ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
ADDIS ABABA INSTITUTE OF TECHNOLOGY
CENTER OF ENERGY TECHNOLOGY

WIND ENERGY RESOURCE ANALYSIS:
A CASE STUDY OF AYSHA WIND FARM

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OFADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENERGY TECHNOLOGY

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any University, and that all the source of materials used for the thesis has been duly acknowledged.

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ABSTRACT

Ethiopia satisfied 92 % of its energy demand using biomass sources while petroleum and electricity (hydropower) only contribute 7 % and 1 %, respectively, in 2009. Due to this limited electricity availability, among the total population only 23.3 % had access to electricity and among 82.7 % of Ethiopians living in rural areas only 2 % in 2011. In addition 99 % of the electricity production is from hydropower source which is highly vulnerable to fluctuations in energy supply due to varying water inflow to reservoirs. However, the country is well endowed with other renewable energy resources (solar, wind and geothermal) that can be used to develop electricity. Among these resources, harnessing Ethiopian wind energy potential (10,000 MW) is a promising solution as it offers better generation mix and seasonal complementarity to avoid vulnerabilities associated with hydropower. It also helps in improving the life of population who are unlikely to have access to electricity supply in foreseeable future. Accordingly, this study is conducted at Aysha Wind Farm with the aim to analyze its wind energy resource based on 10 minute mean data for the year 2008 G.C. Using different software and statistical model, the wind data has been analyzed to: select wind turbine class, power density & estimate farm AEP, develop site wind resource map and perform preliminary turbine micro-sitting. Based on the analysis and site survey, site roughness and wind shear exponent are also determined. Detail wind energy resource study is performed for the site using MS Excel, MATLAB and WAsP software. Analyzing a wind-mast data at a height of 10 m using MATLAB and MS Excel, mean wind speed of 8.455 m/s and average power density of 571 W/m^2 have been found at the farm. To take the effect of the roughness of the site in to consideration, a wind resource map of 28.44 km x 36 km area is performed on the site. This is done based on two nominated wind turbines namely: Sany SE8220III 2 MW and Gamesa G80 2 MW at respective hub heights of 70 m and 67 m using WAsP software. Considering the nearby transmission line capacity i.e., 300 MW, 150 sets of each type of turbine has been put at the farm, analyzed and compared to each other. Accordingly, Gamesa G80 2 MW is selected for its least wind farm cost of 0.0193 USD per kWh. As per the preliminary analysis of the farm based on the selected turbine, total gross AEP of 1819.21 GWh and total net AEP of 1183.62 GWh (after considering total loss factor of 0.651 on the total gross AEP) have been found. In addition the average power density and CF at the wind farm are estimated at 1392.6 W/m^2 and 44.92 %, respectively. Moreover the mean wind speed at hub height (67 m) is 11.83 m/s whereas the average Weibull shape factor (k) and scale factor (A) are estimated at 3.13 and 13.22 m/s, respectively. In conclusion, according to the wind power classes, Aysha wind farm is categorized as class 7 (excellent wind energy resource) which is promising to construct large wind farm. It is, therefore, recommended that Ethiopian government consider investing on Aysha wind farm as the farm has an excellent wind resource potential at a capacity of 300 MW.

KEYWORDS: *Wind Farm, Wind Climate, Energy Production, Wind Resource, Wind Shear Exponent, WAsP, Wind-Mast, Capacity Factor, Ethiopia, Power Density, Wind Turbines*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

2D/3D	: Two/three dimension
AEP	: Annual Energy Production
a.g.l / a.s.l	: Above ground level/ above sea level
CF	: Capacity Factor
CDM	: Clean Development Program
DTU	: Technical University of Denmark
EEPCo	: Ethiopian Electric Power Corporation
EPC	: Engineering Procurement and Construction
GPS	: Geographical Positioning System
GTP	: Growth and Transformation Plan
GW/GWh	: Giga Watt / Giga Watt hour
IEC	: International Electrotechnical Commission
kW/ kWh	: Kilo Watt / Kilo Watt hour
km	: kilometer
m/s	: meters per second
MW/ MWh	: Mega Watt/ Mega Watt hour
OWC	: Observed Wind Climate
PWC	: Predicted Wind Climate
RIX	: Ruggedness index
RWC	: Regional Wind Climate
USD	: United States Dollar
WAsP	: Wind Atlas Analysis and Application Program
WECS	: Wind Energy Conversion System
WTG	: Wind Turbine Generator

CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

The raising concerns over global warming, environmental pollution and energy security have increased interest in developing renewable and environmentally friendly energy resources such as wind, solar, hydropower, geothermal and biomass as the replacements of fossil fuels. Wind energy can provide suitable solutions to the global climate change and energy crises. The utilization of wind power essentially eliminates emission of CO_2, SO_2, NO_x and other harmful wastes as in traditional coal-fuel power plants. Understanding this, the introduction of wind farms dramatically reduces dependence on fossil fuels and strengthening global energy security.

Ethiopia has one of the lowest levels of electric power consumption (kWh per capita) in the world of 51.96 (133th out of 135 countries) [1]. Only about 23.3 % of the Ethiopian population had access to electricity in 2011 [2]. The energy consumption of the country is dominated by a heavy reliance on traditional biomass energy (wood fuels, crop residues and cattle dung) which accounts for 92 % of total energy consumption in Ethiopia in 2009; petroleum and electricity (hydropower) contributed only 7 % and 1 %, respectively [3]. About 82.72 % of Ethiopians living in rural areas and the remaining 17.28 % in urban [2], urban electricity access is estimated at 86 % while only 2 % of rural households had access to electricity [3]; there is a significant bias between the power supply to urban and rural population. Power demand is growing annually on average at 31.6 % from the year 2012 to 2017 [4]. The country has signed deals to supply power to Djibouti, the Sudan and Kenya and is currently under-taking power projects. As part the GTP, Ethiopia's power generating capacity is planned to reach 10,000 MW by 2017 [5]. Power supplies to Djibouti have commenced, while preparations are under way for supply of power to the Sudan and Kenya in the near future [5]. The energy sector in Ethiopia is expanding rapidly; the problem of water level fluctuating will not be solved completely even with the construction of large scale hydro power plants. Most of the dams faced shortage of water due to hydrological problems resulted from climate change. Hence, the power generation system has to be diversified. In the short-run it is necessary to increase the current power generation mix, to cover increasing and unsatisfied power demand and to avoid dependence on fuel imports. Considering the country's wind resource potential, whose assessment is the main objective of this project, the country has enormous untapped potential. The exploitable potential of wind energy is about 10,000 MW [6]. The areas with the great potential are basically the escarpments along the Great Rift Valley extending to the Southern, Eastern, Northeastern part of the country and the central highlands. Harnessing wind energy is a promising solution for improving the life of population, who are unlikely to have access to electricity supply in foreseeable future. Currently, three wind farms such as Ashegoda wind power project with installed capacity of 120 MW, Adama I wind power project with installed capacity of 51 MW and Adama II wind power project with installed capacity of 51 MW have been constructed and made operational. Ethiopian Electric Power Corporation (EEPCo) has planned to implement different wind power projects in several parts/sites of Ethiopia such as Messobo-Harena Wind Farm (51 MW), Assela Wind Farm (100 MW), Aysha Wind Farm (300 MW), Debre Berhan Wind Farm (100 MW) and Galema Wind Farm (275 MW). This proposed thesis investigates one of these sites, namely- Aysha Wind Farm Project (300 MW).

1.2 STATEMENT OF THE PROBLEM

Ethiopia's electricity production from hydropower source is 99 % in 2011[2] which are based on hydropower reservoirs, which are significantly affected during periods of extended drought, resulting in potentially large fluctuations in availability of power. Under these conditions water in reservoirs are depleted and system demand can outstrip supply. On the other hand, the accelerating socio-economic growth and development of Ethiopia has caused increased energy consumption and unmet demand.

Considering the increasing power demand and capacity shortfall in the grid system and to have better generation mixes, wind energy is found an immediate and clean energy solution as wind power is renewable with short construction period and significant advantage of quick result. To overcome the above effects, EEPCo has planned to implement different wind power projects in several parts /sites of Ethiopia because hydropower and wind Power has a winning combination.

Accordingly, this study is conducted on wind energy resource analysis of Aysha Wind Power Project, among one of the above sites, which could play its own contribution to back-up the energy drop of the hydropower plants.

1.3 OBJECTIVES OF THE STUDY

1.3.1 General objective

The main objective of this research work is to conduct wind energy resource analysis of Aysha Wind Farm area, Somali regional state, Ethiopia.

1.3.2 Specific objectives

The specific objectives of this research work include:

1. Analyze the wind data using statistical model (Weibull distribution);

2. Determine wind resource class of the site based on measured wind data;

3. Analyze wind energy resource potential at the site;

4. Generate site wind resource map using WAsP software;

5. Select IEC wind turbine class as per the site wind resource; and

6. Carry out the preliminary Wind Farm micro-turbine sitting, estimation of Wind Farm's annual energy production (AEP) and the capacity factor (CF).

1.4 DESCRIPTION OF THE STUDY AREA

1.4.1 Location

The wind farm is located in Ethiopia, Somali regional state, Shinile zone, Aysha district. More exactly, it is located about 7 km South of Aysha town, about 170 km Northeast of Dire Dawa city, about 148 km Southwest of Djibouti harbor and about 40 km to the border of Somalia.

The 10 m high wind-mast is located at longitude 235162.18 m E and latitude 119163.67 m N with an elevation of 731.7 m a.s.l. Location map of study site is shown in Fig. 1.1.

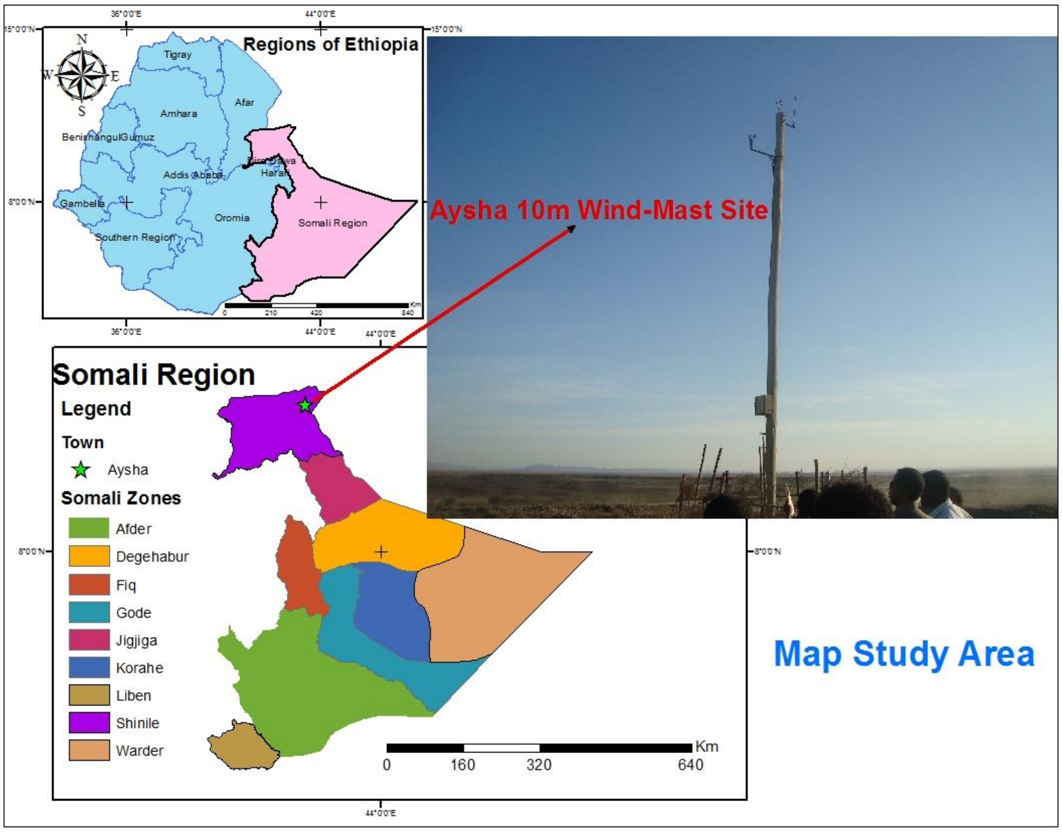

Figure 1.1: Location map of the study site (left) and a photo of 10 m wind-mast (right) [ArcGIS]

1.4.2 Climate

According to Aysha Weather Station (the nearest weather station is located about 7 km northeast of the turbine site), the climate of the study area lies within the semi-arid climate. According to the metrological data from May 2007 to April 2011, the highest temperature was 41.5 ℃ (June), the lowest temperature was 12 ℃ (February). The average annual rainfall is very low (<500 mm/a). Aysha is flat with the slight effects of water erosion after rains [7].

From the data analysis of this study, the one year mean wind speed for the site at a measuring height of 10 m is 8.455 m/s.

1.4.3 Topography

The Wind Farm area considered for the construction is enclosed by rectangular sides with the width of 28.44 km and height of 36 km. It is exactly bounded by the geographical coordinates of the site longitude 220236 m E to 248766 m E and latitude 1164954 m N to 1201674 m N.

The site characteristics are flat terrain, semi-sand and semi-gobi with sparse vegetation. For major part of the site is described by very smooth land surface and the height contours of the terrain ranges from 625 m to 1190 m a.s.l.

The gravel road passes through the site from Dire Dawa to Djibouti city and two 230 kV high voltage transmission lines are also passing through the site from South to North direction.

The site area foreseen for the construction of the wind farm is mainly used for extensive goat farming. Goat milk is the main food of local residents. Most houses are built of trees and rammed earth, the population of the area is low and development slow. The local residents are mainly Somali tribes, mainly engaged in animal husbandry. The topography of the site is presented in the Fig. 1.2 to 1.5.

Figure 1.2: Area considered for the construction of wind farm with gravel road access map of the site [Google Earth]

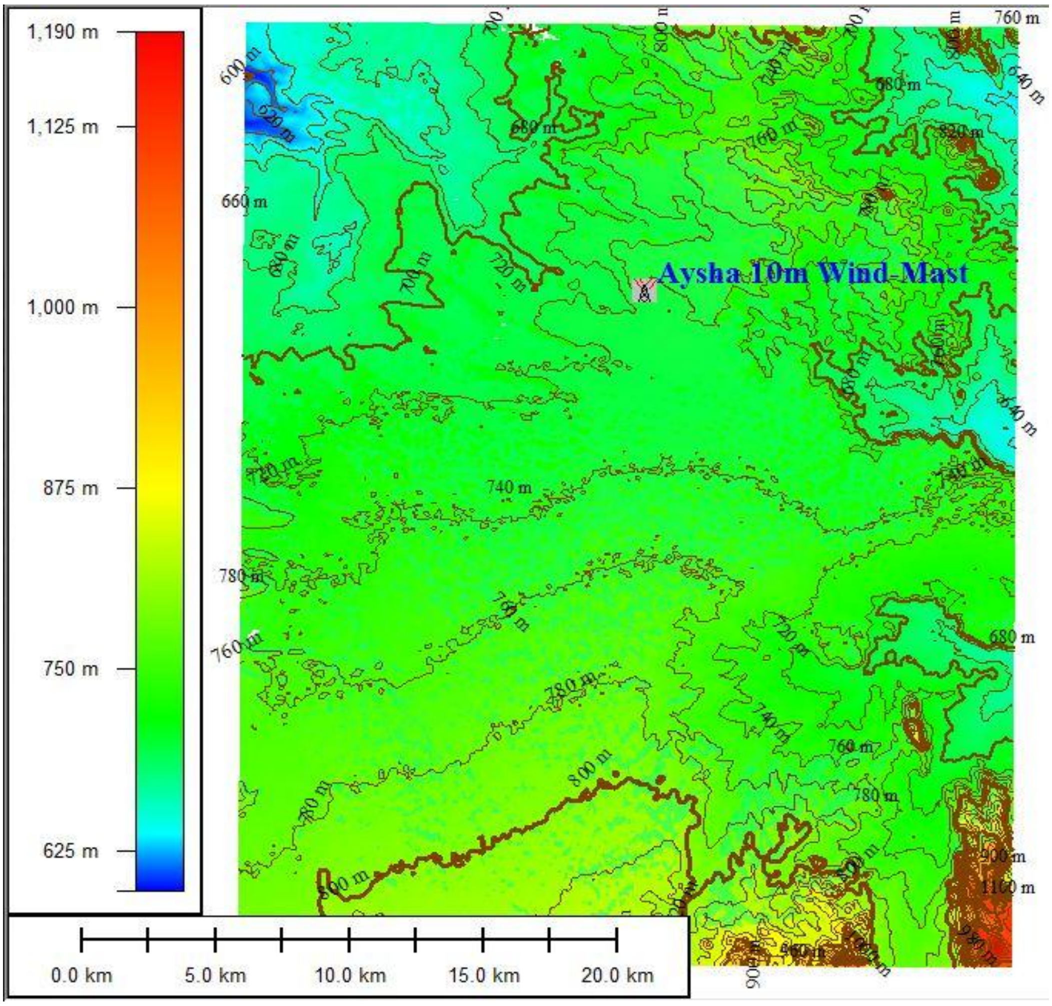

Figure 1.2: Elevation map of the site (2D) [Global Mapper]

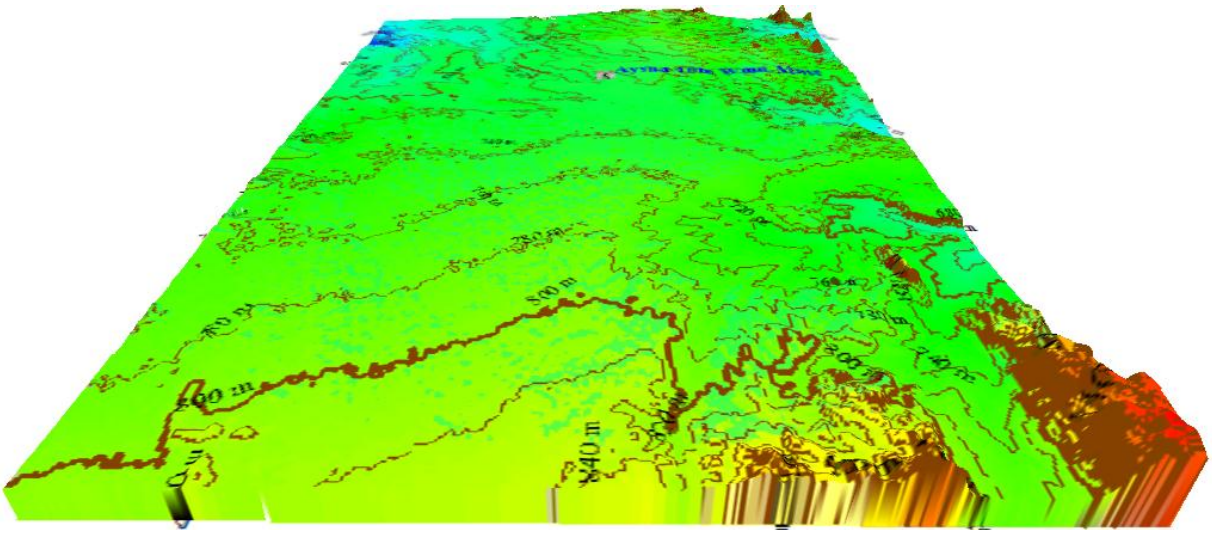

Figure 1.3: Elevation map of the site (3D) [Global Mapper]

Figure 1.4: An overview of site conditions [photo]

1.4.4 Seismicity

Ethiopia is divided into five seismic zones (Zone 0, 1, 2, 3, 4 and 5) risks depending on the distribution of earthquakes as shown in Fig. 1.6 [7, 8]. Seismic hazard is described in terms of the value of the effective ground acceleration (Design Ground Acceleration) in rock or firm soil. Design ground acceleration of the Aysha Wind Farm site is located in seismic zone 4, which is defined as high seismicity that corresponds to the zone of “Destructive Hazards”. In view of this, it is important to design the farm with strict seismic building code of the effective ground acceleration considerations.

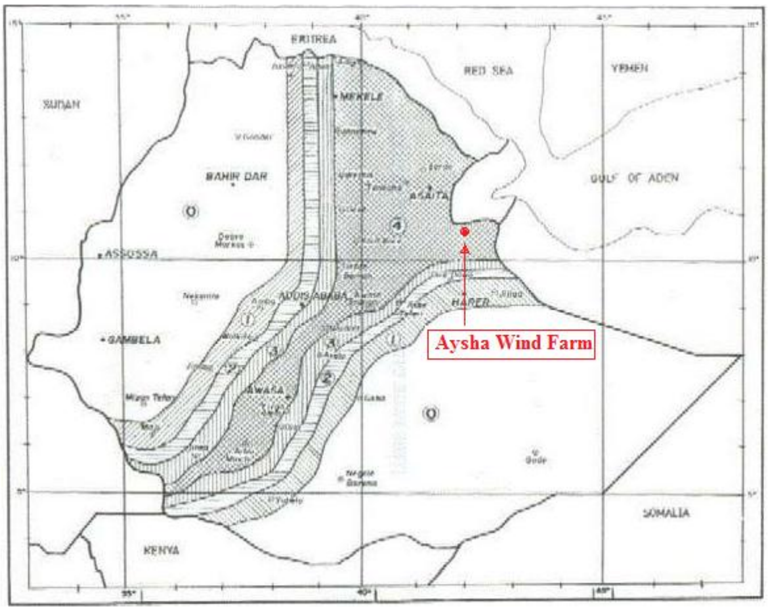

Figure 1.5: Seismic hazard map of Ethiopia [7, 9].

1.5 METHODOLOGY OF THE STUDY

The methodology used in this research work includes:

Related literatures of the relevant materials on wind energy resource analysis are reviewed. Literature is available from different books, publications, journals, manuals, reports, web sites, etc. Site visit is performed to study the condition of the site like sheltering obstacles (position and dimension), roughness of the terrain (terrain classification), mountains terrain (height contour lines), and accessibility of the site, etc. Measured raw wind data and height contour lines map of the site are collected from EEPCo (Aysha Wind Farm Project Office) and friends, respectively. The collected data have been validated as input for the wind data analysis. Statistical tools such as MS Excel and MATLAB software have been implemented to analyze the wind data distribution. Then, the wind farm is analyzed and modeled using WAsP software for predicting of wind climates, wind resources and energy productions from wind turbines and wind farms of the site. Results and discussion. Finally, conclusions and recommendations are made based on the analysis.

1.6 SIGNIFICANCE OF THE STUDY

Energy is a direct requirement of people's daily lives. Access to electricity is very important to lead a better way of life as well as to lessen the work burden of most women in the country. This explains why access to energy is a vital aspect of the overall development of the country. Reduction of forest resource depletion by investing more on wind engineering technology and other renewable energy sources, reduction of negative impact on the environment, due to the use of kerosene lamps and stoves gas emission, upgrading locally available professional skills in installation, manufacturing, operation and maintenance area of wind turbines are the main triggering forces for this project.

Aysha Wind Farm project will have a positive impact on improved energy mix, national energy security, technology transfer, opportunities to be utilized by investments in power sector development; Ethiopia has the wind resource to become Africa’s powerhouse for renewable energy generation and export, and access to modern energy significantly.

1.7 ORGANIZATION OF THE STUDY

The thesis is organized as follows: Chapter one is introduction about the thesis that comprises the background, statement of the problem, objectives of the study, material and method of the study, description of the study area and significance of the study. Chapter two is concerned with the literature review. Chapter three is analyses of the collected data and validation of the data. Chapter four is analysis of the study. Chapter five is the results and discussions of the study and finally, chapter six is the conclusions and recommendations of the study.

CHAPTER TWO

2. LITERATURE REVIEW

For estimating the wind energy potential of any site, the wind data collected from the location should be properly analyzed and interpreted. Using the available long term wind data from the meteorological stations near to the candidate site can be used for making preliminary estimates of the wind resource potential for the site. These meteorological data, which may be available for long periods, should be carefully extrapolated to estimate the wind profile of the site. After this preliminary investigation, field measurements are generally made at the prospective location for shorter periods. One year wind data recorded at the site is sufficient to represent the long term seasonal variations in the wind profile within an accuracy level of 10 % [10].

Modern wind measurement systems provide the mean wind speed at the site averaged over a pre-fixed time periods. 10 minutes mean is very common as most of the standard wind analysis softwares are tuned to handle data over ten minutes. These short term wind data are further grouped over time spans (an hourly, daily, monthly and yearly basis) in which the researchers interested in and analyzed with the help of models and softwares to make precise estimates on the energy available in the wind.

2.1 MEAN WIND VELOCITY

One of the most important information on the wind spectra available at a location is its mean velocity. The mean velocity (V_m) is given by:

$$V_m = \frac{1}{n}\sum_{i=1}^{n} V_i \qquad (2.1)$$

where: V_i = wind velocity and n = number of wind data.

However, Eq. 2.1 will not be used for wind power calculation since wind power is proportional to the cubic rate of wind speed, but it will be used with the power curve for estimating wind power.

2.2 DISTRIBUTION OF WIND VELOCITY

Apart from the mean wind velocity over a period, its distribution is also a critical parameter in wind resource assessment. The wind turbine installed at the two sites with the same mean wind velocity will produce entirely different power output because of differences in the velocity distribution [10].This shows that, along with the mean wind velocity, the distribution of velocity within the site also an important parameter in the wind energy analysis.

One measure for the variability of wind velocities in a given set of wind data is standard deviation (δ_v). Standard deviation indicates the deviation of individual velocities from the mean value. It is given by:

$$\delta_v=\sqrt{\frac{\sum_{i=1}^{n}(V_i-V_m)^2}{n}} \tag{2.2}$$

Lower value of δ_v indicate the uniformity of the wind speed data set at the site.

2.3 STATISTICAL MODELS FOR WIND DATA ANALYSIS

Statistical models are used to represent the wind velocity distributions by standard statistical functions. It is found that the Weibull and Rayleigh distributions are widely accepted and extensively used to describe the wind variations in a regime with an acceptable accuracy level. These models are used to determine the probability density and cumulative distribution functions of wind speed and then to plot their respective graphs.

2.3.1 Weibull distribution

This Weibull distribution is found to fit a wide collection of recorded wind data and is considered as a standard approach. It appeared to indicate the actual data better than Raleigh distribution [10]. The probability density function, (f (V)) indicates the fraction of time (or probability) for which the wind is at a given velocity V. It is given by:

$$f(V)=\frac{k}{A}\left[\frac{V}{A}\right]^{k-1} e^{-(V/A)^k} \tag{2.3}$$

where: k is the Weibull shape factor (dimensionless) and A is scale factor (m/s).

The cumulative distribution function of the velocity V indicates the fraction of time (or probability) that the wind velocity is equal or lower than V. Thus the cumulative distribution F (V) is the integral of the probability density function. It is given by:

$$F(V) = \int_0^{\infty} f(V)\, dv = 1 - e^{-(V/A)^k} \tag{2.4}$$

Under the Weibull distribution, the major factor determining the uniformity of wind is the shape factor k and uniformity of wind at a site increases with the shape factor k.

The mean wind velocity of a regime, following the Weibull distribution, is given by:

$$V_m = \int_0^\infty V\, f(V)\, dv \tag{2.5}$$

Substituting for f (V) and rearranging yields:

$$V_m = \int_0^\infty \left(\frac{V}{A}\right)^k e^{-(V/A)^k} dV \tag{2.6}$$

Applying the standard gamma function, the mean wind velocity is expressed as:

$$V_m = A\, \Gamma\left(1+\frac{1}{k}\right) \tag{2.7}$$

where: Γ is the gamma function.

The standard deviation of wind velocity, following the Weibull distribution is given by:

$$\sigma_V = A \left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]^{1/2} \tag{2.8}$$

For analyzing a wind system following the Weibull distribution, the Weibull parameters k and A must be estimated by the following method:

The common methods for determining k and A are:

a. Graphical method
b. Standard deviation method
c. Moment method
d. Maximum likelihood method, and
e. Energy pattern factor method

In this study, both the graphical (very close to the field observation) and the standard deviation (widely accepted and extensively used for wind regime analysis) methods are discussed [10].

a. Graphical method

In the graphical method, the cumulative distribution function is transformed in to a linear form, adopting logarithmic scales. The expression for the cumulative distribution of wind velocity, Eq. 2.4 can be rewritten as:

$$1 - F(V) = e^{-(V/A)^k} \tag{2.9}$$

Taking the logarithm twice yields:

$$\ln\{-\ln[1 - F(V)]\} = k \ln(V) - k \ln A \tag{2.10}$$

Plotting the above relationship with $\ln(V)$ along the X axis and $\ln\{-\ln[1 - F(V)]\}$ along the Y axis, nearly a straight line is obtained. From Eq. 2.10, k gives the slope of this line and – k ln A represents the intercept. If generate the regression equation for the plotted line and compare with Eq. 2.10, the values of k and A can be determined.

b. Standard deviation method

Estimating of the Weibull factors k and A from the calculated value of mean and standard deviation of wind data, factor k, can be computed by dividing standard deviation with mean velocity given in Eq. 2.8 and Eq. 2.7, and from these equations can be related as:

$$\left(\frac{\sigma_V}{V_m}\right)^2 = \frac{A\Gamma(1+\frac{1}{k})}{\Gamma^2\ (1+\frac{1}{k})} - 1 \qquad (2.11)$$

Once σ_V and V_m are calculated for a given data set, then k can be determine by solving the above expression numerically.

Once k is determined, A is given by:

$$A = \frac{V_m}{\Gamma(1+\frac{1}{k})} \qquad (2.12)$$

In a simpler approach, an acceptable approximation for k and A are [10].

$$k = \left(\frac{\sigma_V}{V_m}\right)^{-1.090} \qquad (2.13)$$

Similarly, A can be approximated from:

$$A = \frac{2V_m}{\sqrt{\pi}} \qquad (2.14)$$

However, for calculating A using Eq. 2.15 is more accurate approximation than using Eq. 2.14 [10], A can be determine from the expression:

$$A = \frac{V_{mk^{2.6674}}}{0.184+0.816k^{2.73855}} \qquad (2.15)$$

In this study, to estimating of the Weibull factors k and A, the standard deviation method has been used because of widely accepted and extensively used for wind regime analysis

2.3.2 Rayleigh distribution

The existing data in the form of the mean wind velocity over a given time period (for example daily, monthly or yearly mean wind velocity), under this situations, Rayleigh distribution is a simplified case of the Weibull distribution can be derived by assuming the shape factor as 2.

