WIND RESOURCE ASSESSMENT AT ADAMA II WIND FARM USING WAsP

By:

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ABSTRACT

This paper presents the Estimation that has been undertaken in order to quantify the wind resource available at Adama II Wind Farm using the Wind Atlas and Application Program (WAsP). It was made through retrieving the data measured by anemometer and wind vanes at Kusaye site which is stored in a data logger from 16/11/2011 to 9/12/2012 at 70 meters above ground level.

Establishment of Wind Farm is asserted by estimation of wind resource at a given site, applying wind flow modeling methodologies. The source data at Adama II Wind Farm indicated that the mean wind speed is 8.62 m/s whereas the emerged mean wind speed and the mean wind power density were obtained to be 8.66 m/s and 440 W/m^2, respectively, at 70 m. Site independent or regional wind climate has also been calculated for five roughness classes and five standard heights along with all sectors of a Wind Rose to estimate the wind climate at the site through utilizing the characteristics of Sany SE7715 Wind Turbine Generator.

The results of the assessment presented that the prevailing wind direction is ENE direction with more than one third of wind is blowing in ENE. From the recorded data at 70 m, the mean wind speed at 50 m is estimated to be 8.22 m/s, which suggests that the wind resource at Adama II is wind class of 6. At the mast location for a single WTG the wind power density is 452 W/m^2 and the Gross Annual Energy Production ranges from 1.5 to 11.99 GWh at 70 m height. Placing the 102 SE7715 WTGs in accordance with the proposed layout at the Wind Farm, the Gross Annual Energy Production is 664.745 GWh and net AEP at the site is 403.669 GWh. After repositioning the WTGs to potential locations, the net AEP is estimated to be 478.786 GWh, an increment of 75.12 GWh on the Net Annual Energy Production, an increase of about 18.6 %.

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ACRONYMS

DTU	Technical University of Denmark
WWEA	World Wind Energy Association
GWEC	Global Wind Energy Council
OECD	Organization for Economic Co-operation and Development
EEPCo	Ethiopian Electric Power Cooperation
WAsP	Wind Atlas Analysis and Application Program
OWC	Observed Wind Climates
MCP	Measure Correlate and Predict
NCEP	US-National Center for Environmental Prediction
PDF	Probability Density Function
HCIE	Hydro China International Engineering Company
PNL	Pacific Northwest Laboratory
UTM	Universal Transverse Mercator
CFD	Computational Fluid Dynamics
NWP	Numerical Weather Prediction
RIX	Ruggedness Index
PWC	Predicted Wind Climate
WTG	Wind Turbine Generator
OEWCs	Observed Extreme Wind Climates

NOMENCLATURE

ρ	Density of air
GW	Giga Watt
MW	Mega Watt
AEP	Annual Energy Production
k	Weibull Shape Parameter
K	VonKarman's constant
Z_o	Roughness length
U	Wind speed
u*	Scaling Velocity
Z	Height
E	Energy
P	Power
Pw	Power Density
A	Weibull Scale parameter
C_T	Thrust Coefficient
C_p	Power Coefficient
GWh	Giga Watt hours

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CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

Energy is one of the crucial inputs for socio-economic development; it plays a significant role in human existence immediate after air, food and shelter [1]. In the past two centuries the development of the globe has changed the way how people live in the world and these changes either forced or motivated people to extract energy, directly or indirectly, from the existing sources and use this energy for variety of functions.

The role played by electricity for the sole functioning of the industries, that the existing development of the world is relied at, is increasing. The energy demand across the globe is also rising along with its side effects to the atmosphere and this requirement leads the world to look forward for an extensive and environmental friendly electrical energy sources like that of the renewable energy sources.

At is estimated that, at least for about 3000 years the power of the wind has been used, windmills were used regardless of the functions they perform like for water pumping and sailing ships. During the European history the rural economy were dependent on the horizontal axis windmills until the time that they started to use cheap fossil fueled engines for electrical energy supply [17].

From around 1990, regardless of the available oil at a very low price, the main driver for the extraction and use of wind turbines to generate electrical power was the very low CO_2 emissions and the potential of wind energy to help in controlling the climate change. Then from around 2006 the very high oil price and concerns over security of energy supplies led to a further increase of interest in wind energy and a succession of policy measures were put in place in many countries to encourage its use. In 2007 the European Union declared a policy that 20% of all energy should be from renewable sources by 2020.

Growing energy demand and environmental consciousness have re-evoked human interest in wind energy. The sudden increase in the price of oil stimulated a number of substantial, government funded programs of research, development and demonstration. As a result of this, wind energy is the fastest growing energy source in the world today [1].

The rate at which energy is being consumed by a nation often reflects the level of prosperity that it could achieve. During the past 10 years, the primary energy use in the industrialized countries increased at a rate of 1.5%, while the corresponding change in developing nations was 3.2%. With this trend prevailing, the global energy demand would increase considerably in the coming years [1].

Consumption of traditional fuels has negative environmental, economic and health impacts such as deforestation, pollution, leading to ecological imbalance, and increased use of agricultural residues and animal dung deprives the land of essential nutrients that are necessary for soil fertility. Furthermore, smoke from the use of fuel wood and dung for cooking contributes to acute respiratory infections. As a result of these the environmental friendly wind power generation will have a priority.

The use of renewable energy sources for everyday activities is increasing. Above all the wind energy is dominant. The world is using the resource either on shore or off shore to generate electricity.

The WWEA report for 2011 presented that, the growth regarding wind energy in the world is accelerating at a rate which is much higher than the other renewable sources of energy. The worldwide wind capacity, extended to 215 GW by the end of June 2011 and at the end of the year it went to 236.749 GW. Worldwide wind capacity grew by 9.3 % within six months and by 22.9 % on an annual basis, whereas, the annual growth rate in 2010 was 23.6 %.

The total installed wind capacity in the whole world was 283 GW by the end of the year 2012. This capacity can cover almost 3 % of the electricity demand all over the world. And it went to 318 GW in 2013.

According to the estimation conducted by WWEA, at least 44 countries added a combined 45 GW of capacity (more than any other renewable technology), increasing the global total by 19% to 283 GW in 2012 and around 12.37% in 2013. Figure 1.1 shows the growth of the world wind potential from 1996 till the end of 2013.

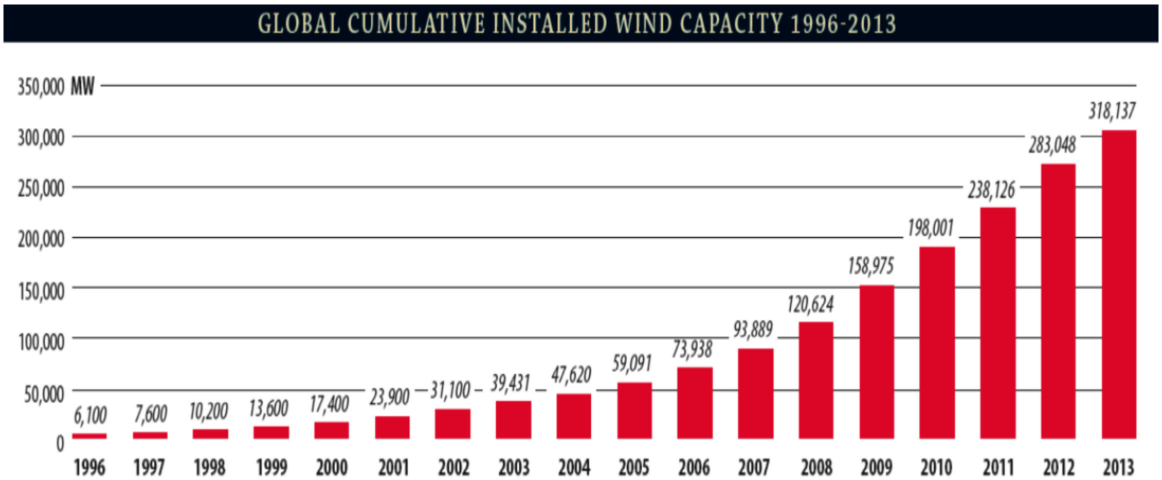


Fig. 1.1 The world wind potential growth (*Source: GWEC Report 2013*)

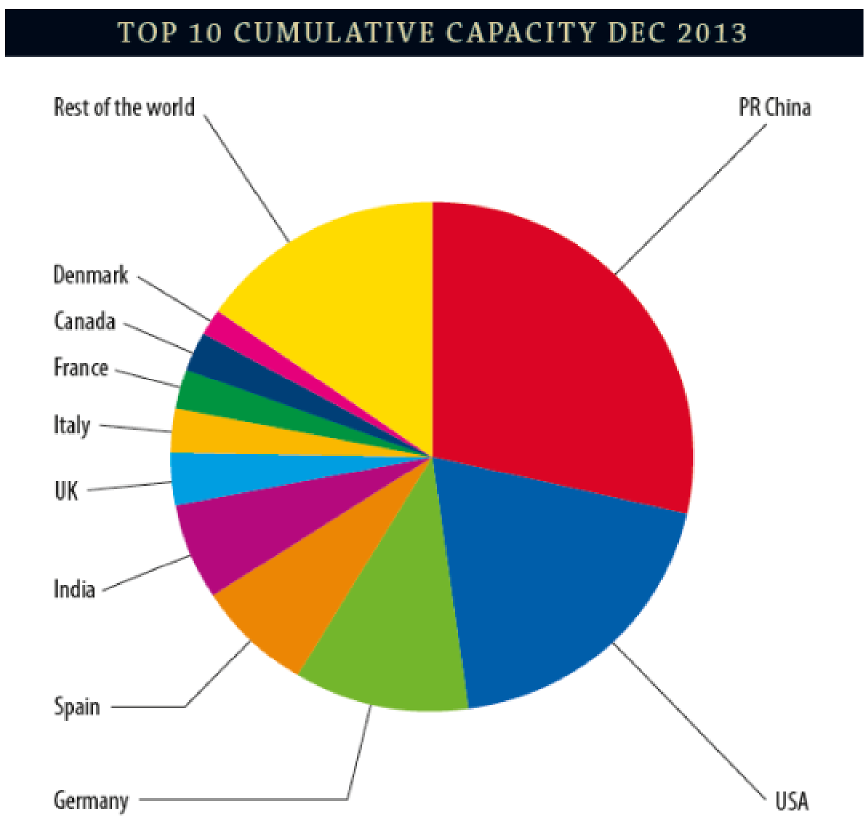


Fig. 1.2 The top 10 countries Installed wind power capacity (*Source: GWEC Report 2013)*

In this rapid growth five leading countries were having the major share of the world capacity of wind turbines and wind power i.e. China, USA, Germany, Spain and India; together they represent a total share of more than 70 % of the global wind energy potential. The global Wind Energy Council (GWEC) released its 2013 report till the end of December; the top ten countries with maximum cumulative wind energy are presented above in Figure 1.2.

Relying upon the imported petroleum is also unsatisfactory to fill the gap between the demand and supply of the electrical power of a nation, since it costs foreign currency and also the sources of the nonrenewable energy are expected to deplete in decades of time. On the contrary, the number of industries are always increasing from time to time, thus a single watt of energy plays a difference in the supply grid system.

To come up with the maximum output of the wind energy from a wind farm, using a given type of wind electric generator, an assessment of the wind resource available at any prospective site is essential to determine the sitting of the wind electric generators.

To secure the investment funds and to present an estimation of the intended profit of a wind energy project, the wind energy resource assessment at the site is extremely essential, since the costs are mainly dependent with the available wind energy resource at the intended site.

The wind energy resource availability is highly variable both geographically and from time to time in a fixed location, hence the need to conduct wind resource assessment plays an important role with regard to exploiting the wind energy resource availability at national or international level.

The real cost of wind generated energy may be uncertain, thus the wind resource assessment campaign represents one of the most important phases in the development of utility-scale Wind Farms. The energy production estimates that are generated based on the results of the wind measurement campaign are essential in determining the feasibility of a proposed Wind Farm project. The most important and valuable information required to successfully implement the establishment of a Wind Farm at a predetermined site is to carry out the wind resource assessment at the intended site [6].

At the end of 2010 the estimated capacity of the Ethiopian grid was 2059.6 MW. The power supply basically relies on hydroelectric power. The constraints regarding the hydroelectric power generation, such as the deficiency of rainfall during dry seasons, the gap between the demand and supply is still wide, are also the reasons for the Ethiopian Electric Power Cooperation (EEPCo) to establish Wind Farms across the windy areas of the country [18].

Approximately more than 90% of Ethiopia’s current electrical energy supply is generated from hydropower, with some MW supplied by temporary diesel generators. Although Ethiopia is said to have a national hydropower potential of 30 to 45,000 MW, it will be difficult to make use of all the potential because two thirds of it are within the catchment of the Blue Nile and therefore it seems to be very dependent on international agreements and relations with the Sudan and Egypt [15].

Previous studies have shown that Ethiopia has sufficient wind speed to produce electricity from wind. Ethiopia is venturing into large-scale wind power generation, as it embarks on an ambitious plan, the growth and transformation plan, to increase its electrical capacity by four-fold in 2015 to meet rising domestic demand and gain export revenues [7].

A reasonable estimate on the wind resource assessment is absolutely crucial to the success of a wind energy project. At the time being, due to the need in accuracy and to save time, the wind resource assessment is conducted in computer programs, which are specifically designed to facilitate accurate predictions of Wind Farm energy production.

These computer programs that have been developed to predict a reliable estimates of the wind power at the selected potential sites such as WAsP, MS-Micro, Wind-Pro, Wind farmer, Windo-grapher, Wind-Sim, MM5 and others will increase the precision of the assessment. Out of these programs, the industry generally opts for simple but effective tools such as WAsP.

The Wind Atlas Analysis and Application Program (WAsP) is the most commonly used tool for wind resource predictions on land as well as offshore. WAsP is a computer program for predicting wind climates and power production. The predictions are based on wind data measured at a station in the same region. The program includes analytic flow model, a roughness change model and a model for sheltering obstacles [9].

In this Thesis, the data collected at Adama II site Wind Farm will be used for the assessment using WAsP to assess the existing wind power potential of the site under consideration. The collected data used for the Thesis is recorded from 16/12/2011 to 9/12/2012, in four measuring heights for measuring the wind speed and at two measuring height for collecting wind direction.

A wind data for a period of one year recorded at the specific site is sufficient to represent the long term variations in the wind profile within an uncertainty level of 10% [2], the site selected for the analysis fulfils the requirement with regard to data range needed for reasonable prediction of energy production potential.

Most wind speed measurements are made using cup anemometers, in which they are placed near the ground at a predefined height, mostly at 10 meters and high above from the ground preferably one third of the hub height of the WTG. The instruments are accompanied by a logger to record the data at specific time interval. The recorded wind data are fed to the intended software to have an organized Wind Atlas generation, wind climate estimation, Wind Farm power production calculations are finally be undertaken after sitting of wind turbines using the data taken from the project. Further re-sitting has been proposed through consideration of the high wind resource areas and reduction of wake effects.

This complementary wind resource assessment technique, using WAsP, will greatly accelerate and facilitate the early stages of Wind Farm development. This will present wind resource potential sites that, by definition, are ground-truthed with a minimum of measurements and more precise and accurate on less complex areas.

1.2 STATEMENT OF THE PROBLEM

Owing to the commitment of reducing GHG emissions and to provide with an adequate energy to the world, efforts are being made throughout the world to supplement the energy base with renewable sources.

People tend to overestimate the wind power available at a site. Some wind power estimations are done mainly depending on the number of wind turbines, wind turbine power curve and characteristics. The estimation should also rely on the wind resource assessment techniques and the WTGs characteristics. The ultimate role of the wind resource assessment is to quantify the available wind energy through a careful utilization of the recorded wind data.

The feasibility and attractiveness of a Wind Farm is determined by the estimated energy production generated based upon on the wind measurement and assessment prior to the construction at the site.

Wind conditions are site-specific and variable, but predictable over a long term. Wind resource assessment programs must be designed to maximize accuracy. Combination of measurement and modeling techniques gives projections close to those experienced in actual operations. Basically, the wind energy industry needs reliable tools for estimating mean wind speeds at selected heights for locations and wider areas where data are sparse. This would allow Wind Farm developments to proceed in less time, without the need to collect years of actual wind data.

In the meantime, the Ethiopian government is engaged in variety of projects to generate an electrical energy. The electrical energy generated from the abundant wind resource has got an emphasis to fill the gap between the supply and the demand across the country. This projects incur a huge capital and requires foreign currency, thus a reasonable study shall be done before investing a huge capital and human resource. The study shall be carried out with latest technology and materials to come to a feasible result.

Wind Farms are composed of sets of WTGs aligned or arranged in a manner that is suitable and profitable to generate the maximum amount of Annual Energy Production. Even though, wind resource estimation is carried out through the installation of anemometer masts at some locations. Since the number of masts are not equivalent with the number of the WTGs, thus extrapolation is mandatory, in order to make the extrapolation precise a wind resource modeling software is one indispensable input.

Determining high wind resource areas or locations is an important procedure to maximize the energy production. However, it is quite difficult and time taking to undertake the estimation manually. The existence and application of flow modeling software will reduce the task and increase the accuracy.

The most commonly used tool for wind resource predictions on land as well as offshore is the Wind Atlas Analysis and Application Program (WAsP). WAsP is developed based on the

Wind Atlas methodology where the Observed Wind Climate data will be converted to generate a standardized free flow wind data (Wind Atlas).

The installation of Wind Turbine Generators at a site should also depend on the assessment conducted for effective turbine locations. The locations of wind turbine generators play an important role in maximizing the power generation, thus optimal and efficient arrangement of these Wind Turbine Generators shall also be pointed out for magnifying the estimated power potential of the site.

1.3 OBJECTIVES OF THE STUDY

The main objective of this project is to analyze wind flow using the wind data collected at the site and to estimate annual wind energy production potential at Adama II site using the WAsP software tool, Along with WTG re-sitting for maximizing the Annual Energy Production at the intended Wind Farm. Through conducting the analysis better acquaintance with the wind flow modeling techniques will be obtained.

The specific objectives include:

- Data extraction from the data logger;
- Analysis of wind data using WAsP climate analysis tool;
- Determination of Wind Atlas;
- Generation of resource map of the area;
- Estimation of AEP using the existing layout;
- Identification of potential areas in the Wind Farm;
- Estimation of Annual Energy Production for each WTGs.

1.4 METHODOLOGY

1.4.1 Site description

ADAMA II wind power project is located about 95 km from Addis Ababa and 7 km from Nazareth, at elevations of 1741~2173 m. The central geographical position of the wind power project is 39° 12' 10" E, 8° 34' 18" N. At the ground surface of the wind power project is mainly covered with shallow grass and small shrubs and some gravels. It is a favorable site for wind power project [18].

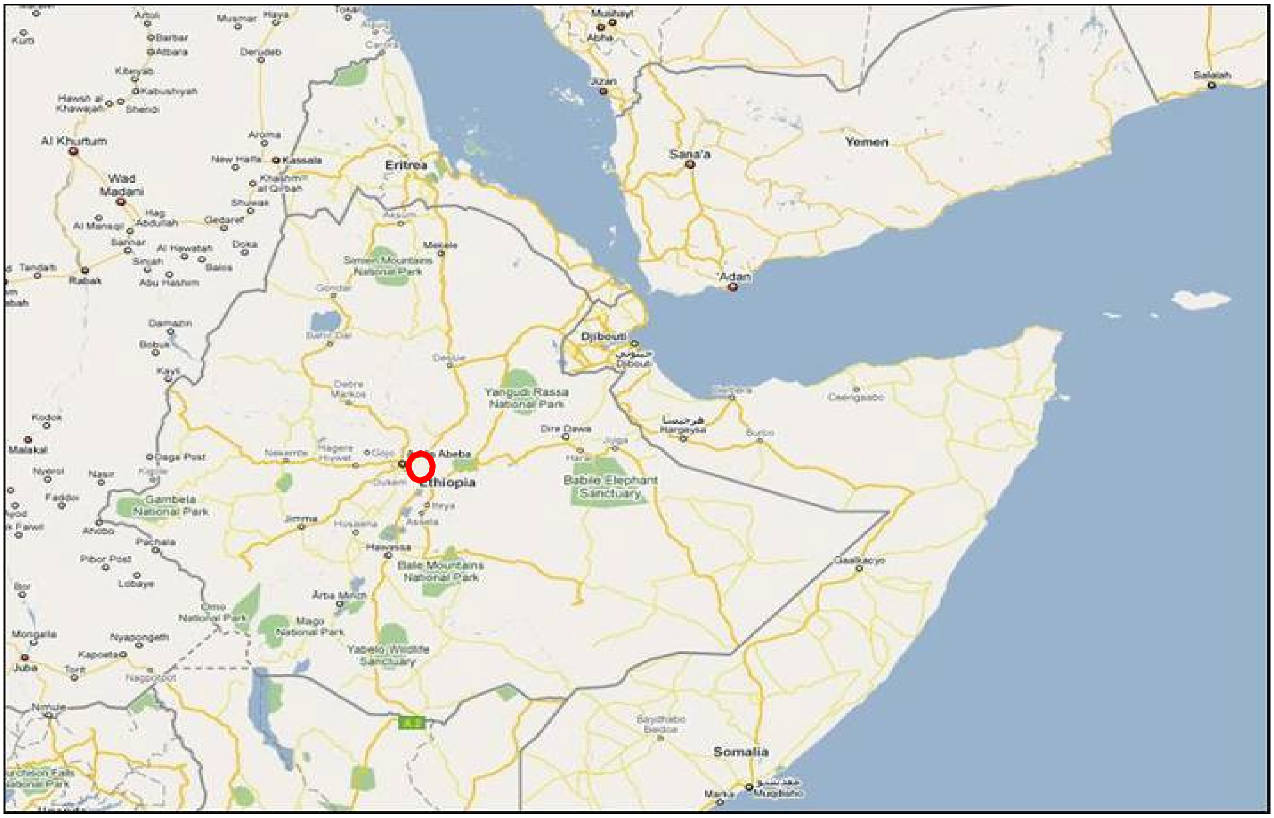
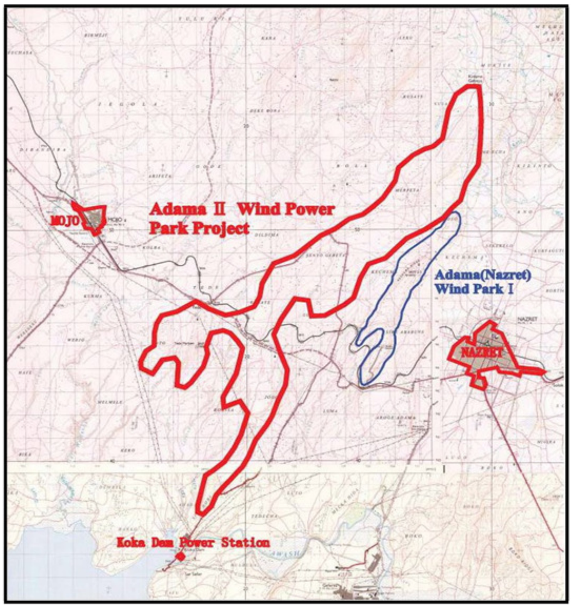


Fig. 1.3 Location of Adama Ⅱ Wind Power Project [18]

The proposed site is located near the Great Rift Valley and the northwest dipping fault crushed zone, the micro topography is slightly undulating hilly ground, the ground on the top of hill is relatively flat, and the relative height difference is small. The ground surface is mainly formed with gravels and broken stones, which are of weathered welded tuff. Small amount of outcrops of rocks, thin overburdens and thick vegetation (mainly shallow grass and small shrubs) are those that covered the surface. There are sparse residents in the wind power project site, medium and strong earthquake activities in this area are relatively frequent [9].



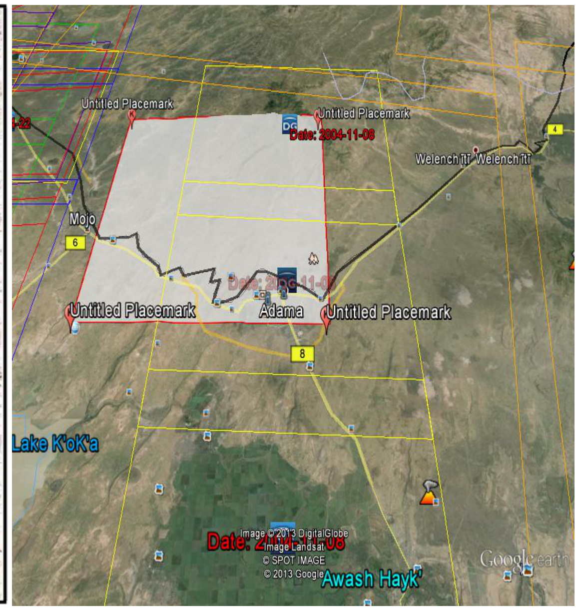


Fig. 1.4 The proposed Wind Park

Fig. 1.5 The Wind Park area for consideration

1.4.2 Material and methods

The materials which are necessary to conduct the research include the contour map of the area which is generated using Global Mapper tool after obtaining the elevation data of Ethiopia from Ministry of mines and Energy, the recorded data is the basic input for the generation of the Wind Atlas and for wind resource estimation.

To achieve the objectives of this study, the relevant methodologies have been used along with the estimated power output at the site with 102 wind turbine generators. Literatures of relevant materials related to wind energy and its resource assessment methods are reviewed in order to come up with the global trends regarding wind energy resource assessment.

The collected wind data within a 10 minute period and the elevation contour map of the area are utilized in accordance with the standard procedure for wind resource assessment using WAsP Climate Analyst tool.

Utilizing the data logger software for validating and verification of data and also exporting raw data files to the WAsP Climate Analyst tool can be considered as the primary step in modeling the wind flow at the site. In conjunction with the Symphonie data retriever, the WAsP Climate Analysis tool are used for analyzing the data that has passed through the validation phase, the results are presented in the form of the wind speed distribution basically the Observed Mean Wind speed has been presented from the measured wind speed and wind direction.

The results of the WAsP Climate Analyst tool are used as an input for the WAsP software to generate the intended output, the results are plotted through presenting the Wind Atlas of the site in which the wind climate have been estimated, estimation of the Annual Energy Production from the site and sitting of the selected WTGs after creating or digitizing the elevation and roughness map of the area is presented. In addition to that, the available wind resource to the grid has also been indicated within the resource spatial view. To come up with the results, the WAsP modeling will basically follow the procedure listed below..

1. **Analysis of raw wind data:** Data retrieved from the data logger is analyzed to present the wind speed and direction at the measuring heights above the ground. The analysis enables any time-series of wind measurements to provide a statistical summary of the observed, site-specific wind climate [10].
2. **Generation of Wind Atlas**: A Wind Atlas is a systematic and comprehensive collection of regional wind climate derived by Wind Atlas methodology. The wind observations have been cleaned with respect to the site-specific conditions. The Wind Atlas data sets are obtained at some reference height above ground the site-independent and the wind distributions have been reduced to certain standard conditions.
3. **Wind climate estimation**: the next step is the estimation of the wind climate by performing the inverse calculation as is used to generate a Wind Atlas. A wind climate is a file which contains detailed results including power density and power production. By introducing descriptions of the terrain around the site, the models can predict the actual, expected wind climate at this site [10].

4. **Estimation of wind power potential:** An estimate of the Annual mean Energy Production of the Wind Turbine Generator can be obtained by providing WAsP with the power curve of the WTG.
5. **Calculation of Wind Farm production**: The final goal of the Thesis is to calculate the Wind Farm Production, and thereby the net Annual Energy Production of each wind turbine and of the entire Wind Farm will be calculated.

1.5 SCOPE AND LIMITATION

The main objective of this Thesis is to optimize the wind energy available at the Wind Farm under consideration. While doing these all the necessary reports will be presented like the observed wind climate, the Wind Atlas and also the reposition of the Wind Turbine Generators for a better power output are the kind of results.

The estimation of the wind resource at Adama II has been investigated and this investigation is very much limited to the available data, the wind speed data recorded at Kusaye site. Accurate results regarding wind resource assessment can be obtained through utilization of long term wind measurement campaigns mainly for more than five years. Apart the limitations of the WAsP software for modeling the site, the accuracy of the results obtained from the modeling software basically relies on the data fed to the software.

The quality of the data gathered at the Wind Farm by the project coordinators and the influences that can be observed on the anemometer mast will also limit the accuracy of the results of the analysis. Extensive Practical observation and consideration of the Wind Farm properties such as elevation, land cover and orography conditions along with the feasible Wind Turbine Generators position will provide more accurate results.

1.6 STRUCTURE OF THE THESIS

The Thesis starts with **Chapter One** describing the background and introduction of the research work followed by the significance of the study under the problem statement, objectives and methodology. **Chapter Two** presents literature reviews and theoretical background of the wind energy extraction, estimation and calculation, wind resource assessment methods and also the assessment software methodologies, basically WAsP software methodologies. **Chapter Three** presents the data manipulation using the data logger software. Contour map digitizing, Wind Turbine Generators power curve, thrust coefficient curve and power coefficient curve is presented along with its locations at the site. Then data analyses at the intended site using WAsP software are discussed in **Chapter Four** under the section of Modeling with WAsP. **Chapter Five** presents the results of the modeling procedure along with discussion leading to the conclusion and recommendation part in **Chapter Six**.

CHAPTER TWO

2. REVIEW OF RELEVANT LITERATURES AND THEORETICAL BACKGROUND

2.1 INTRODUCTION

Human efforts to harness wind energy dates back to the ancient times, when they used sails to propel ships and boats. Later, wind energy served the mankind by energizing grain grinding mills and water pumps. During its transformation from these crude and heavy devices to today's efficient and sophisticated machines, the technology went through various phases of development [2].

The primary causes of atmospheric air motion, or the wind, are uneven heating of the Earth by solar radiation and the Earth's rotation. Differences in solar radiation absorption at the surface of the Earth and transference back to the atmosphere create differences in atmospheric temperature, density, and pressure, which in turn create forces that move air from one place to another.

The extraction of power from the wind with modern turbines and energy conversion systems is an established industry. Machines are manufactured with a capacity from tens of watts to several megawatts, and diameters of about 1m to more than 100 m. Traditional mechanical-only machines have been further developed for water pumping, but the overriding commerce today is for electricity generation [7].

Although the wind is free, the investment and maintenance of the plant caused the cost of electricity to be much higher than that produced by steam plants [6].

In 2011, the worldwide wind energy usage is extended to 236.75 GW. Out of which 18.405 GW were added in the first six months of 2011. Global wind capacity grew by 9.3 % within six months and by 22.9 % on an annual basis. Whereas, the annual growth rate in 2010 was 23.6 %.

In the year 2012, the worldwide wind capacity reached 282,275 Megawatt, from 236,749 Megawatt in 2011, 196,944 Megawatt in 2010 and 159,742 MW in 2009 [17].

In addition to the growing economic attractiveness of wind energy, there are major essential arguments for its use throughout the world, such as:

1. Wind energy is one of the renewable energy systems with the lowest cost of electricity production and with the largest resource available.
2. Wind-power plants emit absolutely no CO_2, the major pollutant when fuels are burned.
3. The operation of wind turbines leaves behind no dangerous residues as do nuclear plants.
4. Decommissioning costs of wind turbines are much smaller than those of many other types of power plants, especially compared with those of nuclear generators.
5. Land occupied by Wind Farms can find other simultaneous uses like agriculture [6].

Passive use of wind energy for ventilation of buildings plays a significant role, and active power production by wind turbines is today a rapidly growing energy technology in many parts of the world. The highest penetration reaching nearly 20% of total electricity provided is found in Denmark [8].

2.2 WIND ENERGY

Wind is a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. This wind flow, or motion energy, when "harvested" by modern wind turbines, can be used to generate electricity [16].

Wind varies with the geographical locations, time of day, season of the year, and height above the earth‘s surface, weather and local landforms. The understanding of the wind characteristics will help to optimize wind turbine design, develop wind measuring techniques and select Wind Farm sites [5].

The variation of the wind makes the measurement of the wind to be difficult and expensive equipment will be used; the two most important parameters regarding the measurement are the wind speed and the wind direction.

2.2.1 Wind Speed

Wind speed generally changes with height, which requires an equation that predicts the wind speed at one height in terms of the measured at another height. Under normal conditions for flat terrain, a wind speed is lower at surfaces near the ground than higher distance above ground because the flow of air above the ground is retarded by frictional resistance by surface features of earth. Roughness of the ground by itself or due to vegetation, buildings and other structures present over the ground are the main causes for retardation of wind speed near the ground [3].

This variation of the wind speed with the height above the flat surface ground is described by logs law, a logarithmic relationship with the height.

$$U(z) = \frac{u*}{K} \ln \frac{z}{Zo} \qquad 2.1$$

where: u*= Scaling velocity

K= VonKarman's constant

Z_o= Roughness length

U= Wind speed and

Z= Height

The variation of wind speed influences the power production of the farm since the rotational speed of the rotor will also vary as the speed changes from time to time. For instance GE 3.6 MW wind turbine, the wind speeds below the cut in speed, 3.5 m/s, the rotor will not rotate as the wind touches the rotor, this indicates that the power is null. Whereas in the range of the speed above 3.5 m/s the power output will rise until the speed reaches 14 m/s, in which case the power reaches the rated power. Due to the limitation on the capacity of the electrical generator and control scheme, the power ceases to increase in the range between 14 m/s and 27 m/s. As described, in Figure 2.1, the turbine shuts itself, for speed above 27 m/s for safety reasons [18].

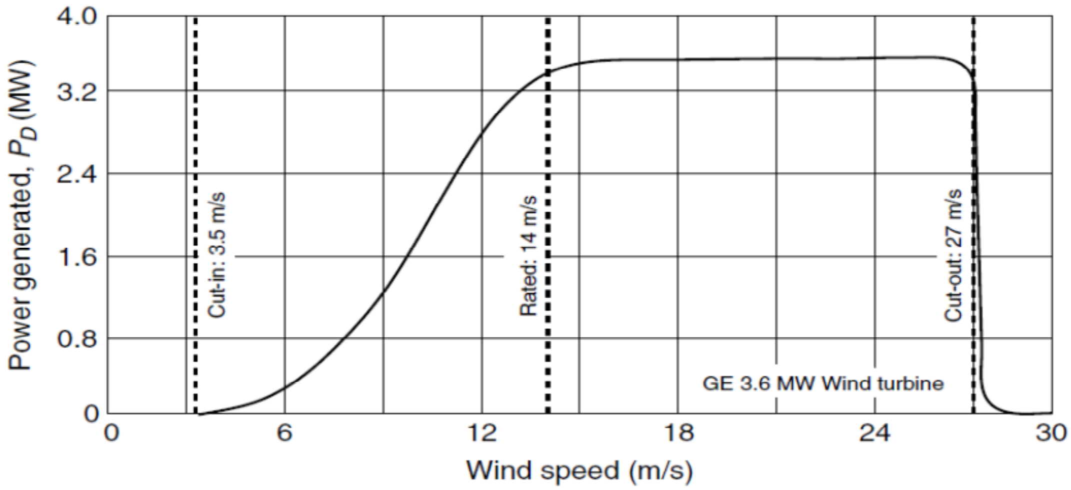


Fig. 2.1 Power output of the GE 3.6 MW wind turbine as a function of wind velocity [18]

2.2.2 Wind Direction

Direction of wind is an important factor in the sitting of a wind energy conversion system. If the major share of energy available in the wind is received from a certain direction, it is important to avoid any obstructions to the wind flow from this side.

Wind vanes were used to show the direction of wind in earlier days of wind distribution data collection. However, most of the anemometers used today have provisions to record the direction of wind along with its velocity.

Information on the speed and direction of wind, in a combined form, can be presented in the Wind Roses. The Wind Rose is a chart which indicates the distribution of wind in different directions [4].

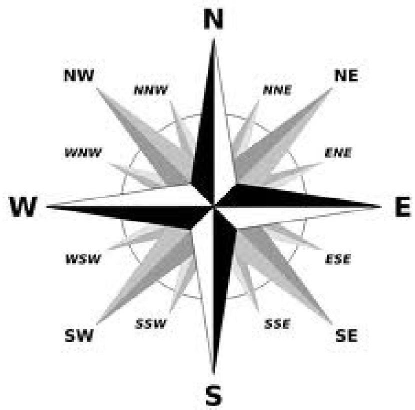


Fig. 2.2 Wind Rose compass

The wind speed can be measured accurately by installing the anemometer at a prospective turbine site at the same height with the turbine hub height and also the wind direction can be measured with wind vanes associated with the anemometer.

A 'Wind Rose' is the term given to the way in which the joint wind speed and direction distribution is defined. For the data collected at Adama site in the august 2012, the Wind Rose is tabulated as follows, where the Wind Rose is generated by the Symphonie data retriever software. The numbers outside the circle are the average turbulence index for speed greater than 4.5 m/s. The outer circle stands for 40% and the inner is for 0 %.

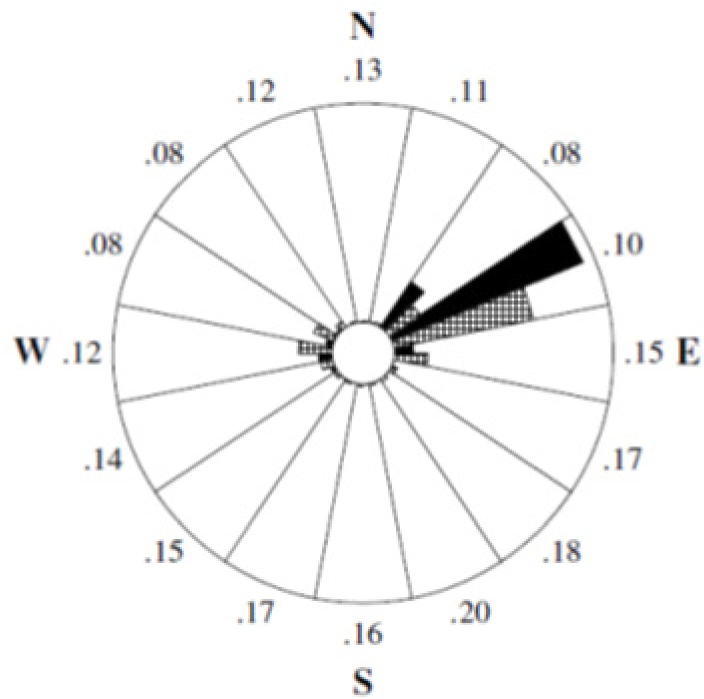


Fig. 2.3 Wind Rose for Kusaye mast site from 11/6/2011 to 6/1/2013

2.2.3 Wind Power

The term Wind power can be defined as the conversion of wind energy into a useful forms of energy, such as using of wind turbines in order to generate electrical power, utilization of windmills for obtaining the so called mechanical power, wind pumps for water pumping or drainage.

