Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical and Industrial Engineering

Wind Resource Assessment: A case study on Dangla Wind Farm

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Declaration

I, Belayneh Yitayew declare that this thesis is my original work and it has not been presented for a degree in any university.

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Abstract

Energy is one of the most crucial inputs for socio-economic development. A rapid growth in energy demand and air pollution has increased the available options of energy-producing methods in the electric industry.

Currently, the wind energy potential of Ethiopia was estimated to be 10,000 MW. However, from these only eight percent of its capacity has been used in the last years. One of the reasons for the low usage of wind energy is the unavailability of correct wind atlas in the country. Therefore, it is necessary to develop correct wind atlas for the entire country so that better sites used for installing wind power plants can be easily identified. Besides, wind energy projects could be planned and implemented in a short time. Hence, in this work, a wind resource assessment is going to be carried out using WAsP at Dangla which plays an important role in identifying potential areas for wind energy applications in the given site.

In this study, three years of wind data which were recorded at a height of 10-meter a.g.l. in 15 minutes interval were used for the analysis. The results showed that the minimum wind speed was 0.12083 m/s whereas the maximum wind speed was 9.96389 m/s. The mean wind speed and power density at a height of 10 m a.g.l. were 1.8 m/s and 9 w/m^2 respectively. The most frequent wind direction was also found to be 210°.

The wind resource assessment was carried out using the Wind Atlas Analysis and Application Program and the results showed that the maximum wind speed was available around hills. Also, the net annual energy production of the site at a turbine height of 80 m a.g.l. was found to be 282.726 GWh (or, 32.27 MW). The capacity factor of the farm was also found to be 9.54% which in turn indicated that the site is classified as lower potential.

The result of the economic analysis showed that the Vestas V100-1.8 MW Grid streamer wind turbine yields the highest cost of 396,547 birr/kW at the site. The economic analysis of the site was analyzed using the current price of electricity in Ethiopia. The result obtained showed that the Levelized cost of electricity was found to be 4.9 birr/kWh. Based on the results obtained, it is possible to conclude that the project is not financialy feasible at the current price of electricity in Ethiopia.

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Acronyms

GoE	Government of Ethiopia
GTZ	German Technical Cooperation
WAsP	Wind Atlas Analysis and Application Program
NAMSA	National Meteorological Survey Agency
WT	Wind Turbine
CFD	Computational Fluid Dynamics
IEC	International Electrotechnical Commission
WTG	Wind Turbine Generator
SRTM	Shuttle Radar Topographic Mission
DC	Duration Curve
GIS	Geographic Information System
AGL	Above Ground Level
ASTER	Advanced Spaceborne Thermal Emission Reflection
GDEM	Global Digital Elevation Model
GLCC	Global Land Cover Characterization
MODIS	Moderate Resolution Imaging Spectro-radiometer
ESA	European Space Agency
PC	Personal Computer
WRF	Weather Research and Forecasting

GWC	Generalized Wind Climate
OWC	Observed Wind Climate
Omwc	Observed mean wind climate
Oewc	Observed extreme wind climate
WGS	World Geodetic System
UTM	Universal Transverse Mercator
DTU	Technical University of Denmark
RIX	Ruggedness Index
CNCF	Carbon Neutral Charitable Fund
O&M	Operation and Maintenance
CO_2	Carbon dioxide
AM	Anti-meridian
PM	Post-meridian
WENG	WAsP Engineering
ETB	Ethiopian Birr
TS	Turbine Site
GS	GreadStreamer

Nomenclatures

MW	Mega Watt
kWh	Kilo Watt-hour
AEP	Annual Energy Production (kWh)
D	Diameter of Rotor (m)
CF	Capacity Factor
$V_m, V_{in}, V_{out}, V_R$	Mean, Cutin, Cutout, and Rated Wind Speed (m/s)
PDF	Probability Density Function
CDF	Cumulative Density Function
K	Weibull Shape Factor
A	Weibull Scale Factor (m/s)
R	Roughness Class
Z_0	Roughness Length (m)
C_t	Thrust Coefficient
P	Power (W)
DR	Data Recovery
N_{valid}	Number of Valid records
N	Total number of possible records
α	Wind Shear Exponent
TI	Turbulence Intensity

kg	kilogram
N_u	Number of Wind Speed Bins
f_i	Frequency of Occurrence
P	Energy Production (kWh)
L	Loss
PD	Power Density (w/m2)
GWh	Giga Watt Hour
MWh	Mega Watt Hour
LCOE	Levelized Cost of Electricity (Birr)
PTC	Production Tax Credit (Birr)
C	Cost (Birr)
NPV	Net Present Value (Birr)
CA	Cash Outflow (Birr)
BA	Cash Inflow (Birr)
CI	Investment Cost (Birr)
T	Time (s)
I	Interest rate (%)
BCR	Benefit to Cost Ratio
PBP	Pay Back Period (year)
IRR	Internal Rate of Return (%)

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Chapter 1: Introduction

1.1 Background

Energy is one of the most crucial inputs for socio-economic development[1]. It plays a significant role in human existence. A rapid growth in energy demand and air pollution has increased the available options of energy-producing methods in the electric industry [2]. Renewable energies are one of the energy sources that have been taped with an increasing trend these days. Currently, the Federal Government of Ethiopia has developed policy and strategy aimed at the production of electric energy from wind and solar [3] & [4].

People use energy for their day to day activity. They use fossil fuels and diesel fuel for different activities. Since the demand for fossil fuel increased its price was also increased. As a result, researchers tried to get another source of energy and they develop alternative green energy sources that are environmentally friendly and cheaper to produce. One of the major alternative sources of green energy is wind [5].

The wind is atmospheric air in motion [6]. It is the natural movement of air across the earth’s surface. It occurrs due to differences in pressure, temperature solar radiation, and rotation of the earth, warmer air raises upward leaving space and this space is replaced by cooler air and this results in the local wind [7]. The rotation of the earth and surface features such as mountains and valleys can change the speed and direction of the wind. Generating energy from wind is not a new technology. Wind turbines have been used for thousands of years for generating electricity, water pumping, oil extraction, milling, and other mechanical power applications [5] & [8]. A Wind turbine is a machine used to convert the kinetic energy of the wind into electrical energy [8].

Any power plant needs fuel to generate electricity. But in the case of a wind power plant, that fuel is the wind. As a result, determining the energy potential of this wind is necessary for wind power generation.

Wind resource assessment is the process of determining how much amount of wind will be available for a wind power plant throughout its useful life. It is used for determining the energy potential of the plant and its importance in developing the economy of the owners. Therefore, an accurate wind resource assessment is necessary for a wind project to be successful [7].

1.1.1 The Energy Sector in Ethiopia

Ethiopia is one of the fastest-growing economies in Africa. It has the ambition to maintain its growth to reach middle-income status and universal access to electricity in the next decade. Hydropower is the most dominant power capacity of the country. However, nowadays, several initiatives are made to improve Ethiopia´s power generation capacity and to diversify the energy mix. Wind energy is expected to play a key role in this transition along with other renewable energy sources such as geothermal and solar energy. In 2015-2020, the Government of Ethiopia plans to increase its power generation by 17,000 MW from different renewable sources, including wind (1,200 MW) [9].

Historically, Ethiopia has focused largely on hydropower for electricity generation, but nowadays the government tries to generate power from other renewable energy sources to increase climate resilience. Consequently, the Government of Ethiopia (GoE) has planned to increase the power generation in the country from 4,180 MW in 2014/15 to 17,000 MW from renewable sources, of which wind energy will have a share of 5,200 MW expected to come from independent power producers modalities [10].

Althaugh Ethiopia has a huge amount of water, wind, solar, and geothermal energy potentials, the energy system is highly dependent on traditional biomass and fossil fuels. In 2010, only about 32% of the population had access to electricity. Given this fact, the country has engaged itself in unprecedented multimillion-dollar energy projects in recent years [11].

Ethiopia is endowed with outstanding and diversified renewable energy resources (i.e. hydro, wind, solar, and geothermal) and biomass. The development of the electricity sector in the country was based on the exploitation of huge hydro resources. The other renewable sources can be efficiently exploited in the power sector to improve energy diversification. The development of these renewable sources in the country has a great contribution in supporting both short and long-term power system resilience, and in supporting the national strategy to become a world-class exporter of large amounts of clean and cheap renewable energies [12].

A stable supply of enough energy is required for industrialization. However, access to energy in Ethiopia is relatively low, less than 16 % in 2005. The Ethiopian Electric Power Corporation and the Government of Ethiopia had been trying to improve the energy access to reach 20% in 2007 by constructing new power plants and expanding the national grid [13].

Access to energy is among the key elements for the economic and social development of a country. In Ethiopia, more than 80% of the country's population is engaged in the small-scale agricultural sector and lives in rural areas. Biomass is the principal source of energy in Ethiopia [14].

The study conducted by central statistics agency at the country level in 2012 suggests that about 81.4 % of the households use firewood, around 11.5 % of them use leaves and dung cakes and only 2.4 % of the households use kerosene for cooking [14].

Currently, hydropower plant is the main electrical energy supply in Ethiopia. Its covers 89 percent (3.743 GW) of the countrys installed capacity (4.206 GW). Eight percent of the country’s electric supply is from wind power plant (337 MW) and the rest three percent is from thermal power plants (126 MW) [15]. The country’s installed capacity will be increased when the country’s major ongoing hydropower, wind power, and geothermal projects are completed in the coming years. Due to the fast economic development of the country in recent years, Ethiopia has been looking for more electrical energy production options to satisfy the high demand for electricity. Wind energy is a good viable option in this regard due to its complementary nature with hydropower [16].

1.1.2 Wind Energy System in Ethiopia

Ethiopia has a good wind energy potential which is estimated to be 10, 000 MW. The velocity is ranging from 7 to 9 m/s. In 1971, the Ethiopian National Meteorological Survey Agency began to work on wind data collection using some 39 recording stations located in selected locations of the country. Even though the accuracy and distribution of wind data are low, the establishment of these stations lets the wind and other weather data to be available to consumers. Ethiopian electric power corporation was planning to develop seven wind sites that are in close proximity to the Interconnected System by 2015, ranging between 50 and 300 MW. In sum, the installed wind power capacity would be approximately 720 MW [17].

Wind energy has been used in a variety of ways for water pumping, flour milling, and in the last half of the century for electric generation. However, in Ethiopia, this technology has begun to be installed not long ago. The Ethiopian electric power corporation gathered data on wind power at four sites, i.e. Mekele, Nazareth, Gondar, and Afar in collaboration with GTZ. Therefore, a large electricity generation system by wind turbines is known to become an alternative energy source in Ethiopia. Some 100 wind pumps are operating in the country, providing drinking water for cattle and humans. For instance, in the Ziway region alone, 67 such wind pumps provide drinking water for more than 120,000 people, which indicates that small scale wind turbines also becoming an increasingly promising way to supply power [18].

In most parts of the country, the average wind speed is in the range of 3.5 to 5.5 m/s. This is not sufficient for large power production [19]. However, some places are having sufficient wind speed which is suitable for power generation.

1.2 Problem Statement

Mostly, global economic changes depend on the availability of energy. For industrialization and growth in economic conditions, access to energy is a key concern [20]. Even though Ethiopia has more renewable energy sources, most of the people living in this country have used biomass and diesel for their day to day activities [21].

The government has also tried to harness electricity towards the people by installing some mega projects like hydroelectric power plants, solar power plants, wind power plants, and waste energy recovery power plants in some parts of the country [22]. But, due to grid problems and low supply of electricity, people living in rural areas haven't used this resource for several years.

Even though I mentioned that most of the electricity problem is highly seen in rural areas, most of our country cities especially zone and Woreda cities don't get enough electricity. As a result, they are getting difficulty to carry out their day to day activities and to improve their socio-economic life. So, it is necessary to harness electricity for the society by introducing low cost, cheaper to produce, and environmentally friendly energy source. One of these energy sources is wind.

According to the Ethiopian minister of water and energy report, the wind energy potential of the country was estimated to be 10,000 MW. However, from these only eight percent of its total capacity has been used in the last years. One of the reasons for the low usage of wind energy in Ethiopia is the unavailability of correct wind atlas in the country. Therefore, it is necessary to develop correct wind atlas for the entire country so that better sites used for installing wind power plants can be easily identified. Besides, wind energy projects could be planned and implemented in a short time. The wind and solar energy assessment carried out by HYDROCHINA Corporation described that Dangla has good wind speed which varies from 1.5 to 6.4 m/s [3]. Hence, in this work, a wind resource assessment is going to be carried out using WAsP at Dangla using local weather conditions which plays an important role in estimating the energy potential of the site and identifying potential areas for wind energy applications in the given site.

1.3 Objectives

1.3.1 General Objective

The main objective of this work is to carry out wind resource assessment for Dangla, Gojjam, Ethiopia site.

1.3.2 Specific Objectives

In order to achieve the main objective, the following specific objectives are carried out.

- Analyzing the wind data for Dangla (generating wind atlas of Dangla and Generating wind resource map,
- Selecting wind turbine based on IEC standard,
- Modeling wind farm (siting of wind turbines, calculating the annual energy production, and efficiency of the wind farm), and
- Conducting the economic analysis of the project.

1.4 Scope of the Study

This research mainly covers the analysis of wind speed and direction, generating wind atlas and wind resource maps, wind farm modeling, estimating the wind energy potential of the farm, and the economic analysis of the wind farm. However, it doesn't cover the grid connection study, environmental analysis, and the design of any wind turbine.

1.5 Organization of the Thesis

The thesis comprises five chapters. Chapter One discusses the introduction of the research which includes the background, statement of problem, objectives, and the scope of the study. Chapter Two describes literature reviews and the theoretical background of wind resource assessment methods. Chapter Three describes the methods and materials used for doing this project. It includes a description of the study area, data collection, characterizing the wind resource, WAsP modeling, and economic analysis. Chapter Four presents the results and analysis of the wind resource assessment using WAsP modeling and its economic analysis along with discussions leading to the conclusion and recommendation part which are discussed in Chapter Five.

Chapter 2: Literature Reviews and Theoretical Background

2.1 Literature Reviews on Wind Resource Assessment

In this section different works of literature about wind energy resource assessment in global and Ethiopian contexts are reviewed in detail.

Ayala et al. [23] studied wind power resource assessment in complex terrain in the Villonaco, Ecuadorian whose power output is 16.5 MW and it produces on average 60 GWh of electricity annually. The objective of their study was to compare actual power production from an existing wind farm. The authors used a one-year wind measured data which was collected from the project site for the performance analysis of the system. In this study, the authors used Meteodyn WT, which is a CFD modeling tool for wind resource assessment. The results showed that the calculation of the annual energy production (AEP) of the Villonaco Wind Farm using Meteodyn WT is equal to 69.0 GWh per year and the authors concluded that the actual wind energy generation was found less than the estimated wind energy from the analysis.

Andri et al. [24] did a detailed analysis of terrain characteristics in the central India region. The authors used both WAsP and WindPRO for determining the wind energy potential of the specified site. In this study, the effect of terrain dependent parameters such as Wind shear exponent, Roughness Index, RIX (Ruggedness Index factor), and roughness length has been discussed. The authors used 1-year onsite measured wind data which were recorded at a height of 10 m and 25 m a.g.l. The result showed that the roughness class of the site was 4 whose roughness length was 1.25 m. In this study, the power-law was used to estimate the wind speeds at a hub height of 80 m. The wind power density was nearly 120 W/m^2. The authors site eight V-90 1.8 MW wind turbines in the typical wind farm according to micro-siting guidelines of wind farm installation. The result showed that the total power output of the wind farm was obtained 31.561 GWh using WAsP and 28.03 GWh using WindPro.

The development of wind resource assessment methods and application to the Waterloo region was studied by Lama [25]. The author used two study areas in the Waterloo region.

i.e., WRESTRC and RIM Park and the research were conducted using wind speed, wind direction, temperature, and pressure data collected from meteorological towers for over two years. The author filters the measured raw data to reduce the effect of icing and tower shadow, and he used MATLAB software for analyzing the data. The result showed that the wind shear and turbulence intensity at WRESTRC were moderate when the wind flowed from the dominant direction and they were very high from other directions even though the terrain is more complex. Also, the capacity factors were ranged from 9.4% to 22%, which is not high enough to suggest a commercial wind farm would be viable at either site. As a result, the author suggests that a small wind turbines less than 50 kW in capacity would be appropriate at both sites. Finally, the author concluded that the WRESTRC farm is more viable than RIM Park due to the availability of more wind speed distribution and higher annual energy production.

Resen [26] tried to estimate the wind energy potential of Ali Al-Gharby Site. He had also developed a wind map for the typical site. He used meteorological data taken from Ali Algharby station to conduct the wind resource analysis for the defined study area. The wind energy potential of the study area was calculated using a software program called Wind Atlas Analysis and Application Program (WAsP). The author also used the WAsP map editor tool for digitalizing the contour map of the Ali Al-Gharby site and he developed the wind map of the site using observed wind climate, digitized contour map, terrain roughness length, obstacle groups, and their porosity as an input to the WAsP model. Using IEC (International Electrotechnical Commission) standard, Vestas V182, 1.65 MW WTG was selected and used for estimating the annual energy production of the site. The calculation was made at 70 m hub height of the turbine and various roughness lengths (0.0, 0.03, 0,1,0,4, 1.5) m for the selected area and the wind speed, power density, and annual energy production of the farm were found to be 7.11 m/s, of 339 w/m^2, and 5.527 GWh respectively. The author concluded that the studied area had good wind power to establish a wind farm that is suitable for investments.

Solyali et al. [27] described the assessment of wind power potential for the Selvilitepe site in Northern Cyprus using maximum likelihood, least squares, and WAsP methods. The authors used seven years of wind data that is collected for 10 min intervals at the Selvilitepe site. The power-law exponent method was used to create diurnal and monthly averaged wind speed variations at the heights of 50 m, 80 m, and 90 m. In this study, the authors tried to determine the Weibull parameters at 30 m and 90 m heights, turbulence parameters, power density, shear profile, power-law exponent, surface roughness, wind power class, and roughness class of the site. According to the study, the dependency on imported fuels can be reduced by implementing renewable energy solutions such as wind energy in the northern part of the island. The authors concluded that wind energy analysis is essential for wind energy assessment studies.

Llombart et al. [28] analyzed the performance of wind resource assessment programs in complex terrain. The purpose of the study was to compare the performance of two models, WAsP, and WindSim in predicting the power production of wind turbines. To study the limitations of this software in assessing the wind power production at a given site, the authors studied one wind farm located in a semi-mountainous terrain and they used two complete annual cycles filtered weather data for estimating the performance of the wind climate analyzed using the two models. The result showed that the CFD model Windsim is reliable than WAsP in the case of sites presenting a simple roughness and a high steepness. However, Windsim commits several errors.

Assowe et al. [29] studied the wind resource assessment and economic analysis in three locations of the Republic of Djibouti in 2019. The increase in electricity demand in the country made the government plan to increase the power supply of the country using renewable energy resources such as wind, solar, and geothermal energy. The wind resource assessment was made using three years of wind data measured by meteorology stations at eight locations. The data was recorded at a height of 40 m a.g.l. in 10 minutes interval and the annual wind speed of the three locations was found more than 6 m/s. The feasibility study of the three wind farms was carried out by the WindPRO program. Google EarthPro was used for loading the background map of the study areas whereas the elevation profile of the study areas was generated from the Space Radar Topography Mission (SRTM) 1-arc resolution. Nordex N90/2500 kW and EWT DW61/750 kW wind turbine generators were selected for estimating the annual energy production of the wind farm which consists of 40 units of Nordex N90/2500 kW and 100 units of EWT DW61/750 kW wind turbines of 80 m height a.g.l. According to the results obtained, the annual energy production of the wind farm was 1073 GWh. The economic analysis was done using the present value cos method and the electric generation cost varied from 7.03 cents/kWh to 9.67 cents/kWh. Based on the results obtained, the authors concluded that wind farms were both technically and economically feasible.

The wind potential assessment and economic analysis was also done by Gul et al. [30] at Hyderabad in Pakistan. In this study, two years of wind data measured at a height of 10 m were used for analyzing the wind resources. These wind data were analyzed using Weibull and Reighley functions. The annual average wind speed of the study area was found 6 m/s. The power law was also used for computing the average wind speed at different hub heights. Eighteen different wind turbine generators whose rating power rating from 0.33 to 2.75 MW was selected to determine the wind power, annual energy production, and the capacity factor of the selected site. The results showed that the selected wind turbines have a good amount of energy production. The economic assessment was done by assuming an initial price of wind turbine 1.2 M$/MW, the initial investment cost of 30% of wind turbine cost, operation, and maintenance cost of 2% of wind turbine cost interest rate of 10%, and life span of 20 years. The result showed that the Cost of Energy per MWh was ranging from $19.27 to $32.8/MWh.

Bekele and Palm [31] assessed the wind energy potential at four typical locations in Ethiopia. The authors used Addis Ababa, Mekele, Nazret, and Debrezeit sites for the study. The authors investigated the wind potential of each site by compiling wind data from different sources and analyzing it using a software tool known as HOMER. The measurements were taken at a height of 10 m. The results are given in terms of the monthly average wind speed, wind speed probability density function (PDF), wind speed cumulative density function (CDF), and wind speed duration curve (DC) for all four selected sites. The results showed that for three of the four locations the wind energy potential was reasonable, with average wind speeds of approximately 4 m/s. However, for the Debrezeit site, the mean wind speed is found to be less than 3 m/s. In general, the authors concluded that the potential may not be sufficient for independent wind energy conversion systems and they recommended that to integrate the wind energy into other energy conversion systems such as PV, diesel generator, and battery to made it feasible.