Taking k = 2 in Eq. 2.7 gives:

$$V_m = A\,\Gamma(\frac{3}{2}) \qquad (2.16)$$

Rearranging the above expression,

$$A = \frac{2V_m}{\sqrt{\pi}} \qquad (2.17)$$

Substituting for A in Eq. 2.3 gives:

$$f(V) = \frac{\pi}{2}\frac{V}{V_m^2}\,e^{-\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2} \qquad (2.18)$$

Similarly, the cumulative distribution is given by:

$$F(V) = 1 - e^{\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2} \qquad (2.19)$$

For this study, the data is adequate wind data which collected over shorter time intervals (the existing data is in the form of the 10 minute mean wind velocity), it has been used the Weibull distribution model.

2.4 WIND DIRECTION

Direction of wind is an important factor in the siting of a wind energy conversation system. The major share of energy available is received in the wind from a certain direction, it is important to avoid any obstructions to the wind flow from this side. Wind roses are information packed plot providing frequencies of wind in different direction and wind speed. It can quickly indicate the dominant wind directions and the direction of strong wind speeds. This helps in identifying the energy available from different directions.

2.5 EXTRAPOLATION OF WIND SPEED WITH HEIGHT

The flow of air above the ground is retarded by frictional resistance offered by the earth surface (boundary layer effect). This resistance caused by the roughness of the ground itself or due to vegetation, buildings and other structures present over the ground will have a significance impact to be considered in the design of wind energy plants. The rate of wind speed increase with height depends on site terrain type. It is usually represented by roughness class or roughness length and wind shear exponent of the site. Therefore, care has to be taken to determine the appropriate surface roughness length and wind shear exponent of the site before extrapolating the wind speed to the required height.

The power law (exponent) and log law (logarithmic) vertical shear profiles are the most common methods of extrapolating measured wind speed to hub height.

2.5.1 Log Law (Logarithmic)

The log law equation which incorporates the surface roughness length in the extrapolation of wind speed to the hub height and is given by:

$$V = V_{ref} * \frac{\ln\left(\frac{z}{z_o}\right)}{\ln\left(\frac{z_{ref}}{z_o}\right)} \qquad (2.20)$$

where:

V = Wind velocity at height z above ground level,

V_{ref} = Reference velocity, i.e. a wind velocity at height z_{ref},

z = Height above ground for the desired velocity, V,

z_o = Surface roughness length of the site,

z_{ref} = Reference height, i.e. the height where the exact wind velocity V_{ref} is known.

2.5.2 Power law (Exponent)

The power law equation relates the wind speed at two different heights with the wind shear exponent and is given by:

$$V = V_{ref} * \left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad (2.21)$$

where: α = wind shear (or power law) exponent.

The wind shear exponent typically ranges from 0.1 to 0.2 [22, 23].

- For very smooth terrain or open water use 0.10,
- For smooth terrain use 1/7 or 0.143 (as used in the initial site screening), and
- For flat terrain with some surface roughness (the Great Plains) use 0.20.

For this study, the power law has been chosen as the model to evaluate because of its simplicity and used by many wind energy researchers as compared to the logarithmic law [11].

2.6 TOPOGRAPHIC EFFECTS ON WIND

2.6.1 The Roughness of a terrain

The collective effect of the terrain surface and obstacles, leading to an overall retardation of the wind near the ground, is referred to as the roughness of the terrain.The roughness surface area is determined by the size and distribution of the roughness elements it contains. The different terrains are divided into four types [12] as given an example in the Fig. 2.1 to 2.4.

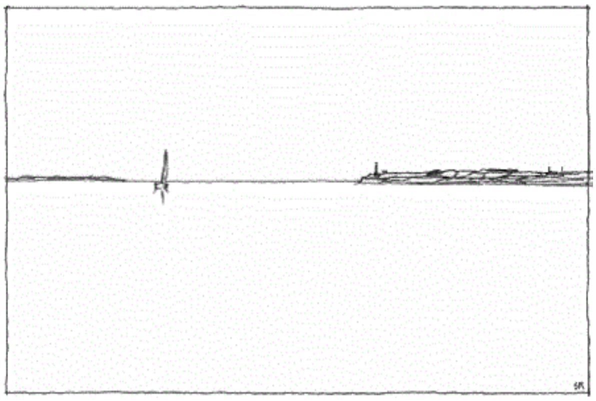

Figure 2.1: Typical of roughness class 0 elements on a terrain [12]

Terrain contains water areas (open sea, fjords and lakes) is refred to as roughness class 0: The roughness length is Z_0 = 0.0002 m. However, the roughness specified as 0.0 m in WAsP.

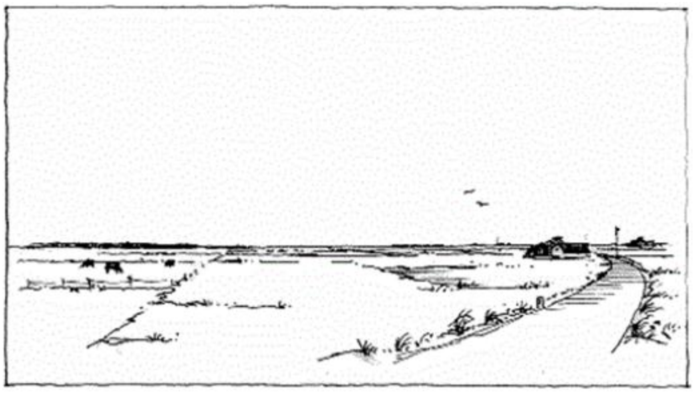

Figure 2.2: Typical of roughness class 1 element on a terrain [12]

Terrain corresponding to roughness class 1: open areas with few windbreaks. Very open and is flat or gently undulating. Single farms and stands of trees and bushes can be found. The roughness length is Z_0 = 0.03 m.

Figure 2.3: Typical of roughness class 2 elements on a terrain [12]

Terrain corresponding to roughness class 2: farm land with wind-breaks, the mean separation of which exceeds 1000 m and some scattered built-up areas. Large open areas between the many windbreaks, giving the landscape an open appearance. Flat or undulating. There are many trees and buildings. The roughness length is Z_0 = 0.10 m.

Figure 2.4: Typical of roughness class 3 elements on a terrain [12]

Terrain corresponding to roughness class 3: urban districts, forests, and farm land with many windbreaks. The farm land is characterized by the many closely spaced windbreaks, the mean separation being a few hundred meters. Forest and urban areas also belong to this class. The roughness length is Z_0 = 0.40 m.

2.6.2 Effect of orography

Orography refers to the description of the height variations of the terrain. Orographic element such as hills, valleys, cliffs and ridges affect the wind velocity profile. Near the summit or crest of these features the wind will accelerate while near the foot and in valleys it will decelerate as shown in the Fig. 2.5. As a result the logarithmic wind profile will be distorted.The degree of distortion depends on the steepness of the terrain, on the surface roughness and the stability. In very steep terrain the flow across the terrain might become detached and form a zone of turbulent separation. As a rule of thumb this phenomena is likely to happen in terrain steeper above 30 % (corresponding to 17 ° slope) [13].

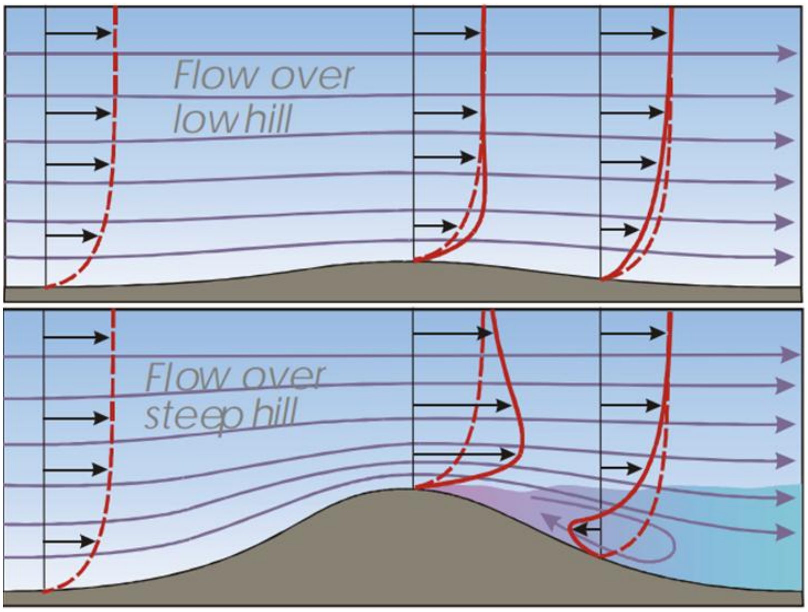

Figure 2.5: Wind flow over low and steep hill [13]

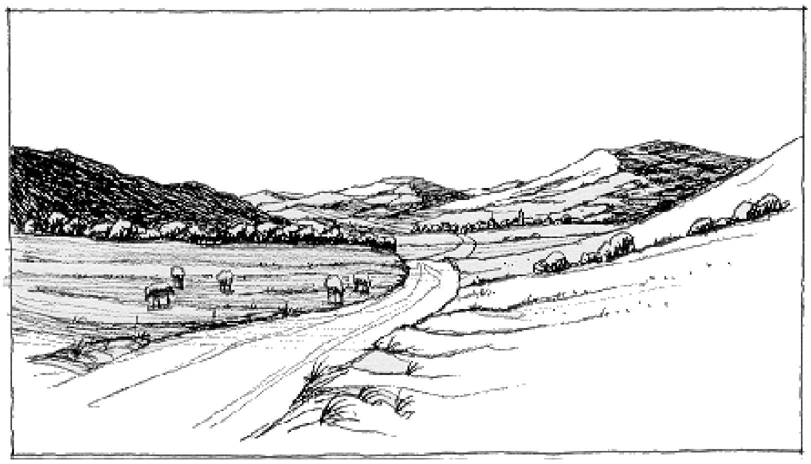

Figure 2.6: Topography element areas [12]

2.6.2.1 Horizontal speed-up profile

The relative speed-up is defined as:

$$\text{Relative speed-up} = \frac{(V_2 - V_1)}{V_1} \qquad (2.22)$$

where: V_2 and V_1 are the wind speeds at the same height a.g.l at the top of the hill and over the terrain upstream of the hill, respectively.

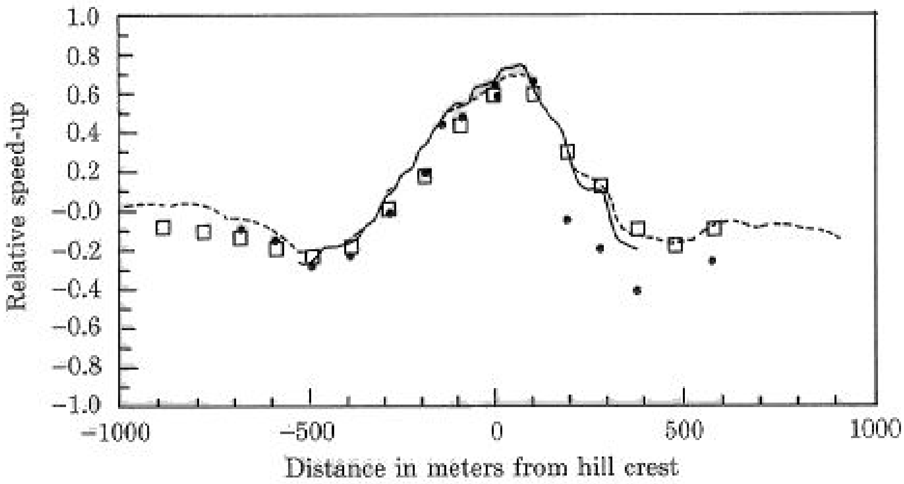

Figure 2.7: The typical relative speed-up [12]

2.6.3 Effect of obstacles

Obstacles to the wind such as buildings, trees, woods and forests, tree lines and rock formations can significantly change the wind speed and direction, in addition to creating turbulence as shown in the Fig. 2.5. The wind stream would flow around an obstacle intersecting its path creating a turbulence zone extending to about 3 times the height of the obstacle in the upwind side and 30 to 40 times of the height in the downwind side. The turbulence occurs more pronaunced at behind the obstacle, and to a lesser extent in front of it. The presence of turbulence in the flow not only reduces the power available in the stream, but also imposes fatigue loads on the wind turbine. Therfore, major obstacles sould be avoided in the siting of wind turbines, particularly if they are located upwind in the prevailing wind direction, or obstacles are taken into account in the calculation of wind energy production at a given site if they are located at less than a 30 to 40 times of the height from a wind turbine at the prevailing wind direction.

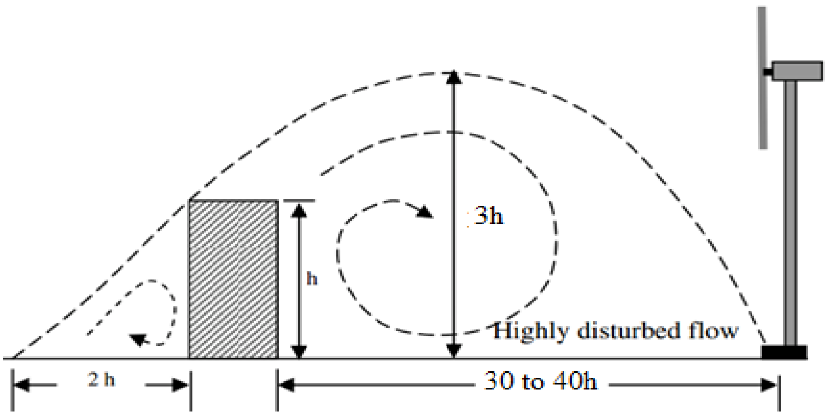

Figure 2.8: Turbulence created by an obstruction [10]

2.7 IEC WIND TURBINE CLASSES DETERMINATION

Since wind speed varies from poor wind speed to extreme wind speed it results in variable wind load to the wind turbine that may affect the turbine mode of operation or may result in the total damage of the system. The typical damage arises from these extreme wind conditions including wind shear events, as well as peak wind speed due to storms and rapid change in wind speed and direction [14]. Therefore, appropriate wind turbines are selected based on IEC standards for the wind farm with respect to their ability to with stand loads during extreme wind speeds.

2.7.1 Wind turbine class according to IEC 61400-1:1999

According to the IEC 61400-1:1999 (wind turbine generator systems-part 1: safety requirements), which are still the prevailing of IEC version for the wind turbine certificate, the wind turbine class should be determined by V_m, $V_{e\ ref}$, and I_{ref} as below [15].

In Table 2.1 and Table 2.2, the parameter values apply at hub height.

Table 2.1: Basic parameters for wind turbine classes by IEC61400-1:1999 Edition 2 [16]

Wind turbine class		**I**	**II**	**III**	**IV**	**S**
$V_{e\ ref}$ [m/s]		50	42.5	37.5	30	Value to be specified by the designer
V_m [m/s]		10	8.5	7.5	6	
A	I_{15} [-]	0.18	0.18	0.18	0.18	
	a [-]	2	2	2	2	
B	I_{15} [-]	0.16	0.16	0.16	0.16	
	a [-]	3	3	3	3	

where:

$V_{e\ ref}$ is the maximum (extreme reference) wind speed to be expected as a mean value over 10 min with a recurrence of 50 years,

V_m is the mean annual wind speed,

A designates the category for higher turbulence characteristics,

B designates the category for lower turbulence characteristics,

I_{15} is the characteristic turbulence intensity at a wind speed of 15 m/s.

As the recommendation from IEC 61400-1:1999 wind turbine class standard, reference wind speed can be estimated as five times the annual mean wind speed:

$$V_{ref} = 5 * V_m \quad (2.23)$$

2.7.2 Wind turbine class according to IEC 61400-1:2005

According to the IEC 61400-1:2005 (wind turbines- part 1: Design requirements), which is the new edition of IEC 61400-1 of wind turbine class designations have been adjusted and now refer to the reference wind speed and the expected value of turbulence intensity only. Based on the two criteria, the wind turbine class should be determined by $V_{e\ ref}$ and I_{ref} as below [15].

Table 2.2: Basic parameters for wind turbine classes by IEC61400-1:2005 Edition 3 [17]

Wind turbine class		**I**	**II**	**III**	**S**
$V_{e\ ref}$ [m/s]		50	42.5	37.5	Value to be specified by the designer
A	I_{ref} [-]	0.16			
B	I_{ref} [-]	0.14			
C	I_{ref} [-]	0.12			

where:

A designates the category for higher turbulence characteristics,

B designates the category for medium turbulence characteristics,

C designates the category for lower turbulence characteristics,

I_{ref} is the reference turbulence intensity at a wind speed of 15 m/s.

As the recommendation from IEC 61400-1:2005 standard wind turbine classes, mean wind speed, using Eq. 2.23, V_m can be estimated as 0.2 times the reference wind speed, V_{ref} (i.e. $V_m = 0.2V_{ref}$).

When selecting the wind turbine class for wind farm should consider the standards of IEC 61400-1:1999 and IEC 61400-1:2005 certification for respective safety class. However, mixing of IEC61400-1:2005 and IEC61400-1:1999 in design assessment and site specific calculations must be avoided as basic idea of standard has changed.

Turbulence intensity (T_I) is the ratio of standard deviation of the horizontal wind speed fluctuations to the 10 minute mean wind speed of 15 m/s at rotor hub height is given by:

$$T_I = \frac{\sigma_V}{v_{m\ 10\ min}} \tag{2.24}$$

Because the fatigue loads of a number of major components in wind turbines are mainly caused by wind turbulence can have a significant impact on turbine performance and loading. The classification of T_I ranges from less than 0.10 in flat terrain the wind speed increases logarithmically with height, to more than 0.25 in complex terrain the wind profile in a simple increase and additionally a separation flow might occur, leading to heavily increased turbulence whereas value between 0.1~0.25 range is medium [18]. Therefore, the T_I at 15 m/s provides a preliminary indication of the suitability of a turbine model for the project site.

2.8 ESTIMATION OF WIND ENERGY

Wind energy density and the energy available in the regime over a period are usually taken as the yardsticks for evaluating the energy potential at the site than wind speed alone. The wind energy density (E_D) is the energy available in the regime for a unit rotor area and time.

When selecting the wind turbines for the site, it must be considered the wind velocity where wind turbines generate their maximum power at the most frequent wind velocity ($V_{F\ max}$) and the velocity contributing the maximum energy ($V_{E\ max}$) to the regime. The peak of the probability density curve indicates $V_{F\ max}$ at the site.

Due to the cubic relationship of velocity and power, the wind velocity contributing the maximum energy is usually higher than the most frequent wind velocity. Therefore, for selecting wind turbines, wind turbine system operates at its design or rated wind velocity should be close as possible at the site to $V_{E\ max}$, if it is not constrained by other factors. Hence, it is more advantageous to produce maximum energy from the site.

Considering both the Weibull and Rayleigh models to estimate the energy potential of a wind regime based on the above indices are discussed.

2.8.1 Weibull based approach

For a unit swept area of the rotor, power available (P_V) in the wind stream of velocity V_i is:

$$P_V = \frac{1}{2} \rho \frac{1}{n} \sum_{i=1}^{n} V_i^3 \qquad (2.25)$$

where: ρ is the air density, kg/m^3 and Vi= wind velocity, m/s

The fraction of time for which this velocity V_i prevails at the site is given by the probability density function f (V). The energy per unit time contributed by V_i is P_V x f (V). Thus the total energy E_D, contributed by all possible velocities at the wind site, available for unit swept rotor area and time is expressed as:

$$E_D = \int_0^{\infty} P_V \, f(V) \, dV \qquad (2.26)$$

Substituting for P_V and f (V) in the above expression and with the standard gamma integral, it gives:

$$E_D = \frac{\rho A^3}{2} \left(\frac{3}{k}\right) \Gamma \left(\frac{3}{k}\right) \qquad (2.27)$$

Once E_D is known, energy available over a period E_I can be calculated as:

$$E_I = TE_D = \frac{\rho A^3 T}{2} \left(\frac{3}{k}\right) \Gamma \left(\frac{3}{k}\right) \qquad (2.28)$$

where: T is the time period.

The most frequent wind velocity, f' (V) = 0, that is denoted by $V_{F\,max}$. Thus

$$V_{F\,Max} = A \left(\frac{k-1}{k}\right)^{\frac{1}{k}} \qquad (2.29)$$

The velocity contributing maximum energy to the regime ($V_{E\,Max}$) is given by:

$$V_{E\,Max} = A \left(\frac{k+2}{k}\right)^{\frac{1}{k}} \qquad (2.30)$$

For this study, the Weibull based approach has been chosen to evaluate the velocity contributing maximum energy to the regime as very close to the design or rated wind velocity of turbines [10].

2.8.2 Rayleigh based approach

Substituting Eq. 2.18 and Eq. 2.25 into Eq. 2.26, the wind energy density at the site can be expressed as:

$$E_D = \int_0^{\infty} P_V\, f(V)\, dV = \int_0^{\infty} \frac{\pi\,\rho}{4V_m^2} V^4\, e^{-\left[\frac{\pi}{4}\left(\frac{V}{Vm}\right)^2\right]}\, dV \qquad (2.31)$$

Rearranging and energy density at the site:

$$E_{D\,=\,\frac{3}{\pi}\rho} V_m{}^3 \qquad (2.32)$$

Energy available for the unit area of the rotor, over a time period, can be estimated as:

$$E_T = TE_D = \frac{3}{\pi} T\rho V_m{}^3 \qquad (2.33)$$

The most frequent wind velocity represented by at the site V_{Fmax} is given by:

$$V_{F\,max} = \sqrt{\frac{2}{\pi}}\; V_m \qquad (2.34)$$

The velocity contributing maximum energy to the regime can be expressed as:

$$V_{E\,max} = 2\sqrt{\frac{2}{\pi}}\; V_m \qquad (2.35)$$

2.9 ENERGY GENERATED BY WIND TURBINE

The factors influencing the energy produced by a wind energy conversion system (WECS) at a given location over a period are: (1) the power response of the turbine to different wind velocities (2) the strength of the prevailing wind regime and (3) the distribution of wind velocity within the regime.

The theoretical maximum available wind power in the wind speed is done by:

$$P = \frac{1}{2}\rho A V^3 \qquad (2.36)$$

where: ρ = Air density, kg/m^3

A= Swept area, m/s

V = Wind speed, m/s

The amount of power which can be extracted from the wind depends on the available wind energy and on the operating efficiency of the wind turbine systems. However, wind machines cannot use 100 % of this power due to the Betz limit. The previous Eq. 2.36 can be rewrite adding a power coefficient (C_p), which defined the maximum efficiency of the Betz limit (0.593), the maximum coefficient of performance is $C_{p, max}$ = 0.43 [10,13].

The actual mechanical power output P_m of the wind turbine is given by:

$$P_m = \frac{1}{2}\rho A V^3 C_p \tag{2.37}$$

where: C_p is the power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind. The power coefficient of a turbine depends on factors such as the profile of the rotor blades, blade arrangement and setting, etc., is given by:

$$C_p = \frac{P_m}{\frac{1}{2}\rho A V^3} = \frac{P_m}{\frac{1}{2}\rho \frac{\pi}{4} D^2 V^3} = \frac{\text{Rotor power}}{\text{Power in the wind}} \tag{2.38}$$

The electrical power output P_e of the wind generator is given by:

$$P_e = \frac{1}{2}\rho\, A\, V^3 c_p\, \eta \tag{2.39}$$

where: η is the efficiency of the gearbox and electrical generator.

The wind energy (E_{AEP}) generated by a wind turbine is given by:

$$E_{AEP} = T \int_0^{\infty} f(V)\, P_m dV \tag{2.40}$$

After rearranging of Eq. 2.36, Eq. 2.37 and Eq. 2.39 to the maximum power density available, the actual mechanical power density output and the electrical power density output from the wind, respectively, as demonstrated in Fig. 2.9.

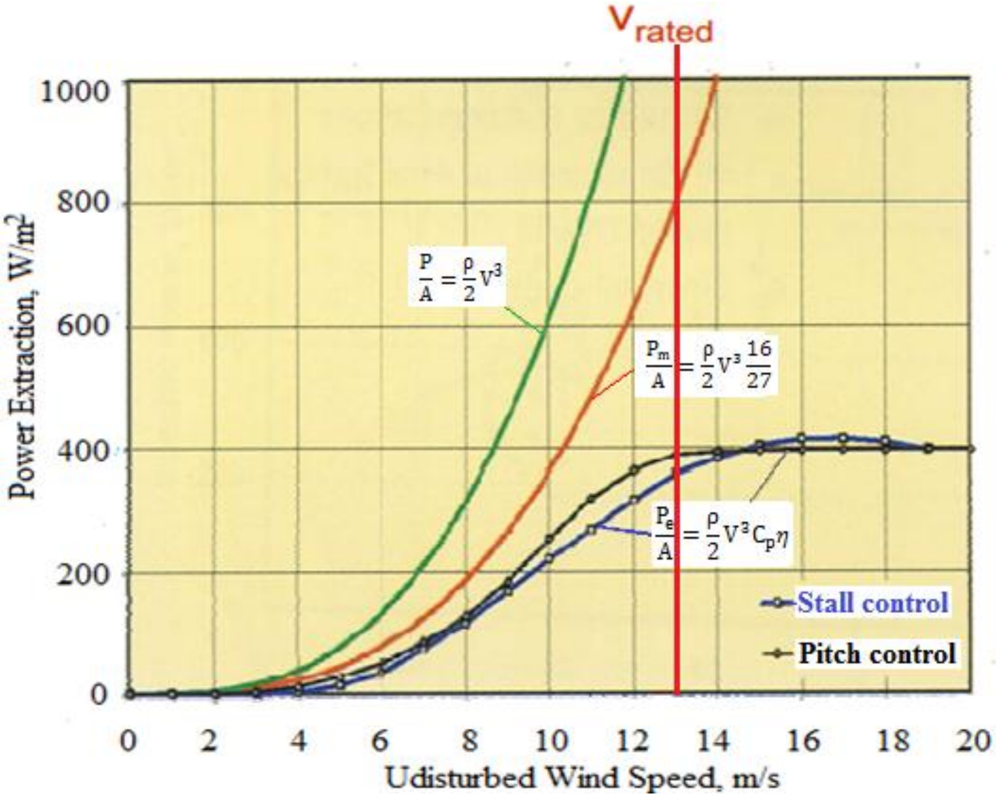

Figure 2.9: Typical power curve overview [24].

Power control

Wind turbines reach the highest efficiency at the designed wind speed, which is usually between 12 to 16 m/s [26]. At this wind speed, the power output reaches the rated capacity. Above this wind speed, the power output of the rotor must be limited to keep the power output close to the rated capacity and thereby reduce the driving forces on the individual rotor blade as well as the load on the whole wind turbine structure. A power curve of a typical wind turbine is shown in Fig. 2.9. The common methods to control the wind power output are:

a. Pitch control:

A wind turbine blade offers its maximum aerodynamic performance at a given angle of attack α.The angle of attack of a given blade profile changes with the wind velocity and rotor speed. Principle of pitch control is illustrated in Fig. 2.10. Here V_R is the rated wind velocity; V_T is the velocity of the blades due to its rotation and α is the angle of attack. In a pitch controlled wind turbine, the electronic sensors constantly monitor the variations in power produced by the system.

According to the variations in power output, the pitch control mechanism is activated to adjust the blade pitch at the desired angle of attack as described below.

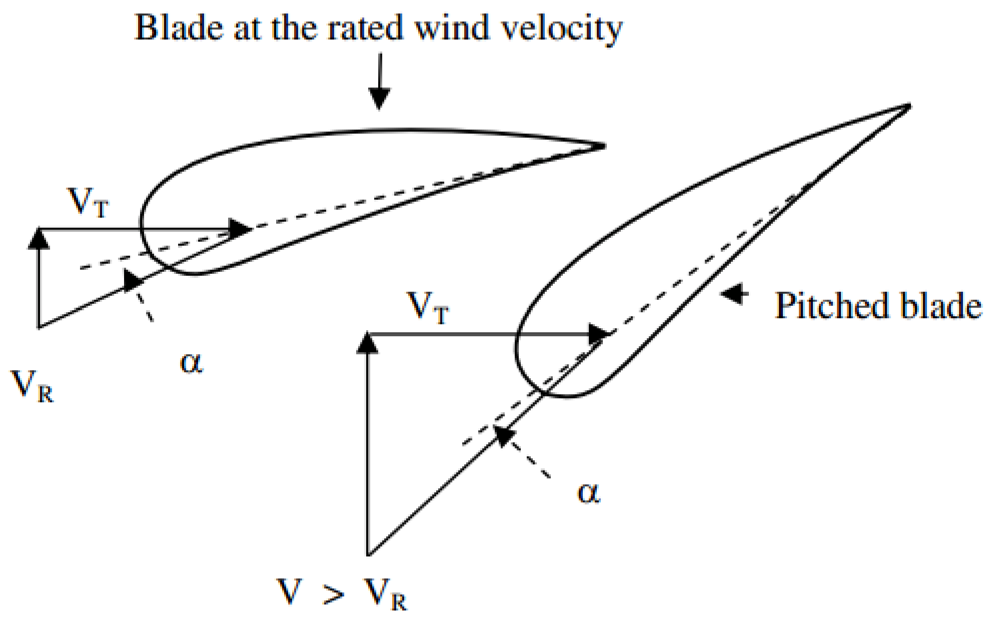

Figure 2.10: Principle of pitch control [10]

Between the cut-in and rated wind speeds, the turbine is made to operate at its maximum efficiency by adjusting the blade pitch to the optimum angle of attack. As the wind velocity exceeds V_R, the control mechanism changes the blade pitch resulting in changes in the angle of attack as shown in Fig. 2.10. Once the velocity goes below the rated value, the blade is pitched back to its optimum position. In a pitch controlled turbine, the blades are to be turned by the pitch control mechanism in tune with the variations in wind speed.

b. Stall control:

The basic principle of stall regulated turbines is illustrated in Fig. 2.11. In these wind turbines, the profile of the blades is designed in such a way that when the wind velocity exceeds beyond the rated limit, the angle of attack is increased as shown in Fig. 2.11. With this increase in angle of attack, air flow on the upper side of the blade ceases to stick on to the blade. Instead, the flow starts whirling in an irregular vortex, causing turbulence. This reduces the lift force on the blades, finally leading to blade stall. Thus, the excess power generated at high wind is regulated.