Wind energy is the kinetic energy of air in motion. Total wind energy flowing through an imaginary area *A* during the time *t* is:

$$E = \frac{1}{2}mU^2 = \frac{1}{2}(AUt\rho)U^2 = \frac{1}{2}At\rho U^3 \qquad 2.2$$

where: ρ = Density of air

U = Mean Wind speed over time interval t (time averaged)

Wind power in an open air stream is thus proportional to the third power of the wind speed; the available power increases eightfold when the wind speed doubles. Wind turbines for grid electricity therefore need to be especially efficient at greater wind speeds.

Power is energy per unit time, so the wind power incident on *A* is:

$$P = \frac{E}{t} = \frac{1}{2} A\rho U^3 \qquad 2.3$$

The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. Wind energy potential is the total amount of energy that can actually be extracted from the wind, taking into account the efficiency of the wind turbine.

2.2.4 Annual Energy Production (AEP)

The goal of any wind project is to produce energy, so an accurate estimate of production is essential when planning a project. AEP is estimated using the wind speed distribution recorded during the wind distribution measurement phase of the resource assessment, along with the manufacturer's power curve. Multiplying the power output of the turbine at each wind speed with the wind speed frequency, results in an estimate of production at that wind speed. Repeating this procedure for each wind speed bin and adding the results produces an estimate for the turbine's overall production.

The Annual Energy Production is the term that is used for securing the fund, the land and other infrastructure requirements. All the economical point of views is determined after a presentation of an estimation of the Annual Energy Production. In addition all the current world Wind Energy productions are compared with the basis of the AEP.

2.2.5 Power density

There are basic outputs and comparison parameters regarding the wind resource assessment that are average annual wind speed, annual wind direction, average power density, Annual Energy Production, wake losses and wind farm layout. These results are obtained using all the mandatory and available data. Out of these the power density is the basic parameter that determines the wind class of a Wind Farm. Along with the Annual Energy Production and mean wind speed the power density is a parameter which presents the general look and potential capacity of the Wind Farm.

There are fundamental physical limits to how much energy we can extract from renewable resources. If we want to rigorously quantify this we calculate an energy source's power density in watts per square meter (W/m^2). Power density in the wind is the amount of energy transported across a unit area in unit time and calculated as:

$$Pw = \frac{1}{2}\rho U^3 \qquad 2.4$$

where: Pw - Power density

ρ - Density of air

U – Wind Speed

The power density of the wind determines how much energy can be extracted by a wind turbine per unit area and is influenced by two factors: wind speed and air density. The power density is proportional to the cube of the wind speed. As air density decreases at higher altitudes and temperatures, the power density decreases proportionally.

To simplify the comparison of the wind resource at different sites, wind power density has been standardized in Wind Power Classes. These classes are based on wind speeds taken at specific heights, generally using sea level air densities. Since the wind speed at any site will vary with height due to the effects of the terrain on the wind flow, the wind class is often defined at more than one height. The following table summarizes the wind power density relation with the wind class.

Table 2.1 Wind class with Wind power Density (*Source: Battelle Wind Energy Resource Atlas*)

Class	10 m		30 m		50 m	
	Wind power density [W/m^2]	Speed [m/s]	Wind power density [W/m^2]	Speed [m/s]	Wind power density [W/m^2]	Speed [m/s]
1	0 - 100	0 - 4.4	0 - 160	0 - 5.1	0 - 200	0 - 5.6
2	100 - 150	4.4 - 5.1	160 - 240	5.1 - 5.9	200 - 300	5.6 - 6.4
3	150 - 200	5.1 - 5.6	240 - 320	5.9 - 6.5	300 - 400	6.4 - 7.0
4	200 - 250	5.6 - 6.0	320 - 400	6.5 - 7.0	400 - 500	7.0 - 7.5
5	250 - 300	6.0 - 6.4	400 - 480	7.0 - 7.4	500 - 600	7.5 - 8.0
6	300 - 400	6.4 - 7.0	480 - 640	7.4 - 8.2	600 - 800	8.0 - 8.8
7	400 - 1000	7.0 - 9.4	640 - 1600	8.2 - 11.0	800 - 2000	8.8 - 11.9

2.3 WIND RESOURCE ASSESSMENT / FLOW MODELING

To optimize the energy production from the wind, it is essential to find and utilize the windiest locations. As the wind has become an economically viable source of energy, the methods of determining where the optimal sites are, have come under increased interest and research.

Geoff Henderson of Wind Flow Technology suggested that knowing the mean annual wind speed to within 0.5 m/s is very important for gaining an accurate indication of energy output and hence the viability of a particular site. Also, given favorable size, orientation and shape, topographic features can maximize wind energy yield potential by up to 100%.

Accurate through monitoring of wind resource at potential sites is a critical factor in the sitting of wind turbines. And also, since the wind is one of the variable renewable energy sources, the output power will be secured using a given type of wind electric generator, thus an assessment of the wind resource available at any prospective site is essential (Landberg 1999).

Wind resource assessment or wind flow modeling is the process of estimating the wind resource or wind power potential at one or several sites or over an area in other words it means that wind flow modeling is extrapolating the data records from meteorological site or mast location using wind flow models of some kind. The results may be represented in the form of, net Annual Energy Production, Power Density, spatial locations of WTGs, Wind direction probability distribution, i.e., Wind Rose, which shows the representation of wind directions at the site and Sector-wise wind speed probability distributions, which show the frequency distribution of wind speeds at the site.

Wind flow modeling is an essential task in wind energy as it allows determination of the technical and economical feasibility of Wind Farm deployment. It comprises the analysis of the spatial and temporal variability of the wind from hundreds of kilometers and decades to tens of meters and minutes. From the wind energy developer perspective, the wind resource is analyzed from the large scale, at national or regional levels, with the use of a Wind Atlas, to the micro scale where the background wind climate is modified by the local topography [1].

The primary reason for the wind resource assessment process to take place at site is the variation of the wind speed from time to time and from location to location. Since the desired output, the power, of the Wind Farm is proportional to the cube of the wind speed in which a small difference on the wind speed at the site play a significant power deviation at the intended site [23].

This process, the wind resource assessment process requires sets of input parameters for the design of the Wind Park, mainly the wind data that has been measured at the Wind Farm or near by the Wind Farm and the topological characteristics of the Wind Farm site.

Wind flow modeling is a technology which is also very time consuming process that requires extensive preparation and organization. First, sufficient meaningful data needs to be collected in an organized fashion which requires choosing the proper data measurement and storage equipment as well as the optimal location to set up the equipment to collect the needed data. The choices of the equipment used, location of equipment, and duration of data collection are different for each specific case yet often share significant similarities. Once sufficient data has been collected it needs to be filtered for anomalies and carefully analyzed to determine if further investigation of the wind resource is required and/or warranted [23].

The data either will pass through software packages or set of statistical estimation like the Weibull distribution and measure correlate and predict (MCP) method in order to come up with the desired results such us the wind energy resources in the form of resource Atlas, Wind Class, Wind Rose, Annual Energy Production (AEP) and Wind Farm Production along with the wake losses.

Studies revealed that the wind measurement conducted at a site or sites will generate the wind energy resource in the form of resource atlas for a site or sites after conducting a set of manipulations and calculation.

Ultimately, the wind energy industry needs reliable tools for estimating mean wind speeds at selected heights for locations and wider areas where data are sparse. This would allow Wind Farm developments to proceed in less time, without the need to collect years of actual wind.

In 1987, scientists at Battelle Pacific Northwest Laboratory (PNL) in the U.S. carefully analyzed and interpreted the available long term wind data for the U.S. and summarized their estimation of the wind energy resources in the form of Wind Energy Resource Atlas of the United States (Elliott et al. 1987). The results are presented in terms of wind power classes based on the annual average power available per square meter of intercepted area.

Scientists at Denmark's Riso National Laboratory have produced a European Wind Atlas (Troen and Petersen 1989) that estimates the wind resources of the European Community countries and summarizes the resource available at 50 m height for five different topographic conditions.

Many countries around the world have recently embarked on high-resolution mapping efforts to quantify their wind resources and identify those areas of highest resource accurately. Wind speed, direction, distribution, and shear can vary significantly over fairly short distances in the horizontal or vertical directions, so in order to get the best possible estimate of the wind energy resource at a particular location, it is important to measure the wind resource at the specific site and height of interest. However, a comprehensive site characterization normally requires measuring the wind for at least 12 months. (Wegley et al., 1980).

This is a very time-consuming and potentially expensive effort. Long-term data from the nearest airport or weather recording station can help determine whether the data obtained at a site are representative of normal winds for the site or of higher or lower than average winds. Wegley et al. (1980) and Gipe (1993) gave suggestions on methods of using available data from nearby sites to estimate site wind speed with minimal on-site data.

In an ideal world, wind flow modeling, like shear and long-term climate adjustments would not be necessary. Wind measurements will be taken at every WTGs location to eliminate any possibility of errors. For most projects this would be an expensive proposition. In practice, wind flow modeling is an essential part of the wind resource practitioner's toolkit. It is also one of the largest sources of uncertainty in most energy production estimates. And also wind flow modeling must account for each turbine's influence on the operation of other turbines - the so-called wake effect. Wake modeling is usually performed separately from wind flow modeling using specialized software [3].

2.3.1 Types of Wind Flow Modeling

As it has been mentioned above, the main purpose of wind flow modeling is present an accurate wind flow prediction, so then assessment of the site wind power potential will be accurate. There are wide varieties of wind flow modeling, in which case a single approach could not be recommended above the others.

2.3.1.1 Experimental or Physical Modeling

Experimental or physical methods refer mainly to creating a sculpted scale model of a wind project area and testing it in a wind tunnel. The conditions in the wind tunnel, such as the speed and turbulence, must be matched to the scale of the model to replicate real conditions as closely as possible. While the wind tunnel is running, the wind speeds are measured at various points on the scale model using tiny anemometers. The results form a picture of how the wind varies across the site. The relative speeds between points are then usually related to a mast where the speeds have been measured in the field. Although studies comparing experimental methods to other methods are scarce, there is no reason to think this type of approach cannot work well under many conditions. It may even provide unique insights in areas where numerical wind flow models are prone to break down, such as near the edge of a steep cliff. Still, few wind resource analysts adopt this method because of the time and special skills required to build an appropriate model and the need for access to a wind tunnel. In addition, the method has some limitations such as the difficulty of modeling thermally stable conditions, and the challenge of appropriately matching atmospheric parameters to the physical scale [3].

2.3.1.2 Conceptual Modeling

Conceptual models are theories describing how the wind resource is likely to vary across the terrain. They are usually based on a combination of practical experience and a theoretical understanding of boundary layer meteorology. A very simple conceptual model might state that the wind resource at one location (a turbine) is the same as that measured at a different location (a met mast). This could be a good model in relatively flat terrain or along a fairly uniform ridgeline, for example. Where the terrain and land cover vary substantially, a more nuanced picture is usually required. This might include theories concerning the influence of elevation on the mean wind speed, the relationship between upwind and downwind slope and topographic acceleration, channeling through a mountain gap, and the impact of trees and other vegetation. These concepts or theories are then turned into practical recommendations for the placement of wind turbines, accompanied by estimates of the wind resource they are likely to experience. As wind projects become larger and are built in ever more varied wind climates, it becomes more and more difficult to implement a purely conceptual approach in a rigorous or repeatable way. Nevertheless, a good conceptual understanding of the wind resource is a valuable asset in all spatial modeling [3].

2.3.1.3 Statistical Modeling

Statistical models are based on relationships derived entirely or primarily from on-site wind measurements. Typically one tests different predictive parameters such as elevation, slope, exposure, surface roughness, and other indicators, to find those that appear to have the strongest relationship with the observed wind resource at several masts. In principle, any parameters can be used, although in practice it makes sense to focus on those for which there is a reasonable theoretical basis for believing a relationship should exist. This is one place where a good conceptual understanding is valuable. One of the potential limitations of statistical methods is that they can produce large errors when making predictions outside the range of conditions used to train the model [3].

2.3.1.4 Numerical Wind Flow Models

The most popular methods of wind flow modeling rely mainly on numerical wind flow models. There are several wind flow models in use by the wind industry today, which are based on a variety of theoretical approaches. All attempt to solve at least some of the physical equations governing motions of the atmosphere, with varying degrees of complexity. The models fall into four general categories: computational fluid dynamics (CFD), mesoscale numerical weather prediction (NWP) model, Jackson-Hunt and Mass consistent models [3].

Jackson-Hunt flow modeling which was developed in 1980s based on a theory advanced by Jackson and Hunt. They go beyond mass conservation to include momentum conservation by solving linearized form of the Navier-Stokes equations. The most important simplification in the Jackson-Hunt theory is that the terrain causes small perturbation to a constant background wind. This assumption allows the equations to be solved using a very fast numerical technique [3].

2.4 WIND ATLAS ANALYSIS AND APPLICATION PROGRAM (WAsP)

Since the late 1980's with the appearance of the European Wind Atlas (Troen and Petersen, 1989), the standard model for wind resource assessment has been WAsP (Wind Atlas Analysis and Application Program, Mortensen et. al., 2009) with its Wind Atlas Methodology. The model, based on a linearization of the Navier Stokes equations originally introduced by Jackson and Hunt (1975), is meant to be used reliably in near-neutral atmospheric conditions over gently undulating terrain, with sufficiently gentle slopes in order to ensure fully attached flows. Nevertheless, due to its simple usage and the increasing experience of the users with the model, WAsP has been also used out of its range of applicability, making use of the ruggedness index (RIX), which accounts for the extent of steep slopes around a site. This index helps judging whether WAsP is working within or outside its performance envelope (Bowen and Mortensen, 1996) and has also been used to correct energy predictions in complex terrain [2].

Wind Atlases are used for regional planning by administrations and for site prospecting by wind energy developers. With the increasing use of mesoscale models, regional wind maps are becoming increasingly popular at resolutions of the order of 1 to 10 km (Larsén et al., 2009). The resolution is not sufficiently high to resolve the speed-up effects generated by the local topography, a task which is taken care of by micro scale models [4].

WAsP, like most of wind prediction models, is based on the hypothesis that wind speed data can be approached in statistical terms by the Weibull distribution, a continuous probability distribution, which is widely accepted among the wind-engineering community. Its probability density is given by the following function:

$$f(u) = \frac{k}{A}\left(\frac{U}{A}\right)^{k-1} e^{\left(-\left(\frac{U}{A}\right)^{k}\right)} \qquad 2.4$$

where: A = The scale parameter

k = Shape parameter

U = Wind speed

f(u)= Probability density

WAsP's most basic assumption is that regional wind climate, for a specific micro scale area, the overall wind condition changes so slowly that the wind climate can be extrapolated from a meteorological station to any point of the region just taking into account the local effects at both sites.

WAsP is a PC-program for the vertical and horizontal extrapolation of wind climate statistics. It contains several models to describe the wind flow over different terrains and close to sheltering obstacles. The program thus contains analysis, application and Wind Farm production parts, which are summarized as follows:

1. **Analysis**

The data which are collected using the wind speed measuring devices at the mast location are Time-series of wind speed and direction data and are called **Observed Wind Climate** (**OWC**) in WAsP. When the Observed Wind Climate data is combined with the meteorological station site description, it results in **Generalized Wind Climate** (**GWC/RWC**) of the site.

2. **Application**

The application of these Generalized Wind Climate site descriptions in WAsP is known as **Predicted Wind Climate** (**PWC**). This Predicted Wind Climate combined with the power curve of the turbine that will be selected will result the **Annual Energy Production** (**AEP**) of wind turbine [22].

3. **Wind Farm Production**

The above Predicted Wind Climates shall be combined with the WTG characteristics to result in the **Gross Annual Energy Production of Wind Farm**.

The Predicted Wind Climate is combined with WTG characteristics and the Wind Farm layout to generate the **Wind Farm wake losses**.

The **Net Annual Energy Production of Wind Farm** can be obtained when the Gross Annual Energy Production is combined with the wake losses.

The observed and recorded data of the intended site, having passed through these procedures of handling data, will be compromised after considering the effects of temperature, terrain feature, obstacles and roughness of the environment.

The result of the analysis will be interpreted by the graphical representation of the **Wind Atlas** and **Analysis Program** [22].

The wind resource assessment by using WAsP software comes up with the estimation of Annual Energy Production after considering the resource assessment factors such as orography effects, roughness effects and obstacles through generating a Wind Atlas for the site.

The term orography refers to the description of the height variations of the terrain. While in relatively flat terrain, the roughness is the most dominant parameter; in hilly or mountainous terrains the shape of the terrain itself has the biggest impact on the profile. Over hill or mountain tops the flow will be generally accelerated. As a consequence, the logarithmic wind profile will be distorted, both steeper and then less steep depending on height. 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 than 30% corresponding to a 17° slope. The location and dimensions of the separation zone depend on the slope and its curvature as well as roughness and stability. In cases of separation, the wind speed profile might show areas with negative vertical gradient, where the wind speed is decreasing with height [9].

In WAsP, orography is resolved up to horizontal scales of tens of kilometers by means of the Bessel-Zooming model (BZ-model), which assumes a potential flow approach. This model resolves the flow at every point of a polar zooming grid around the points under study.

Obstacles in the vicinity of the point under study may play a paramount role in the assessment of wind climates. The magnitude of this effect depends on the dimensions of the object, its orientation and the distance to the point under study. The disturbance in the wind velocity vector due to the shelter produced by surrounding obstacles is modeled by WAsP under a two-dimensional semi-infinite obstacle approach, which extended to three-dimensional cases, as explained in [23]. Since most anemometers are mounted at a standard height of 10 m above ground level and often quite close to buildings, the shelter effect is potentially very serious in the analysis of wind data. On the other hand, a wind turbine with a hub height of 40-50 m above ground level and sited well away from buildings will rarely experience shelter effects at all.

Roughness is also another factor which influences the results of the analysis since it disturbs the wind flow around the turbine site. According to L. Mortensen, this magnitude affects the wind speed profiles in two different ways, namely: as uniform roughness, describing a logarithmic wind velocity profile, and as roughness changes, developing one or more internal boundary layers.

The roughness length is used in numerical models to express the roughness of the surface. It affects the intensity of mechanical turbulence and the fluxes of varies quantities above the surface. The roughness length Zo depends on the frontal area of the average element (facing the wind) divided by the ground width it occupies. A lower roughness length implies less exchange between the surface and the atmosphere, but also stronger wind near the ground [27].

The roughness length of a terrain is one of the factors associated with the wind resource assessment and the correct evaluation of its characteristics is hard and time consuming process. Thus one of the standards for terrain classification based on roughness length is given in the following Table.

Table 2.1 Terrain classification based on roughness length [27]

Roughness class	**Roughness length**	**Terrain and obstacle**
0	0.0002	Open water, sea, lakes
0.5	0.0024	Completely open terrain such as airport runaways
1	0.03	Sparse vegetation with no hedges, scattered buildings, soft rounded hills within 0 to 3km
1.5	0.05	Sparse vegetation with about 7 to 8m tall hedge within a distance of 1200 m, few buildings
2	0.1	Sparse vegetation with about 7 to 8m tall hedge within a distance of 500 m, few buildings
2.5	0.2	Sparse vegetation with about 7 to 8m tall hedge within a distance of 250 m, few buildings
3	0.35	Some villages and small towns with 8 m high hedges, forests less than 250 m and very rough terrain
3.5	0.85	Large cities or high thick forest
4	1.65	Very large cities or very high thick forests

In general terms, accurate estimation using WAsP program may be obtained through:

- The reference site (meteorological station) and predicted site (wind turbine site or met. station) are subject to the same overall weather regime,
- The reference wind data are reliable, and
- The surrounding terrain is sufficiently gentle and smooth to ensure mostly attached flows, and the topographical model inputs are adequate and reliable [9].

Limitations of WAsP include:

- WAsP is designed for relatively gentle and not too steep terrain, in which the wind can follow the terrain surface, i.e. where the flow is attached.
- WAsP is valid for small areas around 50 km from the reference site
- WAsP does not account for thermal variability (horizontally and vertically)
- WAsP provides no insight into dynamical process.

2.5 WIND POTENTIAL STUDIES IN ETHIOPIA

Ethiopia relies heavily on a limited set of renewable energy resources to meet its energy requirements: principally biomass for thermal energy in the residential and commercial sector and large hydropower for electricity.

The Government of Ethiopia has planned to scale up and diversify the Renewable energy mix, to minimize hydropower dependency; thus the focus has been shifted to Renewable energy sources to fulfill the demand. The planned Renewable energy mix for 2015, shown in Figure 2.3, presents 860 MW of energy is expected to be generated from Wind Energy [30].

The Ethiopian Government had prepared a Master Plan for wind and solar energy for investigating the available wind and solar energy resource, which recommends the major policy options to be developed for wind and solar energy expansion along with recommendation of 51 wind projects having a total planned capacity of 6,820 MW [30].

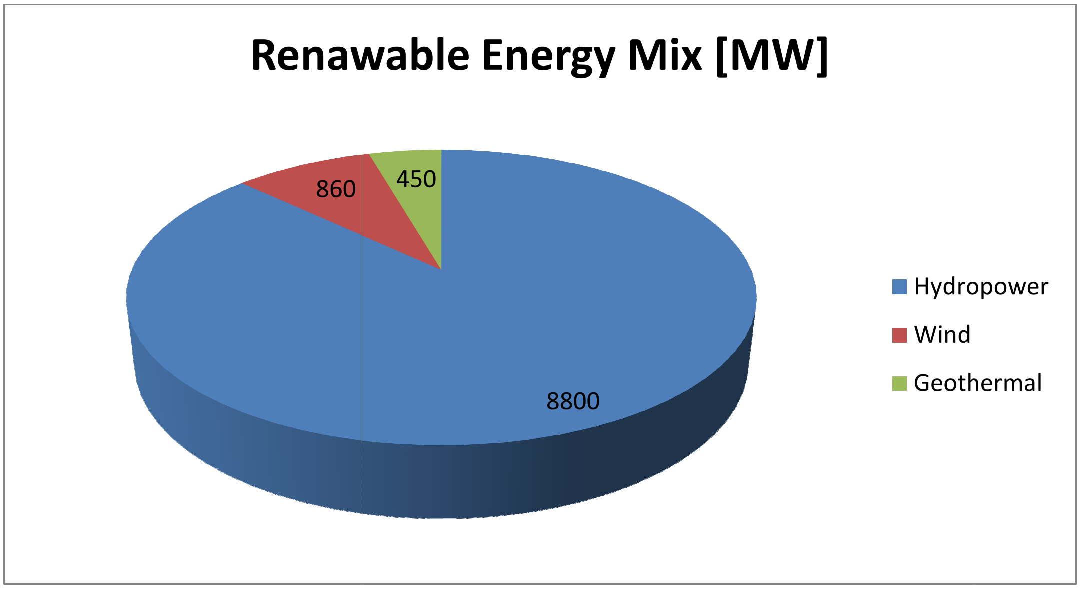


Fig. 2.4 Planned renewable energy mix for 2015

Figure 2.3, taken from the Master Plan, presents distribution of average wind speed available in m/s in the country at 50 m height, which estimates 1350 GW for exploitation [30].

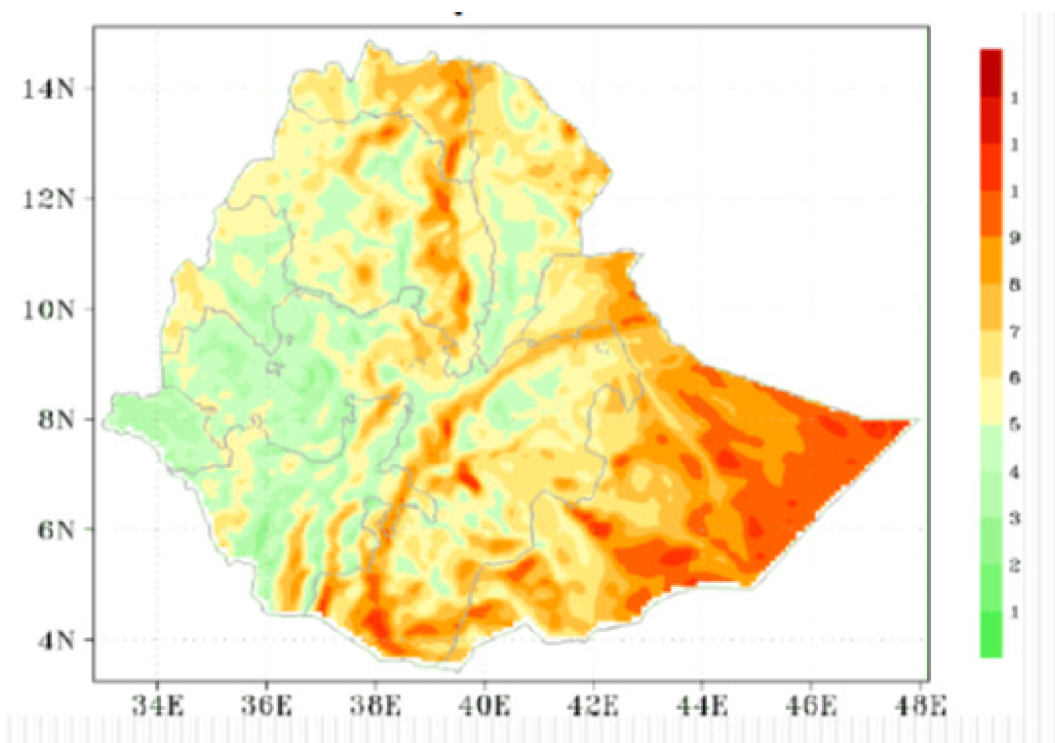


Fig. 2.5 Distribution of average wind speed at 50 m

A wind potential study has been performed at Adama I site and Wind Farm has also been constructed, in the course of the feasibility study, taking into account data from on-site measurement stations. In January 2005, a 10 m measuring mast was installed during the campaign for identification of promising wind potential sites in Ethiopia. Nazareth was considered as a site with favorable wind conditions and second mast been erected in September 2005, equipped with anemometers at 10 m and 40 m above ground level height and a wind vane at10 m height in order to determine the wind conditions close to the hub height of the wind turbines. To provide additional data for validation of the measurements, a third anemometer was established in January 2006 at the nearby. All metrological masts have been equipped with first class cup anemometers [12].

To predict the long-term wind speed at Adama I site, long-term correlations using MCP method have been performed, and using NCEP (US-National Center for Environmental Prediction) reanalysis wind data of a period of 25 years. The findings of this correlations were adapted to the measured wind speeds in order to make them long-term representative. Additionally, the NCEP data were used for validation of the calculated wind resources [12].

The calculations of energy production are executed with the wind resources collected by the wind measurements. Wake effects between the wind turbines were taken into account by applying the PARK model which is integrated in the international standard Wind Park planning software Wind-Pro.

The wind potential assessment at Ashegoda site has been performed with the feasibility study, taking into account data from two measurement stations on-site; the first one of 10 m height erected in January 2005 and the second one with anemometers at heights of 10 m and 40 m above ground level, erected in mid-September 2005. Both masts had been equipped with THIES first class cup anemometers and a wind direction vane (at 10 m above ground level) [13].

The calculations for the expected energy yield at Ashegoda Wind Farm, which is based on the long-term corrected measured wind data, are executed with the international standard Wind Park planning software combination of WindPro and WAsP [13].

With all the methods and also the requirements to conduct and implement wind power assessment and developing the wind Farm, HCIE in a joint-venture with Chinese construction group HydroChina-CGCOC completed a 51MW plant near Nazareth (Adama), equipped with 34 GoldWind 1.5MW turbines and very recently French turbine manufacturer Vergnet had built a 120MW project at Ashegoda using Vergnet and Alstom turbines and also HCIE is developing a 51MW project at Messebo-Harena. Now the Adama II Wind power project is in its very initial stage, thus the main focus of the Thesis is on this proposed Wind Farm.

CHAPTER THREE

3. DATA VALIDATION AND WIND TURBINE GENERATOR

3. 1 DATA RETRIEVING

There are three anemometer masts installed at different geographical locations of the Wind Farm: mast 10357 stands at Kusaye, mast 10358 stands at Jogo and mast 10359 stands at Adama I, as tabulated in Table 3.1.

The wind distribution data that is used for the wind flow modeling and analysis, which has been collected at the site, is stored in the data logger software organized or recorded at 10 minute interval, in which each data represent a ten minute averaged wind speed distribution along with the pressure and the temperature.

Table 3.1 Basic data for anemometer masts in Adama II wind power project

No	Measuring Mast	Coordinates (UTM WGS84 Zone 37)		Height [m]	Measuring Height [m]		Period
		X	Y		Speed	Direction	
1	10357	527043.424	952332.101	70	70 /50 30/10	70/10	16/11/2011 ~ 9/12/2012
2	10358	520906.321	943020.421	70	70 /50 30/10	70/10	05/11/2011 ~ 9/12/2012
3	10359	526468.769	947883.378	70	70 /50 30/10	70/10	01/11/2011 ~ 09/12/2012

The data for the analysis has been recorded from 2011.11.16 to 2012.12.9 using calibrated SymphoniePLUS3 logger, which uses time stamps for indicating the exact 10 minute averaged wind speed and wind directions.

While using the data that has been recorded for more than 18 months at the three mast locations by using calibrated SymphoniePLUS3 logger there might be an occurrence of a non-valid and non-useful data.

There are many possible causes of erroneous data such as faulty or damaged sensors, loose wire connections, broken wires, damaged mounting hardware, data logger malfunctions, static discharges, sensor calibration drift, and icing. These errors and non-valid data are also collected along with the wind distribution. The goal of data validation is to detect as many significant errors from as many causes as possible.

Data that are off the expected range will be screened out by the data logger software in the data screening step. The first part uses a series of validation routines or algorithms to screen all the data for suspected values.

The selection of the data for the analysis depends on the contents of each site along with the fulfillment of all the required data for the intended assessment where the process of data validation will reveal the data which will be appropriate for further analysis. Apart from these methods to determine the feasible data, the location of the mast is the critical factor to select the data to be considered. The Kusaye mast is located nearly at the geographical center of the proposed Wind Farm.

Each mast has four measuring heights for measuring the wind speed 10, 30, 50 and 70m where as there are only two measuring heights for measuring the wind direction that are mounted at 10 and 70 m heights. Thus the two measuring heights are the heights that can be considered prior to analyzing the data.

The 10 meters measuring height can be disturbed and influenced by the ground surface properties, such as bushes, trees in a manner that is more than the 70 meter measuring height. Due to the disturbances the sensors mounted on a data logger will record data of a type which is not valid for the assessment. Since, in a wind flow modeling and analysis the wind speed and wind blowing direction data are mandatory, the wind resource assessment will be conducted using the data at 70 meter height.

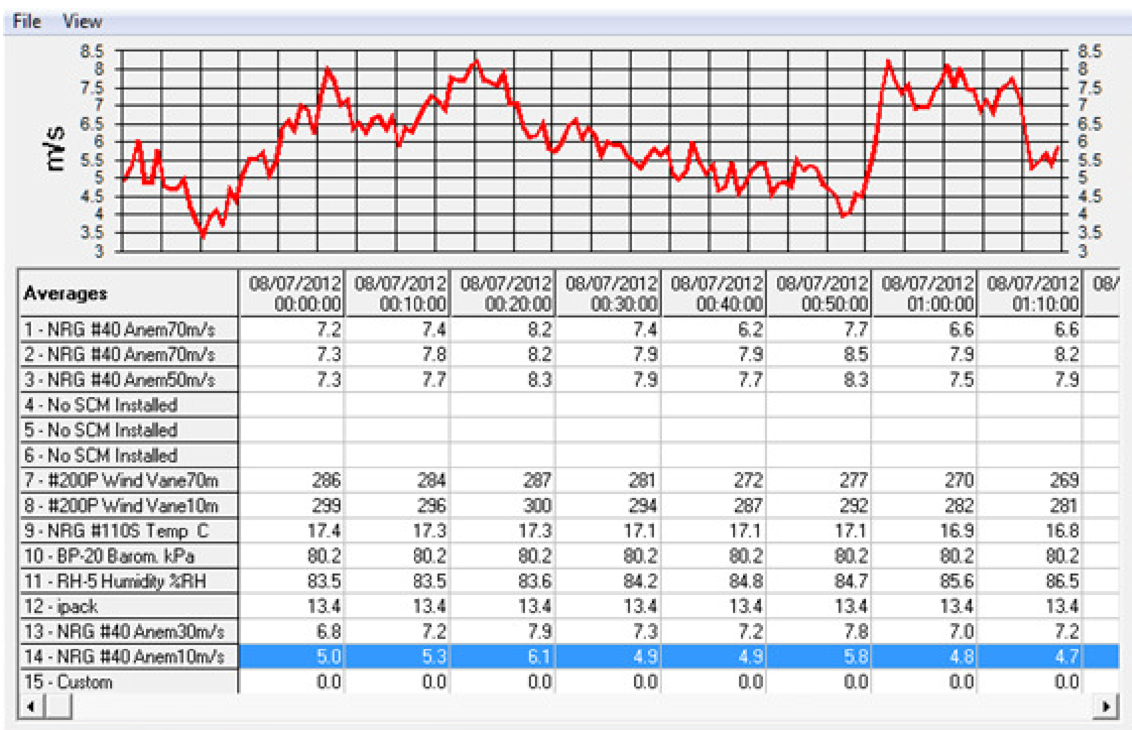
Data validation process has been conducted through the two software SymphoniePLUS3 data logger and the WAsP climate analyst tool. The earlier generates the data quality report by comparing the good data with the icing, invalid bad sensor data. The WASP Climate analyst tool compares the expected and the available data.

3. 2 DATA RECORDING SOFTWARE

The anemometer masts are accompanied with the wind vanes for the sake of recording the wind direction. These data have been recorded using the SymphoniePLUS3 data logger.

SymphoniePLUS3 is a very flexible logging system that can be set up as a standalone unit or as an Internet enabled logging system. When used as a standalone unit, data files are retrieved manually through regular site visits [24]. The SymphoniePLUS3 logger has 15 channels each is having its own data category, like wind speed at 10 m wind direction at the wind vane height. The temperature of the measuring site and the voltage required to run the logger is included in the 15 channels.

The data recorded using The SymphoniePLUS3 logger can be exported to text file for further analysis and also it can generate its own results like the wind rose, the frequency distribution and the data quality reports along with the recorded data set and summary of it. The data will be seen and interpreted the logger software. One such data looks like Figure 3.1.



Averages	08/07/2012 00:00:00	08/07/2012 00:10:00	08/07/2012 00:20:00	08/07/2012 00:30:00	08/07/2012 00:40:00	08/07/2012 00:50:00	08/07/2012 01:00:00	08/07/2012 01:10:00	08/
1 - NRG #40 Anem70m/s	7.2	7.4	8.2	7.4	6.2	7.7	6.6	6.6	
2 - NRG #40 Anem70m/s	7.3	7.8	8.2	7.9	7.9	8.5	7.9	8.2	
3 - NRG #40 Anem50m/s	7.3	7.7	8.3	7.9	7.7	8.3	7.5	7.9	
4 - No SCM Installed									
5 - No SCM Installed									
6 - No SCM Installed									
7 - #200P Wind Vane70m	286	284	287	281	272	277	270	269	
8 - #200P Wind Vane10m	299	296	300	294	287	292	282	281	
9 - NRG #110S Temp C	17.4	17.3	17.3	17.1	17.1	17.1	16.9	16.8	
10 - BP-20 Barom. kPa	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	
11 - RH-5 Humidity %RH	83.5	83.5	83.6	84.2	84.8	84.7	85.6	86.5	
12 - ipack	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	
13 - NRG #40 Anem30m/s	6.8	7.2	7.9	7.3	7.2	7.8	7.0	7.2	
14 - NRG #40 Anem10m/s	5.0	5.3	6.1	4.9	4.9	5.8	4.8	4.7	
15 - Custom	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Fig. 3.1 SymphoniePLUS3 logger display

The SymphoniePLUS3 logger has a fixed averaging interval of 10 minutes. In which each column of the displays shows the 15 channels for recording and each of the rows show that the averages standard deviations and other statistical values are calculated from continuous 1 second data samples. Data intervals are calculated every 10 minutes; time stamped with the beginning time of each interval [24].

3. 3 DATA VALIDATION

3.3.1 Data Quality Reports

As it has been mentioned above the quality of data can be checked in two ways or two approaches. This can be done by using the data logger software and the part of the main modeling software, WAsP climate analyst tool. The SymphoniePLUS3 presents the data in the form of comparison between the extremes like Icing data, bad sensor data and invalid data.

The Icing data is the data collected when ice is accumulated on the sensor, thus it degrades the performance of the sensor. Icing events are characterized by the simultaneous measurements of near-zero standard deviation of wind direction, non-zero wind speed, and near- or below-freezing temperatures.

The approach for collecting an accurate wind distribution data is to take set of measurements preferably at the hub height or one third of the hub height, and again the data recorded at 70 m height fulfills the data measuring for wind resource assessment basics.

After all the data logger is calibrated and mounted in a way to compromise the defects or invalidity of a data that can be collected at the mast station and also the data that seems unacceptable have been filtered from the storage.

The recorded data can be visualized or read after extracting from the data logger for further analysis. In the meantime the data logger presents the data in the forms of frequency distribution, wind rose, hourly average table.

Figure 3.2 shows the data quality report that is extracted from the data logger software and it shows the quality of the data for Kusaye mast, on the month of March 2012, for instance.

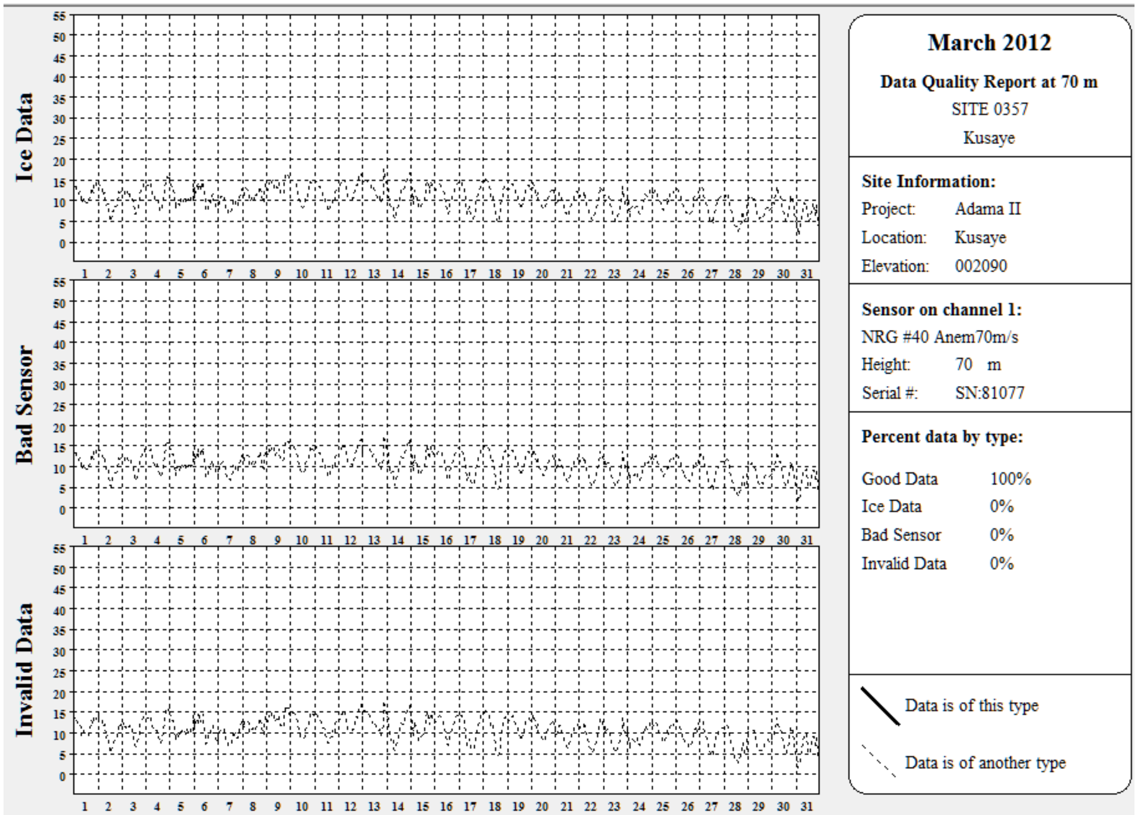


Fig 3.2 Data quality report for Kusaye

Also the Figures in the Annex B show that the data under mast are better quality data to the extent of validation.

