**).

As recent as November, 2011, Energy Commission in conjunction with GEDAP/MOE (World Bank) started taking wind measurements at five selected sites at a height of 60 m. These five sites are Atiteti and Avata in the Volta region, Great Ningo in the Greater Accra region, Ekumfi Edumafa and Gomoa fetteh in the Central region. The Energy Commission in 1999 did wind speed measurement for Gomoa Fetteh as one of the wind recording sites located in the West Greenwich Meridian. Currently, there is a wind resource assessment project going on at Kablavo (near Adafoah) and Anloga at a height of 80 m under a joint venture partnership between the Energy Commission and VESTAS (**Madjinou, 2012**). The actual annual average wind speeds of these most recent wind recording sites in Ghana at the time of writing this thesis were not available since the period of time spent for wind data measurement at these sites was less than a year.

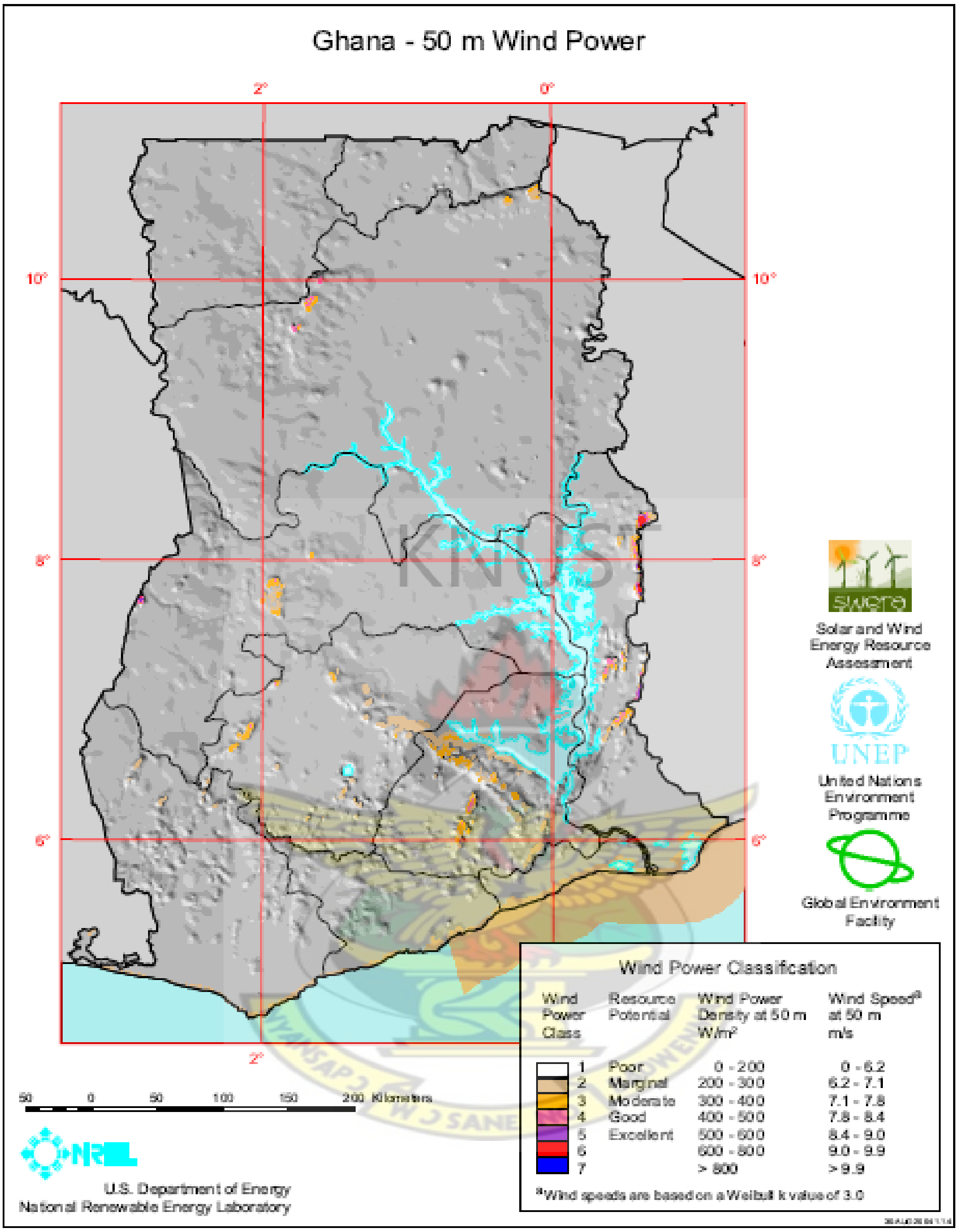

Figure 2.4: Wind Resource Map of Ghana at 50 m

Source: NREL, USA.

2.5 WIND – AIR IN MOTION

Wind is moving air due to spatial distribution of solar radiation or energy that determines areas of low and high pressures. As a result air moves from regions or areas of high pressure to low pressure when the only force acting is the pressure gradient force (**Appiah, 2011; Team C001472, 2000**). Wind is a weather element and therefore is contained in the troposphere (**Mayhew, 2004**). Weather is the state of the atmosphere at a place at a specific time with respect to atmospheric properties such as temperature, moisture, wind velocity, barometric pressure, etc (**Houghton Miffin Co, 2000**). Wind is also said to be the natural motion of air roughly parallel to the Earth's surface. It is caused by the unequal heating and cooling of the earth's surface and the atmosphere which produce differences in air pressure. As the atmosphere shifts air masses to equalize these differences, wind is developed tending to flow from areas of high pressure to areas of low pressure. Other factors also come into play to influence the wind speed and direction. These factors are Earth's rotation, the condensation of water vapor, the formation of clouds, friction over land and water, etc (**WeatherShack, 2011)**.

The term wind is usually applied to horizontally moving air while air moving in a vertical direction is called current. The vertical component of the wind is typically very small (except in thunderstorm updraft) compared to the horizontal component (**National Weather Service, 2010**).

2.5.1 WIND SPEED

This is the magnitude of wind velocity. It is the rate at which air moves in the atmosphere. Wind speed is a scalar quantity. The device used to measure wind speed is the anemometer. Wind speed is generally determined by atmospheric conditions and terrain conditions. Generally, wind speeds are higher in wide open spaces along ridge lines and near the coastlines where few obstructions interfere with air movement (**3Tier® Inc., 2011**). Wind speed generally increases with height.

2.5.2 WIND DIRECTION

Wind direction is the orientation of the wind vector **(US EPA, 2000**). The wind can blow from any direction. The direction of wind is given by the direction from which it originates or blows**.** For example, an easterly wind blows from the east to west and a northeast wind blows from the northeast to southwest. Wind direction is often quoted in cardinal direction or azimuth degrees. However, the direction of wind is best described by its azimuth, measured clockwise from north back to north, that is, from 0 to 360 degrees. A wind of azimuth 200º blows from SSW, a wind of azimuth 45º blows directly from NE **(Calvert, 2000**).

Wind vane and wind Sock are instruments for measuring or showing the direction of the wind. Wind rose is a circular diagram giving a visual summary of the relative amounts of wind available in each of a number of direction sectors (often 12) at a given location and the speed content of that wind **(EWEA,2009**). Diagrams of a wind vane and a wind rose are shown in fig 2.5 below.

Figure 2.5: Vector 200P Wind Vane and a Wind Sock

2.5.3 VERTICAL WIND SPEED GRADIENT

The wind speed decreases from its free velocity, **v** to zero while moving towards the earth's surface. The wind speed at the surface of the earth is zero because of friction between the air and the Earth's surface. The friction between the wind and the ground reduces the wind speed and also causes the wind direction to vary (**Calvert, 2000**). The type of terrain determines the amount of resistance offered to the wind as it approaches the ground. The opposition that the terrain offers to the wind is assigned a value called "coefficient of friction" or "wind shear exponent" depending on the type of terrain over which the wind is flowing **(Wolar, 2008)**. The wind speed increases with height most rapidly near the ground, increasing less rapidly with greater height. At a height of about 2 km above ground level the change in speed with respect to height becomes zero (**Walker and Jenkins, 1997**). An example of a graph of height against wind speed is shown below in figure 2.6.The vertical variation of the wind speed which is also called the wind speed profile or wind shear graph can be expressed by different functions. Two of the more common functions which have been formulated to describe the change in mean speed with height are based on experiments and are given on page 26.

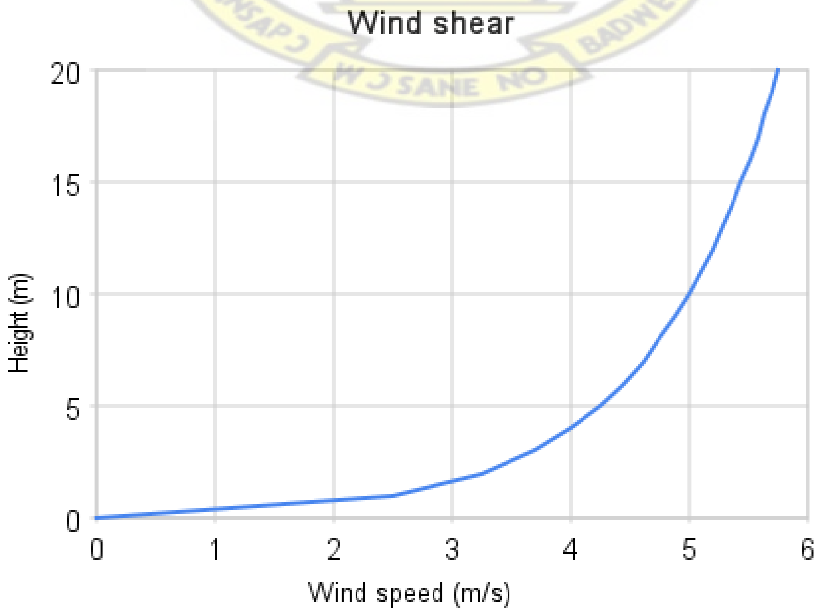

Figure 2.6: Wind Shear Graph. Source: Better Generation Ltd, 2009

2.5.3.1 POWER EXPONENT FUNCTION

The power exponent function is quoted as:

$\mathbf{v(z) = v_r}$

Table 2.2 Wind Speed: Parameters for Calculating a Vertical Profile

TYPE OF TERRAIN	ROUGHNESS CLASS	ROUGHNESS LENGTH, Z_0 (m)	EXPONENT α
Water areas	0	0.001	0.01
Open Country, few surface features	1	0.12	0.12
Farmland with Building and hedges	2	0.05	0.16
Farmland with many trees, forest, villages	3	0.3	0.28

Source: Walker and Jenkins, 1997

2.6 THE POWER IN THE WIND

The kinetic energy of the air by virtue of its motion is the wind energy. Total wind energy (E) flowing through an imaginary area A in the atmosphere during a time, t is given by

E =

2.7 ON-SITE MEASUREMENT

The best most accurate indication of the wind resource at a site is through on-site measurement using the two principal wind instruments (anemometer and wind vane). This is however a fairly costly and time-consuming process (**Gardener et al., n.d**).

On- site wind measurements are often an important input to the prediction of the power production of a single turbine or a wind farm (Siting) or for establishing the power curve of a wind turbine. The accuracy of on-site measurements is crucial since the energy density and wind turbine power output are proportional to the cube of the mean wind speed (**Petersen et al., 1997**).

For any bankable estimate of the energy yield, on-site wind measurements are required. The number of measurement masts required for a specific site depends next to the size of the project mainly on the complexity of the terrain. If the wind measurement is not carried out at the hub height of the proposed wind turbine then the minimum measurement height should be 2/3 (two-thirds) of the hub height of the proposed turbine. An increase in measurement height beyond this leads to reduction in uncertainty in the energy estimation. The measurement period must be one year or more to avoid any seasonal bias. Because the wind speed also varies inter-annually typically up to instruments over level, open terrain is 10 meters above ground level. Open terrain is defined as an area where the distance between the instrument and any obstruction is at least ten (10) times the height of the obstruction (**US EPA 2000)**. Figure 2.7 below shows a typical wind monitoring system making use of the two principal wind sensors – anemometer and wind vane.

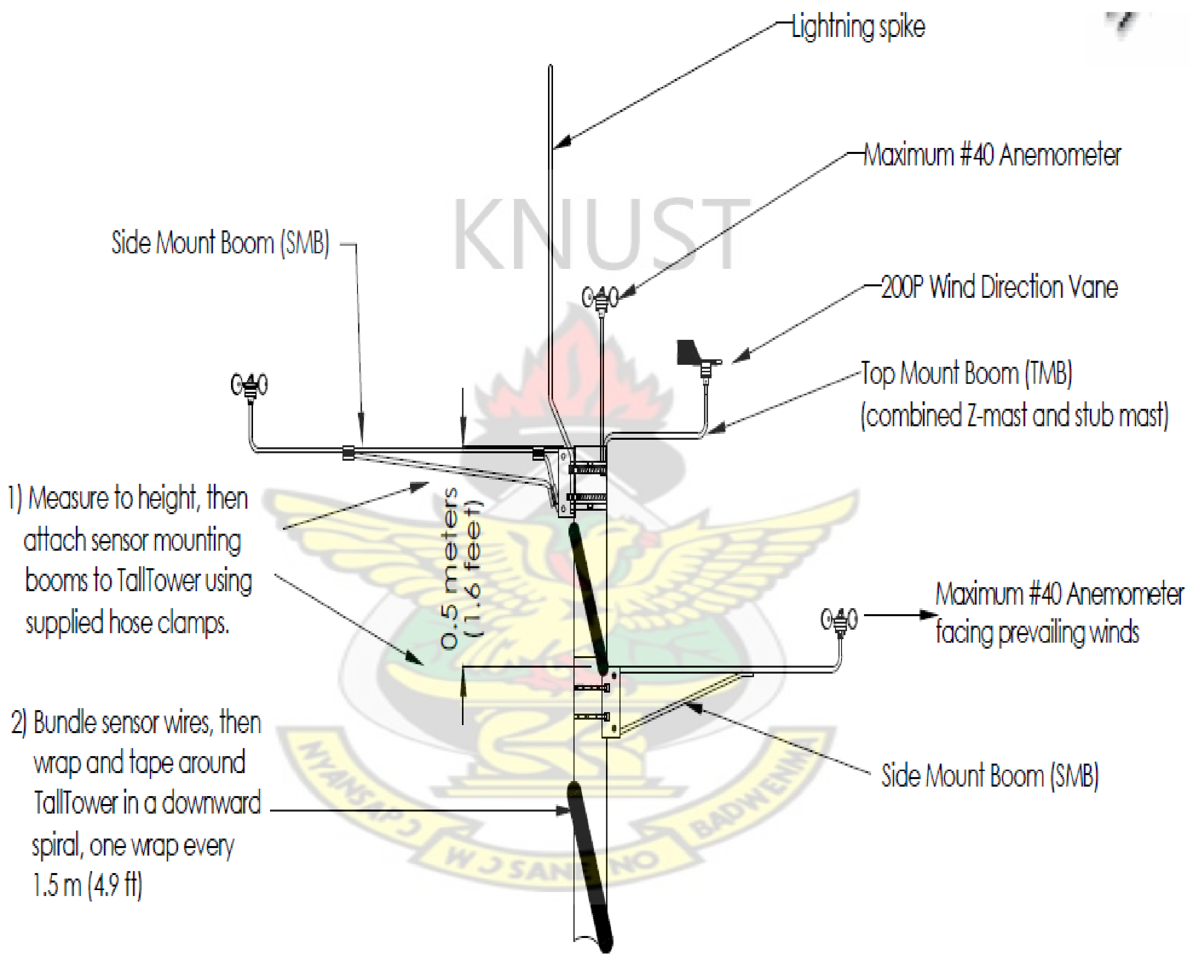

Figure 2.7: A Typical Wind Monitoring System

SOURCE: NRG Systems 2005, Tall Tower Installation Manual Rev-7.12

2.8.1 ANEMOMETERS

Anemometers as indicated under section 2.5.1 are sensing devices used for measuring the wind speeds of an area. Cup and propeller anemometers are the sensor types most commonly used for the measurement of near-horizontal wind speeds (**AWS scientific Inc., 1997**).

Data collected by even accurate anemometers at a candidate wind site at heights below two-thirds (2/3) of the height of the prospective wind turbines to be installed at the site would not have meaningful values for energy capture calculation. Data needs to be collected at a minimum of two levels (three levels are preferred) to determine the turbulence and shear within the wind. This is done by mounting more than one anemometer on a tower at prescribed levels. Two anemometers are recommended at the highest metering point so that either of the anemometers would serve as a backup for the other in case of the failure of anyone of them. Anemometers are placed at various levels to determine the wind shear and the turbulence intensity of wind which may fatigue or put undue stress on the rotor blade over some time. For every 20 m increase in anemometer elevation, the speed of the wind increases 5 % to 15 % depending on the type of ground cover (**Wolar, 2008**). Anemometers mounted on towers should be mounted away from a lattice tower at a distance of 2 (two) to 3 (three) times the tower diameter to reduce the effect of the tower on the air flow. For solid towers, they should be mounted 6 (six) times the tower diameter away (**Nelson, 2009**). According to IEA (1982) an anemometer should have an accuracy of five percent (5%) or better over the range of relevant wind speeds and according to the revised IEA recommendation (1990) an anemometer should be accurate to more complex ones can measure wind speed, wind direction and air pressure (**Harding L., 2005**). Anemometers employed in the wind power industry usually measure wind speed either by simple rotational cup or by the change in reflective properties of light or sound waves due to air movement (**Wind Measurement international Co., n.d)**

Basically, there are two types of anemometers namely, velocity and pressure anemometers.

Examples of velocity anemometers are:

(i) Cup anemometers

(ii) Windmill anemometers or Propeller anemometers.

(iii) Hot-wire anemometers

(iv) LASER - Doppler anemometers

(v) Sonic anemometers

Examples of pressure anemometers are:

(i) Plate anemometers

(ii) Tube anemometers

These types of anemometers can further be grouped into two as those which employ mechanical sensors and those which employ non-mechanical sensors. Examples of those which use mechanical sensors are cup and propeller anemometers. Hot-wire and sonic anemometers are examples of non- mechanical sensors (**US EPA, 2000**). Anemometers can further be classified as rotating and non- rotating. The cup and the propeller anemometers are examples of rotating anemometers while the hot-wire anemometer, Laser-Doppler and sonic anemometers are examples of non-rotating anemometers.

Experience has shown that anemometers may be hand-held, tower/mast mounted or ground based.

2.8.3 CUP ANEMOMETER

Since a cup-type of anemometer was used for the wind measurement carried out by this thesis, the review of literature on this type of anemometer will be relatively extensive.

The rotating cup anemometer consists of either three or four or sometimes six hemispherical or cone shaped cups mounted symmetrically about a vertical axis of rotation (**US EPA, 2000**). The three-cup anemometer designs have been found to be better than the four- cup designs (**Strangeways, 2000**). The three-cup design has been found to exert a more uniform torque throughout a revolution (**US EPA, 2000**). When a cup anemometer is exposed to the wind, the shaft rotates due to the pressure difference between the open side and the backs. The pressure at the open side (Concave end of the cup) is greater than the backs (convex end of the cup). The speed of rotation is nearly linear with respect to the wind speed and only for more precise work is any correction required. This relationship between the speed of rotation and the wind speed exists irrespective of wind direction and more or less of air density (**Strangeways, 2000**). The anemometer factor (ratio of the speed of wind to the anemometer arm radius) is found to depend on the wind speed and the anemometer dimensions. The principles of measuring wind speed with cup anemometers are described for the various types of 3-cup anemometers as follows:

A much simpler and the most usual approach of measuring the speed or the rotation of cup anemometers for manual observations is to count the number of revolutions of the shaft using a mechanical revolution counter. This may be in the form of gears connected to the center of the sensor axis. This anemometer totals the number of revolutions of the shaft over a period. Each revolution of the shaft is proportional to the passage of a known "run of wind". Knowing the elapsed time between two readings of the counter, the total run of wind (or the average wind speed) can be calculated. This type of cup anemometer described as a mechanical type of three-cup anemometer is not suitable for measuring instantaneous speed. A typical three-cup-wheel wind –path anemometer is shown in Figure 2.8 below.

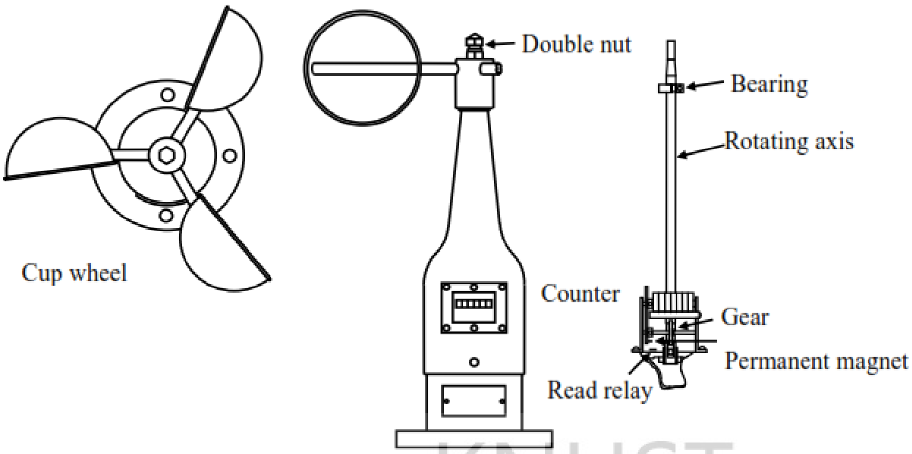

Figure 2.8: Three-Cup-Wheel Wind-Path Anemometer

Source: JMA, 2010

The three-cup-wheel wind-path anemometer is simple in construction, does not require supply of power and remains relatively problem free. However, its body is connected to the counter and it is necessary to read the counter manually for every instance of observation **(JMA, 2010**). For automatic logging of wind speed, the pulse generator three-cup anemometers that produce switch contact closure are usually the most useful. The switch of this type of electric cup anemometer is either a magnetic reed switch or an optical-electronic equivalent. In most designs of the magnetic detector or reed switch type of cup anemometers, a magnet is fixed to the rotating shaft to close a switch once for each revolution. The closures of the switch are processed by a data logger by totaling the number of switch closures over a period being logged to provide the average wind speed, with the possibility of measuring the time between pulses in order to log instantaneous wind speeds and gusts (**Strangeways, 2000**). The lifetime of the reed switch is 10 million closures (**JMA, 2010**). In a typical design of the optoelectronic type of cup anemometer, the rotating cups turn a kind of paddle wheel housed in a metal canister beneath the cup anemometer. Each time the paddle wheel rotates in its canister, it breaks a light beam and generates a pulse of current. An electronic circuit multiplies the pulses and uses the derived pulses to determine the wind speed (**Woodford, 2011**). Figure 2.9 below is an example of a handheld optoelectronic type of cup anemometer.