Biadgo, et al. [32] tried to study wind energy resource development in Ethiopia as an alternative energy future beyond the dominant hydropower. In this study, the authors tried to review the state of the Ethiopian electric power system and wind power technology to gain insight into the main energy sources of the country. The wind energy potential of the country and its energy policy system were also discussed. Reviews on the ongoing and planned wind energy projects together with other renewable energy projects were also carried out. The authors stated that Ethiopia had been relying on hydroelectric plants for power generation and the country was developing wind energy projects in different parts of the country to increase its power capacity. The lack of reliable wind data covering the entire country was identified as one of the reasons for the limited application of wind energy in the country. In 2011, the country generated about 94% of the electricity from hydropower, 5% from wind, and the rest around 2% from geothermal. From 2011 to 2015, the government had committed itself to generate power from wind plants by constructing eight wind farms with total capacities of 1116 MW together with several hydropower plants over the five-year Growth and Transformation Plan period. The result showed that the countries power production relied on hydropower and the author concluded that the country must look into other renewable energy sources by allowing domestic and foreign investors to produce power from all kinds of energy sources without limit on the capacity.

Dagne and Worku [16] determined the wind energy potential of the sites located in East Gojjam. The authors described that the wind energy potential of the country was 10,000 MW and from these less than 8 percent of its capacity has been used. They clearly stated the absence of reliable and accurate wind atlas in a country caused low utilization of wind energy in the country. The study was aimed at determining the wind energy potential of the respective sites and to develop their wind resource map. They collected two years of wind data measured at 10 meters high from Debre Markos and Motta metrological stations. These wind data were analyzed using Microsoft excel, WindPro, and Mathlab so that the wind speed and wind direction distribution, the turbulence intensity of the sites, and the wind shear profile of the sites, and the wind energy potential of the study areas were determined.

The authors used WAsP software for developing the wind resource map of the study areas at a hub height of 50 meters a.g.l. Wind turbines were selected according to IEC standard and the annual energy productions of each farm were estimated. The mean wind speed and power density of a zone at 50 meters above the ground level were found to be 5.35 m/s and 203 W/m^2 respectively.

Tadesse [33] assessed the wind resource available at the Adama II wind farm. The main aim of the study was to analyze the wind flow and to estimate the annual energy production of the farm. The author collected one year's wind data which was measured at 70 meters above ground level from the Kusaye site. The data were analyzed by the Wind Atlas Analysis and Application Program (WAsP) and the mean wind speed and the mean wind power density were obtained to be 8.62 m/s and 440 W/m^2 respectively. The author also calculated regional wind climates for different roughness classes and heights along with all sectors of a Wind Rose through utilizing the characteristics of Sany SE7715 Wind Turbine Generator. The annual energy production of the selected wind farm was also calculated by selecting SE7715 Wind Turbine Generator from the IEC standard and it was found to be 478.786 GWh.

Abdela [34] determined the wind resource potential of Mosobo- Harena wind farm using different statistical methods and software. The Microsoft Excel and MATLAB programs were used to generate time-series graphs of wind speed and direction, frequency distributions of wind speeds, and a wind rose of the site using a one-year wind data taken from the mast at Mosobo-Harena site at heights of 10m and 40m above ground level. The Wind Atlas Analysis and Application Program (WAsP) was also used for generating wind atlas, wind resource map, identifying wind potential sites, siting of wind turbines and determining the annual energy production of the farm. According to the study, the wind speed and power density of the site were found to be 6.79 m/s and 316 w/m^2 at the height of 60m and the Vestas V60-850 kW wind turbine generator was selected from the WAsP documentation catalog. The author proposed a total of 72 wind turbines for the wind farms whose installed capacity was 61.8 MW. The result showed that the net AEP of the study area was 201.6867 Giga Watt-hour whereas the capacity factor of the wind farm was calculated to be 37.6%.

Gaddada et al. [35] tried to estimate wind energy potential and the cost of wind energy conversion systems for electricity generation. The demand for electricity has increased rapidly in the country due to the industrial revolution and the increase in population. The lack of organized weather data in the area causes the wind energy project to be limited in the country. But, nowadays the government tries to identify the wind resource potential of the country by implementing different projects in collaboration with foreign companies. The authors used eight selected sites located in Tigray, Ethiopia for their study. In this study, the authors used POLARIS P15-50, POLA- RIS P50-500, and VESTAS V110-2.0 MW wind turbines for the assessment of electric power generation in eight selected locations of the Tigray region. The economic evaluations of these three wind turbines were estimated using the present value of cost method and the results showed that the highest capacity factor is obtained as 7.873 % using VESTAS V110-2.0 MW at Mekele site, while the lowest at 0.002 % using POLARIS P15-50 at Shire site. According to the study, Atsbi, Chercher, Mekele, and Senkata sites had large wind potential.

In 2015, Wudu [36] tried to analyze the wind energy potential of the Aysha wind farm. Accordingly, the study was conducted to analyze the wind energy potential of Aysha wind farm based on 10 minutes mean data measured at 10 meters height at the Aysha site in 2008. The author used different statistical models and software (i.e. MS Excel, MATLAB, and WAsP software). for analyzing the wind data. The result showed that a mean wind speed of 8.455 m/s and an average power density of 571 W/m^2 had been found at the farm. Based on the results obtained an appropriate wind turbine generators, Sany SE8220III 2 MW, and Gamesa G80 2 MW were selected and the annual energy production of the farm was estimated at respective hub heights of 70 m and 67 m using WAsP software. Based on the selected turbine, the total AEP and net AEP of the study area were found to be 1,819.21 Giga Watt-hour and 1,183.62 Giga Watt-hour (considering total loss factor of 0.651 on the total gross AEP) respectively. In addition to this, the average power density, CF, the mean wind speed at hub height (67 m), the average Weibull shape factor (k), and scale factor (A) were determined. The author concluded that the Aysha wind farm had excellent wind energy resources that enable to install a large wind farm and he also recommended the Ethiopian government to invest in the Aysha wind farm.

In 2019, Zenebe [37] investigated wind energy potential and evaluated the performance of turbines for specific locations in the Amhara Region. The main purpose of this study was to assess wind energy potential, site suitability analysis, and performance evaluation of existing wind turbines with the optimum interaction of wind regime. This study was conducted at Debrebrehan, Enewari, and Mehalmeda wind farms to analyze their wind energy resources based on 10 minutes mean data measured at 10 meters height at the corresponding site. The author used different statistical models and software (i.e. MS Excel, MATLAB, and WAsP software) for analyzing the wind data. The mean wind speed and the mean wind power density of each farm were determined at 70m height. The result showed that the Enewari site had better wind speed and wind power density than the other two sites. The suitability of wind farms was analyzed by using GIS software. Accordingly, the author selected two wind turbines namely Acciona AW-82/1500 and Suny SE8220III whose capacity was 1.5 MW and 2 MW respectively. The performance of wind turbines was predicted by using the "blade element moment" theory and the aerodynamic characteristics of the desired airfoil were predicted by varying the angle of attack. ANSYS software was used to simulate the aerodynamic characteristics of the wind turbine blade. Based on the results obtained by this study, the author concluded that the Enewari site had good wind energy resource potentials and it is also relatively attractive. In this study, the wind farm design, cost estimation of wind resource assessment, and determining energy generation capacity of each site were not included.

Bayray et al. [38] analyzed the wind energy potential of Geba catchment which is located in northern Ethiopia. The study was conducted by using a one year collected data from six measuring masts located in Tigray, Ethiopia. The data was recorded at 10, 30, and 40 m heights a.g.l. in each 10 minutes interval. In this study, the wind data were analyzed using statistical tools and the mean wind speed, power density, wind shear exponent, and turbulence intensity were determined. WAsP was used to model the wind flow. The resource grid map was developed at a hub height of 50 m a.g.l. and the results obtained showed that the study area had good wind power potential.

2.2 Theoretical Background on Wind Resource Assessment

2.2.1 Wind Energy

Wind energy is emerging as one of the most viable alternatives to meet the challenge of increasing energy demand, particularly for electrical energy generation. It is clean, fuel-free, and available almost in every country in the world and in abundance in off-shore [39].

Wind energy is a mature renewable energy source that has been successfully deployed in many countries. It is technically and economically capable of significant continued expansion, and its further exploitation may be a crucial aspect of global GHG reduction strategies. Though average wind speeds vary considerably by location, the world's technical potential for wind energy exceeds global electricity production, and enough technical potential exists in most regions of the world to enable significant wind energy deployment [40].

2.2.2 Statistical Models for Wind Data Analysis

Various probability functions were fitted with the field data to identify suitable statistical distributions for representing wind regimes. It is found that the Weibull and Rayleigh distributions can be used to describe the wind variations in a regime with an acceptable accuracy level.

Weibull Distribution

The distribution (variation) of wind velocity can be characterized by the probability density function and cumulative distribution function in Weibull distribution.

Probability Density Function (PDF)

The probability density function *f(V)*) indicates the fraction of time (or probability) for which the wind is at a given velocity V. It is given by

$$f(V) = \frac{K}{A}\left(\frac{V}{A}\right)^{k-1} e^{-\left(\frac{V}{A}\right)^{k}} \qquad (2.1)$$

Where,

f is the frequency of occurrence,

V is the wind speed in m/s,

A is the Weibull scale factor in m/s, and

K is the Weibull shape factor.

Cumulative Distribution Function (CDF)

It describes the probability of the wind velocity, V that is less than or equal to the wind velocity. Therefore, the cumulative distribution function, F(V) can be calculated by integrating the probability density function, f(V).

Mathematically,

$$F(V) = \int_0^{\alpha} f(V)dV = 1 - e^{-\left(\frac{V}{A}\right)^k} \tag{2.2}$$

Average wind velocity of a regime, following the Weibull distribution is given by

$$V_m = \int_0^{\infty} V\, f(V)dV \tag{2.3}$$

Where, V_m, is the mean wind speed (m/s).

Rayleigh distribution

The reliability of Weibull distribution in wind regime analysis depends on the accuracy in estimating K and A. For the precise calculation of K and A, adequate wind data, collected over shorter time intervals are essential. In many cases, such information may not be readily available. The existing data may be in the form of the mean wind velocity over a given time (for example daily, monthly, or yearly mean wind velocity). Under such situations, a simplified case of the Weibull model can be derived, approximating K as 2. This is known as the Rayleigh distribution.

$$f(V) = \frac{\pi}{2}\frac{V}{V_m{}^2}e^{-\left[\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2\right]} \qquad 2.4$$

Similarly, the cumulative distribution is given by

$$F(V) = 1 - e^{-\left[\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2\right]} \qquad 2.5$$

2.2.3 Vertical Extrapolation of Wind Speed with Height

The WAsP model extrapolates wind speed for turbines of heights starting from 10 m a.g.l. at meteorological station upward to the hub height of the turbine[41], as given by;

$$V_2 = V_1\frac{ln\left(\frac{h}{Z_{o1}}\right)}{ln\left(\frac{h}{Z_{o2}}\right)} \qquad 2.6$$

2.2.4 Horizontal Extrapolation of Wind Speed

The relative speedup is defined as

$$V_r = \frac{U_2 - U_1}{U_1} \qquad 2.7$$

Where U_2 and U_1 are the wind speeds at the same height above ground level at the top of the hill and over the terrain upstream of the hill respectively.

2.2.5 Numerical Wind Flow Modeling

The main purpose of wind flow modeling is to estimate the wind resource at every proposed or potential wind turbine location so that the wind plants' overall production can be calculated and its design can be optimized. There are different types of spatial modeling approaches that can be used to extrapolate the wind resource across a project site. These are conceptual, experimental, statistical, and numerical models. The most common approach is to use a numerical flow model, of which there are linear, non-linear, and dynamic mesoscale atmospheric simulation models [42].

Among these numerical models, WAsP is the most popular model that is currently used for estimating the wind energy production of a site and micro siting decisions for wind turbines. It was enjoying popularity, especially in Europe. It was first developed by the Technical University of Denmark in 1987 and has been further enhanced over time to incorporate different models for the projection of horizontal and vertical extrapolation of data for application over different types of terrain [43]. One of the key simplification of WAsP allowing this double extrapolation is the linearization of the Navier-Stokes equations. This simplification is the main reason for WAsPs limitation in complex terrain where the terrain slope exceeds 30° and flow separation is likely to occur. WAsP is easy to use, cheap and fast, validated limitations are known and can be dealt with however, it is valid only for near-neutral conditions and surface layer. WAsP is also not equipped to handle complex terrain, channeling through gaps, or temperature-driven circulations. Despite its known limitations, WAsP remains popular because many wind project sites do not involve very steep terrain. In addition to this, the results can be improved by installing additional masts to reduce the distance over which the wind flow is modeled, and by adjusting the ruggedness index (RIX) of the terrain. RIX is the proportion of the terrain upwind of a point exceeding a certain slope threshold, such as 30%.

Unlike WAsP, CFD models provide useful insight into complex sites. They do not handle thermally-driven circulations [44]. Mesoscale numerical flow models can solve the most complete set of physical equations, but they require a great deal of computing power. They have not been also adapted to the high spatial resolutions required for wind flow modeling [45].

2.2.6 Topography Effect of Wind

The wind flow is affected by the topographical variations and displacement heights [46]. The topography of a surface includes its roughness, orography, and obstacles which are discussed below.

Roughness

Roughness describes the terrain's surface characteristics. The collective effect of the terrain surface and obstacles, leading to overall retardation of the wind near the ground, is referred to as the roughness of the terrain. However, not all the topographical elements contribute to the roughness. Vegetation and houses are examples of roughness elements, whereas long smooth hills, for example, are not, because they do not themselves cause an increase in the turbulence of the flow. The roughness of a surface is represented by roughness change lines. Each line has a pair of left and right-hand roughness lengths (m) as attributes. Roughness change lines are also represented by several points connected by polygons or connected line segments.

Figure 2.1 Roughness elements [47]

The Roughness of a Terrain

The roughness of a particular surface area is determined by the size and distribution of the roughness elements it contains; for land surfaces, these are typically vegetation, built-up areas, and the soil surface. In the European Wind Atlas, the different terrains have been divided into four types, each characterized by its roughness elements. Each terrain type may be referred to as a roughness class. A description and illustration of four such roughness classes are given in Table 2.1 which furthermore gives the relation between roughness length and roughness class, the former being the commonly used length scale to characterize the roughness of the terrain.

Roughness Length

Roughness length (Zo) is a parameter of some vertical wind profile equations that model the horizontal mean wind speed near the ground; in the log wind profile, roughness length is the same as the height where the wind speed of an area becomes zero. In reality, the wind at this height no longer follows a mathematical logarithm. It is so named because it is typically related to the height of terrain roughness elements. Whilst it is not a physical length, it can be considered as a length-scale representation of the roughness of the surface.

Tables of Roughness Length

The following table describes the relationship between roughness length, terrain surface characteristics, and roughness class given in European Wind Atlas. The table is used for assigning roughness length values.

Table 2.1 Tables of Roughness Length [48]

Physical Zo (m)	Terrain Surface characteristics	Roughness Class	Zo specified in WAsP (m)
1.5		4 (1.5m)	1.5
>1	Tall forest		>1
1.00	City		1.00
0.80	Forest		0.80
0.50	Suburbs		0.50
0.40		3 (0.40 m)	0.40
0.30	Shelter belts		0.30
0.20	Many trees and/or bushes		0.20
0.10	Farmland with closed appearance	2 (0.010 m)	0.10
0.05	Farmland with open appearances		0.05
0.03	Farmland with very few buildings/trees	1 (0.03 m)	0.03
0.02	Airport areas with buildings and trees		0.02
0.01	Airport runaway areas		0.01
0.008	Mown grass		0.008
0.005	Bare soil (smooth)		0.005
0.001	Snow surfaces (smooth)		0.003
0.0003	Sand surface		0.003
0.0002	(used for water surfaces in the Atlas)	0(0.0002 m)	0.0
0.0001	Water areas (lakes, fjords, open sea)		0.0

Orography

Orography describes the terrain height (elevation) variations. Orographic elements include hills, valleys, cliffs, escarpments, and ridges. They exert an additional influence on the wind. Near the summit or crest of these features, the wind will accelerate while near the foot and in valleys, it will decelerate. Orography is represented by height contour lines.

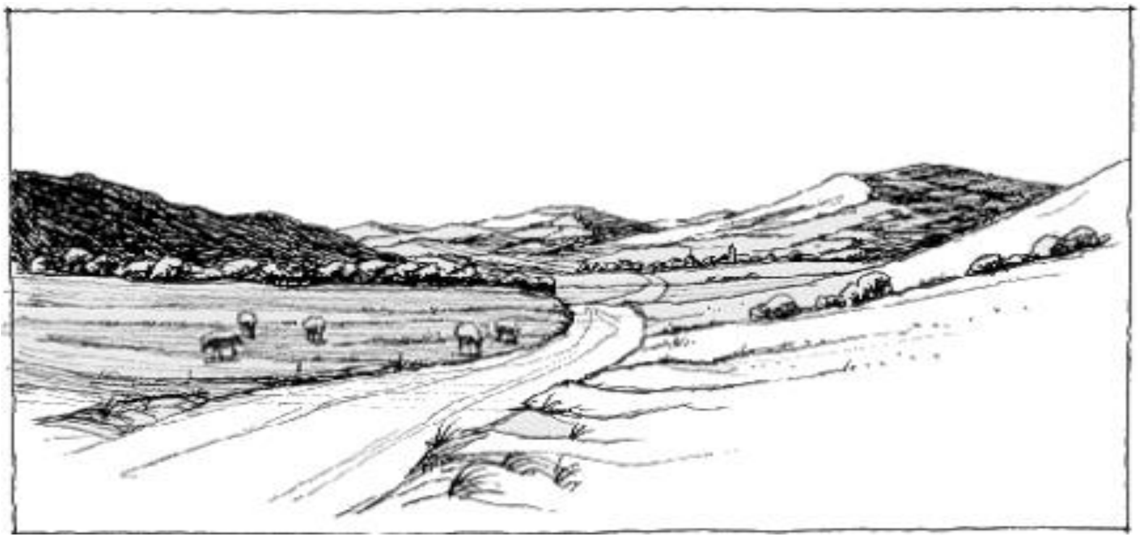


Figure 2.2 Orography elements [47]

Obstacles

Close to an obstacle such as a building the wind is strongly influenced by the presence of the obstacle. The effect extends vertically to approximately three times the height of the obstacle, and downstream to 30 to 40 times the height. If the point of interest is inside this zone, it is necessary to take the sheltering effects into account, whereas if the point is outside the zone the building should be treated as a roughness element.

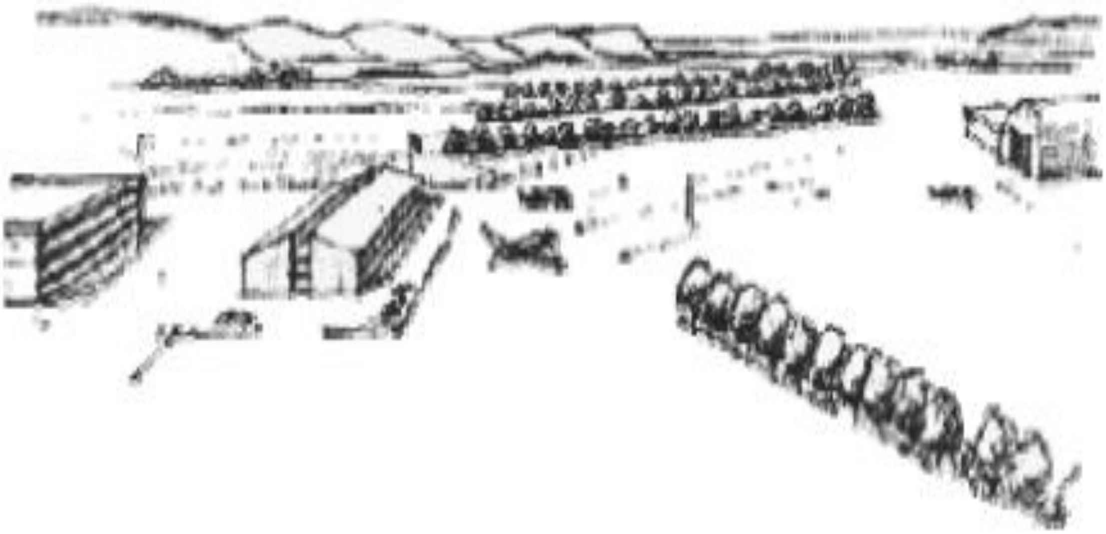


Figure 2.3 Obstacle groups [47]

2.2.7 IEC Classification of Turbines

The preparation of national and international standards containing rules for the design of wind turbines began in the 1980s [49]. One of these standards is the International Electrotechnical Commission (IEC) standard.

The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees. For design criteria of wind turbines, IEC 61400-1 had been prepared by IEC technical committee [50]. Wind turbines can be categorized into different classes based on their ability to withstand the wind speed and the turbulence intensity of the site under which they are expected to operate. The classification of wind turbines by IEC 61400-1:1999 is described in Table 2.2.

Table 2.2 Basic parameter for wind turbine classes by IEC 61400-1: 1999 [51]

WT Classes		I	II	III	IV	S
v_{ref} (m/s)		50	42.5	37.5	30	values to be specified by the designer
$\bar{v}_w$ (m/s)		10	8.5	7.5	6.0	
$v_{G50} = 1.4v_{ref}$		70	59.5	52.5	42	
$v_{G1} = 1.05v_{G50}$		52.5	44.6	39.4	31.5	
A	I_{15}	0.18	0.18	0.18	0.18	
	a	2	2	2	2	
B	I_{15}	0.16	0.16	0.16	0.16	
	a	3	3	3	3	

2.2.8 Project Design and Energy production

2.2.8.1 Site Identification and Setting up a Project

For selecting a wind project site the following factors are considered: wind resource, buildable wind area, proximity to existing transmission lines, road access, land cover, land use restrictions, proximity to residential areas, cultural, environmental, and other concerns [52].

Setting up a project involves importing a variety of graphical images, raster layers, and vector layers describing the important geographical and geophysical features of the project area.