Frequency Distribution of data is typically used to estimate the energy that could be generated by a wind turbine at the site. The graph provides a visual representation of the relative frequency that winds of a given speed occur at the site during some specified period.

The frequency distribution data, together with a wind turbine power curve, generated by a turbine manufacturer, can be used to estimate the wind power a specific turbine can provide in a given wind pattern.

Figure 3.3 shows the screen shot from the SymphoniePLUS3 data retriever representing the frequency of the wind speed at 70 meters above the ground and sample hourly average graph, for the mast 10357. The figure also shows that for more than 20% of the time the wind speed is in the range of 8 to 10 m/s.

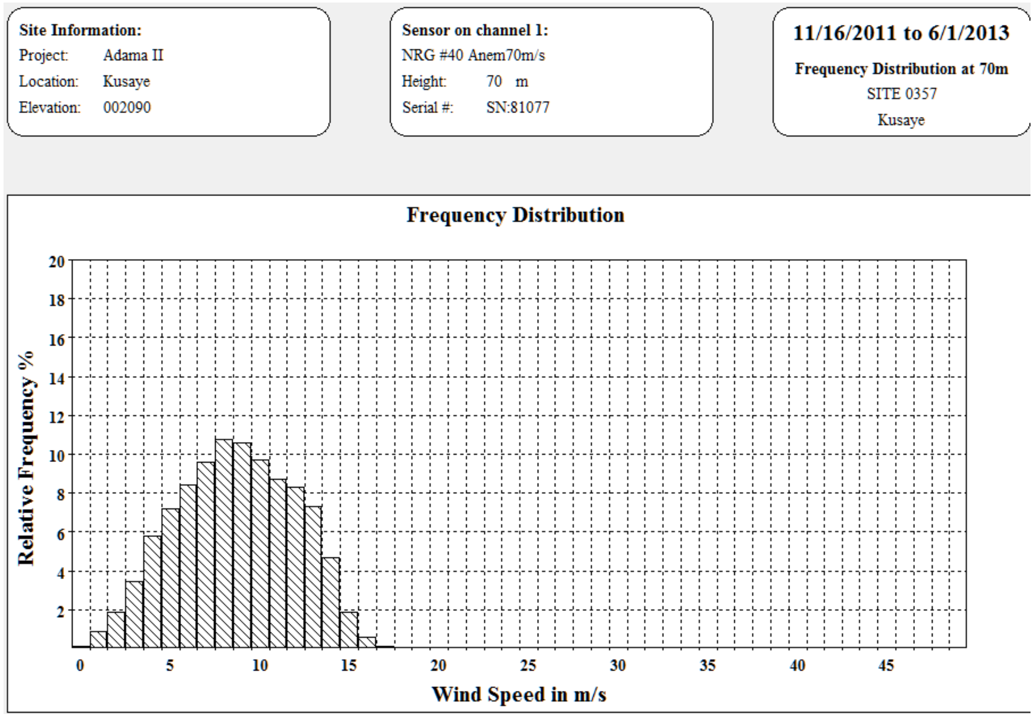


Fig. 3.3 Frequency distribution for mast 10357

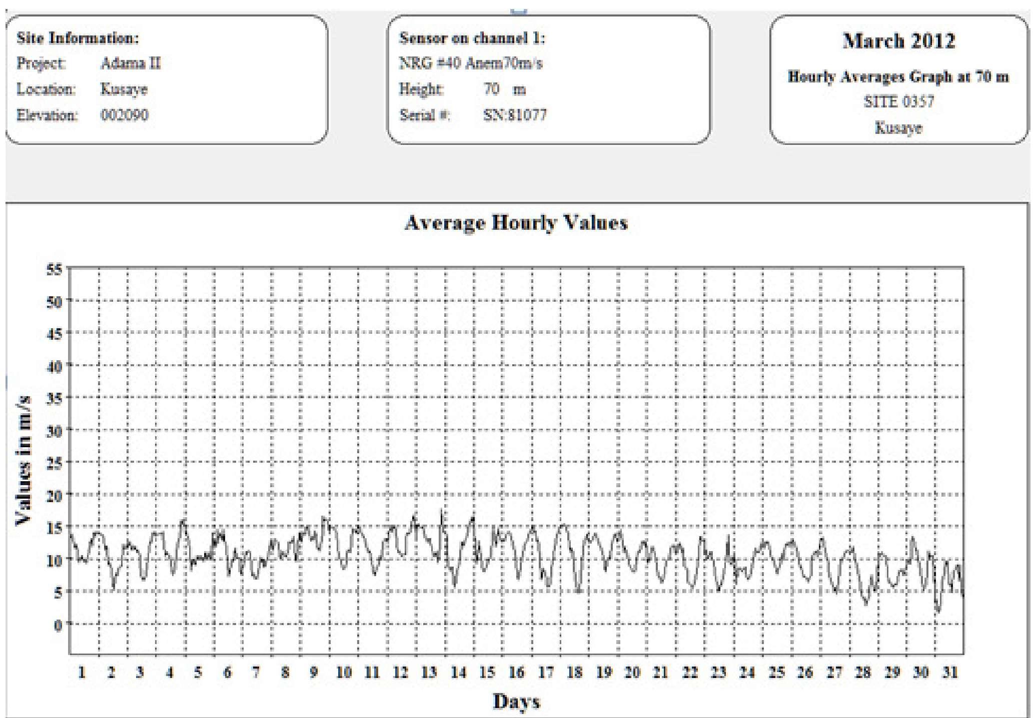


Fig. 3.4 Average hourly wind speed graph for mast 10357

The above two figures, Figure 3.3 and Figure 3.4, show the frequency distribution and hourly average graphs of the Kusaye mast, mast 10357, at 70 meters height.

3.3.2 Data Validation and Screening

The data were stored and checked for quality using the Symphonie PLUS data logger. Whereby, indicating the data available is up to the requirement for further analysis.

3.3.2.1 Wind Shear

The velocity of the wind shall increase as the point of consideration moves further above the ground. There are 931 data sets, for Kusaye mast, providing the mean wind speed at 10 meters is higher than that of the speed at 70 m; this might be the result of low wind speed at the time of recording.

The wind shear exponent relates the velocity and the height. This can be the result of the sensitivity difference of the two anemometers for low speeds or the site roughness and orography. The sample wind shear values are listed in Table 3.2.

Table 3.2 Sample negative wind shear exponents for Kusaye Site

Kusaye Mast 10357			
Date and time	**10 min average wind speed [m/s]**		**Wind shear exponent**
	At 70 m height	**At 10 m height**	
2/25/2012 7:40	1.5	1.6	-0.03317
3/31/2012 2:00	0.4	2.4	-0.92078
3/31/2012 2:10	0.8	1.6	-0.35621
4/2/2012 1:30	0.8	1.2	-0.20837
4/2/2012 1:40	0.4	1.5	-0.67925
4/2/2012 1:50	0.4	0.8	-0.35621
4/8/2012 9:40	6.1	6.3	-0.01658
4/8/2012 9:50	5.9	6.2	-0.02549
4/10/2012 11:50	3.8	3.9	-0.01335
4/11/2012 2:00	3.1	3.2	-0.01632
4/11/2012 3:50	0.6	1.7	-0.5352
9/5/2012 13:30	4.8	4.9	-0.0106
9/5/2012 21:10	0.6	0.7	-0.07922
9/6/2012 9:30	6.4	6.5	-0.00797
9/7/2012 10:00	4.2	4.4	-0.02391
9/12/2012 22:20	0.4	0.6	-0.20837

9/12/2012 22:40	0.4	0.5	-0.11467
9/12/2012 23:20	0.6	1.1	-0.31149

There are 2317 data sets having negative wind shear exponent comprising 2.834% of the whole data set at the Jogo mast site. Masts located at Kusaye and Adama sites have 931 and 761 data sets respectively, indicating 1.15% for Kusaye data and 0.97% for Adama data have negative wind shear exponent values. Thus it can be assumed that the speed at 70 m height is greater than or equal to the speed that can be obtained at 10 m, and preference will be given to the mast at 70 m height. These wind speed values that have negative wind shear exponents are adjusted to be equal to the wind speed measured at 10m.

3.3.2.2 Monthly Averaged Wind Speed

The variation of wind speed with height has been mentioned above; the wind shear exponent has also been calculated. The wind speed with height variation is also presented in Figure 3.5 using the monthly average wind speed. The anemometer at 70 m height is selected due to the fact that the influences of the terrain around the mast are less as compared to the anemometer at 10 m.

The 70 m mast is preferable to the 50 m and 30 m because the 30m and 50 m anemometers are not coupled with wind vane for recording the wind direction. Since for analysis the direction of the wind is important, the 70 m anemometer is selected.

Figure 3.5 shows that the monthly average wind speed, the maximum value can be obtained between November and December. During the periods between March and April 2012 and around the month September 2013 the values of the wind speed for the three measuring heights, 30m, 50m and 70m are close to each other than the rest.

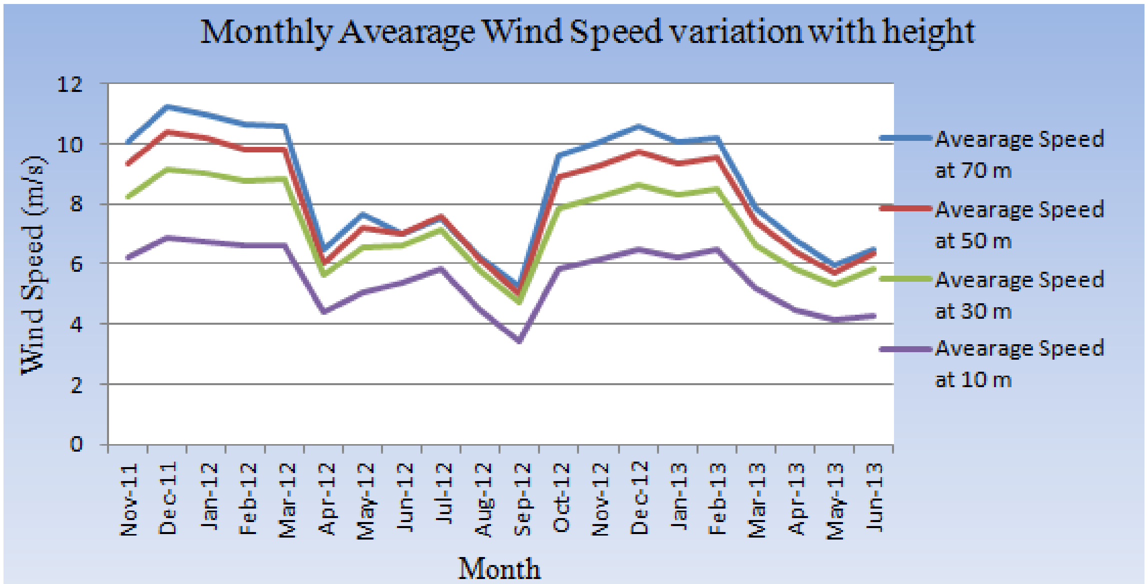


Fig. 3.5 Monthly mean wind speed variation with height

It can be seen from Figure 3.5 the measurement that is taken at 10 m shows deviation from 30, 50 and 70 m masts for instance, in the range between March and July 2012, the variation of the wind speed at 10 m height follows somewhat a straight line. The measurement at 10 m high from the ground can be influenced by the nearby trees and other obstacles. Thus relying on the anemometer and wind vane reading at the hub height of the WTGs is trust worthy for estimating the wind resource available at the Wind Farm area.

3. 4 PROPOSED TURBINE SITTING DATA

Another data which is obtained from the record conducted by the project manager for the analysis is the spatial location of the turbines, where ID stands for the number of the turbine and the coordinates are in UTM coordinate system. The wind power available at some point can be larger than the others, thus placing the turbine at the coordinates where the wind resource is high is also the outcome of the Thesis.

The spatial location of the WTGs presented in Table 3.3 shows the proposed layout. Wind resource assessment can be done using these coordinates or without consideration of the layout. It will be better to model using the proposed layout in order to compare it with the modeling that can be done after re-positioning the WTGs in the potential locations.

Table 3.3 Proposed spatial locations of the WTGs [18]

ID	Y(N)	X(E)	ID	Y(N)	X(E)	ID	Y(N)	X(E)
N1	959170.005	530089.672	N35	950908.808	526903.701	N69	950671.576	525106.427
N2	958996.367	529977.205	N36	955818.273	529938.307	N70	950364.765	524534.195
N3	958835.290	530046.560	N37	955575.644	529910.815	N71	950165.123	524074.330
N4	958099.131	530324.479	N38	955551.377	530443.384	N72	948012.053	523667.551
N5	958172.384	529930.307	N39	955342.213	529975.297	N73	947627.166	523266.969
N6	957824.685	529785.250	N40	955044.300	529984.794	N74	947705.843	523943.871
N7	957496.281	529658.687	N41	954565.640	530018.485	N75	947143.908	523995.556
N8	957300.639	530010.084	N42	954296.819	529853.233	N76	947185.895	523511.098
N9	957253.652	529659.687	N43	954061.688	529834.139	N77	947169.400	523083.223
N10	956550.358	529577.412	N44	954077.783	530136.051	N78	946794.709	523087.222
N11	956307.829	529458.547	N45	954514.855	530299.202	S1	942168.062	520288.047
N12	955660.718	528927.703	N46	954723.307	530485.248	S2	942385.598	520384.918
N13	955368.504	528684.375	N47	956520.566	528890.913	S3	942152.067	520563.566
N14	955314.120	529034.872	N48	956781.990	528948.096	S4	942358.706	520774.304
N15	954972.719	528536.918	N49	957195.569	528984.085	S5	942535.955	520774.004
N16	954609.926	528324.081	N50	957327.430	528524.120	S6	942713.602	520687.929
N17	954770.379	529087.057	N51	956591.545	528281.291	S7	942917.443	520687.929
N18	954498.059	529062.565	N52	956614.138	528029.765	S8	943086.193	520639.443
N19	954265.027	529004.482	N53	956156.472	528265.297	S9	943279.637	520727.917
N20	954030.896	529078.960	N54	955745.792	527779.439	S10	943440.989	520614.750
N21	954050.190	528555.014	N55	955289.326	527813.830	S11	943638.431	520273.850
N22	954023.398	528800.742	N56	955066.391	527772.942	S12	944008.323	520522.876
N23	953586.026	528809.940	N57	954520.851	527455.036	S13	944164.777	520458.695
N24	953257.022	528647.587	N58	954196.846	527490.326	S14	944583.052	517705.601
N25	953467.660	528093.250	N59	953525.341	526422.127	S15	944955.243	517959.126
N26	952623.907	527858.419	N60	953063.789	526352.647	S16	945238.760	518020.908
N27	952843.842	527678.272	N61	952683.988	526390.549	S17	945516.379	518207.053
N28	953134.657	527633.185	N62	952452.555	526283.881	S18	945829.486	516805.563
N29	953195.339	527445.939	N63	952258.813	526775.137	S19	945564.363	516657.807
N30	952904.524	527325.975	N64	952072.967	526645.475	S20	945353.425	516572.132
N31	952620.807	527564.505	N65	951862.429	526556.801	S21	945211.067	516761.777
N32	951994.691	527314.179	N66	951475.541	526213.402	S22	944405.877	516021.494
N33	951851.832	527381.360	N67	951424.157	526684.664	S23	944186.966	515947.116
N34	951667.586	527394.256	N68	950968.190	526196.408	S24	944001.820	516018.496

3. 5 WIND TURBINE GENERATORS

The basis of this Thesis is the Wind Farm under construction at Adama II site. Thus along with the WTGs spatial location, the specification of the wind turbine generator has been proposed for the Wind Farm as summarized in Table 3.6.

Table 3.4 Sany SE7715 Wind Turbine Generator specification [18]

Description	Unit	Qty	Remarks
Quantity	unit	102	
Rated capacity each WTG	kW	1500	
Blade number	piece	3	
Rotor diameter	M	77	
Swept area	m^2	4736	
Cut-in wind speed	m/s	3.5	
Rated wind speed	m/s	11.25	
Cut-out wind speed	m/s	25	Mean value in 10 minutes
Safe wind speed	m/s	59.5	Mean value in 3s
Hub height	M	70	
Rotating speed	rpm	10.6-21.1	Rated rotating speed 12.5
Generator capacity	kW	1500	
Generator power factor		-0.95～+0.95	
Rated voltage	V	690	
Rated current	A	660	
Protection class		IP23	
Insulated level		F（≤150℃）	
Generator series		88	
Unit transformer			
Quantity	Unit	102	
Type		1600kVA 33±2×2.5%/0.69kV	
230kV step-up substation			
Main transformer			
Quantity	Unit	2	
Type		90MVA	
		230±8×1.25%/33kV	
Circuit number		1	

According to the proposal for the Wind Farm, it is planned to construct 102 sets of SE7715 wind turbine generators. Each WTG has a capacity of producing 1500 kW, having a rotor diameter of 77 m and hub height of 70 m.

The generated power will be connected to the Koka substation grid using the 230 kV step-up transformers.

3. 6 WIND TURBINE GENERATOR CHARACTERISTICS

The power curve and thrust coefficient (C_T) of the Wind Turbine Generator are obtained from the manufacturer of the Wind turbine Generators. The site specific parameters like the density of air at the site, 0.95 kg/m^3 is also used to calculate the power.

Table 3.5 Power in kW and thrust coefficient of Sany SE7715 [18]

Speed (m/s)	Power (kW)	Thrust coefficient
4	18.69	0.9821
5	86.03	0.8861
6	175.44	0.7614
7	293.26	0.7343
8	455.36	0.74
9	665.74	0.7436
10	928.15	0.7463
11	1221.73	0.7092
12	1409.43	0.5527
13	1456.4	0.3993
14	1469.75	0.3265
15	1500.37	0.2607
16	1500.37	0.2132
17	1500.37	0.1773
18	1500.37	0.1497
19	1500.37	0.128
20	1500.37	0.1106
21	1500.37	0.0966
22	1500.37	0.085
23	1500.37	0.0754
24	1500.37	0.0673
25	1500.37	0.0605

These two terms are the inputs for modeling the wind flow at the site. Figure 3.6 and Figure 3.7 below show the power curve and thrust curve of the Wind Turbine Generator, respectively, of Sany SE7715. The cut out speed is 25 m/s and the cut in speed is 3.5 m/s.

The density of air at the site is around 0.95 kg/m^3, since the power is also dependent with the density as also with the swept area of the Wind Turbine Generator, thus the rated power will be obtained at the 15 m/s wind speed.

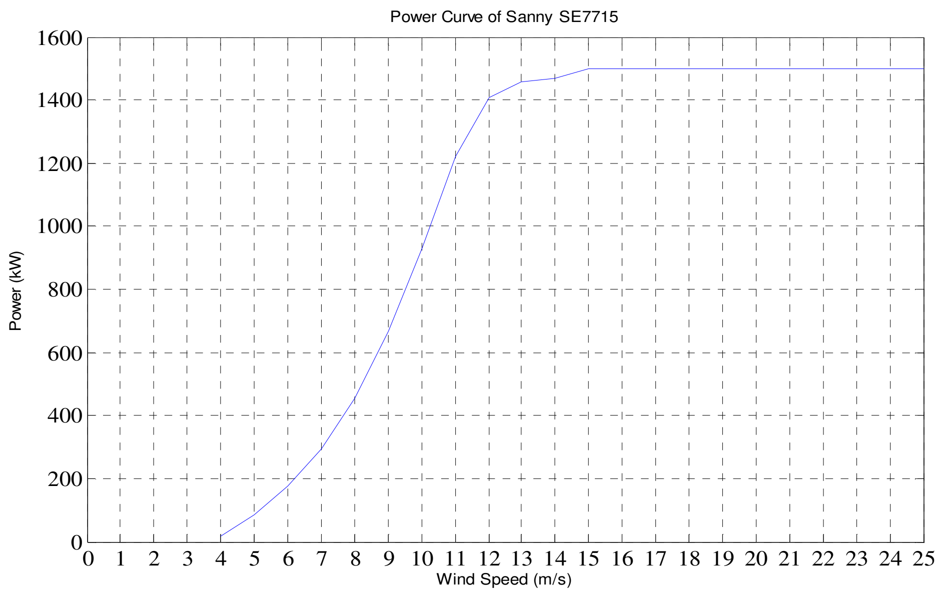


Fig. 3.6 Power curve of the WTG.

Figure 3.6 shows the power curve of Sany SE7715 Wind Turbine Generator that is generated using that the density of air at site is 0.95 Kg/m^3. The rated power is 1500 kW that can be obtained around 15 m/s wind speed.

The Thrust coefficient is the second term which is valuable for the modeling, since the influence that the preceding WTG has on the WTG following it in the wind blowing direction.

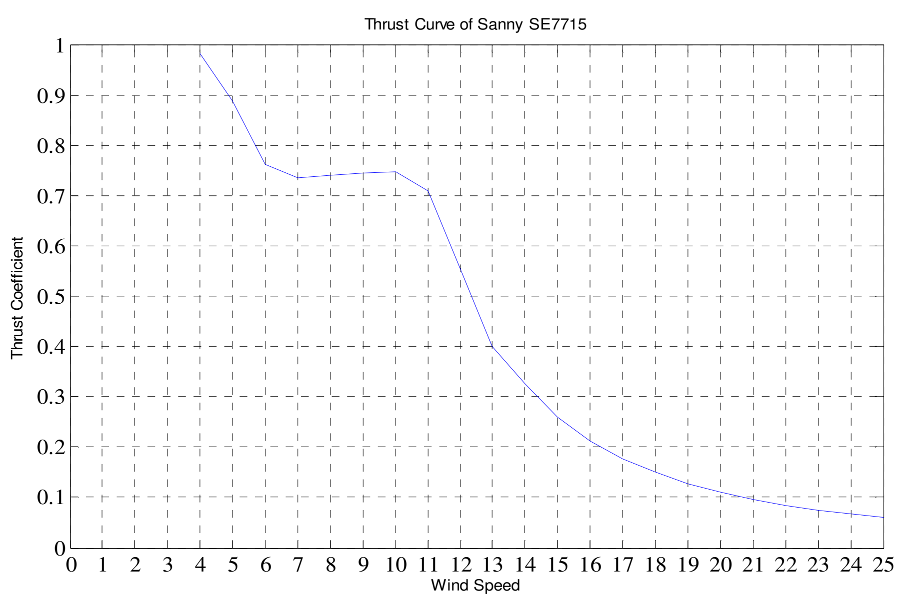


Fig. 3.7 Thrust curve of the WTG

Figure 3.7 shows the thrust curve, the variation of the thrust coefficient with the wind speed of Sany SE7715 Wind Turbine Generator with the wind speed.

Development of wind farms results in a turbine spacing that will cause the neighboring turbines to influence each other. The influence is caused by the so called wake effect. The wake effects have two main consequences that are important for the commercially successful wind farm development: the loss of energy and the increased fatigue loading.

The modeling software, WAsP uses the thrust coefficient for calculating the wake effects, since these effects basically rely on the thrust coefficient of the turbine provided by the manufacturer of the turbine.

Using the above values, the Wind Power Software calculates and plots the power coefficient (C_P) of the turbine. The power coefficient of a turbine is a measure of how efficiently a wind turbine converts the energy in wind to electricity.

Figure 3.8 is screen shot at the Wind Power software, showing the power coefficient of the Wind Turbine Generator, Sany SE7715, along with the power curve obtained from the manufacturer.

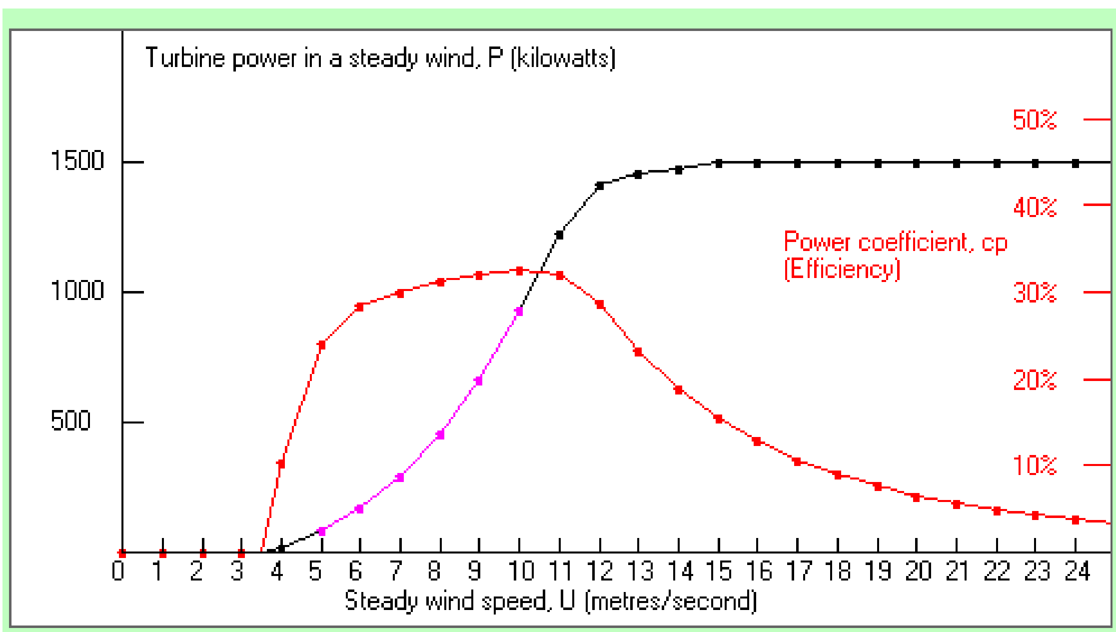


Fig 3.8 Power curve and power coefficient of the WTG using Wind power software

3. 7 ELEVATION MAP

As a mandatory input for the analysis, the topological map of Ethiopia is obtained from Ministry of Mine and Energy. Thus the elevation map of the Wind Farm site can be extracted from the Ethiopian topological map by using Global Mapper software. The geographical coordinates of the site will be used to generate the elevation map of the site. In supplementary to the map collected with other data sets, the Global Mapper software is a tool that has been used for further extraction of the contour map of the area, which can be used for the modeling of the wind flow at the intended site.

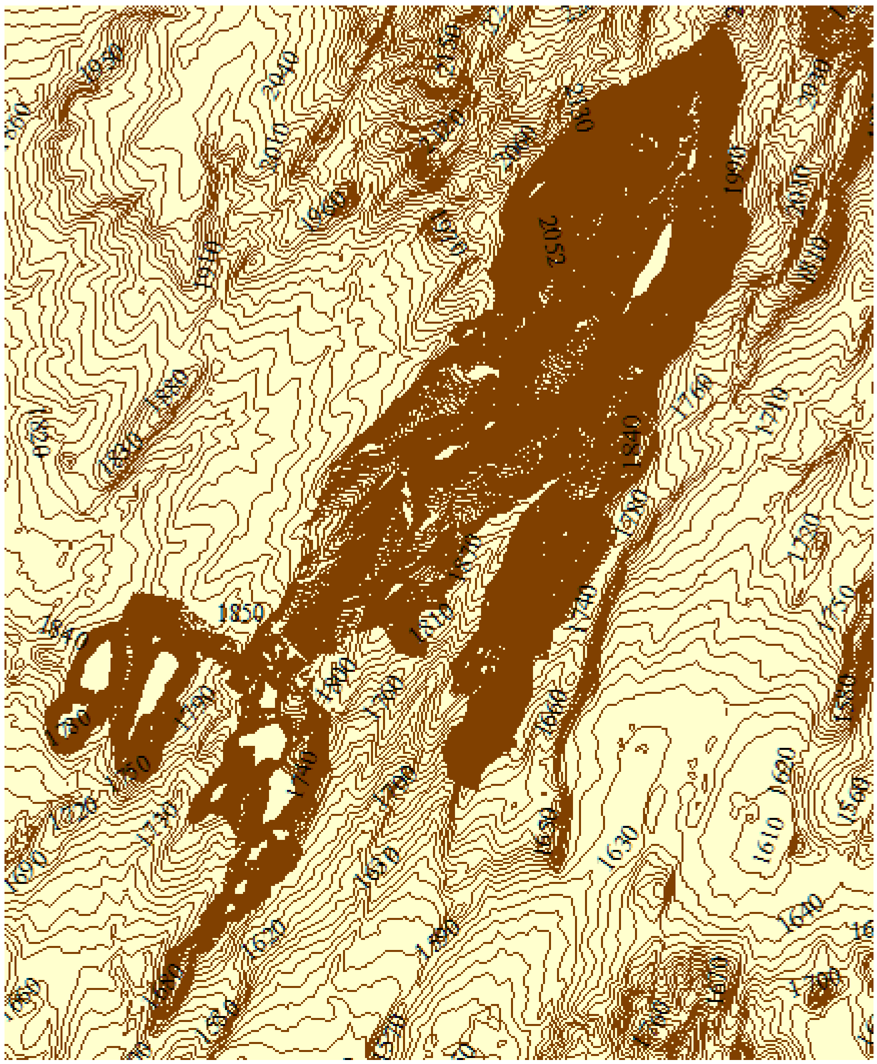


Fig. 3.9 Elevation map of the site

Figure 3.9 shows the elevation map created using a Global mapper tool. The map has 652 elevation contour lines. The darker portion in the map shows Adama I and Adama II Wind Farms. It describes an area in south 510000 m, west 940000 m, north 540000 m and east 967029/ corners thus the width is 30 km, the side length is 27.029 km, and the area is 810.870016 km². The Kusaye mast is located nearly the centre of the elevation map created.

CHAPTER FOUR

4. MODELING WITH WASP

The collected data for wind speed from the anemometer and wind direction using the associated wind vane shall pass through a series of analysis and interpretation stages, apart from the data verifications procedure, in order to estimate the wind resource at the Wind Farm site.

4. 1 WASP CLIMATE ANALYST

As it has been mentioned in the literature review section of the study, WAsP Software is an engineering tool used for extrapolation of wind climate horizontally and vertically. In order to generate the results of the wind climate extrapolation, the WAsP software utilizes its five main calculation blocks, such as Analysis of raw data, generation of wind atlas, wind climate estimation, estimation of power potential and calculation of Wind Farm production.

The procedure in WAsP starts with the analysis of raw wind data, data that has been extracted from a calibrated data logger. This option enables an analysis of any time-series of wind measurements to provide a statistical summary of the observed, site-specific wind climate. This part is implemented in separate software tools: the WAsP Climate Analyst and the older Observed Wind Climate (OWC) Wizard [21].

4.1.1 Pre Analysis on Wasp Climate Analyst

The WAsP Climate Analyst is a program which performs analysis on time-series of meteorological data, is more powerful, flexible and easier to use. The WAsP Climate Analyst in addition to calculating OWCs, it supports the generation of Observed Extreme Wind Climates (OEWCs) for use in WAsP Engineering tool [21].

The results of these analyses are summaries which describe some aspect of the climate. The observed mean wind climate and observed extreme wind climate are the major results to be displayed after the analysis.

The data logger stores the recorded data in the database, which is in the form of NRG file format and it can be exported to time-series data, typically an ASCII file format, thus the Wind climate analyst tool can process the retrieved data.

The retrieved set of data are inserted in WAsP climate analyst tool, to generate a representative of the climate analysis, data which will be used as input for modeling in the main software WAsP.

The WAsP Climate analyst uses geographic coordinates in the form of degrees for latitude and longitude dimensions. The following table summarizes the data conversion from UTM coordinate system to latitude and longitude degrees.

Table 4.1 Measuring mast coordinates conversion

Mast name	(UTM WGS84 Zone 37)			
	X coordinate [m]	Y coordinate [m]	Latitude [Degrees]	Longitude [Degrees]
10357	527043.424	952332.101	8.615320 N	39.245787 E

The Kusaye mast is installed at 8.615320 degrees North Latitude and 39.245787 degrees East longitude. The measuring height for wind speed and direction are 10 and 70m. Figure 4.1 shows the picture taken at the site.

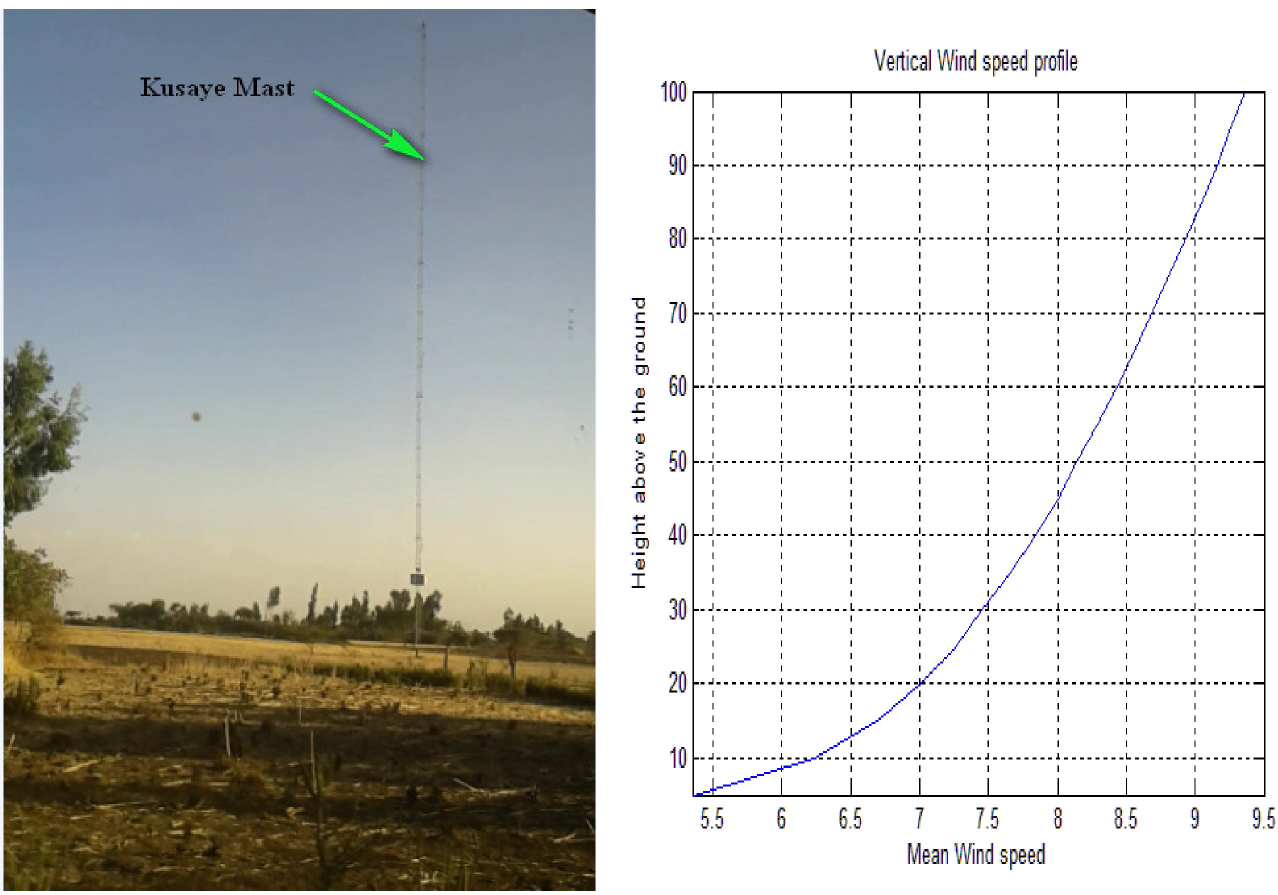


Fig. 4.1 Kusaye Mast and its vertical wind speed profile

Prior to analyzing the data available for the assessment, it is exported as an ASCII and WAsP Climate file formats from the data logger. It is then imported to the WAsP Climate Analyst tool to present the end result of the data import process that is a file containing a single pair of Speed and Direction columns, defining the data stream from a single instrument.

For each data file that is imported to the WAsP Climate analyst tool, a file containing a set of rules for the interpretation of a data file need to be generated or selected. This will be an input for constructing an import protocol.

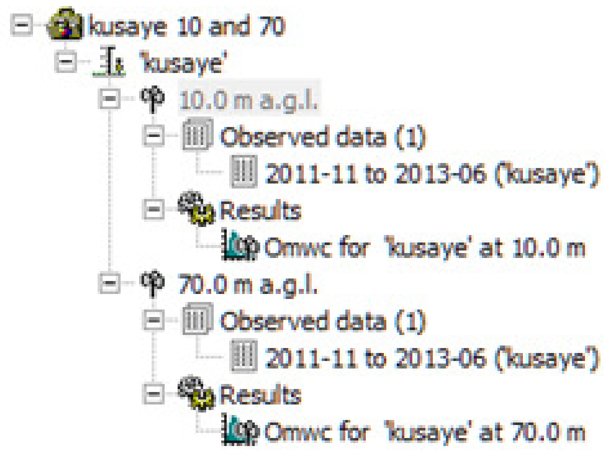


Fig. 4.2 WAsP Climate Analyst hierarchy

The data from the mast has been analyzed in the previous chapter. Here the data available at Kusaye mast will also pass through the Climate Analyst tool to come up with the results. Figure 4.1 shows the screen shoot for the overall appearance of the modeling WAsP Climate Analyst tool for the mast at Kusaye site.

The data set which was imported from the data logger has passed to a process which makes it suitable for the analysis that will be conducted on WAsP Climate Analyst tool.

4.1.2 Wasp Climate Analyst Data Verification

The WAsP Climate Analyst then conducts the process, in which the data will be checked for suitability and completeness for the modeling software. Table 4.2 presents the results of WAsP Climate Analyst tool conducted for Kusaye mast. The results suggested that the data collected from the mast under consideration can be used for further analysis.