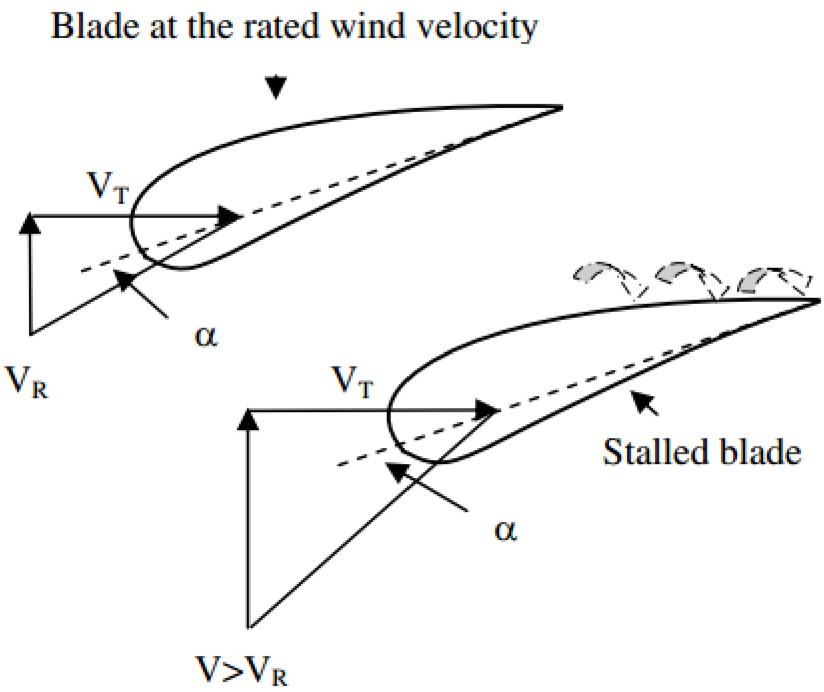

Figure 2.11: Principle of stall control [10]

Power curve of a stall controlled turbine is shown in Fig. 2.9. Performance of these turbines at higher wind speeds is not impressive as the power falls below the rated level.

2.9.1 Weibull based approach

Replacing the Weibull distribution Eq. 2.3 into 2.40, the total wind energy generated by the wind turbine, over a given period of time at its performance region 1 from V_{in} to V_r and region 2 from V_r to V_{out} of the power curve is given by:

$$E_{AEP} = T[\int_{V_{in}}^{V_r} (\frac{k}{A}\left[\frac{v}{A}\right]^{k-1} e^{-(v/A)^k})P_m dV + \int_{V_r}^{V_{out}} (\frac{k}{A}\left[\frac{v}{A}\right]^{k-1} e^{-(v/A)^k})P_m dV] \quad (2.41)$$

where: $P_m = \frac{1}{2} C_p \rho A V^3$ for $V_{in} < V < V_r$

$= \frac{1}{2} C_p \rho A {V_r}^3$ for $V_r < V < V_{out}$

V_{in} = Cut-in wind speed, m/s

V_{out} =Cut-out wind speed, m/s

V_r = Rated wind speed, m/s

For this study, the Weibull based approach has been chosen to evaluate the wind energy generated by wind turbine than Rayleigh based approach [10].

2.9.2 Rayleigh based approach

Replacing the Rayleigh distribution Eq. 2.18 into 2.40, the total wind energy generated by the wind turbine, over a given period of time at its performance region 1 from V_{in} to V_r and region 2 from V_r to V_{out} of the power curve is given by:

$$E_{AEP} = T[\int_{V_{in}}^{V_r} (\frac{\pi}{2}\frac{v}{V_m^2} e^{-\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2})P_m dV + \int_{V_r}^{V_{out}} (\frac{\pi}{2}\frac{v}{V_m^2} e^{-\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2})P_m dV] \tag{2.42}$$

2.9.3 Capacity factor

The capacity factor (CF) is one of the important indices for evaluating the field performance of a wind farm. It is defined as the ratio of the actual energy produced by the system to the energy that could have been produced by it, if the machine would have operated at its rated power throughout the time period. Thus,

$$CF\ (\%) = \frac{\text{Net actual annual energy output}}{(\text{Rated power x hours in a year x no.of turbines})} \text{x } 100\ \% \tag{2.43}$$

The wind farm capacity factor will typically ranges from 20 to 40 % [22]. The lower ends of the range is representative of older technologies installed in average wind regimes while the higher end of the range represents the latest wind turbines installed in good wind regimes [22].

CHAPTER THREE

3. MEASURED WIND DATA ANALYSIS

A proper analysis of measured wind data is very crucial for estimating the wind energy potential at the site, the wind data collected from the location is properly analyzed and validated, before incorporated into site analysis. Accordingly, statistical softwares such as MS Excel and MATLAB have been implemented for the wind-mast site data to perform specialized statistical analysis to obtain the best input to WAsP software.

Therefore, the integrated 10 minute mean wind data for the year 2008 has been used to analyze 10 minute average, daily average, monthly and annual mean wind speeds, wind speed frequency distribution, wind rose diagram, wind power density, wind shear and turbulence intensity are normally used for reporting purposes.

3.1 WIND DATA MEASUREMENT

The two wind-masts were installed in Aysha wind farm, the new GTZ managed public-private partnership (PPP) consortium erected a 40 m high wind-mast which provides data since end of January 2010, located at longitude 234839.30 m E and latitude 1183062.66 m N, and another 10 m high wind-mast was built in 2007 which recorded data since October 2007 to early September 2010, located at longitude 235162.18 m E and latitude 1191631.67 m N, about 9 km away from 40 m high wind-mast in the wind farm as presented in Fig. 3.1.

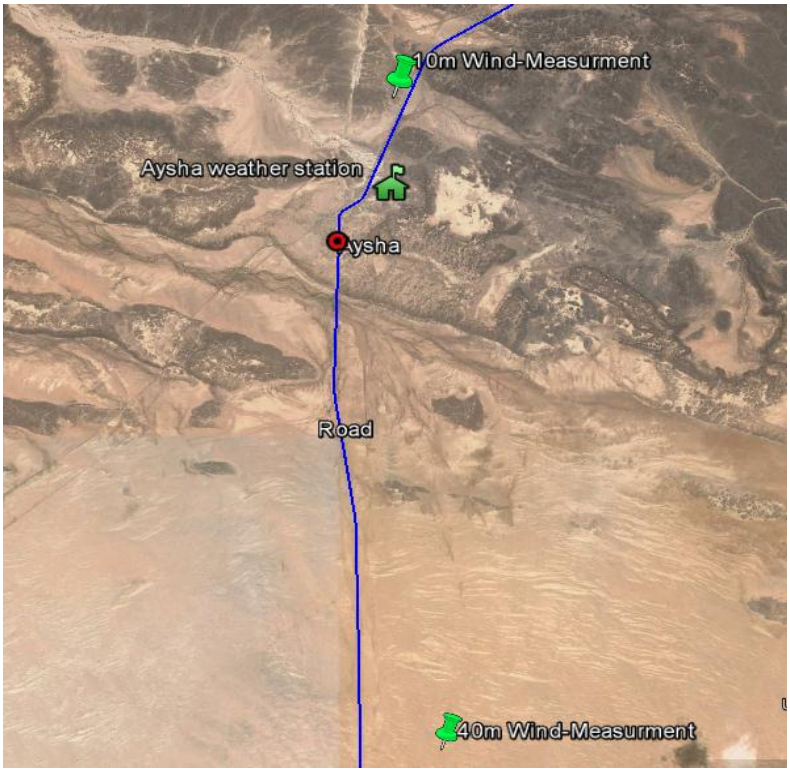

Figure 3.1: The relative position of two wind-masts

Because of failed to obtain a 40 m wind-mast data, the 10 m wind-mast data is used to evaluate the wind energy at the site.

3.2 DATA VALIDATION

Data validation is the inspection of all the collected data for completeness and reasonableness, and the elimination of erroneous values in the data records. Accordingly, the data validation has been done following routines indicated below:

Data screening:

- Arranging the raw data as per their category such as wind speeds, wind directions and standard deviations are computed using MS Excel.
- Checking the availability of the missing data

Data verification:

- Range test: The measured data are compared with upper and lower limiting values.
- Trend test: The measured data are checked based on the rate of change in a value over time.

Finally, the validated data file is created as input to the MS Excel and MATLAB software to analyze the wind data at the wind-mast.

3.2.1 Data arranging

The 10 m wind-mast data given in Table 3.1 are data measured in 2007, 2009 and 2010 are incomplete. The 88.25 % relatively complete data collected at 10 m wind-mast in 2008 is used to evaluate the wind energy resource potential analysis. The remaining 11.75 % measured data were missed. The 10 m wind-mast data of 2007, 2009 and 2010 are used to supplement the missing data of 2008. The wind energy resource analysis at the site is based on the 10 m wind-mast integrated data in 2008. One year integrated data of 2008 is sufficient to represent long term seasonal variation in the wind profile with 90 % confidence level [10].

Table 3.1: The organized result of 10 m wind-mast data

Year	2007	2008	2009	2010
Measurement time	2007.8.1-2007.12.31	2008.1.1-2008.12.31	2009.1.1-2009.12.31	2010.1.1-2010.9.2
Measuring items	19445	46510	37155	29672
Missing measurement time	2007.8.1 0:00 -12:20; 2007.12.14 13:20 -23:50 ; 2007.12.14 13:20 -23:50 2007.12.31;	2008.1.1 0:00 -23:50 2008 .1.31; 2008.2.11 0:00 -12:00; 2008.5.5 0:00 -23:50 2008 5.15; 2008.9.1 0:00 -12:10	2009.1.14 21:00 -23:50 2009.1.31; 2009.2.4 0:00 -14:40; 2008.2.29 0:00 -23:50; 2009.4.1 0:00 -8:10 2009.5.12; 2009.5.24 17:20-15:30 2009.6.7; 2009.9.20 0:00 -10:30 2009 .10.23 ; 2009.12.31 0:00 -12:10	2010.2.12 3:50-23:50 2010.2.29 0:00 -23:50 2010.3.19 0:00 -13:30 2010.3.23 2010.4.13 0:00-12:00 2010.5.25 0:00-13:50 2010. 6.26 2010.9.2 3:10-23:50
Missing measuring items	2587	6194	15405	5608
Items to be measured	22032	52704	52560	35280

Completeness	88.26 %	88.25 %	70.69 %	84.10 %

3.2.2 Missing wind data substitution and averaging

Missing wind data are substituted by averaging wind data with equivalent date and time can significant to reduce the uncertainty in the observed speeds [19] is given in Table 3.2.

Table 3.2: Substituting missing measured wind data

Missing measurement date and time	Substituted by equivalent date and time
2008.1.1 0:00 - 23:50 2008 .1.31	Mean data of 2009 and 2010 0:00 - 20:50
	2009 21:00 - 23:50
2008.2.11 0:00 -12:00	Mean data of 2009 and 2010.2.11 0:00 - 12:00
2008.5.5 0:00 - 23:50 2008 5.15	2010.5.5 0:00 - 8:10 2010.12.05
	Mean data of 2009 and 2010.12.05 8:20-23:50
2008.9.1 0:00 -12:10	Mean data of 2007, 2009 and 2010 0:00 -12:10

3.3 WIND DATA DISTRIBUTION

Histogram is used to analyze the actual measured time series wind data distributions. It provides an information how often the actual measured time series wind speed blowing for which the mean wind speed within the specific range of intervals. To develop this histogram, the wind speed domain is divided into equal intervals with the width of 1 m/s (say 0-1, 1-2, 2-3, etc.) and the number of times the wind record is within this interval is counted. This distribution of wind speed is important in determining the percentage of time during a year, the power that could be generated from the wind turbines. Therefore, the mean wind speed plot for the actual measured time series (hourly and 10 minutes interval) wind data is shown in Fig. 3.2 to 3.5.

The frequency distribution of 10 minutes mean wind speed at 10 m height is given in Fig. 3.2.

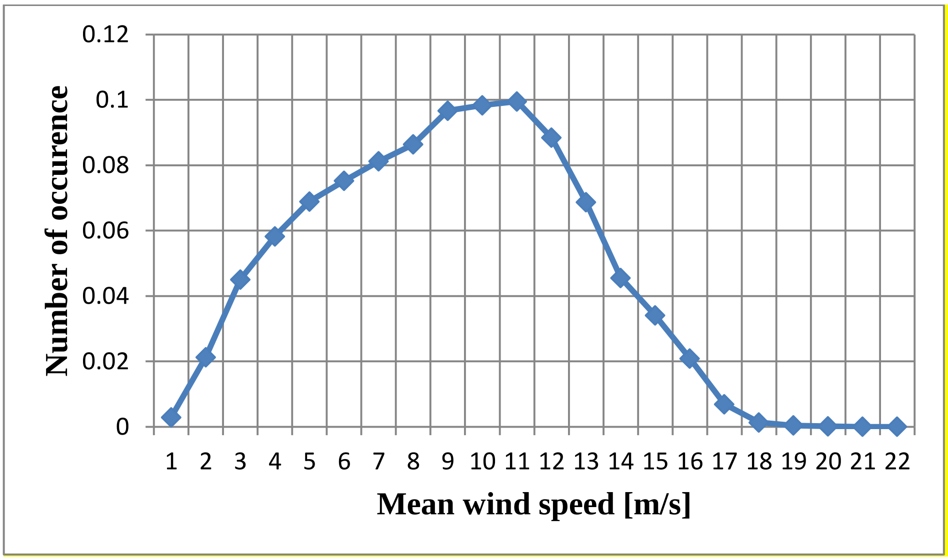

Figure 3.2: 10 min frequency distribution of measured mean wind speed

Fig. 3.2 depicts the most frequent occurrence wind speeds for 10 m height in the range of 10-11 m/s is 0.0995.

The measured data distribution of 10 minutes mean wind speed is presented in Fig. 3.3.

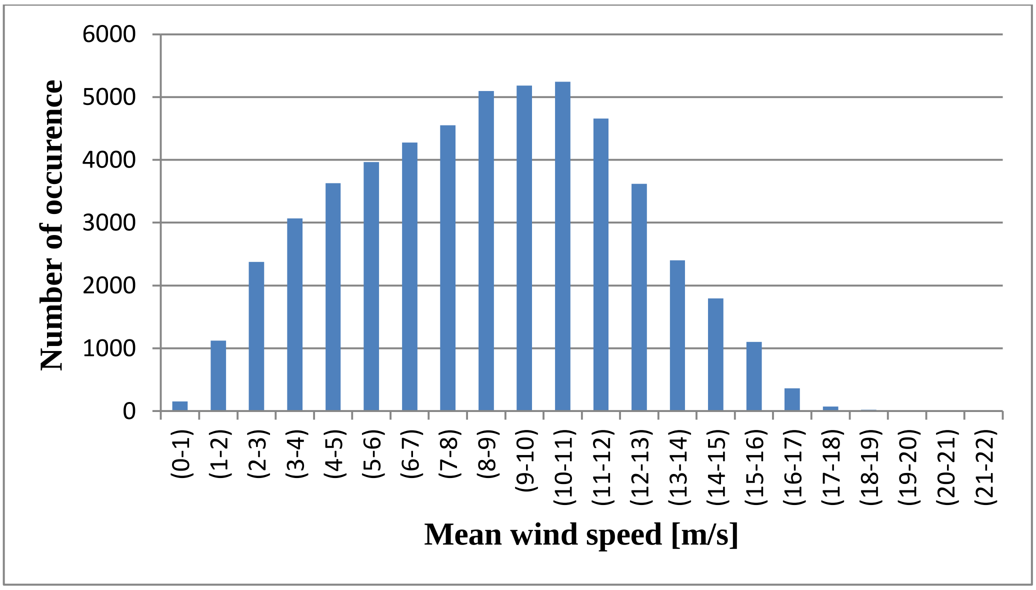

Figure 3.3: 10 min interval distribution of measured mean wind speed

Fig. 3.3 reveals the most frequent wind speeds in number of minutes for 10 m height in the range of 10-11 m/s is 5244.

The frequency distribution graph of hourly mean wind speed is given in Fig. 3.4.

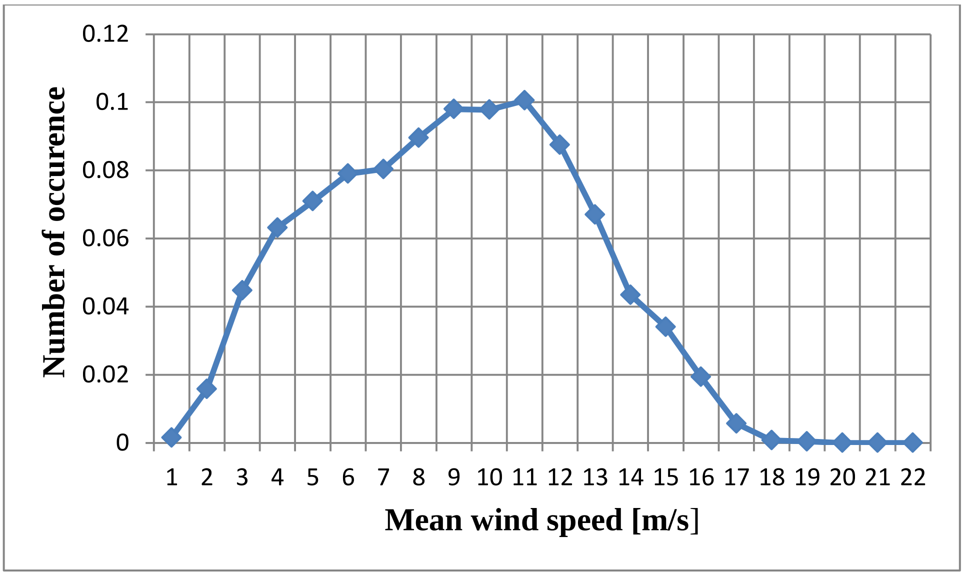

Figure 3.4: Hourly frequency distribution of measured mean wind speed

Fig. 3.4 depicts the most frequent occurrence for 10 m height in the range of 10-11 m/s is 0.0995.

The measured data distribution histogram of hourly mean wind speed is shown in Fig. 3.5

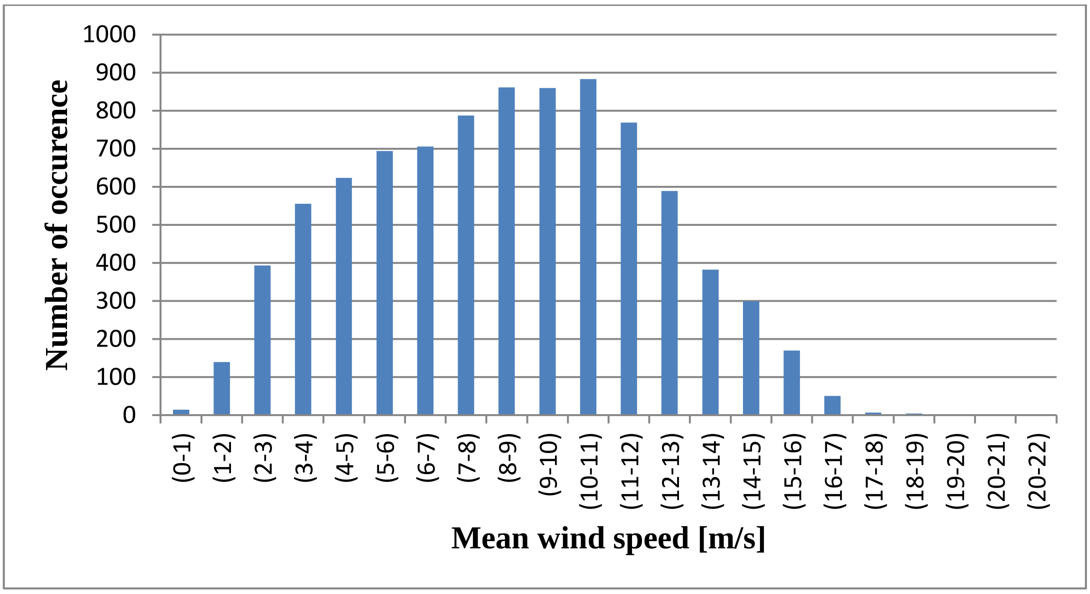

Figure 3.5: Hourly distribution of measured mean wind speed

Fig. 3.5 reveals the most frequent number of hours for 10 m height in range of 10-11m/s is 861.

3.4 TIME VARIATION OF WIND SPEED

Velocity and direction of wind change rapidly with time. In these changes, the power and energy available from the wind also vary. The variations may be short time fluctuation, day-night variation or the seasonal variation. Accordingly, knowledge of these time variations of velocity at a potential wind site is essential to ensure that the availability of power matches with the demand.

The different wind variations based on 10 minutes of hours, hours of a day, days of a year and also months of a year at 10 m height are demonstrated Fig. 3.6 to 3.9.

Fig. 3.6 to Fig 3.9 depict the mean wind speed with these times is the same as 8.455 m/s.

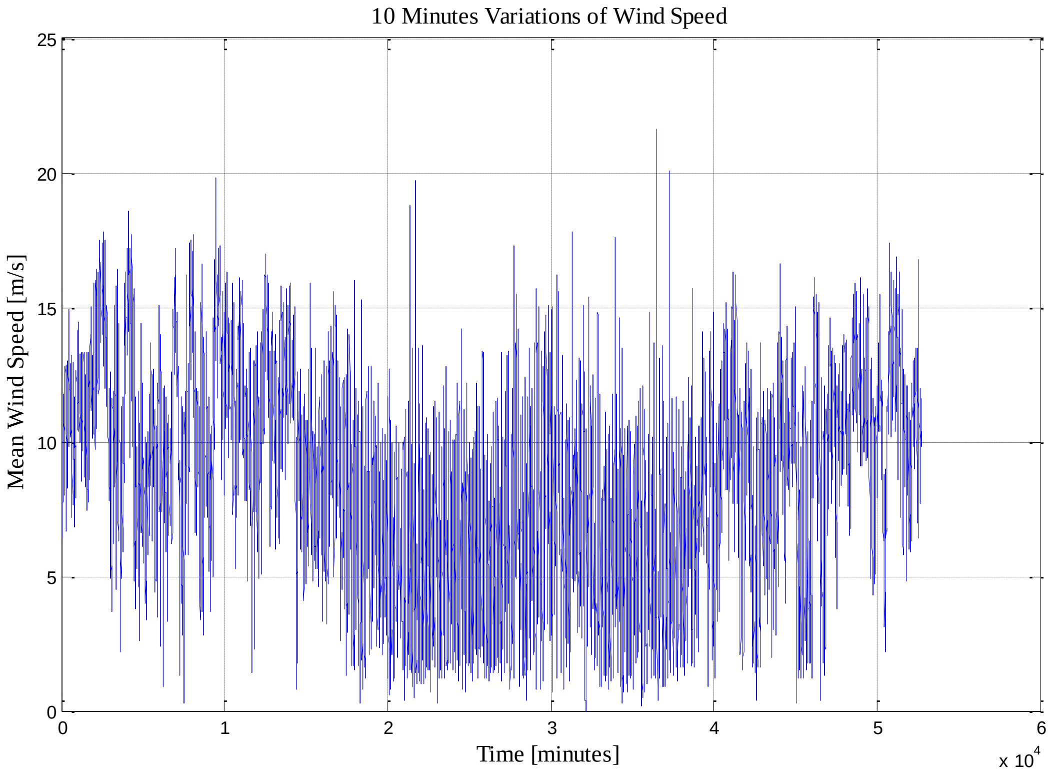

Figure 3.6: Comparison of 10 minute mean wind speed variation

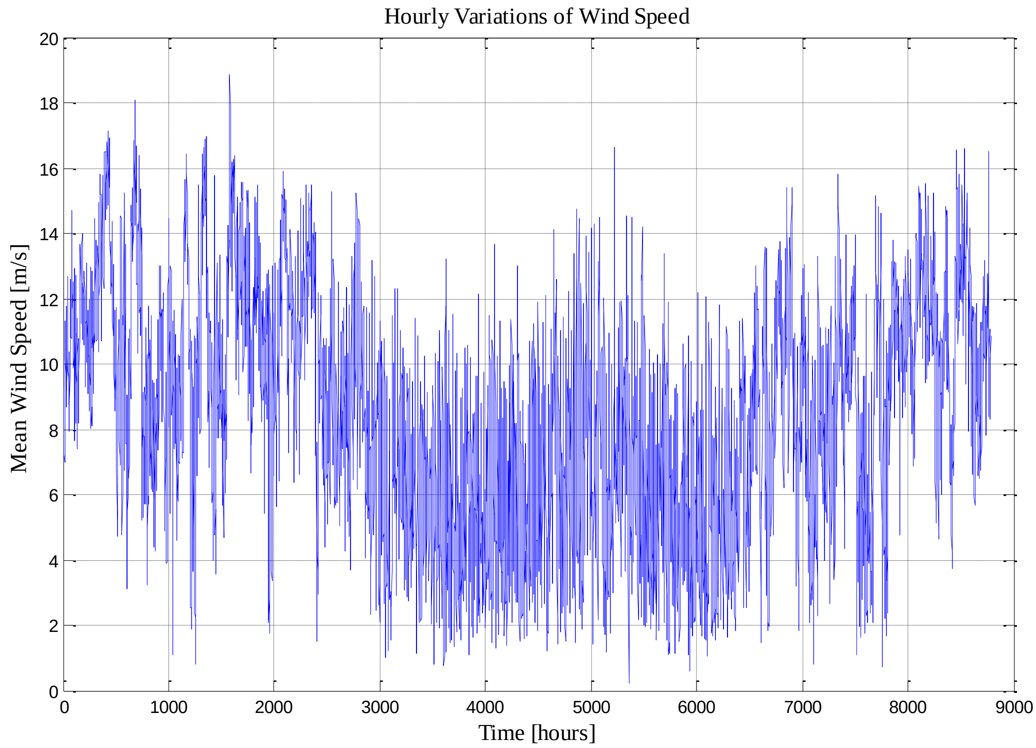

Figure 3.7: Comparison of hourly mean wind speed variation

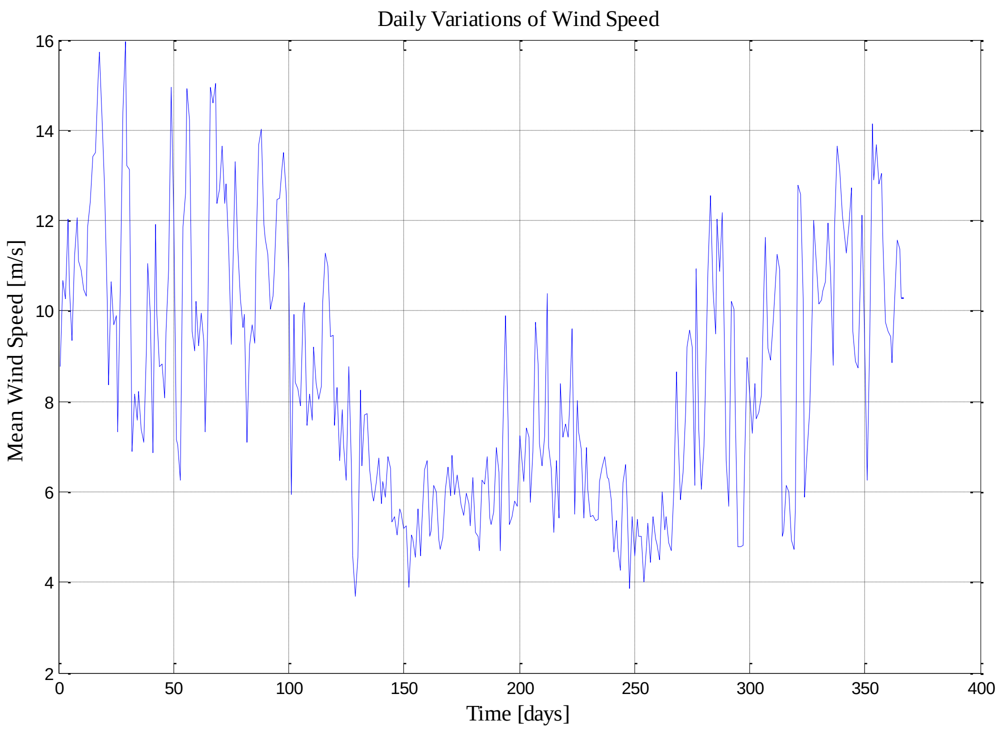

Figure 3.8: Comparison of daily mean wind speed variation

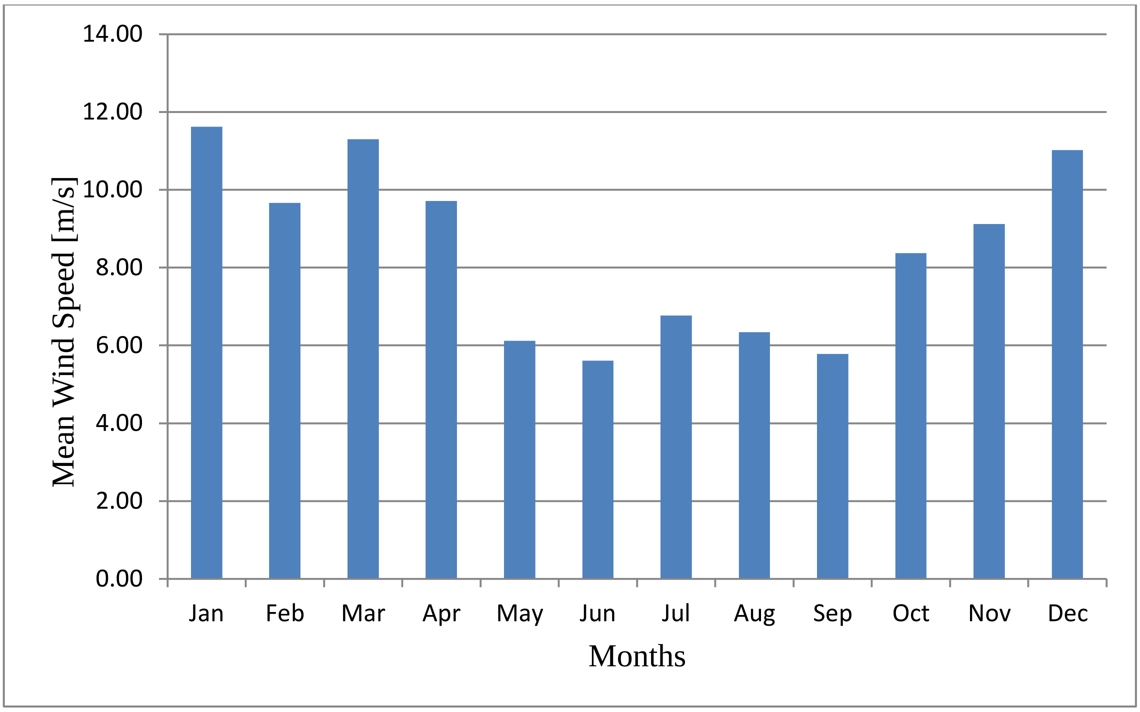

Figure 3.9: Comparison of monthly mean wind speed variation

Fig. 3.9 revels that the period between May to September is less wind speed recorded due to seasonal variation.