2.2.8.2 Estimation of Wind Energy

There are many different numerical methods used to estimate the energy potential of wind. Weibull and Rayleigh's distributions have been most widely used to determine the wind energy potential. In recent years, many studies have been conducted to evaluate the wind energy potential of different regions by using various probability distribution functions and the results have been shown that the Weibull and Rayleigh distributions can describe the probability of wind speed distribution well [53].

The mean wind power generated by a turbine is given by

$$P = \int_0^\infty \left(\frac{K}{A}\right)\left(\frac{U}{A}\right)^{k-1} exp\left(-\left(\frac{U}{A}\right)^k\right) P(u)\, du \qquad 2.8$$

2.3 Research Gap

It is known that the performance of wind flow modeling depends greatly on the availability of accurate maps of terrain height and roughness length Zo. Although many researchers had done on wind resource assessment, they used a terrain roughness map edited manually (which increases errors) and they didn’t assess the wind energy potential of Dangla using local wind characteristics. Hence, my original contribution is to conduct the wind resource assessment of Dangla by Wind Atlas Analysis and Application Program (WAsP) using local weather data and an automatically generated terrain roughness map, which improves the accuracy of the analysis.

Chapter 3: Methods and Materials

3.1 Description of the Study Area

3.1.1 Site Location

Dangla is a small town in northwestern Ethiopia located in the Agew Awi Zone of the Amhara Region, it has a latitude and longitude of 11°16′N 36°50′E with an elevation of 2137 meters above sea level [54]. Dangla town is located at about 80 km southeast of Bahir Dar, the capital city of Amhara Regional State and 485 km North West of Addis Ababa, the capital city of Ethiopia [55]. The area covers 1518 square kilometers.

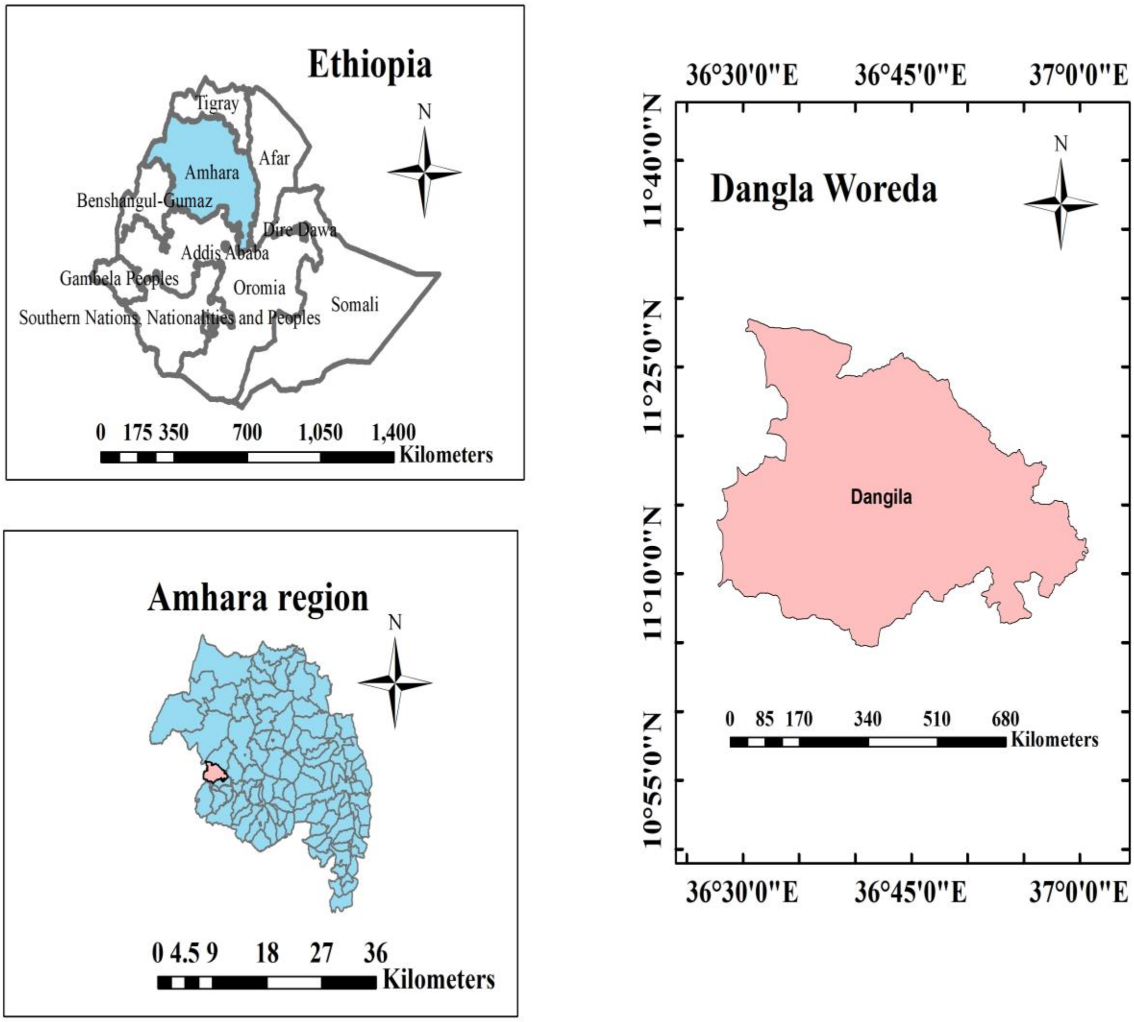


Figure 3.1: Location map of the study area

3.1.2 Climate

The Dangla lies on 2124 m above sea level. Dangla's climate is classified as warm and temperate. When compared with winter, the summers have much more rainfall. This climate is considered to be Cwb (Subtropical highland climate) according to Koppen-Geiger climate classification. In Dangla, the average annual temperature is 16.8 ℃ and the average annual precipitation is about 1554 mm per year.

The least amount of rainfall occurs in January. The average in this month is 5 mm. In July, the precipitation reaches its peak, with an average of 362 mm. The temperatures are highest on average in April, at around 18.3℃. At 15.6 ℃ on average, December is the coldest month of the year.

3.1.3 Topography

Dangla is enclosed by polygons with a width of 61.34 km and heights of 44.5 km. It is covered by the area between 4058883.3 meters East to 4120220.8 meter East longitude and 1232798.9 meters North to 1277307.4 meters North latitude. The site has different topographical features and altitudes ranging from 1099.00 m to 2439.00 m above sea level. Most parts of the site are flat terrain with farmland, semi sand, trees, vegetation, hills, houses, and buildings.

The site area is mainly used for cultivation and irrigation. Most of the peoples lived at Dangla Woreda are farmers. The topography of the land is described in the Figure 3.2.

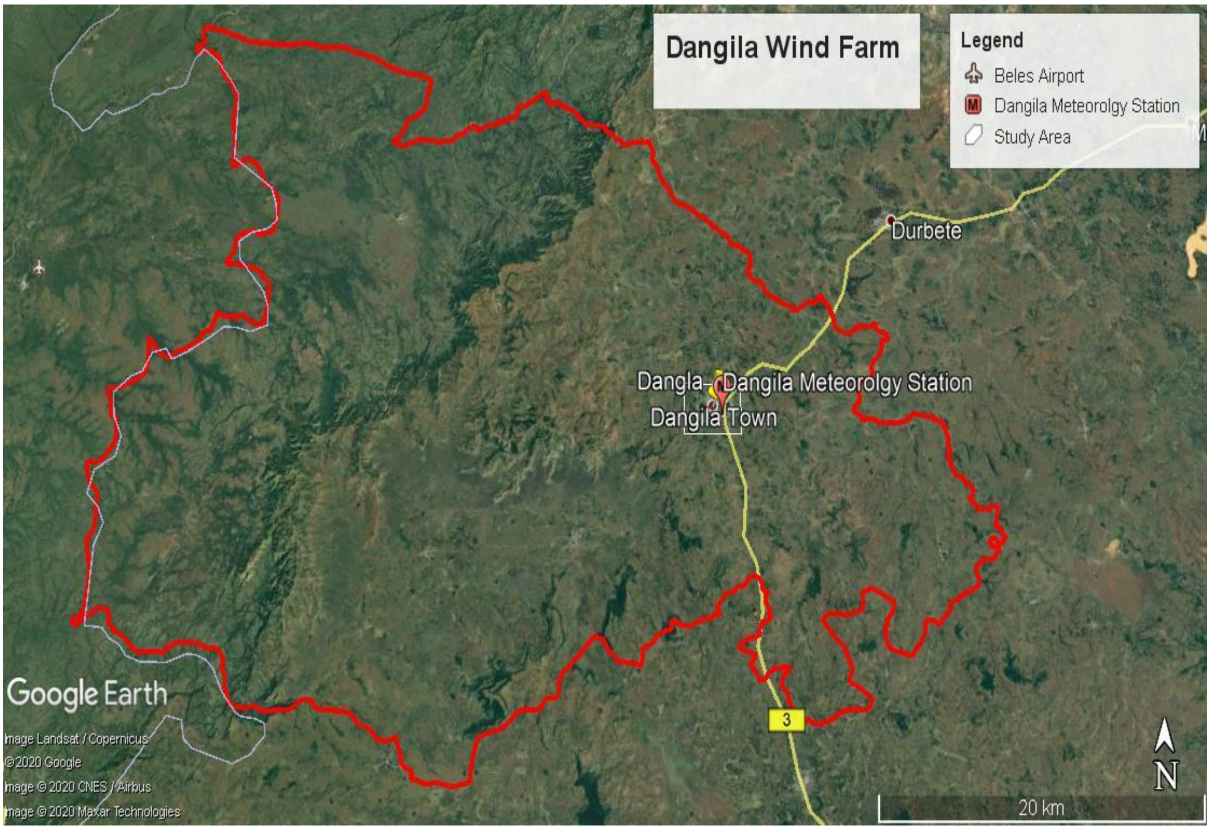


Figure 3.2: Topographic map of Dangla Woreda extracted from Google Earth Pro

3.1.4 Digital Terrain Model

Digital terrain (elevation) model is the digital representation of the elevation of a land surface with respect to a reference datum. The terrain characteristics have an enormous impact on the natural environment and socio-economic activities. The terrain analysis and modeling require the implementation of existing metrics as well as the development of new tools, indices, and parameters that would appropriately describe the terrain and its properties [56]. One of these tools is GIS. Global mapper is a GIS tool that combines a powerful array of spatial data processing tool with different compatible file formats in an easy-to-use application that no GIS proffessional should be without. The digital elevation model data can be generated from different online sources available in Global mapper package. From these sources, ASTER GDEM worldwide elevation data (1 arc resolution) was selected in this study for generating the digital elevation model of the study area (see Figure 3.3 below) due to its accuracy and reliability.

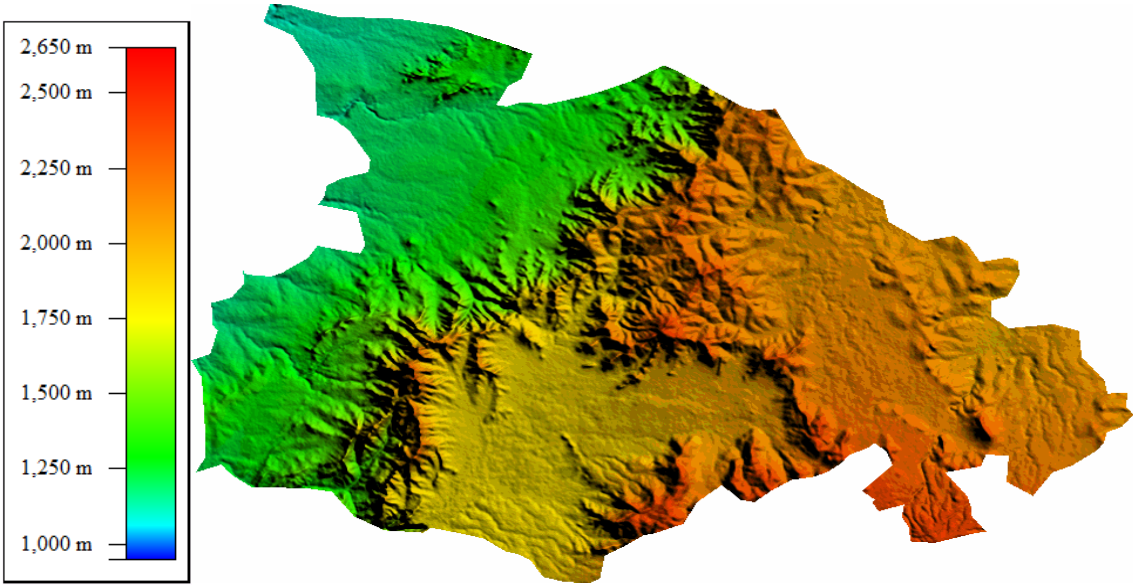


Figure 3.3: Elevation map of Dangla exported from Global mapper

3.1.5 The Roughness of Terrain

The roughness of terrain plays an important role in wind flow modeling [57]. It can be generated either manually or automatically. The manual process involves classifying the land cover data using site visiting and satellite images from google earth pro and other relevant software and assigning the roughness length of each land cover data manually. It is too tiresome and takes a long time to do it. It is also susceptible to errors. Whereas, the automatic method of generating terrain roughness map involves calculating the roughness grid of an area from land cover data (e.g. using a GIS tool known as Global mapper). This is the easiest one and accurate and better results can be obtained through it.

According to Rodger et al. [57] study, the erroneous in roughness length has a great impact on the performance of wind turbines, particularly in forested areas. In this study different automatic methods of generating the roughness map of a site based on land use classifications (i.e. CORINE, ESA GLOBCOVER, MODIS, and GLCC) were discussed. The CORINE provides 44 land cover classification datasets which have the highest spatial resolution at 100 m, but it only covers 33 countries of Europe [58]. The GLOBCOVER dataset has been used in the Global Wind Atlas. It has a low resolution and it has 8 forest classes out of the 23 different land cover classifications. The MODIS Vegetation Continous

Fields is not a true land-use data set. Whereas, the GLCC provides the oldest and a coarse 1000 meter resolution data set. But a recent version of GLCC which has 22 land cover classification and 500 meter resolution is introduced.

In this study, the roughness grid of the study area is calculated from and land cover data of the site automatically using Global mapper V20. The land cover data was taken from ESA CCI (Climate Change Initiative) 2010 (Global Land Cover-500 m resolution). The roughness values are assigned automatically as shown in Figure 3.4 based on the land use data of the study area.

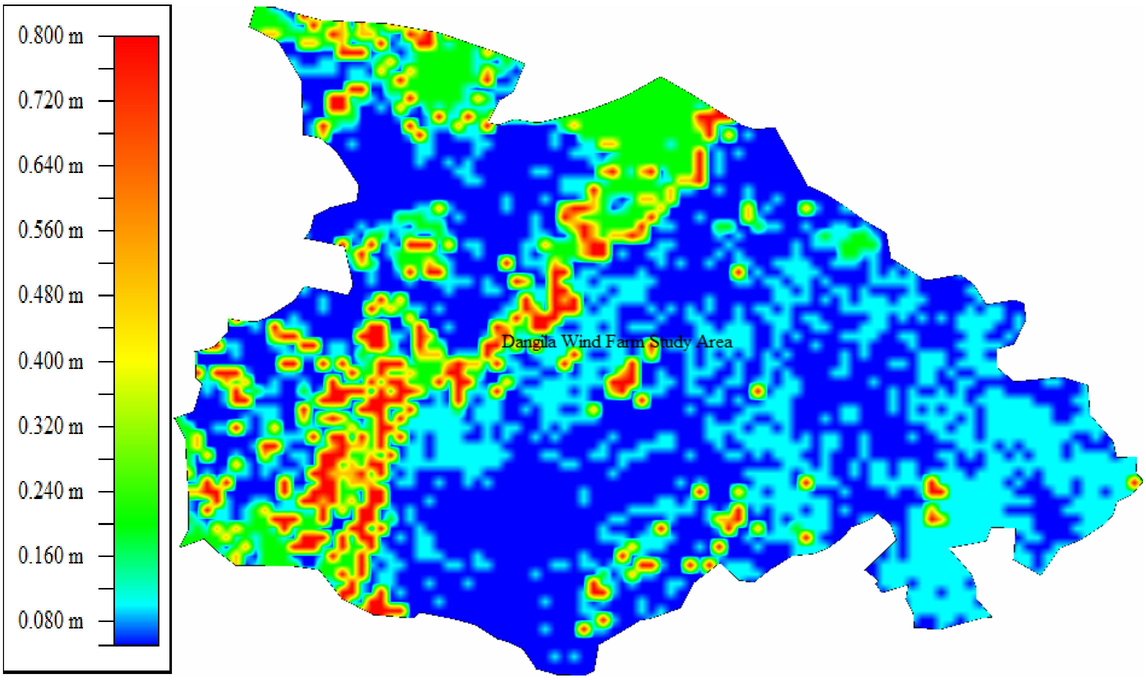


Figure 3.4 Roughness grid Map of Dangla

3.2 Data Collection, Screening, Conversion, and Validation

Data validation is the inspection of all collected data for their completeness and reasonableness and avoids the error values [59]. The wind data (i.e. wind speed and wind direction) used for study the wind resource potential of Dangla Wind Farm is collected from Ethiopian National Meteorology Survey Agency (NAMSA) which is recorded from Dangla meteorology mast located at 10 m a.g.l. in 15 minutes interval. For validating this work a wind data recorded in 10 minutes interval at 40 m a.g.l of Mossobo- Harena meteorology mast was used. The data was recorded by data logger in raw binary format (.raw) and these data were converted into a text file format (.text), database format (.DAT), and excel format (excel workbook). After the conversion of data is completed, the completeness of all data was inspected and checked. The wind speed and wind direction vs time are plotted using MS-Excel to screen the data, to check the missing data, and to observe the quality of data as shown in Figure 3.5 and Figure 3.6 below. The validation process was carried out by checking the missing data, inspecting the average wind speed of each 15 minutes and 10 minutes recorded data, inspecting unrealistic high wind speed and negative value of wind speed and direction.

Table 3.1 Collected data information

Study Area	Dangla	Mossobo Harena
Mast location (°)	11.254° N, 36.8469° E	13.57° N, 39.51° E
Altitude a.s.l.(m)	2124	2401
Mesuring height a.g.l (m)	10 m	40
Interval of time records(minute)	15	10
Duration of recorded data	01/01/2017 to 04/12/2019	01/01/2006 to 31/12/2007

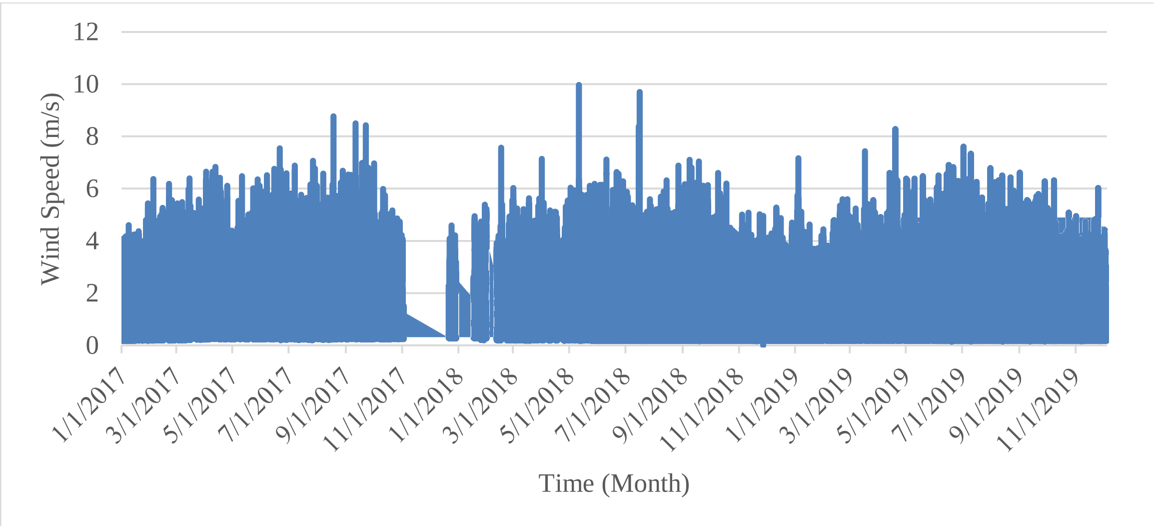


Figure 3.5 Time Vs Wind Speed Graph

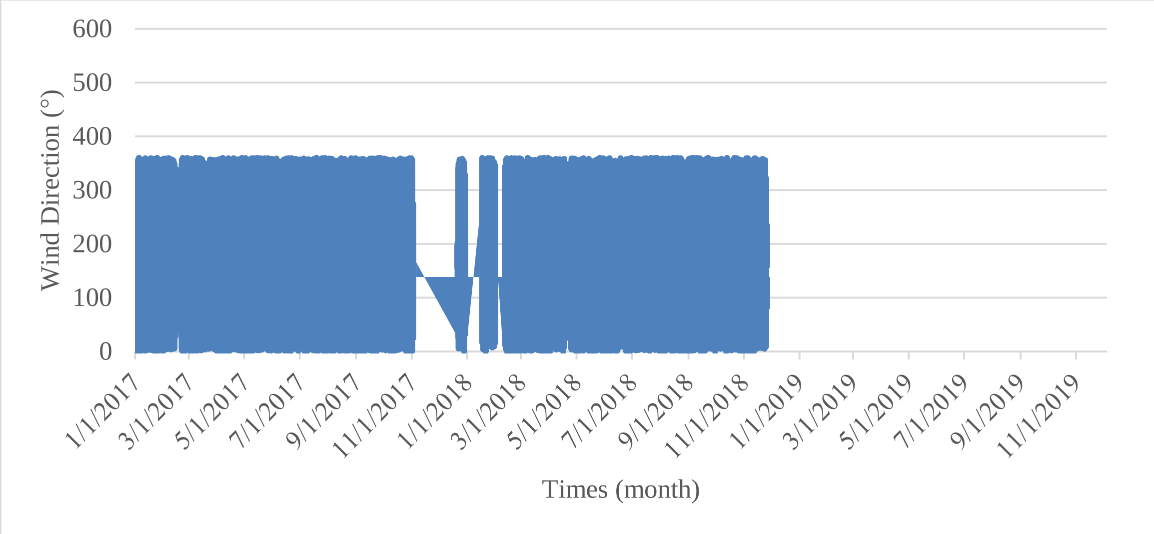


Figure 3.6 Time Vs wind direction graph

3.3 Characterizing the Wind Resource

After the wind resource data validation process is completed, they are analyzed to generate various statistics of measurement that helps to characterize the wind resource. The most common statistical analysis are data recovery, mean speed, speed and direction frequency distribution, wind shear, turbulence intensity, and wind power density.