Figure 2.9: A Handheld Optoelectronic Ames Anemometer used by the Navy
Source: Woodford, 2011

Another design of the optoelectronic type of cup anemometer has an optical disc through which a Light Emitted Diode (LED) passes an infrared light. The infrared light is then detected and one pulse per revolution of the disc is produced. Alternatively, the optical disc may be encoded with an optical pattern that produces many pulses per revolution which can be treated as a frequency or as individual pulses giving an indication of instantaneous wind speed or average wind speed. Optoelectronic cup anemometers take extra power than the reed switch types. The pulse generator principle of measuring wind speed is also used for propeller anemometers. Furthermore, wind speeds of a three-cup anemometer may be measured yet by another method (the generator type method) though this method is widely used with propeller anemometers and for instantaneous readings. The shaft of the cup anemometer may drive a permanent magnet AC generator, producing a voltage proportional to speed, the voltage being displayed on a reading scale some distance away. The Ac voltage may be converted to a DC signal and logged at automatic weather stations as instantaneous wind speeds. An alternative is to measure the frequency of the AC signal rather than the voltage to generate either instantaneous wind speed or (by integration of the cycles) the average wind speed. The starting torque of the larger generator anemometers can be high because the magnetic attraction between the stator and the rotor offers resistance to movement (**Strangeways, 2000**). Figure 2.10 below is a picture of a typical NRG # 40 Maximum three-cup anemometer and it is followed by a list of its technical specification relating mostly to its mechanical features.

Figure 2.10: Type 40 Maximum Cup Anemometer

Source: NRG Systems Inc. of USA.

DESCRIPTION OF ANEMOMETER

Sensor Type: 3-cup Anemometer of conical cross-section, 51 mm in diameter

Applications:

- wind resource assessment instrumentation
- research measurements in environmental studies
- control anemometer for new and existing wind turbines
- sensing wind speeds at sporting events (Typical example is Olympics)
- Engineering studies on wind effects on bridges, skyscrapers

Sensor range: 1 m/s to 96 m/s

Instrument compatibility: all NRG data loggers

Rotor swept diameter: 190 mm

Overall assembly height: 51 mm

Moment of inertia of rotor assembly: 68×10^{-6} S-ft^2 or 92×10^{-6} kg-m^2

Mounting: (using cotter pin and set screw) on a 13 mm mast with a # 35 hole, 11 mm from the top

Materials

Cups - one piece injection-molded black polycarbonate (Lexan)

Body - housing is black ABS plastic

Shaft - beryllium copper, fully hardened

Bearing – modified Teflon, self-lubricating. PV factor of 20000 (at 15 mph, PV is approx. 500; at 100 mph PV is approx. 2000). Upper bearing is centered in the plane of cup thrust for optimal loading

Permanent magnet- indox 1, 25 mm diameter, 13 mm long, 4 poles

Threshold

Starting threshold – 0.78 m/s

Cup distance constant – (63 % recovery) 3 m

Environmental

Operating temperature - 55

Selsyn Motor to generate wind direction signals. The propeller is designed to react with the wind pressure and turns at a rate corresponding to the wind speed. In order to detect the wind direction and to measure the wind speed accurately the tail assembly of a propeller anemometer is designed so that the propeller always faces the wind.

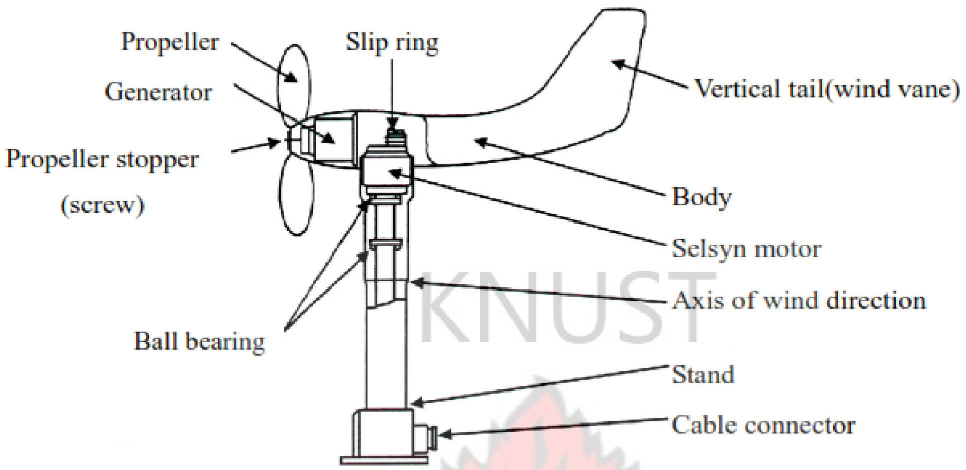

Figure 2.11: Generator-Type Propeller Anemometer

Source: JMA, 2010

Figure 2.12 shows how the AC voltage signal is rectified to a DC voltage and output as an analogue voltage signal proportional to the wind speed. The analogue voltage output signal is transmitted to a wind indicator in which an anemometer is assembled to ascertain the instantaneous wind speed (**JMA, 2010**).

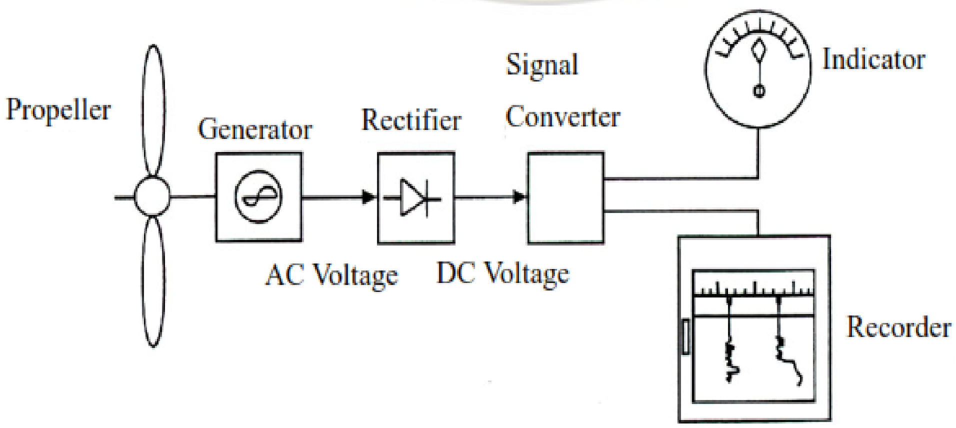

Figure 2.12: Signal Flow Diagram

A different method used by a different type of propeller anemometer called the wind-passage propeller anemometer is described as follows:

As the propeller shaft undergoes a certain number of revolutions for a wind passage of say 60 m a worm gear (i.e. a reducing gear mechanism) coupled to the axis of the generator rotate the reduced gear once; a micro-switch linked to the reduced gear generate electrical pulses which are then combined to calculate the average wind speed over a ten-minute time period. The wind- passage propeller anemometer is a combination of the generator type and the pulse generator type. The wind speed is ascertained by this type of anemometer when it divides the wind passage by the number of time units in a period. This type of propeller anemometer can measure wind speed even in very weak wind conditions when the anemometer only rotates intermittently and when it is difficult to obtain the average speed from the instantaneous wind speed. Wind speed signals are output through slip rings, the brushes and the terminals at the bottom of the stand. The slip rings send electrical signals through the rotor.

If there is a contact fault between the slip ring and brushes as a result of contamination or wear, pulse-shaped noises will occur and the wind speed measurement may have errors. It is therefore important to exercise extra care when carrying out maintenance on slip rings and brushes.

Yet, another type of propeller anemometer to be reviewed in this thesis is a pulse generator type of propeller anemometer. A further classification of this propeller anemometer puts it as an optical pulse generator-type propeller anemometer. Basically, it has the same external features as a generator–type propeller anemometer. The optical pulse generator-type generates voltage pulses using a chopper disk that is directly coupled to the propeller shaft and a photocoupler. A semiconductor device made up of the chopper disk and the photocoupler which converts light to electrical signal constitutes the wind sensor of this type of propeller anemometer. This wind sensor is essentially a Light Emitting Diode (LED) and a phototransistor housed in a sealed mold such that the LED and the phototransistor are positioned to face each other. The chopper disk is positioned so as to interrupt the optical axis of the photocoupler axis. A number of holes are made on the peripheral of the optical disk. These peripheral holes allow the passage or interruption of a beam of light between emitting and receiving devices of the photocoupler. A voltage pulse is generated when the phototransistor receives a beam of light. The number of pulses for each time unit depends on the number of holes while a number of pulse signals proportional to the wind speed is generated or output. The number of holes on the periphery of the optical disk may be 24, 48, 60, etc per revolution). The voltage pulse signals generated after the reception of light by the phototransistor are sampled every 0.25 seconds and the average of a three- second (3 s) period samples is taken as the instantaneous speed. The average wind speed over a ten-minute (10 min) period is obtained using the wind passage method or the capacitor-resistor (CR) integrated circuit method of calculating generated pulses in real time with a microprocessor. In the case of the method with a microprocessor, pulse signals sampled every 0.25 second (s) are processed to obtain the average over one-minute (1 min) period (20 instantaneous values are sampled since an instantaneous value is sampled every 3 s). This average over 1 min. is further averaged to give an overlapping average for a 10 min. period. Since the pulse signals given out or output from optical pulse generator-type are digital they are suitable for computer processing. They are converted to DC analogue signals using Digital/Analogue (D/A) converter for indication or recording on analogue devices (**JMA, 2010**). Figure 2.13 as shown on page 41 depicts a typical type of optical pulse generator-type of propeller anemometer.

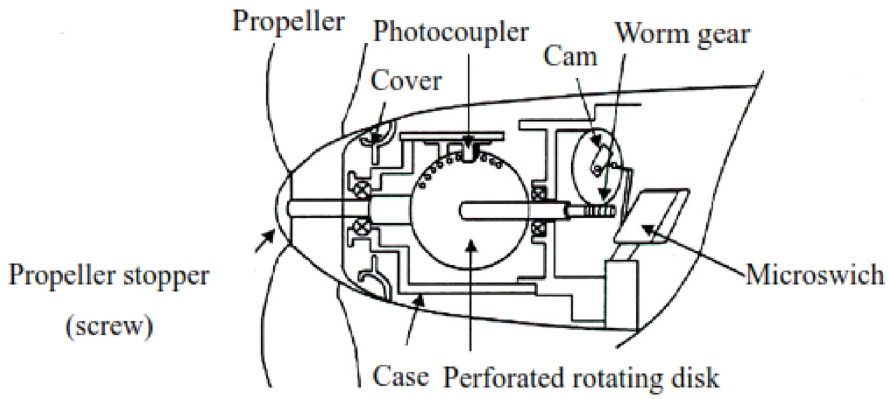

Figure 2.13: Optical Pulse Generator-Type of Propeller Anemometer

Source: JMA, 2010

2.8.5 HOT- WIRE/ THERMAL ANEMOMETER

Hot wire anemometry is the application of a small electrically heated element exposed to a fluid element for the purpose of measuring the velocity of the medium. The Hot-wire anemometer measures the velocity of the fluid by sensing changes in heat transfer from the small electrically heated wire to the flowing fluid (**METU, 2009**). Hot-wire anemometers are used for measuring air speed in rooms, HVAC applications and for measuring turbulence level in wind tunnels, flow patterns around models and blade wakes in radial compressors (**Neu, 2011**).

The purpose of a hot wire anemometer is to measure mean and fluctuating velocities in fluid flows. The hot-wire anemometer computes the flow velocity of a surrounding fluid from its relationship between local flow velocity and the convective heat transfer from the heated element or wire. This type of anemometer consists of a sensor, an electronic equipment and a small electrically heated wire exposed to a fluid flow. The electronic equipment in this anemometer transforms the sensor output into a useful electrical signal. The electronic circuitry of the hot-wire anemometer forms an integral part of the anemometric system and has a direct influence on the probe characteristics. Hot-wire anemometers have very small sensors (**METU, 2009**). Typical dimension of the heated wire are 5

µm in diameter, 1 mm to 3mm in length and 100

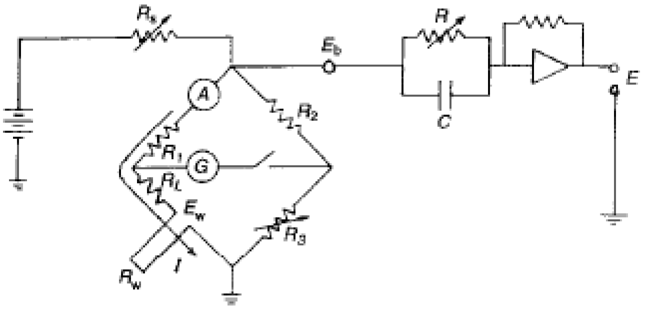

Figure 2.14: Constant Current Anemometer Bridge Circuit

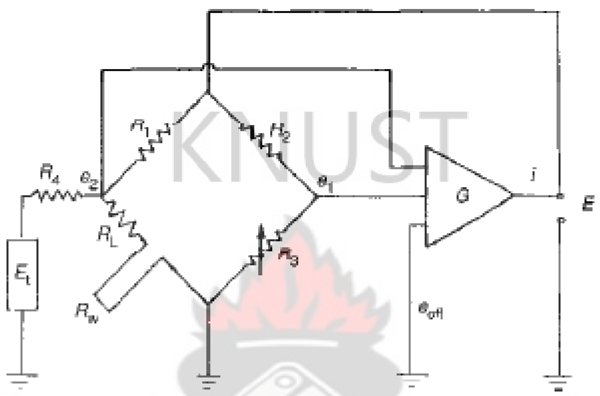

Figure 2.15: Constant Temperature Anemometry Bridge Circuit

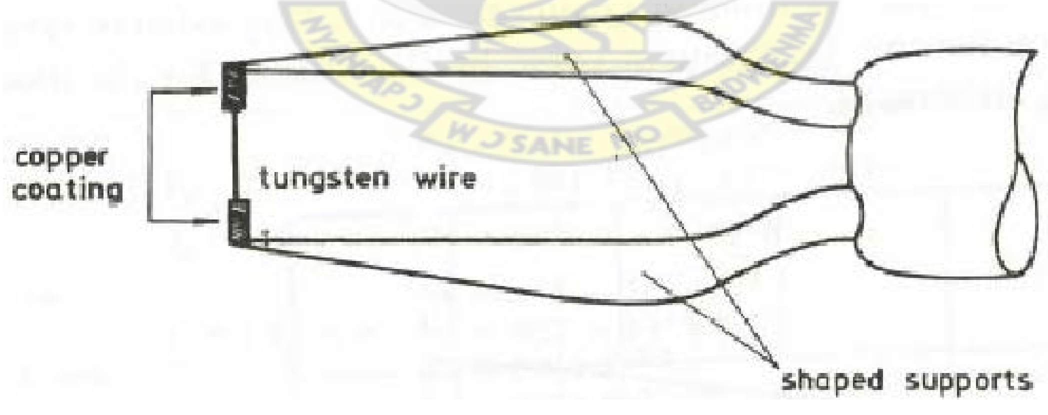

Figure 2.16: Typical Hot-wire Probe Geometry

Source: METU, 2009

2.8.6 THE LASER DOPPLER ANEMOMETER

The Laser Doppler anemometer splits a laser beam into two (by using a mirror partly coated with silver so it allows half of the light to pass through and reflects the other half away), sending one beam outside the anemometer to be scattered and reflected by air particles. The beam that passes through the laser for this matter the inside beam is called the reference beam and the outside beam which is affected by the wind is called the measurement beam. The pattern of vibration of the light waves in the measurement beam is therefore affected by the wind. Since the reference beam is not affected by the wind its phase is not affected. The two beams which travelled on separate paths after being split are later recombined. However, the measurement beam will be slightly out of step with the reference beam causing a strange light pattern to form where they meet and overlap. This strange pattern formed at the boundary of the two beams is called a set of interference fringes. By measuring the spacing of fringes the instrument records how much the measurement beam was affected. The greater the wind speed, the greater the scatter of the measurement beam. Wind speed is derived by comparing the Doppler shift of the reflected beam (measurement beam) with that of the inside beam (reference beam). This results in a very accurate measurement of speed but not direction (**Smith, 2010**). A ground based laser system that measures wind profiles from 10 m to 200 m uses the LIDAR (Light Detection and Ranging) technology. It may offer the most bankable data. This technology may be used to measure wind Speeds up to several kilometers. No tower is required. Its cost is high and has a low penetration in the wind power industry **(Wind Measurement Int. Co, n.d and Nelson, 2009**). Figure 2.17 on page 45 shows a ZephIR Laser Anemometer which operates on the LIDAR technique.

Figure 2.18: ZephIR Laser Anemometer.

Source: Wind Measurement International

2.8.7 SONIC ANEMOMETER

This is a slightly more complex type of anemometer. It uses ultrasonic sound waves to measure the wind speed as well as the direction. Two pairs of ultrasonic transducers (devices that both emit and receive sound waves) are positioned approximately 100 to 200 mm facing one another on a horizontal plane. In turn each transducer emits an ultrasonic sound wave into the wind towards the opposite transducer (**Environmental Canada, 2010**). The ultrasonic wind sensor measures transit time that is the time it takes the ultrasound to travel from one transducer to the other. The transit time is measured in both directions. The transit time depends on the wind velocity along the path of sound. For zero transit time, the forward transit time should be equal to the reverse transit time. With wind along the sound path the upwind transit time increases and the downwind transit time decreases. A microprocessor of a microcontroller of the ultrasonic anemometer calculates the wind speed from the transit times using the formula:

$$V_w = 0.5\, L\, (1/t_f - 1/t_r)$$

Where, V_w is the wind speed, L is the distance between two transducers, t_f is the transit time in the forward direction and t_r is the transit time in the reverse direction. Another formula showing a relationship between the transit time difference

Figure 2.18: Wind Industry Ultrasonic Anemometer and NRG Systems Inc. Ultrasonic Wind Sensor RT20 Anemometer.

2.8.8 PRESSURE ANEMOMETER

This type of anemometer is not a familiar instrument in the wind power industry perhaps because of its less advanced technology, low suitability and limited application in the wind power industry.

2.8.8.1 PLATE ANEMOMETER

Plate anemometers consist of a suspended plate which can be deflected by the wind. They are the oldest form of anemometer. Later versions of this instrument place a spring against the plate to measure the wind force more precisely. Just like propeller anemometers plate anemometers must be faced into the wind to obtain accurate results (**Smith, 2010**).

2.8.8.2 TUBE ANEMOMETER

Tube anemometer or pressure tube anemometer uses the pressure generated by the wind to indicate wind speed. The wind flowing across a tube generates change in pressure proportional to the wind speed, a property of the wind which is measured with the aid of a manometer or pressure gauge.

A typical tube anemometer consists of L-shaped glass tubes, partly filled with liquid, with one open horizontal end which faces into the wind and the other end facing up. The stronger the wind pressure, the further the liquid rise in the vertical arm of the L. This is similar to the design of a barometer and the wind pressure is measured in the same way. These anemometers have no moving parts and their maintenance is very low (**Smith, 2010**). A typical example of a pressure tube anemometer is the pitot-tube.

2.9 ANCILLARY INSTRUMENTS

Excluding the anemometer and the wind vane, wind instruments such as Pressure, temperature and humidity instruments are classified as ancillary instruments. These instruments measure detailed wind climate properties to provide greater certainty of the wind energy potential of a site and the operating environment of future or prospective turbine(s) **– (Wind Measurement International Co., 2010**).

2.10 REMOTE SENSING

Remote sensing is a credible alternative to mast-based measurement. Remote sensors are ground based, using sound or light to measure wind speed and direction at various heights. Remote sensing can reveal the extent of wind shear events, turbulence, wake effects and other conditions that affect a site's suitability. Developers prospecting new sites can use remote sensing systems to quickly identify the most promising turbine locations while eliminating marginal locations. With this intelligence, wind project developers can use fewer meteorological masts and site them more effectively. Remote sensors used in today's commercial wind industry are based on either SODAR (Sound Detection and Ranging) or LIDAR (Light Detection and Ranging) techniques.

Using remote and fixed sensing together creates more comprehensive wind data sets that reduce the uncertainty inherent in wind farm development. Both methods together provide wind farm developers persuasive facts to attract investors and offer investors assurances of earning a return on their money (**Pierce, 2011**).

CHAPTER THREE

METHOD

3.1 EXPERIMENTAL SET-UP

The experimental set-up designed for the wind resource assessment on KNUST campus was made up of two wind sensors, a data acquisition device, a desktop computer, a Data Retriever software and data analysis software. The field monitoring tower used for the wind data collection was actually a building- integrated hybrid meteorological tower. It consisted of a hollow concrete base with a fitted 11.4 cm outside diameter galvanized tubular steel tower or simply a steel tube equipped with one NRG maximum # 40 cup anemometer and a # 200P wind vane and a data logger (Wind Explorer™).The completely assembled Meteorological tower was installed on the rooftop of the new classroom block of the College of Engineering of KNUST thus making it a building-integrated tower. A set of guy wires in four directions was attached to it. The anemometer was installed at a height of 5 m above the rooftop of the building. The anemometer was in effect 20 m above the ground while sitting on a boom mounted on the 5.8 m tall roof- mounted galvanized steel tubular tower. The wind vane was about 10 cm below the anemometer. The fully assembled and raised tower was also electrically protected by using a lightning spike, a grounding rod and a copper conductor. Both the speed and the direction data as measured by the anemometer and the wind or direction vane respectively were captured by the Wind Explorer which had the feature of providing both non-volatile data (held on a DataPlug) and an internal binned wind data (stored in the data logger). The standalone battery operated data logger was powered by two 9-volts alkaline batteries. Due to the special feature of the Wind Explorer™ mentioned above, wind data retrieval and analysis were done in two different ways. The non-volatile data stored on the DataPlug was retrieved using a data retrieving software via a data reader, a serial cable and a desktop computer. The analysis of the output files obtained from the DataPlug was however done using WAsP Climate Analyst and a laptop computer. The organization of the internally binned data was done by manual compilation from the pages of the Wind Explorer™ while the analysis was executed using the Stata software. Detailed description of the data collection and analysis would be given in later sections in this chapter. The experimental set-up is diagrammatically represented in figure 3.1 below.