3.5 WIND SHEAR

Wind shear exponent cannot be calculated because there is only one height of wind-mast at the site. Considering the site, very smooth terrain characteristics, 3 year current wind data records at 70 m height and some uncertain factors of the wind farm, wind shear exponent of 0.1 is used to calculate at the site.

Using Eq. 2.21, the wind shear profile at the mast location for different heights is generated. Fig. 3.10 shows that the wind speed variation in vertical direction is very small at wind-mast location.

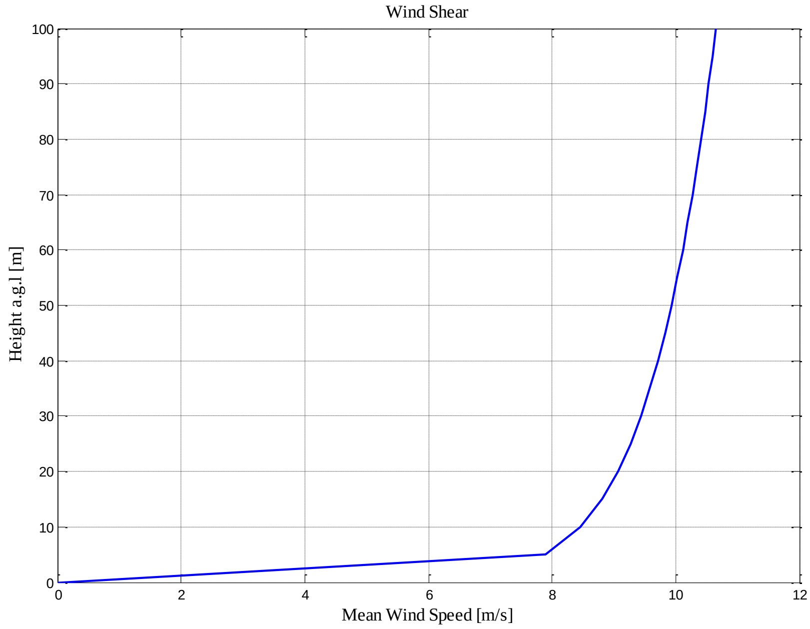

Figure 3.10: Wind shear at wind-mast for different heights

3.6 TURBULENCE INTENSITY

Using Eq. 2.24, the average turbulence intensity at 10 m height is 0.1371 as shown in Fig. 3.11. Therefore, Aysha wind-mast site is considered as moderate turbulence intensity site.

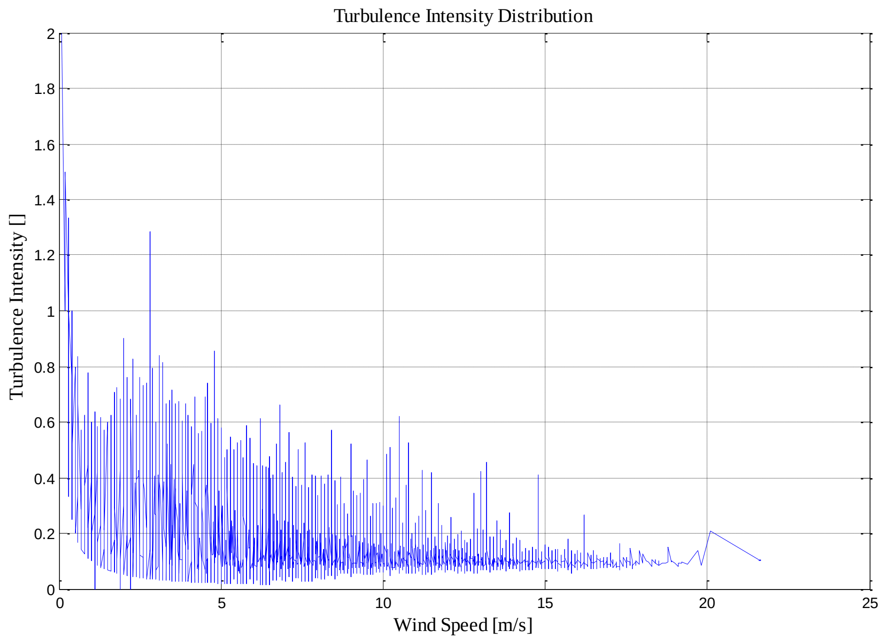

Figure 3.11: Turbulence intensity distribution variation

3.7 WIND ROSE

A wind rose is a graphical tool used to plot frequencies of wind in different directions and wind speed of the site. It is made from dividing the compass into 12 sectors, one for each 30^0 of the horizon. This graphical tool is used to determine and quickly indicate the dominant wind directions and the direction of strong wind speeds. Fig. 3.12 illustrates that the prevailing wind direction is from north-west of 68.4 %, the sub-prevail wind direction is from east of 8.8 % of the time in the wind blowing from these directions.

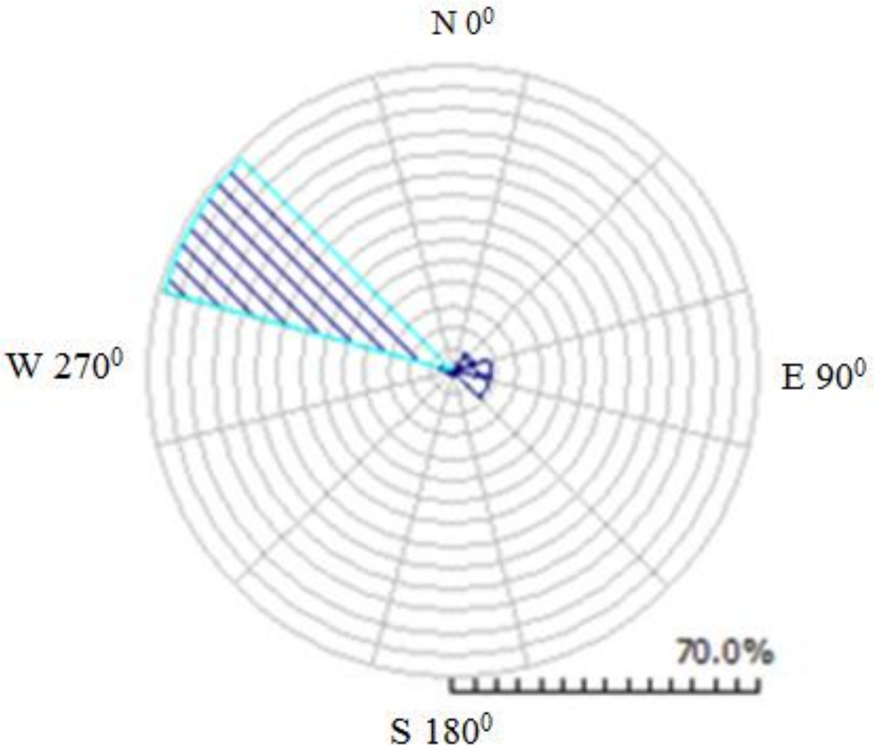

Figure 3.12:10 minutes interval wind frequency rose

3.8 WIND POWER DENSITY

Wind power density (W/m^2) is a comprehensive index in evaluating the wind resource at a particular site that can be estimated by using following equation at 10 m height is given by:

$$\frac{P}{A} = \frac{1}{2}\rho\frac{1}{n}\sum_{i=1}^{n} V_i^3 \qquad (2.44)$$

where: P= power, A= swept area of rotor, ρ = air density and V_i= wind velocity

Based on Eq. 2.44, the average wind power density of the site is calculated 501.97 W/m^2 at height of 10 m whereas wind power density at each wind speed is also plotted as depicted in Fig. 3.13. It can be seen that the power density varies from 0 at 0 m/s to 5441.956 W/m^2 at 21.6 m/s at 10 m height. The wind class of the site can be decided based on annual mean wind speed and annual average power density as shown in appendix B [13]. Accordingly, the mean wind speed of 8.455 m/s and the average power density of 501.97 W/m^2 of the Aysha wind farm site is categorized as class 7 (excellent wind energy resource). For large-scale wind plants, class 4 or higher is preferred [13]. Therefore; the site is promising to construct large wind farm.

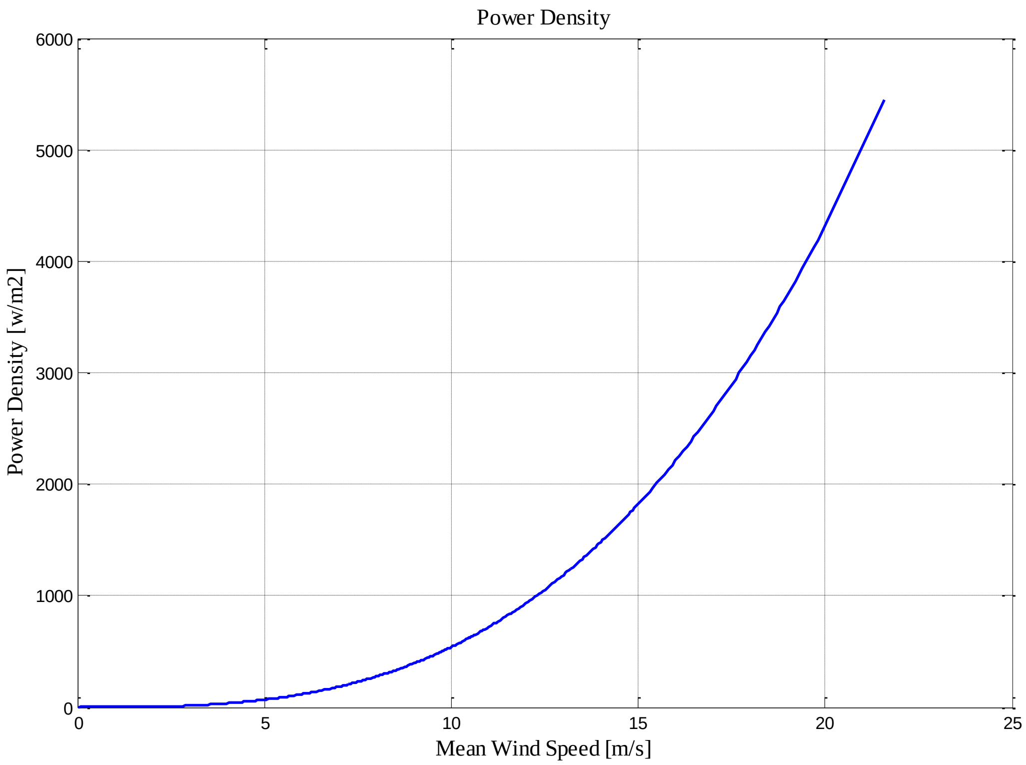

Figure 3.13: Average power density variations

CHAPTER FOUR

4. ANALYSIS OF SITE WIND ENERY RESOURCE POTENTIAL USING WAsP SOFTWARE

4.1 WAsP SOFTWARE

The Wind Atlas Analysis and Application Program (WAsP) is a software program for predicting wind climates, wind resources and power productions from wind turbines and wind farms. The predictions are based on wind data measured on site or from meteorological stations in the same region and considers the effects of surroundings terrain to the wind flow (elevation, roughness and sheltering obstacles).

The strong features of WAsP software are [13]:

- Easy to use
- Cheap and fast
- Validated limitations are known and can be dealt with

Beside the strengths mentioned above, the software has the following limitations [13]:

- Valid only near-neutral conditions
- Problems in complex terrain with flow separation

WAsP software uses wind atlas methodology is shown schematically in Fig. 4.1.

WAsP analysis: from wind data to wind atlas

1. Time-series of wind speed and direction → observed wind climate (OWC)

2. OWC + met. station site description → generalized wind climate (wind atlas)

WAsP application: from wind atlas to predicted wind climate

3. Generalized wind climate + site description → predicted wind climate (PWC)

4. Predicted wind climate + power curve →annual energy production (AEP) of wind turbine

Wind farm production: from predicted wind climate to potential AEP

5. Predicted wind climates + WTG characteristics →gross annual energy production of wind farm

6. Predicted wind climates + WTG characteristics + wind farm layout→wind farm wake losses

7. Gross annual energy productions - wake losses → net annual energy production of wind farm

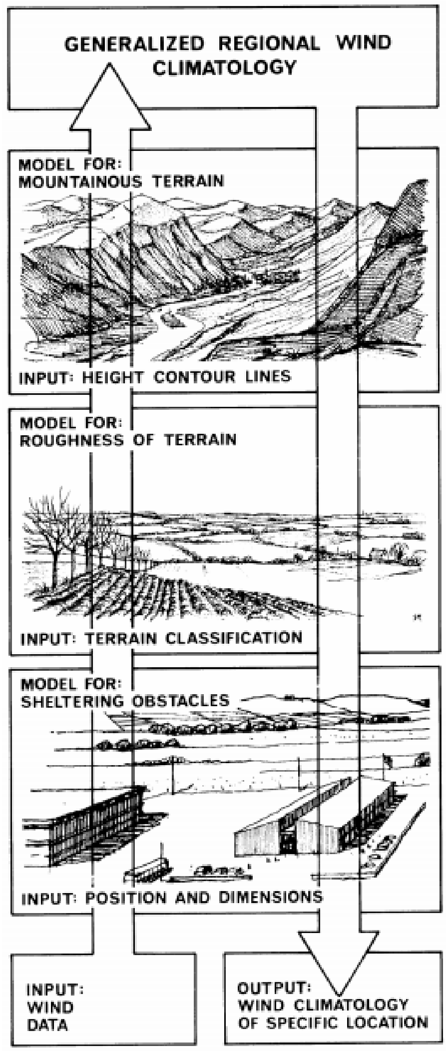

Figure 4.1: The wind atlas methodology of WAsP [12].

The Fig. 4.1 above is a schematic presentation of wind atlas methodology of WAsP that has two step processes:

1. In the analysis part (left and up arrow), the metrological models are used to calculate the generalized wind climatology from the measured data.
2. In the reverse process- the application of wind atlas data (right and down arrow) – the wind climate at any specific site may be calculated from the generalized wind climatology.

As can be deduced from the Fig. 4.1, the analysis of this site using WAsP software is then based on the two assumptions:

1. The predictor (met. station) and predicted sites (wind turbines) should be as similar as possible in the following respects:

- Climatic conditions:
  - Atmospheric stability
  - The generalized wind climate must be the same (synoptic and meso-scale)
- Similar topography:
  - Ruggedness (measured by ruggedness index) must be similar
  - Elevation and exposure
  - Background roughness
  - Distance to significance roughness changes (coastline)

2. The past (historic wind data) are assumed to be representative of the future (the 25-years life time of the wind turbines). The reliability of a given WAsP prediction depends very much on the extent to which these assumptions are fulfilled.

Based on wind atlas methodology of WAsP in Fig. 4.1, the analysis task is performed in the workspace hierarchy as shown in Fig. 4.2.

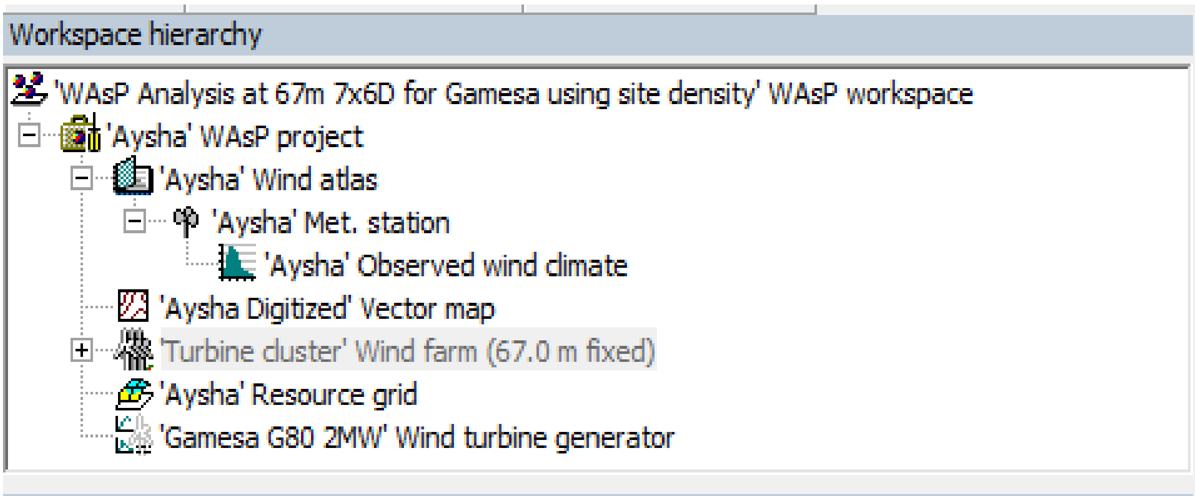

Figure 4.2: Workspace hierarchy

4.2 WASP INPUT PARAMETER

To start working with WAsP 10.2 software modeling, the following main input parameters are required by software [see Fig. 4.1]:

- Time-series of measured wind speed and direction data (OWC).
- Terrain: height contour lines, roughness, obstacles (digitized vector map).
- Turbine data: Quantity, layout and production curve.

Output: Average annual energy production (AEP).

More detail discussions are as given below.

4.2.1 Observed wind climate input

Observed wind climate is given input into WAsP, which contains the wind direction distribution (wind rose) and the sector-wise distribution of the mean wind speed (histogram), as shown in Fig. 4.3.The observed wind parameter file also contains the wind speed sensor (anemometer) at 10 meters height above the ground level and the geographical coordinates of the site: latitude (235162.18 m E) and longitude (1191631.67 m N).

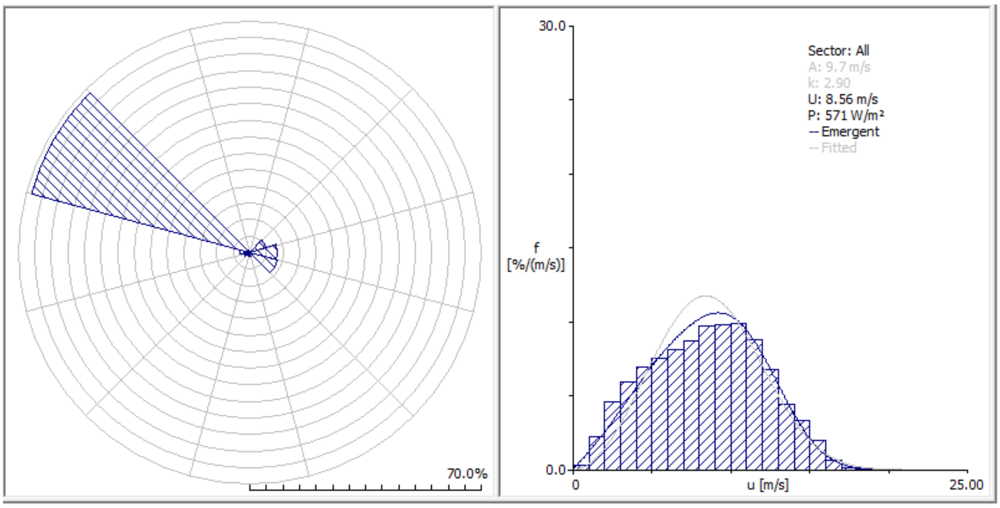

Figure 4.3: Observed wind climate of the site: wind rose (left) and wind speed distribution (right) at 10 m height.

Wind speed is given in meters per second [m/s] and wind direction in degrees clockwise from north [0^0], i.e. from 0^0 (north) through 360^0. The observed wind climate is given for 12 sectors and the wind speed histograms using 1m/s wind speed bins.

4.2.2 Terrain inputs (Digitized vector map)

Terrain inputs to WAsP are given in the digitized vector map, which contain height contour lines, roughness change lines, boarder of the wind farm site and sheltering obstacles. For digitizing vector map, the following detail discussions are given:

4.2.2.1 Height contours (Elevation) map

These lines are generated by importing Ethiopia's generalized height contour lines map into Global Mapper software. These files are then exported as vector map by using WAsP software which is presented in Fig. 4.4. The height contour map covers an area of 28.44 km x 36 km and the contour interval is taken as 25 m spacing from the 600 m to 1175m altitude above sea level where as the average altitude of the turbine site is 761.58 m.

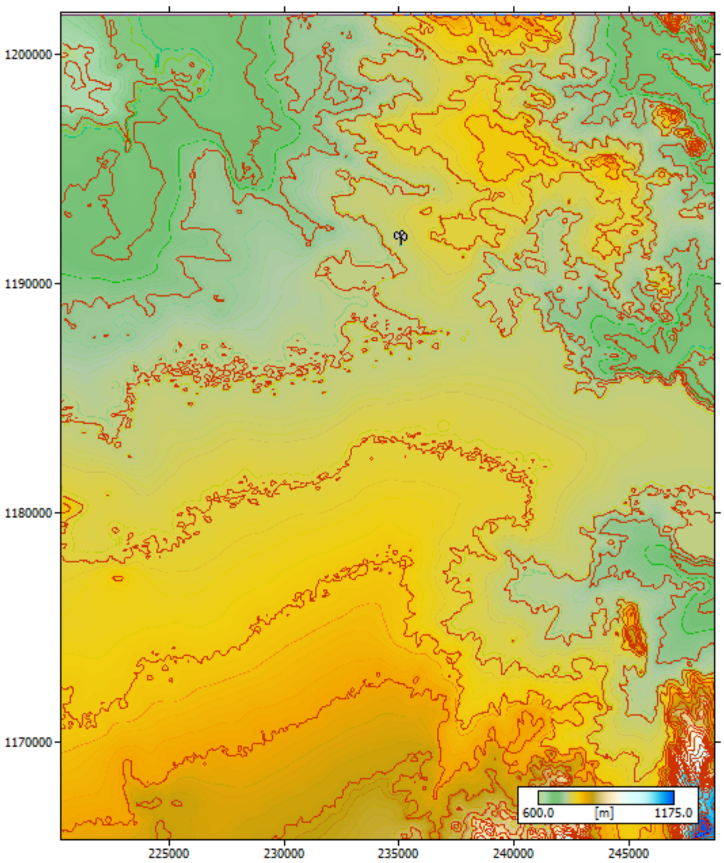

Figure 4.4: Elevation of the site

4.2.2.2 Roughness map

Roughness is classified in different categories of land cover and is given certain color and length as shown in Table 4.1. Roughness of different section is estimated by visiting the site area and using Google Earth software. The roughness map is revealed in Fig. 4.6.

Table 4.1: Roughness type, color and roughness length

No.	Roughness type (land cover)	Color of internal and external roughness change lines	Roughness Length (Zo) [m]
1	Sand surfaces (very smooth)	Internal polygoness enclosed by purple line	0.003
2	Bare soil (smooth)	Internal polygoness enclosed by orange line	0.005
3	Mown grass, grassy plains	External polygoness enclosed by outside yellow line	0.008
4	Exposed ridge tops and semi gobi with sparse vegetation (e.g. grass)	Internal polygoness enclosed by green line	0.03

The following steps have been used to digitize roughness areas using WAsP Map Editor as demonstrated in Fig. 4.5. WAsP Map Editor is a tool used to create digital map files for used by WAsP.

i. Loading the height contours file (see section 4.2.2.1 for details) into WAsP Map Editor.

ii. Loading the background image: This image is taken from Google Earth software that is useful to draw polygons to mark areas of uniform roughness and load into WAsP Map Editor.

iii. Digitizing the roughness areas: Roughness length (Zo) in meters is associated with inside the polygons and anther Zo outside is digitized based on Table 4.1

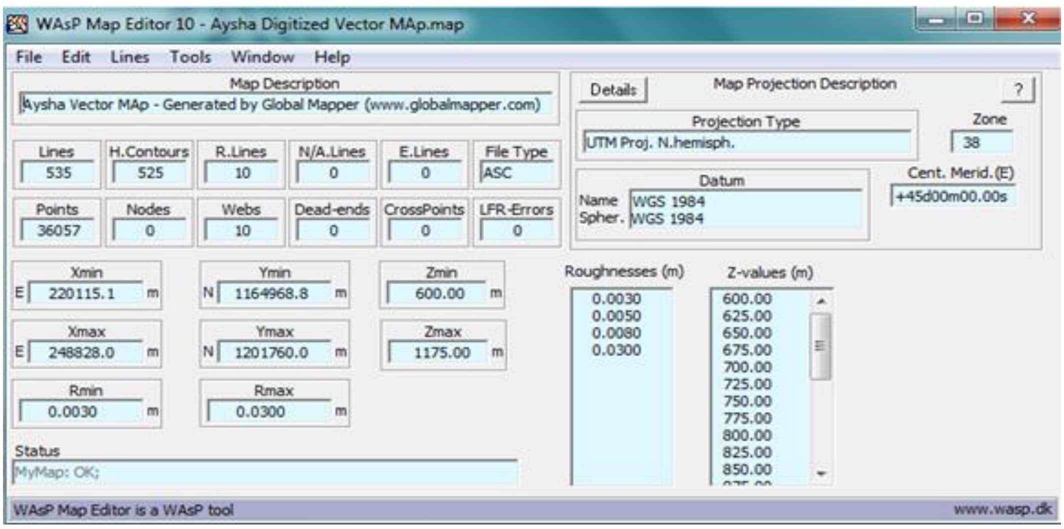

Figure 4.5: WAsP Map Editor Window

The roughness change model in WAsP takes into account the influence of changes in roughness near the site. Accordingly, as a rule of thumb, a map should extend to at least to 10 km (in all directions) from the predictor (met. station) and predicted sites (wind turbines) [12]. Therefore, the roughness map area is covered by 28.44 km from east to west and 36 km from north to south as depicted in Fig. 4.6.

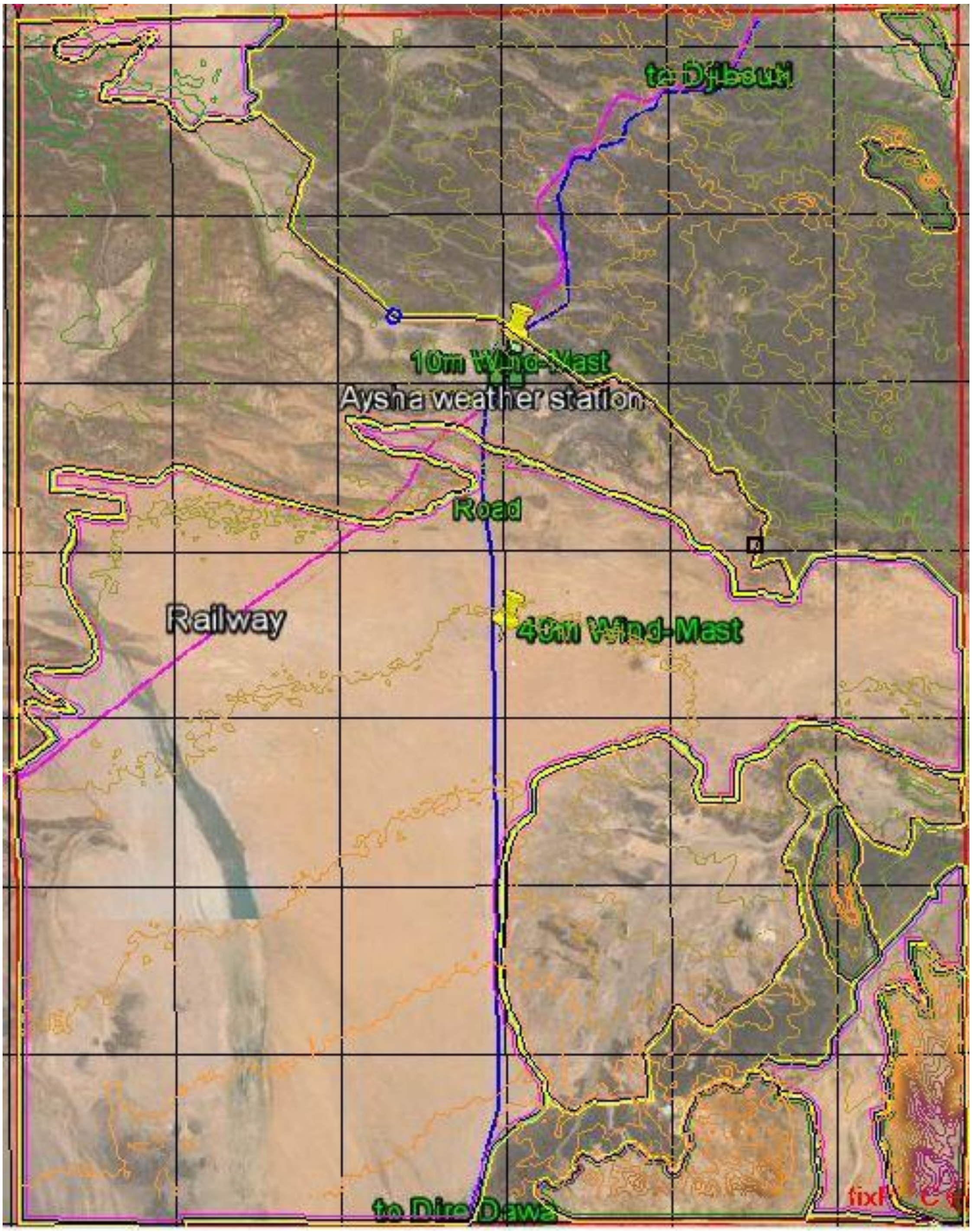

Figure 4.6: Site roughness estimation and elevation

4.2.2.3 Sheltering obstacles

Position and dimension of sheltering obstacles are estimated and checked away from the site (wind-mast, turbine hub and other calculation point) by visiting the site area and using Google Earth software. Accordingly, the sheltering effect is outside this zone which extends vertically up to 3 times the height of the obstacle and horizontally up to 30 to 40 times the heights. Therefore, it is treated as roughness element.