3.3.1 Data Recovery

Data recovery is defined as the ratio of the number of valid data records to the total number of expected records. It is usually expressed by percentage. Mathematically,

$$\mathrm{DR} = \frac{\mathrm{N_{valid}}}{\mathrm{N}} \times 100\ (\%) \qquad 3.1$$

Where DR is data recovery, $\mathrm{N_{valid}}$ is the total number of valid data records, and N is the total number of possible data records.

3.3.2 Mean Wind Speed

The mean wind speed is defined as the average of the total valid data records in the entire period.

$$V_m = \frac{1}{\mathrm{N_{valid}}} \sum_{0}^{\mathrm{N_{valid}}} V_i \qquad 3.2$$

Where, V_m is the mean wind speed, $\mathrm{N_{valid}}$ is the total number of valid data records, and V_i is the wind speed recorded at the ith time.

3.3.3 Wind Shear

Wind shear is defined as the rate of change in horizontal wind speed with height. It is expressed by a dimensionless power-law exponent known as alpha (α).

The power law is used to relate the wind speeds at two different heights as follows.

$$\frac{V_2}{V_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \qquad 3.3$$

Where, V_2 and $V_1$are the wind speeds at a height h_2 and h_1 respectively.

This equation can be inverted to define the wind shear α in terms of wind speeds and heights:

$$\alpha = \frac{\log \frac{V_2}{V_1}}{\log \frac{h_2}{h_1}} \qquad 3.4$$

3.3.4 Turbulence Intensity

Wind turbulence is defined as a rapid fluctuation in wind speed and direction, which can have a major significant impact on turbine performance and loading. It is the ratio of the standard deviation to mean wind speed.

Mathematically,

$$TI = \frac{\sigma_v}{V_m} \qquad 3.5$$

3.4 Wind Atlas Analysis and Application Program (WAsP) Modeling

3.4.1 Introduction to WAsP

WAsP is a software program for the vertical and horizontal extrapolation of wind climate statistics. It contains several models to describe the wind flow over different terrains(i.e. different terrain height and roughness) and close to sheltering obstacles [60]. Conceptually, the WAsP methodology consists of five main calculation blocks. These are Analysis of raw wind data, Generation of wind atlas data, Wind climate estimation, Estimation of wind power potential, and Calculation of wind farm production. The general methodology of WAsP is described in Figure 3.7 below.

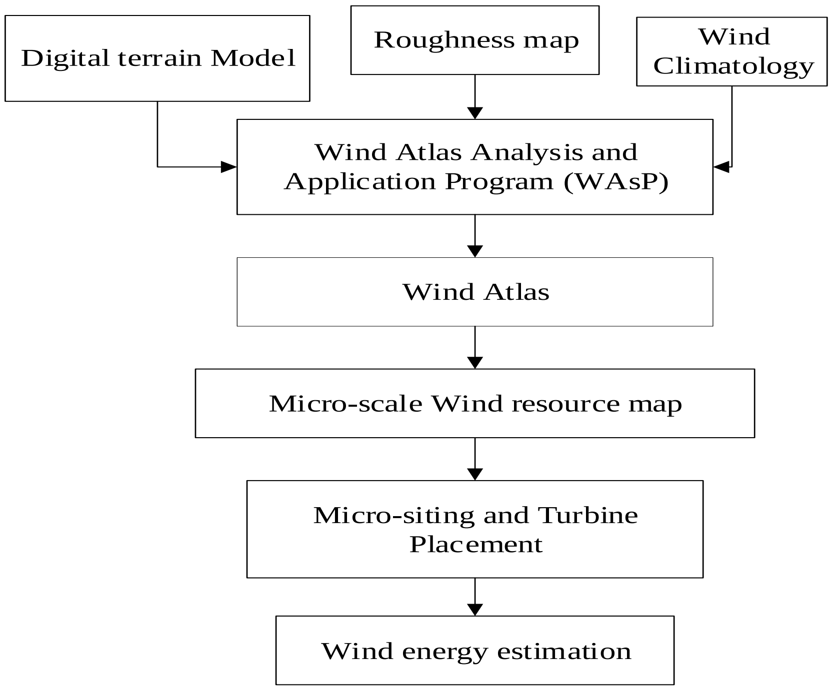


Figure 3.7 General methodology used to estimate the wind energy potential of a site using WAsP

Analysis of Raw Wind Data

The analysis of raw wind data is done through WAsP climate analyst to provide a statistical summary of the time series of wind measurements and observed wind climate for a specific site.

Generation of Wind Atlas Data

The wind atlas(Generalized Wind Climate) data can be generated by converting the analyzed(observed) wind data using WAsP. WAsP requires observed wind climate data and site description to generate the wind atlas data set. They are independent of the site and the wind variation has been decreased to certain standard conditions.

Wind Climate Estimation

The wind climate of a specific point or area at a certain height can be estimated using a generalized wind climate and terrain data (vector map) of a site. This calculation of estimating wind climate can be done by WAsP.

Estimation of Wind Power Potential

The annual wind power(energy) potential of the mean wind can be determined by WAsP. WasP requires predicted wind climate and power curve of the wind turbine for calculating the annual energy production(AEP) of a turbine.

Calculation of Wind Farm Production

The net annual energy production (NAEP) of a wind farm is the difference in gross annual energy production of a wind and wake losses. The gross annual energy production (GAEP) of wind can be calculated by WAsP using wind turbine generator characteristics and predicted wind climate data whereas, determining the wake loss requires wind farm layout in addition to wind turbine generator characteristics and predicted wind climate data. So that WAsP calculates the wake loss of each turbine in a wind farm.

Even though Windsim, WindPro, Meteodyn WT, and WRF are used for wind resource assessment, WAsP is selected for my work because it is simple to use, low cost, takes less computation time, reliable for smooth terrain, and requires less computing power than others.

3.4.2 WAsP Input Parameters

The Wind Atlas Analysis and Application software use the following input data to perform its analysis. These are:

- Observed wind climate data
- Vector map
- Meteorology station
- Obstacle group
- Wind turbine generator
- Reference site, and
- Resource grid

3.4.2.1 Observed Wind Climate (OWC)

OWC is a summary of the wind data recorded at a meteorology station. The summary consists of a wind rose (wind direction frequency distribution) and wind speed frequency distributions – one for each sector. The observed wind climate data can be generated from raw wind data containing the wind speed, wind direction, and location of a meteorology station using a WasP tool known as WasP climate analyst tool. The WAsP Climate Analyst tool requires raw wind data(recording time or timestamp, wind speed in m/s, and wind direction in degree) in DAT file format and meteorology station data. In this study area, three years of wind data and meteorology station data are imported to a WasP climate analyst to generate the observed wind climate data as shown in Figure 3.8 below. The data is measured from Dangla meteorology station at 10 m a.g.l. in which whose meteorology mast is located at 264939.30 m E longitude and 1244926.81 m N latitude. In this analysis, the discretization width of mean wind speed and direction was taken as 0.0000001 and 0.0001 respectively. Whereas, the calm threshold value was set to be 0.55 m/s. The result of the Observed Wind Climate of this site in 12 sectors is described in Figure 3.9 below.

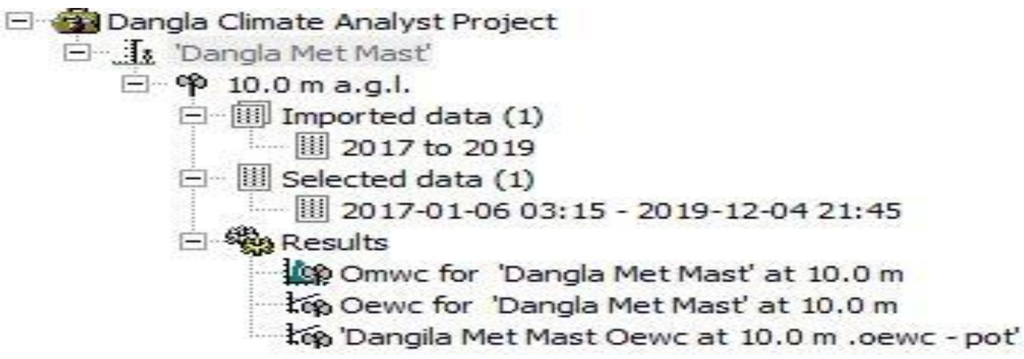


Figure 3.8 WAsP Climate Analyst Setup for wind data analysis and calculating Observed Wind Climate

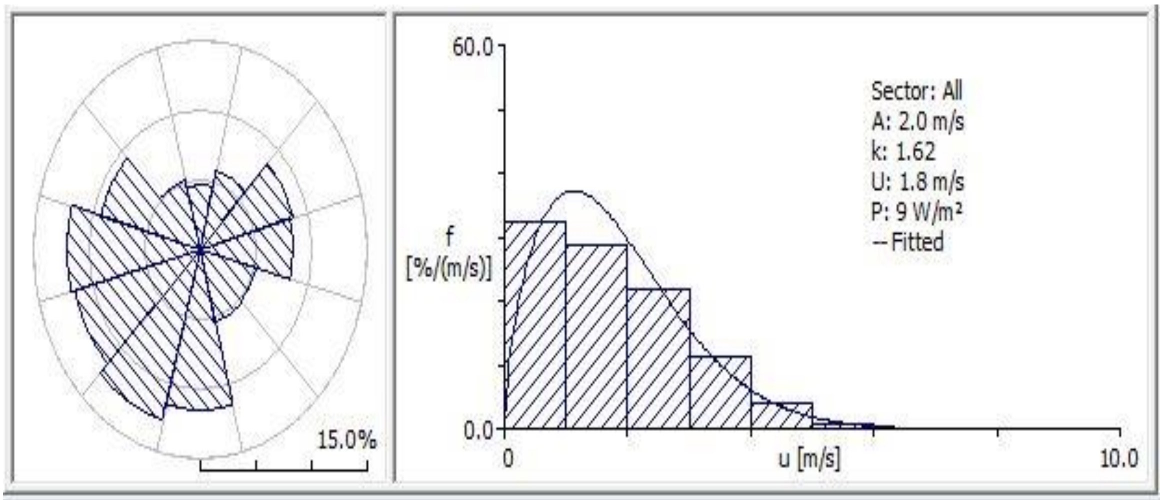


Figure 3.9 Observed Wind Climate of Dangla Met station at 10-meter a.g.l.

3.4.2.2 Vector Map of the Study Area

WAsP uses vector maps to get information about the elevation and roughness data of the landscape in which the modeling is being done. Maps can appear in various places in the workspace hierarchy, but typically each project will have one map. In this study, one vector map is used for the met. station and for the prediction sites. The vector map is generated using the WAsP map editor. The WAsP map editor uses a contour map and roughness map of a site in vector format. Both the contour map and roughness map are generated using a GIS tool known as Global mapper from terrain data of ASTER GDEM worldwide elevation data (1 arc resolution) and land cover data of ESA CCI (climate change initiative) 2010

(Global land cover - 500 m resolution). After exporting the two data in the WAsP map format, the exported results are imported into the WAsP map editor. So that a digitized vector map can be generated. For this analysis, the map projection used is WGS 1984 and the projection type is UTM-Proj.-N.hemisphere. The time zone is set to 37. The summary of these results is described in Figures 3.10 and 3.11 below.

In the vector map of Dangla (see Figure 3.11 below) the red colored lines indicate the contour map whereas the green-colored lines are the roughness change lines.

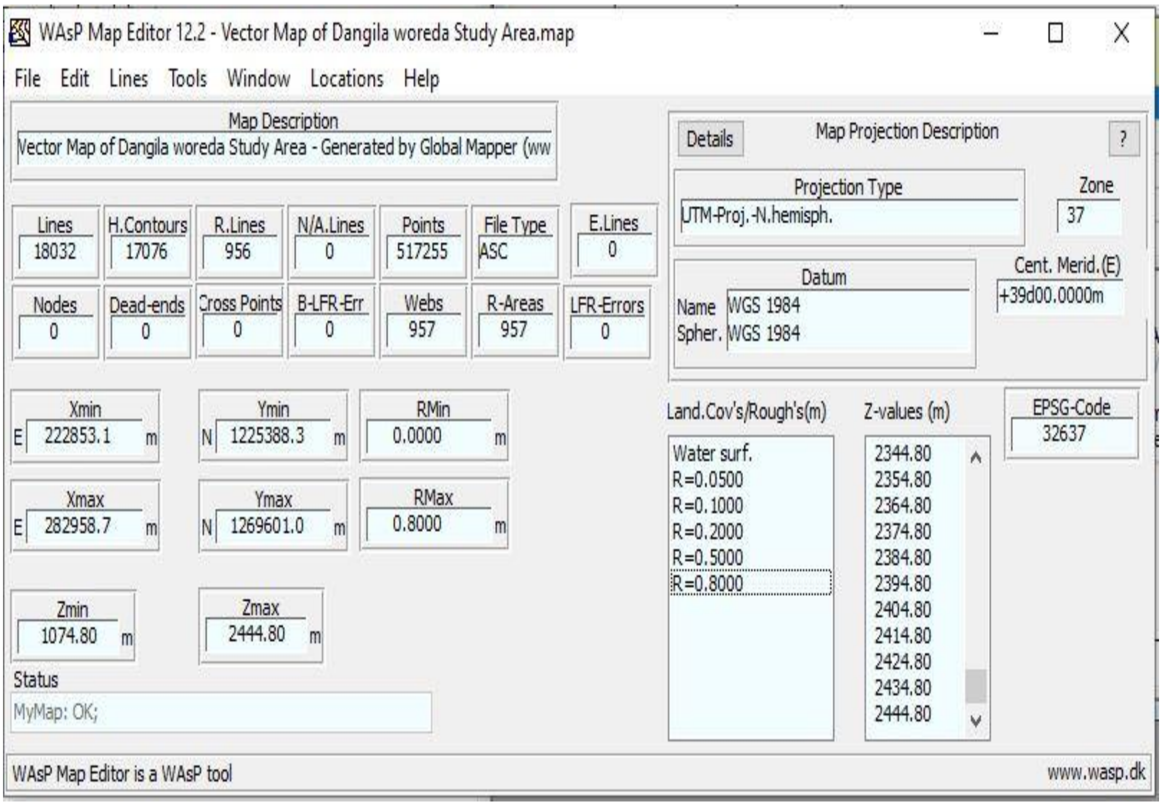


Figure 3.10 WAsP map editor results of Dangla

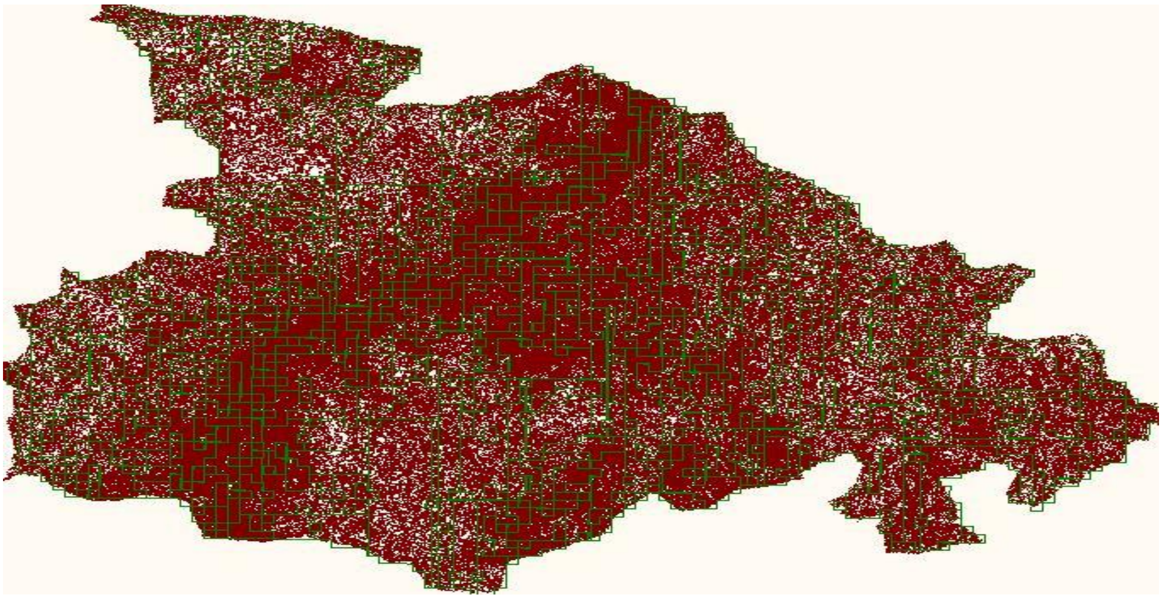


Figure 3.11 Vector map of Dangla Wind Farm

3.4.2.3 Obstacle Group

Meteorology stations and (less commonly) turbine sites can have sheltering obstacles in their surroundings. An obstacle group is a description of some sheltering obstacles which can be associated with one or more sites. It includes terrain features such as shelters belts, houses, walls, and a group of trees. According to a rule of thumb if the distance of an obstacle and point of interest for calculation is less than 50 times the obstacle height and its height is lower than 3 times obstacle height, then the feature is treated as sheltering obstacle whereas if the distance between an obstacle and the point of interest is greater than fifty times of its height and the height is lower than thrice of its height, then the feature is treated as a roughness element [61]. However, in this case, no obstacle group is presented and the feature is treated as a roughness element. As a result, a roughness of terrain is assigned.

3.4.2.4 Reference Site

Reference sites are used to support the calculation of a wind farm power curve, i.e. the production of a given wind farm as a function of the wind speed and direction at the reference site. Reference sites are similar to turbine sites since they calculate a predicted wind climate for a particular point. The reference site used for this analysis is located at geographic coordinates of 247450 m E and 1251550 m N. The height of the reference site is taken to be 10 m a.g.l.

3.4.2.5 Turbine Site

A turbine site is used to estimate the power production which would result from locating a turbine somewhere in an associated map. A turbine site does not have any data except its location in the map, the hub height of the turbine, and user-specified corrections. A turbine site may be associated with a list of obstacles surrounding the station and also a description of the roughness lengths of the surrounding area. A set of user corrections can be associated with a turbine site. It provides a way of informing WAsP about some site-specific adjustments which cannot be described using the other hierarchy members.

The turbine sites are located according to the Danish Wind Energy Association rule of thumb. It states that the wind turbines in wind parks are usually installed in a distance between 5D and 9D in the prevailing wind direction and between 3D and 5D in the direction perpendicular to the prevailing winds.

3.4.2.6 Wind Turbine Generator

A wind turbine generator member describes the way that a turbine's power output changes with wind speed and also the thrust characteristics of the wind turbine. It can be associated with wind turbine sites or wind farms.

The annual energy production of the typical wind farm mainly depends on the wind resource characteristics and type of wind turbine selected. So, an appropriate wind turbine generator is selected by considering its suitability for the site, price, warranty, cutin speed, cutout speed, capacity, and accessibility. The suitability of the turbine for the site is done according to IEC classification of turbines [62] as it is provided in Table 3.2.

In order to check the suitability of the site, the wind characteristics at different hub height are calculated using power-law by taking the wind shear exponent as 0.36521. The energy production capacity of different wind turbines was analyzed as it is discussed in section 4.3.7.

Table 3.2 Basic parameter of wind at hub height and corresponding wind turbine classes

Hub height a.g.l. (m)	V_{m} (m/s)	V_{ref} (m/s)	V_{G50} (m/s)	TI (m^2/s^2)	WT class
10	1.8	9	12.6	0.1	IV B
40	3	15	21	0.14	IV B
70	3.66	18.3	25.6	0.12	IV B
80	3.85	19.25	30	0.113	IV B
100	4.17	20.85	29.2	0.1	IV B

It is known that the wind speed distribution and cost of the turbine increases with hub height but as it is shown in Table 3.2 above, the increase in hub height has no significant effect on mean wind speed. So, by considering the cost, power production capacity, availability, and suitability of the turbine, Vestas V100-1.8 MW GridStreamer wind turbine generator is selected from the WAsP catalog. The cut-in wind speed and cut-out wind speed of the selected wind turbine generator are 3 m/s and 20 m/s respectively whereas its rated wind speed is 12 m/s.