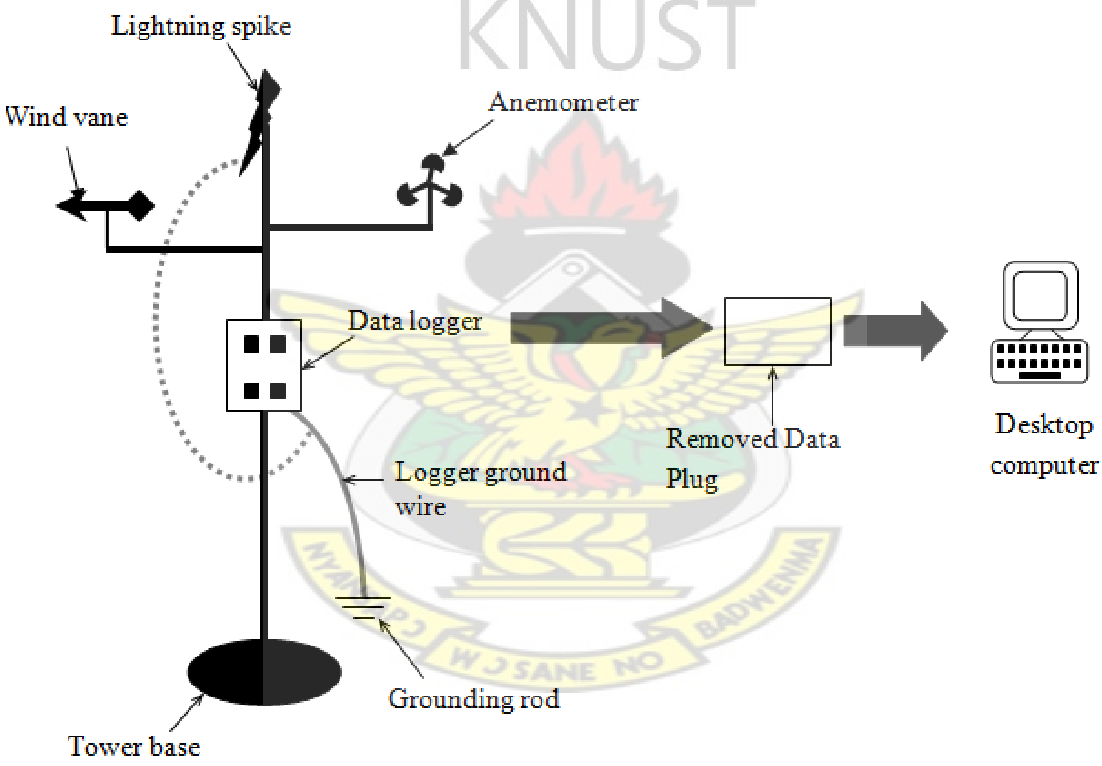

Figure 3.1: Layout of Experimental Set-Up

3.2 SITE DESCRIPTION

The site used for the wind measuring instrument campaign is located on the campus of Kwame Nkrumah University of Science and Technology (KNUST) which is a few meters northeast of the Kumasi –Accra road. The University is actually located in a suburb of

Kumasi at geographic coordinates of latitude, 6.4

Figure 3.2: Wind Monitoring System

Figure 3.3: Obstruction at KNUST Site 0001

Figure 3.4: Partial Layout of KNUST campus

Source: Google Earth Map (slightly modified)

3.3 FOUNDATION CONSTRUCTION AND ATTACHMENT OF ACCESSORIES TO TOWER

The rooftop of the new College of Engineering Classroom block of KNUST was inspected and some free floor space closely behind an existing satellite dish (approximately 2.8 m in diameter on a 2.2 m high tower) and a telecommunication tower (about 35 m agl) was prepared and locations for the mast base and guy-wire anchor supports were laid. A concrete was cast around a 14 cm outside diameter steel tube to make a hollow concrete foundation measuring 50 cm x 50 cm x 150 cm. Four anchors in the form of eye hooks supported in separate concrete foundations each measuring 30 cm x 30 cm x 30 cm were also constructed in the four cardinal directions around the main concrete tower foundation. The picture of the concrete foundation is shown in appendix A. The construction dates for the main concrete tower foundation and that of the anchors are 31 January, 2011 and 2

February, 2011 respectively. Other pictures of the wind measuring site are also shown in appendix A.

A locally procured 11.4 cm outside diameter galvanized steel tubular tower was placed in such a way that it leaned against a table with the proposed top end projecting about 60 cm beyond the table and the bottom end supported by the rooftop of the College of Engineering new classroom block. A single 11.4 cm O/D galvanized steel tubular tower of length, 5.8 m was used to support the wind sensors and the accompanying hardware.

A set of guy-wires arranged in the four cardinal directions on a guy-ring was carefully aligned on top of the tower and then pushed down on the steel tubular tower from the top to a distance of about 0.7 m with the bent ends of the guy ring facing down.

The side or lateral booms were already assembled so stainless steel hose clamps were passed through the slit or hole in the first half of the bracket over the boom, through the other half and around the steel tubular tower at a length of 5 m on it with reference to the prospective foot of the tower for the anemometer boom while the vane boom was placed a little below the anemometer boom. The hose clamps were then tightened with a flat screw driver just enough to prevent them from sliding down the steel tubular tower. Each hose clamp for the two booms was adjusted for the side booms to become horizontally positioned. The hose clamps were finally tightened using a flat screw driver to make it ready to admit the wind sensors. A picture taken after the installation of the complete wind monitoring system is shown in appendix A to depict the above description and subsequent descriptions that would be done for the wind monitoring system. Since there is the need to protect the wind sensors from damage due to lightning strikes a lightning spike or an arrestor was attached to the top of the steel tubular tower. The lightning spike had about 30 cm of its length projecting above the tower. A grounding cable/wire of about 4 m was attached to the lightning spike and allowed to run along the table-supported tower for a final connection to a copper grounding rod which was attached to the tower after the tower has been installed. Due to the homebrew nature of the tower construction, the copper grounding rod was attached to the lower section of the tower just above the concrete base after the tower has been raised.

3.4 CONNECTION OF CABLES TO SENSORS AND MOUNTING OF THE CABLE-CONNECTED SENSORS ON THE BOOM

Only one anemometer and a wind vane were considered for wind data gathering for this project. No ancillary sensors such as temperature sensors, barometers, hygrometers, pyranometers, etc. were used for this project. The correct signal cable for each of the sensors under consideration was properly and securely attached to its respective sensor leaving out their bare shield wires for later connection to the Wind Explorer™.

The connection of the anemometer signal cable was done by passing the thinned ends of the cable through the rubber sensor terminal boot's sleeve. The cable was pulled through until the end of the cable with lugs was projecting above the boot. The rubber sensor terminal boot was slid down on the stub of the boom with the boot being pushed slightly away from the vertical stub to give room for the mounting of the anemometer. Loosening of the nut on the left stud on the anemometer was done and the lug of the white sheathed wire in the anemometer cable was connected to it and tightened with a 6 mm spanner. The anemometer stud is identified as such when the setscrew hole is to your right. The lug of the black wire in the anemometer signal cable was attached to the second stud. The anemometer was then secured on the vertical stud of the boom using a split pin and a setscrew. Some amount of Petroleum jelly was applied to the terminals of the anemometer and this was followed by the sliding of the rubber boot over the bottom of the anemometer. Electrical tape was used to secure the bottom of the rubber boot ensuring that the hole for moisture drainage is not blocked. The cable was spirally wrapped around the boom and on the mast leaving the end of the cable for a final connection to the data logger after the tower has been raised. The spiral wrapping of the cable on the mast was done to promote vortex shedding and to prevent the cable from oscillating at a frequency which is equal to the natural frequency of the mast. The wind vane cable had one wire more than that of the anemometer. Unlike the anemometer signal cable which could be connected anyhow on the anemometer, the connection of the wind vane cable to its sensor had some requirements to satisfy. Satisfying the requirements for the connection of the wind vane the red wire terminal on the instrument was first identified and the wire connected to it .The white wire was also connected to the middle stud and the black wire connected to the third stud on the wind vane. After the above connections for the wind vane, the procedure used for the mounting of the anemometer on the stub of the boom was repeated for the wind vane. However, there was no rubber terminal boot sleeve on the boom used to support the wind vane so an electrical tape was used to cover the terminals of the vane in order to protect it from the elements of the weather.

The wind vane was oriented to the magnetic north using a magnetic compass. The anemometer boom was equally adjusted on the other boom to be horizontally parallel with the wind direction boom which was mounted slightly below the anemometer boom on the tower. The wind vane cable was also spirally wrapped around its boom leaving its end hanging for a final connection to the data logger later.

The rubber boot was pulled over the anemometer to protect its signal cable from the elements of the weather and also to prevent them from coming loose as a result of strong winds which may cause it to flutter.

3.5 RAISING THE TOWER

A crew of five men was used to do the lifting of the steel tubular tower with steel strips welded around it to produce a tight fit into the 14 cm tube embedded in the concrete cast foundation. The 5.8 m long steel tower was raised to a vertical position and sent very close to the concrete foundation. Two members of the crew were made to stand on a table of about 70 cm high placed closely to the hollow concrete foundation after the tower has been sent very close to the concrete foundation. These crew men were detailed to help in the lifting as well as to support the tower in the vertical position on the table after the other three members of the crew had raised the steel tube tower vertically onto the table. Three crew members were then used to lift the steel tubular tower from the table into the hollow concrete foundation while the two other members of the crew were tasked to adjust two opposing guy-wires as a means of guiding or stabilizing the tower. It is necessary to adjust the correct opposing guy-wires while raising the tubular tower into the hollow steel tube embedded in the concrete foundation.

A spirit level was used to plumb or check whether the tower was standing upright. Vertical deviations of the tower were corrected by adjusting the guy wires. Finally, the four guy-wires were tensioned onto their respective concrete anchors using wire-rope clamps and a 13 mm spanner to tighten the wire-rope clamps.

A grounding copper rod/ conductor manufactured by NRG System Inc. was attached to the mast beginning right from the top of the hollow concrete foundation and covering a length of about 1 m along the steel tubular mast toward the sky. The copper cable/wire connected to the lightning spike was then attached to the grounding copper rod clamped onto the tower. One end of a separate copper cable/wire of about 30 m was attached to the grounding copper rod attached to the tower and the other end joined to the earth grounding terminal provided in the soil.

3.6 CONNECTION OF WIND SENSORS TO THE WIND EXPLORER ™

The Wind Explorer was housed in a locally manufactured shelter box. This housed unit was mounted on the existing telecommunication tower by passing a hose clamp through a slot at the back of the shelter box and tightening it around the tower. The tower-mounted Wind Explorer™ is at a height of 4.8 meters with reference to the rooftop of the KNUST COE new classroom block. The Wind Explorer was not mounted on the wind measuring mast but on the adjacent telecommunication tower due to insufficient length of the wind vane cable (length of wind vane cable supplied was 1.2 m).

The anemometer's shield wire which was not connected to the anemometer itself makes the number of wires in the anemometer cable to be three. The shield wire of the anemometer was first connected to the Earth ground terminal of the data logger (Wind Explorer™) and the other two wires of the anemometer cable were made to touch the earth terminal in order to ensure that there was no static electricity built up in the anemometer. The white sheathed wire from the anemometer was connected to the first terminal at the top of the wind Explorer while the black wire of the anemometer was connected to the second terminal at the top of the Wind Explorer. These two terminals on the Wind Explorer to which the white and black sheathed wires of the anemometer cable were connected are both labeled "SPD".

Now the wind vane cable which was spirally wrapped around its boom and left hanging free in air as described in section 3.2.4 above was also spirally wrapped around the existing telecommunication tower which supported the Wind Explorer™. The spirally wrapped and tied wind vane cable hanging beyond the wind vane was finally spirally wrapped and secured with an electrical tape on the existing telecommunication mast.

A fourth wire in the wind vane cable (a shield wire) was not connected to the wind vane itself. Connection of the shield wire of the wind vane to the ground terminal of the Wind

Explorer™ was also the first thing to be done when the vane wires were being connected to the Wind Explorer™. The other three wires in the wind vane cable were made to touch the earth terminal separately to ensure that there was no static electricity built up in the wind vane just as it was done for the anemometer wires. The three wind direction sensor wires were then connected to the wind explorer in the following manner. The NRG 200P wind vane cable that was used as indicated in section 3.2.4 had red, white and black sheathed wires. The red wire was connected from the left end terminal on the wind vane to terminal 3 on the Wind Explorer, labeled "V"+. The white wire was connected from the centre terminal on the wind vane to terminal 4 on the logger labeled "VS". The black wire was connected from the right end terminal on the wind vane to the terminal 5 on the data logger labeled "V" −". A grounding copper cable/wire was connected to the Wind Explorer's ground terminal and stretched to the copper grounding rod to which it was finally connected

Figure 3.5 on page 59 shows the front view of a Wind Explorer with nine wire terminals for connecting the cables from meteorological sensors to the Wind Explorer. Table 3.1 illustrates the mode of connection of the wires in an NRG # 40 maximum cup anemometer, a # 200P wind vane and any extra instrument such as a pyranometer (for measuring solar radiation) or a temperature probe which may be available for connection or use.

Figure 3.5: NRG Wind Explorer™

Table 3.1:Sensor Cable Connectios to Wind Explorer™

TERMINAL	WIRE COLOR	LABEL / POLARITY	TYPE OF ANEMOMETER
1	White	SPD (neutral)	Anemometer
2	Black	SPD (neutral)	Anemometer
3	Red	V+	Wind Vane
4	White	VS	Wind Vane
5	Black	V−	Wind Vane
6	Red	V+	Extra Instrument
7	White	VS	Extra Instrument
8	Black	V−	Extra Instrument
9	−	GND	All shield wires/grounding wire

3.7 DATA COLLECTION AND ANALYSIS

The wind monitoring system was completely installed on 18 February, 2011 but was test run until 28 February, 2011 when actual data logging began at 14:50 P.M. During the test-run period the NRG # 40 maximum anemometer was compared to a Deuta Anemo brand hand-held anemometer in the absence of a standard calibrator. During the above simple calibration process it was realized that the values recorded by the NRG # 40 maximum anemometer was greater than the values recorded by the hand anemometer by 0.5 m/s to 1 m/s. Two DataPlugs were used with the first DataPlug starting logging as indicated above and was removed and replaced by the second anemometer on 1 April, 2011 at 10:20 A.M. and data logging for thesis was stopped on 1 October, 2011. The first DataPlug was connected to a desktop computer via the data reader and a serial port cable for the retrieval of the time-series data for the month of March. The time-series data for the months, April, May and June which were contained on the second DataPlug were lost accidentally while it was being retrieved. As a result data collection was continued from July to September, 2011 in order to satisfy the intended objective of collecting time-series data for three continuous months. In-built Wind Explorer™ data in the form of wind speed and wind direction distributions for the seven month period of wind measurements i.e. March through June to September were also retrieved from the Wind Explorer manually.

As indicated earlier a special feature possessed by the NRG Wind Explorer is its ability to hold data in two forms namely the in-built wind data frequency distribution tables held on the pages of the data logger and the time-series data held on the DataPlug. In other words the Wind Explorer™ stores wind data in its memory and as well stores a maximum of seven month time series data on an accompanying DataPlug.

Wind data in the form of wind speed and direction were sampled every two seconds by the Wind Explorer™. These data in addition to the standard deviations of the wind data were averaged and stored every ten minutes by the NRG Wind Data logger (Wind Explorer™). During these 10 minutes averaging periods a binary file is generated and held on the DataPlug. These binary files were later combined with a site file and converted into an ASCII text file using the NRG software called the NRG Data Retriever Software. The ASCII text was subsequently imported into a Notepad and an excel spreadsheet. A statistical analysis software called Stata was used to analyze the seven month in-built wind data stored in the Wind Explorer™. Stata was used to create bar and line graphs which depict mean monthly variations in the wind data for the seven separate months of March to

September. It was also used to create the hourly frequency distributions of wind speed and wind direction for the entire period of wind measurements. A program called Wind Climate Analyst distributed alongside the main WAsP Software Worldwide by the Wind Energy Department of Risøe DTU of Denmark was used to generate time-series graphs of the wind direction and wind speed using the wind data for the three contiguous months of July, August and September, 2011. This software was also used to produce wind rose, wind speed histogram and some calculations based on the wind data for the third quarter of the year, 2011 for Kumasi.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 SITE INFORMATION RECORD SHEET/ SITE DESCRIPTION FORM

The necessary information required to identify the site which was used for the wind measurements carried out by this project was sought for and used to prepare a site information record or a site information sheet as shown in Table 4.1. The site information sheet describes the selected site for the wind monitoring task executed by this project. The site was designated as KNUST COE New Classroom Block Wind Monitoring Site and assigned site number 0001. The geographical coordinates of KNUST campus are latitude, 6.4

Table 4.1: Site Information Sheet / Site Description Form

Site Designation	KNUST COE New Classroom Block Wind Monitoring Site
Site Number	0001
LOCATION	KNUST Campus
Latitude	6.4° N
Longitude	1.3° W
Magnetic Declination	−4.18 or 4.18 W
Elevation	263 m asl
Tower Type	Concrete & Galvanized Steel Tube hybrid Building – Integrated Tower
Tower Height	20.8 m agl
Anemometer Height	20 m agl
Wind Vane height	19.90 m agl
Wind Explorer Model Number	2333
Type of Terrain	Urban
Type of Climate	Tropic
Prevailing Wind Direction	North-West
Project Data Logging Start Date	28 February, 2011
End Date of Project Data Logging	1 October, 2011

4.2 DEPICTION OF MONTHLY FREQUENCY DISTRIBUTION OF WIND SPEED AND DIRECTION BY STATA GRAPHS

The Stata graphs shown in Figures 4.1a and 4.1 b are monthly distributions of wind speed and direction respectively for the month of March, 2011. Figures 4.2a and 4.2b are monthly distributions of wind speed and direction respectively for April while Figures 4.3 (a & b) through Figures 4.5 (a & b) to Figures 4.7 (a & b) all shown after page 63 are monthly distributions of wind speed and direction respectively for May, 2011 through July to September, 2011 (with the numbering of the figures in line with the chronological order of the months covered during the period of measurements). Each of the above described graph is obtained from its respective Wind Explorer™ Monthly Log sheet shown in Appendix B.

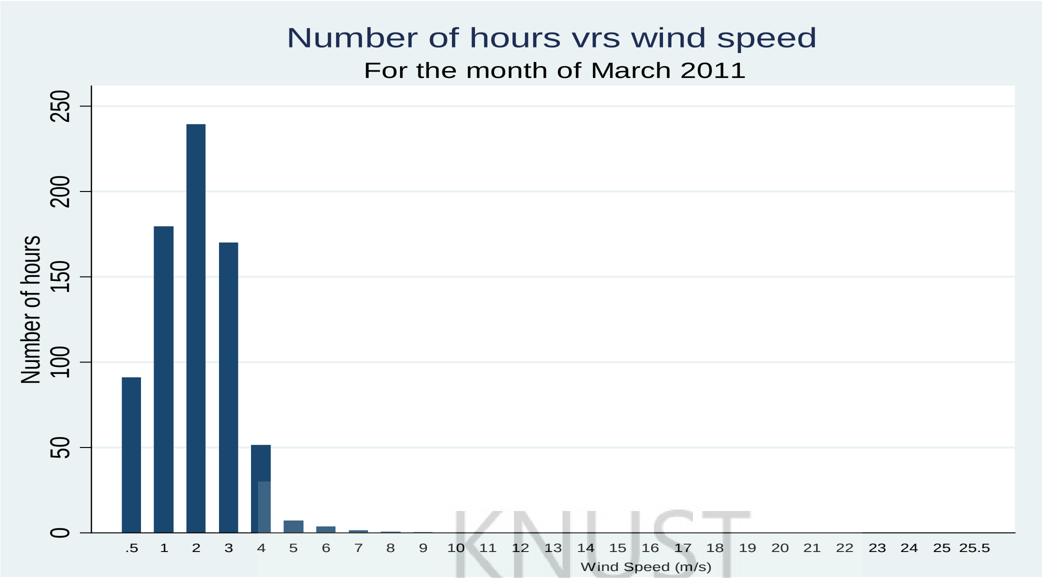

Figure 4.1a: Frequency of Occurrence of Wind Speed in Hours for March, 2011 at Site 0001, KNUST

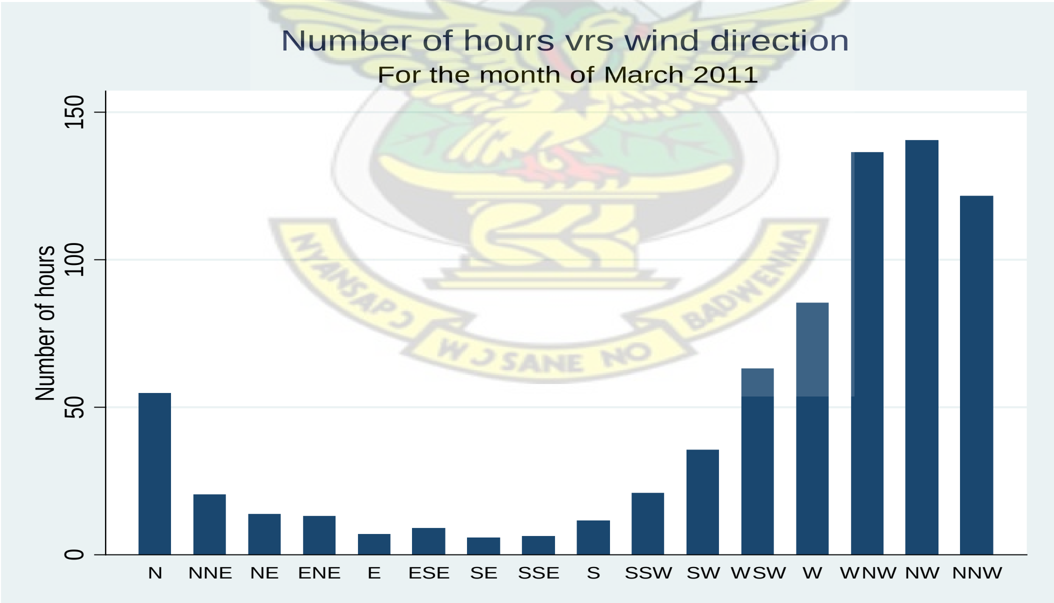

Figure 4.1b: Frequency of Occurrence of Wind Direction in Hours for March, 2011 at Site 0001, KNUST

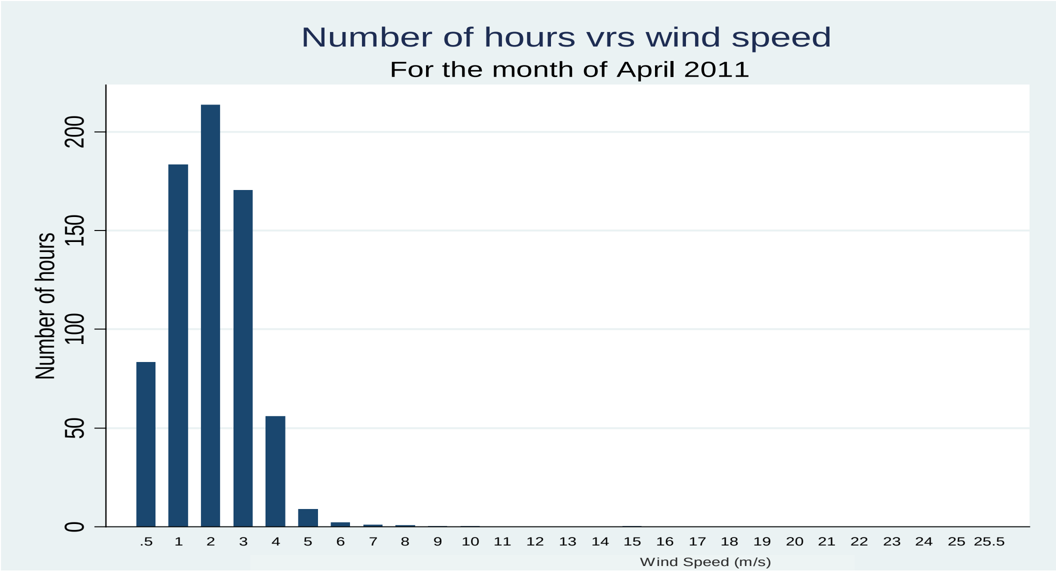

Figure 4.2a: Frequency of Occurrence of Wind Speed in Hours for April, 2011 at Site 0001, KNUST