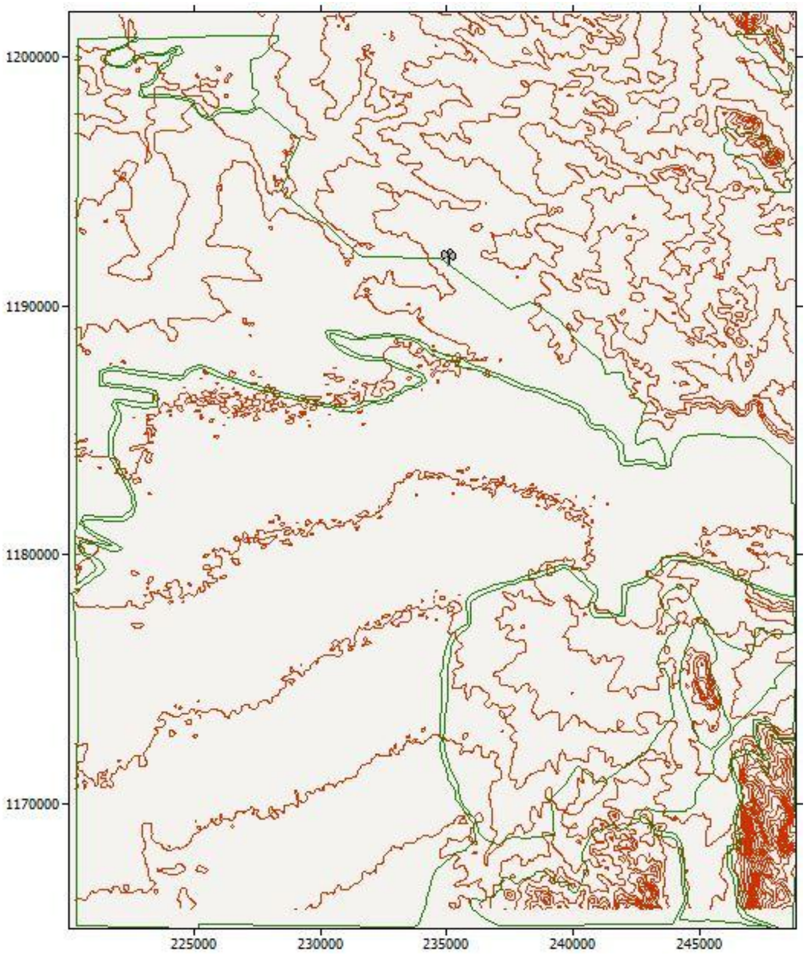

Figure 4.7: Digitized vector map consisting elevation and roughness

Digitized vector map file contains both elevation and roughness information but the sheltering obstacle is not found as shown in Fig. 4.7. The digitized vector map file is then loaded into the main WAsP application.

4.2.3 Turbine data inputs

The turbine data inputs to WAsP consist of the quantity of turbines, optimal layout or micro-sitting of the wind farm (turbine site coordinates) and the characteristics of the wind turbine generators: hub height, rotor diameter and the site-specific power and thrust curve.

4.3 WIND TURBINES SELECTION AS PER IEC STANDARD, LAYOUT AND ESTIMATION OF AEP

4.3.1 Selection of wind turbine class as per IEC

The wind turbine class is selected under consideration of the following site parameters at deferent heights resulted from the wind-mast data analysis:

- Annual mean wind speed, V_m
- Reference wind speed, V_{ref}
- Turbulence intensity, T_I

Annual mean wind speeds (V_m) and reference wind speeds (V_{ref}) at different heights have been found using the following steps:

i. Extrapolating 10 minute average wind speed at 10 meter height to respective heights using Eq. 2.21.
ii. 10 minute average extrapolated wind speeds (for the different heights) have been provided as observed wind climate, on WAsP, to produce the respective Weibull shape factor (A), scale factor (k) and annual mean wind speed (V_m) for each height as shown in Fig. 4.8 to 4.14.
iii. Reference wind speed (V_{ref}) is then calculated from annual mean wind speed (V_m) using Eq. 2.23.

In addition, the following steps have been used to calculate the turbulence intensity (T_I) for the respective heights:

i. Turbulence intensity is calculated at 10 meter height using Eq. 2.24.
ii. Turbulence intensity above 10 m cannot be calculated using empirical methods because no wind speed or standard deviation data is available except for 10 meter height. Accordingly, the turbulence intensity above 10 m is estimated by taking into account the fact that turbulence intensity decreases with height above ground level in flat terrain as the near ground turbulence effects minimize with height [16].

In general, annual mean & reference wind speed as well as turbulence intensity calculated above are summarized in Table 4.2.

Table 4.2: The turbulence intensity, mean and reference wind speed at different heights

Parameters	H [10 m]	H [30 m]	H [50 m]	H [67 m]	H [70 m]	H [80 m]	H [100 m]
Height [m]	10	30	50	67	70	80	100
V_m [m/s]	8.56	9.56	10.04	10.35	10.41	10.54	10.76
V_{ref} [m/s]	42.8	47.80	50.20	51.75	52.05	52.70	53.80
T_I [-]	0.1371	< 0.1371					

The class of wind turbine to be installed at Aysha wind farm is IB judging by the V_m, V_{ref} and T_I under the instruction of IEC 614001-1999, and the class is IB by the V_{ref} and T_I under the instruction of IEC 614001-2005.

However, considering the turbulence intensity of the existing wind farms in Ethiopia and also taking the safe operation into account, it is proposed that wind turbine of IEC IA shall be installed at Aysha wind farm.

4.3.2 Turbine Selection

According to IEC classification, the following points are considered to select the wind turbines.

- Cut-in, rated and cut-out wind speed
- Turbine rating at wind speed for maximum energy generation
- Availability of the wind turbines in the market
- Technology improvements
- Transport and construction conditions

Accordingly, as a first step, the measured site wind characteristics (Weibull distribution function) and the wind turbine generators characteristics (wind speed versus power curve) need to match properly. And the wind turbine should be rated at the wind speed at which maximum energy is available. Thus, the wind speed for maximum energy generation using Eq. 2.30 and $V_{E\ max\ 2} = (1.2\text{-}1.5)*V_m$ [13] of the site values are estimated in Table 4.3.

Table 4.3: The wind speed for maximum energy generation at different heights

Parameters	H [10 m]	H [30 m]	H [50 m]	H [67m]	H [70 m]	H [80 m]	H[100 m]
Height [m]	10	30	50	67	70	80	100
V_m [m/s]	8.56	9.56	10.04	10.35	10.41	10.54	10.76
A [m/s]	9.7	10.9	11.40	11.80	11.80	11.90	12.20
k [-]	2.9	2.92	2.88	2.92	2.90	2.88	2.90
V_E max1 [m/s]	11.62	13.03	13.69	14.11	14.14	14.29	14.62
V_E max2 [m/s]	10.27-12.84	11.47-14.34	12.05-15.06	12.42-15.53	12.49-15.62	12.65-15.81	12.91-16.14

The annual mean wind speed is indicated (10.35-10.41) m/s and rated wind speed as (14.11-14.14) m/s which is considered to have high energy loss and the units to be less efficient for this site. Therefore the second Eq. is used to evaluate.

Fig. 4.8 to 4.14 show the Observed Wind Climate for different heights at the wind-mast:

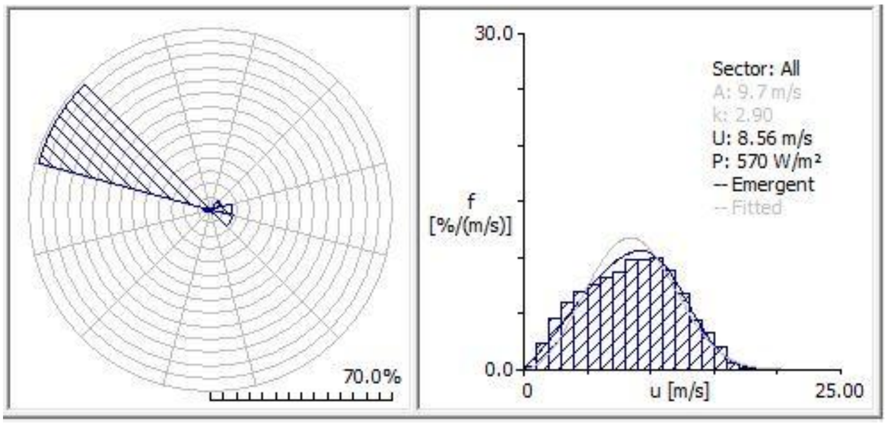

Figure 4.8: Observed Wind Climate at 10 m height

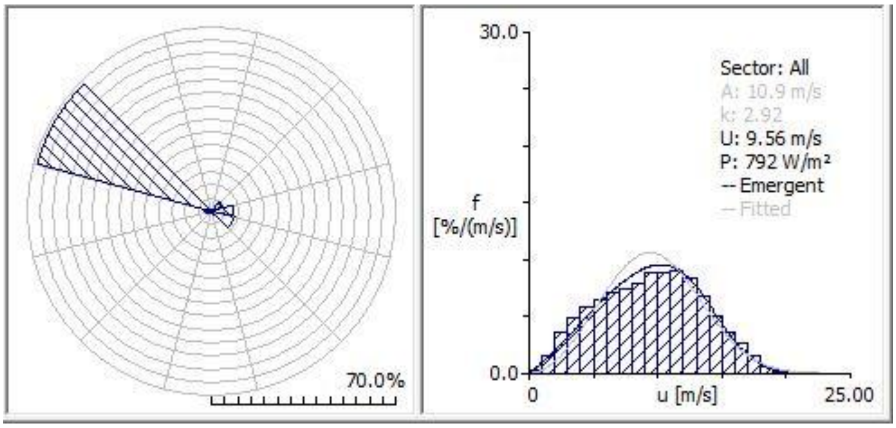

Figure 4.9: Observed Wind Climate at 30 m height

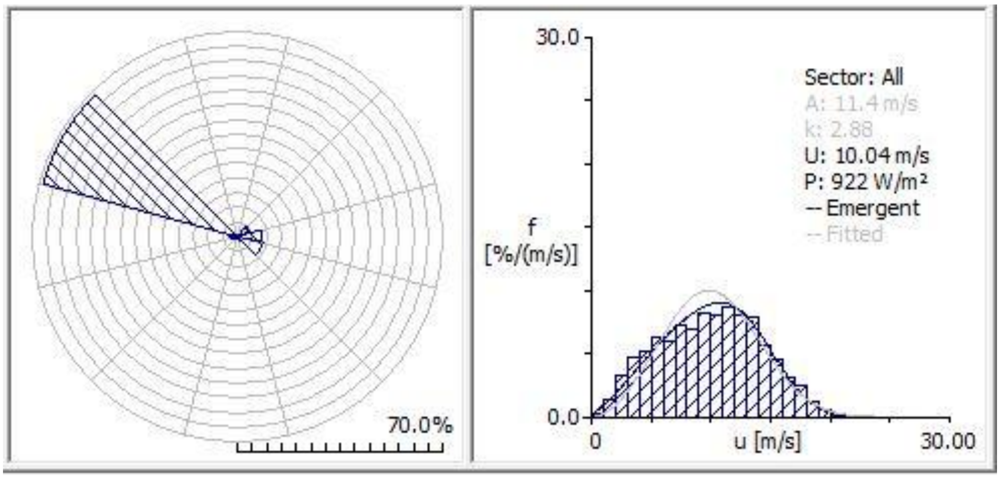

Figure 4.10: Observed Wind Climate at 50 m height

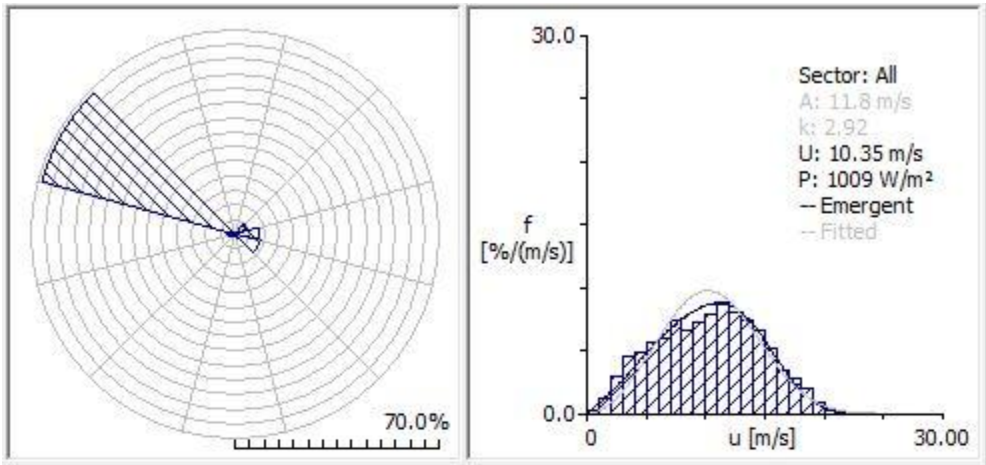

Figure 4.11: Observed Wind Climate at 67 m height

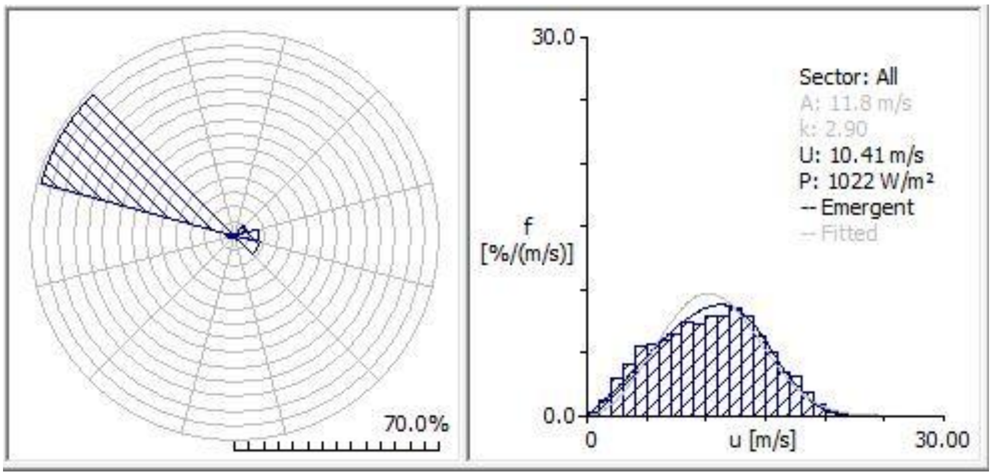

Figure 4.12: Observed Wind Climate at 70 m height

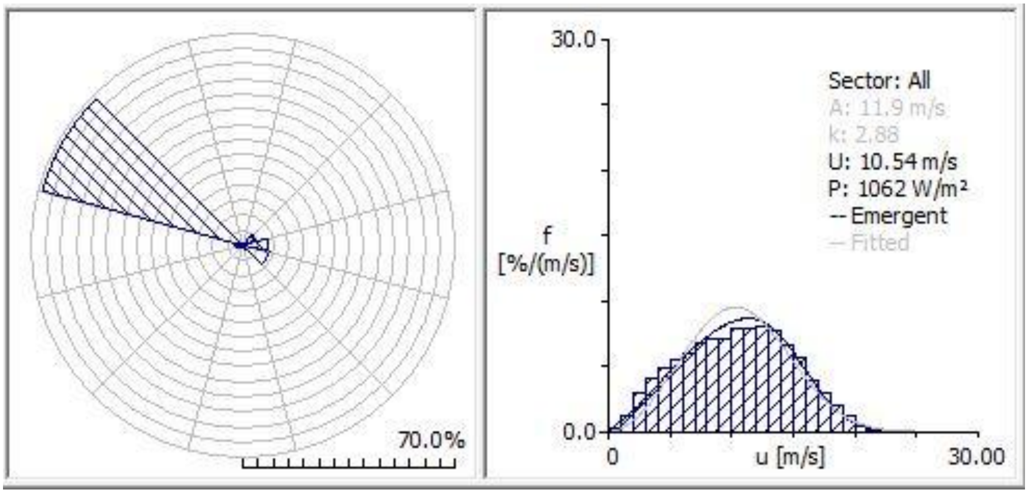

Figure 4.13: Observed Wind Climate at 80 m height

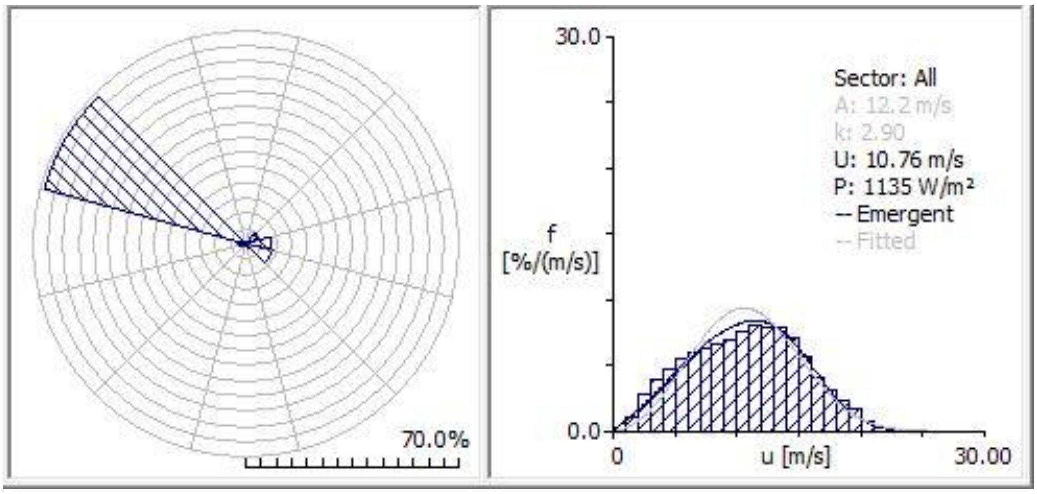

Figure 4.14: Observed Wind Climate at 100 m height

Therefore, based on the above criteria's, two wind turbines namely Gamesa G80 2 MW and Sany SE8220III 2 MW are chosen from the top 16 wind turbine manufacturers in the world (Goldwind (China), Sany (China), Gamesa (Spain), Alstom Wind (Spain), Enercon (Germany), etc.).

The basic technical parameters of the two wind turbines are given in Table 4.4 but appendix D provides more detailed technical parameters.

Table 4.4: Technical data of nominated wind turbines [20]

Wind turbine model	Rated power [MW]	Cut- in wind speed [m/s]	Rated wind speed [m/s]	Cut -out wind speed [m/s]	Rotor diameter [m]	Swept area [m²]	Wind class IEC	Hub Height [m]	Maximum power coefficient [-]
Gamesa G80 2 MW	2	4	15	25	80	5027	Ia/IIa	67	0.433
Sany SE8220III 2 MW	2	3.5	12.82	25	82.5	5346	Ia/IIa	70	0.364

4.3.3 Power curve site air density correction (normalization)

Site air density at 10m height:

There is no temperature and air pressure observation data of 10 m wind-mast, the average temperature of Aysha Weather Station measured and the site average altitude are used to calculate average air density using the given formula is:

$$\rho = \left(\frac{353.05}{T}\right) e^{-0.034\left(\frac{Z}{T}\right)} \qquad (2.45)$$

where:

ρ is the air density, kg/m^3

Z is the project area average altitude, m

T is the average Kelvin temperature (273+^{0}C)

The average temperature of the wind farm from Aysha Weather Station is **27.02 ^{0}C**, and the wind turbine site average altitude is **761.582 m** at 10 m height.

Therefore, the calculated site air density at 10 m height using Eq. 2.45 is **1.079 kg/m^3.**

Site air density at hub height:

The annual average temperature at hub height is estimated by taking into account the fact that temperature falls by roughly 6.5 ^{0}C for every 1,000 m increase in altitude [22].

By using this rate, the average temperature of the site at 67 m hub height is:

= (0.0065 ^{0}C /1 meter) x 67 m hub height

=0.4355 ^{0}C is decreased per 67 m height

=27.02-0.4355 ^{0}C

=**26.5845 ^{0}C**

The wind turbine site average altitude at 67 m hub height is:

=761.58 at 10 m height + 67 m at hub height

= **828.58 m**

Therefore, the calculated site air density at 67 m height using Eq. 2.45 is **1.072 kg/m^3.**

It is known that wind turbine manufacturers provide power curve, for a specific wind turbine, based on sea level air density rather than site specific air density. Thus, in order to get an accurate prediction of AEP for a specific site it is important to perform power curve air density correction. Accordingly, site specific power curve correction for this study is done as explained below.

The two nominated wind turbines have pitch control system so wind speed correction is used .The corrected wind speed is obtained from Eq. 2.46 [21].

$$V_{site} = V_{std} \left(\frac{\rho_{std}}{\rho_{site}}\right)^{\frac{1}{3}} \quad (2.46)$$

where:

ρ_{std} is the standard air density, 1.225 kg/m^3

ρ_{site} is the site air density, 1.072 kg/m^3

V_{site} is the normalized wind speed, m/s

V_{std} is the measured mean wind speed over 10 min, m/s

The power output of the WECS is calculated by entering in the original power curve with the corrected wind speed.

Corrected power curves using site air density of 1.072 kg/m^3 are shown Fig. 4.15 and 4.16.

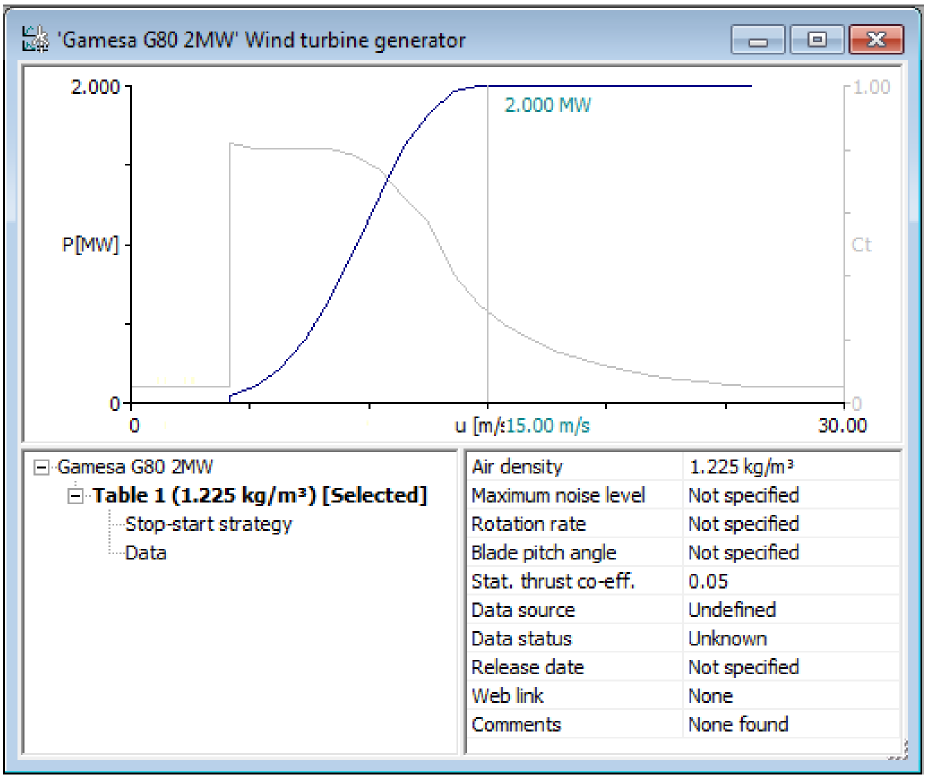

Figure 4.15: Corrected power curve of Gamesa WTG

Table 4.5: Power curve air density correction of Gamesa WTG

V std [m/s]	V site [m/s]	Power [kW]	Thrust coefficient [-]
4	4.18	43	0.818
5	5.23	105	0.806
6	6.27	215	0.804
7	7.32	402	0.805
8	8.36	660	0.806
9	9.41	971	0.78
10	10.45	1315	0.737
11	11.50	1617	0.649
12	12.55	1822	0.571
13	13.59	1970	0.41
14	14.64	2000	0.314

15	15.68	2000	0.249
16	16.73	2000	0.202
17	17.77	2000	0.167
18	18.82	2000	0.14
19	19.86	2000	0.118
20	20.91	2000	0.101
21	21.95	2000	0.088
22	23.00	2000	0.076
23	24.05	2000	0.067
24	25.09	2000	0.059
25	26.14	2000	0.052

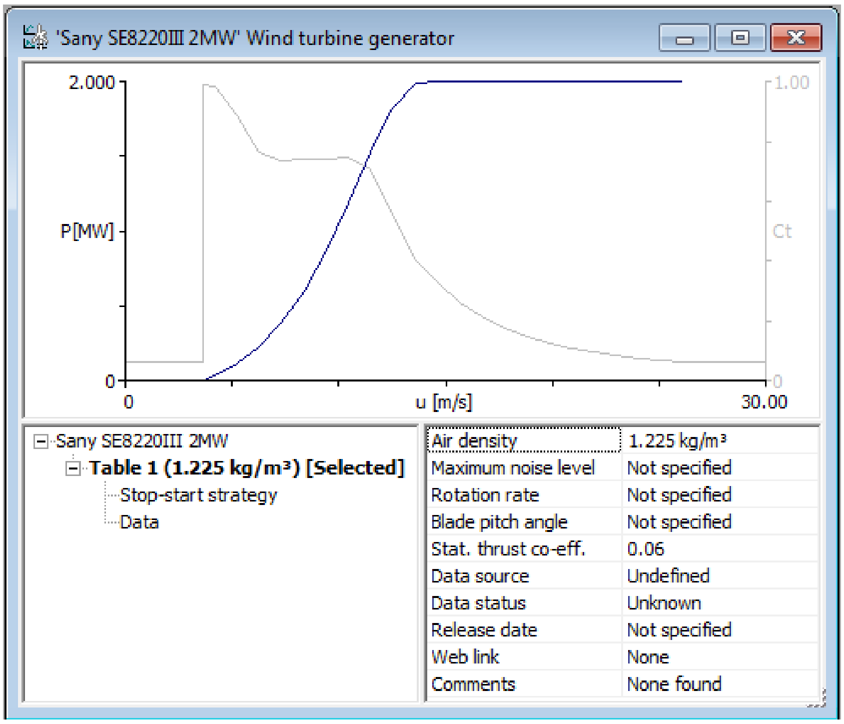

Figure 4.16: Corrected power curve of Sany WTG

Table 4.6: Power curve air density correction of Sany WTG

V std [m/s]	V site [m/s]	Power [kW]	Thrust coefficient [-]
3.5	3.66	5	0.9921
4	4.18	35	0.9821

5	5.23	119	0.8861
6	6.27	232	0.7614
7	7.32	388	0.7343
8	8.36	598	0.74
9	9.41	868	0.7436
10	10.45	1189	0.7463
11	11.50	1525	0.7092
12	12.55	1826	0.5527
13	13.59	1989	0.3993
14	14.64	2000	0.3265
15	15.68	2000	0.2607
16	16.73	2000	0.2132
17	17.77	2000	0.1773
18	18.82	2000	0.1497
19	19.86	2000	0.128
20	20.91	2000	0.1106
21	21.95	2000	0.0966
22	23.00	2000	0.085
23	24.05	2000	0.0754
24	25.09	2000	0.0673
25	26.14	2000	0.0605

4.3.4 Wind resource map

The wind resource distribution maps for the wind farms at 67 m and 70 m hub heights are demonstrated in Fig. 4.17 and 4.18. It can be seen that the deeper blue, blue and blue-lime colored areas represent low, average and high energy-density distributions respectively. Accordingly, high energy-density location is chosen for wind turbine site.

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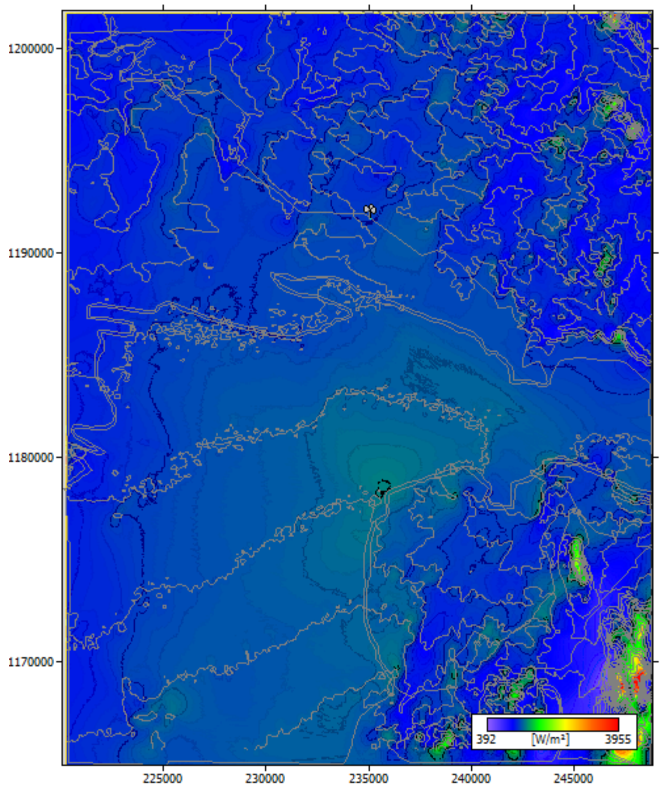

Figure 4.17: Site power density distribution map at 67 m hub height

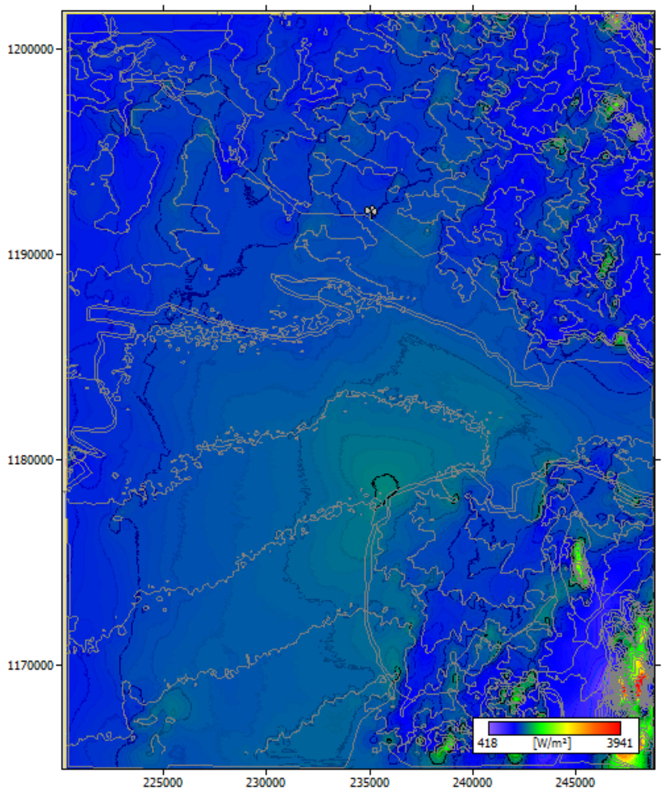

Figure 4.18: Site power density distribution map at 70 m hub height

4.3.5 Wind turbines Layout

4.3.5.1 The principle of wind turbine layout

Wind turbines inside a farm shall be laid out based on the following basic principles.