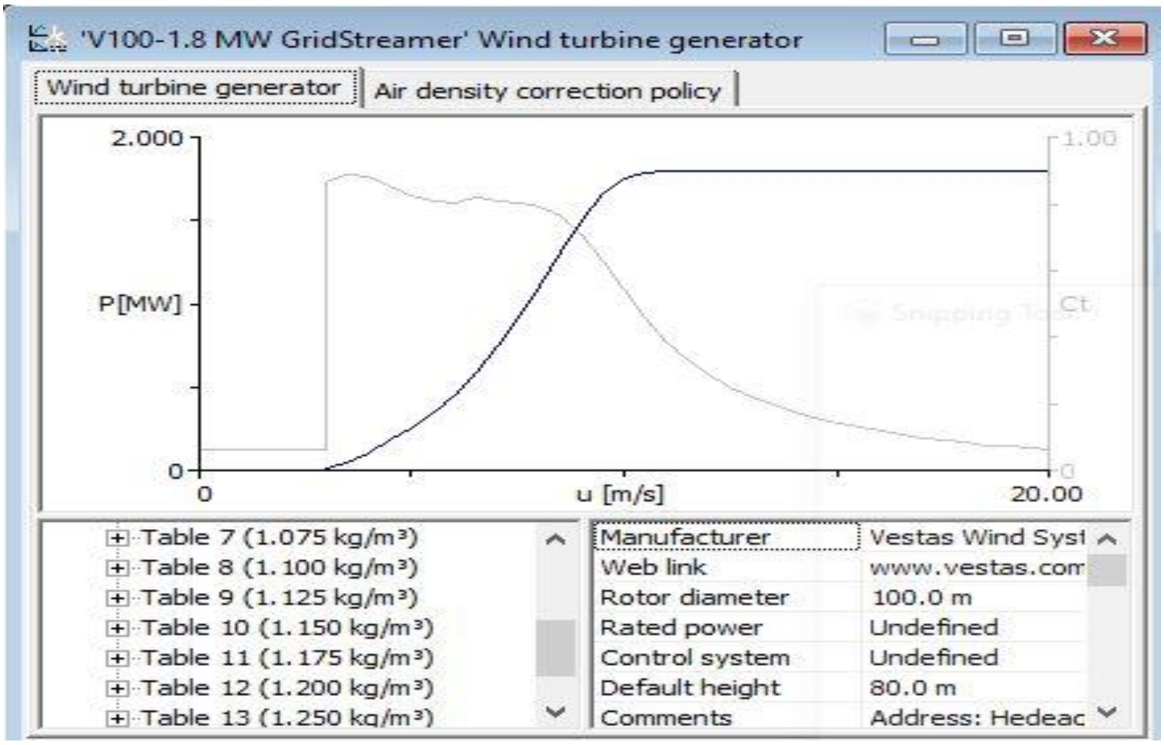


Figure 3.12 Power curve of selected wind turbine generator

Table 3.3 Basic characteristics of Vestas V100-1.8 MW GreadStreamer wind turbine generator

Rated power	1,800 kW
V_{in}	3 m/s
V_R	12 m/s
V_{out}	20 m/s
Wind Class	IIIa
D_{rotor}	100 m
Swept area	7,854 m^2
Blades	3
Hub height	80 m
Manufacturer	Vestas Wind System A/S (Denmark)
Price	€1,875,000

3.4.2.7 Wind Farm

Wind farms are collections of turbine sites which are calculated in a batch. Wind farms offer a convenient way to work with several sites together. In addition to the estimation of the wind climate and power production of the wind farm and wind turbines, the wind farm member also holds information about the wake losses in the wind farm.

3.4.2.8 Resource Grid

Resource grids are collections of 'light-weight' turbine sites calculated in a batch that are arranged in a regular grid covering an area. The extension of the grid and the grid cell size are chosen to map the wind climate or wind resource anywhere in the map and with as much detail as is required. Resource grids can be masked to reduce calculation time.

Table 3.4 Grid Setup

Height a.g.l.	10 m, 40 m, 70 m, 80 m, and 100 m
Resolution	100 m
Nodes extent	(233600, 1234200) to (265500, 1256600)
Boundary extent	(233550, 1234150) to (265550, 1256650)

3.4.3 Creating WAsP Hierarchy Files

WAsP hierarchy files are the added items or files to the workspace that are arranged in a hierarchy to work with WAsP. The hierarchy contains WAsP workspace, projects, terrain data, wind climate data, site data, wind turbine generators, and resource grids [63].

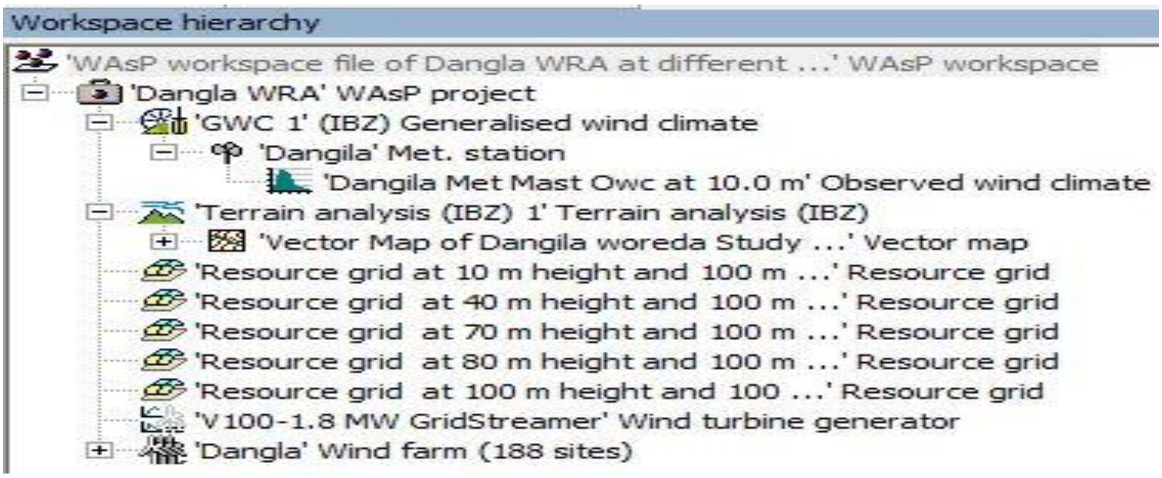


Figure 3.13 WAsP workspace hierarchy

All members of the hierarchy (except the hierarchy root) can be inserted, moved around or deleted. For creating WAsP hierarchy files a map projection of WGS 1984 is selected for my study area zone (i.e. Zone 37). The workspace hierarchy and the data it contains are saved in a WAsP workspace hierarchy file (*.wwh).

3.4.4 Calculating the Generalized Wind Climate (Wind Atlas)

Wind atlas contains data describing a site-independent characterization of the wind climate for an area. The WAsP models are used to analyze the wind data collected from meteorology stations to produce wind atlases and applying the atlas to estimate the wind climate (and power production) at turbine sites. WAsP needs observed wind climate data, meteorology station data, and terrain data to calculate the wind atlas of a turbine site at different heights and roughness classes. This is presented schematically in the wind atlas (generalized wind climate) methodology of Wind Atlas Analysis and Application Program (WAsP) as Figure 3.14 below.

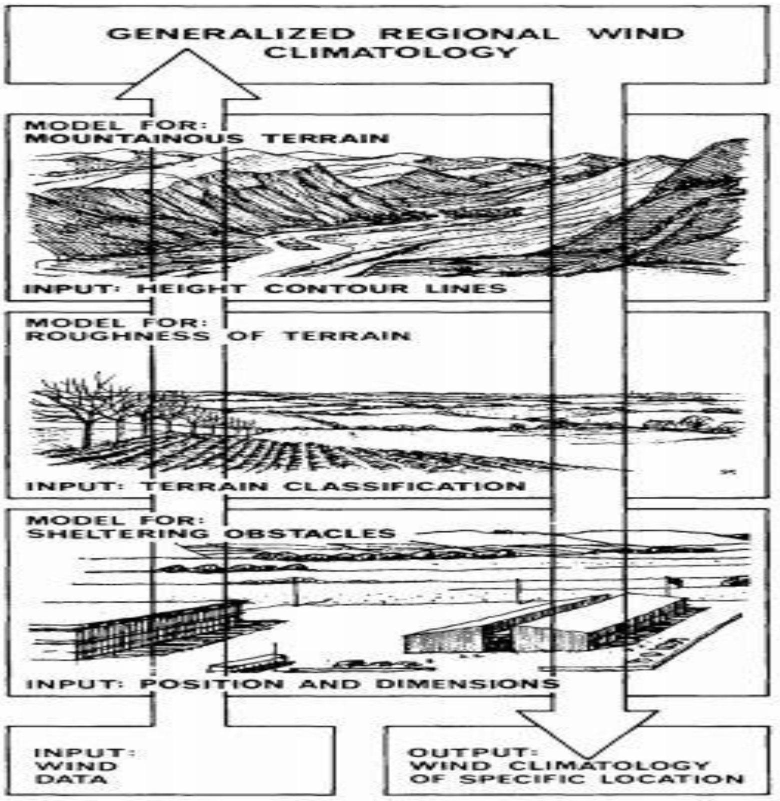


Figure 3.14 Wind atlas methodology of WAsP [64]

3.4.4.1 Setting up a Meteorology Station

The generalized wind climate is generated from the wind measurements taken from the Dangla Meteorological Station located at 1244926.81 m N (Y-axis) and 264939.30 m E (X-axis) at 10 m a.g.l.

3.4.5 Estimating Wind Power

In WAsP, the energy potential of wind is determined using Weibull distributions. With WAsP 12, the total power production is calculated as the sum of the sector-wise power production. Once the power curve and the probability density function at hub height is determined, the mean wind power generated by a turbine is given by

$$P = \int_0^\infty \left(\frac{K}{A}\right)\left(\frac{U}{A}\right)^{k-1} exp\left(-\left(\frac{U}{A}\right)^k\right) P(u)\, du \qquad 3.6$$

WAsP needs the generalized wind climate, site description (vector map), and a power curve describing the generating characteristics of the turbine to determine the wind energy potential of the turbine site. The detailed procedures are discussed in the following sections.

3.4.5.1 Setting up a Turbine Site

Once the project contains a generalized wind climate (GWC) with site-independent wind climate data, it is possible to apply those data to the proposed turbine site. WAsP can adjust the data for the situation found at the turbine site and can produce a prediction of the wind climate for the site itself. So a turbine site hierarchy member is added to the workspace.

3.4.5.2 Assigning the Power Curve

In order to predict how much power will be produced by the turbine, WAsP needs to know the power production characteristics of the turbine. This information is provided to WAsP by associating a wind turbine generator hierarchy member with the turbine site. Since the hub height is different from the default prediction height (1 m a.g.l.), the prediction height is changed to the actual hub height [65].

The air density at the respective hub height (80 m a.g.l.) was calculated using the air density calculator to manage the air density correction policy.

The air density correction policy is managed in the 'Air density correction policy'- tab and the power curve is adjusted to each site dominant mean air density and the calculated air density selecting the closest air density to it which is 0.97 kg/m^3.

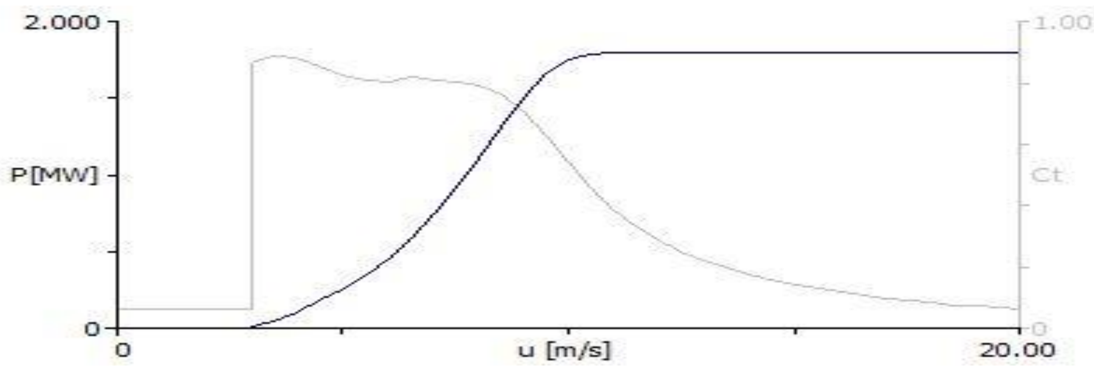


Figure 3.15 Power curve of selected wind turbine generator

3.4.5.3 Predicting Wind Climate and Annual Energy Production

Once the wind atlas, the vector map in which the resource grid is located, a power curve describing the generating characteristics of the resource grid, and the resource grid is configured, WAsP predicts the wind climate at the turbine site.

3.4.6 Wind Resource Mapping

The wind resource map contains resource grids. A wind resource grid is a data structure that describes how the wind resource varies across the site. For these resource grids, WAsP is used to calculate and show Weibull shape and scale factor values, mean wind speed, power density, elevation, ruggedness index RIX, performance indicator DRIX, and annual energy production of each point in a grid which leads to estimate the wind energy production of the wind farm [63].

WAsP needs the generalized wind climate, site description (vector map), a power curve describing the generating characteristics of the turbine, and the resource grid, to determine the wind energy potential of the turbine site. The detailed procedures are discussed in the following sections.

3.4.6.1 Setting up a Resource Grid

To make a map of the wind resource over an area, a resource grid hierarchy member is added to the workspace. As a result, new resource grids with a hub height of 10, 40, 70, 80, and 100 m a.g.l. are inserted as a child of the project. The wind turbine generator is moved to the project level to make all calculations for this turbine type and height. The terrain map, wind turbine generator, and generalized wind climate data set are thus common for all three calculating members in this hierarchy.

3.4.6.2 Configuring the Resource Grid

After a resource grid is set up, WAsP requires the location and structure of the resource grid in the map to calculate the wind climate and annual energy production of the farm. The resource grid is configured according to the grid setup presented in Figure 3.16 below so that the predicted wind climates and annual energy production of the farm can be calculated.

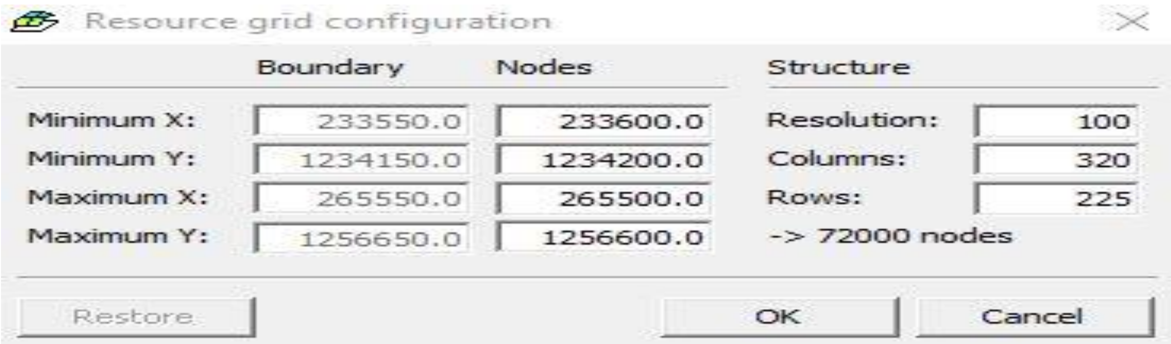


Figure 3.16 Grid Setup of Dangla Wind Farm

3.4.7 Estimating Wind Farm Production

A wind farm is a collection of wind turbines located on the same site to produce electricity. They may vary in size according to the number of wind turbines covering an area. Wind farms can be either onshore or offshore. In this case, an onshore wind farm is developed using WAsP 12.

The wind energy industry requires a correct estimation of how much amount of energy can be produced from a wind farm in a lifetime of normally 20 years [66]. The wind farm production rate can be measured by calculating either the gross annual energy production (GAEP) or net annual energy production (NAEP) of the wind farm. Gross energy production is the total power output of a wind plant without a wake or other losses in one year. It can be calculated for each turbine on a farm using the following equation:

$$GAEP_k = 8760 \sum_i^{N_D} \sum_j^{N_u} f_{ijk}\, p_{ijk} \quad 3.7$$

Where, N_D is the number of direction sectors N_u is the number of wind speed bins, f_{ijk} is the fractional frequency of occurrence, and p_{ijk} is the energy production for direction sector i and wind speed bin j.

Net annual energy production is the gross annual energy production minus the production losses. There are six categories of production losses which are expressed as a percentage of gross annual energy production. These are wake losses, availability uses, turbine performance losses, electrical losses, environmental losses, and losses due to curtailments. The total production losses can be calculated as:

$$L_{total} = 100\% - \prod_i (100\% - L_i) \qquad 3.8$$

Where Li denotes the production loss i in percentage.

The categories of losses and their range of values is described in Table 3.5.

Table 3.5 Loss categories and typical values

Loss category	Minimum	Typical	Maximum
Wake effect, %	3	6.7	15
Availability, %	2	6.0	10
Electrical, %	2	2.1	3
Turbine performance, %	0	2.5	5
Environment, %	1	2.6	6
Curtailment, %	0	0	5
Total losses, %	7.8	18.5	37.0

Source: AWS Truepower.

There are different software used to estimate the energy production of a wind farm using different wind farm models. However, in the Wind Atlas Analysis and Application Program (WAsP), the wind farm is modeled using a park model to predict the wake effect of each turbine and the power production of the wind farm. It is predicted based on the mathematical model of the wake behind the wind turbine. This model uses a momentum deficit theory to predict the flow field in a very simple way; the wake is assumed to expand linearly behind the rotor. The wind farm geometry and flow field used by the park model is shown below.

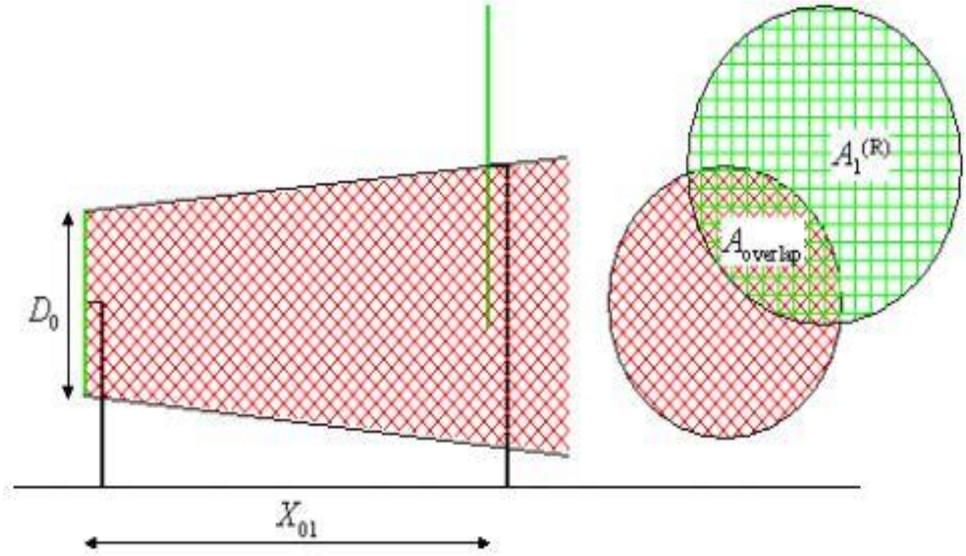


Figure 3.17 The geometry of the park model used by WAsP [67]

Mathematically, the effective downwind speed deficit at the wind turbine is

$$\delta V_{01} = U_0\left(1 - \sqrt{1 - C_t}\right)\left[\frac{D_0}{D_0 + 2kX_{01}}\right]^2 \frac{A_{overlap}}{A_1^{(R)}} \quad 3.9$$

Where,

U_0 is the undisturbed wind speed at the upwind direction ("O") with a rotor diameterD_0,

C_t is thrust coefficient,

X_{oi} is the horizontal distance of downwind between the wind turbines, and

K is wake decay constant.

WAsP needs predicted wind climate, the layout of the wind farm, and wind turbine generator to estimate the wind farm production. The detailed procedures are discussed below.

3.4.7.1 Setting up a Wind Farm

A wind farm can be set up by adding a wind farm hierarchy member to the workspace. Then new turbine sites can be added to the wind farm. WAsP requires the locations of wind farm turbine sites in the map and a description of the type of wind turbine that is proposed to use to calculate the wind farm production.

3.4.7.2 Locating the Turbine Sites

The turbine sites are located based on the rule of thumb of the Danish Wind Energy Association. Using Google Earth synchronization, the turbines are placed at places where there are relatively high wind speed, low RIX values, and they are clear from obstacles, towns, homes, water bodies, and roads. They are spaced between 500 m to 900 m apart in the prevailing wind direction, and between 300 m and 500 m apart in the direction perpendicular to the prevailing winds.

The location of the sites can be adjusted to their exactly specified positions by using the site dialog box, which can be reached at any time from the right-click menu of the turbine site icon in the workspace hierarchy by choosing Show or in the map itself.

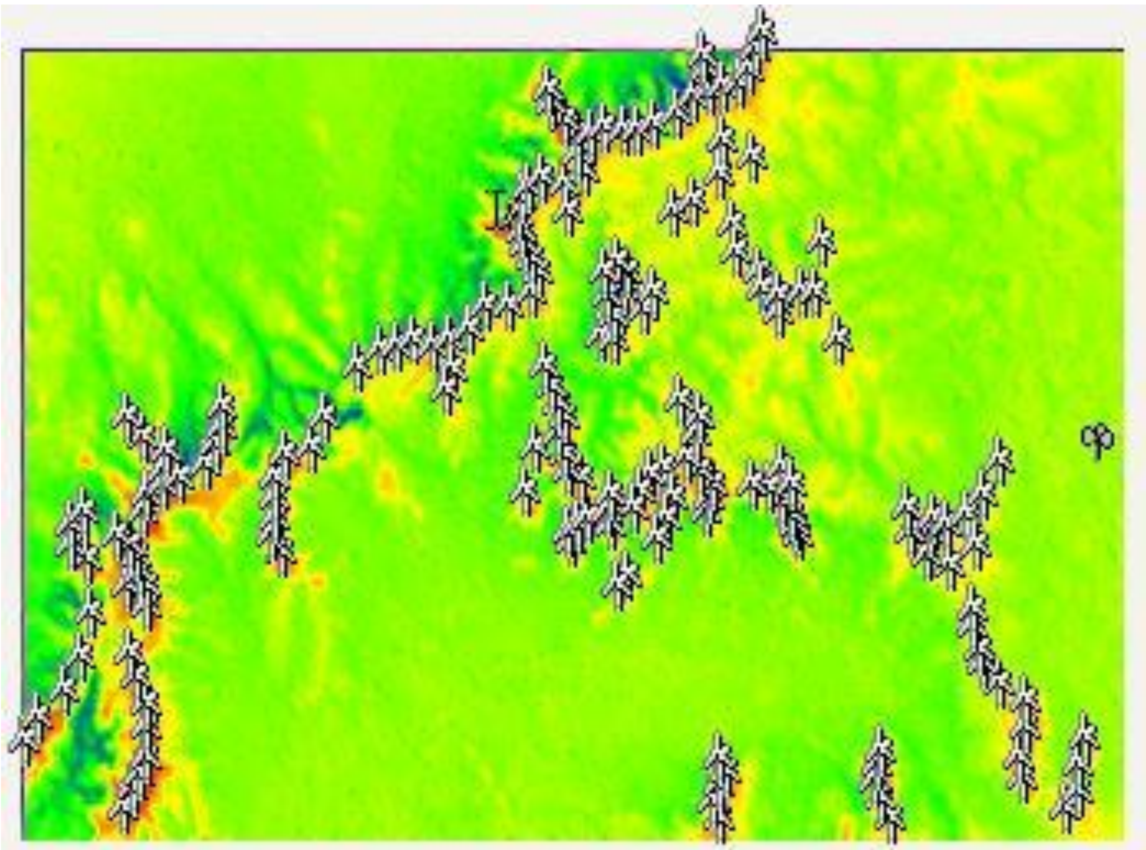


Figure 3.18 Windfarm layout of Dangla

3.4.7.3 Assigning Wind Turbine Generators

WAsP needs the power production and thrust curve of each turbine to predict how much power will be produced by the wind farm. The turbines on the farm are all of the same types. The turbine information (Vestas V100 -1.8 MW Grid Streamer wind turbine generator) is provided to WAsP by associating a wind turbine generator hierarchy member with the wind farm.