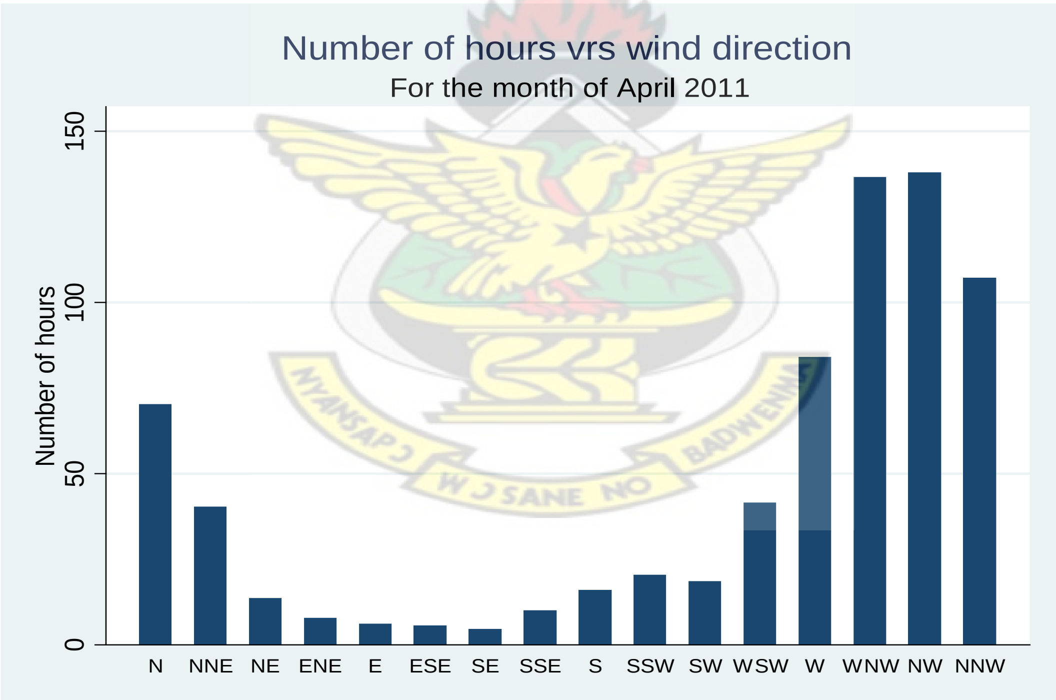

Figure 4.2b: Frequency of Occurrence of Wind direction in Hours for April, 2011 at Site 0001, KNUST

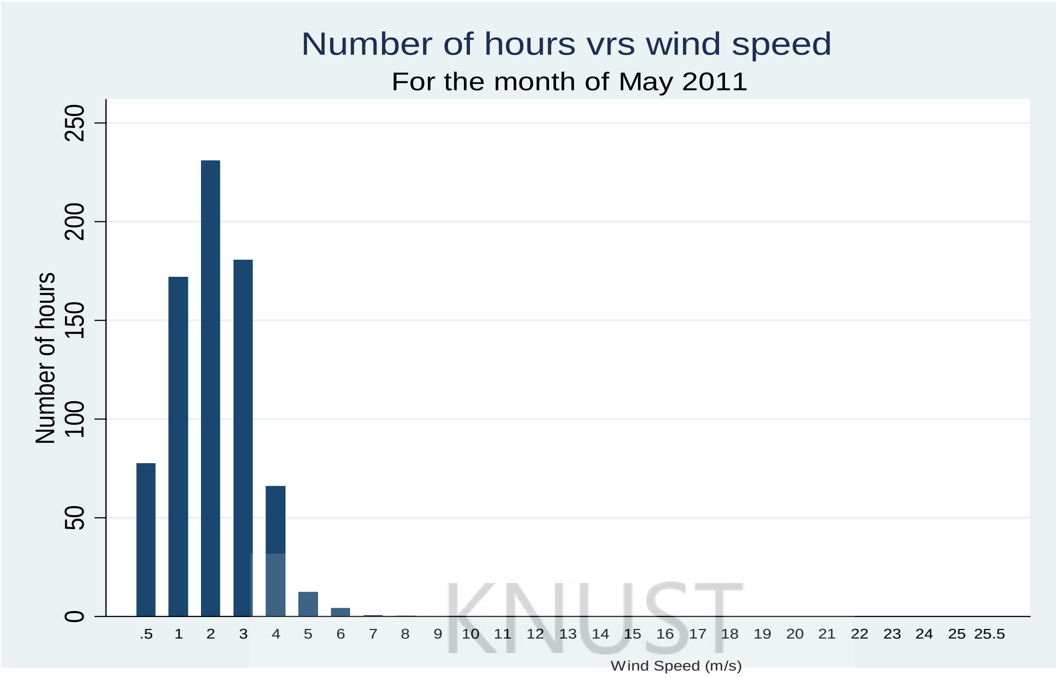

Figure 4.3a: Frequency of Occurrence of Wind Speed in Hours for May, 2011 at Site 0001, KNUST

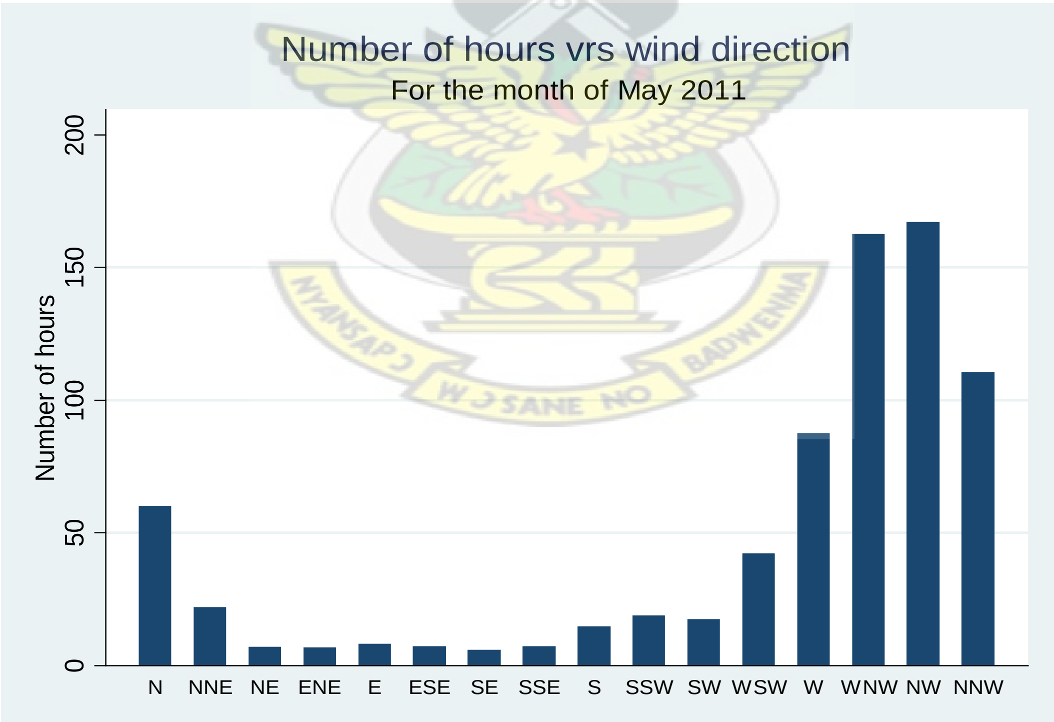

Figure 4.3b: Frequency of Occurrence of Wind direction in Hours for May, 2011 at site 0001, KNUST

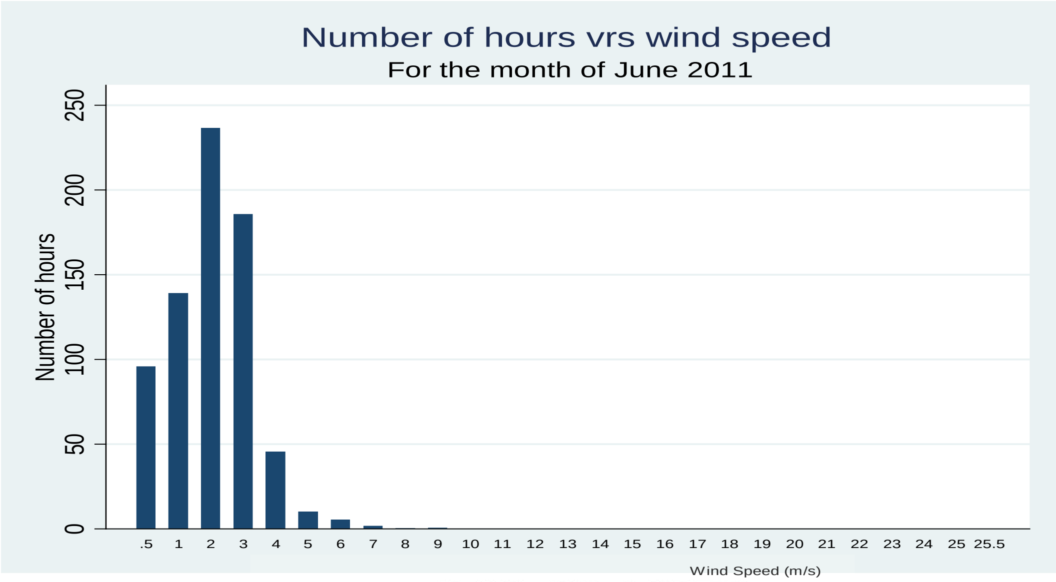

Figure 4.4a: Frequency of Occurrence of Wind Speed in Hours for June, 2011 at Site 0001, KNUST

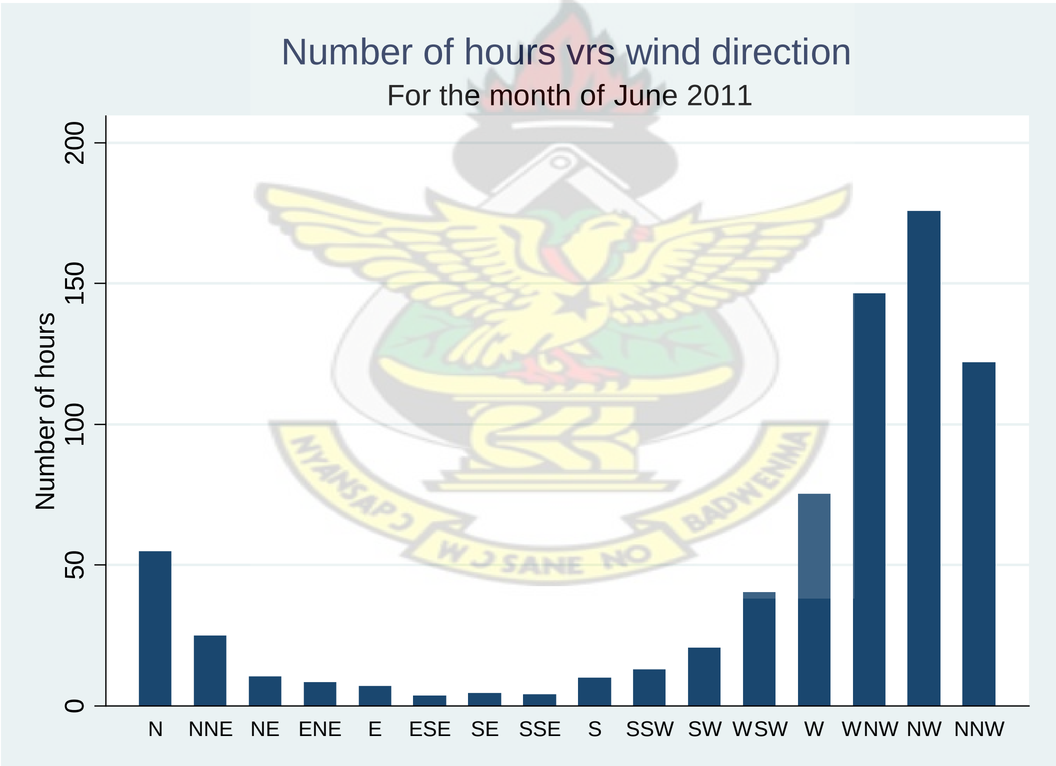

Figure 4.4b: Frequency of Occurrence of Wind direction in Hours for June, 2011 at Site 0001, KNUST

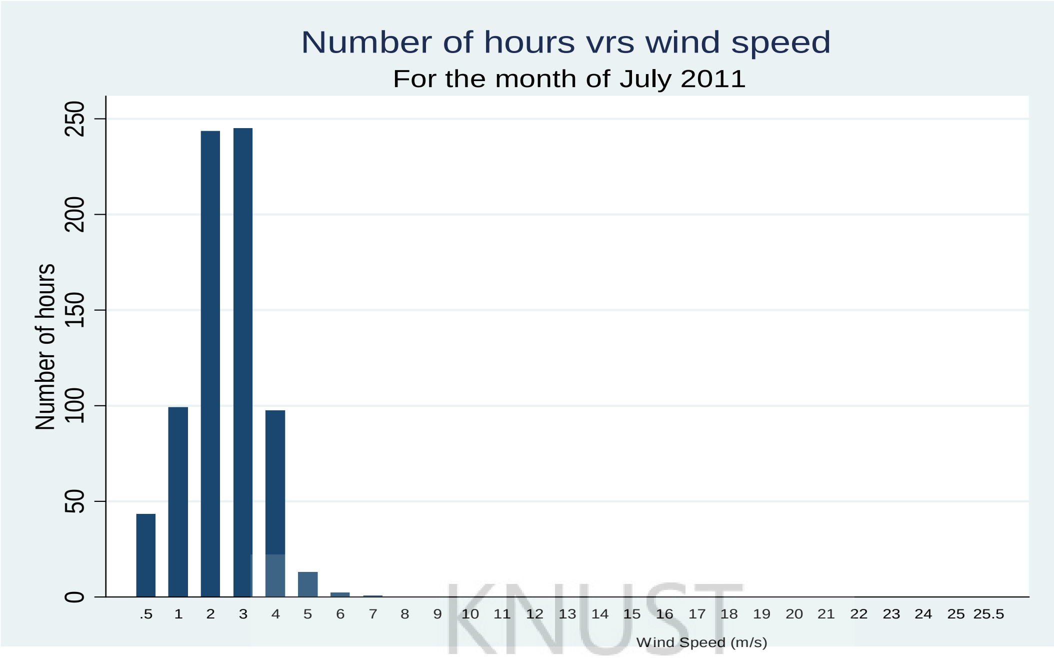

Figure 4.5a: Frequency of Occurrence of Wind Speed in Hours for July, 2011 at Site 0001, KNUST

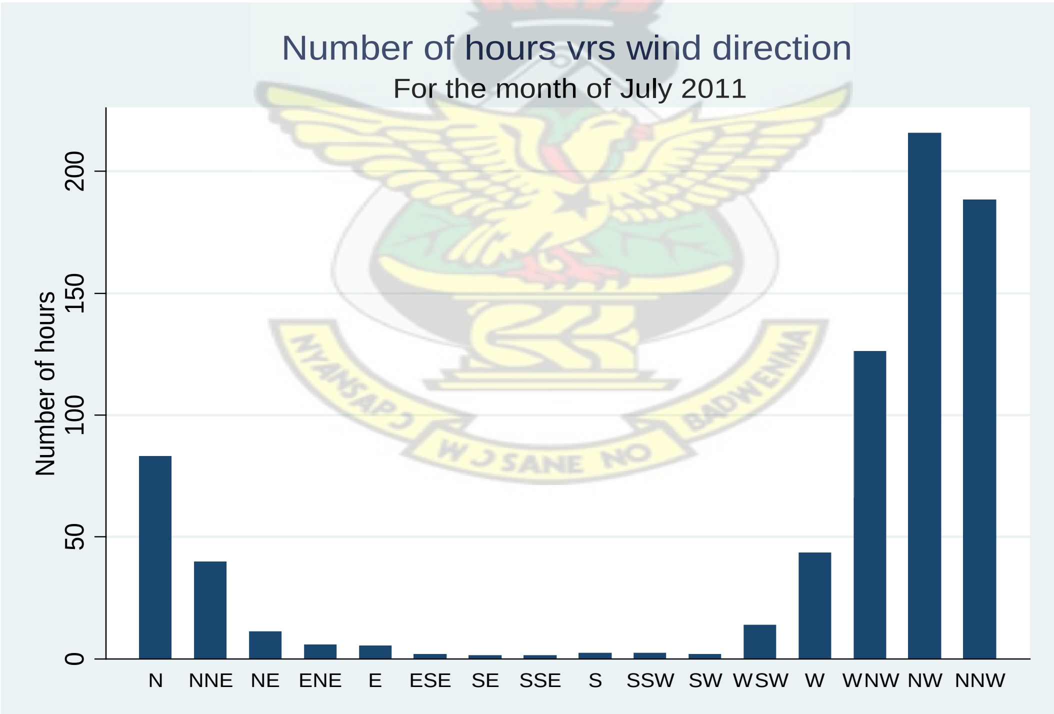

Figure 4.5b: Frequency of Occurrence of Wind direction in Hours for July, 2011 at Site 0001, KNUST

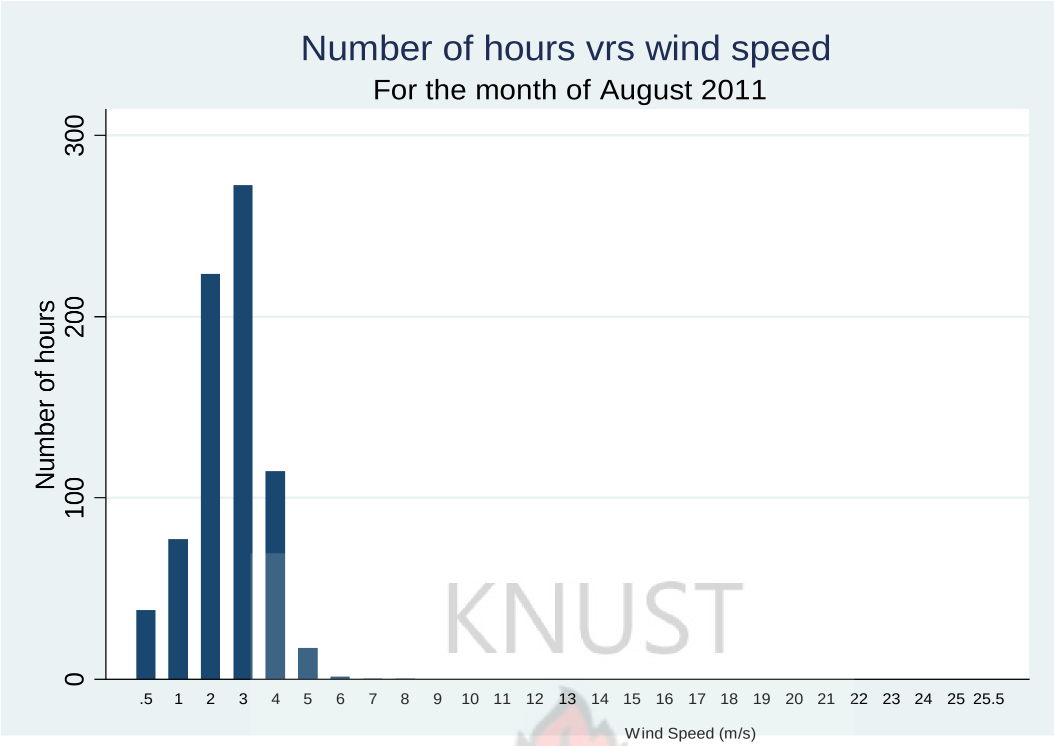

Figure 4.6a: Frequency of Occurrence of Wind Speed in Hours for August, 2011 at Site 0001, KNUST

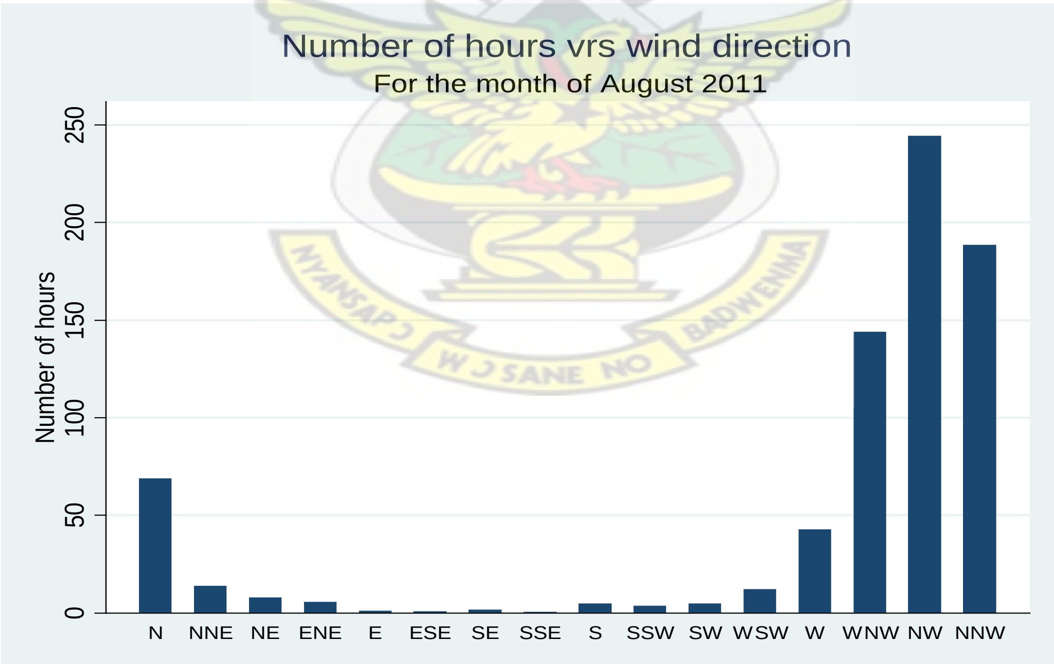

Figure 4.6b: Frequency of Occurrence of Wind direction in Hours for August, 2011 at Site 0001, KNUST