- Based on the wind rose, the space between wind turbines shall be set in a way that it maximizes AEP output with minimal wake effects.
- A location, inside the wind farm site, having a relatively flat terrain with higher energy density distribution shall be selected for turbine installation so as to get higher AEP.
- A layout that results in shorter transmission line requirement as well as easy transportation and installation of wind turbine sets shall be chosen.
- The site layout shall be compact so as to save land, reduce electrical cable and road length inside the farm as well as for easy facility management. This results in reduced project cost and energy losses.
- A layout that makes the visual appearance of the site beautiful.

4.3.5.2 Optimal layout of turbines or Micro-sitting

Based on the rule of thumb that is used to design a wind farm layout, turbines in wind farm are usually spaced somewhere between 5 to 9 times the rotor diameters apart in the prevailing wind direction, and between 3 to 5 times the rotor diameters apart in the direction perpendicular to the prevailing winds. As shown in Fig. 4.17 and 4.18, the site under this study has very flat terrain with higher energy density distribution. This condition makes it easy to install turbines according to spacing specified above. Accordingly, 7x4D, 7x5D, 7x6D and 6x6D (i.e., 7D is in rows and 4D, 5D and 6D are in columns) layouts are used to install the turbines at the site and compared to each other so as to identify the layout producing the highest AEP with low wake affection. AEP of the four layouts using site air density are given in Table 4.7 and 4.8.

Table 4.7: Comparison of different layouts between Gamesa wind turbines at 67 m hub height

Layouts	Total gross AEP[GWh]	Total net AEP[GWh] after wake loss	Wake loss [%]	Farm efficiency [%]
7x4D	1819.291	1684.727	7.4	92.56

7×5D	1820.114	1698.266	6.69	93.31
7x6D	1819.208	1713.324	5.82	94.18
6x6D	1820.269	1712.576	5.92	94.08

Table 4.8: Comparison of different layouts between Sany wind turbines at 70 m hub height

Layouts	Total gross AEP[GWh]	Total net AEP[GWh] after wake loss	Wake loss [%]	Farm efficiency [%]
7x4D	1799.346	1661.516	7.66	92.34
7×5D	1799.824	1679.151	6.7	93.3
7x6D	1798.767	1693.852	5.83	94.17
6x6D	1799.748	1693.508	5.9	94.1

Comparing the four layouts, there is little difference between them. The total net AEP of 7x 6D layout is greater than the remaining layouts, and the wake effect is relatively little. Aysha wind farm wake loss falls in the lower most range value between 0 to 20 % [22]. Therefore, the chosen layout for the wind farm is 7x 6D.

4.3.6 Type selection

While selecting the types, the following points are considered

- Annual energy production
- Capacity factor
- Wind farm capital cost per kWh

The selection considers the higher the annual energy production and capacity factor with the least wind farm capital cost per kWh.

Costs: A recent similar project in Ethiopia has been used as a benchmark to set the capital cost of Aysha Wind Farm. This cost of wind turbines has remained the largely static for the past three years [4]. Table 4.7 provides the overview of costs for wind projects in Ethiopia such as Ashogoda-I, Ashogoda-II, Adama-I and Adama-II. A more detailed capital cost breakdown of these wind farms is given in appendix E.

Table 4.9: Wind farm costs

Technology	Capital	Operating	
		Fixed cost	Variable cost
Wind Farm	$1900/kW	$25/kW/year	$0.01/kWh

The capital cost includes the cost of the turbines, balance of plant (civil work and labour costs) and connection to a relatively close grid. The operational costs include spare parts, and operation and maintenance costs as well as the cost for onsite personnel.

Table 4.10: Comparison of nominated wind turbines

Wind turbine model	Net AEP [GWh] after total loss	CF [%]	Total energy production in 25 years [GWh]	Wind farm capital cost [USD]	Wind farm capital cost Per kWh [USD/kWh]
Gamesa G80 2 MW	1183.623	44.92	29590.57	570, 000,000	0.0193
Sany SE8220III 2 MW	1170.199	44.41	29254.97	570,000,000	0.0195

Therefore, the higher annual energy production and capacity factor with the least wind farm capital cost per kWh is found using Gamesa G80 2 MW wind turbine generator than Sany SE8220III 2 MW as shown in Table 4.10.

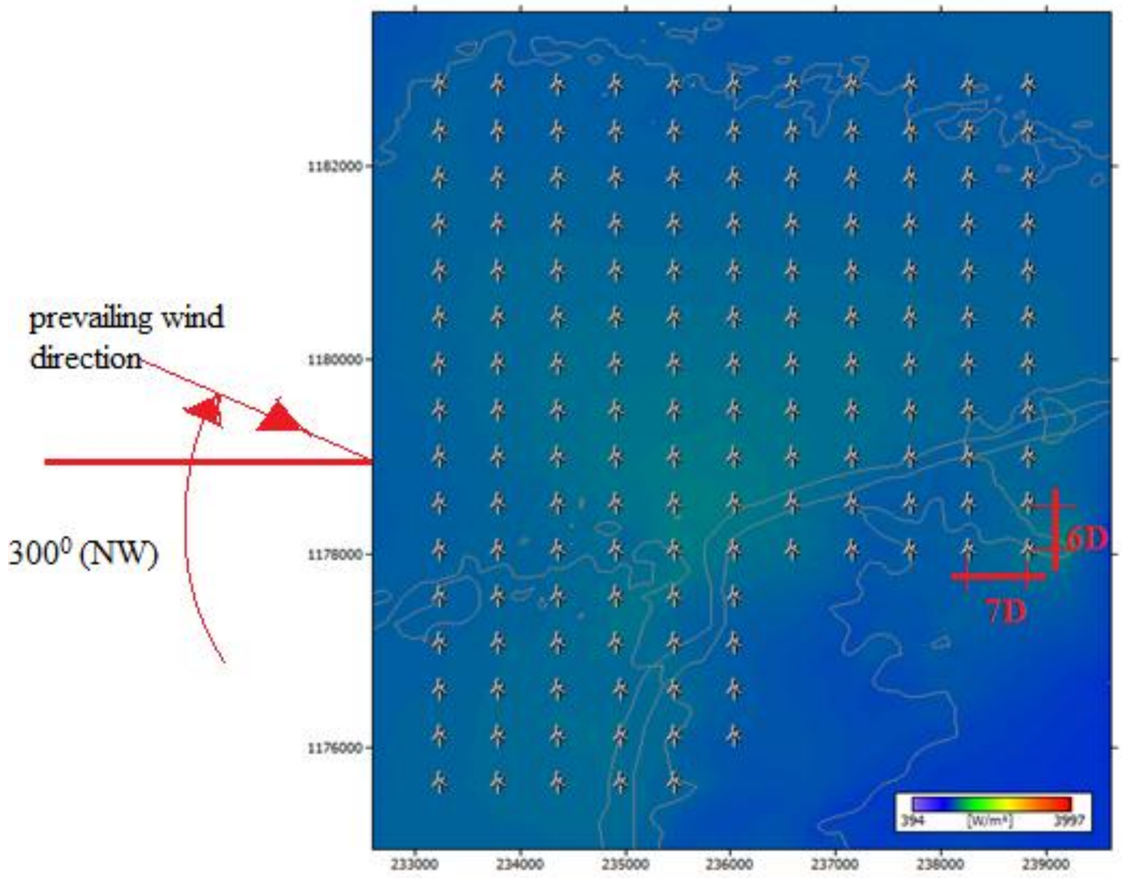

Figure 4.19: 7x 6D layout of the wind farm (3D all view)

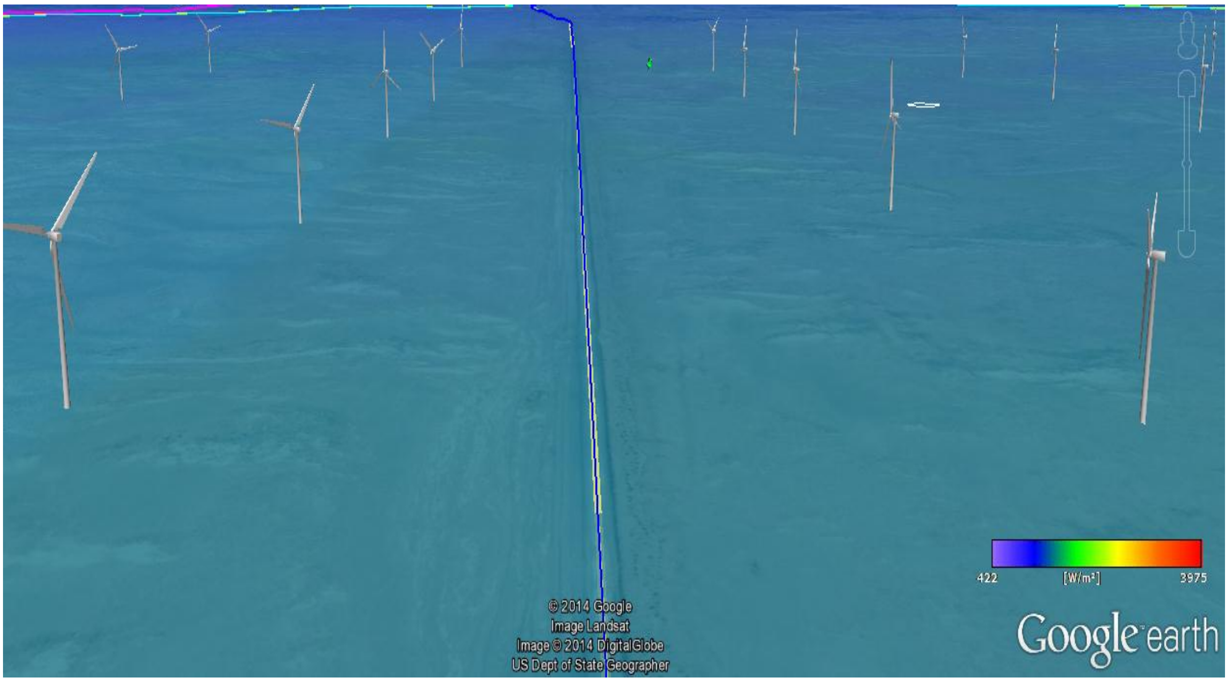

Figure 4.20: 7x 6D layout of the wind farm (3D typical view)

In order to get better performance, it is a usual practice to leave a clearance of ($h_{T} + D_{T}$) from the roads, where h_T is the hub height and D_T diameter of the turbine [10]. Accordingly, as shown in Fig. 4.20, turbines on this site are installed 147 meters apart on both sides of the road as the hub height (h_T) is 67 meters and diameter of the turbine (D_T) is 80 meters.

4.3.7 AEP estimation

Based on the preceding analysis and comparisons, 150 sets of Gamesa G80 2 MW type wind turbine generators are recommended to be installed at the site as the total capacity of the nearby transmission line is 300 MW. To estimate the site AEP the following energy losses are considered.

Power curve air density correction losses: Power curve air density correction brings a 4-5% over estimation of AEP for part of the power curve below the rated speed [21]. Thus a correction factor of 5 % is applied in order to obtain more accurate AEP estimation of the farm.

Wake losses: It is known that the interaction between wind turbines gives rise to wake losses. This loss is estimated by WAsP software at 5.82 % [computed by WAsP, see Table 4.7].

Turbulence losses: Taking in to consideration the local climate of the wind farm characteristics the turbulence intensity is generally moderate. Thus control and turbulence loss factor of 5 % [7] is taken for this study.

Environmental: The wind farm is characterized by very flat; semi-desert area with sparse vegetation and little rain fall. The blade surface is easily polluted by blowing sand that reduces aerodynamics characteristics of airfoil thus the pollution loss factor is 5 % [7, 22].

Plant availability: Wind turbines availability factor is taken as 95 % considering failure and maintenance of wind turbines, power grid failure, and arrangement of routine maintenance in low wind energy month, wind turbine overhaul and accident. In other words a 5 % [22, 25] unavailability factor is assumed for wind farms.

Turbine performance: Manufacturer’s Guarantee for the reliability of power curve is 95 % as power curve is developed in wind tunnels inside a laboratory and not in real site conditions, thus a loss of 5 % [25] in the farm power output.

Electrical losses: Energy losses of auxiliary power system and transmission lines, transformer and substation within the wind farm takes about 7 % [22, 25] of the total gross power output.

Meteorological data losses: The analysis is done based on the 10 m high wind-mast data, the derived results can be biased with the actual results while converting/using 10 m high wind speed data to hub height wind speed, a 4 % [7] loss is considered on the gross wind farm power output.

In general, the total energy loss factor in the wind farm is found by multiplying all the above factors and it gives us:

Total loss factor = (1-0.05)*(1-0.0528)*(1-0.05)*(1-0.05)*(1-0.05)*(1-0.05)*(1-0.07)*(1-0.04) = 0.651

This reveals that only 65.1 % of the gross wind farm power is converted to useful power.

Total gross AEP (before total loss factor):

=1819.208 GWh (total gross AEP, see Table 4.7)

Total net AEP (after total loss factor):

= 1819.208 GWh*0.651

= **1183.623 GWh**

The average hours of AEP = $\frac{1183.62\ \text{GWh}}{150*2\ \text{MW}}$ = **3945.41 hrs**

Using Eq. 2.43, the wind farm capacity factor (CF):

$$\mathbf{CF} = \frac{1183.623\ \text{GWh}}{150*2\ \text{MW}*8784\text{hr}} = \mathbf{44.92\ \%}$$

CHAPETR FIVE

5. RESULTS AND DISCUSSION

This section categorizes results found in this study into three. The first subsection deals with details of the wind atlas of the site at five reference heights and for five roughness lengths, whereas the second section discusses the resource potential based on results of the resource grid at 67 m (hub height). In addition the last subsection shows each turbine's climate characteristics and energy production potential within the turbine cluster.

5.1 WIND ATLAS OF THE SITE

The analysis of the wind atlas contains prediction of regional wind climate distributions for 5 reference roughness lengths (0.000 m, 0.003 m, 0.005 m, 0.008 m, 0.030 m) and 5 reference heights (10 m, 30 m, 50 m, 67 m, 100 m) above ground level. Please note that results in this section are all found at wind-mast location as reference conditions.

Table 5.1: Regional wind climate summary

Height a.g.l	Parameter	Roughness length				
		0.00 m	**0.003 m**	**0.005 m**	**0.008 m**	**0.03 m**
10.0 m	Weibull A [m/s]	11.5	10.0	9.7	9.4	8.4
	Weibull k [-]	2.91	2.72	2.73	2.71	2.72
	Mean speed [m/s]	10.27	8.88	8.60	8.33	7.46
	Power density [W/m²]	947	639	579	528	378
30.0 m	Weibull A [m/s]	12.8	11.6	11.3	11.1	10.2
	Weibull k [-]	2.97	2.89	2.89	2.86	2.86
	Mean speed [m/s]	11.38	10.38	10.11	9.86	9.07
	Power density [W/m²]	1277	982	909	848	660
50.0 m	Weibull A [m/s]	13.4	12.6	12.3	12.0	11.1
	Weibull k [-]	3.01	3.05	3.04	3.00	2.98
	Mean speed [m/s]	11.94	11.23	10.97	10.71	9.93
	Power density [W/m²]	1463	1208	1127	1058	846
67.0 m	Weibull A [m/s]	13.8	13.2	12.9	12.6	11.7
	Weibull k [-]	3.01	3.17	3.16	3.11	3.09
	Mean speed [m/s]	12.28	11.80	11.53	11.27	10.49
	Power density [W/m²]	1591	1374	1284	1208	977

100.0 m	Weibull A [m/s]	14.3	14.2	13.9	13.6	12.7
	Weibull k [-]	3.00	3.21	3.21	3.18	3.20
	Mean speed [m/s]	12.78	12.72	12.43	12.15	11.34
	Power density [W/m²]	1797	1710	1596	1497	1213

Table 5.1 shows that for a specific roughness, as the height increase from 10 m to 100 m all wind climate parameters increases. On the other hand for a specific height, the Weibull scale factor, mean wind speed and power density decreases as one goes from roughness class 0 (0.000 m) to class 4 (0.03 m) whereas the Weibull shape factor is more or less uniform. This implies that all wind climate parameter of the site are affected by change in roughness lengths.

Table 5.2: Site effects at different sectors

Sector		Roughness			Obstacles	Orography		
number	angle [°]	changes	reference [m]	speed-up [%]	speed-up [%]	speed-up [%]	deflection [°]	RIX [%]
1	0	0	0.008	0.00	0.00	1.66	-0.7	0.0
2	30	0	0.008	0.00	0.00	0.28	-0.6	0.0
3	60	0	0.008	0.00	0.00	-0.31	0.1	0.0
4	90	0	0.008	0.00	0.00	0.49	0.7	0.0
5	120	0	0.007	0.00	0.00	1.85	0.6	0.0
6	150	1	0.005	0.59	0.00	2.34	-0.1	0.0
7	180	1	0.004	0.33	0.00	1.54	-0.7	0.0
8	210	0	0.004	0.00	0.00	0.24	-0.6	0.0
9	240	0	0.005	0.00	0.00	-0.28	0.1	0.0
10	270	0	0.006	0.00	0.00	0.51	0.7	0.0
11	300	0	0.007	0.00	0.00	1.85	0.6	0.0
12	330	0	0.008	0.00	0.00	2.44	-0.1	0.0
All								0.0

Table 5.2 depicts that the average horizontal speed-up percentage due to roughness, obstacles and orography are 0.08 %, 0 % and 1.05 %, respectively. This implies there is a very small wind speed variation due to site effects.

5.2 RESOURCE GRID OF THE SITE

Results regarding the resource grid analysis of the desired resolution, columns and rows are mainly performed for the size of the grid area and the resolution cell size within the area explained in the grid setup Table 5.3

Table 5.3: Grid Setup

Structure	951 columns and 1224 rows at 30 m resolution gives 1164024 calculation sites.
Boundary	(220236 m E, 1164954 m N) to (248766 m E, 1201674 m N)
Nodes	(220251 m E, 1164969 m N) to (248751 m E, 1201659 m N)

Height a.g.l	67 m

Table 5.3 reveals that the resource grid of the site is constructed at 30 m resolution (recommended grid resolution: 20-50 m [12], based on the computer memory capacity) which forms a total dimension of 951 columns x 1224 rows and gives 1,164,024 cell sizes at 67 m hub height.

Mean Speed (m/s)

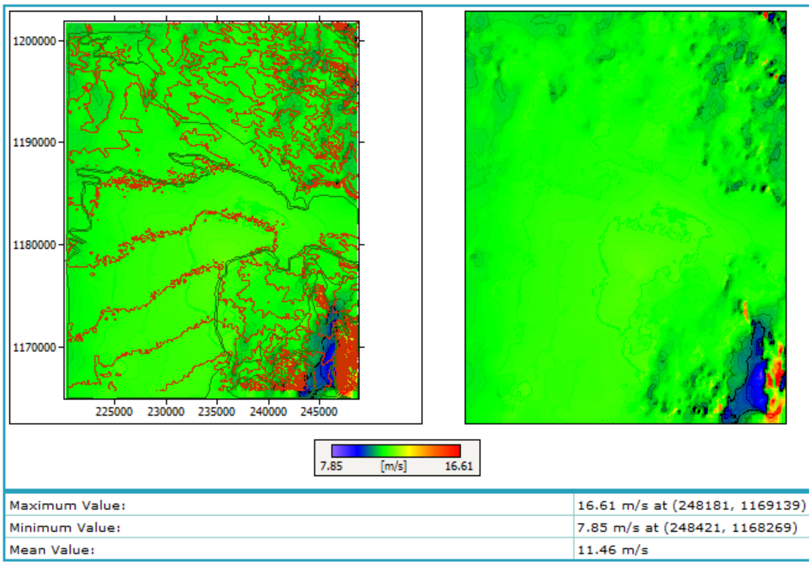

Figure 5.1: Resource grid showing wind speed distribution at 67 m height

Power Density (W/m²)

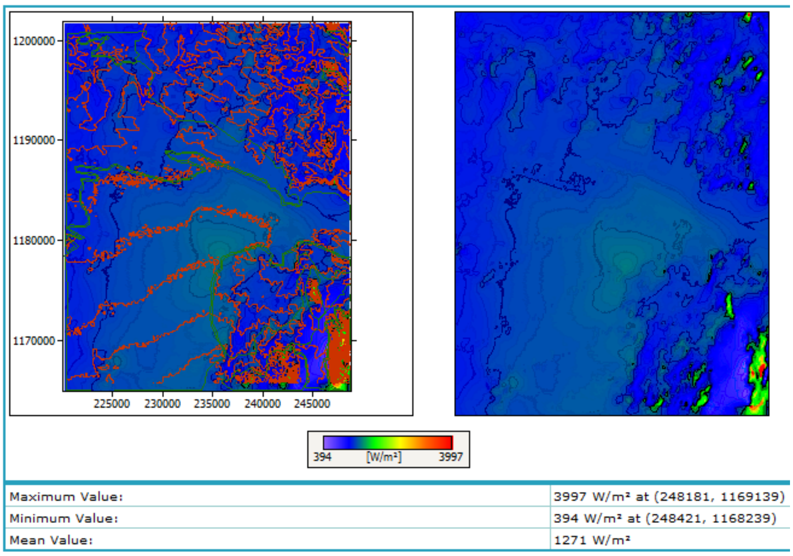

Figure 5.2: Resource grid showing wind power density distribution at 67 m height

Fig. 5.1 and 5.2 illustrate that the minimum mean wind speed and power density are 7.85 m/s and 394 W/m² at a coordinate of 248421 E, 1168239 N, respectively. According to standards on classes of wind power density [13] this minimum value is found as a good wind resource. And considering the mean and maximum values of wind speed as well as power density it can clearly be seen that this resource is an excellent wind resource based on standards on classes of wind power density.

AEP (GWh)

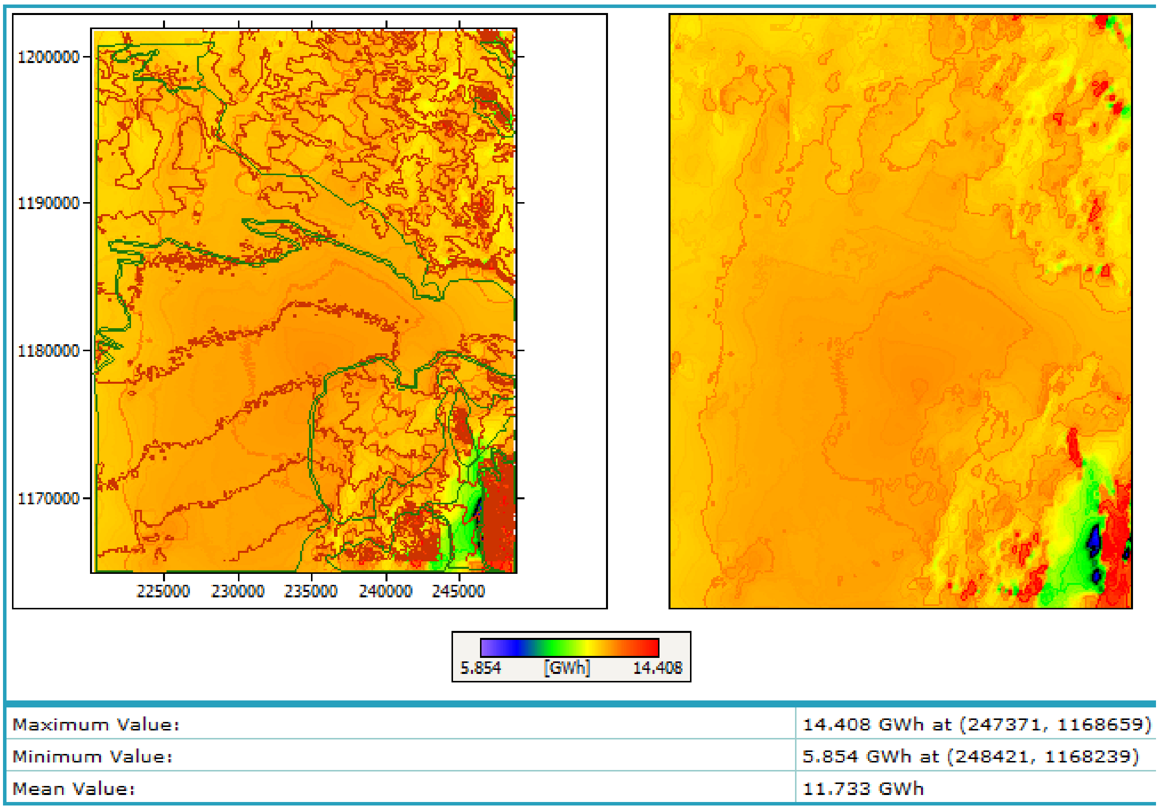

Figure 5.3: Resource grid showing AEP distribution at 67 m height

Fig. 5.3 shows that the minimum AEP is 5.854 GWh at a coordinate 248421 E, 1168239 N, the maximum AEP is 14.408 GWh at a coordinate 247371 E, 1168659 N and average value of AEP is 11.733 GWh. The maximum values of power density and AEP are found at different positions of the site, as given in Fig. 5.2 and 5.3. This implies a site position with maximum power density won't necessarily produce maximum AEP mainly due to the fact that AEP is calculated based on the power density as well as frequency distribution. The same holds true for minimum values of power density and AEP.

RIX (%)

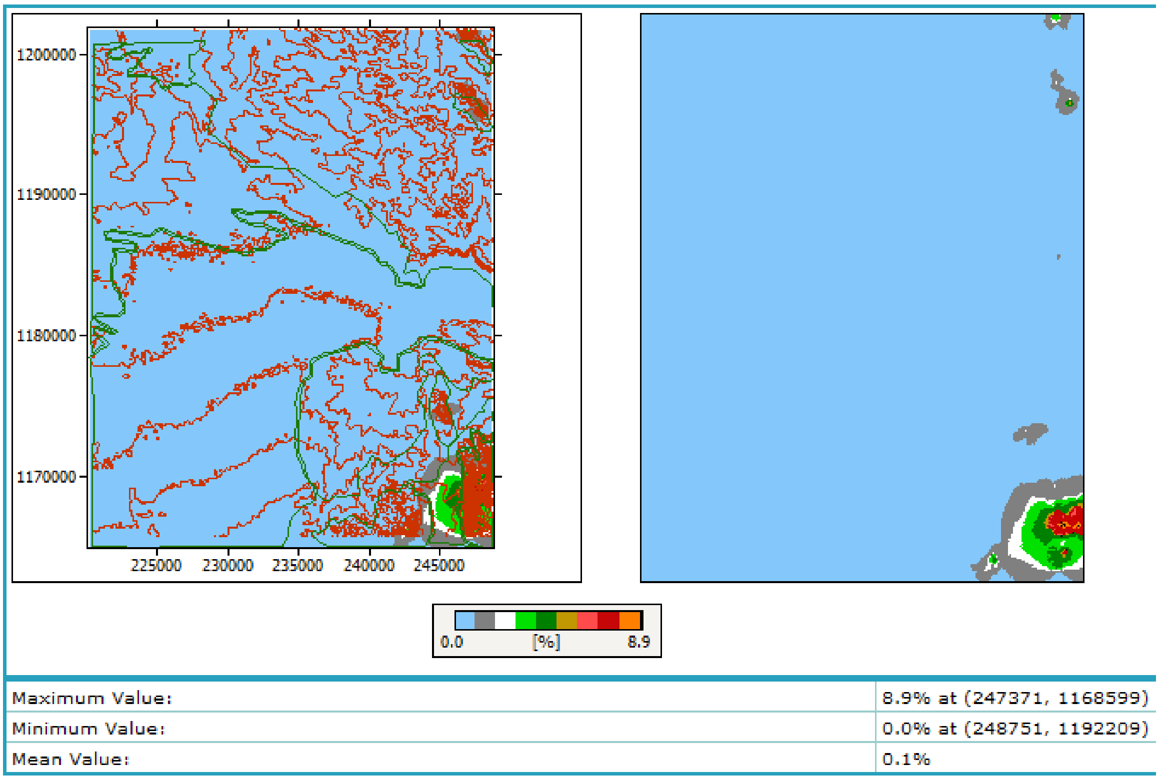

Figure 5.4: Ruggedness index of the site

Fig. 5.4 depicts that the minimum RIX is 0% at a coordinate 248751 E, 11922099 N, whereas the maximum RIX (8.9%) is found in Somalia regional state. This implies that the Aysha wind farm is very flat.

Table 5.3 summarizes the wind resource grid over all statistics (results) discussed above.