3.4.7.4 Predicting Wind Farm Production

Once the wind atlas, the vector map in which the wind farm sites are located, a power curve describing the generating characteristics of the turbines, and a wind farm is set, WAsP is now ready to predict the wind farm production. The wind farm production can be calculated by selecting “Calculate the wake losses and summary statistics for a wind farm” from the wind farm's right-click menu.

3.5 Economic Analysis of Wind Farm

The cost of a wind energy system is commonly expressed by cost per unit rated capacity of the turbine, cost per unit rotor size, and cost per unit kWh of electricity generated. Among these methods, the cost/kWh is a better economic indicator [68].

Wind power is characterized by low variable costs and relatively high fixed costs. The main factors governing wind power economics are [45]:

- Investment costs, including wind turbines, foundations, and grid connection
- Operation and maintenance (O&M) costs, including regular maintenance, repairs, insurance, spare parts, and administration
- Wind turbine’s electricity production cost, which highly depends on the wind turbine capacity, wind farm size, and average wind speed at the chosen site
- Wind turbine lifetime and
- Discount rate

The capital cost of the wind power plant mainly depends on the price of wind turbines. Most studies described that the lifetime of wind power plants ranges from 20 to 30 years. In this period, an investor gets income from selling electricity and different incentives like production tax credit and income from greenhouse gas emission reduction. According to the World Bank report [69], the electricity tariff in Ethiopia is going to be increased to $0.07/kWh in 2021 and according to CNCF, 1 kWh of electricity produced from a coal-burning plant will generate 0.94 kg of CO_2 emission to the atmosphere. The average price of a CO_2 allowance is €25/tCO_2 [70].

The economic and financial analysis of the project can be determined by the Levelized cost of electric energy, net present value, benefit-cost ratio, payback period, and internal rate of return.

Levelized Cost of Electricity, LCOE

The Levelized Cost of electricity is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. It is also defined as the present value of the price of the produced electrical energy in cents/kWh. An electric price above the LCOE would yield a great return on capital, while the price below it would yield a lower return on capital, or even a loss [71].

For wind power plants, considering the economic life of the plant and the costs incurred in the construction, operation and maintenance, the capacity factor CF, and the Production Tax Credit PTC;

$$LCOE_{wind} = \frac{\sum_{i=1}^{i=n} \frac{(I_t + O\&M - PTC)}{(1+i)^t}}{CF \sum_{i=1}^{i=n} P_t} \qquad 3.10$$

Electricity Cost Per Unit Energy

The electric cost per unit energy is calculated by estimating the sum of the total investment and the discounted value of operational and maintenance costs in all years.

$$C = \frac{NPV(C_A)_{1-n} - CI}{P} \qquad 3.11$$

Net Present Value (NPV)

The net present value (NPV) is the net value of all benefits (cash inflows) and costs (cash outflows) of the project, discounted back to the beginning of the investment. It is given by

$NPV = NPV(B_A)_{1-n} - \{C_I + NPV(C_A)_{1-n}\}$ or 3.12

The project is economically acceptable and the investor gets profit if the net present value is greater than zero.

Benefit-Cost Ratio (BCR)

A benefit to cost ratio is the ratio of the accumulated present value of all the benefits to the accumulated present value of all costs, including the initial investment.

$BCR = \frac{NPV(B_A)_{1-n}}{C_I + NPV(C_A)_{1-n}}$ or 3.13

Pay Back Period (PBP)

The payback period is the year in which the net present value of all costs equals the net present value of all benefits. Hence, PBP indicates the minimum period over which the investment for the project is recovered. At PBP,

$NPV(B_A)_{1-n} = C_I + NPV(C_A)_{1-n}$ or 3.14

For obvious reasons, the project with a low payback period is preferred.

Internal Rate of Return (IRR)

The internal rate of return is the discount rate at which the accumulated present value of all the costs become equal to that of the benefits. It is the discount rate at which the net present value of a project is zero. With IRR as the discounting rate, the IRR can be solved from the following equation using trial and error method or numerical techniques like Newton - Raphson Method.

$NPV(B_A)_{1-n} = C_I + NPV(C_A)_{1-n}$ 3.15

Where,

C_I is the initial cost of investment

I is the interest rate

M is the percentage of operation and maintenance cost

N is the life span of the project

B_A is the total cash inflow

C_A is the total cash outflow

Economic analysis is carried out on a simple national economic basis. Taxes, depreciation, and risk premiums are not taken into account [70] and all calculations are based on the following assumptions:

- The total initial investment cost (wind turbine cost + civil work cost + electrical work cost + installation cost) of the project is 130% of the cost of wind turbine [72],
- The annual operation and maintenance cost is 2% of the initial investment,
- The useful life of the project is 25 years,
- The discount rate is taken as 7% based on the interest rate of commercial bank of Ethiopia,
- The local electricity price is $0.07 (or 2.54 Birr)/kWh,
- The profit is 20% of the cost of electricity
- The cost of emission avoided is €25/tCO_2,
- Production Tax Credit (PTC) is $0.023/kWh for the first 10 years,
- The capital is in the form of available invested funds, not borrowed funds, and
- The land is free.

Chapter 4: Results and Discussions

4.1 Data Screening and Validation

The data screening and validation process were conducted according to section 3.2 and the result showed that the wind data used for this analysis were recorded from Jan 01, 2017, to Dec 04, 2019, in 15 minutes (90 s) interval. In this time interval, a total of 92,683 data were recorded and 9,344 data were missed from 2/15/2017/11:45 AM to 2/21/2017/12:15 AM, 11/2/2017/7:45AM to 12/21/2017/6:30 PM, 12/29/2017/ 2:15 PM to 1/17/2018/ 3:30 AM, 1/31/2018/5:30 PM to 2/11/2018/12:00 PM, 4/3/2018/8:15 PM to 4/7/2018/9:30 PM, and 4/18/2018/12:00 PM to 4/24/2018/7:15 PM. Not only missing records but also, there were 2 invalid records which were recorded on 11/27/2018 at 10:36 AM and 10:48 AM and there were 18 incorrect records of wind direction (records above 360 degrees) which were recorded on from 12/21/2018/12:15 PM to 12/21/2018/4:30 PM. As a result, the filling of the missing data and replacement of the incorrect measures were done by taking the average value of the consecutive year's data and the invalid records had been removed. The summary of data screening and validation results is described in Table 4.1 below.

Table 4.1 Data screening and validation result

No.	Items	Quantity	
		Before Validation	After Validation
1.	Count of selected records	92,683	101,796
2.	Recording interval (s)	900	900
3.	Expected recording count	102,027	102,027
4.	Missing records	9,344	231
5.	Recordings with invalid values	2 (0.00 %)	0 (0.00 %)
6.	Entirely valid recordings accepted	92,681 (90.84 %)	101,796 (99.77 %)

4.2 Characterizing the Wind Resource

After the wind resource data validation process is completed, they are analyzed to generate various statistics of measurement that helps to characterize the wind resource. The most common statistical analysis are data recovery, mean speed, speed and direction frequency distribution, wind shear, turbulence intensity, and wind power density.

4.2.1 Data Recovery

Data recovery is defined as the ratio of the number of valid data records to the total number of expected records. It is usually expressed by percentage.

The data recovery rate was calculated using equation 3.1 and it was found to be 90.84 % before validating the raw data and 99.77 % after screening and validation process is carried out.

4.2.2 Mean wind speed

The mean wind speed is defined as the average of the total valid data records in the entire period. The wind speed of the Dangla meteorology station for the years from Jan 01, 2017, to Jan 04, 2019, was varied from 0.12083 m/s to 9.96389 m/s. The average wind speed of the site was 1.8 m/s.

4.2.3 Wind Shear

Wind shear is defined as the rate of change in horizontal wind speed with height. It is expressed by a dimensionless power-law exponent known as alpha (α).

The wind shear of the Dangla meteorology mast was calculated based on the mean wind speeds recorded at 2m (i.e. Vm = 1 m/s) and 10 m (i.e. Vm = 1.8 m/s) heights above ground level by using power-law or equation 3.4 and the wind shear coefficient was obtained to be 0.36521. Using this wind shear coefficient value, the wind shear profile of the site was plotted as sown in Figure 4.1 below.

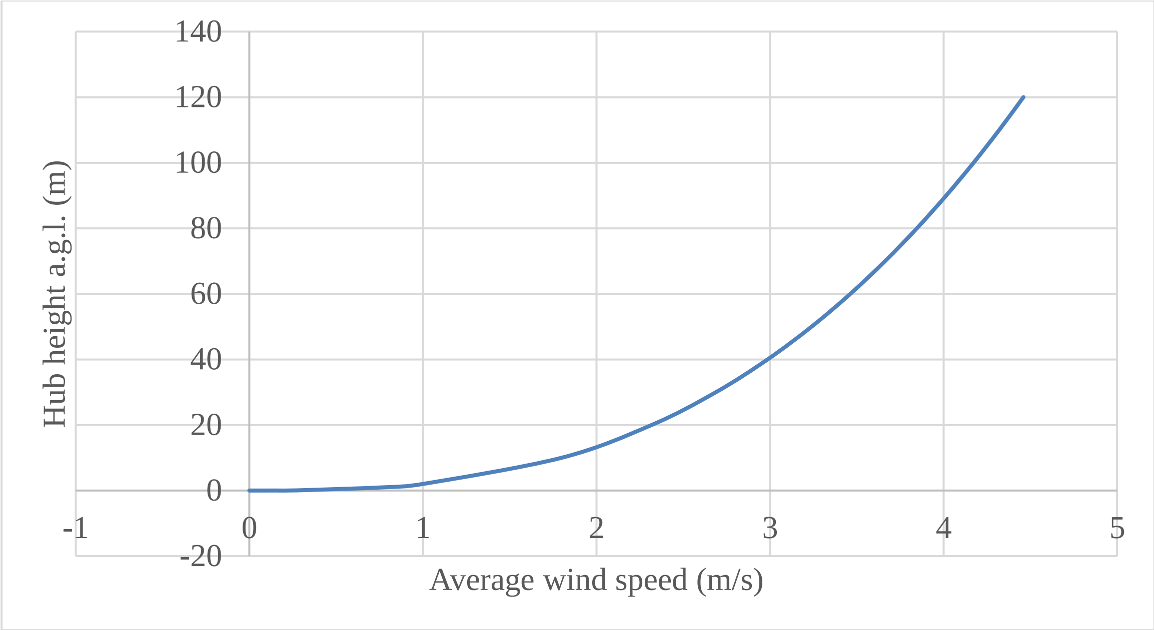


Figure 4.1 Wind shear profile of Dangla Met. Mast

4.2.4 Turbulence Intensity

The turbulence intensity at respective hub height was calculated by WAsP Engineering (WENG 4.0) using Kaimal et al (1972) spectrum type and the result showed that the turbulence intensity of the wind at a hub height of 80m was found to be 11.3%.

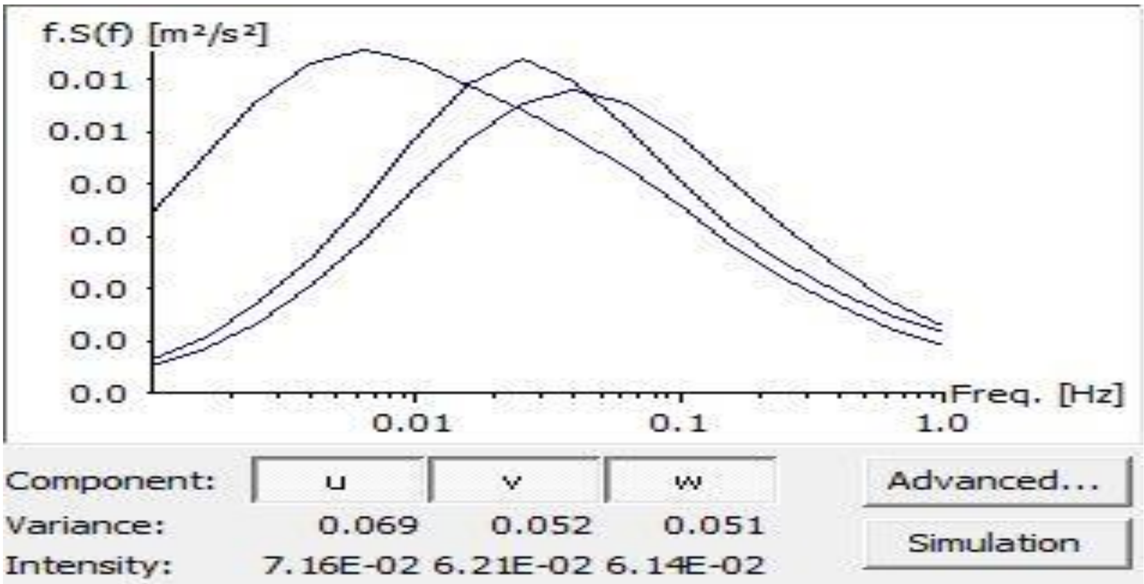


Figure 4.2 Turbulence intensity of Dangla Meteorology Mast

4.3 Results of WAsP Modeling and Analysis

4.3.1 Time Series Data

The data screening and validation process were conducted according to section 3.2 and the result showed that the wind data used for this analysis were recorded from Jan 01, 2017, to Dec 04, 2019, in 15 minutes (90 s) interval. In this time interval, a total of 101,796 data were recorded and 231 data were missed. The time-series graph of both Dangla and Mossobo Masts is described in Figures 4.3 and 4.4 below to show the precision of the data and the variation of wind speed and wind direction with time.

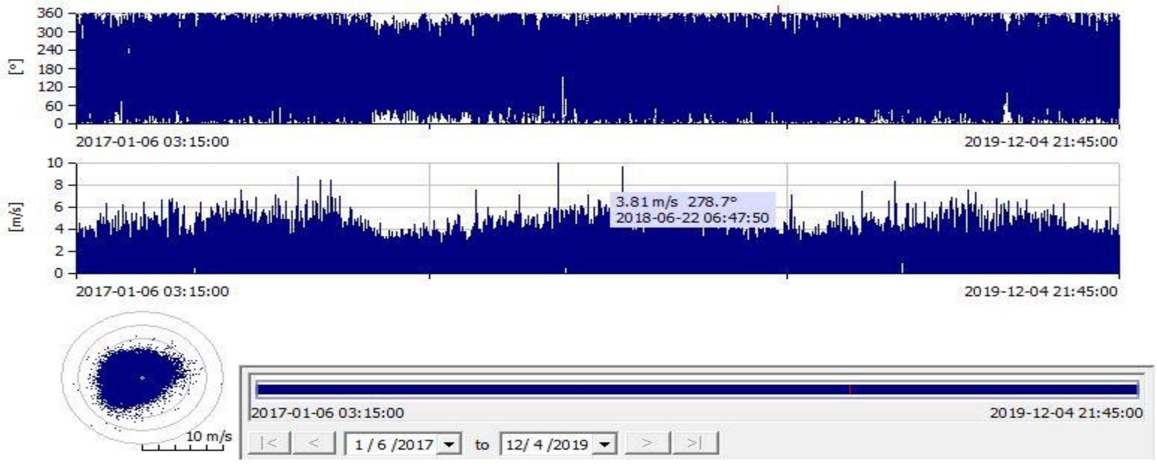


Figure 4.3 Time window data of Dangla Met Mast

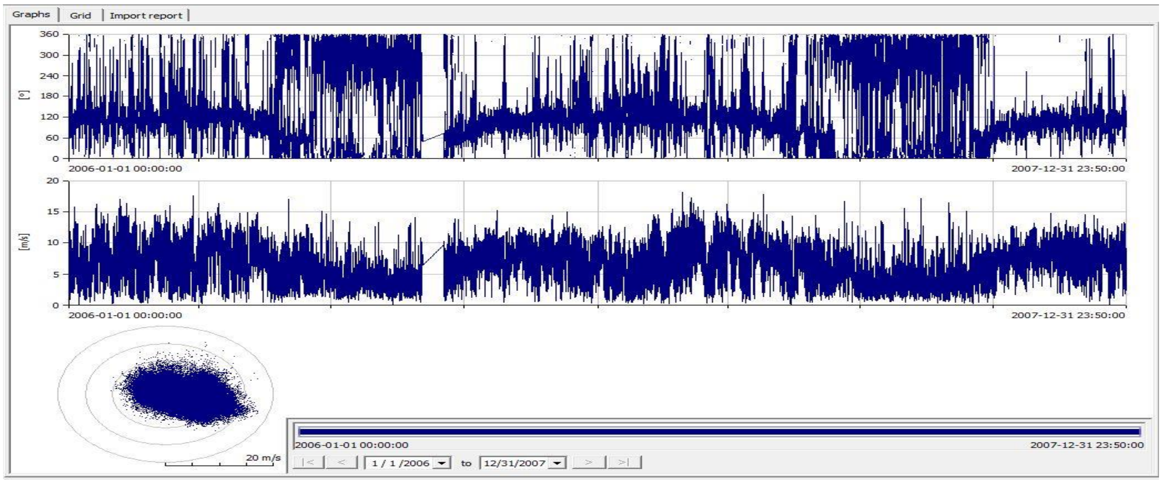
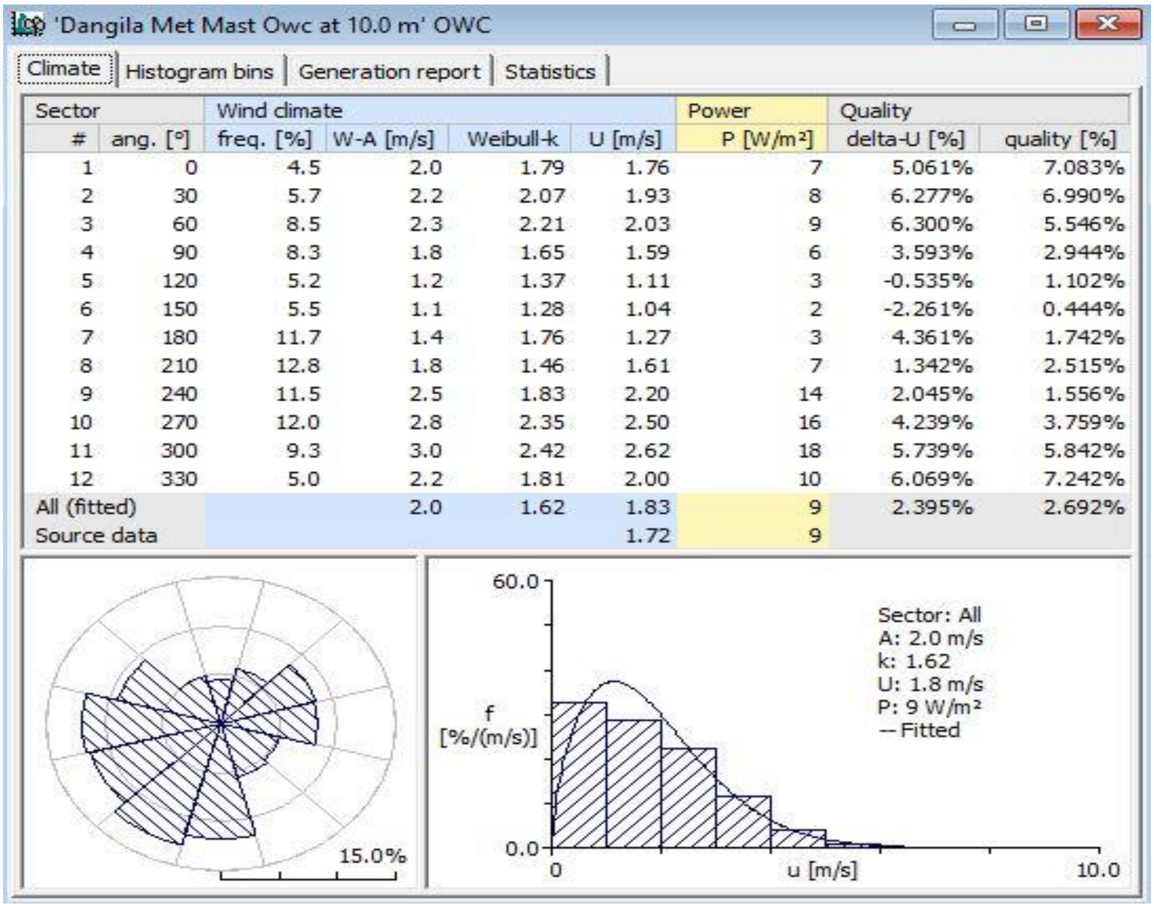


Figure 4.4 Time window data of Mossobo Harena Met Mast

4.3.2 Observed Wind Climate

The average wind speed and direction measured from the Dangla meteorology station have been analyzed using WAsP climate Analyst tool as shown Figure 4.4, 4.5, and 4.6 below and the result showed that the most frequent wind direction falls between the angle 210° and 270° with frequencies of 12.8% and 12.0%, whereas, better wind speed is available from 5:00 AM to 12:00 PM throughout the day. In addition to this, the maximum wind speed was recorded in June and the minimum wind speed was obtained in November and December. The mean wind speed and power density of the site throughout the entire period were also found to be 1.8 m/s and 9 w/m^2 respectively.