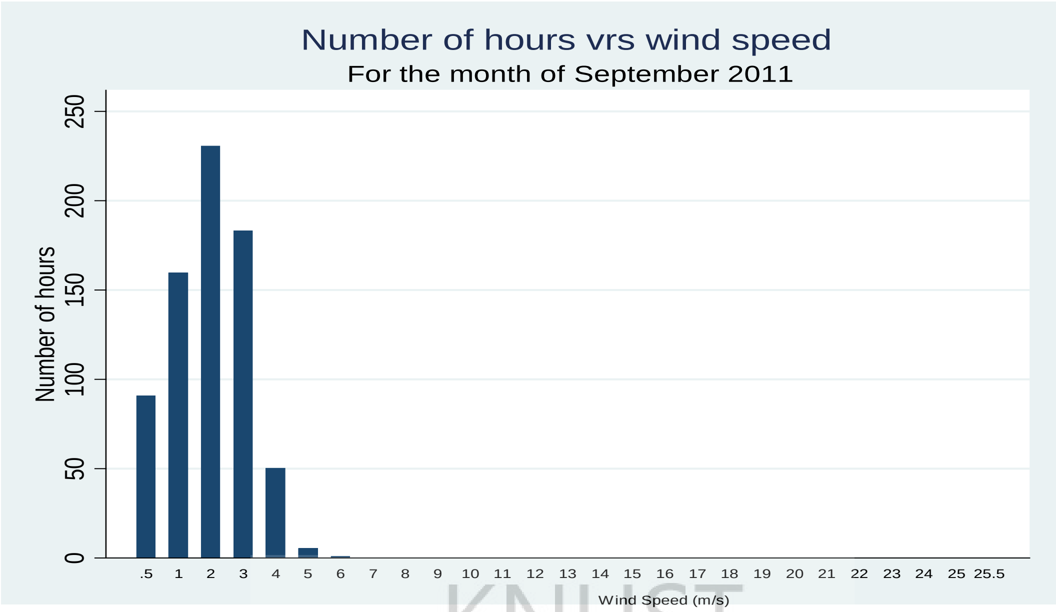

Figure 4.7a: Frequency of Occurrence of Wind Speed in Hours for September, 2011 at Site 0001, KNUST

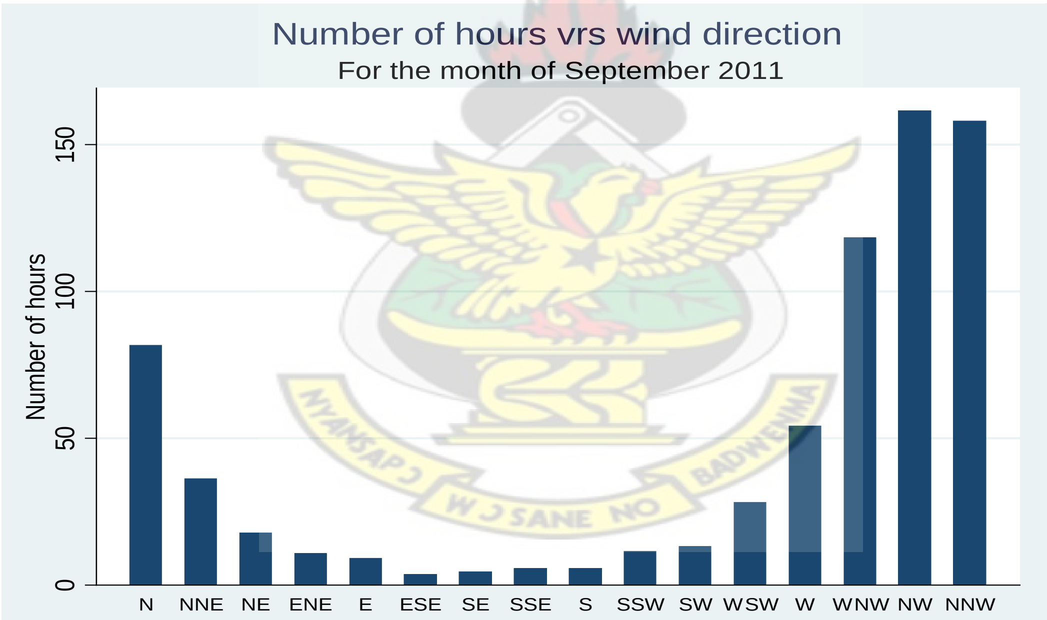

Figure 4.7b: Frequency of Occurrence of Wind direction in Hours for September, 2011 at Site 0001, KNUST

4.3 DATA SUMMARY TABLES FOR FURTHER STATA ANALYSIS

Monthly average wind speeds, gusts and gust directions made available on the average wind speed and direction summary pages of the Wind Explorer™ are assembled to provide a summary table of wind data as shown in Table 4.2 below. This data is said to be internally binned.

The shapes or patterns of the monthly frequency distribution graphs of wind speed on one hand and direction on the other hand as shown above (Figures 4.1a & b to 4.7a & b) exhibit close resemblance among themselves. Thus, the monthly frequency distribution graph of wind speed just as that of wind direction by way of bar charts are said to be similar. This wind characteristic exhibited at KNUST wind monitoring Site 0001 suggests that the wind speed and direction distributions do not vary significantly in terms of the range of wind speeds and directions that occur at the site though the frequency of occurrence may differ. The shape of the wind speed histograms shown above provides useful information about the energy content of the available wind resource at Site 0001 on KNUST campus.

Table 4.2: Summary of Monthly Average Wind Speeds and Gusts

MONTH	WIND SPEED (m/s)	WIND GUST (m/s)	GUST DIRECTION (°)
MARCH	2	19.1	177
APRIL	2.1	24.1	200
MAY	2.1	15.3	190
JUNE	2.1	18.4	156
JULY	2.5	12.3	58
AUGUST	2.6	11.9	332
SEPTEMBER	2	13.8	96

Further preliminary analysis of the non-volatile data stored in the memory of the Wind Explorer™ was carried out using statistical organization to produce summaries of wind data. Internally binned data captured during the seven-month period of wind measurements (March, 2011 to September, 2011) were organized to provide summary tables. Tabular representation of monthly hourly distributions of wind speed and direction observed at Site 0001 at KNUST are shown in Tables 4.3a and 4.3b respectively.

Table 4.3a: Hourly Accumulation of Monthly Frequency Distribution of Wind Speed for the Entire Measurement Period for Site 0001 at KNUST

	HOURLY DISTRIBUTION OF WIND SPEEDS FOR THE MEASUREMENT DURATION (HRS)							
WIND SPEED (m/s)	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	TOTAL
< 0.5	91.1	83.4	77.4	95.7	43.4	38.0	90.7	519.7
1	179.6	183.5	172.0	138.9	99.1	77.1	159.5	1009.7
2	239.4	213.7	230.8	236.4	243.4	223.3	230.5	1617.5
3	170.0	170.5	180.6	185.6	245.0	272.2	183.1	1407.0
4	51.4	55.9	65.9	45.5	97.6	114.6	50.2	481.1
5	7.0	9.0	12.5	10.2	13.0	17.2	5.5	74.4
6	3.7	2.2	4.2	5.5	2.3	1.5	0.8	20.2
7	1.3	1.0	0.7	1.7	0.7	0.3	0	5.7
8	0.7	0.7	0.3	0.3	0	0.2	0	2.2
9	0.2	0.3	0	0.5	0	0	0	1
10	0	0.2	0	0	0	0	0	0.2
11	0.2	0	0	0	0	0	0	0.2
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0
15	0	0.2	0	0	0	0	0	0.2
TOTAL	744.6	720.6	744.4	720.3	744.5	744.4	720.3	5139.1

Table 4.3b: Hourly Accumulation of Monthly Frequency Distribution of Wind direction for the Entire Measurement Period for Site 0001 at KNUST

	HOURLY DISTRIBUTION OF WIND DIRECTION FOR THE MEASUREMENT DURATION (HRS)							
WIND DIRECTION (°)	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	TOTAL
NORTH	54.7	70.2	60.0	54.9	83.1	68.7	81.7	473.3
NNE	20.3	40.2	21.9	24.9	39.9	13.7	36.2	197.1
NE	13.7	13.5	7.0	10.3	11.2	7.8	17.8	81.3
ENE	13.0	7.8	6.7	8.3	5.8	5.7	10.7	58.0
E	7.0	6.0	8.2	7.0	5.3	1.0	9.2	43.7
ESE	9.0	5.5	7.2	3.5	1.8	0.8	3.7	31.5
SE	5.8	4.5	5.8	4.5	1.5	1.7	4.5	28.3
SSE	6.2	10	7.3	4.0	1.5	0.5	5.7	35.2
S	11.5	16	14.8	10.0	2.3	4.7	5.7	65.0
SSW	20.8	20.3	18.7	12.8	2.5	3.5	11.5	90.1
SW	35.5	18.5	17.3	20.5	1.8	4.8	13.3	111.7
WSW	63.0	41.4	42.2	40.4	13.8	12.2	28.2	241.2
W	85.4	83.9	87.4	75.2	43.5	42.7	54.2	472.3
WNW	136.3	136.6	162.5	146.4	126.1	143.9	118.4	970.2
NW	140.4	137.9	167.0	175.6	215.8	244.4	161.6	1242.7
NNW	121.6	107.1	110.4	121.9	188.3	188.3	158.0	995.6
TOTAL	744.2	719.4	744.4	720.2	744.2	744.4	720.4	5137.2

Further preliminary analysis of the internally binned wind data (i.e. wind data recorded on Wind Explorer's Display Pages) for the entire period of wind measurements on KNUST Site 0001 was done by applying the Stata program to generate further vertical bar and line charts. A bar graph depicting the monthly mean wind speeds over the seven-month period of wind measurements derived from Table 4.2 above is shown in Figure 4.8. Line graphs showing the general variations of monthly wind speeds and directions by way of hourly proportions of occurrence versus its corresponding wind speed or direction are also shown in Figure 4.9 and Figure 4.10 respectively. These graphs were respectively derived from Tables 4.3a and 4.3b above.

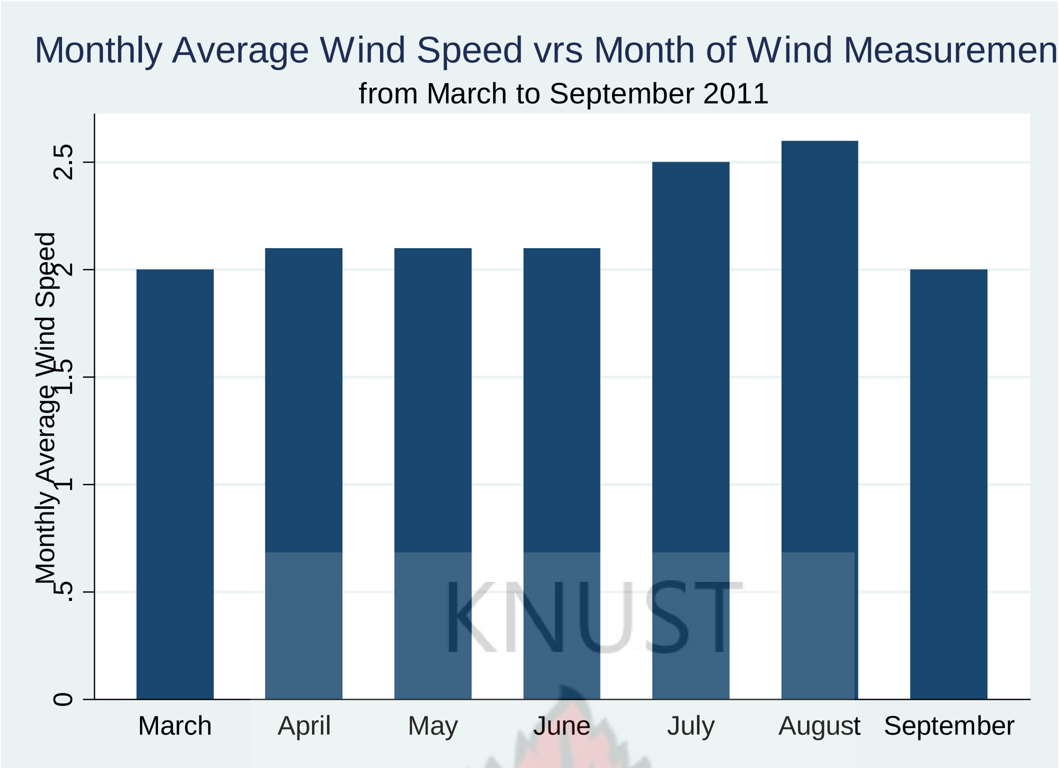

Figure 4.8: Mean Monthly Variations of Wind Speed at 20 m for Site 0001 at KNUST

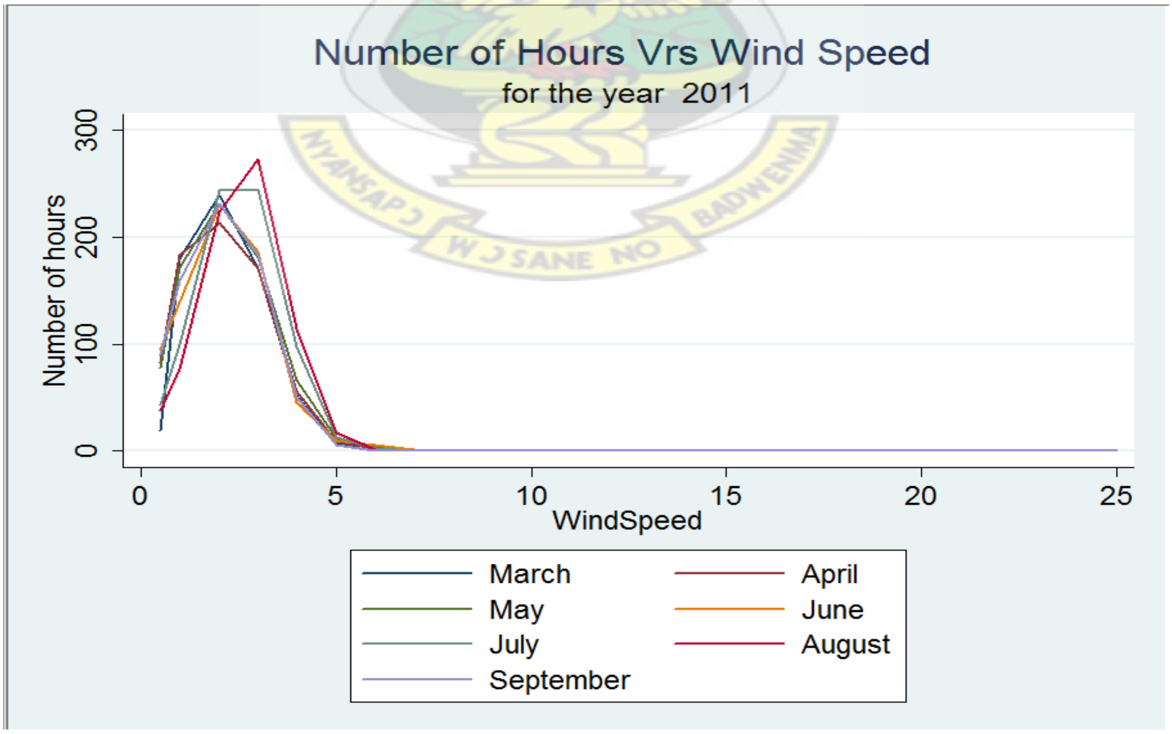

Figure 4.9: Graph of Number of Hours against Wind Speeds

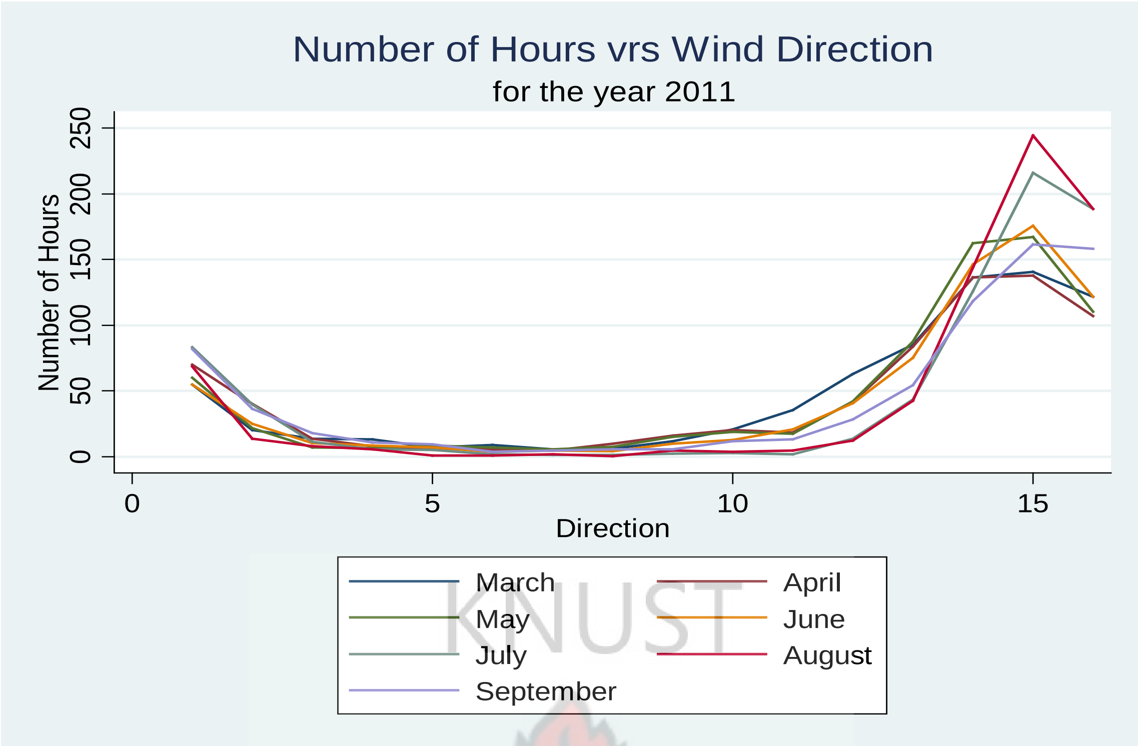

Figure 4.10: Graph of Number of Hours against Wind Directions

Shown on page 76 are Figures 4.11 and 4.12 which depict the total hourly frequency distributions of wind speed and wind direction respectively for the whole period of wind measurements in the form of bar graphs using again the data compiled in Tables 4.3a and 4.3b respectively.

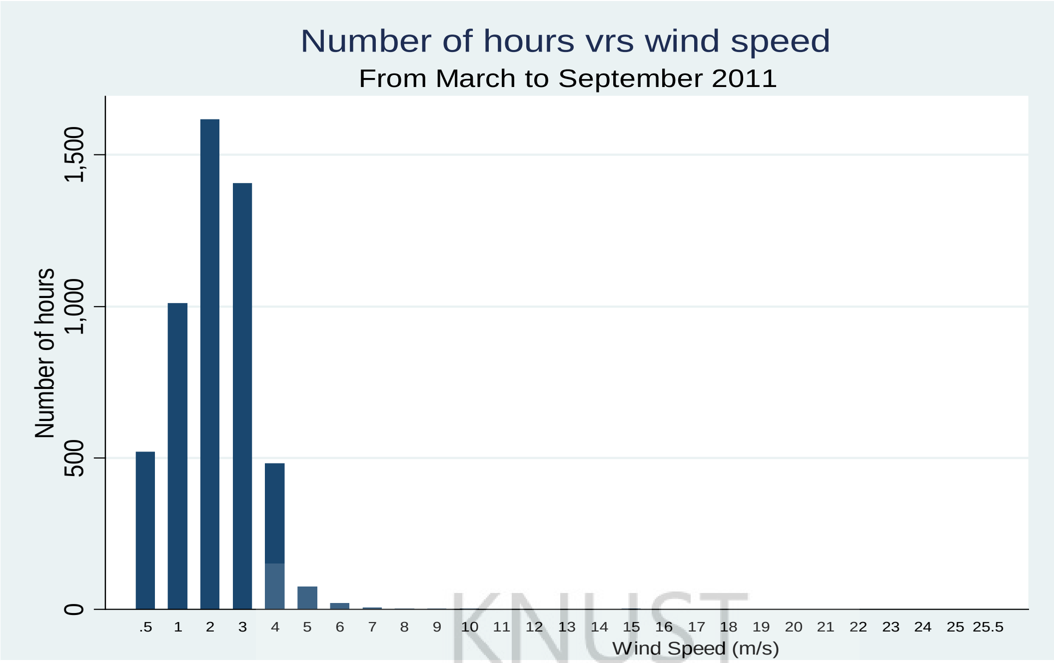

Figure 4.11: Hourly Frequency Distribution of Wind Speed for the entire Period of Wind Measurements (March 1 – September 30, 2011)

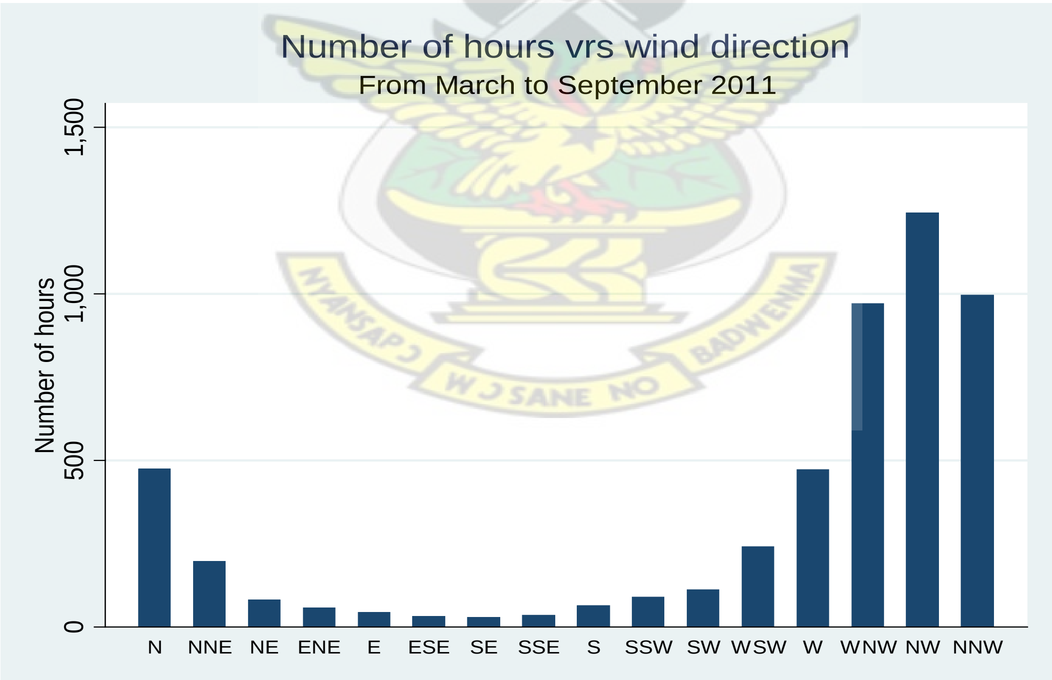

Figure 4.12: Hourly Frequency Distribution of Wind direction for the entire Period of Wind Measurement (March 1 – September 30, 2011)

4.4 MICROSOFT EXCEL SOFTWARE ANALYSIS OF WIND SPEED DISTRIBUTION FOR THE THIRD- QUARTER OF THE YEAR, 2011

At this juncture, this thesis begins to consider the summary and analysis of the time-series wind data collected on the DataPlug (described as non-volatile data since the Wind Explorer's DataPlug does not lose it from its memory when there is power failure). This time-series wind data (wind speed and direction) used for this thesis covered a period of three months (July, 2011- September, 2011) as already mentioned in the scope of work. The time-series wind data can be described as actual wind data since its graph or plot shows how the wind data observed at a site varies continuously over a given time interval in steps of a prescribed sampling frequency or average time. A time-series graph of any characteristic simply shows the variations of the given quantity with respect to a given time stamp. Basically, it is a graph of a series of values for a given quantity against series of unit intervals which aggregate to the total time interval. It shows the trend and variability of a quantity with respect to time.