Table 5.4: Aysha wind farm resource grid over all statistics

Parameter	Average	Minimum	at	Maximum	at
Weibull-A	12.8 m/s	8.8 m/s	(248421,1168269)	18.6 m/s	(248181,1169139)
Weibull-k	3.12	2.60	(247011,1165749)	3.42	(248421,1168119)
Mean speed	11.46	7.85 m/s	(248421,1168269)	16.61 m/s	(248181,1169139)
Power density	1271 W/m^2	394 W/m^2	(248421,1168239)	3997 W/m^2	(248181,1169139)
Elevation	744.1 m	600 m	(220521,1200009)	1175 m	(248391,1166259)
RIX	0.1 %	0.0 %	(248751,1192209)	8.9 %	(247371,1168599)
Delta-RIX	0.1 %	0.0 %	(248751,1192209)	8.9 %	(247371,1168599)
AEP	11.733 GW	5.854 GW	(248421,1168239)	14.408 GW	(247371,1168659)

5.3 WIND FARM

Each turbine's wind climate characteristics as well as energy production potential is put in the Table 5.5.

Table 5.5: Aysha wind farm turbine cluster overall result and wind climate characteristics

Turbine site	Location [m]	Elevation [m] a.s.l.	Gross AEP[GWh]	Net AEP[GWh]	Wake loss [%]	Efficiency[%]	A [m/s]	k [-]	V [m/s]	P/A [W/m²]	RIX [%]
001	(233251, 1182745)	750.84	12.11	11.84	2.17	97.83	13.2	3.15	11.79	1373	0
002	(233811, 1182745)	751.63	12.10	11.79	2.56	97.44	13.2	3.15	11.78	1371	0
003	(234371, 1182745)	751.75	12.10	11.77	2.67	97.33	13.2	3.15	11.78	1370	0
004	(234931, 1182745)	750.73	12.08	11.75	2.73	97.27	13.2	3.14	11.77	1367	0
005	(235491, 1182745)	750.47	12.08	11.75	2.73	97.27	13.1	3.14	11.76	1366	0
006	(236051, 1182745)	749.76	12.07	11.74	2.71	97.29	13.1	3.14	11.76	1363	0
007	(236611, 1182745)	749.89	12.07	11.74	2.66	97.34	13.1	3.14	11.75	1362	0
008	(237171, 1182745)	750.28	12.08	11.77	2.56	97.44	13.1	3.14	11.77	1367	0
009	(237731, 1182745)	749.99	12.07	11.79	2.33	97.67	13.1	3.14	11.75	1363	0
010	(238291, 1182745)	749.75	12.08	11.86	1.83	98.17	13.2	3.14	11.77	1368	0
011	(238851, 1182745)	749.04	12.06	11.97	0.76	99.24	13.1	3.13	11.76	1365	0
012	(238851, 1182265)	750.00	12.05	11.58	3.92	96.08	13.1	3.13	11.75	1361	0
013	(238291, 1182265)	750.22	12.07	11.45	5.16	94.84	13.1	3.13	11.76	1368	0
014	(237731, 1182265)	751.02	12.08	11.38	5.76	94.24	13.2	3.14	11.77	1368	0
015	(237171, 1182265)	751.74	12.10	11.37	6.03	93.97	13.2	3.14	11.79	1376	0
016	(236611, 1182265)	751.10	12.08	11.33	6.17	93.83	13.1	3.14	11.76	1366	0
017	(236051, 1182265)	751.94	12.08	11.33	6.23	93.77	13.2	3.14	11.77	1368	0
018	(235491, 1182265)	751.86	12.08	11.33	6.25	93.75	13.2	3.14	11.77	1368	0

019	(234931, 1182265)	752.30	12.09	11.34	6.23	93.77	13.2	3.14	11.78	1372	0
020	(234371, 1182265)	753.09	12.11	11.38	5.98	94.02	13.2	3.14	11.79	1376	0
021	(233811, 1182265)	750.53	12.08	11.49	4.85	95.15	13.1	3.14	11.77	1366	0
022	(233251, 1182265)	752.32	12.13	11.82	2.56	97.44	13.2	3.14	11.82	1384	0
023	(233251, 1181785)	753.38	12.13	11.81	2.65	97.35	13.2	3.14	11.81	1384	0
024	(233811, 1181785)	753.65	12.11	11.51	4.96	95.04	13.2	3.14	11.8	1380	0
025	(234371, 1181785)	754.98	12.12	11.32	6.63	93.37	13.2	3.14	11.81	1384	0
026	(234931, 1181785)	754.73	12.11	11.25	7.12	92.88	13.2	3.14	11.8	1381	0
027	(235491, 1181785)	754.44	12.11	11.23	7.28	92.72	13.2	3.14	11.8	1378	0
028	(236051, 1181785)	754.74	12.11	11.23	7.3	92.7	13.2	3.14	11.8	1380	0
029	(236611, 1181785)	753.40	12.09	11.21	7.28	92.72	13.2	3.13	11.79	1376	0
030	(237171, 1181785)	753.29	12.10	11.23	7.16	92.84	13.2	3.13	11.79	1377	0
031	(237731, 1181785)	751.64	12.07	11.25	6.87	93.13	13.2	3.13	11.77	1369	0
032	(238291, 1181785)	751.64	12.07	11.32	6.25	93.75	13.1	3.13	11.77	1368	0
033	(238851, 1181785)	750.33	12.05	11.45	5	95	13.1	3.13	11.75	1364	0
034	(238851, 1181305)	752.70	12.08	11.42	5.44	94.56	13.2	3.13	11.77	1372	0
035	(238291, 1181305)	753.74	12.09	11.28	6.68	93.32	13.2	3.13	11.79	1375	0
036	(237731, 1181305)	754.35	12.10	11.22	7.28	92.72	13.2	3.13	11.8	1381	0
037	(237171, 1181305)	755.48	12.12	11.20	7.58	92.42	13.2	3.13	11.81	1386	0
038	(236611, 1181305)	756.22	12.12	11.19	7.67	92.33	13.2	3.13	11.82	1386	0
039	(236051, 1181305)	757.27	12.13	11.20	7.67	92.33	13.2	3.13	11.82	1388	0
040	(235491, 1181305)	757.35	12.13	11.21	7.58	92.42	13.2	3.13	11.83	1389	0
041	(234931, 1181305)	757.62	12.14	11.24	7.35	92.65	13.2	3.13	11.83	1391	0
042	(234371, 1181305)	757.60	12.14	11.33	6.65	93.35	13.2	3.13	11.84	1393	0
043	(233811, 1181305)	756.74	12.14	11.54	4.98	95.02	13.2	3.14	11.83	1391	0

044	(233251, 1181305)	755.35	12.14	11.81	2.68	97.32	13.2	3.14	11.83	1389	0
045	(233251, 1180825)	757.36	12.13	11.81	2.69	97.31	13.2	3.14	11.83	1388	0
046	(233811, 1180825)	759.42	12.15	11.55	4.98	95.02	13.2	3.13	11.85	1397	0
047	(234371, 1180825)	760.46	12.16	11.36	6.64	93.36	13.3	3.13	11.86	1401	0
048	(234931, 1180825)	760.54	12.16	11.27	7.33	92.67	13.3	3.13	11.86	1402	0
049	(235491, 1180825)	760.26	12.16	11.23	7.64	92.36	13.3	3.13	11.86	1402	0
050	(236051, 1180825)	759.91	12.15	11.21	7.76	92.24	13.2	3.13	11.85	1401	0
051	(236611, 1180825)	759.00	12.15	11.20	7.78	92.22	13.2	3.13	11.85	1399	0
052	(237171, 1180825)	757.85	12.14	11.20	7.72	92.28	13.2	3.13	11.84	1395	0
053	(237731, 1180825)	756.68	12.13	11.23	7.43	92.57	13.2	3.13	11.83	1392	0
054	(238291, 1180825)	755.63	12.11	11.29	6.84	93.16	13.2	3.13	11.81	1386	0
055	(238851, 1180825)	754.56	12.10	11.42	5.62	94.38	13.2	3.13	11.8	1381	0
056	(238851, 1180345)	753.61	12.10	11.41	5.71	94.29	13.2	3.12	11.8	1384	0
057	(238291, 1180345)	755.14	12.12	11.28	6.92	93.08	13.2	3.12	11.83	1392	0
058	(237731, 1180345)	756.87	12.14	11.23	7.49	92.51	13.2	3.12	11.84	1399	0
059	(237171, 1180345)	759.01	12.16	11.22	7.75	92.25	13.3	3.12	11.87	1406	0
060	(236611, 1180345)	760.76	12.17	11.22	7.8	92.2	13.3	3.12	11.88	1410	0
061	(236051, 1180345)	762.10	12.18	11.23	7.76	92.24	13.3	3.12	11.88	1413	0
062	(235491, 1180345)	762.97	12.18	11.26	7.59	92.41	13.3	3.13	11.88	1412	0
063	(234931, 1180345)	763.50	12.18	11.30	7.29	92.71	13.3	3.13	11.88	1411	0
064	(234371, 1180345)	763.37	12.18	11.37	6.62	93.38	13.3	3.13	11.87	1407	0
065	(233811, 1180345)	762.03	12.16	11.56	4.98	95.02	13.3	3.13	11.86	1401	0
066	(233251, 1180345)	759.87	12.13	11.81	2.69	97.31	13.2	3.14	11.83	1390	0
067	(233251, 1179865)	762.64	12.13	11.80	2.68	97.32	13.2	3.14	11.82	1387	0
068	(233811, 1179865)	764.73	12.16	11.56	4.96	95.04	13.3	3.13	11.86	1402	0

069	(234371, 1179865)	766.40	12.19	11.39	6.59	93.41	13.3	3.13	11.89	1413	0
070	(234931, 1179865)	766.26	12.21	11.32	7.24	92.76	13.3	3.13	11.91	1421	0
071	(235491, 1179865)	765.04	12.20	11.28	7.54	92.46	13.3	3.12	11.91	1423	0
072	(236051, 1179865)	763.44	12.20	11.26	7.71	92.29	13.3	3.12	11.91	1422	0
073	(236611, 1179865)	761.31	12.18	11.24	7.78	92.22	13.3	3.12	11.9	1418	0
074	(237171, 1179865)	758.78	12.16	11.22	7.76	92.24	13.3	3.12	11.88	1411	0
075	(237731, 1179865)	755.47	12.14	11.22	7.52	92.48	13.2	3.12	11.85	1401	0
076	(238291, 1179865)	753.20	12.11	11.27	6.97	93.03	13.2	3.12	11.82	1392	0
077	(238851, 1179865)	751.23	12.09	11.39	5.77	94.23	13.2	3.12	11.8	1383	0
078	(238851, 1179385)	748.69	12.03	11.32	5.87	94.13	13.1	3.12	11.75	1366	0
079	(238291, 1179385)	750.06	12.09	11.25	7	93	13.2	3.12	11.81	1389	0
080	(237731, 1179385)	754.44	12.13	11.22	7.53	92.47	13.2	3.12	11.85	1402	0
081	(237171, 1179385)	757.89	12.16	11.22	7.75	92.25	13.3	3.11	11.88	1415	0
082	(236611, 1179385)	760.69	12.19	11.25	7.74	92.26	13.3	3.12	11.91	1423	0
083	(236051, 1179385)	764.24	12.21	11.28	7.64	92.36	13.3	3.12	11.93	1431	0
084	(235491, 1179385)	766.63	12.23	11.31	7.47	92.53	13.3	3.12	11.94	1434	0
085	(234931, 1179385)	768.43	12.22	11.34	7.19	92.81	13.3	3.13	11.92	1426	0
086	(234371, 1179385)	769.31	12.20	11.40	6.55	93.45	13.3	3.13	11.9	1417	0
087	(233811, 1179385)	767.37	12.15	11.55	4.96	95.04	13.2	3.14	11.85	1397	0
088	(233251, 1179385)	765.46	12.13	11.81	2.67	97.33	13.2	3.14	11.82	1386	0
089	(233251, 1178905)	768.46	12.11	11.79	2.66	97.34	13.2	3.14	11.8	1380	0
090	(233811, 1178905)	769.90	12.15	11.55	4.94	95.06	13.2	3.14	11.84	1395	0
091	(234371, 1178905)	772.05	12.20	11.40	6.52	93.48	13.3	3.13	11.9	1415	0
092	(234931, 1178905)	770.76	12.23	11.36	7.1	92.9	13.3	3.12	11.94	1433	0
093	(235491, 1178905)	769.45	12.25	11.35	7.35	92.65	13.4	3.12	11.97	1446	0

094	(236051, 1178905)	765.69	12.24	11.32	7.5	92.5	13.4	3.11	11.96	1444	0
095	(236611, 1178905)	759.62	12.19	11.26	7.65	92.35	13.3	3.11	11.91	1427	0
096	(237171, 1178905)	754.98	12.13	11.19	7.72	92.28	13.3	3.11	11.85	1406	0
097	(237731, 1178905)	753.72	12.07	11.15	7.6	92.4	13.2	3.12	11.79	1381	0
098	(238291, 1178905)	750.85	12.06	11.21	7.04	92.96	13.2	3.12	11.78	1378	0
099	(238851, 1178905)	744.64	12.08	11.39	5.74	94.26	13.2	3.1	11.82	1395	0
100	(238851, 1178425)	747.64	12.14	11.45	5.66	94.34	13.3	3.11	11.86	1408	0
101	(238291, 1178425)	750.00	12.04	11.20	7.01	92.99	13.1	3.12	11.76	1371	0
102	(237731, 1178425)	750.00	12.02	11.12	7.52	92.48	13.1	3.12	11.74	1365	0
103	(237171, 1178425)	750.75	12.05	11.13	7.65	92.35	13.2	3.11	11.78	1378	0
104	(236611, 1178425)	758.95	12.17	11.26	7.46	92.54	13.3	3.1	11.9	1422	0
105	(236051, 1178425)	767.09	12.23	11.34	7.28	92.72	13.4	3.1	11.96	1446	0
106	(235491, 1178425)	774.59	12.27	11.40	7.14	92.86	13.4	3.12	11.99	1453	0
107	(234931, 1178425)	773.84	12.21	11.35	7.03	92.97	13.3	3.13	11.92	1424	0
108	(234371, 1178425)	773.59	12.16	11.37	6.51	93.49	13.3	3.13	11.86	1402	0
109	(233811, 1178425)	772.74	12.13	11.53	4.93	95.07	13.2	3.14	11.82	1388	0
110	(233251, 1178425)	771.54	12.10	11.78	2.64	97.36	13.2	3.15	11.79	1374	0
111	(233251, 1177945)	773.79	12.09	11.77	2.63	97.37	13.2	3.14	11.78	1372	0
112	(233811, 1177945)	774.62	12.12	11.53	4.91	95.09	13.2	3.13	11.82	1388	0
113	(234371, 1177945)	774.47	12.13	11.34	6.51	93.49	13.2	3.13	11.84	1393	0
114	(234931, 1177945)	774.68	12.16	11.31	6.99	93.01	13.3	3.13	11.86	1405	0
115	(235491, 1177945)	775.09	12.23	11.39	6.86	93.14	13.4	3.12	11.95	1436	0
116	(236051, 1177945)	767.21	12.17	11.36	6.63	93.37	13.3	3.11	11.89	1420	0
117	(236611, 1177945)	759.14	12.13	11.32	6.7	93.3	13.3	3.11	11.86	1406	0
118	(237171, 1177945)	751.89	12.02	11.20	6.84	93.16	13.1	3.11	11.75	1369	0

119	(237731, 1177945)	749.77	12.05	11.24	6.71	93.29	13.2	3.12	11.77	1373	0
120	(238291, 1177945)	746.97	12.06	11.28	6.42	93.58	13.2	3.11	11.78	1379	0
121	(238851, 1177945)	748.03	12.18	11.51	5.44	94.56	13.3	3.1	11.9	1424	0
122	(236051, 1177465)	765.19	12.07	11.35	5.95	94.05	13.2	3.12	11.79	1381	0
123	(235491, 1177465)	771.68	12.14	11.32	6.76	93.24	13.2	3.12	11.85	1401	0
124	(234931, 1177465)	776.06	12.20	11.37	6.81	93.19	13.3	3.12	11.91	1424	0
125	(234371, 1177465)	775.73	12.15	11.37	6.42	93.58	13.3	3.13	11.86	1401	0
126	(233811, 1177465)	775.74	12.12	11.53	4.87	95.13	13.2	3.14	11.82	1387	0
127	(233251, 1177465)	775.00	12.09	11.77	2.6	97.4	13.2	3.14	11.78	1372	0
128	(233251, 1176985)	776.13	12.10	11.79	2.54	97.46	13.2	3.14	11.79	1376	0
129	(233811, 1176985)	777.61	12.14	11.56	4.8	95.2	13.2	3.13	11.84	1394	0
130	(234371, 1176985)	777.34	12.15	11.39	6.32	93.68	13.3	3.13	11.86	1401	0
131	(234931, 1176985)	775.84	12.17	11.35	6.76	93.24	13.3	3.13	11.88	1410	0
132	(235491, 1176985)	772.18	12.14	11.34	6.58	93.42	13.2	3.12	11.85	1402	0
133	(236051, 1176985)	764.76	12.03	11.34	5.73	94.27	13.1	3.12	11.74	1363	0
134	(236051, 1176505)	767.83	12.04	11.36	5.63	94.37	13.1	3.13	11.75	1364	0
135	(235491, 1176505)	774.82	12.15	11.37	6.47	93.53	13.3	3.13	11.86	1403	0
136	(234971, 1176505)	777.29	12.15	11.35	6.56	93.44	13.3	3.12	11.86	1403	0
137	(234371, 1176505)	779.56	12.16	11.42	6.15	93.85	13.3	3.13	11.87	1406	0
138	(233811, 1176505)	779.98	12.15	11.58	4.68	95.32	13.2	3.13	11.85	1398	0
139	(233251, 1176505)	778.70	12.11	11.82	2.44	97.56	13.2	3.14	11.81	1382	0
140	(233251, 1176025)	781.49	12.13	11.86	2.21	97.79	13.2	3.14	11.82	1387	0
141	(233811, 1176025)	782.26	12.16	11.62	4.43	95.57	13.3	3.13	11.86	1401	0
142	(234371, 1176025)	781.15	12.17	11.45	5.89	94.11	13.3	3.13	11.87	1408	0
143	(234971, 1176025)	777.86	12.16	11.41	6.2	93.8	13.3	3.12	11.87	1408	0

144	(235491, 1176025)	773.32	12.11	11.41	5.75	94.25	13.2	3.13	11.81	1385	0
145	(236051, 1176025)	767.31	11.99	11.32	5.56	94.44	13.1	3.13	11.7	1345	0
146	(235491, 1175545)	775.23	12.10	11.50	4.91	95.09	13.2	3.13	11.8	1381	0
147	(234971, 1175545)	777.89	12.14	11.48	5.48	94.52	13.3	3.12	11.86	1402	0
148	(234371, 1175545)	781.55	12.15	11.54	5.05	94.95	13.2	3.13	11.85	1401	0
149	(233811, 1175545)	783.84	12.15	11.72	3.57	96.43	13.2	3.13	11.85	1398	0
150	(233251, 1175545)	783.92	12.13	11.97	1.38	98.62	13.2	3.14	11.83	1390	0
Farm	**…**	**761.6**	**12.13**	**11.42**	**5.82**	**94.18**	**13.22**	**3.13**	**11.83**	**1392.6**	**0**

Table 5.6 summarizes the turbine cluster climate characteristics as well as energy production potential.

Table 5.6: Turbine cluster summary results at the wind turbine site

Parameter	Total	Average	Minimum	Maximum
Gross AEP [GWh]	1819.208	12.128	11.991	12.272
Net AEP [GWh] after wake loss	1713.32	11.422	11.120	11.972
Wake loss [%]	5.82	-	0.76	7.8
Farm efficiency [%]	94.18	-	92.2	99.24
Mean wind speed [m/s]	-	11.83	11.70	11.99
Power density [W/m^2]	-	1392.6	1345	1453
Weibull-A [m/s]	-	13.22	13.10	13.40
Weibull-k	-	3.13	3.10	3.15
Elevation [m]	-	761.58	744.64	783.92
RIX [%]	-	0.00	0.00	0.00

Table 5.5 and 5.6 reveal that the total gross AEP, the total net AEP and wake loss are 1819.208 GWh, 1713.32 GWh and 5.82 %, respectively. This wake loss falls in the lower end of a typical value for a well-designed wind farm which ranges from 0 to 20 % [22]. And considering total loss factor (0.651), the total net AEP of the wind farm is 1183.62 GWh

The wind farm prevailing wind direction and the subsequent prevailing directions of net & gross AEP, wake losses and power density are shown in Fig. 5.5 to 5.8

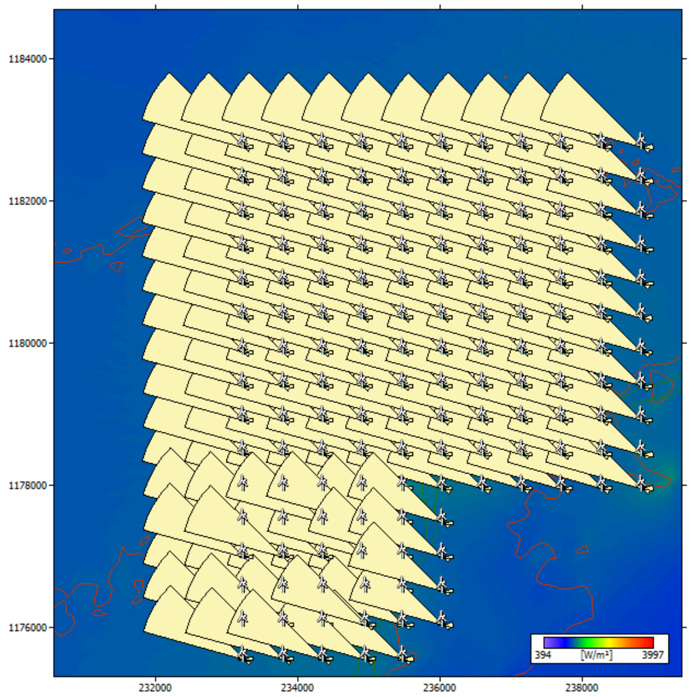

Figure 5.5: Direction of net AEP

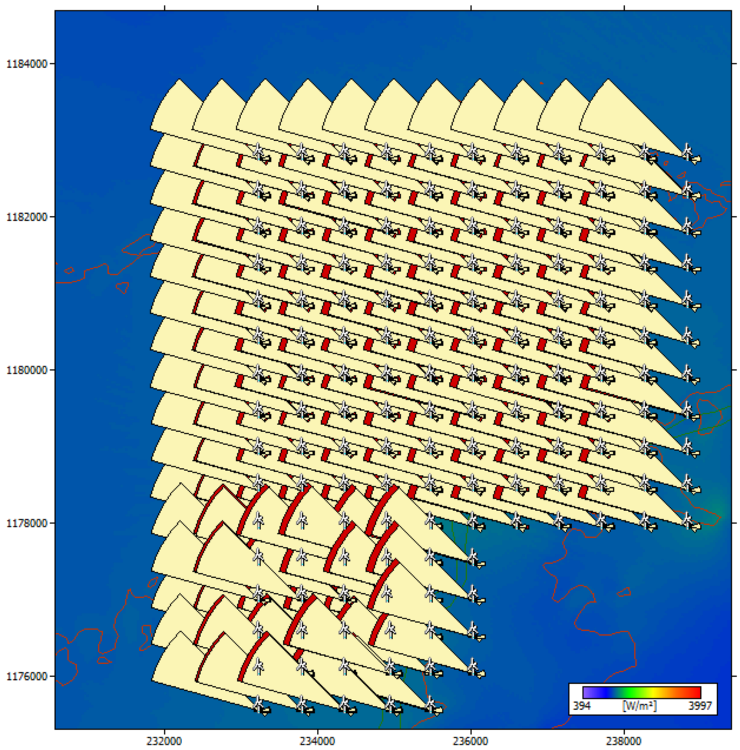

Figure 5.6: Direction of gross AEP and wake loss

Fig. 5.6 illustrates that more wake losses in the wind farm are in the center of the farm, whereas the lower are a way from the center.

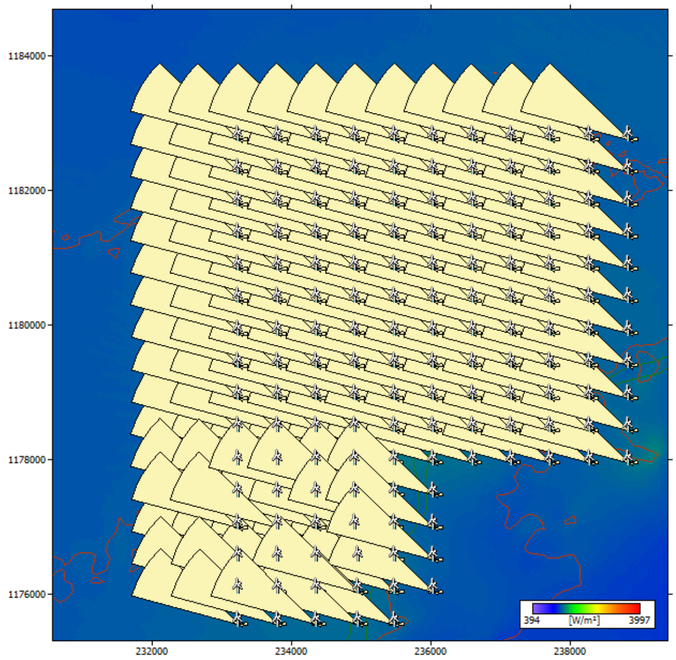

Figure 5.7: Direction of power density

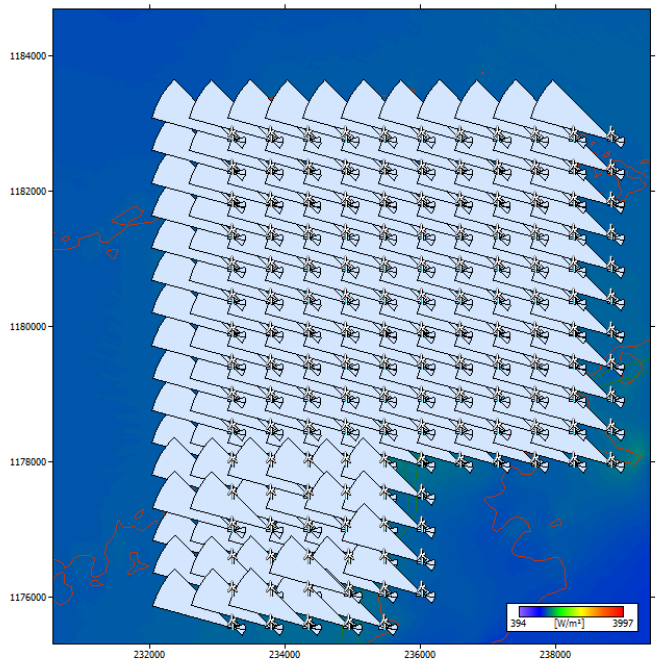

Figure 5.8: Direction of predicted wind frequency

Fig. 5.5 to 5.6 show that all prevailing direction of the farm such as gross AEP, net AEP, power density and wind frequency are in the direction of NE.

Wind farm capacity factor

The capacity factor of the wind farm is 44.92 %, which falls in the higher end of a typical wind farm capacity factor that ranges from 20 % to 40 %. This represents the latest wind turbines installed in excellent wind regimes.

CHAPETR SIX

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This study is conducted at Aysha Wind Farm site with the aim to analyze it's wind energy resource based on 10 minute mean data for the year 2008 WAsP, MATLAB and MS Excel has been used to analyze the wind data to: select wind turbine class, estimate farm AEP & power density, develop site wind resource map and perform preliminary turbine micro-sitting.

The mean wind speed at 10 m high wind-mast is found to be 8.56 m/s whereas the average wind power density is 571 W/m^2. The calculated mean wind speed at hub height of 67 m is 11.83 m/s and average wind power density is 1392.6 W/m^2 while the prevailing wind direction is from NW of 68.4 %. Therefore, based on classes of wind power density, it has been concluded that Aysha Wind Farm is categorized as class 7 (excellent wind energy resource potential), which implies a rich wind energy potential that can be used to construct large wind farm.

In addition, the farm has been observed to have turbulence intensity less than 13.7 and a reference wind speed of 50.98 m/s at hub height of 67 m. Thus, based on IEC standard, class I wind turbines are found to be suitable for the farm. Accordingly the wind farm results in a total net AEP of 1183.62 GWh and a capacity factor of 44.92 % for the year 2008 G.C. Therefore, it is concluded that the farm is a high energy producing site since its capacity factor falls in the higher end of the typical wind farms range values from 20 % to 40 %.

An average ruggedness index of 0.0 %, at the turbine site, implies that the site is very flat terrain. This serves a crucial purpose in reducing the uncertainty while predicting the wind speed using WAsP flow model. In general it is concluded that the wind farm terrain is suitable for more accurate wind speed prediction and easy construction.

6.2 RECOMMENDATIONS

Based on the above conclusion, the following recommendations are forwarded:

- Aysha Wind Farm has an excellent wind energy resource potential; thus the Ethiopian Government should give due attention in harnessing this potential as soon as possible.
- Predominant wind direction with higher power density is in Northwest direction hence obstacle from this direction should be avoided or taken in to account in the future.
- Higher quality wind measurement instruments should be installed close to the hub height to measure wind speed, temperature, pressure and humidity, for many years, in order to calculate air density to a better accuracy. This in turn helps in reducing uncertainties related to predicting the annual energy production of the site.
- Arrangement of routine maintenance of the wind farm shall be done between May and September since the wind energy resource is at its minimum value during this time of the year.
- Monitoring and maintenance of the mast should be given due attention not to miss long range data due to failure of anemometer or wind vane that arises from prevalence of high wind and blowing sand which is common at the site.