Table 4.2 WAsP Climate Analyst data validation for Kusaye mast

Data parameters	**Mast 10357**
Count	80352
Start time	2011-11-16 00:00:00
End time	2013-06-01 00:00:00
All recordings were examined	Yes
Recording Below lower limit (0)	None
Recording above upper limit (999)	None
Valid Reading Accepted	80352 (100%)
Accepted Values range	0.4 m/s to 20.2m/s
Calms (speeds below zero)	None
Valid Reading Accepted	80352 (100%)
Accepted Values range	0.0 to 359 degree
Expected Recording Count	81090
Count of recording in file	80352 (99.1%)
Recording with invalid values	0 (0.00%)
Entirely valid recording accepted	80352 (100%)
Recovery percentage(Vs Expected)	99.1%

From the above table, the valid reading accepted and the recovery percentage for mast at Kusaye are 80352 and 99.1%, respectively, from the total 81090 data set. Thus for further modeling the Kusaye data is preferable to be used for the analysis due to the following basic reasons along with the availability of good data:

1. As it can be seen from Table 4.1 and Figure 4.3, the mast is located nearly at the centre of the expected Wind Farm wind turbine generator clusters, where as the mast 10358 is very close to the border of the expected Wind Farm.

2. The wake effects from the wind turbine generators installed at Adama I can't cause the same effects as they can on Mast 10359, since the mast 10359 is very close to Adama I.

3. The entire valid record and count of recording in the file is in the middle between the other two masts.

4. The number of available data plays a significant role on the analysis as the number gets very large, the accuracy will also increase. Thus the data available is greater than mast 10359 but lower than 10358, this suggests that the data is

second to the mast 10358 but the recovery reveals that mast 10357 precedes mast 10358, in quality.

4. 2 WAsP MAP EDITOR

The masts are located in their geographical positions where the Kusaye mast is close to Wind Turbine Generators (WTGs) of the north direction which is almost at the centre of the proposed Wind Farm, where as the Jogo Mast is close to the WTGs of the south and Adama I is placed at Adama I. Thus the emphasis is given to Kusaye mast. Figure 4.2 is the snapshot of the Kusaye mast location at the Wind Farm.

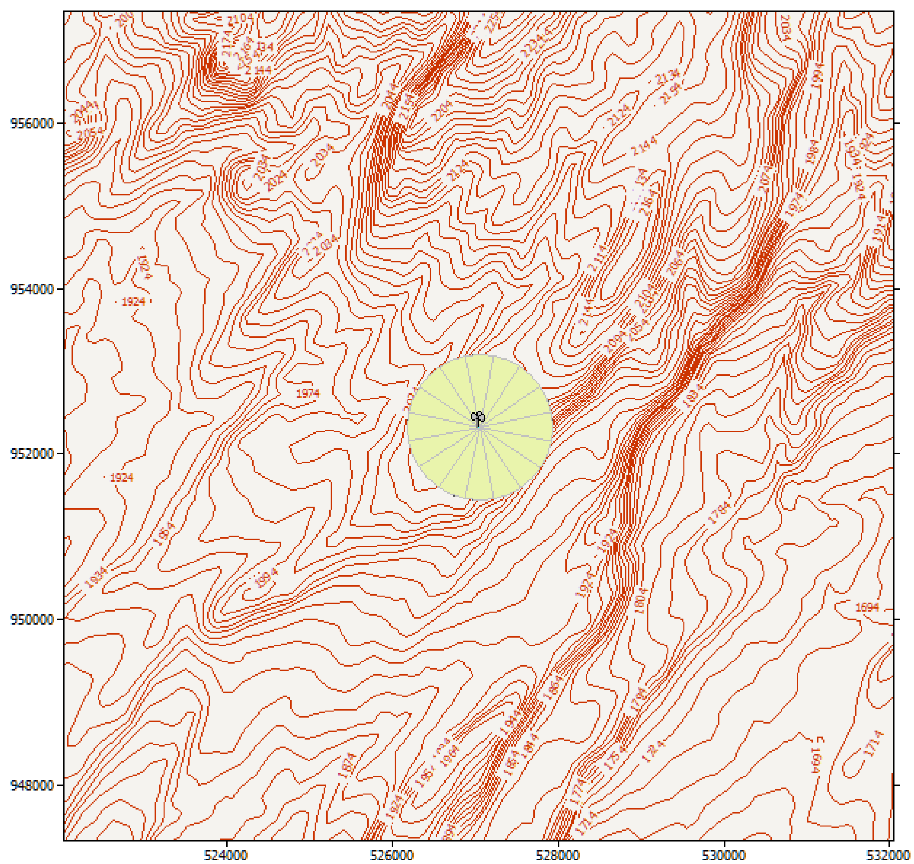


Fig. 4.3 Kusaye mast location

The contour or the vector map of the area has been generated using the Global Mapper software, after collecting the terrain feature, from the topographical map of Ethiopia by inserting the four corners of the rectangle which encompasses the Wind Farm.

Since roughness classes and roughness lengths are the characteristics of the landscape that are used to evaluate wind conditions at a potential Wind Farm site, the wind resource assessment requires the contour map to encompass the associated roughness characteristics of the area. This digitizing can be done using the WAsP Map Editor Program.

WAsP Map Editor results a vector map that can be used for the Wind flow modeling using WAsP software tool. This map has the elevation difference and also the site roughness. The snapshot on Figure 4.4 shows the data generated from the map that describes the landscape properties of the site. The lower left corner of the map editor window presented the status of the map for the analysis is good.

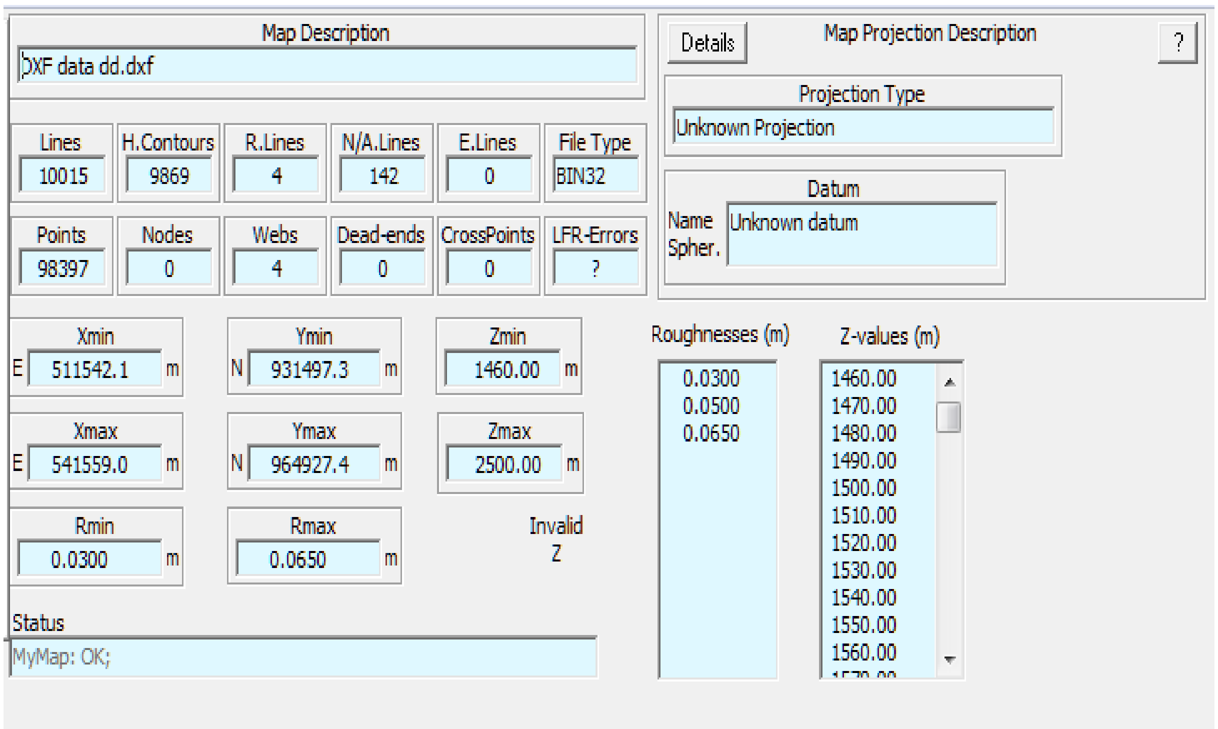


Fig. 4.4 Snapshot of WAsP Map Editor Window

The roughness of the study site is categorized under one of the roughness classes with softly rounded hills and open agricultural area with some houses and without fences. Likely the influence of the roughness is low since the measuring height is at 70 meters above the ground as the hub height of the turbine and the site is undulating.

4. 3 WASP TURBINE EDITOR

The wind resource assessment program requires inputs like those mentioned above and others like the power and thrust curves of the wind turbine generator. These two parameters are the properties of a wind turbine generator that can be generated or produced at the manufacturing company.

Risoe DTU National laboratory also developed the WAsP Turbine Editor tool to establish the power and thrust curve files of a wind turbine generator for WAsP program. The power production and wake losses of a wind turbine generator are related to the two parameters, the power curve and the thrust curve along with the speed of the wind.

Figure 4.4 below shows the snapshot of the WAsP Turbine Editor window, which presents the relation between the wind turbine generator wind speed and the power and thrust coefficient. The turbine model SE7715 with a hub height of 70 m and a rotor diameter of 77 m has been analyzed and established for further analysis on WAsP. For precise analysis, the density of air at the site of 0.95 kg/m^3 has been inserted.

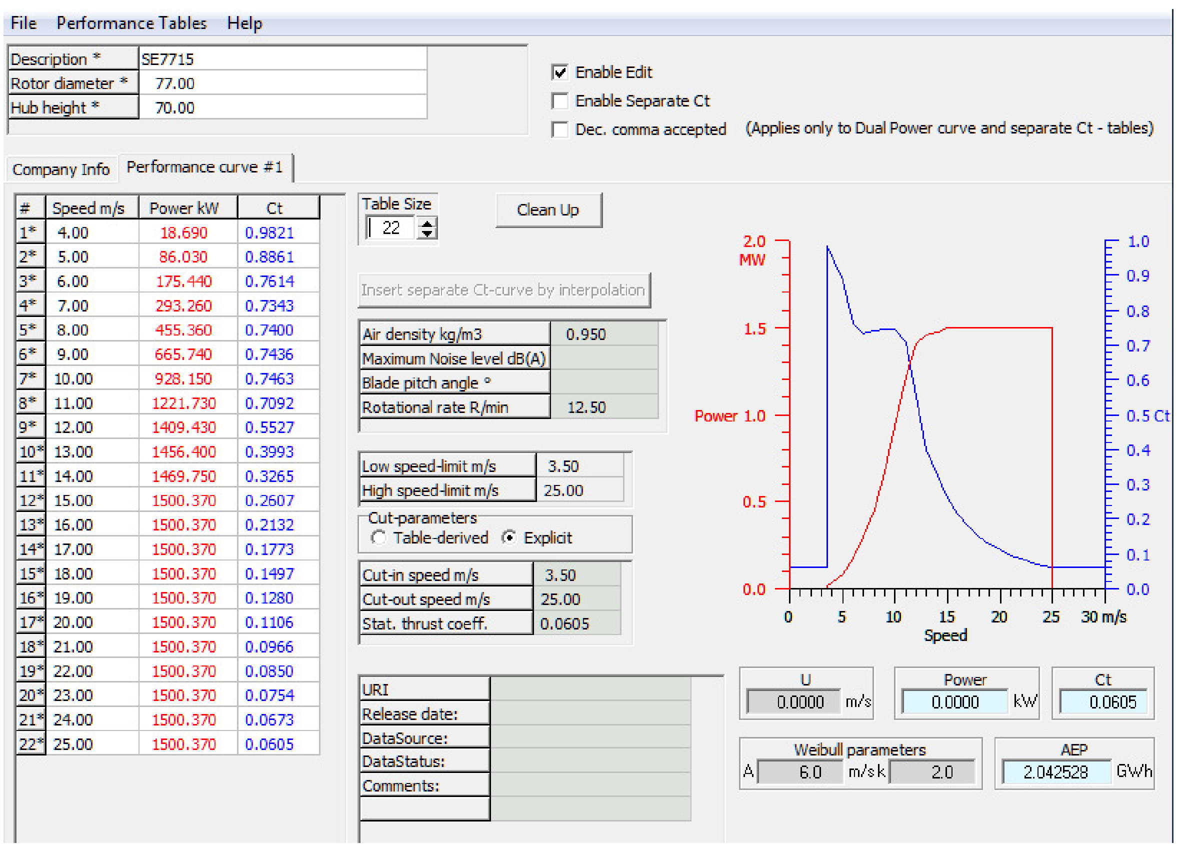


Fig. 4.5 WAsP Turbine Editor Window

The modeled WTGs' power curve and the thrust curve are depicted below, the enlarged view of Figure 4.4, above, It represents the variation of the thrust coefficient and the power of the turbine with the speed of the wind.

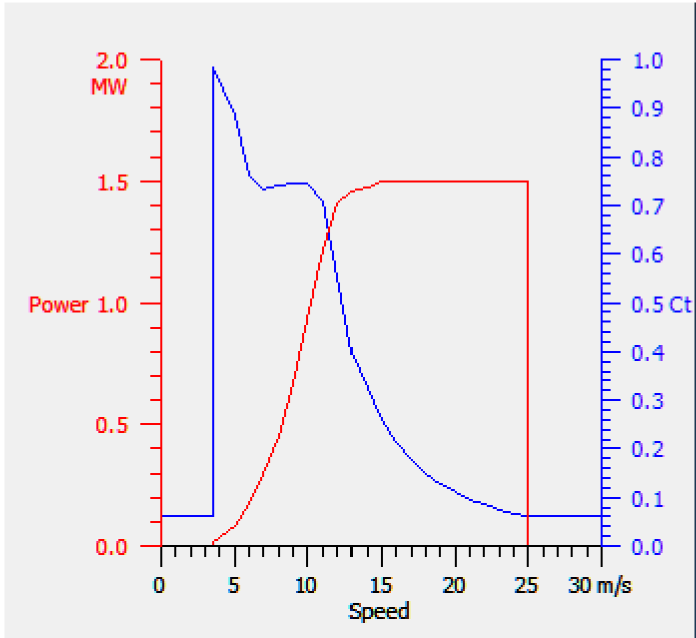


Fig. 4.6 Thrust and power curve of SE7715.

4. 4 LOCATION OF WIND TURBINE GENERATORS

The location of each wind turbine generator is fed to the software; the locations for the analysis are listed on Table 3.3. In the map, it can be presented along the anemometer mast placed at the centre of the Wind Farm. As it has been mentioned on previous chapters, there are 102 SE7715 WTGs, each located on the map, Figure 4.6. The coordinate projections are in the UTM (Universal Transverse Mercator) projection technique.

The wind turbines in the south part of the vector map are named S1 to S24 and the northern are named N1 to N78. The size of the map is made to be larger than the intended Wind Farm, in order to make the wind resource assessment to cover areas outside the Wind Farm.

4. 5 WAsP WIND FLOW MODELING

In the previous sections the data were inserted in the blocks of the modeling software, WAsP. Thus all the results from the components are fed to the main block to generate the Wind Atlas and the expected wind resource available at the intended Wind Farm.

The WAsP software is a tool like many other wind prediction models; it is based on the hypothesis that wind speed data can be approached in statistical terms by the Weibull distribution, a continuous probability distribution, which is widely accepted among the wind-engineering community.

As velocity distributions at a given point are denoted by their Weibull function in WAsP, in order to be able to represent wind velocities at several points as a wind velocity profile, the mean value instead of the complete statistical distribution has to be used, although it means a simplification of information. The main advantage is that, besides obtaining a scalar to represent wind profiles, it is a very intuitive variable in order to compare different wind conditions [24].

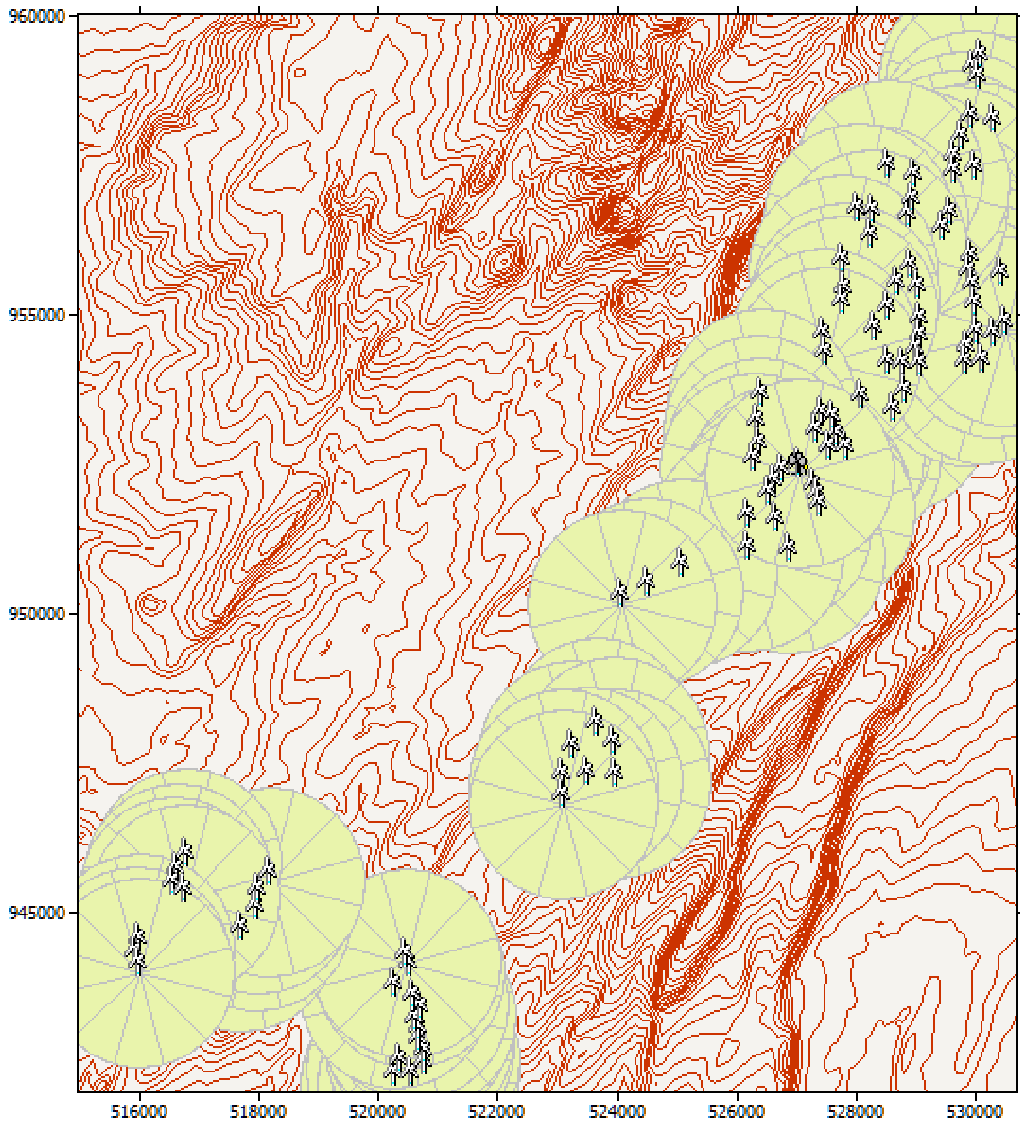


Fig. 4.7 Locations of the wind turbine generators

In WAsP the most basic assumption is that, for a specific area, the overall wind conditions change so slowly that the wind climate can be extrapolated from a meteorological station to any point of the region just taking into account the local effects at both sites. The so called the site effects are the surrounding topography, roughness and obstacles existing at the reference point.

The measured data at the reference point, the Observed Wind Climate will be extrapolated to the point where the required assessment area. The results of the extrapolation can be obtained after cleaning the site effects from the wind condition at the reference point, then results the regional wind climate. This generalized wind climate is wind climate for standard conditions given by at terrain of uniform roughness.

This regional wind climate can be extrapolated to a point where the ambient condition of the reference is nearly the same as the point of consideration. The overall trend for extrapolating a wind condition using WAsP for wind resource assessment can be summarized as shown in Figure 4.7.

4. 5.1 Conditions of Wind Flow Modeling Using WAsP

There are requirements that shall be considered while conducting a wind resource assessment program using any convenient method for estimating the available wind resource at any Wind Farm. Accurate wind resource assessment program using WAsP program may be obtained provided that the following conditions are fulfilled: (Bowen and Mortensen, 1996; Mortensen and Petersen, 1998).

1. The reference (meteorological) station and predicted site are subject to the same overall weather regime,
2. The prevailing weather conditions are close to being neutrally stable,
3. The reference wind data are reliable,
4. The surrounding terrain (of both sites) is sufficiently gentle and smooth to ensure mostly attached flows, and
5. The topographical model inputs are adequate and reliable.

Apart from the requirement, WAsP program is most widely used wind resource program, implying that it has been tested and concluded that it can be used for wind resource assessment.

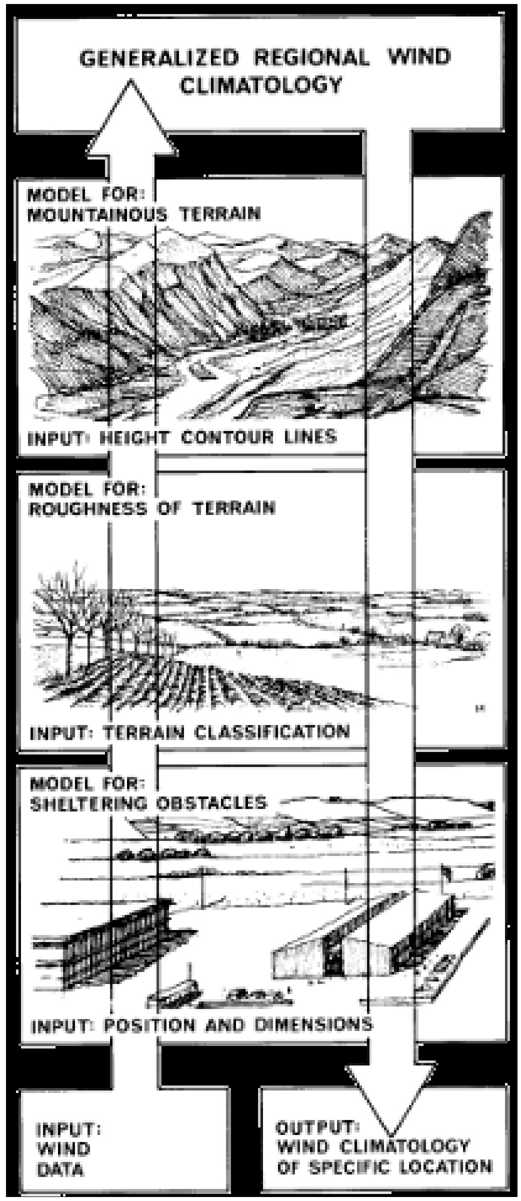


Fig. 4.8 Wind Atlas methodology of WAsP [9]

4. 5.2 Advantages and Disadvantages of WAsP

The strong and positive aspects of WAsP program makes the software dominant than others. Basically the following attributes make the software a reliable tool for estimating a wind power resource.

1. The software is easy to learn and easy to use,
2. Modeling using WAsP can be conducted within a certain period of time if all the requirements and the data are collected,
3. WAsP software is flexible,

4. The cost of an assessment conducted using WAsP software is less costly than others,
5. The limitation arising from the analysis and the uncertainties regarding the results have already been determined, and
6. The technical support team is always upgrading the software for further analysis.

WAsP is used all over the world for wind resource assessment. Typical errors of the annual energy prediction of wind turbines are about 10%. In complex terrain as for example mountains, etc. larger errors may be expected.

It has been mentioned above that WAsP wind flow modeling software had its own advantages. There are some disadvantages that can be seen when modeling wind resources at complex terrain features; its validity is constrained to topographical surfaces that are neutrally stable. The disadvantages also include the following:

1. The effect of the variation of air temperature, horizontally and vertically, is not considered for the wind resource assessment, and
2. Inaccurate prediction results are obtained on very steep hills.

The components of WAsP software, WAsP Climate Analyst tool, WAsP Map Editor and Wasp Turbine Editor programs present the Observed Wind Climate (OWC) conditions, the vector map and the characteristic curves of the wind turbine generator, respectively. These parameters are the inputs that will be inserted into WAsP program.

The overall Wind Resource Assessment on WAsP modeling results in the Annual Energy Production (AEP). The procedure for conducting the assessment starts from collecting wind speed and direction data then producing the Observed Wind Climate using WAsP Climate Analyst tool till the point where the annual wind resource is predicted. Figure 4.8 below shows the snap shot from the window where the modeling has been done.

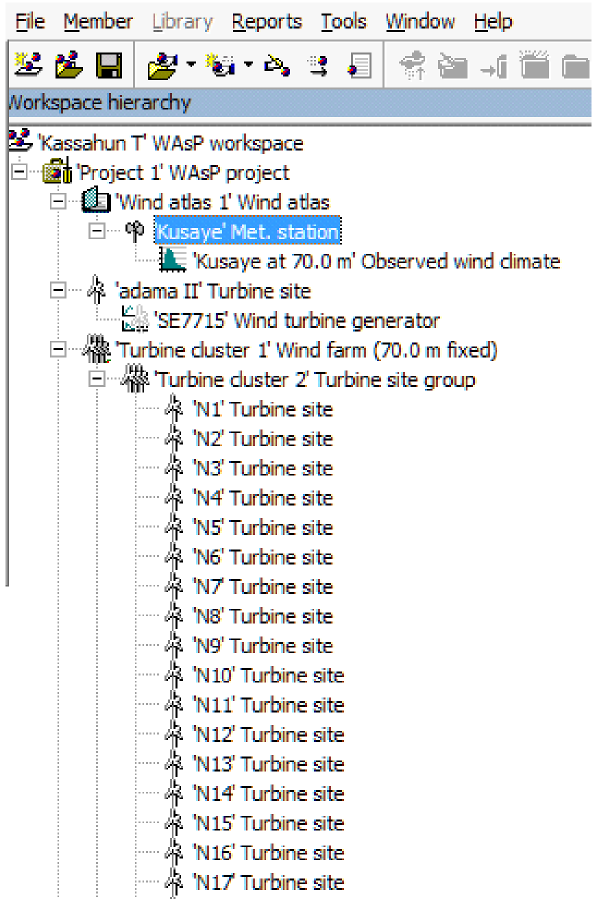


Fig. 4.9 WAsP wind modeling at Kusaye site

4. 6 EXPECTED RESULTS

A wind resource assessment or a wind flow modeling program will result in estimating or prediction of the available wind resource, the annual energy production in a Wind Farm and a wind resource on a grid. The following are the expected results that will be discussed in the next chapter.

1. Observed wind climate
2. Statistical summary of wind condition
3. Wind distribution
4. Wind Atlas and predicted wind climate
5. Power density calculation
6. Annual energy production

CHAPTER FIVE

5 RESULTS AND DISCUSSIONS

5.1 OBSERVED WIND CLIMATE

The Observed Wind Climate is a file which presents the statistical summary of the wind condition, contains the frequencies of occurrence of the wind in all sectors of a Wind Rose. Also it presents the Wind rose and the histogram for all sectors. The results of the WAsP Climate Analyst tool were the inputs to the WAsP wind modeling software. The WAsP Climate Analyst tool converted the data obtained from the data logger to observed wind climate data.

The emergent distribution is the weighted sum of the Weibull distributions from all the directional sector wind parameters, mean wind speed and mean power density are presented below. The discrepancy is also presented indicating that the discrepancy is greater than zero. This discrepancy implies that the uncertainty of the modeling is less.

Table 5.1 Mean wind speed and power density

Site description: 'Kusaye'; Position: 8.62°N 39.25°E; Anemometer height: 70.00 m a.g.l.			
Parameter	Measured	Emergent	Discrepancy
Mean wind speed [m/s]	8.62 m/s	8.66	0.5%
Mean power density [W/m²]	439 W/m²	440 W/m²	0.2%

Table 5.1 shows the summarized mean wind speed and the mean wind power density for all sectors of a Wind Rose. The emerged mean wind speed and the power density are 8.66 m/s and 440 W/m^2 respectively.

There are 12 sectors in the wind rose each sector comprises 30 degrees, for instance sector 1 starts from 345 degree to 15 degrees in the sector and the midpoint of the degree range is 0 degree, that how it is arranged. Then the second sector starts from 15 degrees to 45 degrees again the midpoint is 30 degrees as that can be seen in the figure 5.1.

Figure 5.1 is snapshot on the WAsP Modelling software, summarizes the observations and wind speed distribution for each sector and in all sectors of the wind rose.

Sector		Wind climate				Power
number	angle [°]	frequency [%]	Weibull-A [m/s]	Weibull-k	speed [m/s]	power density [W/m²]
1	0	0.6	5.5	1.39	5.04	187
2	30	2.1	8.4	3.11	7.55	282
3	60	51.7	11.6	4.95	10.68	670
4	90	15.8	8.5	3.19	7.63	286
5	120	1.9	4.4	2.58	3.93	44
6	150	0.9	3.7	2.30	3.27	28
7	180	0.7	3.8	2.35	3.39	31
8	210	1.0	4.7	2.69	4.14	50
9	240	3.5	6.6	3.08	5.93	137
10	270	13.5	7.3	3.59	6.60	176
11	300	7.0	6.6	3.19	5.92	134
12	330	1.3	5.9	1.89	5.24	138
All (emergent)					8.66	440
Source data					8.62	439

Fig. 5.1 Summarized wind observation

Figure 5.1 shows a summary of wind observation; the observation indicates that the mean power density observed at 70 m height is 439 W/m^2 where as the emerged is 440 W/m^2. According to the summarized wind climate 51.7 % of the wind blows in sector 3 with mean speed and power density of 10.68 m/s and 670 W/m^2 respectively. The graphical presentation of the observed wind climate summarizes all the data available on the 12 sectors of a wind rose.

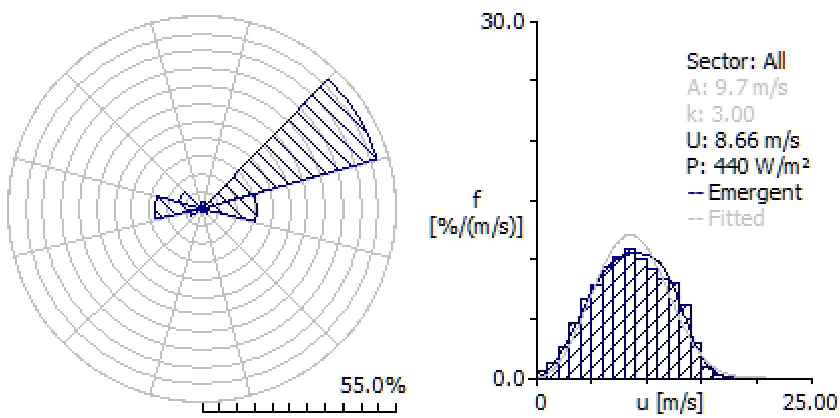


Fig 5.2 Wind Rose and histogram for the observed wind climate

On the left is a wind rose, showing the relative frequencies of wind direction for each sector. The graph to the right shows a histogram of the frequencies of wind speeds at the collection site. The Weibull-A and Weibull-k parameters for the distribution are pre-calculated and numerically Weibull-A parameter is 9.7 m/s and Weibull-k is to be 3. The derived Weibull curve is overlaid onto the histogram.

According to the feasibility study the prevailing wind direction is ENE direction just like what has been presented in Figure 5.2.

The statistical summary for all the 12 sectors is given below. The Weibull parameters, the wind speed and wind power densities are calculated for each sector of the wind rose.

Table 5.2 Sector wise summarized wind condition

sectors	1	2	3	4	5	6	7	8	9	10	11	12
A (m/s)	5.5	8.4	11.6	8.5	4.4	3.7	3.8	4.7	6.6	7.3	6.6	5.9
K	1.39	3.11	4.95	3.19	2.58	2.30	2.35	2.69	3.08	3.59	3.19	1.89
U (m/s)	5.04	7.55	10.68	7.63	3.93	3.27	3.39	4.14	5.93	6.60	5.92	5.24
Pw (W/m^2)	187	282	670	286	44	28	31	50	137	176	134	138
F (‰)	0.6	2.1	51.7	15.8	1.9	0.9	0.7	1.0	3.5	13.5	7.0	1.3

The wind speed varies from time to time from place to place; these variations can be recorded through measuring the available wind condition at the mast location. Histograph bins, the sector wise and total frequencies distribution, of the wind speed is given in table A.1, in the annex. The rated power of 1.5 MW is obtained when the wind speed reaches 15.03 m/s, thus the Histograph shows attaining 15.03 m/s is 4.3% of the time.

The wind is not steady and it is mandatory to conduct statistical analysis. The analysis on the observed wind climate in all sectors is presented in Table 5.3. This table shows the all-sector (Omni-directional) wind speed statistics.

Table 5.3 Wind climate statistical summary

Distribution	Weibull-A [m/s]	Weibull-k [-]	Mean speed [m/s]	Power density [W/m²]
Source data	-	-	8.62	439
Fitted	9.7	3.00	8.71	440
Emergent	9.7	3.00	8.66	440
Combined	9.7	2.93	8.66	440

Table 5.3 presents the observed and the fitted distributions for the mean wind speed and for mean power density along with the Weibull parameters.

The fitted Weibull distribution is a Weibull distribution fitted to an all-sector wind speed histogram. And the combined one is also a Weibull distribution matching the mean speed and power density with the weighted sum of the sector-wise mean speeds and power densities, respectively. The combined Weibull distribution has the same mean speed and power density as the emergent distribution.

According to RISO Laboratory, the use of the emergent all-sector distribution for production calculations has been found to be more accurate and consequently this distribution is the standard total or all-sector distribution referred to. Thus in WAsP modeling software, Wind Farm productions calculations are based on the so-called emergent distribution.

The summary of the wind data recorded at a meteorological Station has been dealt in the previous paragraphs. The summary consists of a wind rose and several wind speed frequency distributions for each and all sectors.

5.2 WIND ATLAS

A Wind Atlas is a systematic and comprehensive collection of regional wind climate (observed wind climate) derived by the Wind Atlas methodology. The Wind Atlas methodology transfers detailed information about the mean wind climate from one location (the predictor site) to another location (the predicted site) [25].

The Wind Atlas procedure transforms the site specific wind climate to regional wind climate through the integration of the site descriptions into the modelling software. In the procedure for Wind Atlas generation the observed wind climate is reduced to certain standard conditions i.e., power density, Weibull shape and scale parameters with some standard heights and roughness classes.

A report is generated after placing a predictor site with its characteristics like mast height and geographic coordinates. The observed wind climate will then be reduced to certain standard conditions, for five standard heights and five roughness classes in all sectors of a wind rose. The following table presents the regional summary of the Wind Atlas.

A roughness class and roughness lengths are characteristics of the landscape used to evaluate wind conditions at a potential site. The roughness length can be defined as the height above the ground at which the wind speed is theoretically equal to zero. It can be considered as a length scale a representation of the roughness of the surface, approximately one tenth of the height of the landscape element.

Table 5.4 Generated Wind Atlas for Kusaye site

Mast Height [m]	Roughness length [m]	Weibull Parameters		Mean wind speed [m/s]	Power density [W/m2]
		A[m/s]	K		
10	0.000	8.6	2.51	7.65	335
	0.033	6.0	2.38	5.35	119
	0.036	6.0	2.38	5.30	116
	0.038	6.0	2.38	5.28	114
	0.040	5.9	2.38	5.24	112
30	0.000	9.6	2.57	8.52	455
	0.033	7.5	2.52	6.62	216
	0.036	7.4	2.52	6.57	212
	0.038	7.4	252	6.55	210
	0.040	7.3	2.52	6.52	206
50	0.000	10.1	2.61	8.98	526
	0.033	8.3	2.64	7.35	286
	0.036	8.2	2.65	7.30	281
	0.038	8.2	2.65	7.28	278
	0.040	8.2	2.64	7.25	274
70	0.000	10.5	2.60	9.31	589
	0.033	8.9	2.77	7.92	348
	0.036	8.8	2.76	7.87	341
	0.038	8.8	2.76	7.85	339
	0.040	8.8	2.76	7.81	334
100	0.000	10.9	2.58	9.70	669
	0.033	9.7	2.78	8.63	448
	0.036	9.6	2.78	8.57	440
	0.038	9.6	2.78	8.55	436
	0.040	9.6	2.78	8.51	430

The mast 10357 or the Kusaye mast is the reference mast that has been used as the predictor site and it is placed at a geographical coordinates of 8.62°N 39.25°E or in Universal Transverse Mercator (527043.424, 952332.101) at 70 m above the ground.

The Wind Atlas contains wind distributions for 5 reference roughness lengths, a roughness classes that span and represent site conditions, (0.000 m, 0.033 m, 0.036 m, 0.038 m, 0.040 m) and 5 reference heights (10 m, 30 m, 50 m, 70 m, 100 m) above ground level. The roses of Weibull parameters have 12 sectors each. The result is a site-independent characterization of the wind climate for the entire map (A generalized wind climate of the area under consideration).

The hub height of the proposed Wind Turbine generator is 70 m and the surface roughness of the site is variable in the ranges given, and thus the highlighted rows of the table are the predicted wind climate 70m above the ground. The predicted wind climate condition is given in the figure below showing that the majority of the wind blows in third sector.