The Microsoft Excel Program was used to analyze the time-series wind data of KNUST Site 0001 after the DataPlug via a data reader and a data retrieving Software all manufactured by NRG Systems Inc. converted the raw data held on the DataPlug into an ASCII file which was finally changed to a note pad text file. Figures 4.13 and 4.14 shown on pages 78 and 79 respectively depict Monthly variations of hourly mean wind speed and monthly variations of diurnal or daily mean wind speed respectively. A glance at figure 4.13 reveals that the wind speeds of KNUST Site 0001 are generally higher during the day and not at night. It was also observed that the highest wind speed which occurred between the hours, 0:00 and 7: 00 was recorded in August at about 3:30 A.M. and the least in September. However, the highest wind speed between the hours, 7:00 and 20:00 was recorded in July at about 11:00 A.M. while the least was registered in September. This highest wind speed recorded between the hours of 7: 00 and 20: 00 happened to be the overall highest wind speed to be recorded during the three continuous months for time-series wind data collection. Between the hours of 20: 00 and 24: 00, the highest night wind speed also occurred in August at about 23: 00 with the least occurring in September. A similar glance at figure 4.10 shows that the highest monthly variation of daily mean speed occurred on the 13th day of August and the least occurring on the 27th day of September. On the whole the best monthly daily average wind speed was recorded in August and the least in September as indicated by Figure 4.14.

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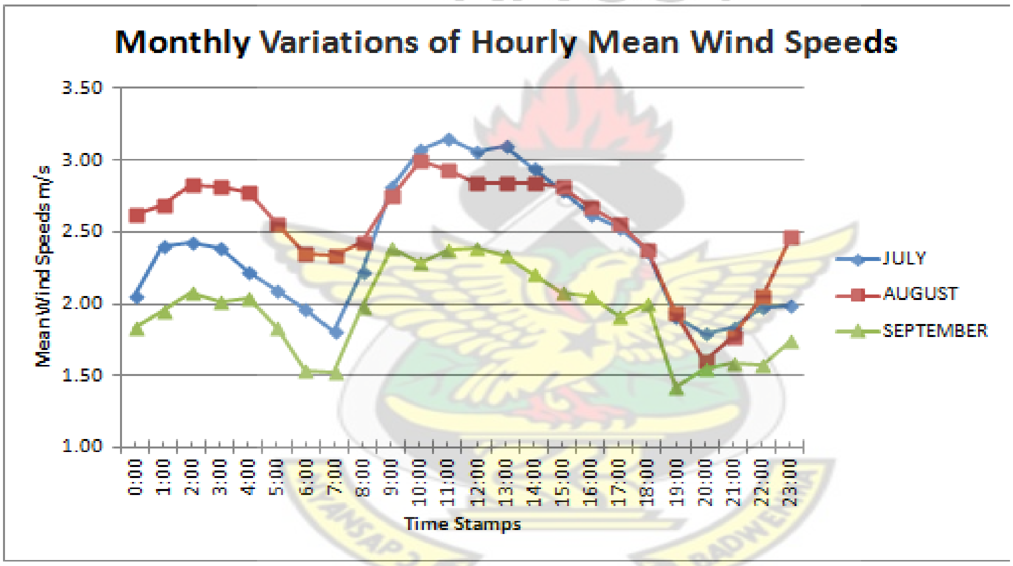

Figure 4.13: Monthly Variations of Hourly Mean Wind Speed

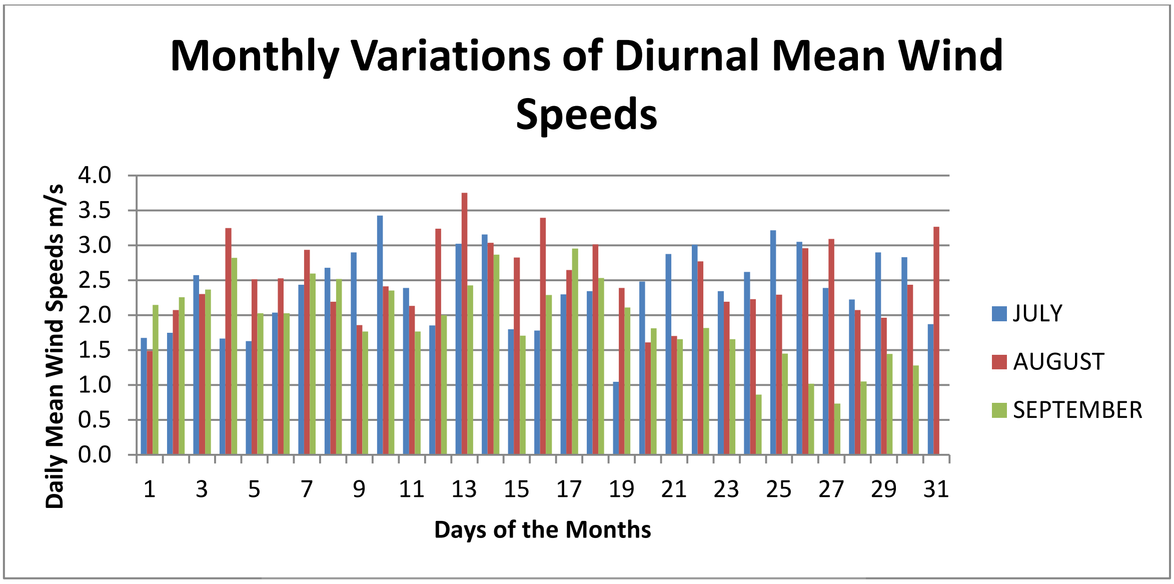

Figure 4.14: Monthly Variations of Daily Mean Wind Speed

4.5 WAsP SOFWARE ANALYSIS OF WIND SPEED AND DIRECTION DISTRIBUTIONS FOR THE THIRD-QUARTER OF THE YEAR, 2011

A note pad text file version of the time-series wind data was initially pre-processed, filtered and validated by the protocol editor of WAsP and subsequently used for detailed analysis by a subsidiary program of WAsP known as the Observed Mean Wind Climate (OMWC) which generated results from which Tables 4.4 and 4.5 were extracted. Table 4.4 and 4.5 are manually constructed summary tables of the calculated values generated by the Wind Climate Analyst.

In addition, the Wind Climate Analyst program was used to create time-series graphs for average wind directions and average wind speeds collected at site 0001 at KNUST from July1 to September 30, 2011 as shown in Figure 4.15.

Figure 4.16 as shown on page 82 also depicts the wind rose or the frequency rose of Site 0001 for the same duration of wind measurements as mentioned above.

The wind data sets collected at Site 0001 were treated as statistical and reliability life data because of its variability. Wind as air in motion was regarded as the life time of air while calm or still air was considered as the death of air or failure of air to move. Air moves with varying speeds and thus can or cannot be harnessed to perform certain functions depending on its speed or intensity. Thus it was imperative for this thesis to look at the proportions of the time the wind as a variable atmospheric element blows at given wind speeds at Site 0001 at KNUST using the time-series wind data. As a result, a reliability life mathematical tool called the Weibull distribution curve was employed to provide a good fit to the observed wind climate of Site 0001 in order to determine the distribution of the wind speed at this site over the three continuous months in which time series data was recorded. The WAsP Weibull tool which was employed in this project to perform the above-mentioned task is shown in Figure 4.17 on page 82. By extension the Weibull distribution curve is a mathematical tool employed to determine the probability of obtaining each of the wind speed or greater wind speeds found in the wind speed bin of the wind data logger over a specified period of time and in this case the period for recording the time-series data (three months).

Table 4.4: WAsP All- Sectors Statistics

	WEIBULL-A (m/s)	WEIBULL-k	MEAN SPEED (m/s)	POWER DENSITY (W/m^2)
SOURCE DATA (13105)	-	-	2.31	13
FITTED	2.7	2.66	2.42	13
EMERGENT	-	-	2.37	13
COMBINED	2.7	2.44	2.37	13

Table 4.5: Summary of Wind Data Generated by Wind Climate Analyst

Number of Data Counts	13406
Count of Calms (Speeds below 0)	698 (5.33 %)
Valid Wind Speed Readings Accepted	13105 (97.75 %)
Accepted Values of Wind Speeds	0 – 7.70 m/s
Valid Wind Direction Readings Accepted	13105 (97.75 %)
Accepted Values of Wind Directions	0 - 338°
Weibull A / Weibull K	2.7 m/s / 2.44 m
Air Density	1.2 kg/m^3
Mean Speed (moment # 1)	2.394284 m/s
Median Speed	2.323423 m/s
Maximum Frequency	0.3669082
Speed of Maximum Frequency	2.175205 m/s
Speed of Maximum Power Density	3.450778
Variance	1.096337 m/s
Maximum Power Density	5.14159 W/m^2
Total Power Density	13.22603 W/m^2

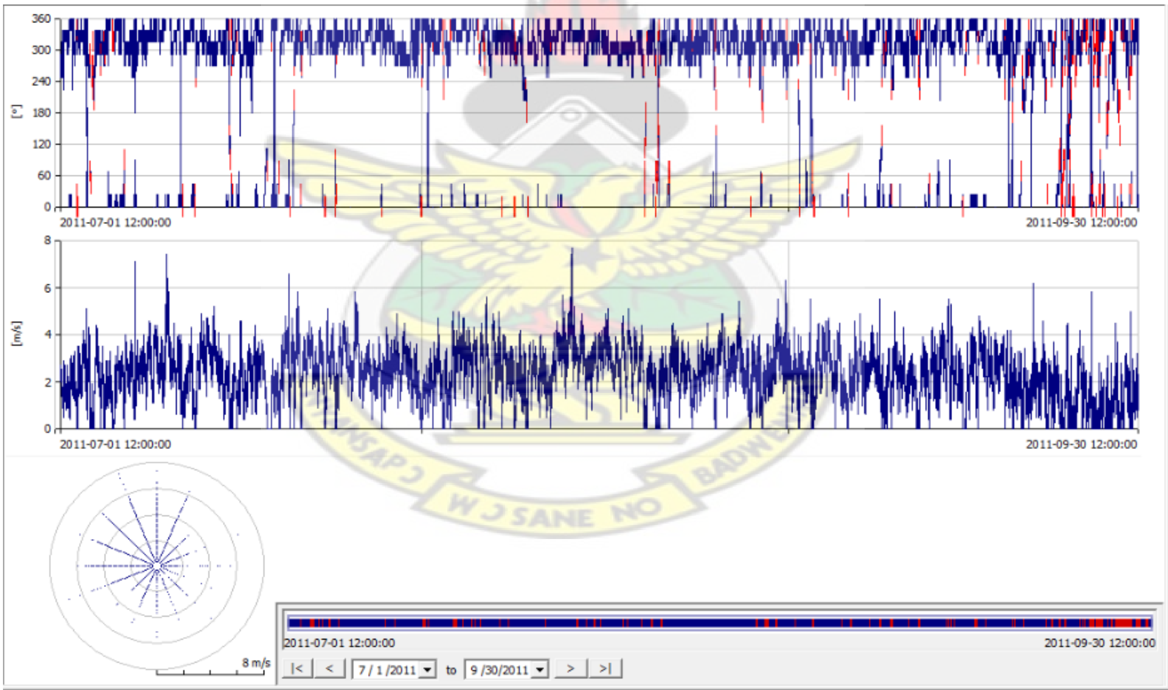

Figure 4.15: Time Series Graph of Wind Direction and Wind Speed

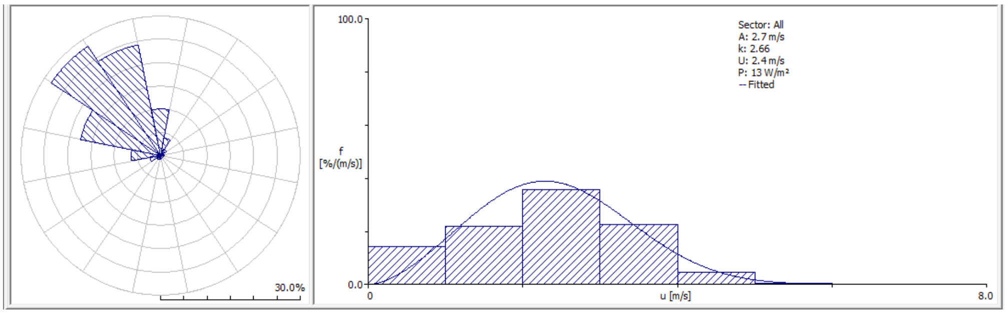

Figure 4.16: Wind Rose and Wind Speed Distribution for July 2011 to September 2011

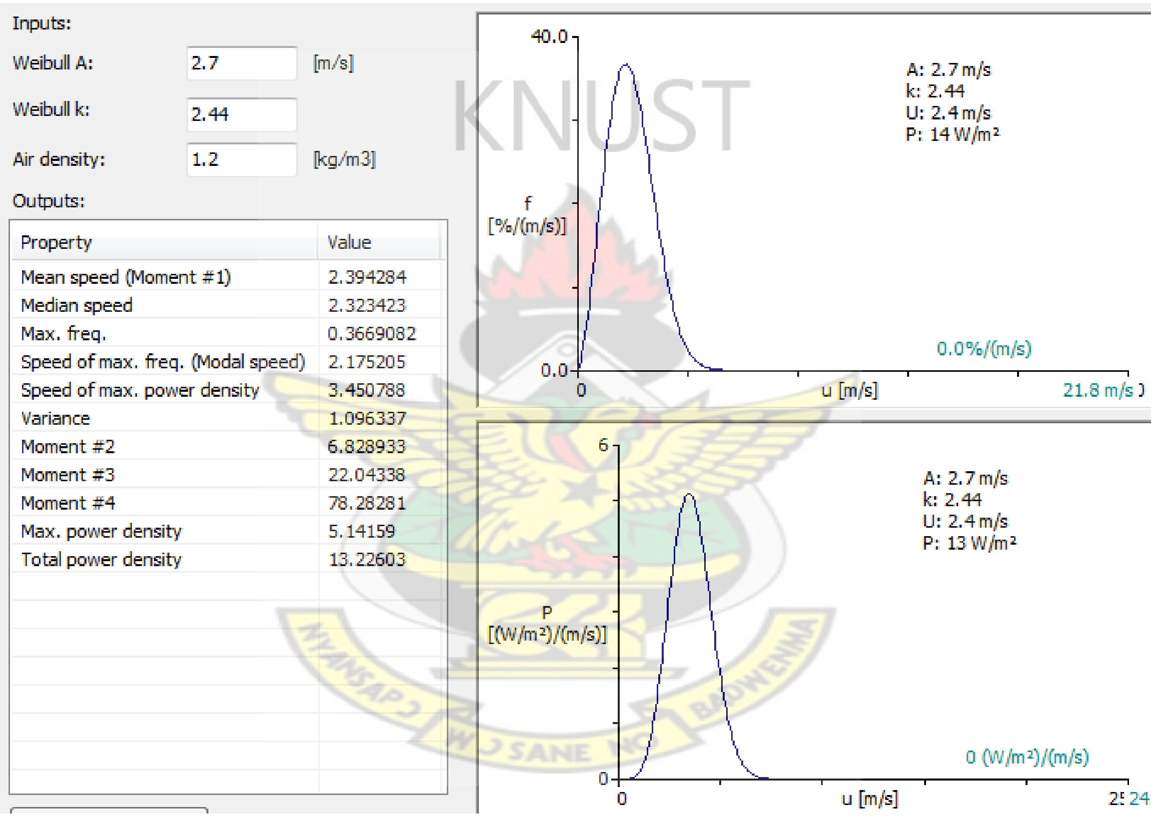

Figure 4.17: WAsP Weibull Distribution Curve for Wind Speeds from July1 to September 30, 2011 for Site 0001, KNUST

4.6 COMPARISON OF MEASURED WIND SPEEDS WITH OTHER SOURCES OF WIND SPEEDS.

RETScreen has developed several clean energy project analysis tools to support decision making on both the technical and economic viability of renewable energy technology projects. One of these clean energy project analysis tools is the wind power technology decision tool. In this vein, monthly average wind speeds taken at the standard meteorological height of 10 m for Kumasi by RETScreen and made available in the Wind power technology section of the RETScreen Software were adopted by this thesis for comparison purposes. Another comparable source of wind speed adopted for further comparison with the observed wind speeds at KNUST Site 0001 is the 2011 monthly average wind speeds for Kumasi recorded or obtained by Weather Underground Inc. Before the wind speed data collected at KNUST Site 0001 is compared with any of the secondary sources of wind speeds for Kumasi, the wind speeds from the two secondary sources are compared as shown in Table 4.6 below. Another preliminary comparative analysis is done for the directly measured monthly average wind speeds at KNUST Site 0001 and the Weather Underground Inc. 2011 monthly average wind speeds for Kumasi by tabulating the monthly average wind speeds for these two wind data sources in a five column table as shown in Table 4.7 on page 85. The height at which the Weather Underground monthly average wind speeds were recorded was not specified on the Weather Underground Inc web page which displayed the atmospheric or climatic conditions of Kumasi for the year, 2011. Hence it is conventionally assumed that the climatic conditions of Kumasi as reported by Weather Underground Inc. were measured at the standard meteorological height of 10 m. In order to establish a justifiable basis for comparing the directly measured wind speeds at 20 m at KNUST Site 0001 and any of the secondary sources of wind data, the wind speeds of the secondary sources are vertically extrapolated from 10 m to 20 m. This is done to have the wind measurements from the Primary source and the Secondary sources normalized or referenced to a common height to justify their comparisons (In this case 20 m agl, the height at which wind data for KNUST Site 0001 was measured). The vertical extrapolations in this section of the thesis were done by applying the 1/7 power law to obtain extrapolated wind speeds at 20 m.

Following Table 4.7 is Table 4.8 which shows the RETScreen obtained monthly average wind speeds at 10 m, extrapolated RETScreen monthly average wind speeds from 10 m to 20 and the observed monthly average wind speeds at 20 m for KNUST Site 0001. In both Table 4.7 and Table 4.8, the directly measured wind speeds at KNUST Site 0001 are considered as the reference or true values for the determination of the percentage error values. The percentage error signifies the percentage difference between the directly observed wind speeds at Site 0001 and the extrapolated wind speeds derived from the secondary sources of wind speeds. Furthermore, this thesis has extrapolated each of the directly measured monthly average wind speeds at 20 m up to a height of 50 m in steps of 10 m. The observed monthly average wind speeds and their corresponding extrapolated wind speeds at the various heights (30 m to 50 m) are presented in Table 4.9. This table was manually generated using the 1/7 Power Law.

Table 4.6: Comparison of RETScreen Historical Monthly Average Wind Speed for Kumasi and Weather Underground Inc. 2011 Monthly Average Wind Speeds for Kumasi

MONTH	RETScreen HISTORICAL WIND SPEED AT 10 m FOR KUMASI (m/s)	WEATHER UNDERGROUND INC. WIND SPEED AT 10 m FOR 2011 FOR KUMASI (m/s)	ESTIMATED PERCENTAGE ERROR (%)
JANUARY	1.5	1.1	26.7
FEBRUARY	2.1	1.4	33.3
MARCH	2.1	1.7	19.0
APRIL	2.1	1.9	9.5
MAY	2.1	2.2	- 4.8
JUNE	2.1	1.9	19.0
JULY	2.6	1.9	26.9
AUGUST	2.1	2.2	-4.8
SEPTEMBER	2.1	1.9	9.5
OCTOBER	2.1	1.7	19.0
NOVEMBER	1.5	1.7	-13.3
DECEMBER	1.5	1.4	6.7
Annual Mean Wind Speed	23.9/12 = 1.9917 ≈ 2.0	21/12 = 1.7500 ≈ 1.8	12.13 ≈ 10.0

Table 4.7: Comparison of Weather Underground Inc. 2011 Monthly Average Wind Speeds for Kumasi and the Directly Observed Wind Speeds at KNUST Site 0001

Month /Year, 2011	Wind Speed, m/s (Measured by Weather Underground Inc. at 10 m)	Wind Speed, m/s (Weather Underground Inc. Obtained Wind Speeds Extrapolated from 10 m to 20 m)	Wind Speed , m/s (Directly Measured at KNUST Site 0001 at 20 m)	Estimated Percentage Error ,% (using Wind Speed at 20 m at KNUST Site 0001 as Reference)
JANUARY	1.1	1.2	N/A	N/A
FEBRUARY	1.4	1.5	N/A	N/A
MARCH	1.7	1.9	2.0	5.0
APRIL	1.9	2.1	2.1	0
MAY	2.2	2.4	2.1	-14.3
JUNE	1.9	2.1	2.1	0
JULY	1.9	2.1	2.5	16.0
AUGUST	2.2	2.4	2.6	7.7
SEPTEMBER	1.9	2.1	2.0	- 5.0
OCTOBER	1.7	1.9	N/A	N/A
NOVEMBER	1.5	1.7	N/A	N/A
DECEMBER	1.5	1.7	N/A	N/A

TABLE 4.8: Comparison of RETScreen Monthly Average Wind Speeds for Kumasi and the Directly Observed Wind Speeds at KNUST Site 0001

Month	Wind Speed, m/s (Measured by RETScreen at 10 m)	Wind Speed, m/s (RETScreen Obtained Wind Speed at 10 m Extrapolated to 20 m)	Wind Speed, m/s (Measured at KNUST Site 0001 at 20 m)	Estimated Percentage Error, % (Using Wind Speed at 20 m at KNUST Site 0001 as reference Value)
JANUARY	1.5	1.7	N/A	N/A
FEBRUARY	2.1	2.3	N/A	N/A
MARCH	2.1	2.3	2.0	-15.0
APRIL	2.1	2.3	2.1	-9.5
MAY	2.1	2.3	2.1	-9.5
JUNE	2.1	2.3	2.1	-9.5
JULY	2.5	2.9	2.5	-16.0
AUGUST	2.1	2.3	2.6	11.5
SEPTEMBER	2.1	2.3	2.0	-15.0
OCTOBER	2.1	2.3	N/A	N/A
NOVEMBER	1.5	1.7	N/A	N/A
DECEMBER	1.5	1.7	N/A	N/A

TABLE 4.9: Directly Measured Monthly Average Wind Speeds Extrapolated from 20 m up to 50 m

MONTH	DIRECTLY MEASURED WIND SPEED AT 20 m (m/s)	WIND SPEED EXTRAPOLATED FROM 20 m TO 30 m (m/s)	WIND SPEED EXTRAPOLATED FROM 20 m TO 40 m (m/s)	WIND SPEED EXTRAPOLATED FROM 20 m TO 50 m (m/s)
MARCH	2.0	2.1	2.2	2.3
APRIL	2.1	2.2	2.3	2.4
MAY	2.1	2.2	2.3	2.4
JUNE	2.1	2.2	2.3	2.4
JULY	2.5	2.6	2.8	2.9
AUGUST	2.6	2.8	2.9	3.0
SEPTEMBER	2.0	2.1	2.2	2.3

4.7 BASIC ESTIMATIONS AND POWER PERFORMANCE OF SELECTED WIND TURBINES

Though, wind data measurements carried out at the site under review covered a seven - month duration, the annual average wind speed for the site is estimated by this thesis.