In Dangla's observed wind climate, the fitted Weibull distribution, histogram bin, and mean wind speed distribution are described in Figures 4.5, 4.6, and 4.7 respectively.



Sector		Wind climate				Power	Quality	
#	ang. [°]	freq. [%]	W-A [m/s]	Weibull-k	U [m/s]	P [W/m²]	delta-U [%]	quality [%]
1	0	4.5	2.0	1.79	1.76	7	5.061%	7.083%
2	30	5.7	2.2	2.07	1.93	8	6.277%	6.990%
3	60	8.5	2.3	2.21	2.03	9	6.300%	5.546%
4	90	8.3	1.8	1.65	1.59	6	3.593%	2.944%
5	120	5.2	1.2	1.37	1.11	3	-0.535%	1.102%
6	150	5.5	1.1	1.28	1.04	2	-2.261%	0.444%
7	180	11.7	1.4	1.76	1.27	3	4.361%	1.742%
8	210	12.8	1.8	1.46	1.61	7	1.342%	2.515%
9	240	11.5	2.5	1.83	2.20	14	2.045%	1.556%
10	270	12.0	2.8	2.35	2.50	16	4.239%	3.759%
11	300	9.3	3.0	2.42	2.62	18	5.739%	5.842%
12	330	5.0	2.2	1.81	2.00	10	6.069%	7.242%
All (fitted)			2.0	1.62	1.83	9	2.395%	2.692%
Source data					1.72	9		

Figure 4.5 Observed wind climate data of Dangla Met Mast at 10 m a.g.l.

Bin	Sector												
#	1	2	3	4	5	6	7	8	9	10	11	12	Total
<= 1	385	320	263	373	555	587	433	331	211	173	203	356	325
<= 2	206	217	246	317	302	292	449	411	290	202	159	180	287
<= 3	276	314	340	238	120	92	93	157	258	301	244	248	222
<= 4	114	130	124	53	19	26	19	57	147	219	259	161	115
<= 5	17	18	19	13	3	3	4	29	70	88	119	48	41
<= 6	1	1	6	4	1	0	1	10	21	15	14	6	8
<= 7	0	1	1	1	0	0	0	3	3	1	1	0	1
<= 8	0	0	0	0	0	0	0	0	0	0	0	0	0
<= 9	0	0	0	0	0	0	0	0	0	0	0	0	0
<= 10	0	0	0	0	0	0	0	0	0	0	0	0	0
	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

Figure 4.6 Histogram bin result of Dangla Met. Mast

Mean wind speeds (hourly, by month)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	3	3	3	3	3	3	3	3	3	3	2	2	3
1	3	3	3	3	3	3	3	3	3	3	2	2	3
2	3	3	3	3	3	4	3	3	4	3	3	3	3
3	3	3	3	3	3	4	4	3	4	3	3	3	3
4	3	3	3	3	3	4	3	3	3	3	3	3	3
5	3	3	3	3	3	3	3	3	2	3	2	3	3
6	2	2	3	3	3	2	2	2	2	2	2	2	2
7	1	2	2	2	2	2	2	2	2	2	1	1	2
8	2	2	2	2	2	2	1	1	1	1	1	1	2
9	1	2	2	2	2	2	1	1	1	1	1	1	1
10	1	1	2	2	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	0	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	2	2	2	2	2	2	2	2	2	2	2	2
22	2	2	2	2	3	2	2	2	2	2	2	2	2
23	3	2	2	3	3	3	2	2	2	2	2	2	2
Average	2	2	2	2	2	2	2	2	2	2	1	2	2

Mean wind speeds (yearly, by month)

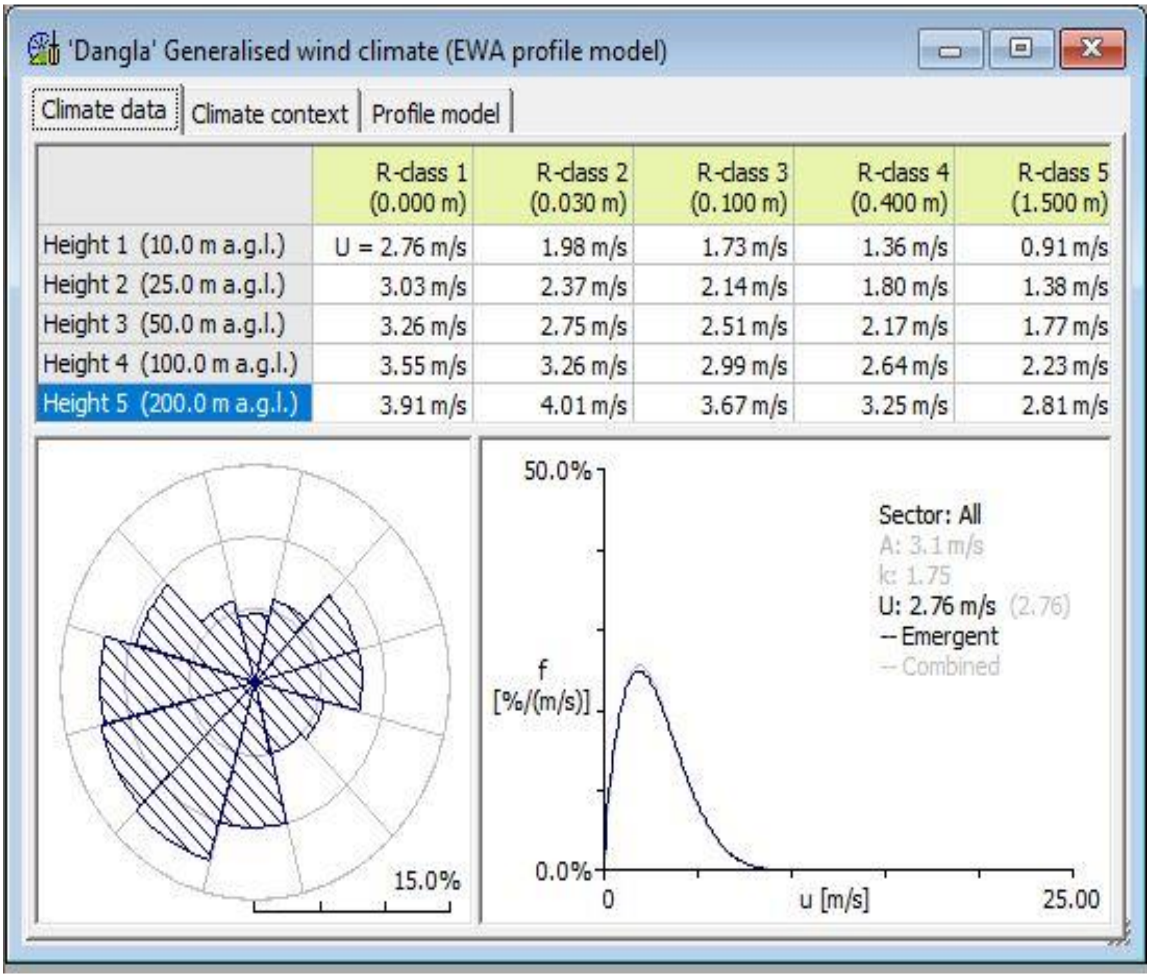
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2017	2	2	2	2	2	2	2	2	2	2	1	1	2
2018	2	2	2	2	2	2	2	2	2	2	1	2	2
2019	2	2	2	2	2	2	2	2	2	2	2	2	2
Average	2	2	2	2	2	2	2	2	2	2	1	2	2

Figure 4.7 Mean wind speeds distribution in hourly, monthly, and yearly basis

4.3.3 Wind Atlas (Generalized Wind Climate)

The wind atlas or regional wind climate is generated from observed wind climate and terrain data of Dangla using WAsP 12.3. The wind atlas contains the wind rose and the wind speed frequency distribution in the same sectors. The wind climates were specified in five roughness classes (R = 0 m, 0.03 m, 0.1 m, 0.4 m, and 1.5 m) and five reference heights (H = 10 m, 25 m, 50 m, 100 m, and 200 m). Unlike observed wind climate, in wind atlas, there are no local terrain effects.

In wind atlas, the emergent and combined Weibull distributions are shown as in Figure 4.8 below. As shown in figure and table below it is observed that the wind speed increases with height but the effect of surface roughness decreases with an increase in height.



	R-class 1 (0.000 m)	R-class 2 (0.030 m)	R-class 3 (0.100 m)	R-class 4 (0.400 m)	R-class 5 (1.500 m)
Height 1 (10.0 m a.g.l.)	U = 2.76 m/s	1.98 m/s	1.73 m/s	1.36 m/s	0.91 m/s
Height 2 (25.0 m a.g.l.)	3.03 m/s	2.37 m/s	2.14 m/s	1.80 m/s	1.38 m/s
Height 3 (50.0 m a.g.l.)	3.26 m/s	2.75 m/s	2.51 m/s	2.17 m/s	1.77 m/s
Height 4 (100.0 m a.g.l.)	3.55 m/s	3.26 m/s	2.99 m/s	2.64 m/s	2.23 m/s
Height 5 (200.0 m a.g.l.)	3.91 m/s	4.01 m/s	3.67 m/s	3.25 m/s	2.81 m/s

Figure 4.8 Wind Atlas (GWC) of Dangla

Table 4.2 Tables of Wind Atlas

		Roughness length 0.000 m	Roughness length 0.030 m	Roughness length 0.100 m	Roughness length 0.400 m	Roughness length 1.500 m
Height at 10.0 m	A (m/s)	3.10	2.21	1.93	1.53	1.02
	K	1.75	1.60	1.63	1.67	1.71
	U (m/s)	2.76	1.98	1.73	1.36	0.91
	PD (w/m2)	28	12	8	4	1
Height at 25.0 m	A (m/s)	3.40	2.66	2.40	2.02	1.55
	K	1.80	1.70	1.72	1.76	1.79
	U (m/s)	3.03	2.37	2.14	1.80	1.38
	PD (w/m2)	36	19	13	8	3
Height at 50.0 m	A (m/s)	3.67	3.10	2.83	2.45	2.00
	K	1.88	1.87	1.87	1.88	1.92
	U (m/s)	3.26	2.75	2.51	2.17	1.77
	PD (w/m2)	43	26	20	13	7
Height at 100.0 m	A (m/s)	3.99	3.68	3.38	2.98	2.52
	K	1.88	1.99	1.98	1.97	1.96
	U (m/s)	3.55	3.26	2.99	2.64	2.23
	PD (w/m2)	56	41	32	22	13
Height at 200.0 m	A (m/s)	4.39	4.52	4.14	3.67	3.17
	K	1.83	1.92	1.92	1.91	1.88
	U (m/s)	3.91	4.01	3.67	3.26	2.81
	PD (w/m2)	77	78	60	42	28

4.3.4 Wind Resource Map

The wind resource grid was developed at different hub heights using WAsP 12. It covers an area of 31.9 km × 22.4 km area. The grids were spaced 100 m and 72000 nodes were obtained in 320 rows and 225 columns. The wind resource grid calculated by WAsP 12 showed that the mean speed, mean power density, mean AEP of the resource grid increases with height. The detailed resource grid results obtained from WAsP 12 (wind speed, power density, ruggedness index, and annual energy production, etc.) are described below.

Mean wind speed

The mean wind speed of Dangla Wind Farm at 10, 40, 80, and 100 m heights a.g.l. were calculated using WAsP and the following results were obtained.

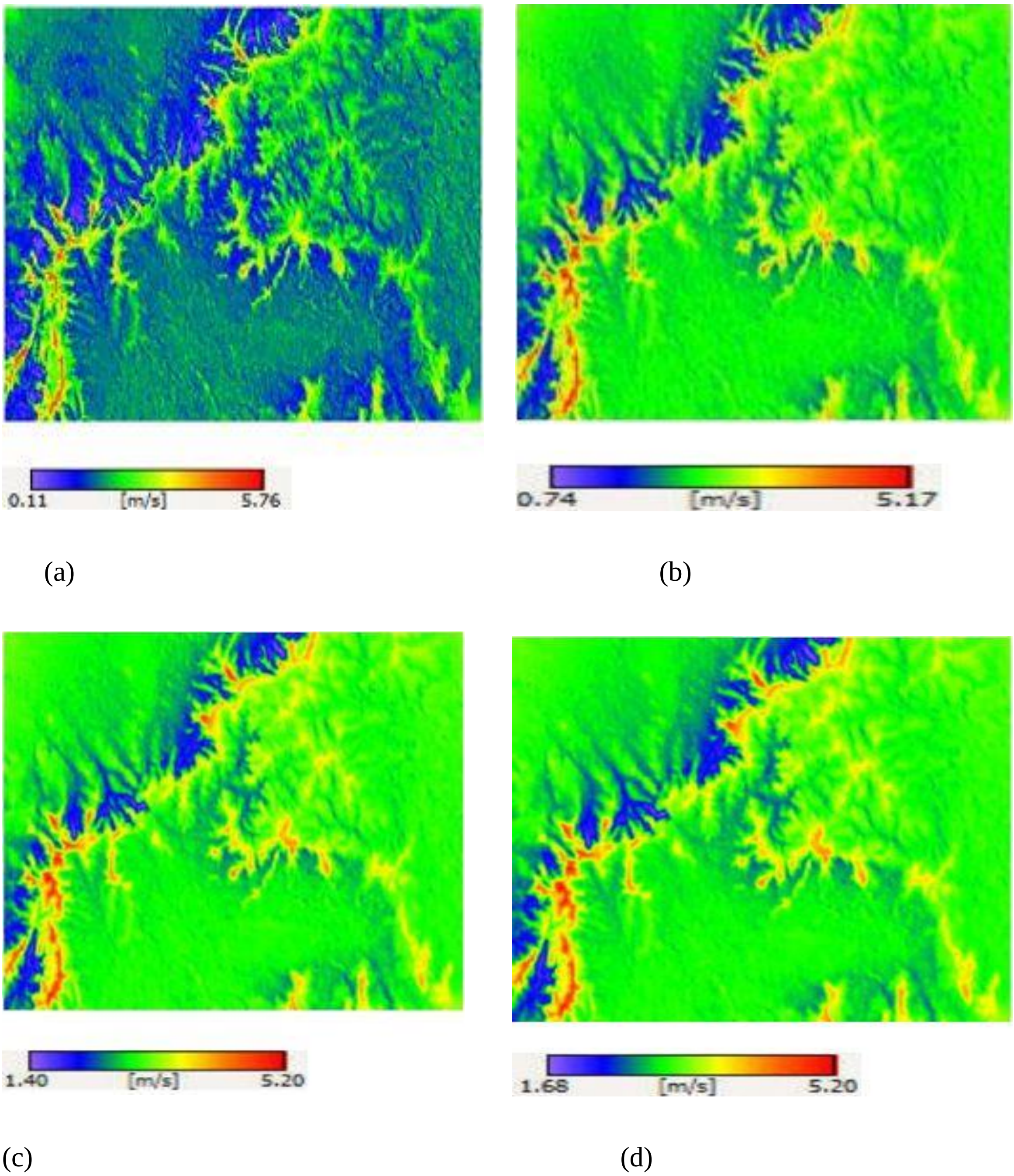


Figure 4.9 Resource grid map showing mean wind speed at (a), 10m (b), 40m (c), 80m (d) 100m height a.g.l. and 100 m resolution

Table 4.3 Summary of resource grid results of Wind speed at different heights a.g.l. (m/s)

Height(m) a.g.l.	10	40	80	100
Minimum Value	0.11 m/s at (252500, 1256000)	0.74 m/s at (243300, 1246400)	1.40 m/s at (252800, 1255500)	1.68 m/s at (252800, 1255500)
Maximum Value	5.76 m/s at (237100, 1245300)	5.17 m/s at (236700, 1242000)	5.20 m/s at (236700, 1242000)	5.20 m/s at (236700, 1242000)
Mean Value	1.90 m/s	2.54 m/s	2.99 m/s	3.15 m/s

The results obtained showed that the mean wind speed was increased with an increase in hub height and maximum wind speed was available at hills.

Wind Power density

The power density of Dangla Wind Farm at a hub height of 80 a.g.l. was calculated using WAsP and the result showed that the wind power density ranged from 4 - 130 W/m^2 with a mean value of 27 W/m². The wind power density graph and its summary results are shown in figure 4.10 and table 4.4 below.

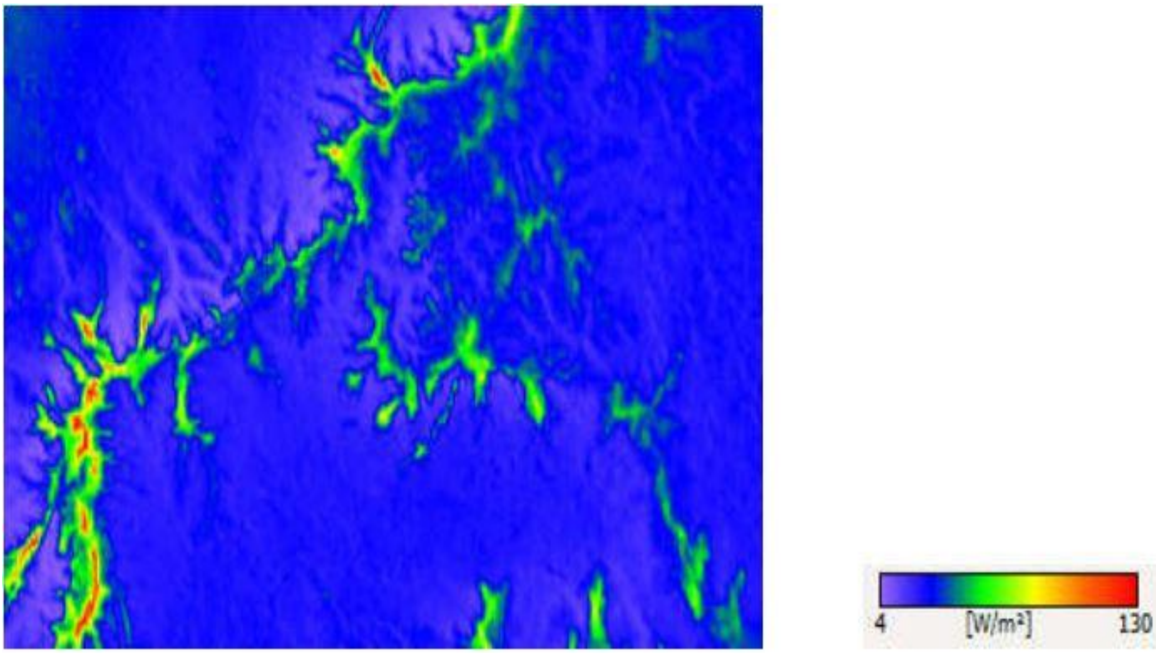


Figure 4.10 Wind resource grid showing the power density of Dangla Wind Farm at 80-meter above ground level

Table 4.4 Summary of resource grid results of power density at different heights a.g.l.

Height(m) a.g.l.	10	40	80	100
Minimum Value	0 W/m² at (252500, 1256000)	1 W/m² at (243300, 1246400	4 W/m² at (252500, 1255700)	6 W/m² at (252500, 1255700)
Maximum Value	325 W/m² at (234900, 1238000)	152 W/m² at (234900, 1238000)	130 W/m² at (236700, 1242000)	127 W/m² at (236700, 1242000)
Mean Value	11 W/m²	18 W/m²	27 W/m²	30 W/m²

Annual Energy Production

The annual energy production of the farm at a hub height of 80 a.g.l. was calculated by WAsP 12 using Vestas V100-1.8 MW GridStreamer wind turbine generator. The result showed that the annual energy production of the wind farm ranged from 0.027–3.359 GWh with a mean value of 0.657 GWh. The annual energy production graph of the farm and its summary results are shown in figure 4.11 and table 4.5 below.

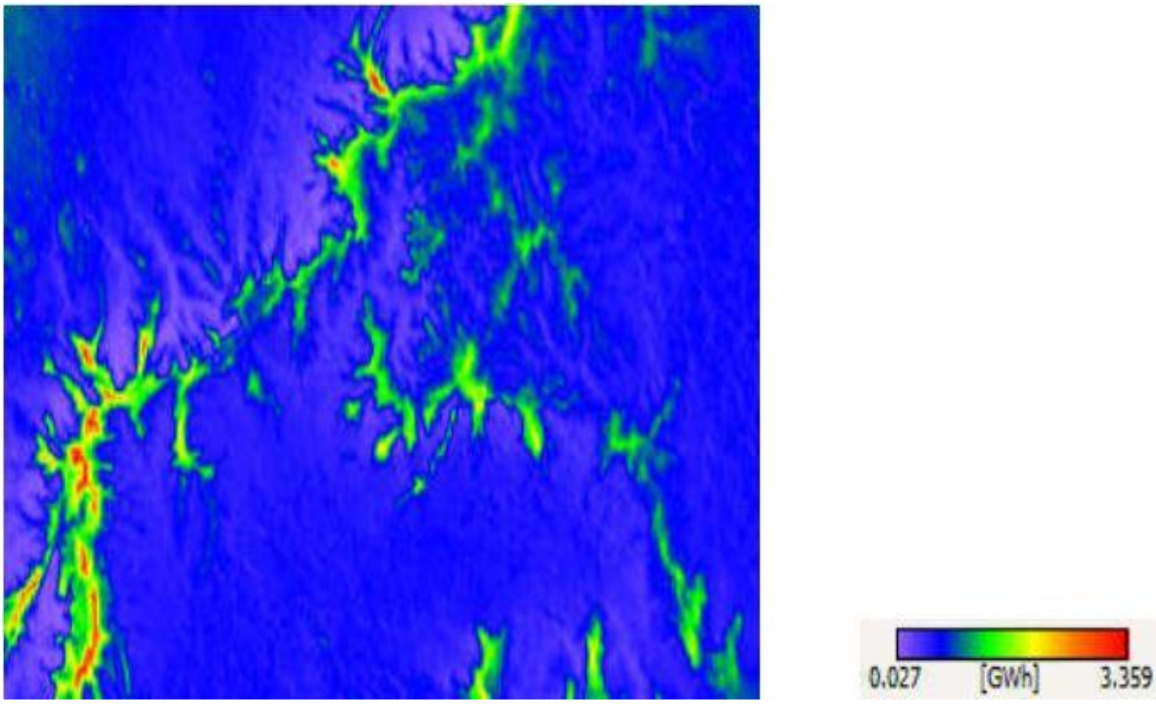


Figure 4.11 Wind resource map showing the Annual Energy Production of Dangla Wind Farm at 80 meters above ground level

Table 4.5 Summary of resource grid results of AEP at different heights a.g.l.