		R-class 0 (0.000 m)	R-class 1 (0.033 m)	R-class 2 (0.036 m)	R-class 3 (0.038 m)	R-class 4 (0.040 m)
Height 1 (z = 10 m)	U [m/s] P [W/m²]	7.65 335	5.35 119	5.30 116	5.28 114	5.24 112
Height 2 (z = 30 m)	U [m/s] P [W/m²]	8.52 455	6.62 216	6.57 212	6.55 210	6.52 206
Height 3 (z = 50 m)	U [m/s] P [W/m²]	8.98 526	7.35 286	7.30 281	7.28 278	7.25 274
Height 4 (z = 70 m)	U [m/s] P [W/m²]	9.31 589	7.92 348	7.87 341	7.85 339	7.81 334
Height 5 (z = 100 m)	U [m/s] P [W/m²]	9.70 669	8.63 448	8.57 440	8.55 436	8.51 430

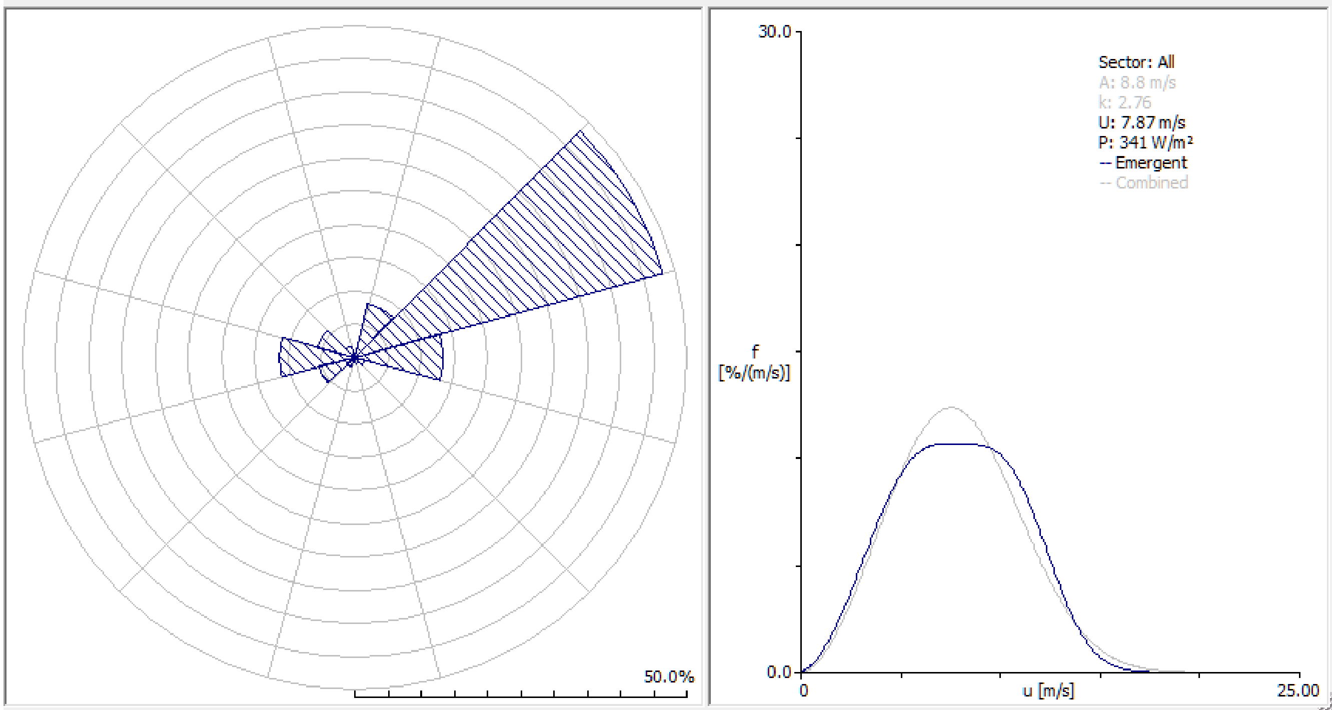


Fig. 5.3 Wind Rose and Sector Histograph

For each combination of a roughness length and a standard height, there is a wind rose. For each sector in each rose, there is a wind speed distribution graph. And the figures 5.3, shows the generated Wind Atlas for five roughness lengths and for five standard heights. The wind rose shows the prevailing wind direction for 70 m height and for 0.036 m roughness length to be sector. The histogram also shows the emergent distribution which is the sum of the sector-wise Weibull make up, for 70 m height and roughness length of 0.036 m the wind speed and power density are 7.87 m/s and 341 W/m^2.

5.3 WIND CLASS

The power density and mean wind speed are the parameters that will determine the wind class of the Wind Farm site, most of the time the power density of a Wind Farm is predicted at the heights of 10 m, 30 m and 50 m above the ground. Power density value combines the effect of the distribution of wind speeds and the dependence of the power density on air density. The following figures represent the power density at 50 m for all sectors of the rose.

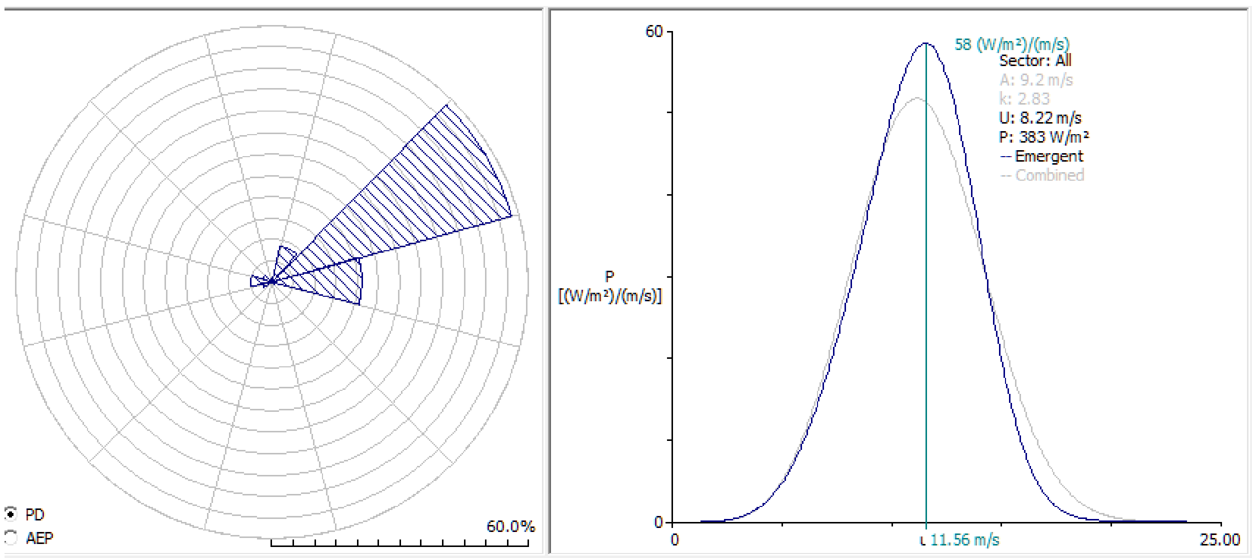


Fig. 5.4 Power density at 50 m

Figure 5.4 presents the variation of wind power density wind rose and the histogram for the power density with the wind speed at 50 m above the ground. The mean wind power density for all sectors is 383 W/ m^2 with the mean wind speed of 8.22 m/s. And the maximum wind power density is obtained at wind speed of 11.56 m/s. According to Battle Wind Energy Resource manual for selecting the power density, if the mean wind speed at 50 m above the ground line is between 8 and 8.66 m/s the wind class of the site is class 6. And using the power density category, the wind class is class four through extrapolation without consideration of the effects of temperature and uncertainty of the modeling. While the report on feasibility study presented that the wind class is class 6 through consideration of the mean wind speed.

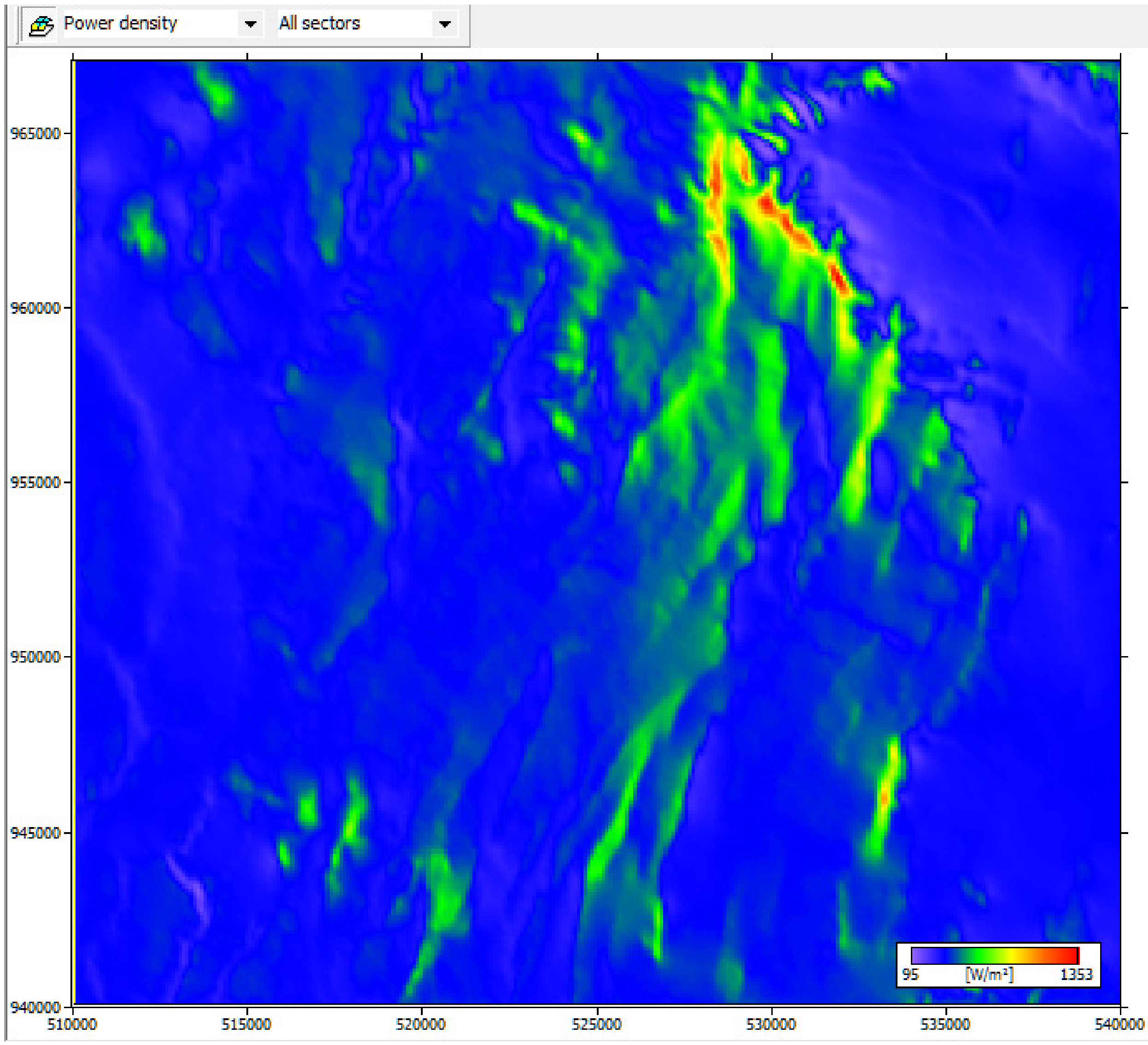


Fig. 5.5 Wind power density spatial view at 50 m

Figure 5.5 shows the wind power density at hub height of the proposed wind turbine, 50 m, for the prevailing wind direction and for all sectors of the wind rose. The spatial view shows that the wind power density of the Wind Farm in all sector ranges from 95 W/ m^2 to 1353 W/ m^2.

5.4 PREDICTED WIND CLIMATE

In a Wind Atlas data set the wind distributions have been cleaned with respect to the site-specific conditions and reduced to standard conditions using a Wind Atlas data set calculated as described above.

A turbine site (one of the members of the WAsP modeling hierarchy) calculates a predicted wind climate by taking a Wind Atlas which describes the generalized wind climate of an area, the Vector map and Wind Turbine Generator characteristics and then applying it to a particular location, adjusting for the effects of the features of the site itself.

Thus the predictor can be located in space, (x, y) coordinates and two points in z axis: the elevation of the site and the height above ground level for which the prediction is generated. Then the WAsP program can estimate the wind climate at any particular point by performing inverse calculation as is used to generate a Wind Atlas, i.e. by reintroducing the actual topographic conditions of the application or predicted site.

Taking the turbine site to be placed at the mast location with the Wind Turbine generator of SE7715, the predicted wind climate at 70 m is obtained. The following figures show the predicted wind climate at the mast location.

Sector		Wind climate				Power		
number	angle [°]	frequency [%]	Weibull-A [m/s]	Weibull-k	speed [m/s]	power density [W/m²]	annual prod. [GWh]	wake losses [%]
1	0	1.1	7.8	1.86	6.91	324	0.042	-
2	30	7.1	10.9	3.92	9.89	571	0.548	-
3	60	40.9	11.6	4.67	10.57	659	3.604	-
4	90	20.5	9.8	3.19	8.78	436	1.251	-
5	120	2.6	5.8	1.96	5.13	126	0.047	-
6	150	0.9	3.9	2.34	3.46	33	0.003	-
7	180	0.7	4.0	2.22	3.52	36	0.003	-
8	210	1.3	5.2	2.40	4.64	77	0.015	-
9	240	4.7	8.0	3.28	7.14	232	0.173	-
10	270	11.6	7.4	3.48	6.65	182	0.340	-
11	300	6.8	6.7	3.15	6.00	141	0.149	-
12	330	1.8	6.3	2.26	5.57	140	0.037	-
All (emergent)					8.76	452	6.213	-

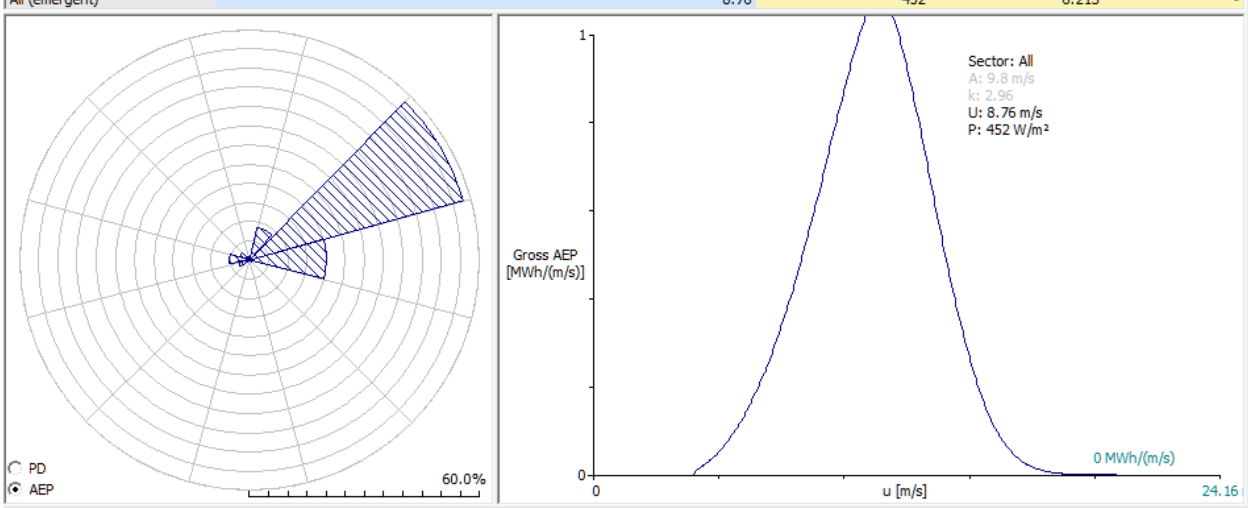


Fig. 5.6 Predicted wind climate at mast location

Figure 5.6 shows that the results obtained when placing a single SE7715 Wind Turbine Generator at the predictor site. The result presented that the mean wind speed is 8.76 m/s and power density of 452 W/m^2 at 70 m hub height. And with regard to the gross Annual Energy Production is 6.213 GWh out of this 3.6 GWh will be produced on the prevailing wind direction.

5.4.1 Predicted Power Density at Mast Location in Prevailing Wind Direction

The prevailing wind is on sector 3, ENE direction, as can be seen on figure 5.5 and 5.6 the sector is dominant in regard to Annual energy production, power density and mean wind speed. The wind power density rose shows the contributions to the total power density.

The power curve of the Wind Turbine Generator and the probability density function of the wind speed at hub height are the two parameters for calculating the power density. The product of these two functions gives the power density, the integral of which is the mean power production (European Wind Atlas, 1989). The figure given below presents the estimated wind power density rose and power density curve at the mast location at hub height of 70 m with the given Wind Turbine Generator Production at sector 3.

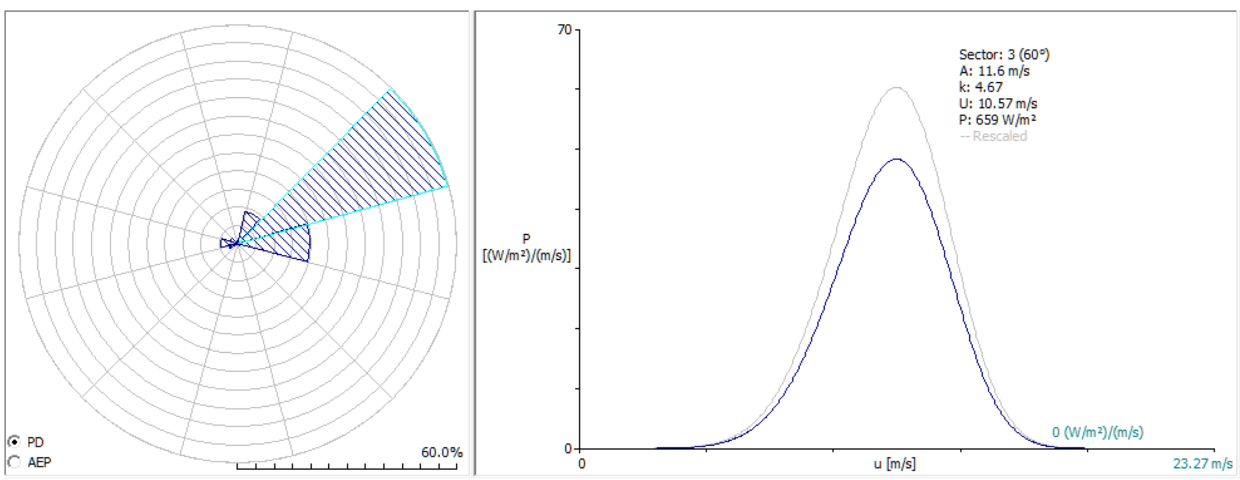


Fig. 5.7 Power density at mast location

The power density, the amount of energy transported across a unit area in unit time, at 70 m height and at the specific geographic coordinated where the Kusaye mast located is 659 W/m^2. The power density of a Wind Farm site plays a significant role in construction and installation of Wind Turbine Generator including the selection of Wind Turbine Generators.

Figure 5.8, given below, shows the snapshot of the WAsP modeling window in the spatial view; the power density at site in the prevailing wind direction is estimated using the anemometer mast installed at the site.

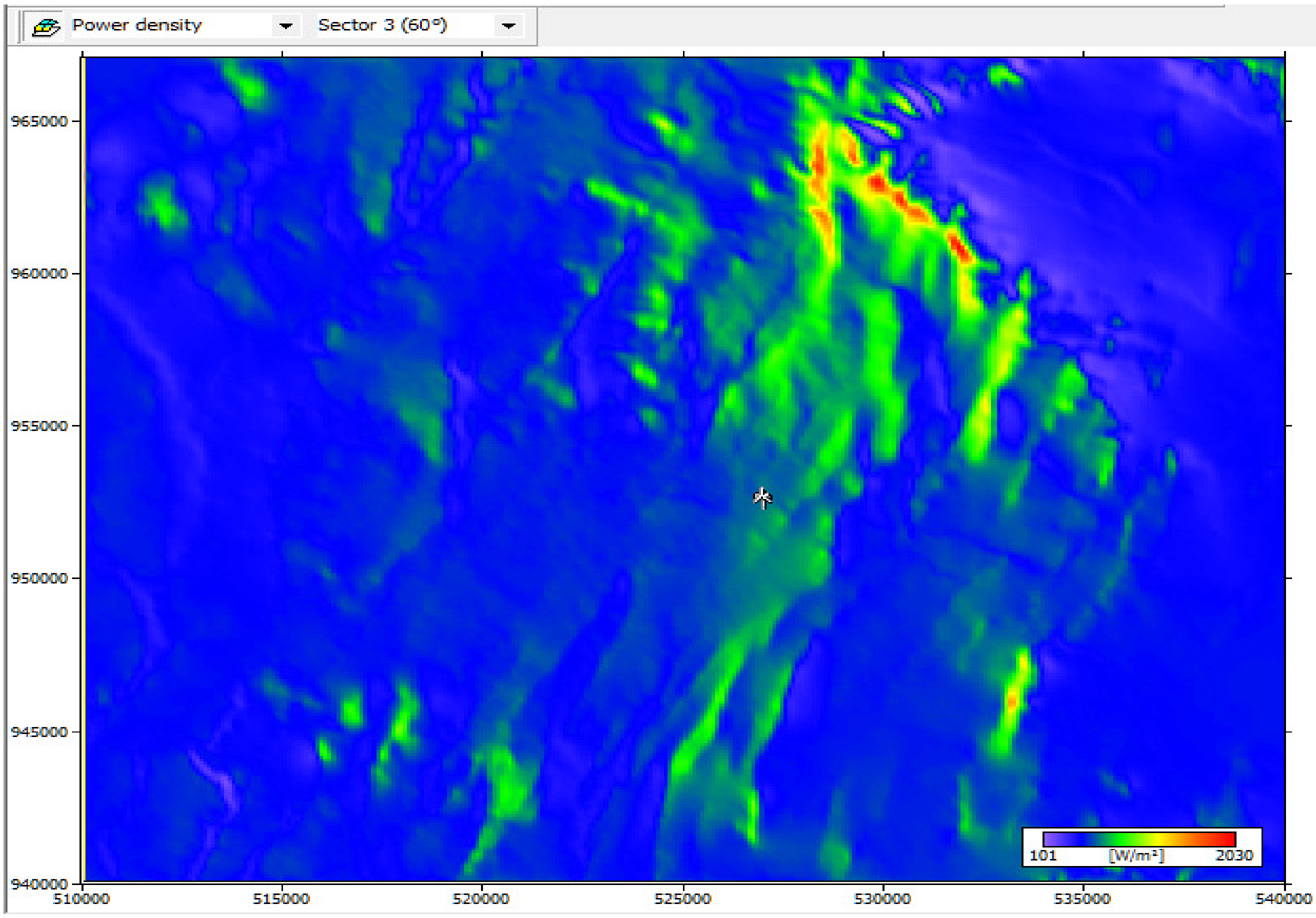


Fig. 5.8 Predicted power density in the prevailing wind direction

Figure 5.8 shows the estimation conducted using an imaginary Wind Turbine generator installed at Kusaye mast location for the sake of analysis. And it presented that the power density in the area ranges from 101 W/m^2 to 2030 W/m^{2}at 70 m high above the ground without consideration of wake losses since it's assumed that there is only one wind turbine generator.

5.4.2 Predicted AEP at Mast Location in Prevailing Wind Direction

Based on previously calculated the generalized wind climate (Wind Atlas) of the region, the power curve for a turbine at the Turbine site are combined to calculate the rose and the graph for the predicted Annual Energy Production. The AEP rose shows the contributions to the total AEP from the different sectors in percent. The graph shows the variation of AEP with the wind speed. The following figure presents the estimated Annual Energy Production at the Turbine site in the prevailing wind direction.

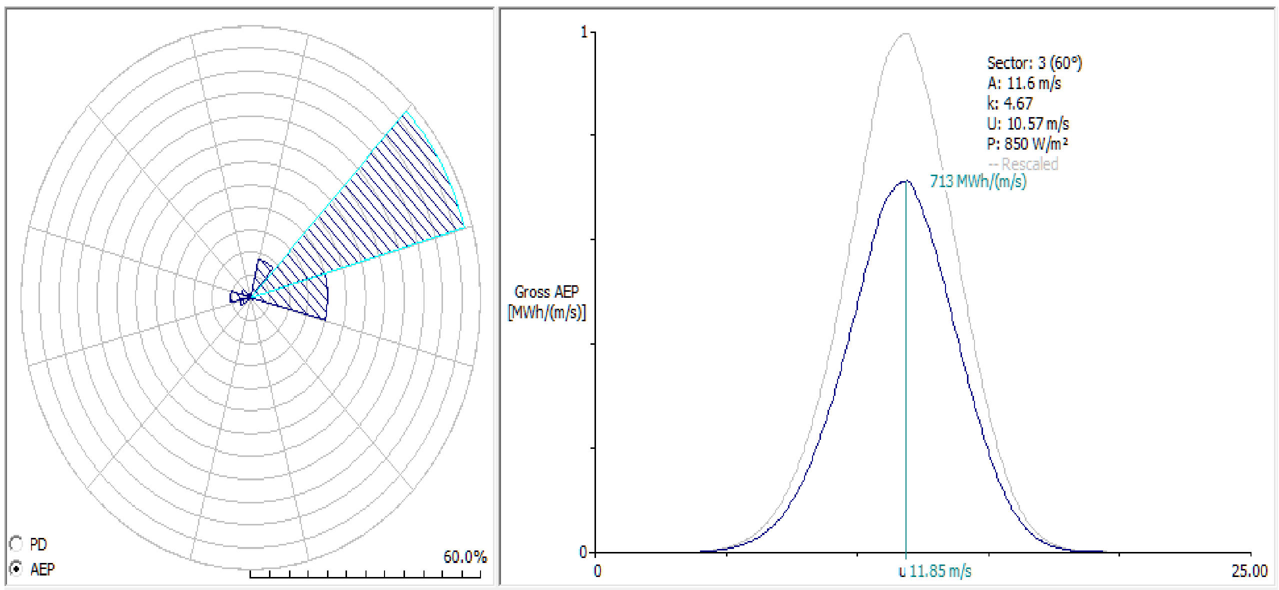


Fig. 5.9 Estimated AEP in prevailing wind direction

Figure 5.9 shows that above 55% of the Annual Energy production (AEP) is along sector 3. The rest is from the other 11 sectors. Thus installing the Wind Turbine Generators after consideration of the prevailing wind direction will produce maximum amount of the required Annual Energy Production.

Further analysis has been done to present the predicted power density and the Annual Energy Production. As the vector map with the roughness attributes are included in the calculation for the predicted wind climate, along with the Wind Turbine Generator characteristic curves. These estimations can be seen in the wind map at the spatial view of the turbine site.

In the same manner the Annual Energy Production at the site is estimated using the mast located at Kusaye. Figure 5.10, given below, shows the estimated Annual Energy Production in the prevailing wind direction ranges from 1.5 to 11.99 GWh.

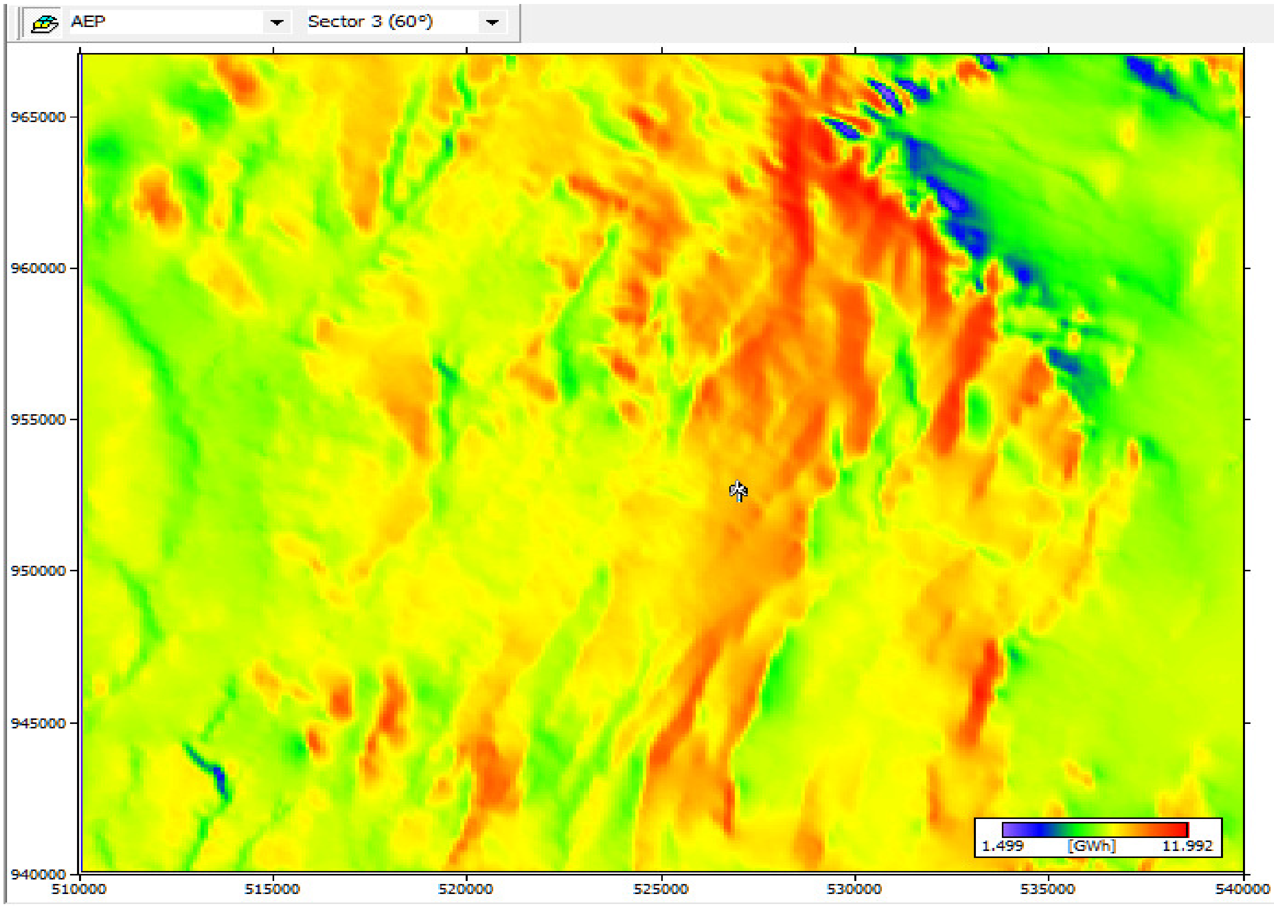


Fig. 5.10 Predicted AEP spatial view in prevailing wind direction

5.5 ANNUAL ENERGY PRODUCTION

The result of the turbine site analysis under WAsP modeling has presented the wind power that can be extracted from the site using the same kind of Wind Turbine Generator, Sany SE7715. Besides the type, characteristics and efficiency of the Wind Turbine Generator, the orientation or the placement of the intended turbines will play a significant role in extracting the maximum amount of energy.

There are 102 sets of Wind Turbine Generators in the Wind Farm, each of the Wind Turbine generators are 1.5 MW name plate capacity. According to the feasibility study conducted the turbines were placed in a coordinates as mentioned on Table 3.4.

Prior to repositioning the Wind Turbine Generators to a position the analysis is conducted using the available data, spatial location and the turbine characteristics as mentioned on chapter 3, the total energy production for each turbine and the net annual energy production in the prevailing wind direction and in all the 12 sectors are tabulated on the Annex section, Table A.2.

Table A.2 shows the annual energy production for the entire Wind Farm with 102 wind turbine generators the sum total annual energy production in the prevailing wind direction and in all sectors are 393.017 GWh and 663.493 GWh can be extracted from the Wind Farm before considering any losses and after deducting the losses from wake effects the Annual Energy Production is 621.658 GWh, as it summarized in Table 5.7.

The same result can be spatially described in the spatial view the net AEP. Figure 5.11 presents the Annual Energy Production. It indicates that most of the annual energy production is available in the ENE direction. The red sectioned part of the roses show the wake effects associated with each WTG.

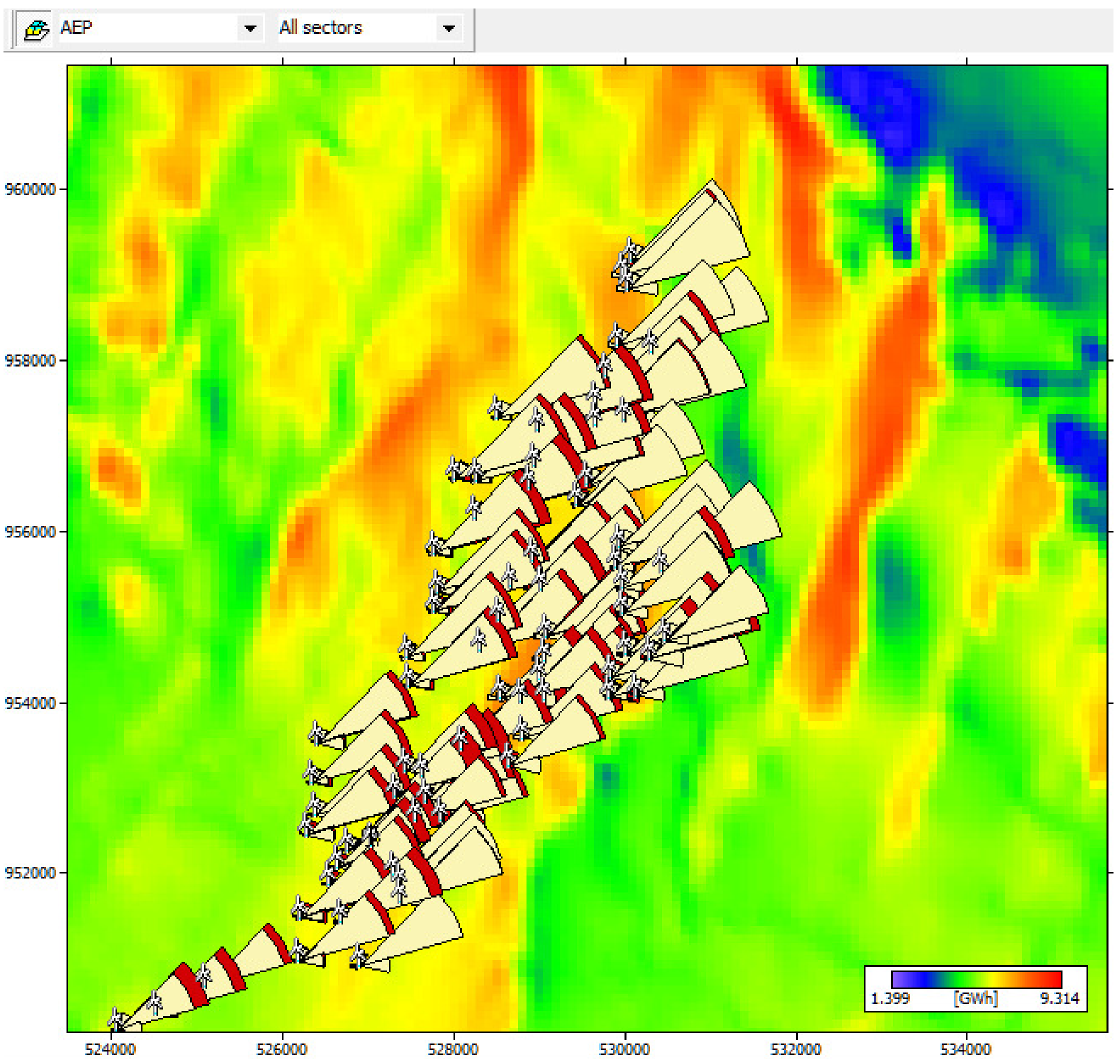


Fig. 5.11 Annual Energy Production with wake loss in spatial view

Most of the WTGs installed using the proposed arrangement or layouts have been influenced by the wake effects generated by the nearby WTGs. Thus it makes it mandatory to rearrange the WTGs not only to reduce the associated wake losses but also to improve the Annual Energy production.

The all sector result shows the average of the whole 12 sectors. The maximum and minimum net annual energy production is estimated to be 7.7 and 4.895 GWh respectively from a single Wind Turbine Generator; this implies that there still can be a better result after replacing the Wind Turbine Generators to a location where maximum Annual Energy Production can be obtained.

Table 5.5 All sector summary results

Parameter	Total	Minimum	Maximum
Net AEP [GWh]	621.658	4.895	7.703
Gross AEP [GWh]	663.493	5.446	7.864
Proportional wake loss [%]	6.31	0.41	19.2
Mean speed [m/s]		8.21	10.19
RIX		0.2	3.9

Table 5.5 summarizes the results of the analysis on the resource assessment; the net Annual Energy Production in all sectors of the wind rose is to be 621.658 GWh and the maximum Wake loss is 19.2 percent and minimum one is 0.41 percent as it can be seen from the above tables.

Though the wake loss is in the range which is acceptable it can also be further reduced to some lower values. This result, the minimizing wake loss, is limited to the available area of the Wind Farm. Thus the optimization is also bounded to the Wind Farm area.

The annual energy production with 102 wind turbine generators placed at a geographical location has generated the 621.658 GWh of amount of energy in all sector in a year before the consideration of any losses. The WTGs can further be rearranged to generate an Annual Energy Production greater than what has been mentioned above.

5.6 WTG RE-SITTING

The wind resource is certainly the most important factor to consider when choosing a site for a wind project. There are many factors affecting the spatial locations of Wind Turbine Generators in a Wind Farm including physical, social and economic factors. Re-sitting has been done through taking into consideration of the spatial locations with maximum energy output and with minimum wake losses.

Other factors associated with installing WTGs like the suitability of the ground to install WTGs, economic and social factors are considered to have a minor role. And these factors require a detailed investigation and experience in the field and so many field measurements. Table 5.6, below, presents the annual energy production after repositioning the Wind Turbine Generators.