To estimate the annual average wind speed of a wind recording site whose duration of measurement is less than one year, the idea of a simple correlation factor that relates to the wind speeds of the site whose annual average wind speed is to be estimated and similar wind speeds obtained from a different source is employed (**Iowa Education Centre, n.d**). The duration of measurement for the similar source of data should be one year and preferably it should be the same year within which the less than a year's wind speed data was measured. This implies that the measurement of the wind speeds for the two sources of wind data (say Primary and Secondary sources) should be taken concurrently. Due to the significance of the annual average wind speed in wind energy assessment and power performance of wind turbines, this thesis employs the above idea to estimate the annual average wind speed of Site 0001 by using the seven-month wind speeds of Site 0001 and each of the above mentioned secondary sources of wind speeds to do the annual average wind speed estimation for Site 0001. Thus two different annual average wind speed estimate would be obtained for Site 0001 with one value each for each of the two secondary sources of wind data considered in section 4.6 for comparison with wind speeds of KNUST Site 0001. The following information and steps were used to arrive at the estimated annual average wind speed

Average monthly wind speed over the seven month duration of wind speed measurements at KNUST Site 0001 is 2.2 m/s.

Similarly, the average wind speed for the same seven month duration in the case of the Extrapolated RETScreen wind speeds at 20 meters is 2.4 m/s.

Using the relation,

Obtaining the correlation factor as 1, the estimated annual average wind speed for KNUST Site 0001 based on Weather Underground Inc. wind speed data is found to be 1.9 m/s.

This thesis also attempts to estimate the wind power densities of site 0001 at KNUST. It does this by utilizing the estimated annual mean wind speed of 2.0 m/s (to 1 d.p.) at 20 m for KNUST Site 0001. The vertically extrapolated value of this estimated annual mean wind speed to 50 m is 2.3 m/s (per 1/7 power law) and this value is used in a second case to determine the power density of KNUST Site 0001 for the year, 2011.

Assume standard air density of 1.225 kg/m^3 (constant value based on US standard atmosphere at sea level). Also use the universally adopted Weibull shape factor of 2 (Rayleigh distribution factor) and not K = 2.44 generated by the Wind Climate Analyst for Site 0001 on KNUST campus. This value of K generated by the Wind Climate Analyst was not used for the annual wind power density estimation because it only represents the wind distribution at KNUST Site 0001 for the third- quarter of the year (2011) and not for the whole year. Applying the formula:

WPD = ½

Corrected

ρ for Kumasi = 1.225

A Wind Velocity Calculator designed by Meteotest for Suisse Eole of Switzerland was used to generate values of unknown wind speeds at different heights by supplying the program with the following known parameters: the known height above ground, the wind speed and the roughness length. The roughness class and roughness length of the site under review were fixed by assuming that the type of land cover for Kumasi falls within the category of villages, small towns, agricultural land with many or tall sheltering hedges with a distance of approximately 250 m. This land cover type is assigned a roughness class of 3 which corresponds to a roughness length of 0.4 m by the European Wind Atlas classification table of landscape roughness. This Classification is also made available on a web page at the Windenergie-Daten der Schweiz (i.e. Swiss Wind Power Data Website) mandated by the Swiss Federal office of Energy. The above-assumed roughness length together with the annual average wind speed of 2 m/s (estimated value) and the measuring height of 20 m were enough to generate the wind velocity profile shown in Figure 4.18. The insertion of these inputs generated the velocity profile shown in Figure 4.18 and the wind shear table of values shown in Table 4.10. The calculated turbulence intensity for KNUST Site 0001 for the third-quarter of the year (2011) is found to be almost equal to the assumed roughness length of 0.4 used for the generation of the wind velocity profile by the Windenergie-Daten der Schweiz Velocity Profile Calculator.

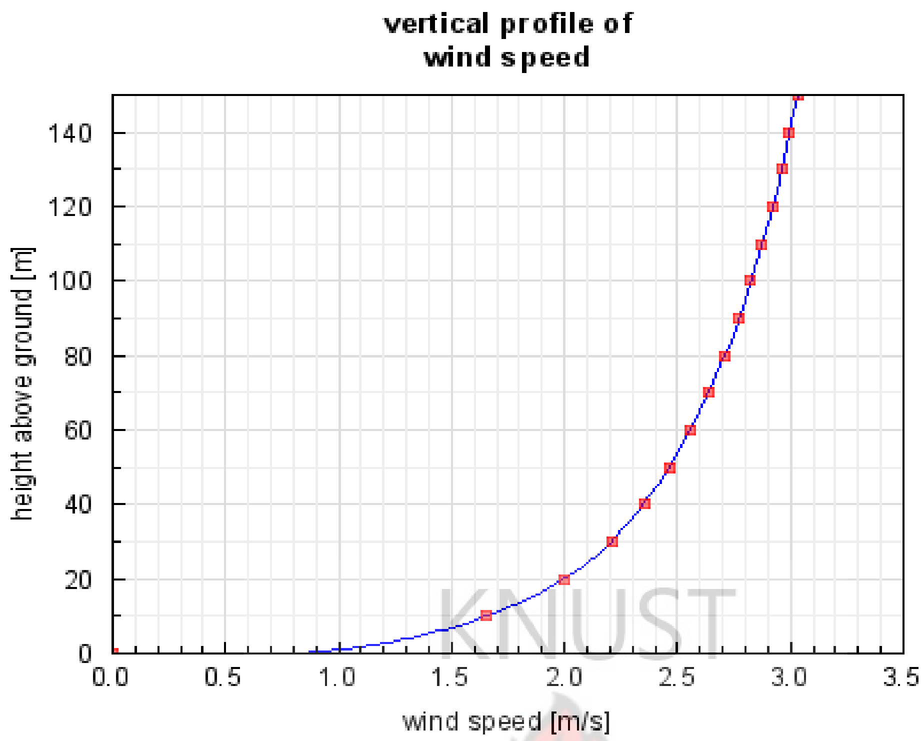

Figure 4.18: Wind Velocity Profile for Site 0001 based on annual mean speed of 2 m/s at 20 m (Generated by Windenergie-Daten der Schweiz Wind VelocityProfile Calculator)

Table 4.10: Wind speeds generated for respective heights by the wind speed calculator for Roughness class 3 and Length of 0.4 m with an Input of 2 m/s at 20 m

HEIGHT (m)	WIND SPEED (m/s)
150	3.03
140	2.99
130	2.96
120	2.92
110	2.87
100	2.82
90	2.77
80	2.71
70	2.64
60	2.56
50	2.47
40	2.35
30	2.21
20	2
10	1.65

The wind velocity profile as depicted in Figure 4.18 as well as Table 4.10 above show how the wind speed varies with height (wind shear). The trend of variation depicted by these visual representations generated some interest which warranted the construction of a table of values for vertically extrapolated wind speeds for the heights of 30 m up to 150 m based on the estimated annual average wind speed of 2 m/s for site 0001 at KNUST as well as the 1/7 power law. This table is shown as Table 4.11 below.

The manually extrapolated wind speeds provided by Table 4.11 when compared to their counterparts generated by the Wind Speed Profile Calculator revealed an average difference of 0.27 m/s between them (i.e. sum of differences divided by sample number or 3.51/13 ms^{-1}). In a way this is suggesting that the recording site used for this study and by extension Kumasi is characterized by a wind regime which cannot record a wind speed of over 4 m/s even at a height as high as 150 m in the absence of atmospheric disturbance or harsh weather conditions for a considerable length of time.

Table 4.11: Vertically Extrapolated Wind Speeds Based on Estimated Annual Average Wind Speed

Heights (m) for the extrapolation of the estimated annual mean wind speed of 2 m/s at 20 m	Extrapolated Wind Speeds (m/s) obtained from estimated annual mean wind speed of 2 m/s at 20m
150	2.67
140	2.64
130	2.61
120	2.58
110	2.55
100	2.52
90	2.48
80	2.44
70	2.39
60	2.34
50	2.28
40	2.21
30	2.12

4.7.2 ESTIMATION OF THE POWER OUTPUT FOR AVENTA (AV-7 kW) AND FUHRLANDER (FL 30.0 kW) WIND TURBINES SELECTED FROM THE LIBRARY OF AN INTERACTIVE MODEL POWER CALCULATOR

With the power of information technology (IT) and the desire of some people to share information and software application tools with others, access to an interactive power calculator was obtained on the internet at the Swiss Wind Power Data Website (http://www.wind-data.ch/tools/power calculator) to simply estimate the power output of a contemplated turbine for installation at the candidate wind site. This Power Calculator developed by Meteotest on behalf of Suisse Eole of Switzerland is user friendly and has six cells with three of them being selectable by two option buttons. The sixth and bottom cell may be described as a special cell since it is not an assignable cell like the others and may be described as an executable or result cell. A click on this cell produces the results of the Power Calculator.

The option buttons mentioned above are the Weibull Parameter and the Mean Wind Speed option buttons. The option buttons are activated for the estimation of the power output of a selected turbine from the wind turbine library or the database of the Power Calculator Model. The Weibull Parameter selection or option button activates the Weibull, A (scale factor) cell and/or the Weibull, K (shape factor) cell. One or both elements of the Weibull Parameter group may be assigned for the estimation of the power production of a selected turbine at a candidate site. The cells that are activated by the two option buttons may be described as the principal cells. The other cells seen on the interface of this Power Calculator model are the Air Density cell and the Type of Turbine cell (this cell is a pull-down menu). These two cells can be described as supplementary or supporting cells since they are just required to provide detailed and turbine-specific information for the estimation of the power performance of the contemplated wind turbine and are not “selectable”. The activation of either the Weibull Parameter or the Mean Wind Speed option button by a user of the Power Calculator deactivates the other principal parameter as a decision on the kind of parameter a user of the model wishes to use to estimate the power production for a selected turbine at a candidate wind site. The beauty of this model under discussion is that the activation of any one of the option buttons produces results including a value or values of the unassigned principal parameter. In a case where the activated button is the Mean wind Speed, befitting values of Weibull A and K (inactivated Weibull Parameters) will be generated to characterize the Weibull distribution which in turn helps in the calculation of the wind power output of a selected turbine on a candidate site with a known air density specified in the Air Density cell. Similarly, in a case where the inactivated option button is the Mean Wind Speed then the Power Calculator will generate the required mean wind speed, v to characterize the power production of a selected turbine to be installed on a candidate site with a known air density. Both the user assigned parameters and the model generated values (unassigned values) are always respectively supplied and generated within prescribed upper limits. A parameter is said to be user assigned in the case of the principal parameters when its option button is activated or selected after its value (in the case of the mean wind speed parameter) or values (in the case of the Weibull parameter) have been entered into its cell(s). The supporting parameters are said to be assigned when their required values are entered into their cells. The supporting parameters have cells which are not “selectable”.

This thesis estimated the power output at KNUST Site 0001 for two small-scale wind turbines selected from the turbine library of the Power calculator. These turbines are contemplated to be installed on KNUST Site 0001 to utilize the wind energy resource at the site.

The Weibull K and the air density,

With the above supplied input parameters, the power produced by the wind turbines, Aventa AV-7(6.75 kW) and Fuhrlander FL 30 (30 kW) according to the Power Calculator are presented in Tables 4.13 and 4.15 respectively. In fact the actual power calculations by the Power calculator take place within the model's internal algorithm and the results are made visible to the user as shown in Tables 4.13 and 4.15. In calculating the power output of selected turbine types, 100 % availability is assumed by the Power Calculator Model. A little more familiarization with this Power Calculator model revealed that the lower limit value of wind speed, v and the Weibull scale factor, A, are 0.9 m/s and 1 m/s respectively. In addition the upper limit value for both the wind speed, v and the Weibull, A is 20 m/s for all the types of turbines made available in the database of the Power Calculator though the highest wind speed value inside the power curve of most of the turbines including those selected for the power performance assessment in this study was greater than 20 m/s. In other words, the power calculator executes its function or runs per instructions or commands without resorting to outputs based on default values only when the activated Wind Speed or the Weibull Parameters (A and/or K) range(s) from the lower limit to the upper limit. The Weibull scale parameter, A is a function of the wind speed, v. The power calculator adopted by this thesis had default values for both the principal and supporting parameters as follows:

Weibull scale parameter, A = 6 m/s, Weibull shape parameter, K = 2, Wind speed, v = 2 m/s and Air density, The low capacity factors generated by the Power Calculator as illustrated in Tables 4.13 and 4.15 may be attributed to the low wind speed at KNUST Site 0001 and the fact that the selected turbines were designed to operate effectively at an average wind speed of 5 m/s.

Table 4.12: TABULAR REPRESENTATION OF THE POWER CURVE OF AVENTA AV-7 WIND TURBINE

WIND SPEED (m/s)	OUTPUT POWER (kW)
1	0
2	0.1
3	0.7
4	1.5
5	3.1
6	5.8
7	6.2
8	6.2
9	6.2
10	6.2
11	6.2
12	6.2
13	6.2
14	6.2
15 - 30	0

Table 4.13: Results of Aventa AV-7 given Annual Average Wind Speed of 2 m/s, K = 2 and Generated A = 2.3 m/s for KNUST Site 0001

WIND CHARACTERISTICS AT KNUST SITE 0001 (Estimated by Thesis)	Annual average wind speed = 2 m/s, Weibull, K = 2
WEIBULL, A GENERATED BY POWER CALCULATOR	Weibull , A = 2.3 m/s
TURBINE MANUFACTURER	AVENTA
TYPE	AV-7
CAPACITY	7 kW
ROTOR DIAMETER	12.9 m
POWER PRODUCTION	3002 kWh/year
CAPACITY FACTOR	5.3 %
FULL LOAD HOURS	462 hours/year
OPERATING HOURS	5632 hours/year

Table 4.14: TABULAR REPRESENTATION OF THE POWER CURVE OF FUHRLANDER, FL 30 WIND TURBINE

WIND SPEED (m/s)	OUTPUT POWER (kW)
1	0
2	0
3	0
4	0.4
5	3.19
6	6.92
7	11.33
8	15.70
9	19.54
10	22.70
11	25.19
12	26.97
13	28.25
14	29.14
15	29.57
16	29.78
17	29.93
18	30.00
19	30.02
20	29.95
21	29.79
22	29.54
23	29.26
24	29.00
25	28.77
26 - 30	0

Table 4.15: Results of Fuhrlander FL 30 (30 kW) given Annual Average Wind Speed of 2 m/s, K = 2 and generated A = 2.3 for KNUST Site 0001

WIND CHARACTERISTICS AT KNUST SITE 0001 (Estimated by Thesis)	Annual average wind speed = 2 m/s, Weibull, K = 2
WEIBULL, A GENERATED BY POWER CALCULATOR	Weibull , A = 2.3 m/s
TURBINE MANUFACTURER	FUHRLANDER
TYPE	FL 30
CAPACITY	30 kW
ROTOR DIAMETER	13 m
POWER PRODUCTION	854 kWh/year
CAPACITY FACTOR	0.3 %
FULL LOAD HOURS	28 hours/year
OPERATING HOURS	791 hours/year

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This research work designed, built and installed a wind monitoring system at a selected site on KNUST Campus. Measurements were taken at a height of 20 m. Apart from the comprehensive wind climate data obtained for Site 0001 at KNUST over the 7-month period of wind measurements and the useful calculations presented in this work, this thesis actually exhibits good quality summary of wind data using NRG Wind Explorer and its accompanying wind sensors (# 40 maximum cup anemometer and # 200P vane) for wind resource assessment.

A wind velocity profile of the wind recording site was also generated using a Wind Velocity Calculator developed by Meteotest of Switzerland. The calculated value of the turbulence intensity of the air flow and the Weibull shape factor, K for KNUST Site 0001 was 0.4 and 2.44 respectively. The calculation of the turbulence intensity and the Weibull shape factor was based on the time-series wind data. Data was captured from the recording site in the form of time- series graphs, histogram plot, total hourly variations of wind speed and wind direction (for the seven-month period of wind measurement) in the form of bar and line charts. The patterns of both the monthly wind speed and direction histograms (or bars) were similar for the respective months covered in the period of wind measurement. However, these wind data varied from month to month by way of frequency of occurrences.

Raw wind data stored on the DataPlug in the binary format was read by the DataPlug Reader and retrieved to a window desktop computer through the NRG Data Retriever Software and a serial port cable. An output file in the form of an ASCII text file was converted to a notepad text file and exported to the WAsP Wind Climate Analyst program for analysis. The ASCII text file was also exported to Microsoft Excel for analysis. The results from these analyses have been presented in this thesis mainly as graphical representations. Similarly, the internally binned wind data was equally taken care of by the Stata Software. Notwithstanding the poor wind potential of the site used for this thesis, a better site possibly one that is in the open field and well exposed to the wind would yield a better result.

5.2 RECOMMENDATIONS

It is recommended that ancillary sensors such as barometers, temperature probes and hygrometers should be used in conjunction with the two principal wind sensors (anemometer and wind vane) used for this research work to provide greater certainty of the wind energy potential of future wind measurement sites. This will also provide detailed description of the state of the wind at the site at any given time.

The velocity profile for the site presupposes that the measurement of wind speeds at the selected site even if carried out at a height of 150 m cannot yield an annual average wind speed greater than 4 m/s if there is no occurrence of severe storm or atmospheric disturbance for a considerable length of time. This inference should be further investigated to establish its validity.

Considering the relative obstructive nature of the site used for the study it is being recommended that a more credible and suitable site should be acquired to undertake extensive research into wind energy technologies by The Energy Center- KNUST.

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APPENDIX A: SITE PICTURES

WIND MONITORING SYSTEM OF SITE 0001 On KNUST CAMPUS

ATTACHMENT OF SHELTERED DATA LOGGER TO COMMUNICATION TOWER

Satellite Dish at Wind Monitoring Site 0001 on KNUST CAMPUS

PARTIAL VIEW OF HYBRID WIND MAST AT SITE 0001 ON KNUST CAMPUS

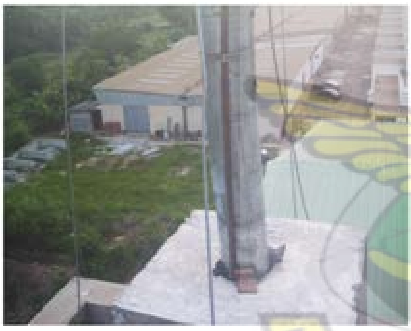
Hose clamp secures Earth rod

Foundation Space of Meteorological Tower

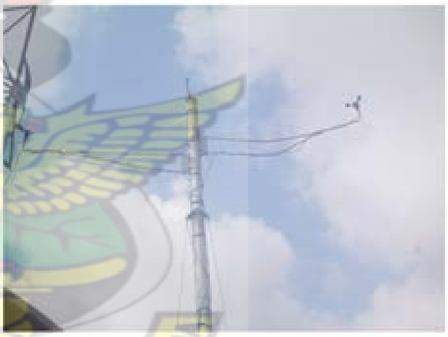
Relative Positions of Telecommunication Tower and Satellite Dish

AERIAL VIEW

ATTACHMENT OF EARTH ROD TO THE MAST



RELATIVE POSITIONS OF INFRASTRUCTURE ON SITE



Front View of NRG Wind Explorer with Accessories

GROUND POINT

GUY WIRE REELS

Enclosed Wind Explorer Data Logger

WORKING TOOLS

DATAPLUG AND SERIAL PORT CABLE

APPENDIX B: FREQUENCY DISTRIBUTION TABLES OF WIND SPEED AND DIRECTION

Table B-1: Frequency Distribution of Wind speed and Direction for March, 2011 at KNUST Site 0001

Wind Explorer Monthly Log Sheet

Month	MARCH	Year	2011
Monthly Average	2.0 m/s		
Gust Speed	19.1 m/s		
Gust Direction	177°		
Gust Time	21.19 pm.		
Gust Date	12 March, 2011		

Frequency Distribution of Wind Speed		
Speed	Hours	%Time
< 0.5 m/s	91.1	12
1 m/s	179.6	24
2 m/s	239.4	32
3 m/s	170.0	23
4 m/s	51.4	7
5 m/s	7	1
6 m/s	3.7	0
7 m/s	1.3	0
8 m/s	0.7	0
9 m/s	0.2	0
10 m/s	0	0
11 m/s	0.2	0
12 m/s	0	0
13 m/s	0	0
14 m/s	0	0
15 m/s	0	0
16 m/s	0	0
17 m/s	0	0
18 m/s	0	0
19 m/s	0	0
20 m/s	0	0
21 m/s	0	0
22 m/s	0	0
23 m/s	0	0
24 m/s	0	0
25 m/s	0	0
>25 m/s	0	0

Frequency Distribution of Wind Direction		
Direction	Hours	%Time
North	54.7	7
NNE	20.3	3
Northeast	13.7	2
ENE	13.0	2
East	7.0	1
ESE	9.0	1
Southeast	5.8	1
SSE	6.2	1
South	11.5	2
SSW	20.8	3
Southwest	35.5	5
WSW	63.0	8
West	85.4	12
WNW	136.3	18
Northwest	140.4	19
NNW	121.6	16

Table B-2: Frequency Distribution of Wind Speed and Direction for April, 2011 at KNUST Site 0001

Wind Explorer Monthly Log Sheet

Month	APRIL	Year	2011
Monthly Average	2.1 m/s		
Gust Speed	24.9 m/s		
Gust Direction	200°		
Gust Time	18.21 pm.		
Gust Date	17 April, 2011		

Frequency Distribution of Wind Speed

Speed	Hours	%Time
< 0.5 m/s	83.4	12
1 m/s	183.5	26
2 m/s	213.7	30
3 m/s	170.5	24
4 m/s	55.9	8
5 m/s	9	1
6 m/s	2.2	0
7 m/s	1.0	0
8 m/s	0.7	0
9 m/s	0.3	0
10 m/s	0.2	0
11 m/s	0	0
12 m/s	0	0
13 m/s	0	0
14 m/s	0	0
15 m/s	0.2	0
16 m/s	0	0
17 m/s	0	0
18 m/s	0	0
19 m/s	0	0
20 m/s	0	0
21 m/s	0	0
22 m/s	0	0
23 m/s	0	0
24 m/s	0	0
25 m/s	0	0
>25 m/s	0	0