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APPENDICES

APPENDIX A

Sample Set of Raw Wind Data (Aysha, April 2008)

Time Series 30-04-2008

T 04/30/08 00:00:00 1*600 V5.0

73 86 52 6 306 309 287 5
80 92 64 6 309 309 298 1
80 100 62 6 307 309 298 4
77 98 55 6 308 309 298 3
80 102 60 7 309 309 298 2
76 94 59 7 309 309 298 2
75 101 54 7 308 309 287 4
74 92 55 7 303 309 287 6
79 100 60 8 307 309 287 4
83 103 57 9 301 309 287 6
88 113 60 11 301 309 276 6
91 113 67 7 308 309 298 3
96 119 72 9 308 309 287 3
93 119 68 10 302 309 287 6
92 110 69 7 306 309 287 5
94 118 73 9 307 309 298 4
89 107 63 8 308 309 287 3
87 108 71 7 309 309 298 2
88 107 59 9 308 309 287 3
90 107 68 8 309 309 298 2
88 104 61 8 308 309 298 3
80 97 59 7 307 309 298 4
82 96 58 6 308 309 287 4
80 100 61 6 309 309 298 2
74 86 58 6 309 309 298 2
71 85 58 6 308 309 298 2
76 92 59 7 304 309 287 6
73 90 56 6 300 309 287 6
75 88 61 5 301 309 287 6
75 92 53 7 303 309 287 6
70 89 50 7 306 309 298 5
75 91 61 6 307 309 287 4
73 89 60 6 307 309 287 4
79 96 62 6 299 309 287 6
76 90 61 6 293 309 276 6
74 89 63 5 293 309 276 6
76 90 60 5 295 309 276 5
64 79 47 6 296 309 287 5
58 71 46 5 295 309 276 6
58 67 47 4 289 309 276 6
61 74 45 5 286 298 264 6
61 75 48 4 286 298 276 5
57 70 44 4 289 298 276 6
58 70 46 4 294 309 276 6
69 82 52 5 299 309 276 6
69 83 52 7 301 309 287 5
70 88 54 7 302 309 287 6
73 93 57 6 306 309 287 5
74 90 54 7 304 309 287 6
83 97 56 7 306 309 287 5
86 102 67 5 305 309 287 5
86 109 63 8 306 309 287 5
91 113 70 8 303 309 287 7
89 111 71 7 304 309 287 6
88 105 60 8 303 309 287 6
86 107 64 7 304 309 287 6
75 110 48 10 303 309 276 7
74 91 47 9 297 309 276 8
75 96 51 9 298 309 276 8
79 98 58 7 305 309 287 6
78 102 60 7 301 309 276 8
80 100 54 9 308 309 298 3
76 99 55 8 306 309 276 5
74 99 51 9 307 309 276 5
64 88 38 9 304 309 276 8
65 87 41 9 296 309 264 11
61 86 31 12 300 84 264 11
58 84 34 11 299 84 264 11
54 83 26 13 303 84 276 13
53 73 31 9 300 309 264 9
40 89 10 19 307 84 264 29
49 89 13 15 303 84 276 20
58 87 26 12 291 309 242 17
54 122 23 16 274 309 231 22
56 83 27 11 283 309 242 18
47 90 20 14 272 309 231 28
61 97 28 15 301 84 276 16
49 88 13 18 295 309 231 16
55 96 15 15 296 84 231 29
58 89 29 12 298 84 264 12
67 117 26 21 298 84 253 18
54 98 24 17 286 309 231 17
52 90 23 14 299 84 253 12
54 91 23 17 281 309 231 16
39 91 16 17 263 309 231 20
42 82 8 18 265 51 62 55
38 86 11 17 290 84 231 32
40 69 7 12 271 51 62 28
65 95 34 14 293 309 242 16
65 101 32 13 296 84 253 31
63 112 33 15 296 309 253 14
76 113 42 17 284 309 253 15
59 90 24 12 296 309 253 14
71 115 21 18 300 309 253 10
87 130 50 18 294 309 264 14
58 87 28 13 283 309 231 22
79 130 47 18 298 309 264 12
78 111 45 14 295 309 253 11
86 121 47 15 302 309 264 9
79 111 40 14 296 309 264 12
76 99 49 11 296 309 264 9
97 146 57 17 302 309 276 8
89 119 53 14 294 309 264 10
101 142 70 13 304 309 287 6
114 153 76 16 298 309 264 9
116 160 90 13 308 309 298 3
121 154 79 15 300 309 276 8
120 149 90 12 306 309 287 5
116 145 75 13 303 309 287 7
117 141 89 11 301 309 276 7
114 152 86 12 306 309 287 5
120 144 88 10 307 309 287 4
112 141 77 12 297 309 276 7
114 137 89 10 306 309 287 5
109 137 83 10 303 309 287 6
107 139 82 10 301 309 287 6
116 139 92 10 301 309 287 5
117 140 84 9 303 309 287 6
108 139 75 12 303 309 287 6
108 137 82 11 300 309 276 7
103 133 75 11 301 309 276 6
115 136 82 11 299 309 287 6
116 139 85 9 306 309 287 5
115 140 83 10 304 309 287 6

110 133 80 10 304 309 287 6
109 137 74 12 307 309 287 4
106 135 79 12 309 309 298 2
104 141 71 14 308 309 287 3
113 144 78 12 308 309 298 2
119 140 82 10 309 309 298 2
110 136 80 11 306 309 287 5
124 152 85 12 308 309 298 3
118 147 93 10 307 309 298 4
120 147 82 12 309 309 298 2
119 146 81 12 309 309 298 2
110 136 85 11 309 309 298 2
109 138 75 12 309 309 287 2
105 128 76 11 309 309 298 2
102 127 80 9 309 309 298 2
97 120 73 9 308 309 287 3
101 128 74 10 309 309 298 2
105 132 77 11 307 309 287 4
111 146 81 13 307 309 287 4
125 155 86 11 308 309 287

APPENDIX B

Table 1.1: Wind power classes at 10 m and 50 m height [(a)] [13]

		10 m height		**50 m height**	
Wind power class	**Resource potential**	**Wind power density [W/m^2]**	**Mean wind speed[(b)] [m/s]**	**Wind power density [W/m^2]**	**Mean wind speed[(b)] [m/s]**
1	Poor	< 100	< 4.4	< 200	< 5.6
2	Marginal	100-150	4.4-5.1	200-300	5.6-6.4
3	Moderate	150-200	5.1-5.6	300-400	6.4-7.0
4	Good	200-250	5.6-6.0	400-500	7.0-7.5
5	Excellent	250-300	6.0-6.4	500-600	7.5-8.0
6	Excellent	300-350	6.4-7.0	600-800	8.0-8.8
7	Excellent	> 400	> 7.0	> 800	> 8.8

(a) Vertical Extrapolation wind speed based on the 1/7 power law.

(b) Mean wind speed is based on the Raleigh speed distribution (the shape factor, k = 2.0) with of the of equivalent average wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3 %/1000 m elevation.

APPENDIX C

Table C-1: Roughness length [12]

Physical z_0 [m]	Terrain surface characteristics	Roughness Class z_0	specified in WAsP [m]
1.5		**4** (1.5 m)	1.5
> 1	tall forest		> 1
1.00	city		1.00
0.80	forest		0.80
0.50	suburbs		0.50
0.40		**3** (0.40 m)	0.40
0.30	shelter belts		0.30
0.20	many trees and/or bushes		0.20
0.10	farmland with closed appearance	**2** (0.10 m)	0.10
0.05	farmland with open appearance		0.05
0.03	farmland with very few buildings/trees	**1** (0.03 m)	0.03
0.02	airport areas with buildings and trees		0.02
0.01	airport runway areas		0.01
0.008	mown grass		0.008
0.005	bare soil (smooth)		0.005
0.001	snow surfaces (smooth)		0.003
0.0003	sand surfaces (smooth)		0.003
0.0002	(used for water surfaces in the Atlas)	**0** (0.0002 m)	0.0
0.0001	water areas (lakes, fjords, open sea)		0.0

APPENDIX D

Table D-1: Technical parameters of Gamesa wind turbine

Properties of the model		
General data	Manufacturer	Gamesa (Spain)
	Model	G80/2000
	Wind class	IEC Ia / IEC IIa
	Offshore model	No
	Power density	0.026 m²/kW
	Commissioning	2003
Operation data	Rated power	2000 kW
	Rated wind speed	15.0 m/s
	Cut-in wind speed	4.0 m/s
	Cut-out wind speed	25.0 m/s

ROTOR	Diameter	80 m
	Swept area	5027 m²
	Rotational speed	9.0 - 19.0 rpm
	Manufacturer	Gamesa
BLADES	Number of blades	3
	Length	39 m
	Airfoils	NACA 63. XXX - FFA-W3
	Material	Pre-impregnated epoxy glass fiber
	Manufacturer	Gamesa
TOWER	Type	Modular
	Height	67 m
GEAR BOX	Type	1 planetary stage 2 parallel stages
	Ratio	1:100,5 (50Hz) 1:120,5 (60Hz)
	Manufacturer	Echesa (Gamesa Group), Hansen, Bosch Rexroth, Winergy
GENERATOR 2.0 MW	Type	Asynchronous, double fed induction
	Rated power	2.0 MW
	Voltage	690V AC
	Frequency	50Hz / 60Hz
	Potection class	IP 54
	Power factor	0.95 CAP - 0.95 IND throughout the power range
	Manufacturer	Cantarey (Gamesa Group), ABB, Indar
CONTROL AND PROTECTION SYSTEM	Power control	Pitch
	Speed control	Variable via microprocessor, active blade pitch control
	Main brake	Individual blade pitch control
	Second brake system	Disk brake
	Yaw control system	4 electric gear motor(s)
	Manufacturer of control system	Gamesa, Ingeteam and ABB
	SCADA-System	Gamesa WindNet® via fixed line, GSM or satellite

Table D-2: Power curves of wind turbine using the density of 1.225 kg/m^3

	Gamesa G80 2 MW	
Speed [m/s]	Power [kW]	Thrust Coefficient [ ]
4	43.0	0.818
5	105.2	0.806
6	215.2	0.804
7	401.7	0.805
8	660.0	0.806
9	970.9	0.78
10	1315.2	0.737
11	1616.5	0.649
12	1822.2	0.571
13	1970.4	0.41
14	2000.0	0.314
15	2000.0	0.249
16	2000.0	0.202
17	2000.0	0.167
18	2000.0	0.14
19	2000.0	0.118
20	2000.0	0.101
21	2000.0	0.088
22	2000.0	0.076
23	2000.0	0.067
24	2000.0	0.059
25	2000.0	0.052

Table D-3: Technical specifications of Sany wind turbine

Properties of the model		
General data	Manufacturer:	Sany (China)
	Model	SE8220III
	Wind class	IEC Ia / IEC IIa
	Power control	Pitch
	Offshore model	No
	Power density	0.027 m²/kW
	Commissioning	2010
Operation data	Rated power	2000 kW
	Temperature conditions	-30oc- 400c
	Cut-in wind speed	3.5 m/s
	Cut-out wind speed	25.0 m/s
	Rated wind speed	12.82.0 m/s
Rotor	Diameter	82.5 m
	Swept area	5346 m²
	Rotor speed	18 rpm
	Rotational direction	Clockwise
Tower	Height	70 m
Blade	Number of blades	3
	Length	40.6 m
Gearbox	Type	One stage planetary Gearbox with one spur gear stage
	Transmission ratio	2200 kW
	Rated power	33.3
Generator	Type	Double-fed asynchronous
	Rated power	2060 kW
	Voltage	690 V
	Rotated frequency	50 HZ
	Rotational speed	600 rpm

Table D-4: Power curves of nominated wind turbines using the density of 1.225 kg/m^3

	Sany SE8220III 2 MW	
Speed [m/s]	Power [kW]	Thrust Coefficient [ ]
3.5	4.8	0.9921
4	35.1	0.9821
5	119.4	0.8861
6	232.1	0.7614
7	388.4	0.7343
8	597.9	0.74
9	868.4	0.7436
10	1188.9	0.7463
11	1525.4	0.7092
12	1825.9	0.5527
13	1988.7	0.3993
14	2000.0	0.3265
15	2000.0	0.2607
16	2000.0	0.2132
17	2000.0	0.1773
18	2000.0	0.1497
19	2000.0	0.128
20	2000.0	0.1106
21	2000.0	0.0966
22	2000.0	0.085
23	2000.0	0.0754
24	2000.0	0.0673
25	2000.0	0.0605

APPENDIX E

Table E-1: Wind plant capital cost breakdown

Capital Cost Breakdown	%	$US/MW
Supply of WTGs	59.63 %	1,133,019
Supply of cabling	3.87 %	73,504
Supply substation equipment	11.15 %	211,940
Supply of control, monitoring and metering equipment and associated cabling	0.43 %	8,148
Supply of transmission line cabling, equipment and towers	3.23 %	61,406
Installation of above	0.77 %	14,668
Foundations	6.00 %	113,990
Roads, hard standings and drainage	3.70 %	70,299
Substation foundations and buildings	3.93 %	74,700
Transmission line foundations	0.26 %	4,915
Commissioning	0.02 %	426
Price for individual spare parts in the proposed spares list	1.15 %	21,924
Price for tools	0.03 %	651
Design costs	1.42 %	27,059
Site project costs including mobilization, site management, temporary facilities etc.	0.77 %	14,573
EPC management and contingency	1.67 %	31,682
Balance of electrical costs	1.05 %	20,043
Balance of civil costs	0.67 %	12,680
C&I Costs, including all related C&I costs	0.23 %	4,373
Total	**100 %**	**1,900,000**

APPENDIX F

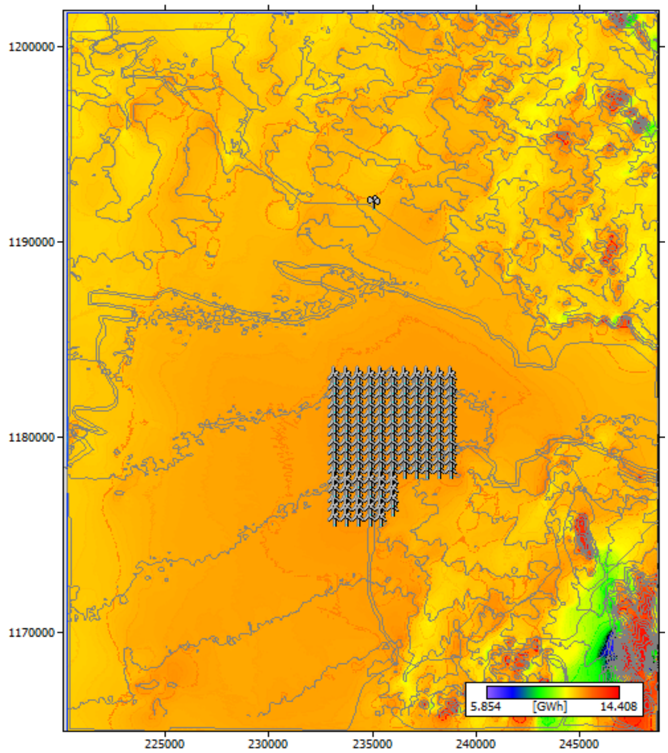

Figure F-1: Resource grid of AEP with turbine cluster

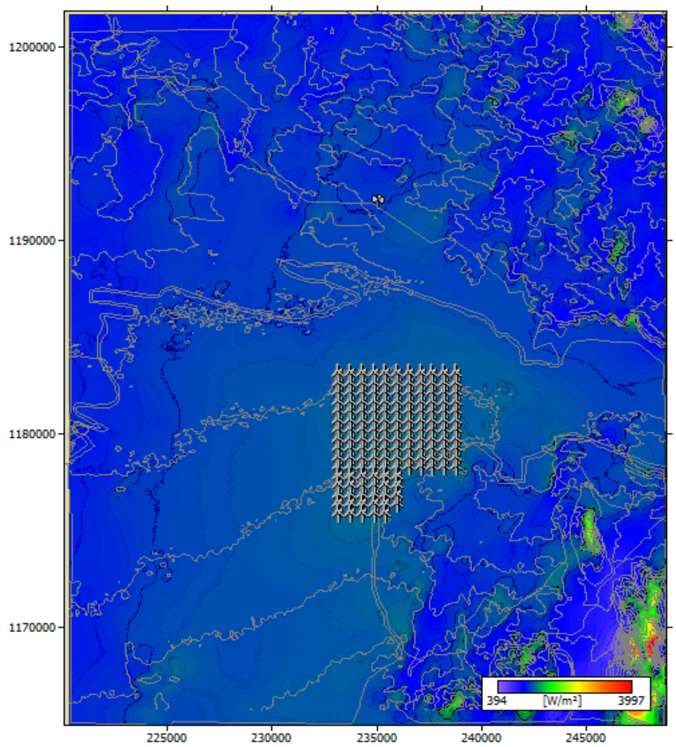

Figure F-2: Resource grid of power density with turbine cluster

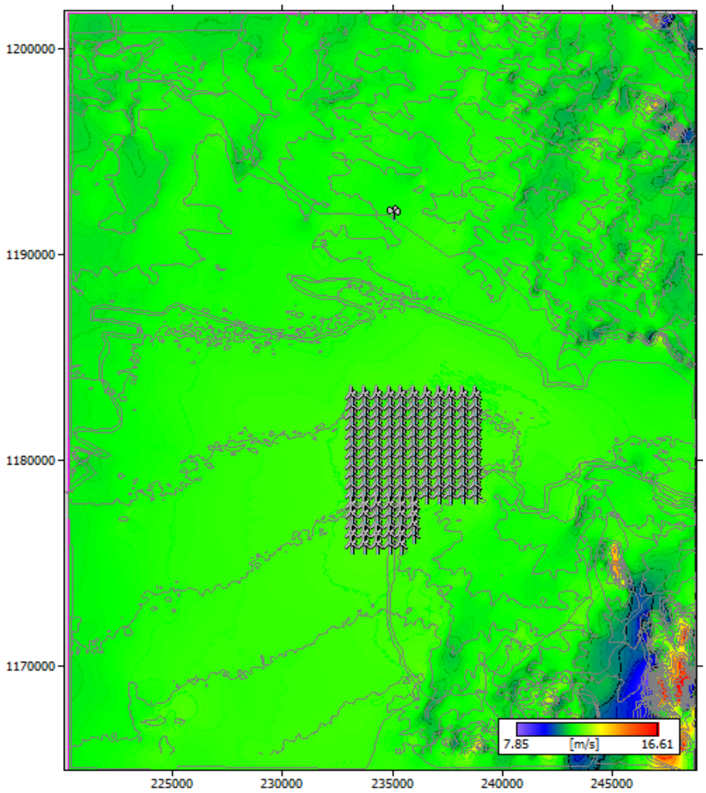

Figure F-3: Resource grid of wind speed with turbine cluster

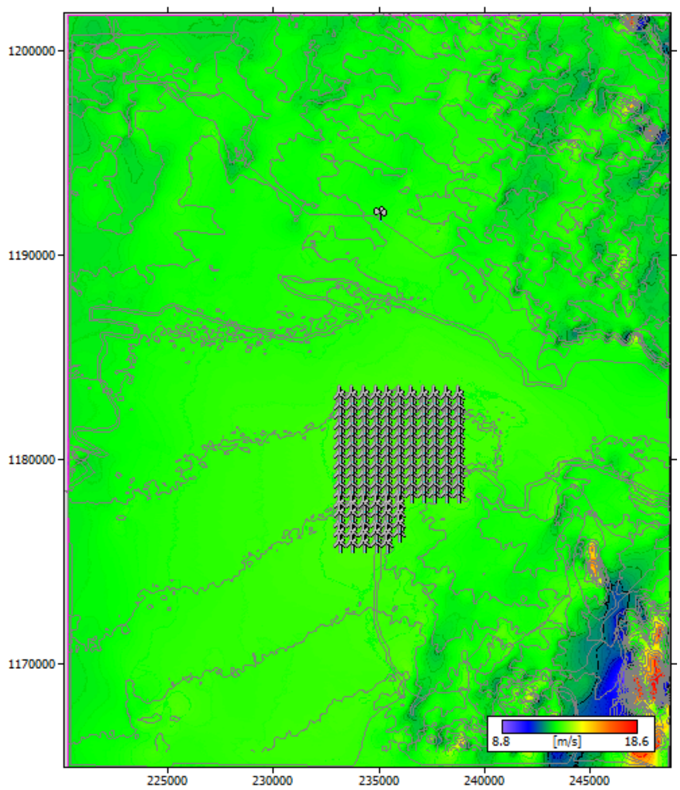

Figure F-4: Resource grid of Weibull -A with turbine cluster

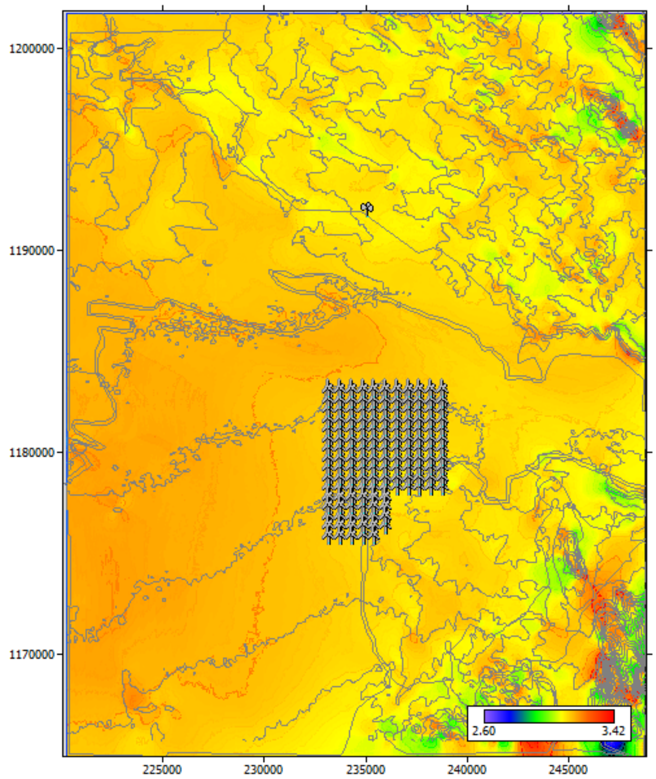

Figure F-5: Resource grid of Weibull –k with turbine cluster

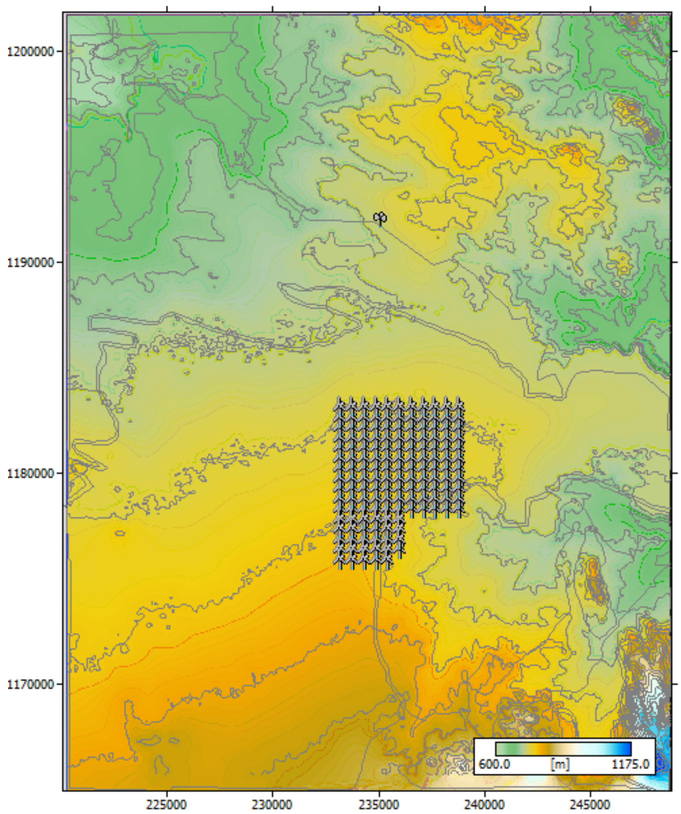

Figure F-6: Resource grid of Elevation with turbine cluster

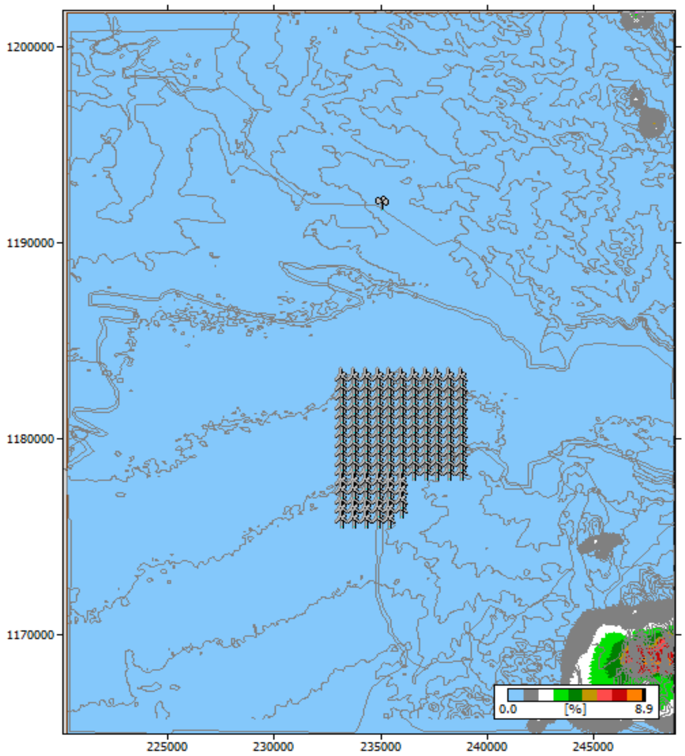

Figure F-7: Resource grid of RIX with turbine cluster

APPENDIX G

The following figures are screen shoot from the synchronization results of WAsP 10.2 with Google Earth to show the reader 3D representation of the wind farm:

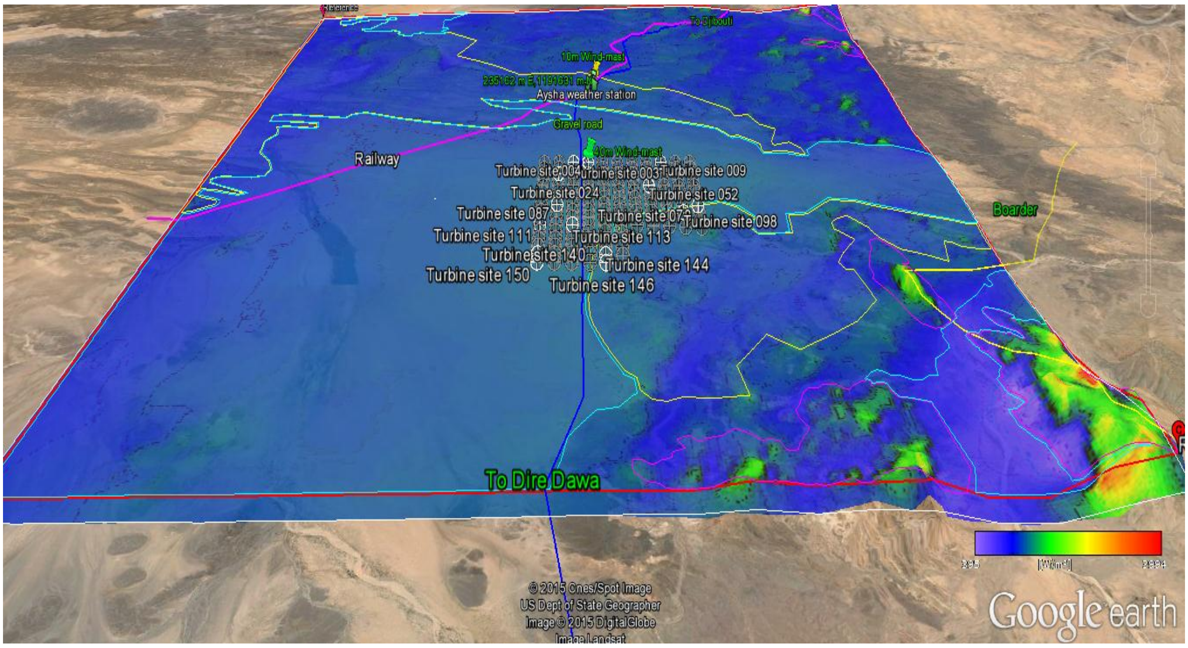

Figure G-1: Synchronized power density distribution with Google Earth showing potential wind turbine site areas

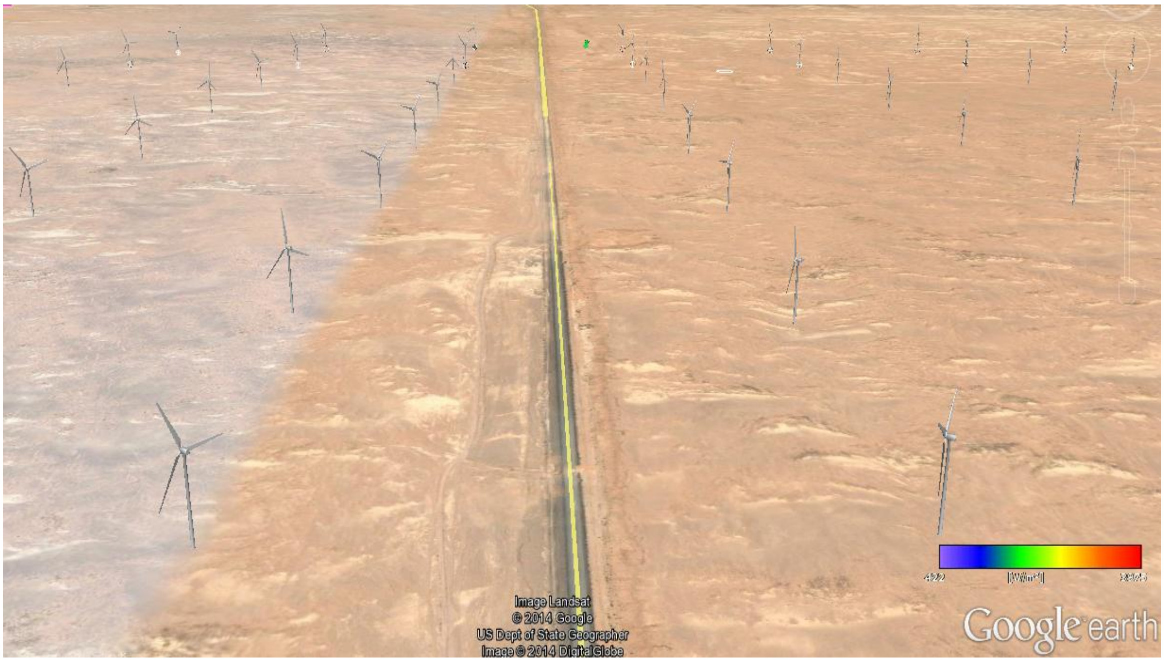

Figure G-2: Synchronized wind turbines with Google Earth showing at both sides of the road