Table 5.6 Annual Energy Production after repositioning of Sany SE7715 WTG

Site No	Location [m]	Net AEP [GWh]	RIX [%]	DRIX [%]	Wake loss [%]
N1	(530089.7,959170.0)	6.995	3.2	2.1	1.03
N2	(530062.6,959007.9)	7.062	2.8	1.7	2.19
N3	(530046.6,958835.3)	7.095	2.3	1.3	1.99
N4	(530070.0,958421.2)	7.063	2.2	1.1	0.99
N5	(530147.9,958199.2)	6.830	2.7	1.7	1.76
N6	(529923.0,957808.8)	6.822	1.9	0.8	2.45
N7	(529996.0,957594.5)	7.012	2.4	1.3	1.39
N8	(530015.0,957120.9)	7.108	2.7	1.7	1.25
N9	(529992.5,956933.4)	6.980	3.0	1.9	1.91
N10	(530013.2,956681.9)	7.101	3.3	2.2	1.2
N11	(530023.9,956471.1)	7.068	3.2	2.2	1.29
N12	(528927.7,955660.7)	6.124	3.5	2.4	6.01
N13	(528922.2,955966.2)	5.942	3.4	2.3	6.48
N14	(529106.4,955130.0)	6.989	3.5	2.4	4.85
N15	(528846.2,954464.1)	6.656	3.1	2.0	9.27

N16	(528509.9,959624.2)	7.374	0.5	-0.6	2.65
N17	(529027.1,954790.4)	6.985	3.3	2.2	6.36
N18	(528952.1,954627.2)	6.837	3.5	2.4	7.92
N19	(528780.1,954274.4)	6.773	3.2	2.2	7.26
N20	(528705.1,954098.1)	6.827	3.0	1.9	7.22
N21	(528625.8,953882.0)	6.963	2.8	1.7	6.16
N22	(529066.8,954953.6)	7.049	3.4	2.3	5.63
N23	(528809.9,953586.0)	6.250	2.4	1.4	7.06
N24	(528647.6,953257.0)	5.834	2.6	1.6	7.39
N25	(528283.9,952842.3)	6.496	2.3	1.2	4.72
N26	(527936.4,952589.5)	5.864	1.5	0.4	9.19
N27	(528290.6,953228.7)	6.176	2.5	1.4	12.05
N28	(528517.9,953632.4)	6.283	2.7	1.6	10.58
N29	(527557.1,955343.1)	6.219	3.7	2.6	4.97
N30	(525996.9,955300.1)	6.688	1.7	0.7	4.47
N31	(527741.2,952319.7)	6.141	1.3	0.3	5.52
N32	(527314.2,951994.7)	6.123	0.9	-0.1	7.56
N33	(527381.4,951851.8)	6.461	0.7	-0.3	3.85
N34	(527394.3,951667.6)	6.291	0.7	-0.4	3.49
N35	(528751.9,960801.3)	8.186	3.6	2.5	0.04
N36	(530050.1,956215.0)	6.885	3.4	2.4	1.2
N37	(530185.3,955785.9)	6.919	3.6	2.5	1.46
N38	(530249.4,955600.4)	7.035	3.2	2.2	1.47
N39	(530337.7,955341.7)	7.012	3.0	1.9	1.55
N40	(530278.4,955063.6)	6.845	3.1	2.0	2.3
N41	(530210.1,954544.0)	6.886	3.7	2.7	2.02
N42	(529941.8,958007.1)	6.340	1.8	0.8	8.76
N43	(530078.4,955999.6)	6.833	3.6	2.5	1.27
N44	(530136.1,954077.8)	6.734	3.7	2.6	3.05

N45	(530205.5,954311.5)	7.037	3.8	2.8	2.02
N46	(530205.5,954767.3)	6.733	3.5	2.4	2.8
N47	(528890.9,956520.6)	5.732	2.9	1.8	6.72
N48	(528889.4,957075.2)	5.966	2.2	1.2	6.98
N49	(527906.2,957901.6)	6.914	1.2	0.2	3.62
N50	(528584.9,959817.9)	7.533	1.3	0.2	1.45
N51	(527637.4,957546.0)	6.821	2.3	1.3	8.95
N52	(527337.4,957194.2)	7.014	3.1	2.0	10.4
N53	(527194.1,957024.4)	6.932	2.9	1.8	10.29
N54	(526277.6,956090.9)	7.200	3.9	2.9	4.79
N55	(526185.9,955885.6)	7.377	3.7	2.6	4.77
N56	(528242.2,958478.6)	6.733	0.5	-0.6	2.42
N57	(527057.8,956818.9)	6.972	2.9	1.8	7.05
N58	(526937.6,956580.6)	6.611	2.8	1.7	6.01
N59	(526133.2,955671.8)	7.032	2.7	1.7	4.62
N60	(527562.1,956353.5)	6.745	3.2	2.2	4.38
N61	(527475.7,957355.0)	7.117	2.8	1.7	8.76
N62	(527787.1,957721.2)	6.931	1.7	0.6	6.63
N63	(528742.7,960352.4)	7.985	3.3	2.3	0.32
N64	(530007.5,957368.3)	7.128	2.5	1.5	1.23
N65	(529984.9,958610.2)	7.008	2.1	1.0	2.41
N66	(528748.2,960583.8)	8.086	3.6	2.5	0.25
N67	(528240.1,953001.9)	6.364	2.5	1.5	8.91
N68	(528393.2,953455.9)	6.047	2.6	1.5	12.49
N69	(528571.3,951580.7)	6.568	0.8	-0.3	1.4
N70	(528594.7,951836.8)	6.848	1.6	0.5	1.35
N71	(528485.0,951397.9)	6.332	0.7	-0.4	3.57
N72	(528473.6,959408.1)	7.282	0.3	-0.8	2.0
N73	(528391.1,959130.4)	7.098	0.3	-0.8	2.5

N74	(516895.7,946026.9)	6.695	0.8	-0.2	1.61
N75	(518195.2,945635.1)	7.034	0.7	-0.4	1.22
N76	(518115.7,946208.0)	6.700	0.3	-0.8	0.89
N77	(528697.2,960129.4)	7.660	2.6	1.5	0.97
N78	(520896.1,942693.8)	6.671	1.0	-0.1	5.2
S1	(520376.9,942277.6)	6.320	1.0	-0.1	10.82
S2	(520560.7,942695.2)	6.405	1.2	0.2	10.44
S3	(520563.6,942152.1)	6.208	0.6	-0.4	3.33
S4	(520871.3,942536.8)	6.661	1.0	0.0	5.0
S5	(520515.9,942462.4)	6.129	1.1	0.0	12.78
S6	(520945.6,942893.1)	6.815	1.2	0.2	3.53
S7	(520544.2,942863.9)	6.763	1.4	0.4	5.4
S8	(520639.4,943086.2)	7.028	1.3	0.2	0.6
S9	(520615.7,943316.5)	6.808	1.4	0.3	1.44
S10	(520614.8,943441.0)	6.757	1.4	0.3	0.56
S11	(520676.2,943882.8)	6.826	1.1	0.1	1.2
S12	(520522.9,944008.3)	6.651	1.2	0.1	0.83
S13	(520458.7,944164.8)	6.822	1.3	0.2	0.51
S14	(517608.3,944381.3)	6.862	1.9	0.9	2.66
S15	(517958.4,945035.2)	7.745	2.6	1.5	3.33
S16	(518020.9,945238.8)	7.541	2.7	1.6	3.93
S17	(518110.3,945417.9)	7.424	1.8	0.7	2.69
S18	(516725.7,945828.6)	6.648	1.3	0.2	6.57
S19	(516705.3,945663.5)	7.139	1.6	0.5	3.43
S20	(516722.8,945491.1)	7.027	1.5	0.4	2.74
S21	(517874.0,944882.5)	7.226	1.7	0.6	5.71
S22	(516021.5,944405.9)	7.147	2.1	1.0	2.82
S23	(516049.9,944233.6)	7.107	1.9	0.9	3.05
S24	(517484.1,944157.3)	7.048	2.0	0.9	3.83

After repositioning the Wind Turbine Generators, considering the potential locations and the wake effects, the Annual Energy Production after a reduction of wake losses for all the 102 Wind Turbine Generators is 696.171 GWh. The maximum Annual Energy production after wake loss for a single WTG is 8.186 GWh which is located at (528751.9, 960801.3) coordinates and the minimum is 5.732 GWh.

The available Wind Farm area is the major constraint for further reducing the wake effects, in Figure 5.12, the spatial view of Annual Energy Production is presented along with the wake percentages.

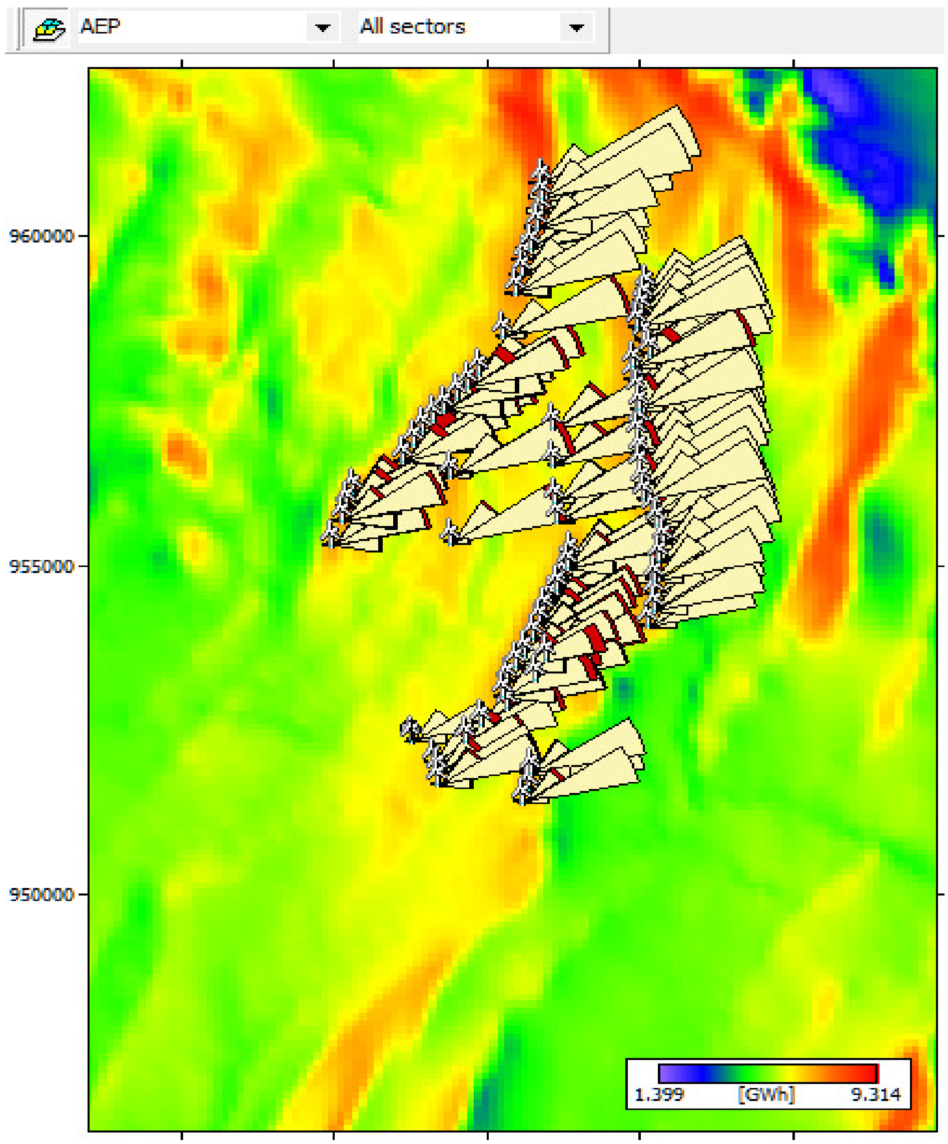


Fig. 5.12 Annual Energy production and wake losses after re-sitting

Table 5.7 Summary results after re-sitting

Parameter	Total	Minimum	Maximum
Net AEP [GWh]	696.171	5.732	8.186
Gross AEP [GWh]	727.270	6.145	8.190
Wake loss [%]	4.28	0.04	12.78
Mean speed [m/s]	-	8.56	10.32
RIX	-	0.2	3.8

Table 5.7 summarized the results of the modeling after repositioning the Wind Turbine Generators on the Windy areas of the wind map. The summarized table revealed that the proportional wake losses have been reduced from 6.31 to 4.28%, in Annual Energy terms it reduced the losses to be 31.099 GWh from 39.1851 GWh an increment on the net Annual Energy Production of 674.513 GWh. The reduction in wake losses also reduced the turbulence of the wind consequently it can minimize the dynamic mechanical loading on the Wind turbine Generators.

The Net Annual Energy Production, after reduction of wake losses has increased from 621.658 GWh to 696.171 GWh through repositioning of the Wind Turbine Generators only using the most dominant parameters.

5.7 RESOURCE GRID

A resource grid manages a rectangular set of points for which predicted wind climate data are calculated. The points are regularly spaced and are arranged into rows and columns. That lets to see a pattern of wind climate or wind resources for an area.

Each point in the grid is like a simpler version of a normal turbine site. All the points have the same height above ground level. The resource grid always shows the gross annual energy production without taking into account the occurrence of any turbines in the area. Likewise, the wind speeds and power densities are unobstructed, i.e. no wake effects from any turbines affect these values [10].

For the general estimation of the wind power characteristics the resource grid is set up to summarize all the results. In the Resource grid there are 81000 points to calculate, 270 rows with 300 columns having a resolution of 100. The wind map has been generated using the resource grid. This wind map plays a significant role for future wind energy development. The following figure shows the wind resource at 70 m above the ground. And Table A.5 in the annex summarizes the resource grid results for all the 12 sectors of the wind rose.

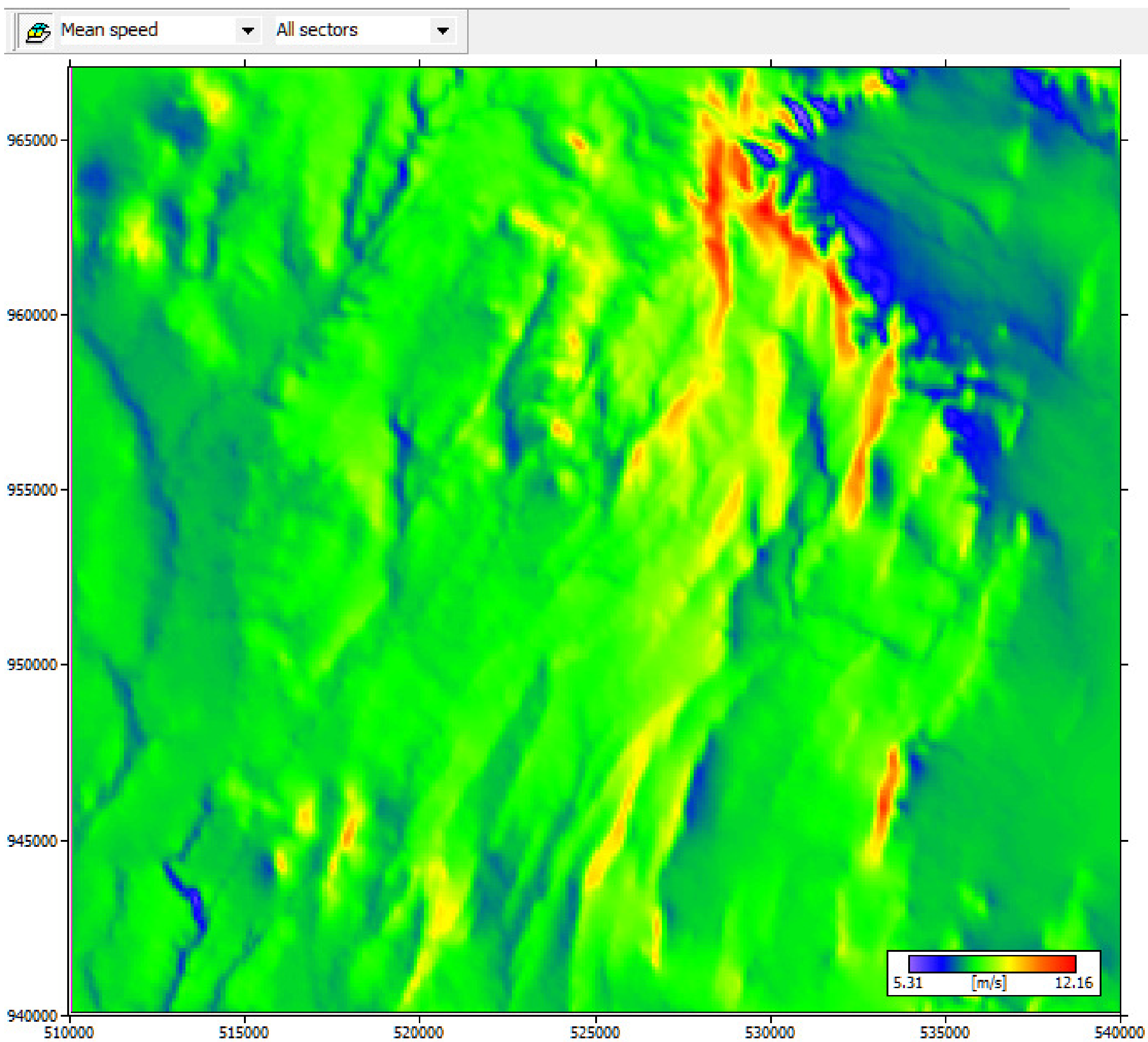


Fig. 5.13 Wind map at 70 m

5.8 OTHER LOSSESS

The modeling has resulted in the expected production after consideration of the available data. As there are uncertainties regarding the estimation of Annual Energy Production, the following table summarizes the intended results after consideration of uncertainties.

WAsP RIX value ranges from 0.2 to 3.9 %, which implies the presented results will deviate within 3 to 4 %. And other uncertainties like the availability of the WTGs, variation of density from one turbine location to other have been considered in the following table.

Table 5.8 Uncertainties to be considered [19]

No	Factors	Reduction Coefficient [%]
1	Turbine Availability	5
2	Air density Difference	0.36
3	Control and Turbulence	3
4	Blade pollution	4
5	Power Curve	5
6	Electricity Line Loss	3
7	Weather Influence	2
8	Roughness	4
9	Influence Between WTGs	2
Total Reduction		**28.36**

Table 5.8 presented the factors associated with the assessment. Thus the total reduction coefficient is the sum of all the coefficients including WAsP uncertainties (4%). The Net output energy before re-sitting the WTGs is 403.67 GWh and after repositioning the WTGs to potential location through consideration of one factor only, the available wind power potential, is 478.786 GWh.

CHAPTER SIX

6 CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

The data that has been recorded, using a calibrated SymphoniePLUS3 logger, at Kusaye site for wind resource estimation of Adama II Wind Farm is analyzed and modeled by using Wind Atlas Application Program. The Anemometer mast is located at a geographical position of 527043.424 m in x direction and 952332.101 m in y direction. The data used for the analysis is recorded from 16/11/2011 to 9/12/2012.

Using the data available for assessment, the modeling using the WAsP Climate Analyst tool has presented the observed wind climate, indicating that the mean wind speed at 70 m height above ground line is 8.66 m/s and the power density at 70 m is 440 W/m^2, whereas the measured wind speed and power density are 8.62 m/s and 439 W/m^2 respectively. These discrepancies suggest that the data that was collected at the Wind Farm under consideration is not affected by terrain characteristics.

Meanwhile the power density at 50 m above the ground line is 383 W/m^2 suggesting that the wind class is class 4 and according to the mean wind speed, 8.22 m/s, the wind class at the site class 6. The variation of the density of air from atmospheric density of air and the uncertainty of the modeling might be the reason for the discrepancy. To solve this issue, the wind class can be taken as class 4 to class 6. This is an indication that the wind potential at Adama II site is up to the requirement.

Taking the Sany SE7715 Wind Turbine Generator's characteristics and the topographical map of the area, the direction where the wind blows most often has been determined. More than 40 % of the wind blows along sector 3 of the wind rose, which implies that the prevailing wind direction is ENE direction. Around 60 % of the Annual Energy Production that can be obtained in the Wind Farm is generated in the prevailing wind direction.

The Ruggedness Index is a parameter for accurate estimation of the wind resource using WAsP. The ruggedness index ranges from 0.2 to 3.9 % which implies that the uncertainty of the modeling which has been undertaken by WAsP modeling software deviates up to 4%.

Placing the Wind Turbine Generators at the locations where the feasibility study has been done, with its performance characteristics, resulted that the Annual Energy Production after consideration of modeling uncertainties and Energy Reduction Parameters like WTG maintenance break down is 403.67 GWh.

Wind Turbine Generators re-sitting has been done through consideration of only the first and most dominant parameter, the Wind potential locations at the Wind Farm. After re-sitting the Wind Turbine Generators the Annual Energy Production is 478.786 GWh. The re-sitting of Wind Turbine Generators will increase the Annual Energy Production by 75.12 GWh.

6.2 RECOMMENDATION

The Wind resource estimation is an important and mandatory procedure for optimization or quantification of the wind resource at a site. The results of the wind flow modeling shall be incorporated with the overall design of the Wind Farm. The wind flow modeling that has been done using WAsP suggested that re-sitting the Wind Turbine Generators as mentioned in WTG re-sitting section will add an Annual Energy Production of 75.12 GWh.

The Wind Turbine Generator reaches its rated power output when the wind speed gets 15 m/s. According to the observed wind climate the frequency of getting 15 m/s and more in wind speed is 4.3%. Thus replacing the Wind Turbine Generator with the Wind Turbine Generator used for Adama I Wind farm might increase the Annual Energy Production.

Since, the Wind Turbine Generator that is used for modeling and estimation of wind resource at the site is a newly developed Wind Turbine Generator, its capacity and efficiency has not been tested yet. In addition replacing the Wind Turbine Generator with the Wind Turbine Generator used for construction of Adama I will also contribute the reduction of the losses that can be seen in regard to maintenance and spare parts.

6.3 FUTURE WORKS

These days development of Wind Farm is undertaken by modeling the wind flow at the intended Wind Farm using wind flow modeling tools like WAsP. As a future work the data that has been analyzed using the WAsP tool can be cross checked with the CFD tool for reducing the uncertainties and errors that arise from the modeling.

The Wind Resource Assessment is carried out through retrieving the data stored for Kusaye site. Thus including the Jogo and Adama Mast and Using three resource grid set up a comparison can be done in the future.

The Wind Turbine Generators re-sitting has been done through consideration of the wind potential locations at the Wind Farm. Thus placing the Wind Turbine Generators requires a detailed site investigation and experience in the field, this can also be done in the future.

The Wind Atlas is a parameter that can be used for an assessment of wind resource at a site. The Wind Atlas for the Wind Farm under consideration has been done including for future expansion if that might be included in the plan for further expanding the site. As a future work Wind Atlas Generation for windy areas can be done.

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ANNEX A

Table A.1 Histogram bins for the all the 12 sector

sector / U (m/s)	1	2	3	4	5	6	7	8	9	10	11	12	All
1.0	77	16	1	3	25	67	47	32	10	4	8	40	5
2.0	126	47	2	7	58	144	146	81	28	10	22	101	13
3.0	141	50	4	22	177	256	241	135	61	25	51	113	27
4.0	154	72	8	52	278	228	246	239	95	60	102	149	47
5.0	84	84	15	73	253	180	185	222	144	129	151	121	66
6.0	98	70	25	108	112	92	77	163	181	155	186	102	79
7.0	61	86	40	145	60	13	42	85	179	190	164	101	93
8.0	47	151	70	151	23	14	11	19	138	157	148	86	102
9.0	43	142	100	139	8	3	6	22	89	142	107	85	108
10.0	49	115	122	114	4	1	0	1	45	88	41	35	101
11.0	38	71	136	80	0	1	0	0	19	33	15	30	91
12.0	25	39	140	56	1	0	0	0	7	6	3	16	84
13.0	12	25	143	33	1	0	0	0	3	0	1	5	80
14.0	22	12	113	12	0	0	0	0	1	0	0	11	61
15.0	5	10	57	3	0	0	0	0	0	0	0	3	30
16.0	2	4	19	1	0	0	0	0	0	0	0	0	10
17.0	8	2	5	1	0	0	0	0	0	0	0	0	3
18.0	4	2	1	0	0	0	0	0	0	0	0	0	0
19.0	2	0	0	0	0	0	0	0	0	0	0	0	0
20.0	0	1	0	0	0	0	0	0	0	0	0	0	0
21.0	0	1	0	0	0	0	0	0	0	0	0	0	0

Table A.2 Net Annual Energy production before re-sitting

Turbine	Location [m]	Sector 3 Net AEP [MWh]	All sector Net AEP [MWh]	RIX [%]	DR [%]	Wake loss [%]
N1	(530089.7,959170.0)	4218.158	7039.337	3.6	2.8	0.41
N2	(529977.2,958996.4)	4383.336	6988.923	3.5	2.7	4.06
N3	(530046.6,958835.3)	4650.924	7192.520	3.4	2.6	0.65
N4	(530324.5,958099.1)	4463.189	6713.778	3.4	2.6	2.07
N5	(529930.3,958172.4)	4466.307	6756.675	3.4	2.6	2.4
N6	(530039.1,957815.2)	4225.217	6484.029	3.5	2.6	5.6
N7	(529996.0,957594.5)	4447.527	6432.390	3.2	2.4	4.33
N8	(530010.1,957300.6)	4625.483	7022.401	3.2	2.4	3.08
N9	(530130.4,957029.1)	4352.586	6237.243	3.3	2.4	5.93
N10	(529947.6,956700.0)	4427.476	6544.302	3.0	2.2	2.28
N11	(530020.8,956407.4)	4191.896	6182.040	3.3	2.4	3.82
N12	(528927.7,955660.7)	4350.932	6252.936	3.0	2.2	4.04
N13	(528922.2,955966.2)	4187.935	5851.881	2.9	2.0	9.01
N14	(529034.9,955314.1)	4216.504	6340.332	3.0	2.1	7.34
N15	(528777.5,954451.2)	3877.691	5493.878	2.8	1.9	10.91
N16	(528574.9,958299.6)	3981.240	5510.652	2.6	1.8	9.72
N17	(529087.1,954770.4)	3765.337	6915.142	2.7	1.9	6.58
N18	(529062.6,954498.1)	3754.439	6808.364	2.5	1.7	6.59
N19	(529004.5,954265.0)	3674.222	6536.953	2.4	1.6	8.37
N20	(528751.2,953914.8)	3595.730	5851.393	2.3	1.5	11.12
N21	(528555.0,954050.2)	3292.904	6175.985	2.3	1.5	16.34

N22	(529037.6,955016.5)	3448.212	6053.565	2.2	1.3	16.2
N23	(528809.9,953586.0)	3609.523	6245.012	2.2	1.3	7.13
N24	(528647.6,953257.0)	3553.373	5852.286	2.2	1.3	7.1
N25	(528283.9,952842.3)	3199.734	5874.481	2.0	1.2	9.78
N26	(527858.4,952623.9)	3163.759	5983.634	1.3	0.5	7.51
N27	(528166.1,953192.2)	3162.379	5675.509	1.5	0.6	8.62
N28	(528356.4,953591.9)	2986.194	5205.201	1.7	0.8	13.94
N29	(527557.1,955343.1)	3095.255	5195.381	1.6	0.8	13.26
N30	(526338.6,955336.0)	2803.990	4894.804	1.2	0.4	19.27
N31	(527564.5,952620.8)	3267.901	5440.770	1.1	0.3	13.21
N32	(527314.2,951994.7)	3713.080	6286.462	0.8	0.0	5.08
N33	(527381.4,951851.8)	3821.549	6454.595	0.7	-0.1	3.96
N34	(527394.3,951667.6)	3873.845	6318.284	0.7	-0.1	3.07
N35	(526903.7,950908.8)	3983.281	6135.856	0.7	-0.1	2.49
N36	(530093.9,956060.1)	4530.901	6526.301	3.1	2.3	1.55
N37	(530185.3,955785.9)	4288.925	6104.118	3.2	2.3	3.75
N38	(530249.4,955600.4)	4618.154	6849.573	2.8	1.9	2.71
N39	(530249.4,955314.0)	3949.741	5966.165	2.8	2.0	7.35
N40	(530202.7,955038.5)	4207.174	6392.724	2.7	1.9	3.35
N41	(530018.5,954565.6)	3999.624	6121.177	2.6	1.8	9.89
N42	(529853.2,954296.8)	3607.289	5659.996	2.7	1.9	12.26
N43	(529834.1,954061.7)	3562.189	5540.572	2.4	1.6	12.03
N44	(530136.1,954077.8)	4293.534	6620.309	2.7	1.9	4.69
N45	(530299.2,954514.9)	3923.899	6364.904	2.7	1.9	9.01

N46	(530485.2,954723.3)	3930.552	6018.687	2.6	1.8	2.87
N47	(528890.9,956520.6)	4251.843	5747.845	3.4	2.6	6.46
N48	(528889.4,957075.2)	4198.140	5919.923	3.2	2.4	6.78
N49	(528046.2,957815.2)	4075.714	5710.260	3.3	2.5	8.84
N50	(528430.1,958016.4)	4129.841	5760.910	3.3	2.4	5.11
N51	(527672.2,957576.0)	4198.371	5785.263	3.4	2.6	10.32
N52	(527175.8,957297.0)	4190.472	5747.846	3.4	2.6	8.56
N53	(527473.2,956878.4)	4006.886	5716.705	3.3	2.5	8.74
N54	(526291.1,956133.2)	4063.807	5876.795	3.2	2.4	8.2
N55	(526057.1,955818.4)	4119.546	6002.026	3.0	2.2	5.45
N56	(527519.0,956009.2)	4028.646	5778.535	2.9	2.1	7.71
N57	(527007.2,956768.5)	4180.418	5963.217	2.3	1.5	7.15
N58	(527480.9,956447.1)	3791.500	5642.967	2.2	1.3	8.95
N59	(526129.2,955512.3)	3573.753	5641.689	1.1	0.3	6.22
N60	(527506.3,955666.5)	3605.057	5250.282	0.9	0.1	7.06
N61	(527693.6,957175.8)	3412.634	5533.444	0.8	0.0	7.84
N62	(527918.7,957493.9)	3253.423	5340.060	0.7	-0.1	9.68
N63	(529270.1,952906.7)	3175.473	5498.337	0.8	-0.1	9.52
N64	(529745.9,956922.9)	3191.931	5311.642	0.7	-0.2	12.52
N65	(530088.4,958445.7)	3360.991	5394.541	0.7	-0.1	10.81
N66	(528451.6,950698.7)	3362.018	5417.409	0.7	-0.2	10.54
N67	(526684.7,951424.2)	3477.705	5733.255	0.6	-0.2	9.68
N68	(526196.4,950968.2)	3433.134	5426.905	0.6	-0.2	8.28
N69	(527150.4,951324.8)	2989.701	5039.308	0.6	-0.2	7.48

N70	(528594.7,951836.8)	3021.214	5245.228	0.6	-0.2	8.46
N71	(528485.0,951397.9)	2934.579	5269.341	0.7	-0.1	9.87
N72	(523667.6,948012.1)	3624.715	5579.251	0.8	0.0	1.17
N73	(523267.0,947627.2)	3441.816	5162.394	0.8	0.0	6.34
N74	(520895.4,946021.8)	3695.458	5409.038	0.7	-0.1	1.72
N75	(518159.0,945896.9)	3828.477	5403.999	1.0	0.1	1.91
N76	(518068.1,946248.9)	3680.417	5223.178	0.8	0.0	5.31
N77	(523083.2,947169.4)	3499.655	5424.378	0.8	0.0	7.25
N78	(520520.7,945022.7)	3209.383	5092.176	0.9	0.0	8.37
S1	(520376.9,942277.6)	2975.620	5339.618	0.5	-0.3	16.9
S2	(520495.5,942490.9)	3492.031	6224.161	0.8	-0.1	12.38
S3	(520563.6,942152.1)	3348.468	5736.251	0.6	-0.3	10.68
S4	(520834.3,942392.8)	4210.930	6541.204	0.8	0.0	3.51
S5	(520774, 942536)	4127.193	6876.932	0.8	0.0	1.92
S6	(520803.7,942870.3)	4112.058	6985.738	0.9	0.1	1.0
S7	(520554.8,942811.0)	4282.636	7075.080	0.9	0.1	0.76
S8	(520639.4,943086.2)	4344.075	6882.170	0.9	0.1	2.66
S9	(520727.9,943279.6)	4304.850	6754.656	0.9	0.1	1.02
S10	(520614.8,943441.0)	4521.599	6742.167	1.0	0.1	0.78
S11	(520542.9,943688.2)	4292.402	6412.168	0.8	0.0	2.05
S12	(520522.9,944008.3)	4556.188	6638.531	0.9	0.1	1.02
S13	(520458.7,944164.8)	4496.631	6806.031	1.0	0.1	0.74
S14	(517638.5,944447.0)	3318.106	6386.646	0.8	-0.1	2.96
S15	(517959.1,944955.2)	4191.769	7702.559	1.3	0.4	2.06

S16	(518020.9,945238.8)	3973.505	7644.822	1.4	0.5	2.62
S17	(518148.2,945466.5)	3803.137	7149.428	0.7	-0.2	1.47
S18	(516805.6,945829.5)	4220.787	7067.756	0.7	-0.1	0.94
S19	(516737.5,945668.0)	4396.984	7068.341	0.8	0.0	2.65
S20	(516784.9,945419.1)	4058.580	6452.005	0.7	-0.1	4.18
S21	(516761.8,945211.1)	4074.781	6352.630	0.7	-0.1	2.96
S22	(516021.5,944405.9)	4339.812	7159.187	1.1	0.2	2.66
S23	(516049.9,944233.6)	3536.934	5821.734	0.8	0.0	4.53
S24	(516132.9,943996.5)	3288.158	5678.276	0.4	-0.4	3.48
total		393017.131	621657.850			

Table A.3 Summarized site description before repositioning WTG

Site description	X-location [m]	Y-location [m]	Elev. [m]	RIX [%]	DR [%]	Height. [m]	U [m/s]	Gross [GWh]	Net AEP [GWh]	Loss [%]
Reference site	527043.4	952332.1	2067.7	0.8	0.0	70.0	8.76	-	-	
N1	530089.7	959170.0	2192.4	3.6	2.8	70.0	9.47	7.068	7.039	0.41
N2	529977.2	958996.4	2204.0	3.5	2.7	70.0	9.67	7.285	6.989	4.06
N3	530046.6	958835.3	2192.8	3.4	2.6	70.0	9.64	7.239	7.193	0.65
N4	530324.5	958099.1	2140.4	3.4	2.6	70.0	9.29	6.856	6.714	2.07
N5	529930.3	958172.4	2171.7	3.4	2.6	70.0	9.35	6.923	6.757	2.4
N6	529785.3	957824.7	2168.8	3.5	2.6	70.0	9.30	6.868	6.484	5.6
N7	529658.7	957496.3	2163.6	3.2	2.4	70.0	9.17	6.723	6.432	4.33
N8	530010.1	957300.6	2155.5	3.2	2.4	70.0	9.64	7.246	7.022	3.08
N9	529659.7	957253.7	2155.7	3.3	2.4	70.0	9.09	6.630	6.237	5.93

N10	529577.4	956550.4	2154.8	3.0	2.2	70.0	9.15	6.697	6.544	2.28
N11	529458.5	956307.8	2149.5	3.3	2.4	70.0	8.92	6.428	6.182	3.82
N12	528927.7	955660.7	2142.9	3.0	2.2	70.0	9.00	6.516	6.253	4.04
N13	528684.4	955368.5	2133.2	2.9	2.0	70.0	8.93	6.431	5.852	9.01
N14	529034.9	955314.1	2140.4	3.0	2.1	70.0	9.27	6.842	6.340	7.34
N15	528536.9	954972.7	2113.3	2.8	1.9	70.0	8.71	6.167	5.494	10.91
N16	528324.1	954609.9	2101.7	2.6	1.8	70.0	8.66	6.104	5.511	9.72
N17	529087.1	954770.4	2161.6	2.7	1.9	70.0	9.75	7.402	6.915	6.58
N18	529062.6	954498.1	2156.7	2.5	1.7	70.0	9.64	7.289	6.808	6.59
N19	529004.5	954265.0	2146.6	2.4	1.6	70.0	9.51	7.134	6.537	8.37
N20	529079.0	954030.9	2106.4	2.3	1.5	70.0	9.06	6.584	5.851	11.12
N21	528555.0	954050.2	2164.0	2.3	1.5	70.0	9.72	7.382	6.176	16.34
N22	528800.7	954023.4	2152.0	2.2	1.3	70.0	9.58	7.223	6.054	16.2
N23	528809.9	953586.0	2100.1	2.2	1.3	70.0	9.17	6.725	6.245	7.13
N24	528647.6	953257.0	2073.7	2.2	1.3	70.0	8.83	6.300	5.852	7.1
N25	528093.3	953467.7	2126.2	2.0	1.2	70.0	9.00	6.511	5.874	9.78
N26	527858.4	952623.9	2081.4	1.3	0.5	70.0	8.97	6.469	5.984	7.51
N27	527678.3	952843.8	2093.6	1.5	0.6	70.0	8.77	6.211	5.676	8.62
N28	527633.2	953134.7	2098.1	1.7	0.8	70.0	8.65	6.049	5.205	13.94
N29	527445.9	953195.3	2093.4	1.6	0.8	70.0	8.60	5.990	5.195	13.26
N30	527326.0	952904.5	2086.8	1.2	0.4	70.0	8.66	6.063	4.895	19.27
N31	527564.5	952620.8	2083.9	1.1	0.3	70.0	8.81	6.269	5.441	13.21
N32	527314.2	951994.7	2058.4	0.8	0.0	70.0	9.09	6.623	6.286	5.08
N33	527381.4	951851.8	2047.4	0.7	-0.1	70.0	9.16	6.720	6.455	3.96

N34	527394.3	951667.6	2022.4	0.7	-0.1	70.0	9.00	6.518	6.318	3.07
N35	526903.7	950908.8	1984.0	0.7	-0.1	70.0	8.81	6.293	6.136	2.49
N36	529938.3	955818.3	2123.2	3.1	2.3	70.0	9.10	6.629	6.526	1.55
N37	529910.8	955575.6	2110.9	3.2	2.3	70.0	8.86	6.342	6.104	3.75
N38	530443.4	955551.4	2094.4	2.8	1.9	70.0	9.46	7.040	6.850	2.71
N39	529975.3	955342.2	2103.3	2.8	2.0	70.0	8.94	6.439	5.966	7.35
N40	529984.8	955044.3	2097.3	2.7	1.9	70.0	9.08	6.614	6.393	3.35
N41	530018.5	954565.6	2076.9	2.6	1.8	70.0	9.23	6.793	6.121	9.89
N42	529853.2	954296.8	2058.4	2.7	1.9	70.0	8.95	6.451	5.660	12.26
N43	529834.1	954061.7	2039.9	2.4	1.6	70.0	8.84	6.298	5.541	12.03
N44	530136.1	954077.8	2030.8	2.7	1.9	70.0	9.37	6.946	6.620	4.69
N45	530299.2	954514.9	2055.2	2.7	1.9	70.0	9.40	6.995	6.365	9.01
N46	530485.2	954723.3	2034.9	2.6	1.8	70.0	8.76	6.197	6.019	2.87
N47	528890.9	956520.6	2143.0	3.4	2.6	70.0	8.69	6.145	5.748	6.46
N48	528948.1	956782.0	2155.8	3.2	2.4	70.0	8.86	6.350	5.920	6.78
N49	528984.1	957195.6	2162.2	3.3	2.5	70.0	8.79	6.264	5.710	8.84
N50	528524.1	957327.4	2180.0	3.3	2.4	70.0	8.63	6.071	5.761	5.11
N51	528281.3	956591.5	2169.6	3.4	2.6	70.0	8.95	6.451	5.785	10.32
N52	528029.8	956614.1	2176.2	3.4	2.6	70.0	8.81	6.286	5.748	8.56
N53	528265.3	956156.5	2147.6	3.3	2.5	70.0	8.79	6.264	5.717	8.74
N54	527779.4	955745.8	2144.3	3.2	2.4	70.0	8.90	6.402	5.877	8.2
N55	527813.8	955289.3	2129.2	3.0	2.2	70.0	8.86	6.348	6.002	5.45
N56	527772.9	955066.4	2121.1	2.9	2.1	70.0	8.79	6.261	5.779	7.71
N57	527455.0	954520.9	2098.8	2.3	1.5	70.0	8.92	6.422	5.963	7.15