Frequency Distribution of Wind Direction

Direction	Hours	%Time
North	70.2	10
NNE	40.2	6
Northeast	13.5	2
ENE	7.8	1
East	6.0	1
ESE	5.5	1
Southeast	4.5	1
SSE	10.0	1
South	16.0	2
SSW	20.3	3
Southwest	18.5	3
WSW	41.4	6
West	83.9	12
WNW	136.6	19
Northwest	137.9	19
NNW	107.1	15

Table B-3: Frequency Distribution of Wind Speed and Direction for May, 2011 at KNUST Site 0001

Wind Explorer Monthly Log Sheet

Month	MAY	Year	2011
Monthly Average	2.1 m/s		
Gust Speed	15.3 m/s		
Gust Direction	190°		

Frequency Distribution of Wind Speed

Speed	Hours	%Time
< 0.5 m/s	77.4	10
1 m/s	172.0	23
2 m/s	230.8	31
3 m/s	180.6	24
4 m/s	65.9	9
5 m/s	12.5	2
6 m/s	4.2	1
7 m/s	0.7	0
8 m/s	0.3	0
9 m/s	0	0
10 m/s	0	0
11 m/s	0	0
12 m/s	0	0
13 m/s	0	0
14 m/s	0	0
15 m/s	0	0
16 m/s	0	0
17 m/s	0	0
18 m/s	0	0
19 m/s	0	0
20 m/s	0	0
21 m/s	0	0
22 m/s	0	0
23 m/s	0	0
24 m/s	0	0
25 m/s	0	0
>25 m/s	0	0

Direction	Hours	%Time
North	60.0	8
NNE	21.9	3
Northeast	7.0	1
ENE	6.7	1
East	8.2	1
ESE	7.2	1
Southeast	5.8	1
SSE	7.3	1
South	14.8	2
SSW	18.7	3
Southwest	17.3	2
WSW	42.2	6
West	87.4	12
WNW	162.5	22
Northwest	167.0	23
NNW	110.4	15

Table B-4: Frequency Distribution of Wind Speed and Direction for June, 2011 at KNUST Site 0001

Wind Explorer Monthly Log Sheet

Month	JUNE	Year	2011
Monthly Average	2.1 m/s		
Gust Speed	18.4 m/s		
Gust Direction	156°		

Frequency Distribution of Wind Speed

Speed	Hours	%Time
< 0.5 m/s	95.7	13
1 m/s	138.9	19
2 m/s	236.4	33
3 m/s	185.6	26
4 m/s	45.5	6
5 m/s	10.2	1
6 m/s	5.5	1
7 m/s	1.7	0
8 m/s	0.3	0
9 m/s	0.5	0
10 m/s	0	0
11 m/s	0	0
12 m/s	0	0
13 m/s	0	0
14 m/s	0	0
15 m/s	0	0
16 m/s	0	0
17 m/s	0	0
18 m/s	0	0
19 m/s	0	0
20 m/s	0	0
21 m/s	0	0
22 m/s	0	0
23 m/s	0	0
24 m/s	0	0
25 m/s	0	0
>25 m/s	0	0

Frequency Distribution of Wind Direction

Direction	Hours	%Time
North	54.9	8
NNE	24.9	3
Northeast	10.3	1
ENE	8.3	1
East	7	1
ESE	3.5	0
Southeast	4.5	1
SSE	4.0	1
South	10.0	1
SSW	12.8	2
Southwest	20.5	3
WSW	40.4	6
West	75.2	10
WNW	146.4	20
Northwest	175.6	24
NNW	121.9	17

Table B-5: Frequency Distribution of Wind Speed and Direction for July, 2011 at KNUST Site 0001

Wind Explorer Monthly Log Sheet

Month	JULY	Year	2011
Monthly Average	2.5m/s		
Gust Speed	12.3 m/s		
Gust Direction	58°		

Frequency Distribution of Wind Speed		
Speed	Hours	%Time
< 0.5 m/s	43.4	6
1 m/s	99.1	13
2 m/s	243.4	33
3 m/s	245	33
4 m/s	97.6	13
5 m/s	13	2
6 m/s	2.3	0
7 m/s	0.7	0
8 m/s	0	0
9 m/s	0	0
10 m/s	0	0
11 m/s	0	0
12 m/s	0	0
13 m/s	0	0
14 m/s	0	0
15 m/s	0	0
16 m/s	0	0
17 m/s	0	0
18 m/s	0	0
19 m/s	0	0
20 m/s	0	0
21 m/s	0	0
22 m/s	0	0
23 m/s	0	0
24 m/s	0	0
25 m/s	0	0
>25 m/s	0	0

Frequency Distribution of Wind Direction		
Direction	Hours	%Time
North	83.1	11
NNE	39.9	5
Northeast	11.2	2
ENE	5.8	1
East	5.3	1
ESE	1.8	0
Southeast	1.5	0
SSE	1.5	0
South	2.3	0
SSW	2.5	0
Southwest	1.8	0
WSW	13.8	2
West	43.5	6
WNW	126.1	17
Northwest	215.8	29
NNW	188.3	25

Table B-6: Frequency Distribution of Wind Speed and Direction for August, 2011 at KNUST Site 0001

Wind Explorer Monthly Log Sheet

Month	AUGUST	Year	2011
Monthly Average	2.6 m/s		
Gust Speed	11.9 m/s		
Gust Direction	332°		

Frequency Distribution of Wind Speed

Speed	Hours	%Time
< 0.5 m/s	38.0	5
1 m/s	77.1	10
2 m/s	223.3	30
3 m/s	272.2	37
4 m/s	114.6	15
5 m/s	17.2	2
6 m/s	1.5	0
7 m/s	0.3	0
8 m/s	0.2	0
9 m/s	0	0
10 m/s	0	0
11 m/s	0	0
12 m/s	0	0
13 m/s	0	0
14 m/s	0	0
15 m/s	0	0
16 m/s	0	0
17 m/s	0	0
18 m/s	0	0
19 m/s	0	0
20 m/s	0	0
21 m/s	0	0
22 m/s	0	0
23 m/s	0	0
24 m/s	0	0
25 m/s	0	0
>25 m/s	0	0

Frequency Distribution of Wind Direction

Direction	Hours	%Time
North	68.7	9
NNE	13.7	2
Northeast	7.8	1
ENE	5.7	1
East	1.0	0
ESE	0.8	0
Southeast	1.7	0
SSE	0.5	0
South	4.7	1
SSW	3.5	0
Southwest	4.8	1
WSW	12.2	2
West	42.7	6
WNW	143.9	19
Northwest	244.4	33
NNW	188.3	25

Table B-7: Frequency Distribution of Wind Speed and Direction for September, 2011 at KNUST Site 0001

Wind Explorer Monthly Log Sheet

Month	SEPTEMBER	Year	2011
Monthly Average	2.0 m/s		
Gust Speed	13.8 m/s		
Gust Direction	96°		

Frequency Distribution of Wind Speed		
Speed	Hours	%Time
< 0.5 m/s	90.7	13
1 m/s	159.5	22
2 m/s	230.5	32
3 m/s	183.1	26
4 m/s	50.2	7
5 m/s	5.5	1
6 m/s	0.8	0
7 m/s	0	0
8 m/s	0	0
9 m/s	0	0
10 m/s	0	0
11 m/s	0	0
12 m/s	0	0
13 m/s	0	0
14 m/s	0	0
15 m/s	0	0
16 m/s	0	0
17 m/s	0	0
18 m/s	0	0
19 m/s	0	0
20 m/s	0	0
21 m/s	0	0
22 m/s	0	0
23 m/s	0	0
24 m/s	0	0
25 m/s	0	0
>25 m/s	0	0

Frequency Distribution of Wind Direction		
Direction	Hours	%Time
North	81.7	11
NNE	36.2	5
Northeast	17.8	2
ENE	10.7	1
East	9.2	1
ESE	3.7	1
Southeast	4.5	1
SSE	5.7	1
South	5.7	1
SSW	11.5	2
Southwest	13.3	2
WSW	28.2	4
West	54.2	8
WNW	118.4	16
Northwest	161.6	23
NNW	158.0	22

APPENDIX C: MATERIALS AND EQUIPMENT FOR PROJECT

CIVIL WORKS – CONCRETE FOUNDATION

i) 2

ix) Safety Razor Blade (for cutting electrical tape)

x) Electrical tape

xi) Charcoal

xii) Petroleum jelly

DATA MONITORING & ACQUISITION EQUIPMENT/ ACCESSORIES

Most of these equipment are manufactured and supplied by NRG Systems Inc. of USA and they are listed as follows;

i) One # 40 maximum Anemometer

ii) One # 200P Wind direction vane

iii) One NRG Wind Explorer data logger

iv) Two data plugs

v) One data reader and matching serial port cable

vi) 2 (9 V) alkaline dry cell batteries

vii) Silica gel

viii) 8 m anemometer cable

ix) 1.5m wind vane cable

x) One NRG software retrieving CD

xi) WAsP Software (Not Supplied)

xii) Desk-top computer

xiii) Two side booms (already assembled for mounting sensors)

xiv) Shelter box (locally manufactured)

xv) One lightning spike

xvi) Two copper rods and

xvii) Copper grounding wire (locally procured)

xviii) One 19 feet (5.8 m) long galvanized steel tube.

xix) Guy Rings and wire- rope clamps.

FUNCTIONS OF EQUIPMENT

(i) TUBE: to build mast or tower

(ii) SIDE BOOM: to hold anemometer and wind vane

(iii) GUY- WIRE: to provide additional support for the tower and prevent it from toppling over.

(iv) EARTH/ GROUNDING ROD: to protect the measuring instrument and mast from lightning or electrical surges.

(v) HOSE CLAMPS: to secure the side booms, the shelter box and the earth rods or grounding spike on the mast.

(vi) ANEMOMETER: to measure wind speed. The NRG # 40 maximum anemometer is a 3-cup anemometer.

(vii) WIND DATA LOGGER: to record wind measurements over the measurement period. It does this by collecting data from wind data sensors such as an anemometer and a wind vane.

(viii) WIND DATAPLUG: to record time-series wind data

(ix) DATA RETRIEVER SOFTWARE: to decode and transfer raw data from the DataPlug to a Windows PC in the form of a text file with the aid of a data reader and a serial cable. It combines the raw data with a site file to produce a raw file.

(x) DATAPLUG READER: to read the data stored on a DataPlug to Windows personal computer (PC).

(xi) WAsP SOFTWARE: to predict the wind climate and to estimate the energy potential of the wind resource of an area.

(xii) COMPUTER: communicates with the data reader, provides the system with analysis capabilities and displays the output.

APPENDIX D: SOME OUTPUTS OF WAsP WIND CLIMATE ANALYST

TABLE D-1: SAMPLE OF WIND DATA VALIDATED BY WAsP CLIMATE ANALYST

Record Number	Time stamp	Mean speed [m/s]	Direction [°]
1	2011-07-01 12:00:00	2.00	293.0
2	2011-07-01 12:10:00	2.10	293.0
3	2011-07-01 12:20:00	2.60	270.0
4	2011-07-01 12:30:00	2.40	270.0
5	2011-07-01 12:40:00	2.20	270.0
6	2011-07-01 12:50:00	2.10	248.0
7	2011-07-01 13:00:00	2.70	248.0
8	2011-07-01 13:10:00	2.40	270.0
9	2011-07-01 13:20:00	2.50	248.0
10	2011-07-01 13:30:00	2.30	248.0
11	2011-07-01 13:40:00	1.70	248.0
12	2011-07-01 13:50:00	1.50	270.0
13	2011-07-01 14:00:00	1.90	248.0
14	2011-07-01 14:10:00	2.10	248.0
15	2011-07-01 14:20:00	2.10	270.0
16	2011-07-01 14:30:00	2.50	293.0
17	2011-07-01 14:40:00	2.00	315.0
18	2011-07-01 14:50:00	1.40	270.0
19	2011-07-01 15:00:00	1.70	315.0
20	2011-07-01 15:10:00	1.70	315.0
21	2011-07-01 15:20:00	1.50	270.0
22	2011-07-01 15:30:00	1.40	315.0
23	2011-07-01 15:40:00	1.80	315.0
24	2011-07-01 15:50:00	1.80	338.0
25	2011-07-01 16:00:00	0.90	270.0
26	2011-07-01 16:10:00	1.10	270.0
27	2011-07-01 16:20:00	1.30	248.0
28	2011-07-01 16:30:00	1.40	248.0
29	2011-07-01 16:40:00	1.80	248.0
30	2011-07-01 16:50:00	1.70	270.0
31	2011-07-01 17:00:00	1.60	293.0
32	2011-07-01 17:10:00	1.40	270.0
33	2011-07-01 17:20:00	1.40	270.0
34	2011-07-01 17:30:00	1.20	225.0
[illegible]	[illegible]	[illegible]	[illegible]

Table D-2: Histogram Bins

CLIMATE REPORT FOR KNUST COE NEW CLASSROOM BLOCK WIND MONITORING SITE 0001 FOR KUMASI - WAsP Climate Analyst - [Omwc for 'KNUST COE WIND MONITORING SITE 001']

Climate | Histogram bins | Generation report | Statistics

Sector 1	2	3	4	5	6	7	8	9	10	11	12	Total
152	298	595	729	804	711	762	588	349	206	73	68	144
223	300	324	199	98	135	89	229	316	320	215	191	219
334	265	63	13	58	92	84	144	238	305	424	387	359
220	96	13	34	23	40	47	16	70	125	244	287	225
53	28	0	17	13	17	0	22	16	38	42	60	47
15	10	0	8	5	5	19	0	5	5	2	6	6
3	2	5	0	0	0	0	0	3	0	0	0	1
1	0	0	0	0	0	0	0	3	0	0	0	0

Table:D-3 Generation Report

Graphs | Grid | Import report

File information:	
Source file name:	00010630Notepad.txt
Source file path:	C:\Users\User\Documents
Last modified:	2011-10-10 13:32:20
Protocol:	'Protocol created for importing 0001063 NOT CORRECT' (edited)
Recordings in file:	
Count:	13406
Start time:	2011-06-30 09:50:00
End time:	2011-10-01 12:00:00
Recordings used:	
Count:	13105
Start time:	2011-07-01 12:00:00
End time:	2011-09-30 12:00:00
Mean wind speed ('mean wind speed') data:	
Readings below lower limit (0):	none
Readings above upper limit (26):	none
Calms (speeds below 0 m/s):	698 (5.33%)
Valid readings accepted:	13105 (97.75%)
Accepted values range:	0.00 m/s to 7.70 m/s
Mean wind direction ('mean wind direction') data:	
Readings below lower limit (0):	none
Readings above upper limit (360):	none
Calms (speeds below 0 m/s):	698 (5.33%)
Valid readings accepted:	13105 (97.75%)
Accepted values range:	0.0° to 338.0°
Data recovery:	
Expected recording count:	13105
Count of recordings in file:	13406 (102.3%)
Recordings with invalid values in one or more fields:	0 (0.0%)
Entirely valid recordings accepted:	13105 (97.75%)
Recovery percentage (vs. expected):	100.0%

APPENDIX E: Workspace of Stata

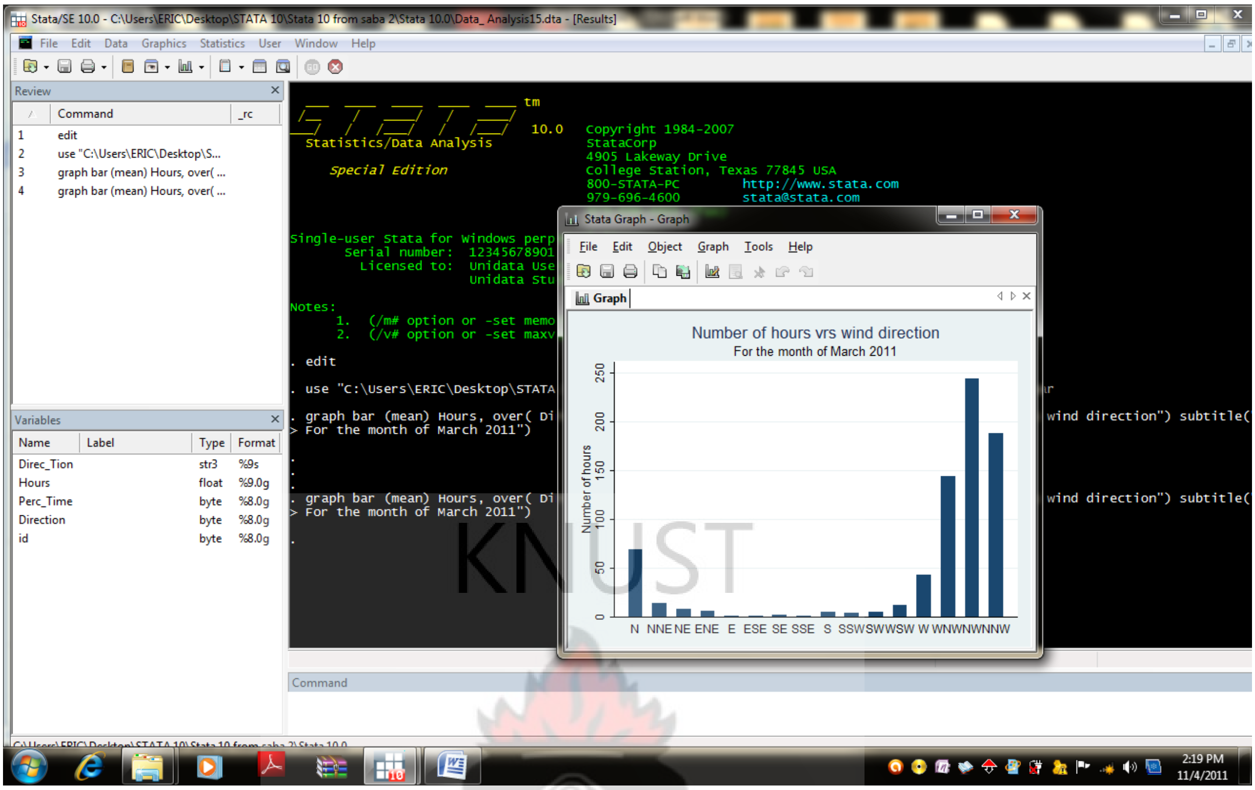


FIGURE E-1: Stata Workspace

APPENDIX F: Interactive Wind Profile Calculator Interface

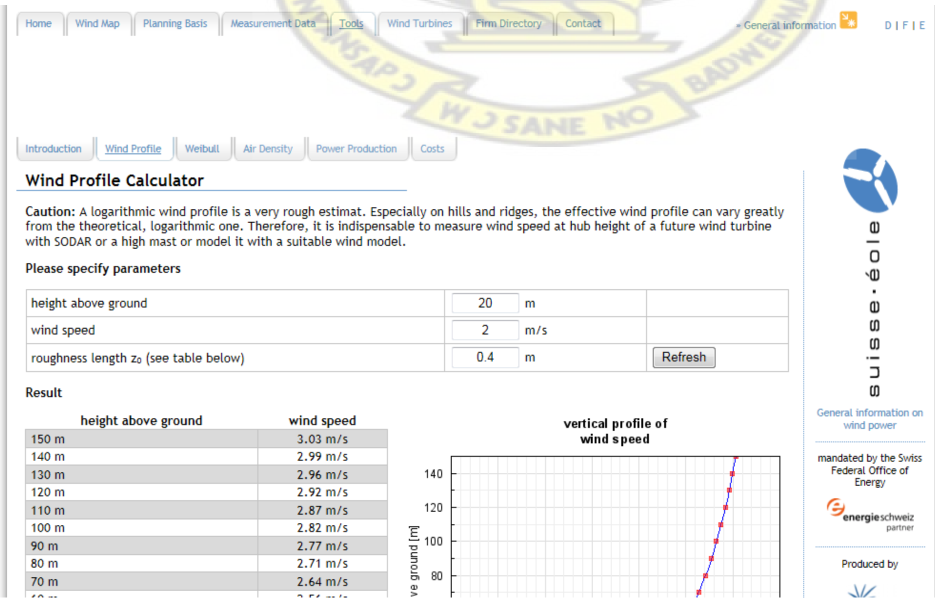


Figure: F-1: windenergie-Daten der Schweiz Wind Profile Model

APPENDIX G: Interactive Wind Power Calculator Interface

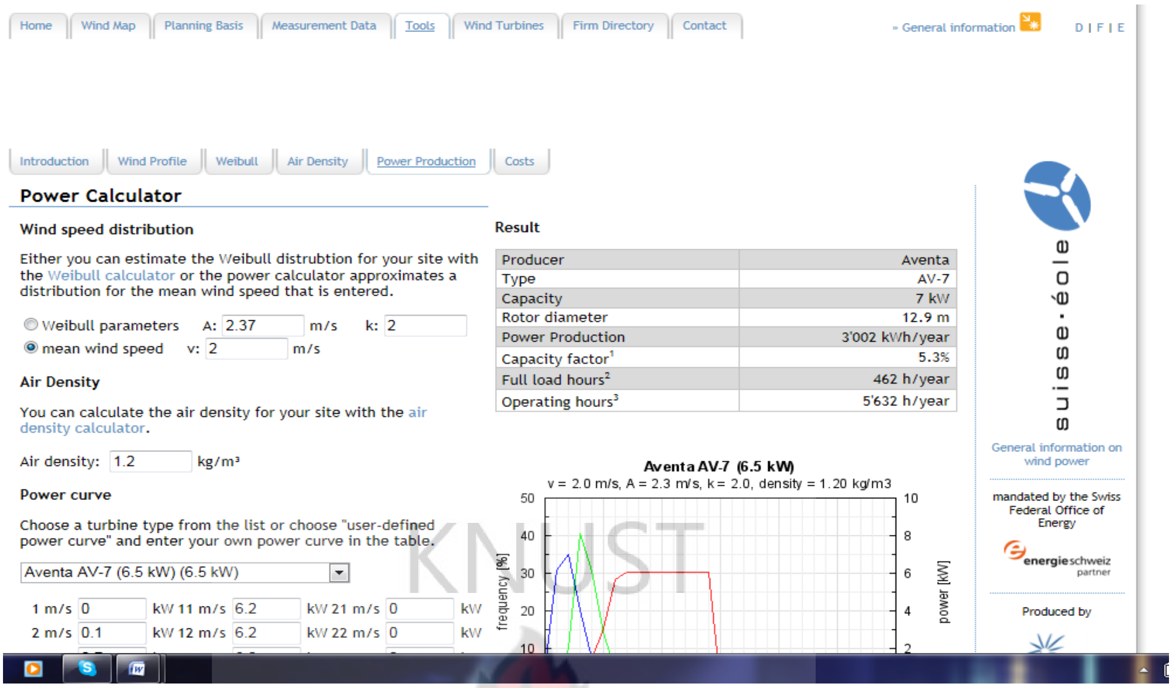


Figure G – 1: Windenergie-Daten der Schweiz Power Calculator Model