N58	527490.3	954196.8	2079.9	2.2	1.3	70.0	8.73	6.197	5.643	8.95
N59	526422.1	953525.3	2049.8	1.1	0.3	70.0	8.60	6.016	5.642	6.22
N60	526352.6	953063.8	2023.7	0.9	0.1	70.0	8.31	5.649	5.250	7.06
N61	526390.5	952684.0	2050.2	0.8	0.0	70.0	8.60	6.004	5.533	7.84
N62	526283.9	952452.6	2046.8	0.7	-0.1	70.0	8.54	5.912	5.340	9.68
N63	526775.1	952258.8	2061.7	0.8	-0.1	70.0	8.66	6.077	5.498	9.52
N64	526645.5	952073.0	2056.3	0.7	-0.2	70.0	8.66	6.072	5.312	12.52
N65	526556.8	951862.4	2050.8	0.7	-0.1	70.0	8.64	6.049	5.395	10.81
N66	526213.4	951475.5	2038.8	0.7	-0.2	70.0	8.65	6.056	5.417	10.54
N67	526684.7	951424.2	2037.6	0.6	-0.2	70.0	8.87	6.348	5.733	9.68
N68	526196.4	950968.2	1999.9	0.6	-0.2	70.0	8.53	5.917	5.427	8.28
N69	525106.4	950671.6	1990.9	0.6	-0.2	70.0	8.21	5.446	5.039	7.48
N70	524534.2	950364.8	1992.5	0.6	-0.2	70.0	8.41	5.730	5.245	8.46
N71	524074.3	950165.1	1987.4	0.7	-0.1	70.0	8.50	5.846	5.269	9.87
N72	523667.6	948012.1	1894.3	0.8	0.0	70.0	8.32	5.645	5.579	1.17
N73	523267.0	947627.2	1875.9	0.8	0.0	70.0	8.22	5.512	5.162	6.34
N74	523943.9	947705.8	1881.7	0.7	-0.1	70.0	8.21	5.503	5.409	1.72
N75	523995.6	947143.9	1865.5	1.0	0.1	70.0	8.21	5.509	5.404	1.91
N76	523511.1	947185.9	1873.6	0.8	0.0	70.0	8.22	5.516	5.223	5.31
N77	523083.2	947169.4	1884.2	0.8	0.0	70.0	8.49	5.848	5.424	7.25
N78	523087.2	946794.7	1863.0	0.9	0.0	70.0	8.26	5.557	5.092	8.37
S1	520288.0	942168.1	1806.1	0.5	-0.3	70.0	8.93	6.425	5.340	16.9
S2	520384.9	942385.6	1845.9	0.8	-0.1	70.0	9.49	7.104	6.224	12.38
S3	520563.6	942152.1	1796.3	0.6	-0.3	70.0	8.92	6.422	5.736	10.68

S4	520774.3	942358.7	1823.2	0.8	0.0	70.0	9.22	6.779	6.541	3.51
S5	520774.0	942536.0	1847.9	0.8	0.0	70.0	9.41	7.012	6.877	1.92
S6	520687.9	942713.6	1857.3	0.9	0.1	70.0	9.45	7.056	6.986	1.0
S7	520687.9	942917.4	1862.2	0.9	0.1	70.0	9.52	7.130	7.075	0.76
S8	520639.4	943086.2	1858.8	0.9	0.1	70.0	9.47	7.070	6.882	2.66
S9	520727.9	943279.6	1855.6	0.9	0.1	70.0	9.26	6.824	6.755	1.02
S10	520614.8	943441.0	1848.8	1.0	0.1	70.0	9.23	6.795	6.742	0.78
S11	520273.9	943638.4	1855.0	0.8	0.0	70.0	9.02	6.547	6.412	2.05
S12	520522.9	944008.3	1876.6	0.9	0.1	70.0	9.17	6.707	6.639	1.02
S13	520458.7	944164.8	1887.2	1.0	0.1	70.0	9.30	6.857	6.806	0.74
S14	517705.6	944583.1	1897.2	0.8	-0.1	70.0	9.05	6.581	6.387	2.96
S15	517959.1	944955.2	1951.3	1.3	0.4	70.0	10.19	7.864	7.703	2.06
S16	518020.9	945238.8	1964.0	1.4	0.5	70.0	10.16	7.850	7.645	2.62
S17	518207.1	945516.4	1956.8	0.7	-0.2	70.0	9.61	7.256	7.149	1.47
S18	516805.6	945829.5	1935.4	0.7	-0.1	70.0	9.53	7.135	7.068	0.94
S19	516657.8	945564.4	1932.9	0.8	0.0	70.0	9.65	7.261	7.068	2.65
S20	516572.1	945353.4	1908.5	0.7	-0.1	70.0	9.19	6.734	6.452	4.18
S21	516761.8	945211.1	1891.0	0.7	-0.1	70.0	9.02	6.546	6.353	2.96
S22	516021.5	944405.9	1873.4	1.1	0.2	70.0	9.73	7.355	7.159	2.66
S23	515947.1	944187.0	1830.4	0.8	0.0	70.0	8.68	6.098	5.822	4.53
S24	516018.5	944001.8	1806.0	0.4	-0.4	70.0	8.51	5.883	5.678	3.48

Table A.4 All sector Summary after repositioning

Site	Location [m]	Height [m a.g.l.]	A [m/s]	k	U [m/s]	Pw [W/m²]	RIX [%]	DRIX [%]
N1	(530089.7,959170.0)	70	10.6	2.89	9.47	578	3.2	2.1
N2	(530062.6,959007.9)	70	10.8	2.85	9.61	610	2.8	1.7
N3	(530046.6,958835.3)	70	10.8	2.81	9.64	621	2.3	1.3
N4	(530070.0,958421.2)	70	10.7	2.77	9.55	609	2.2	1.1
N5	(530147.9,958199.2)	70	10.5	2.79	9.38	573	2.7	1.7
N6	(529923.0,957808.8)	70	10.6	2.81	9.41	576	1.9	0.8
N7	(529996.0,957594.5)	70	10.7	2.81	9.52	597	2.4	1.3
N8	(530015.0,957120.9)	70	10.8	2.81	9.60	613	2.7	1.7
N9	(529992.5,956933.4)	70	10.7	2.79	9.53	602	3.0	1.9
N10	(530013.2,956681.9)	70	10.8	2.75	9.61	622	3.3	2.2
N11	(530023.9,956471.1)	70	10.8	2.75	9.59	619	3.2	2.2
N12	(528927.7,955660.7)	70	10.1	2.80	9.00	505	3.5	2.4
N13	(528922.2,955966.2)	70	10.0	2.82	8.86	481	3.4	2.3
N14	(529106.4,955130.0)	70	10.9	2.93	9.71	619	3.5	2.4
N15	(528846.2,954464.1)	70	10.8	3.03	9.68	602	3.1	2.0
N16	(528509.9,959624.2)	70	11.2	2.87	9.94	672	0.5	-0.6
N17	(529027.1,954790.4)	70	11.0	2.97	9.80	631	3.3	2.2
N18	(528952.1,954627.2)	70	10.9	2.99	9.76	621	3.5	2.4
N19	(528780.1,954274.4)	70	10.8	3.05	9.65	593	3.2	2.2
N20	(528705.1,954098.1)	70	10.8	3.06	9.69	601	3.0	1.9
N21	(528625.8,953882.0)	70	10.9	3.06	9.75	612	2.8	1.7
N22	(529066.8,954953.6)	70	11.0	2.96	9.81	636	3.4	2.3

N23	(528809.9,953586.0)	70	10.3	2.96	9.17	519	2.4	1.4
N24	(528647.6,953257.0)	70	9.9	2.95	8.83	464	2.6	1.6
N25	(528283.9,952842.3)	70	10.4	2.99	9.24	528	2.3	1.2
N26	(527936.4,952589.5)	70	10.0	3.08	8.96	473	1.5	0.4
N27	(528290.6,953228.7)	70	10.5	3.05	9.41	550	2.5	1.4
N28	(528517.9,953632.4)	70	10.5	3.06	9.41	550	2.7	1.6
N29	(527557.1,955343.1)	70	10.1	2.79	9.02	510	3.7	2.6
N30	(525996.9,955300.1)	70	10.5	3.01	9.39	551	1.7	0.7
N31	(527741.2,952319.7)	70	10.1	3.03	8.99	482	1.3	0.3
N32	(527314.2,951994.7)	70	10.2	2.96	9.09	504	0.9	-0.1
N33	(527381.4,951851.8)	70	10.3	2.95	9.16	518	0.7	-0.3
N34	(527394.3,951667.6)	70	10.1	2.90	9.00	495	0.7	-0.4
N35	(528751.9,960801.3)	70	12.0	2.73	10.68	860	3.6	2.5
N36	(530050.1,956215.0)	70	10.6	2.76	9.41	583	3.4	2.4
N37	(530185.3,955785.9)	70	10.6	2.78	9.45	588	3.6	2.5
N38	(530249.4,955600.4)	70	10.7	2.81	9.55	603	3.2	2.2
N39	(530337.7,955341.7)	70	10.7	2.83	9.53	597	3.0	1.9
N40	(530278.4,955063.6)	70	10.6	2.85	9.42	575	3.1	2.0
N41	(530210.1,954544.0)	70	10.6	2.89	9.43	572	3.7	2.7
N42	(529941.8,958007.1)	70	10.5	2.81	9.37	570	1.8	0.8
N43	(530078.4,955999.6)	70	10.5	2.76	9.36	575	3.6	2.5
N44	(530136.1,954077.8)	70	10.5	2.88	9.37	562	3.7	2.6
N45	(530205.5,954311.5)	70	10.7	2.90	9.57	597	3.8	2.8

N46	(530205.5,954767.3)	70	10.5	2.87	9.35	559	3.5	2.4
N47	(528890.9,956520.6)	70	9.8	2.74	8.69	463	2.9	1.8
N48	(528889.4,957075.2)	70	10.0	2.74	8.92	498	2.2	1.2
N49	(527906.2,957901.6)	70	10.7	2.96	9.55	586	1.2	0.2
N50	(528584.9,959817.9)	70	11.2	2.90	10.00	680	1.3	0.2
N51	(527637.4,957546.0)	70	11.0	3.07	9.81	622	2.3	1.3
N52	(527337.4,957194.2)	70	11.3	3.06	10.12	684	3.1	2.0
N53	(527194.1,957024.4)	70	11.2	3.07	10.02	662	2.9	1.8
N54	(526277.6,956090.9)	70	11.1	3.06	9.88	636	3.9	2.9
N55	(526185.9,955885.6)	70	11.2	3.04	10.05	672	3.7	2.6
N56	(528242.2,958478.6)	70	10.5	2.78	9.33	566	0.5	-0.6
N57	(527057.8,956818.9)	70	11.0	3.08	9.81	622	2.9	1.8
N58	(526937.6,956580.6)	70	10.5	3.05	9.42	553	2.8	1.7
N59	(526133.2,955671.8)	70	10.9	3.01	9.71	611	2.7	1.7
N60	(527562.1,956353.5)	70	10.6	2.79	9.47	590	3.2	2.2
N61	(527475.7,957355.0)	70	11.3	3.06	10.09	678	2.8	1.7
N62	(527787.1,957721.2)	70	10.9	3.03	9.76	616	1.7	0.6
N63	(528742.7,960352.4)	70	11.7	2.85	10.40	773	3.3	2.3
N64	(530007.5,957368.3)	70	10.8	2.81	9.62	617	2.5	1.5
N65	(529984.9,958610.2)	70	10.8	2.78	9.59	615	2.1	1.0
N66	(528748.2,960583.8)	70	11.9	2.76	10.56	825	3.6	2.5
N67	(528240.1,953001.9)	70	10.5	3.05	9.38	545	2.5	1.5
N68	(528393.2,953455.9)	70	10.4	3.08	9.32	532	2.6	1.5

N69	(528571.3,951580.7)	70	10.2	2.83	9.12	523	0.8	-0.3
N70	(528594.7,951836.8)	70	10.5	2.88	9.35	559	1.6	0.5
N71	(528485.0,951397.9)	70	10.1	2.82	9.03	510	0.7	-0.4
N72	(528473.6,959408.1)	70	11.0	2.84	9.81	651	0.3	-0.8
N73	(528391.1,959130.4)	70	10.9	2.83	9.67	624	0.3	-0.8
N74	(516895.7,946026.9)	70	10.4	2.94	9.24	533	0.8	-0.2
N75	(518195.2,945635.1)	70	10.6	3.00	9.50	572	0.7	-0.4
N76	(518115.7,946208.0)	70	10.3	2.84	9.20	537	0.3	-0.8
N77	(528697.2,960129.4)	70	11.3	2.90	10.09	697	2.6	1.5
N78	(520896.1,942693.8)	70	10.6	2.92	9.43	568	1.0	-0.1
S1	(520376.9,942277.6)	70	10.6	2.97	9.47	569	1.0	-0.1
S2	(520560.7,942695.2)	70	10.7	2.92	9.54	588	1.2	0.2
S3	(520563.6,942152.1)	70	10.0	2.91	8.92	482	0.6	-0.4
S4	(520871.3,942536.8)	70	10.6	2.89	9.42	569	1.0	0.0
S5	(520515.9,942462.4)	70	10.6	2.97	9.42	561	1.1	0.0
S6	(520945.6,942893.1)	70	10.6	2.92	9.46	573	1.2	0.2
S7	(520544.2,942863.9)	70	10.7	2.89	9.54	591	1.4	0.4
S8	(520639.4,943086.2)	70	10.6	2.85	9.47	584	1.3	0.2
S9	(520615.7,943316.5)	70	10.5	2.82	9.33	562	1.4	0.3
S10	(520614.8,943441.0)	70	10.4	2.78	9.23	549	1.4	0.3
S11	(520676.2,943882.8)	70	10.5	2.81	9.34	564	1.1	0.1
S12	(520522.9,944008.3)	70	10.3	2.78	9.17	537	1.2	0.1
S13	(520458.7,944164.8)	70	10.4	2.81	9.30	556	1.3	0.2

S14	(517608.3,944381.3)	70	10.6	3.04	9.43	555	1.9	0.9
S15	(517958.4,945035.2)	70	11.6	3.01	10.32	733	2.6	1.5
S16	(518020.9,945238.8)	70	11.4	3.02	10.16	696	2.7	1.6
S17	(518110.3,945417.9)	70	11.1	3.04	9.94	650	1.8	0.7
S18	(516725.7,945828.6)	70	10.7	2.88	9.52	590	1.3	0.2
S19	(516705.3,945663.5)	70	11.0	2.89	9.78	637	1.6	0.5
S20	(516722.8,945491.1)	70	10.8	2.86	9.63	611	1.5	0.4
S21	(517874.0,944882.5)	70	11.2	3.00	9.99	664	1.7	0.6
S22	(516021.5,944405.9)	70	10.9	2.88	9.73	629	2.1	1.0
S23	(516049.9,944233.6)	70	10.9	2.87	9.72	628	1.9	0.9
S24	(517484.1,944157.3)	70	10.8	2.97	9.68	609	2.0	0.9

Table A.5 Sector 3 wind summary before re-sitting WTGs

Turbine	A [m/s]	k	Freq. [%]	U [m/s]	MWh (free)	MWh (park)	Eff. [%]
N1	12.6	4.66	42.56	11.55	4218.158	4218.158	100.0
N2	13.0	4.66	44.19	11.87	4512.699	4383.336	97.13
N3	13.0	4.66	45.50	11.88	4650.924	4650.924	100.0
N4	12.5	4.67	45.56	11.43	4463.189	4463.189	100.0
N5	12.6	4.66	45.20	11.52	4466.307	4466.307	100.0
N6	12.6	4.66	45.67	11.48	4493.011	4225.217	94.04
N7	12.4	4.67	46.92	11.35	4555.146	4447.527	97.64
N8	13.0	4.65	45.18	11.90	4625.483	4625.483	100.0
N9	12.3	4.67	46.34	11.23	4439.870	4352.586	98.03

N10	12.3	4.67	46.02	11.26	4427.476	4427.476	100.0
N11	12.0	4.67	45.31	10.93	4192.804	4191.896	99.98
N12	12.1	4.67	46.40	11.08	4371.402	4350.932	99.53
N13	12.0	4.67	47.10	11.02	4406.460	4187.935	95.04
N14	12.5	4.66	45.05	11.42	4406.161	4216.504	95.7
N15	11.8	4.67	47.51	10.77	4303.766	3877.691	90.1
N16	11.7	4.67	47.53	10.71	4267.890	3981.240	93.28
N17	12.8	4.65	39.53	11.74	3989.889	3765.337	94.37
N18	12.7	4.66	39.30	11.57	3902.474	3754.439	96.21
N19	12.5	4.66	39.48	11.40	3852.964	3674.222	95.36
N20	12.0	4.67	42.05	10.95	3896.999	3595.730	92.27
N21	12.7	4.65	37.89	11.58	3767.630	3292.904	87.4
N22	12.5	4.66	38.58	11.44	3781.421	3448.212	91.19
N23	12.1	4.67	41.24	11.06	3876.626	3609.523	93.11
N24	11.7	4.67	41.91	10.66	3737.127	3553.373	95.08
N25	11.7	4.67	39.61	10.73	3570.597	3199.734	89.61
N26	11.6	4.66	37.46	10.63	3328.097	3163.759	95.06
N27	11.4	4.67	39.63	10.46	3435.998	3162.379	92.04
N28	11.3	4.68	41.18	10.36	3516.221	2986.194	84.93
N29	11.3	4.68	41.66	10.33	3538.343	3095.255	87.48
N30	11.4	4.68	41.41	10.40	3558.500	2803.990	78.8
N31	11.5	4.67	39.61	10.53	3470.308	3267.901	94.17
N32	12.0	4.66	40.80	10.97	3794.103	3713.080	97.86
N33	12.1	4.66	40.97	11.09	3861.945	3821.549	98.95

N34	12.0	4.66	42.08	10.96	3902.774	3873.845	99.26
N35	11.8	4.65	43.86	10.82	3995.336	3983.281	99.7
N36	12.3	4.68	47.30	11.22	4530.901	4530.901	100.0
N37	11.9	4.68	46.65	10.88	4288.925	4288.925	100.0
N38	12.7	4.67	46.18	11.64	4618.154	4618.154	100.0
N39	12.0	4.68	46.25	10.97	4299.141	3949.741	91.87
N40	12.1	4.68	45.20	11.11	4276.172	4207.174	98.39
N41	12.3	4.68	44.38	11.26	4271.096	3999.624	93.64
N42	11.9	4.68	44.65	10.90	4114.423	3607.289	87.67
N43	11.7	4.68	42.66	10.66	3805.316	3562.189	93.61
N44	12.4	4.68	44.02	11.39	4293.534	4293.534	100.0
N45	12.5	4.67	43.01	11.42	4210.861	3923.899	93.19
N46	11.6	4.69	44.40	10.60	3930.552	3930.552	100.0
N47	11.8	4.65	48.52	10.77	4393.060	4251.843	96.79
N48	12.0	4.67	48.39	10.98	4505.285	4198.140	93.18
N49	11.9	4.67	48.42	10.90	4459.281	4075.714	91.4
N50	11.7	4.67	48.32	10.69	4327.496	4129.841	95.43
N51	12.1	4.63	48.67	11.10	4590.731	4198.371	91.45
N52	11.9	4.67	48.39	10.91	4463.431	4190.472	93.88
N53	11.9	4.67	48.22	10.89	4438.540	4006.886	90.27
N54	12.1	4.67	47.77	11.03	4473.247	4063.807	90.85
N55	11.9	4.67	46.57	10.92	4302.179	4119.546	95.75
N56	11.8	4.67	47.02	10.84	4297.928	4028.646	93.73
N57	12.1	4.67	47.46	11.04	4451.142	4180.418	93.92

N58	11.8	4.66	45.83	10.77	4152.489	3791.500	91.31
N59	11.5	4.67	43.88	10.52	3833.622	3573.753	93.22
N60	11.2	4.67	45.95	10.24	3842.076	3605.057	93.83
N61	11.4	4.67	43.14	10.44	3724.897	3412.634	91.62
N62	11.3	4.67	42.26	10.31	3578.854	3253.423	90.91
N63	11.4	4.67	41.60	10.45	3600.050	3175.473	88.21
N64	11.4	4.67	41.79	10.45	3615.845	3191.931	88.28
N65	11.4	4.67	41.82	10.42	3603.405	3360.991	93.27
N66	11.4	4.68	42.85	10.44	3704.875	3362.018	90.75
N67	11.8	4.67	43.17	10.77	3908.723	3477.705	88.97
N68	11.4	4.67	43.60	10.38	3734.255	3433.134	91.94
N69	10.8	4.69	42.48	9.84	3311.390	2989.701	90.29
N70	11.0	4.69	42.21	10.09	3445.758	3021.214	87.68
N71	11.1	4.69	42.10	10.18	3488.738	2934.579	84.12
N72	11.1	4.68	44.27	10.14	3644.036	3624.715	99.47
N73	11.0	4.68	45.29	10.05	3667.046	3441.816	93.86
N74	11.0	4.68	45.76	10.04	3701.188	3695.458	99.85
N75	11.0	4.69	47.09	10.07	3828.477	3828.477	100.0
N76	11.0	4.69	46.01	10.05	3723.400	3680.417	98.85
N77	11.2	4.68	43.31	10.28	3646.373	3499.655	95.98
N78	11.0	4.68	44.45	10.06	3604.524	3209.383	89.04
S1	11.7	4.64	38.34	10.73	3450.998	2975.620	86.22
S2	12.5	4.66	40.47	11.44	3968.687	3492.031	87.99
S3	11.9	4.63	40.66	10.86	3720.848	3348.468	89.99

S4	12.3	4.67	43.75	11.27	4210.930	4210.930	100.0
S5	12.5	4.67	42.18	11.42	4127.193	4127.193	100.0
S6	12.6	4.66	41.77	11.48	4112.058	4112.058	100.0
S7	12.7	4.66	42.88	11.63	4282.636	4282.636	100.0
S8	12.7	4.65	43.65	11.62	4354.911	4344.075	99.75
S9	12.4	4.66	44.27	11.36	4304.850	4304.850	100.0
S10	12.5	4.65	46.23	11.43	4524.350	4521.599	99.94
S11	12.1	4.67	45.65	11.09	4304.590	4292.402	99.72
S12	12.4	4.68	47.31	11.30	4570.201	4556.188	99.69
S13	12.5	4.68	46.20	11.40	4514.661	4496.631	99.6
S14	11.7	4.66	37.21	10.73	3352.449	3318.106	98.98
S15	13.4	4.65	39.93	12.29	4216.750	4191.769	99.41
S16	13.3	4.65	38.45	12.16	4018.800	3973.505	98.87
S17	12.5	4.67	39.12	11.44	3835.247	3803.137	99.16
S18	12.6	4.68	42.93	11.51	4242.324	4220.787	99.49
S19	12.8	4.68	43.88	11.71	4421.801	4396.984	99.44
S20	12.1	4.68	43.20	11.11	4084.203	4058.580	99.37
S21	12.0	4.68	44.12	11.00	4116.090	4074.781	99.0
S22	13.0	4.67	43.53	11.86	4441.431	4339.812	97.71
S23	11.4	4.68	42.09	10.45	3640.449	3536.934	97.16
S24	11.2	4.66	40.50	10.28	3412.479	3288.158	96.36
Sector 3 total	-	-	-	-	412508.455	393017.131	95.27

Table A.6 Sector 3 wind summary after re-sitting WTGs

Turbine	A [m/s]	k	Freq. [%]	U [m/s]	MWh (free)	MWh (park)	Eff. [%]
N1	12.6	4.66	42.56	11.55	4218.158	4218.158	100.0
N2	12.9	4.66	44.09	11.79	4470.896	4470.896	100.0
N3	13.0	4.66	45.50	11.88	4650.925	4650.925	100.0
N4	13.0	4.66	47.16	11.84	4805.207	4805.207	100.0
N5	12.7	4.66	46.24	11.58	4598.008	4598.008	100.0
N6	12.7	4.65	44.93	11.60	4473.694	4473.694	100.0
N7	12.8	4.65	45.22	11.74	4562.460	4562.460	100.0
N8	13.0	4.65	44.91	11.84	4572.915	4572.915	100.0
N9	12.9	4.65	45.91	11.79	4651.800	4651.800	100.0
N10	13.0	4.66	47.86	11.93	4913.752	4913.752	100.0
N11	13.0	4.67	48.28	11.90	4945.561	4945.561	100.0
N12	12.1	4.67	46.40	11.08	4371.402	4144.288	94.8
N13	11.9	4.67	45.73	10.88	4204.246	3971.487	94.46
N14	12.9	4.65	40.91	11.78	4143.281	3970.868	95.84
N15	12.7	4.65	38.32	11.59	3810.434	3555.841	93.32
N16	13.3	4.63	41.66	12.17	4354.617	4353.725	99.98
N17	12.9	4.65	39.34	11.81	3994.644	3846.194	96.28
N18	12.8	4.65	38.85	11.74	3917.936	3752.749	95.78
N19	12.6	4.65	37.96	11.50	3744.415	3604.962	96.28
N20	12.6	4.65	37.67	11.53	3727.560	3585.907	96.2
N21	12.7	4.66	38.06	11.61	3794.213	3657.680	96.4
N22	13.0	4.65	40.00	11.87	4082.595	3928.004	96.21

N23	12.1	4.67	41.24	11.06	3876.626	3691.205	95.22
N24	11.7	4.67	41.91	10.66	3737.129	3608.796	96.57
N25	12.2	4.66	39.74	11.12	3759.244	3629.626	96.55
N26	11.6	4.66	37.40	10.64	3323.986	2880.834	86.67
N27	12.3	4.66	38.22	11.21	3653.566	3350.326	91.7
N28	12.3	4.65	37.63	11.20	3594.053	3452.151	96.05
N29	12.2	4.66	46.20	11.14	4383.216	4181.760	95.4
N30	12.3	4.65	38.84	11.26	3734.795	3635.303	97.34
N31	11.8	4.65	37.99	10.75	3431.244	3263.992	95.13
N32	12.0	4.66	40.80	10.97	3794.104	3403.254	89.7
N33	12.1	4.66	40.97	11.09	3861.946	3809.447	98.64
N34	12.0	4.66	42.08	10.96	3902.775	3882.034	99.47
N35	14.6	4.62	46.79	13.32	5256.455	5256.455	100.0
N36	12.7	4.67	48.06	11.65	4814.900	4814.900	100.0
N37	12.8	4.67	47.26	11.67	4742.779	4742.779	100.0
N38	12.9	4.67	45.98	11.76	4648.926	4648.926	100.0
N39	12.8	4.67	45.25	11.69	4550.257	4550.257	100.0
N40	12.6	4.67	44.77	11.53	4432.736	4432.736	100.0
N41	12.6	4.67	43.34	11.48	4267.747	4267.747	100.0
N42	12.6	4.66	45.46	11.56	4509.105	4060.709	90.06
N43	12.7	4.67	47.99	11.59	4779.151	4779.151	100.0
N44	12.4	4.68	44.02	11.39	4293.535	4293.535	100.0
N45	12.7	4.67	43.21	11.64	4321.739	4321.739	100.0

N46	12.5	4.67	44.17	11.41	4316.983	4316.983	100.0
N47	11.8	4.65	48.52	10.77	4393.061	4140.737	94.26
N48	12.1	4.67	48.51	11.06	4557.422	4271.549	93.73
N49	12.6	4.66	40.84	11.54	4044.642	3959.893	97.9
N50	13.3	4.62	40.30	12.18	4215.892	4215.892	100.0
N51	12.7	4.67	38.15	11.66	3821.924	3446.069	90.17
N52	13.2	4.65	37.47	12.04	3882.213	3385.572	87.21
N53	13.0	4.65	36.96	11.90	3782.495	3287.150	86.9
N54	12.8	4.67	38.38	11.75	3877.779	3630.754	93.63
N55	13.1	4.66	38.32	11.99	3953.331	3801.118	96.15
N56	12.6	4.64	45.63	11.55	4520.850	4462.412	98.71
N57	12.7	4.66	37.54	11.64	3754.854	3559.884	94.81
N58	12.3	4.67	39.09	11.22	3741.372	3653.454	97.65
N59	12.8	4.64	38.37	11.66	3840.420	3733.462	97.21
N60	12.8	4.67	46.30	11.70	4657.009	4505.555	96.75
N61	13.1	4.66	37.85	12.01	3910.879	3534.544	90.38
N62	12.7	4.67	39.02	11.65	3906.451	3721.810	95.27
N63	14.0	4.61	41.58	12.75	4523.721	4523.721	100.0
N64	13.0	4.65	45.35	11.87	4629.901	4629.901	100.0
N65	13.0	4.66	46.40	11.87	4739.185	4739.185	100.0
N66	14.3	4.61	45.16	13.11	5017.532	5017.532	100.0
N67	12.2	4.66	38.17	11.18	3637.693	3222.284	88.58
N68	12.1	4.67	37.95	11.06	3565.127	3088.054	86.62

N69	12.3	4.63	43.56	11.22	4165.515	4165.515	100.0
N70	12.5	4.63	41.45	11.44	4058.476	4058.476	100.0
N71	12.2	4.64	44.29	11.14	4196.707	4171.255	99.39
N72	13.2	4.63	43.05	12.06	4463.182	4463.182	100.0
N73	13.0	4.63	43.09	11.90	4405.883	4405.883	100.0
N74	12.2	4.68	42.33	11.16	4028.564	4014.653	99.65
N75	12.5	4.67	40.10	11.40	3916.507	3904.903	99.7
N76	12.3	4.67	45.06	11.28	4345.605	4330.663	99.66
N77	13.4	4.61	39.90	12.28	4203.219	4203.219	100.0
N78	12.5	4.66	41.81	11.45	4103.748	4103.748	100.0
S1	12.5	4.66	40.08	11.42	3919.996	3386.888	86.4
S2	12.7	4.65	41.50	11.59	4130.344	3741.801	90.59
S3	11.9	4.63	40.66	10.86	3720.854	3674.065	98.74
S4	12.5	4.67	43.04	11.47	4231.578	4231.578	100.0
S5	12.4	4.66	40.56	11.36	3941.893	3361.628	85.28
S6	12.6	4.66	41.80	11.48	4116.903	4116.903	100.0
S7	12.7	4.65	42.25	11.64	4224.599	4211.264	99.68
S8	12.7	4.65	43.65	11.62	4354.911	4353.932	99.98
S9	12.6	4.65	44.87	11.49	4422.074	4421.013	99.98
S10	12.5	4.65	46.23	11.43	4524.347	4523.222	99.98
S11	12.6	4.67	45.99	11.50	4536.881	4534.603	99.95
S12	12.4	4.68	47.31	11.30	4570.202	4567.489	99.94
S13	12.5	4.68	46.20	11.40	4514.660	4511.458	99.93

S14	12.3	4.65	37.53	11.25	3602.162	3594.019	99.77
S15	13.6	4.65	39.15	12.39	4165.590	4158.110	99.82
S16	13.3	4.65	38.45	12.16	4018.800	3985.661	99.18
S17	13.0	4.66	38.48	11.86	3926.204	3916.943	99.76
S18	12.6	4.68	44.18	11.56	4386.922	4075.140	92.89
S19	13.0	4.68	43.87	11.87	4484.396	4416.067	98.48
S20	12.8	4.68	44.80	11.73	4520.419	4454.258	98.54
S21	13.1	4.66	39.50	11.99	4075.460	3979.066	97.63
S22	13.0	4.67	43.53	11.86	4441.431	4328.360	97.45
S23	13.0	4.67	44.25	11.87	4519.858	4397.389	97.29
S24	12.8	4.65	39.52	11.68	3964.170	3943.189	99.47
Sector 3 total	-	-	-	-	429171.507	417745.928	97.34

Table A.7 Sector wise Resource grid Summary

Sector [°]	Variable	Mean	Min	at	Max	at
All	Weibull-A	9.0 m/s	5.9 m/s	(530800, 965829)	13.7 m/s	(531900, 960829)
All	Weibull-k	2.77	2.22	(533200, 960029)	3.41	(530700, 965929)
All	Mean speed	8.02 m/s	5.31 m/s	(530800, 965829)	12.16 m/s	(529900, 962929)
All	Power density	366 W/m²	95 W/m²	(530800, 965829)	1353 W/m²	(531900, 960829)
All	Elevation	1840.4 m	1454.0 m	(538600, 945929)	2494.0 m	(528500, 963329)
All	RIX	1.3%	0.0%	(540000, 962929)	19.8%	(530100, 963729)
All	Delta-RIX	0.2%	-1.1%	(540000, 962929)	18.7%	(530100, 963729)
All	AEP	5.224 GW	1.399 GW	(530800, 965829)	9.314 GW	(528400, 963529)
000	Sector frequency	1.0%	0.4%	(530300, 964229)	4.8%	(533400, 966929)
000	Weibull-A	6.2 m/s	2.2 m/s	(530300, 964229)	13.1 m/s	(532000, 966429)
000	Weibull-k	1.65	1.48	(518800, 956929)	3.39	(533300, 967029)
000	Mean speed	5.58 m/s	1.95 m/s	(530300, 964229)	11.65 m/s	(532000, 966429)
000	Power density	208 W/m²	10 W/m²	(530300, 964229)	1113 W/m²	(532000, 966429)
000	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.034 m	(518600, 957029)
000	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
000	Orographic turn	0.0°	-30.6°	(529500, 964729)	24.6°	(529500, 963429)
000	Orographic speed	0.07%	-60.13%	(530300, 964229)	53.31%	(532200, 966429)
000	RIX	0.8%	0.0%	(540000, 967029)	37.8%	(530400, 962629)
000	Roughness changes	1.888889E-03	0	(540000, 967029)	2	(518600, 956429)
000	Roughness speed	0.00%	-0.88%	(518400, 955529)	0.00%	(540000, 967029)
000	Delta-RIX	0.8%	0.0%	(540000, 967029)	37.8%	(530400, 962629)
000	AEP	2.605 GW	69.491 MW	(530300, 964229)	8.989 GW	(532200, 966429)
030	Sector frequency	9.0%	3.7%	(530400, 964329)	25.6%	(533100, 960129)
030	Weibull-A	10.9 m/s	4.5 m/s	(529700, 964629)	16.3 m/s	(532000, 960729)
030	Weibull-k	3.94	3.06	(529500, 963429)	4.09	(540000, 966929)
030	Mean speed	9.86 m/s	4.04 m/s	(529700, 964629)	14.72 m/s	(532000, 960729)
030	Power density	571 W/m²	39 W/m²	(529700, 964629)	1937 W/m²	(532000, 960729)
030	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.035 m	(518200, 957029)

030	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
030	Orographic turn	0.2°	-22.3°	(533300, 967029)	29.1°	(530300, 964229)
030	Orographic speed	0.26%	-59.19%	(529700, 964629)	51.36%	(532000, 960729)
030	RIX	0.7%	0.0%	(540000, 967029)	40.5%	(529400, 963629)
030	Roughness changes	1.432099E-03	0	(540000, 967029)	2	(518000, 956529)
030	Roughness speed	0.00%	-0.32%	(517800, 956129)	0.00%	(540000, 967029)
030	Delta-RIX	0.7%	0.0%	(540000, 967029)	40.5%	(529400, 963629)
030	AEP	7.662 GW	402.125 MW	(529700, 964629)	11.480 GW	(530300, 962629)
060	Sector frequency	45.9%	12.6%	(529500, 964729)	57.8%	(529500, 963429)
060	Weibull-A	10.7 m/s	6.2 m/s	(530800, 965829)	16.7 m/s	(531900, 960829)
060	Weibull-k	4.63	3.09	(529500, 964729)	4.69	(540000, 963129)
060	Mean speed	9.82 m/s	5.65 m/s	(530800, 965829)	15.21 m/s	(531900, 960829)
060	Power density	539 W/m²	101 W/m²	(530800, 965829)	2030 W/m²	(531900, 960829)
060	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.036 m	(517900, 957129)
060	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
060	Orographic turn	0.2°	-14.3°	(533100, 960129)	30.4°	(529500, 964729)
060	Orographic speed	0.75%	-42.21%	(530800, 965829)	60.31%	(531900, 960829)
060	RIX	1.1%	0.0%	(540000, 967029)	40.8%	(529300, 964329)
060	Roughness changes	1.148148E-03	0	(540000, 967029)	2	(517500, 956829)
060	Roughness speed	0.00%	-0.16%	(516900, 956429)	0.00%	(540000, 967029)
060	Delta-RIX	-0.1%	-1.1%	(540000, 967029)	39.7%	(529300, 964329)
060	AEP	7.685 GW	1.499 GW	(530800, 965829)	11.992 GW	(529900, 963029)
090	Sector frequency	14.3%	7.3%	(533100, 959929)	49.8%	(529400, 964729)
090	Weibull-A	7.5 m/s	4.8 m/s	(533200, 960129)	14.0 m/s	(528400, 963329)
090	Weibull-k	2.99	2.56	(529600, 963429)	4.23	(529700, 964629)
090	Mean speed	6.73 m/s	4.25 m/s	(533200, 960129)	12.52 m/s	(528400, 963329)
090	Power density	214 W/m²	52 W/m²	(533200, 960229)	1249 W/m²	(528400, 963429)
090	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.035 m	(517900, 957229)
090	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
090	Orographic turn	-0.1°	-20.9°	(533100, 959929)	23.3°	(533300, 967029)
090	Orographic speed	0.99%	-33.58%	(533200, 960229)	67.40%	(528400, 963329)

090	RIX	1.9%	0.0%	(540000, 967029)	40.3%	(528000, 963529)
090	Roughness changes	1.37037E-03	0	(540000, 967029)	2	(517500, 957429)
090	Roughness speed	0.00%	-0.21%	(517100, 957429)	0.00%	(540000, 967029)
090	Delta-RIX	-4.7%	-6.6%	(540000, 967029)	33.7%	(528000, 963529)
090	AEP	3.243 GW	647.114 MW	(533200, 960229)	9.989 GW	(528400, 963329)
120	Sector frequency	1.9%	1.0%	(529500, 963429)	9.8%	(529700, 964629)
120	Weibull-A	4.1 m/s	1.8 m/s	(533100, 959929)	8.3 m/s	(529400, 966329)
120	Weibull-k	2.31	1.86	(529400, 964629)	2.87	(533400, 966929)
120	Mean speed	3.67 m/s	1.62 m/s	(533100, 959929)	7.34 m/s	(529400, 966329)
120	Power density	46 W/m²	3 W/m²	(533100, 959929)	339 W/m²	(529400, 966329)
120	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.034 m	(518100, 957529)
120	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
120	Orographic turn	-0.2°	-25.2°	(529500, 963429)	17.3°	(533400, 966929)
120	Orographic speed	0.77%	-50.67%	(533100, 959929)	64.06%	(528400, 963229)
120	RIX	2.0%	0.0%	(540000, 967029)	49.4%	(529300, 963629)
120	Roughness changes	1.691358E-03	0	(540000, 967029)	2	(517700, 957929)
120	Roughness speed	0.00%	-0.34%	(517200, 958129)	0.00%	(540000, 967029)
120	Delta-RIX	-0.9%	-2.9%	(540000, 967029)	46.5%	(529300, 963629)
120	AEP	580.628 MW	137 kW	(533100, 959929)	4.322 GW	(529400, 966329)
150	Sector frequency	0.9%	0.5%	(529500, 963429)	1.9%	(533400, 966929)
150	Weibull-A	3.4 m/s	1.7 m/s	(529600, 963429)	5.3 m/s	(530100, 965629)
150	Weibull-k	2.35	1.92	(529400, 964729)	2.41	(533400, 967029)
150	Mean speed	3.02 m/s	1.52 m/s	(529600, 963429)	4.67 m/s	(530100, 965629)
150	Power density	22 W/m²	3 W/m²	(529600, 963429)	79 W/m²	(530100, 965629)
150	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.034 m	(518400, 957729)
150	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
150	Orographic turn	-0.1°	-29.2°	(530300, 964229)	19.7°	(533100, 959929)
150	Orographic speed	0.33%	-49.25%	(529600, 963429)	55.92%	(532200, 966429)
150	RIX	1.3%	0.0%	(540000, 967029)	39.1%	(529700, 965429)
150	Roughness changes	2.111111E-03	0	(540000, 967029)	2	(518100, 958329)
150	Roughness speed	0.00%	-0.96%	(517500, 959029)	0.00%	(540000, 967029)

150	Delta-RIX	-0.9%	-2.2%	(540000, 967029)	36.8%	(529700, 965429)
150	AEP	189.011 MW	213 kW	(529600, 963429)	1.134 GW	(530100, 965629)
180	Sector frequency	0.8%	0.4%	(530300, 964229)	1.4%	(533400, 966929)
180	Weibull-A	3.7 m/s	1.5 m/s	(530300, 964229)	6.1 m/s	(532200, 966429)
180	Weibull-k	2.27	1.99	(532800, 959429)	2.36	(533400, 967029)
180	Mean speed	3.30 m/s	1.30 m/s	(530300, 964229)	5.40 m/s	(532200, 966429)
180	Power density	30 W/m²	2 W/m²	(530300, 964229)	127 W/m²	(531900, 966429)
180	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.034 m	(518700, 957829)
180	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
180	Orographic turn	0.0°	-30.6°	(529500, 964729)	24.6°	(529500, 963429)
180	Orographic speed	0.07%	-60.13%	(530300, 964229)	53.31%	(532200, 966429)
180	RIX	0.6%	0.0%	(540000, 966929)	39.9%	(530300, 966029)
180	Roughness changes	1.790123E-03	0	(540000, 967029)	2	(518600, 958629)
180	Roughness speed	0.00%	-0.72%	(518400, 959129)	0.00%	(540000, 967029)
180	Delta-RIX	0.6%	0.0%	(540000, 966929)	39.9%	(530300, 966029)
180	AEP	309.323 MW	11 kW	(530300, 964229)	1.921 GW	(531900, 966429)
210	Sector frequency	1.6%	0.8%	(529500, 964729)	3.6%	(533200, 960129)
210	Weibull-A	5.4 m/s	2.1 m/s	(529700, 964629)	8.5 m/s	(530200, 962629)
210	Weibull-k	2.40	1.83	(529500, 963429)	2.91	(533400, 966929)
210	Mean speed	4.75 m/s	1.90 m/s	(529700, 964629)	7.50 m/s	(530200, 962629)
210	Power density	84 W/m²	5 W/m²	(529700, 964629)	324 W/m²	(530200, 962729)
210	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.035 m	(518800, 957929)
210	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
210	Orographic turn	0.2°	-22.3°	(533300, 967029)	29.1°	(530300, 964229)
210	Orographic speed	0.26%	-59.19%	(529700, 964629)	51.36%	(532000, 960729)
210	RIX	0.6%	0.0%	(540000, 966729)	43.1%	(530900, 966129)
210	Roughness changes	1.308642E-03	0	(540000, 967029)	2	(519200, 958529)
210	Roughness speed	0.00%	-0.32%	(519200, 958529)	0.00%	(540000, 967029)
210	Delta-RIX	0.6%	0.0%	(540000, 966729)	43.1%	(530900, 966129)
210	AEP	1.219 GW	4.143 MW	(529700, 964629)	4.458 GW	(530200, 962629)
240	Sector frequency	5.5%	1.7%	(529500, 964729)	11.3%	(529600, 963429)

240	Weibull-A	7.4 m/s	4.3 m/s	(530800, 965829)	11.3 m/s	(529900, 963029)
240	Weibull-k	3.31	1.93	(529500, 964729)	3.37	(522100, 959029)
240	Mean speed	6.64 m/s	3.86 m/s	(530800, 965829)	10.15 m/s	(529900, 963029)
240	Power density	188 W/m²	36 W/m²	(530800, 965829)	667 W/m²	(529900, 963029)
240	Meso roughness	0.03 m	0.03 m	(540000, 966229)	0.035 m	(518900, 957829)
240	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
240	Orographic turn	0.2°	-14.3°	(533100, 960129)	30.4°	(529500, 964729)
240	Orographic speed	0.75%	-42.22%	(530800, 965829)	60.31%	(531900, 960829)
240	RIX	1.0%	0.0%	(540000, 966629)	38.1%	(531600, 965729)
240	Roughness changes	1.37037E-03	0	(540000, 967029)	2	(519800, 958129)
240	Roughness speed	0.00%	-0.55%	(519800, 958129)	0.00%	(540000, 967029)
240	Delta-RIX	1.0%	0.0%	(540000, 966629)	38.1%	(531600, 965729)
240	AEP	2.983 GW	368.736 MW	(530800, 965829)	7.858 GW	(529900, 963029)
270	Sector frequency	11.2%	6.7%	(533300, 967029)	18.2%	(530300, 964229)
270	Weibull-A	6.2 m/s	4.0 m/s	(533200, 960029)	10.3 m/s	(528400, 963329)
270	Weibull-k	3.49	2.77	(529600, 963429)	3.52	(520100, 957129)
270	Mean speed	5.58 m/s	3.55 m/s	(533200, 960029)	9.28 m/s	(528400, 963329)
270	Power density	111 W/m²	29 W/m²	(533200, 960029)	496 W/m²	(528400, 963329)
270	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.035 m	(519000, 957329)
270	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
270	Orographic turn	-0.1°	-20.9°	(533100, 959929)	23.3°	(533300, 967029)
270	Orographic speed	0.99%	-33.59%	(533200, 960229)	67.40%	(528400, 963329)
270	RIX	1.9%	0.0%	(540000, 965929)	40.3%	(531300, 963629)
270	Roughness changes	1.419753E-03	0	(540000, 967029)	2	(520000, 957429)
270	Roughness speed	0.00%	-0.51%	(520000, 957429)	0.00%	(540000, 967029)
270	Delta-RIX	1.9%	0.0%	(540000, 965929)	40.3%	(531300, 963629)
270	AEP	1.670 GW	256.815 MW	(533200, 960129)	6.820 GW	(528400, 963329)
300	Sector frequency	5.9%	3.0%	(529500, 963429)	13.4%	(529700, 964629)
300	Weibull-A	5.5 m/s	2.7 m/s	(533100, 959929)	8.8 m/s	(528400, 963229)
300	Weibull-k	3.17	2.68	(530400, 964329)	3.28	(530900, 967029)
300	Mean speed	4.90 m/s	2.39 m/s	(533100, 959929)	7.86 m/s	(528400, 963229)

300	Power density	79 W/m²	9 W/m²	(533100, 959929)	319 W/m²	(528400, 963229)
300	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.034 m	(518800, 957129)
300	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
300	Orographic turn	-0.2°	-25.2°	(529500, 963429)	17.3°	(533400, 966929)
300	Orographic speed	0.77%	-50.67%	(533100, 959929)	64.06%	(528400, 963229)
300	RIX	2.1%	0.0%	(540000, 967029)	48.0%	(531900, 962029)
300	Roughness changes	1.617284E-03	0	(540000, 967029)	2	(519900, 956629)
300	Roughness speed	0.00%	-0.58%	(519900, 956629)	0.00%	(540000, 967029)
300	Delta-RIX	2.1%	0.0%	(540000, 967029)	48.0%	(531900, 962029)
300	AEP	1.112 GW	9.418 MW	(533100, 959929)	4.803 GW	(528400, 963229)
330	Sector frequency	1.9%	0.6%	(529500, 964729)	4.8%	(533400, 966929)
330	Weibull-A	5.5 m/s	2.8 m/s	(529600, 963429)	8.2 m/s	(530100, 965629)
330	Weibull-k	2.38	1.62	(529500, 964729)	2.53	(532600, 966429)
330	Mean speed	4.85 m/s	2.46 m/s	(529600, 963429)	7.30 m/s	(530100, 965629)
330	Power density	91 W/m²	12 W/m²	(529600, 963429)	305 W/m²	(529800, 965629)
330	Meso roughness	0.03 m	0.03 m	(540000, 967029)	0.034 m	(518800, 957029)
330	Obstacles speed	0.00%	0.00%	(540000, 967029)	0.00%	(540000, 967029)
330	Orographic turn	-0.1°	-29.2°	(530300, 964229)	19.7°	(533100, 959929)
330	Orographic speed	0.33%	-49.25%	(529600, 963429)	55.92%	(532200, 966429)
330	RIX	1.5%	0.0%	(540000, 967029)	43.4%	(531100, 962229)
330	Roughness changes	1.950617E-03	0	(540000, 967029)	2	(519400, 955929)
330	Roughness speed	0.00%	-0.88%	(519300, 955829)	0.00%	(540000, 967029)
330	Delta-RIX	1.5%	0.0%	(540000, 967029)	43.4%	(531100, 962229)
330	AEP	1.327 GW	50.035 MW	(529600, 963429)	4.199 GW	(529900, 965629)

ANNEX B

This section presents sample data quality reports retrieved and screenshots from the data logger.

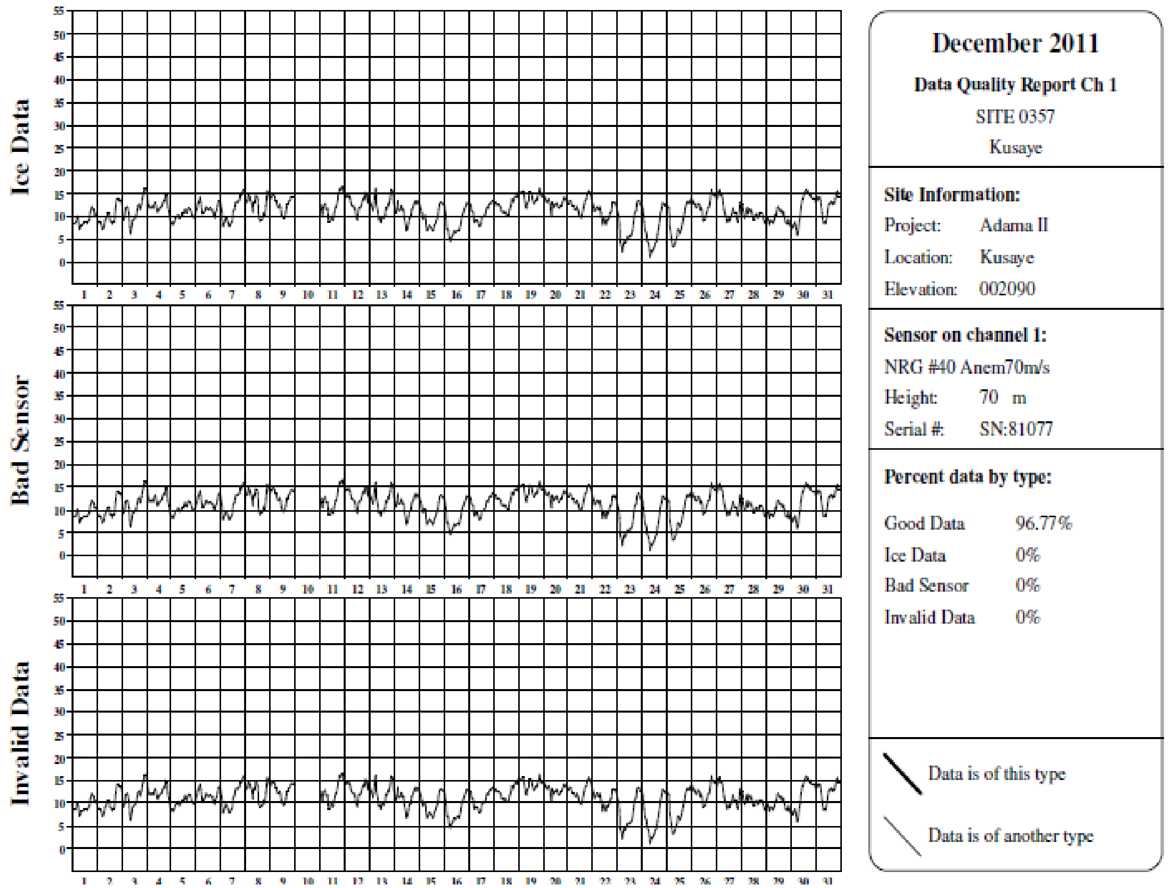

Fig. B.1 Data quality report for December 2011

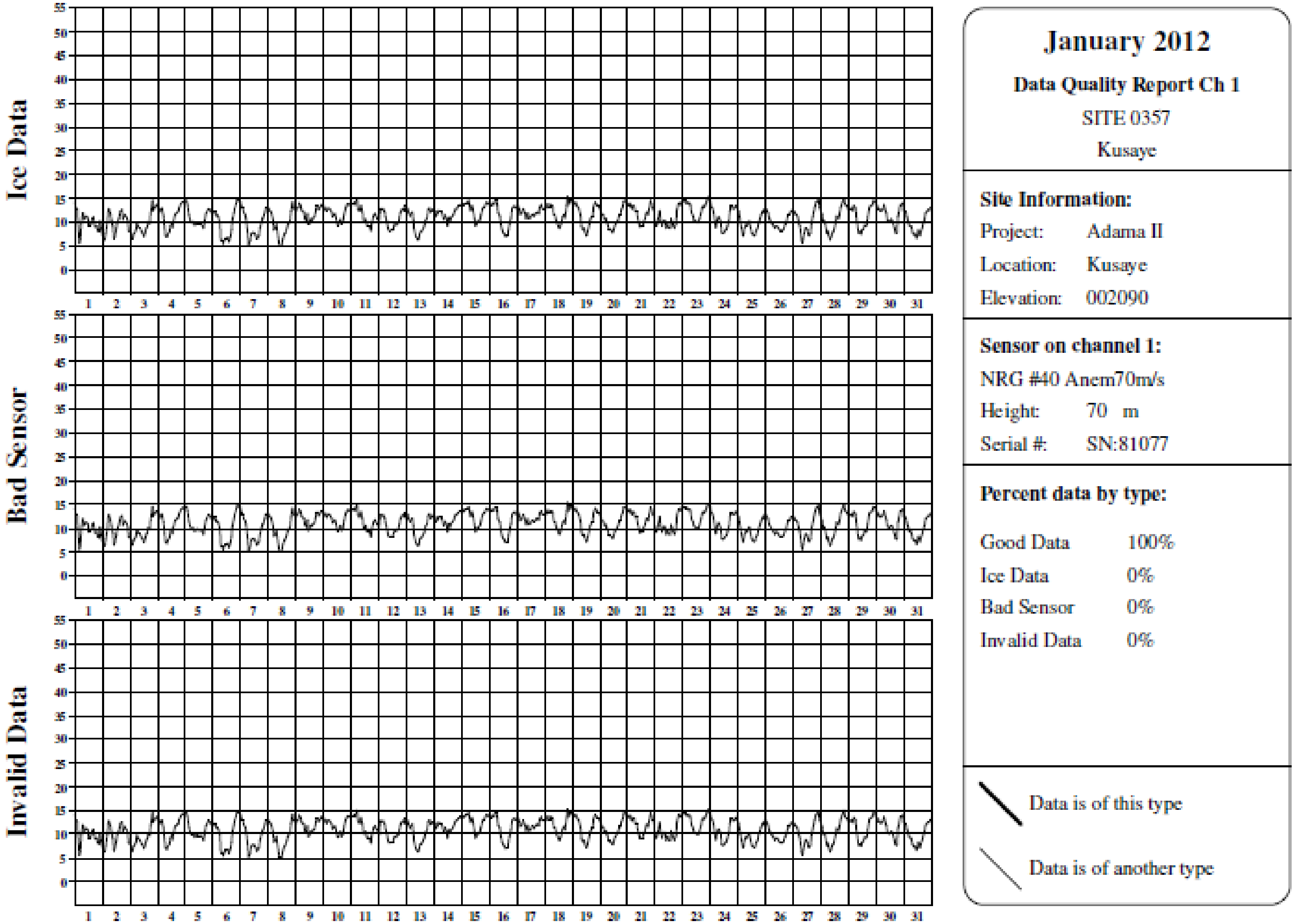

Fig. B.2 Data quality report for January 2012

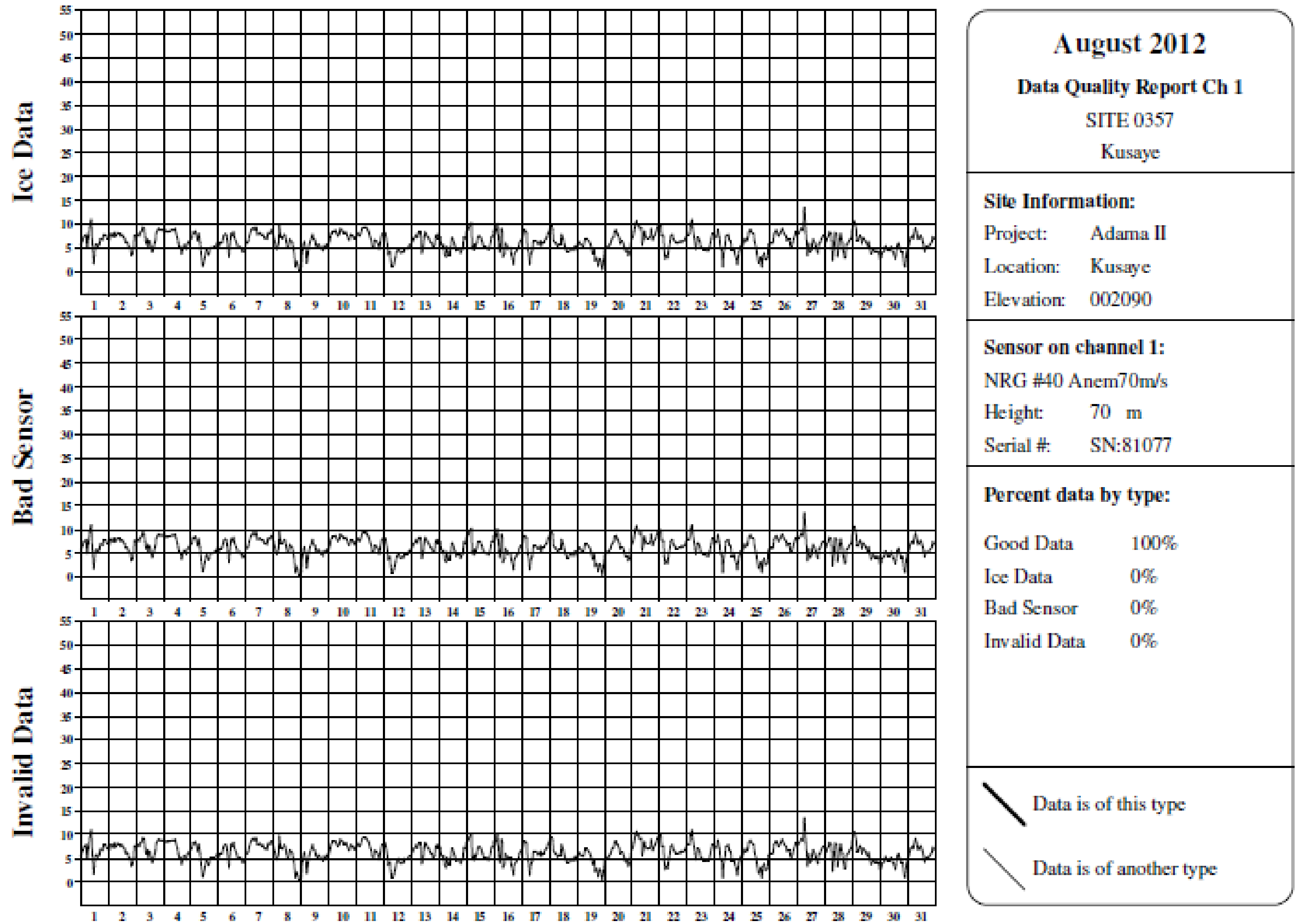

Fig. B.3 Data quality report for April 2012

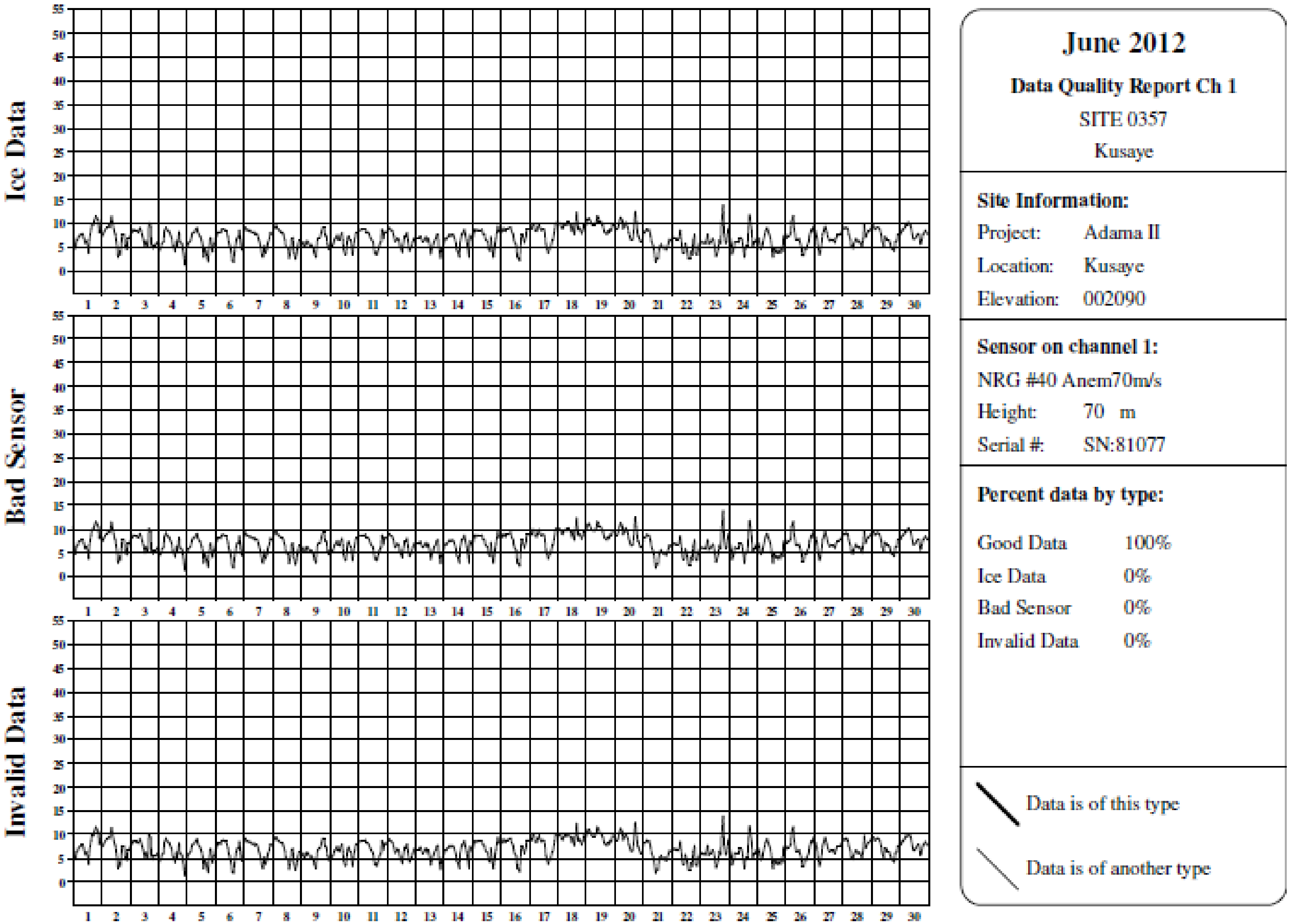

Fig. B.4 Data quality report for June 2012

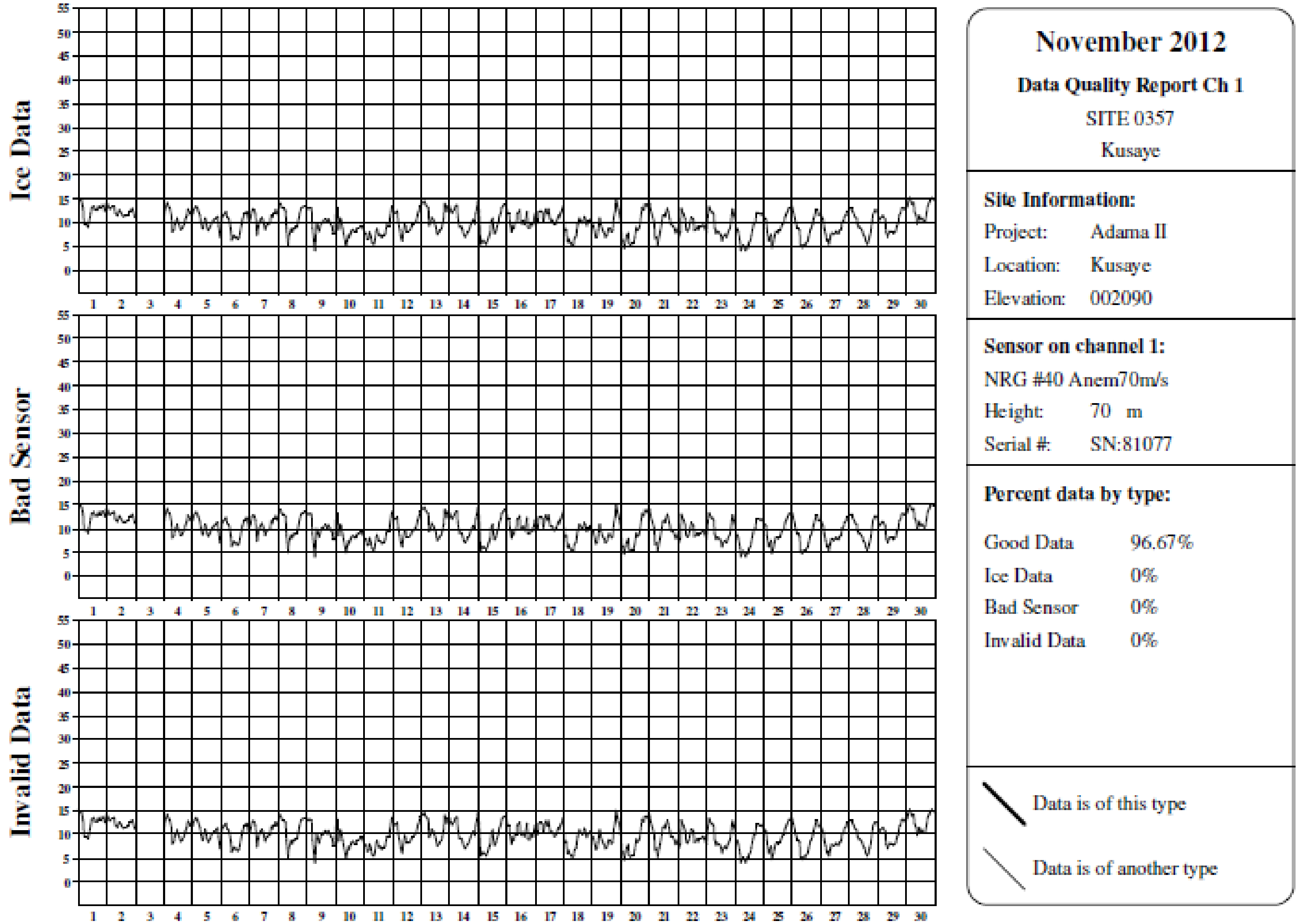

Fig. B.5 Data quality report for November 2012

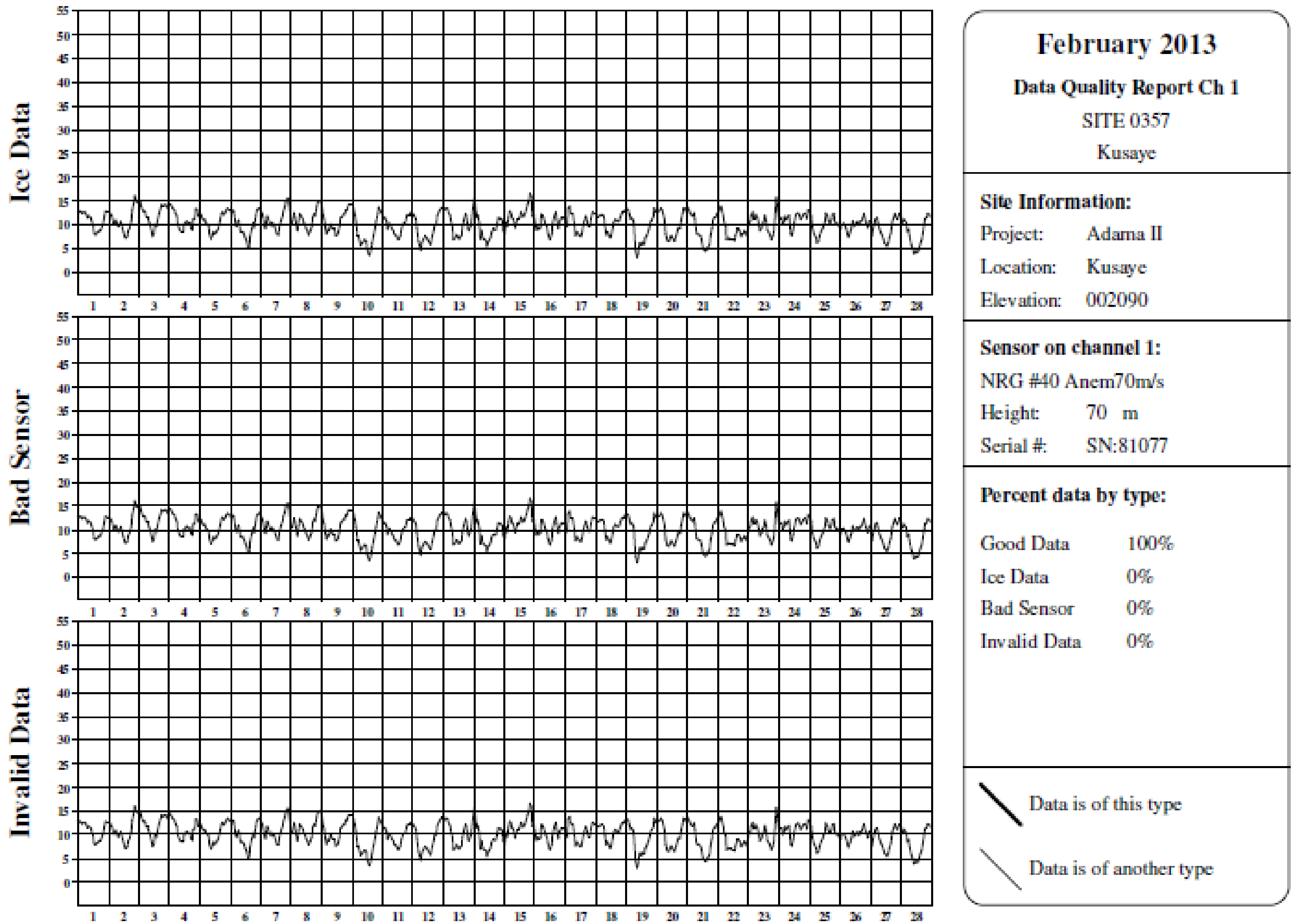

Fig. B.6 Data quality report for February 2013

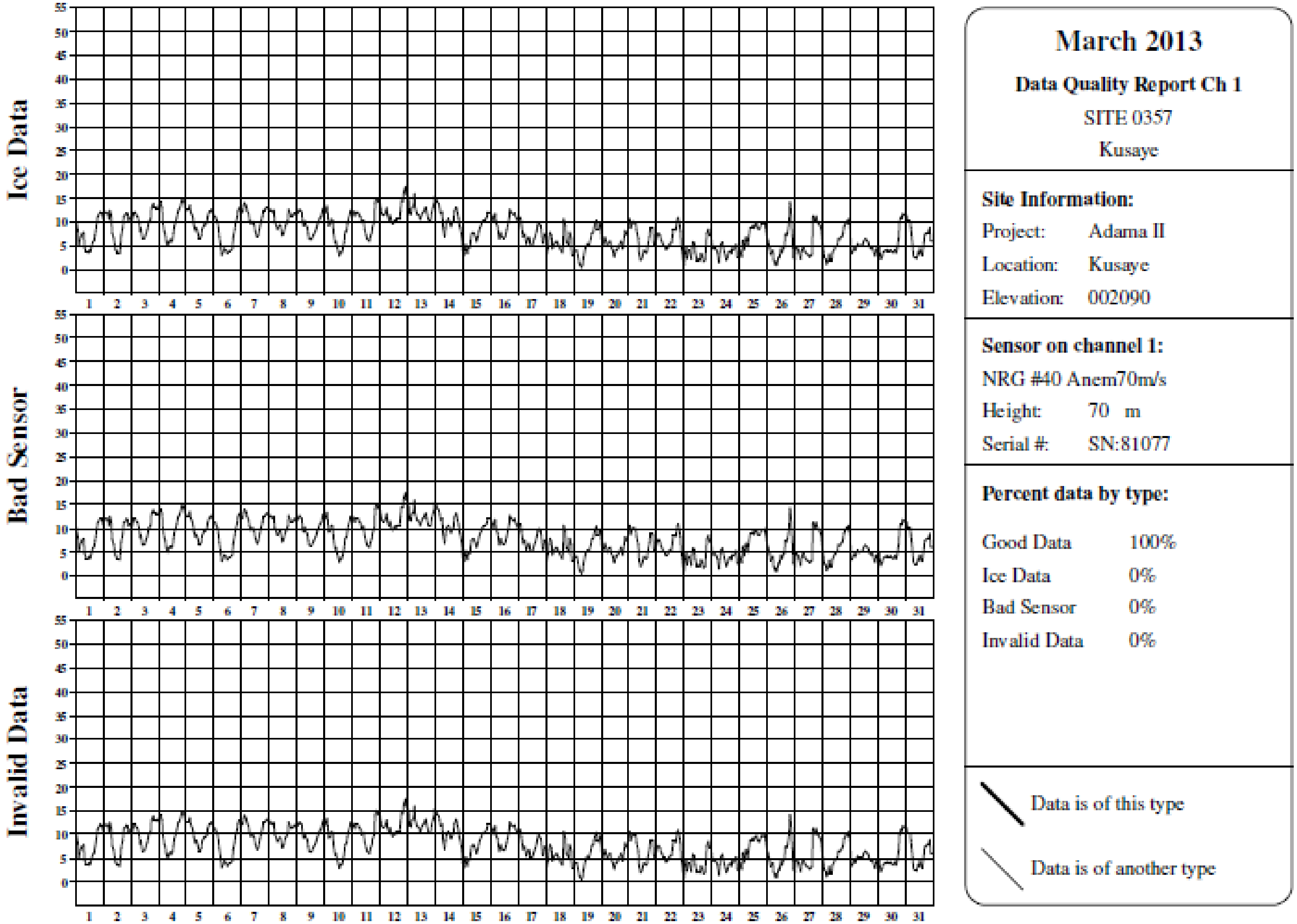

Fig. B.7 Data quality report for February 2013

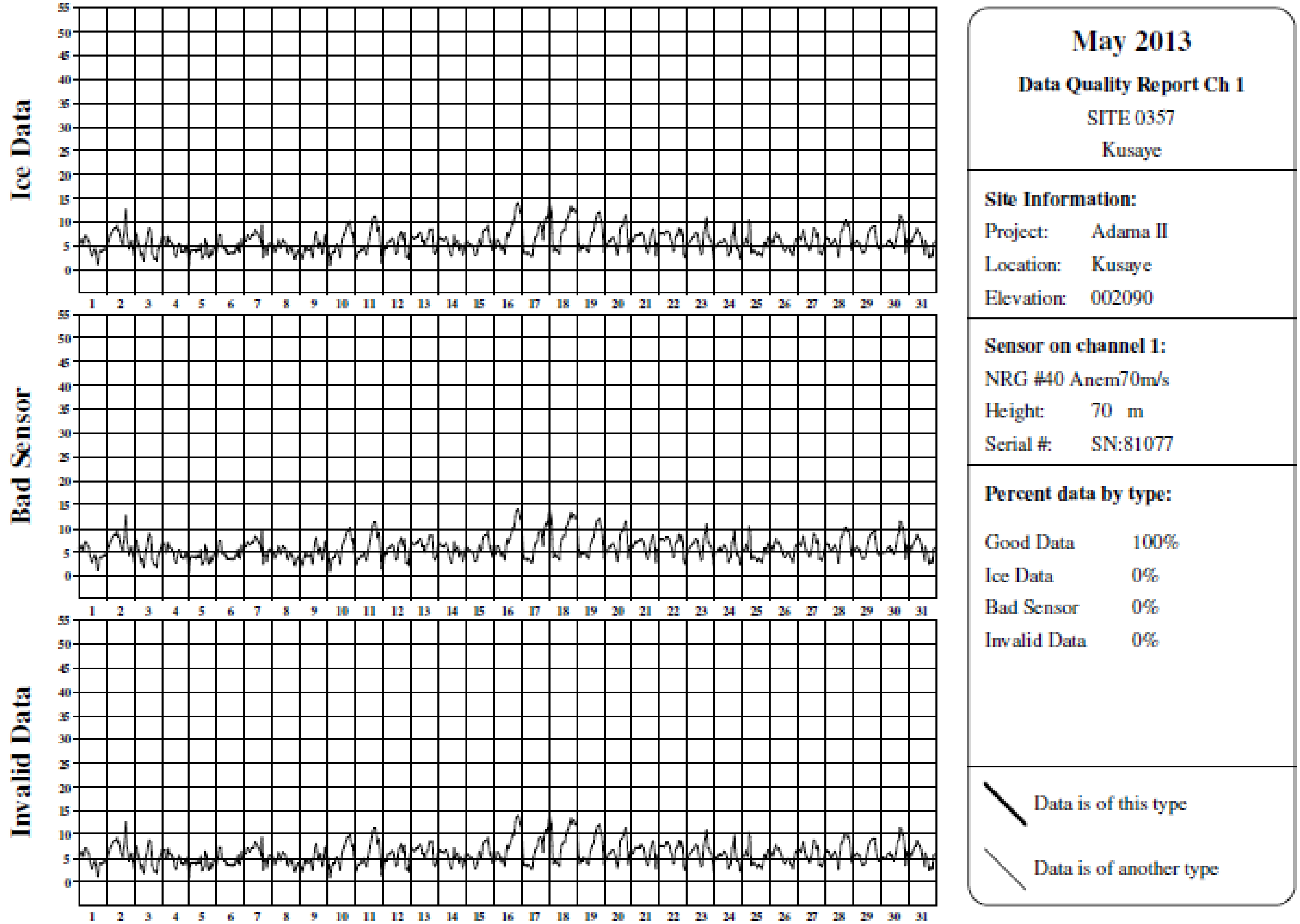

Fig. B.8 Data quality report for February 2013