Height(m) a.g.l.	10	40	80	100
Minimum Value	0.000 GWh at (252500, 1256000)	0.000 GWh at (251100, 1254800)	0.027 GWh at (252100, 1255400)	0.060 GWh at (252500, 1255800)
Maximum Value	4.461 GWh at (237100, 1245300)	3.492 GWh at (237300, 1237500)	3.359 GWh at (236700, 1242000)	3.330 GWh at (236700, 1242000)
Mean Value	0.223 GWh	0.417 GWh	0.657 GWh	0.766 GWh

Ruggedness index (RIX)

The ruggedness index (RIX) was calculated using WAsP and the result showed that the ruggedness index of the terrain varies from 0% to 35.7% with an average RIX value of 7.4%. Based on the results obtained, the site could be classified as a flat site because the RIX is less than 30% [63].

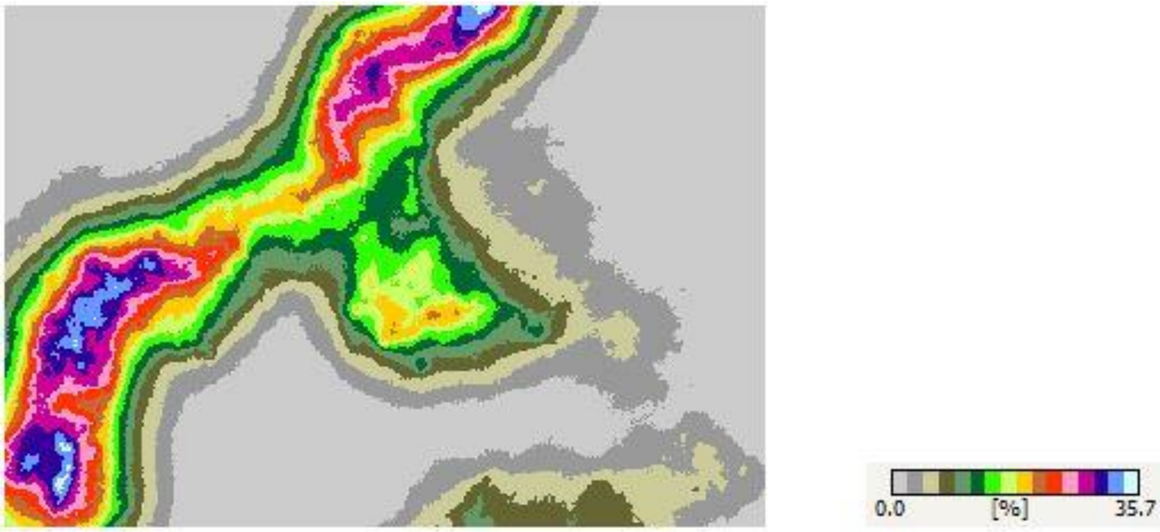


Figure 4.12 Resource grid map showing the ruggedness index of Dangla Wind Farm

Table 4.6 Summary of resource grid results of RIX.

Parameter	Minimum Value	Maximum Value	Mean Value
Values	0.0% at (241500, 1256600)	35.7% at (235800, 1236000)	7.4%

4.3.5 Wind Farm Production

The typical wind farm covers 31.9 Km × 22.4 Km area. In this area, a total of 188 wind turbines of uniform hub height (80 m a.g.l.) and a rotor diameter of 100 m were installed according to the rule of thumb. The mean wind speed at turbine heights was ranging from 3.39 m/s to 5.2 m/s which indicates that the site is lower potential [73]. The wind farm production calculated by WAsP 12 showed that a total of 307.111 GWh energy was produced annually with a wake loss of 7.94 %. Its net AEP was determined to be 282.726 Giga Watt-hour. The minimum, average, and maximum net energy production were 839 MWh, 1504 MWh, and 3078 MWh respectively.

The wind farm contains the location of the turbines, the height of the turbines above ground level and sea level, estimated overall wind climate, estimated power density or power production, wake loss, and net annual energy production of a wind farm. The detail and summary results of a typical wind farm are presented in Annex I.

4.3.6 Capacity Factor of Wind Farm

The capacity factor is the ratio of the actual energy output of the turbine to the expected output energy. The Expected (possible) output energy of the wind farm is the product of the total number of turbines installed on a wind farm and the rated capacity of the selected wind turbine generator.

Expected output energy = 188×1.8 Mw×8760 hr = 2,964,384 MWh=2,964.384 GWh. Whereas, the net AEP was 282.726 GWh. Thus, the capacity factor of the wind farm is,

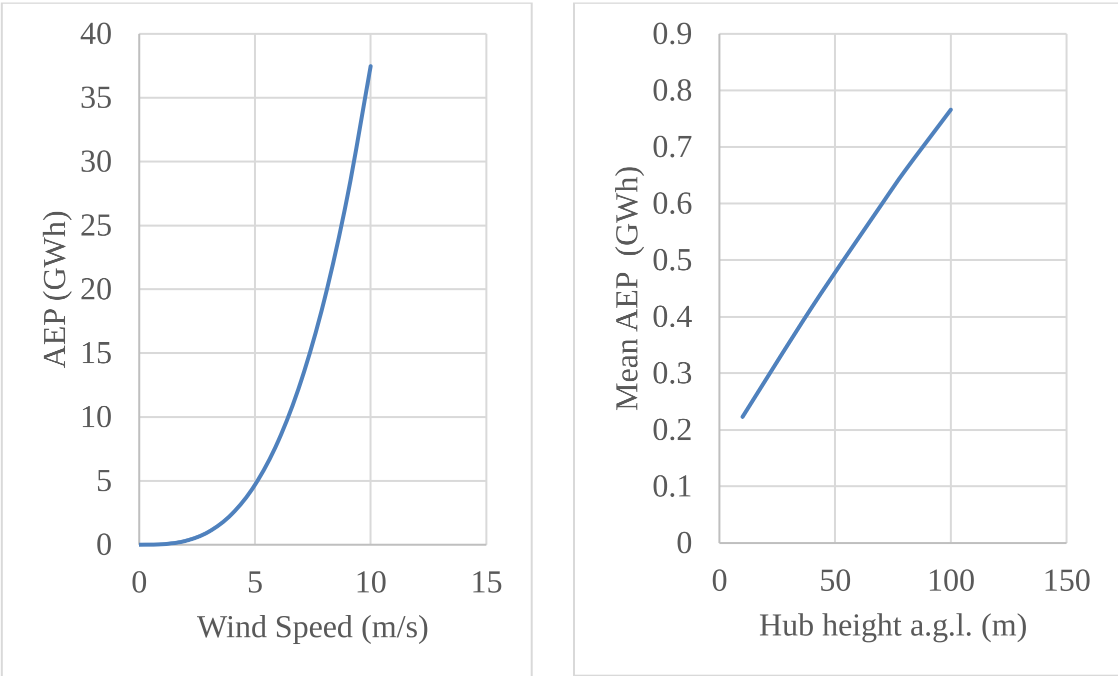
$$CF = \frac{282.726\ \text{GWh}}{2{,}964.384\ \text{GWh}} \times 100 = 9.54\%$$

4.3.7 Sensitivity Analysis

It studies the impact of change in input variables on the output of a mathematical model. In this case, the output is taken as the energy production of the wind farm whereas the input variables are wind speed, power density, hub height, boundary, air density, and type of wind turbine generator.

Effect of Wind Speed and Turbine height on Annual Energy Production of a Turbine

The annual energy production of a specific site is dependent on the mean wind speed at a specified measuring height. According to the recently collected data by meteorologists, wind speed increases with turbine installation height according to the 1/7 power law [73]. The effect of variation of wind speed of a farm and hub height on the annual energy production of a turbine is described in Figure 4.13 (a) and (b) below.



a) b)

Figure 4.13 Variation of wind power density (a) and AEP (b) with wind speed

Effect of Rotor Diameter and Air Density on Annual Energy Production of a Turbine

The effect of variation of rotor diameter of a turbine and air density on its annual energy production is shown in Figure 4.14 (a) and (b) below.

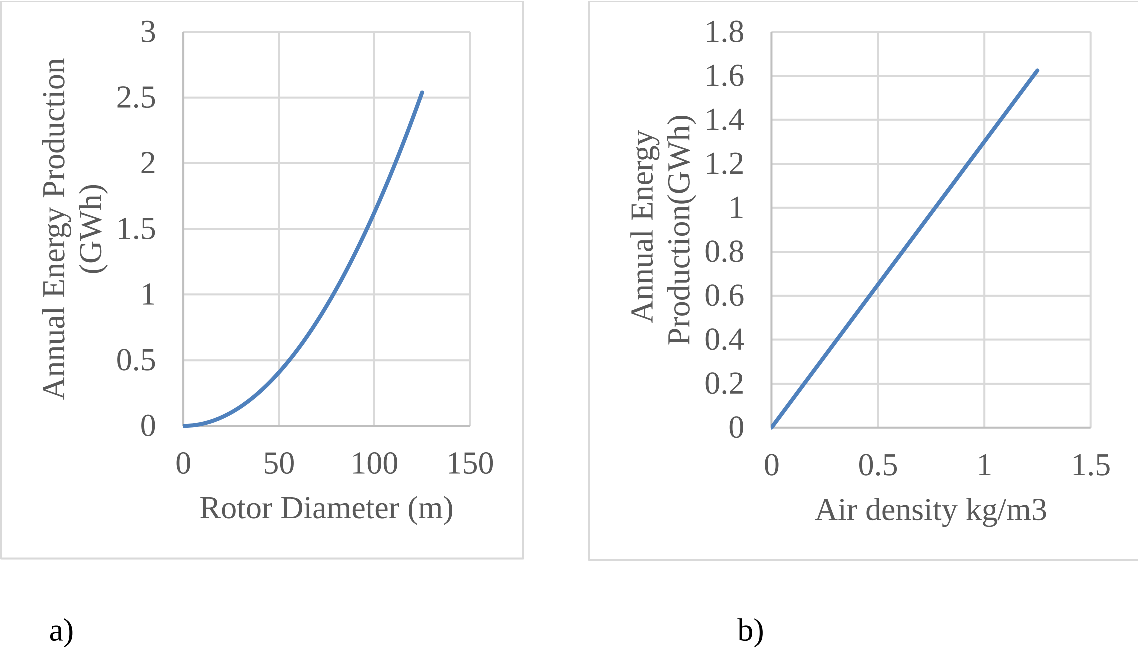


Figure 4.14 Variation of Rotor Diameter (a) and Air Density (b) with AEP of a Turbine

Effect of Resource Grid Resolution on Wind Speed of a Wind Farm

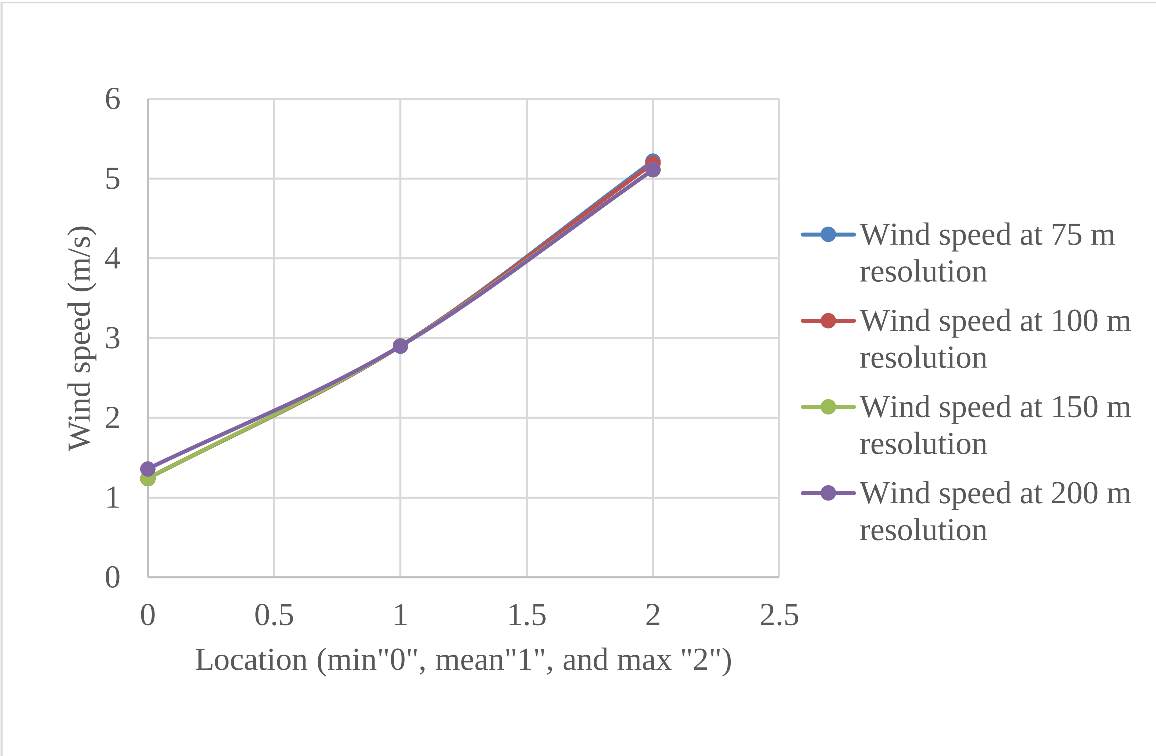


Figure 4.15 Effect of resource grid resolution on the wind speed of a wind farm

As it is shown in Figure 4.15, the resource grid resolution has no significant effect on the wind speed. As a result, a grid resolution of 100 m was selected to reduce the calculation time. Based on this, it is also possible to say that its effect is insignificant on power density and the annual energy production of the wind farm.

Effect of Wind Turbine Generator on Annual Energy Production of A Wind Farm

The energy production and capacity of the wind farm is highly dependent on the type of wind turbine generator used. Low capacity wind turbines have low energy output compared to large capacity wind turbines. In this study, different wind turbines were used for analyzing the effect of the type of wind turbine on the annual energy production of the wind farm. The result showed that Vestas V100 -1.8 MW GS Wind turbine yields better energy output to the wind farm.

Table 4.7 Effects of the type of Wind Turbine Generators on AEP of a Wind Farm

Type of WTG	RD (m)	HH (m)	V_{in} (m/s)	V_{out} (m/s)	Capacity (MW)	NAEP of Wind Farm (GWh)	CF (%)
V82 of 1650 kW	82	70	3	25	1.65	173.15	6.37
V80 of 2.0 MW GS™	80	80	3	25	2	167.682	5.09
V60-850 kW	60	60	3	20	0.85	102.047	7.29
V90-1.8 MW GS™	90	80	4	25	1.8	223.094	7.53
V90-2.0 MW GS™	90	80	4	25	2	223.697	6.79
V100-1.8 MW GS™	100	80	3	20	1.8	282.726	9.54
V100-2.0 MW GS™	100	80	3	20	2	269.3	8.18

Table 4.8 Sensitivity analysis

Input Variables	% increase	Output Variable	% increase
Wind speed (1.4 m/s)	271.43 % (5.20 m/s)	Mean AEP	12340.7%
Hub height (80 m)	25 % (100 m)	Mean AEP	16.59 %
Wake loss (%)	10	Mean AEP	10%

4.4 Economic Analysis of Wind Farm

A wind farm consists of 188 turbines worth €1875000 (68,076,764.95 ETB) individually. So, the total cost of the wind turbines is 12,798,431,811 ETB. The economic analysis of the wind project was studied based on the assumptions discussed in section 3.5 and the result showed that the total initial investment cost and the annual operation and maintenance cost was found to be 1,663,7961,354 ETB and 332,759,227.1 ETB respectively. The financial analysis of the project was also calculated based on the equations discussed in section 3.5 and the results showed that at the current price of electricity in Ethiopia, the Levelized Cost of Energy, net present value, internal rate of return, benefit-cost ratio, and payback period were calculated to be 4.9 ETB, -7,783,581,461 ETB, 1 %, 0.62, and 46.9766 years respectively.

Table 4.9 Summary of financial analysis results

Price of Electricity (ETB)	Net Present Value (ETB)	Internal Rate of Return (%)	The benefit to Cost Ratio	Pay Back Period (years)	Financially Feasible
2.54	-7,783,581,461	1	0.62	46.9766	No
16.46	38,071,490746	29	2.856	7.6	Yes

Based on, the results obtained above, the project is not financialy feasible at the current price of electricity in Ethiopia.

4.5 Validation

This thesis work was validated using a two-years wind data of Mossobo Harena site which was measured at a height of 40m. The met mast was located at 13.57° N and 39.51°E. The study area taken for validating this work covered a 10*10 km square area which was bounded by 550445.5 mE to 560445.5 mE and 149496.35 mN to 150496.5 mN.

The terrain data (contour map) of the study area was generated from ASTER GDEM and that of land cover (terrain roughness map) was generated from the ECA climate change initiative 2010 using a GIS tool known as Global mapper. Both of these data were exported to WasP format by Global mapper and they are imported and digitized using WAsP map editor.

The wind data was analyzed using the WAsP climate analyst tool and the following results were observed. The most frequent wind direction fell between the angles 90° and 120° with frequencies of 20% and 28%. The mean wind speed and power density were found to be 6.44 m/s and 276 w/m^2 respectively. As shown in figures 4.16 and 4.17 below, my result is the same as the previously published work.

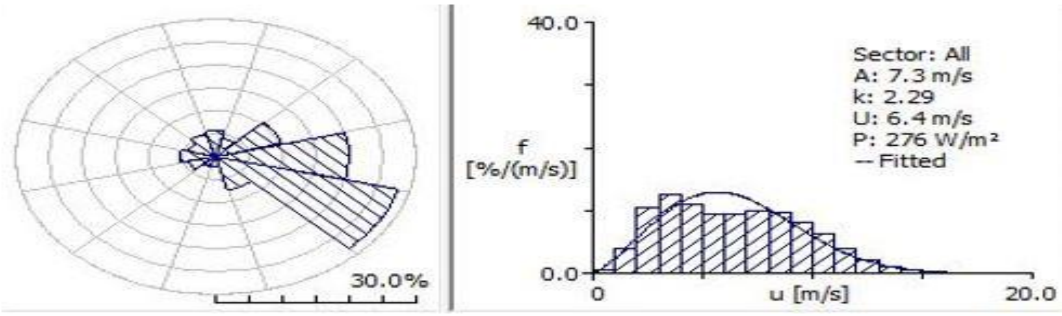


Figure 4.16: Observed wind climate data of Mossobo Harena Met Mast at 40 m a.g.l.

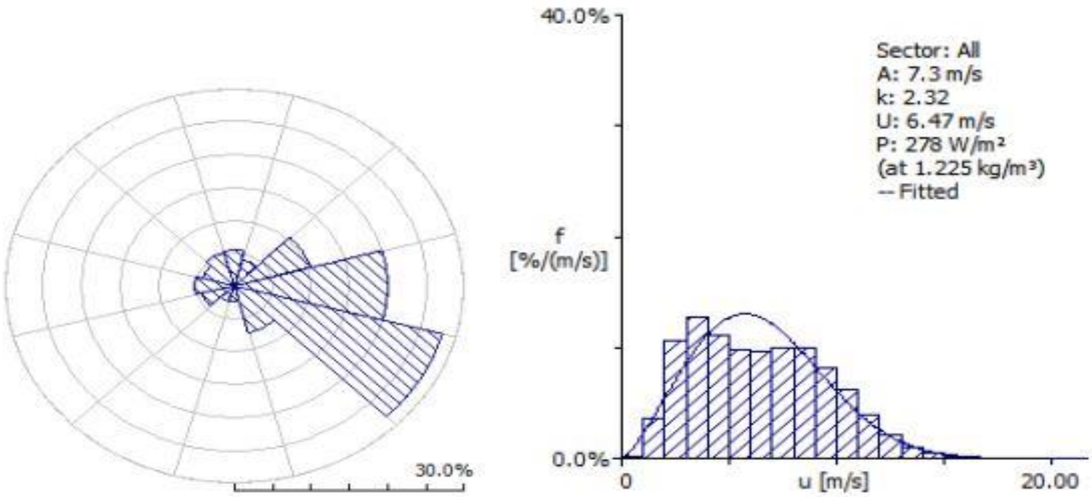


Figure 4.17: Observed wind climate data of Mossobo Harena Met Mast at 40 m a.g.l. [74]

Resource Grid Results

The overall resource grid result map of the study area developed at 98 m above ground level are described below.

Mean wind speed

The wind speed of the study area at a hub height of 98-meter a.g.l. was calculated by WAsP 12 and the minimum and maximum wind speeds were 4.25 m/s and 8.76 m/s which is the same as the result of [74].

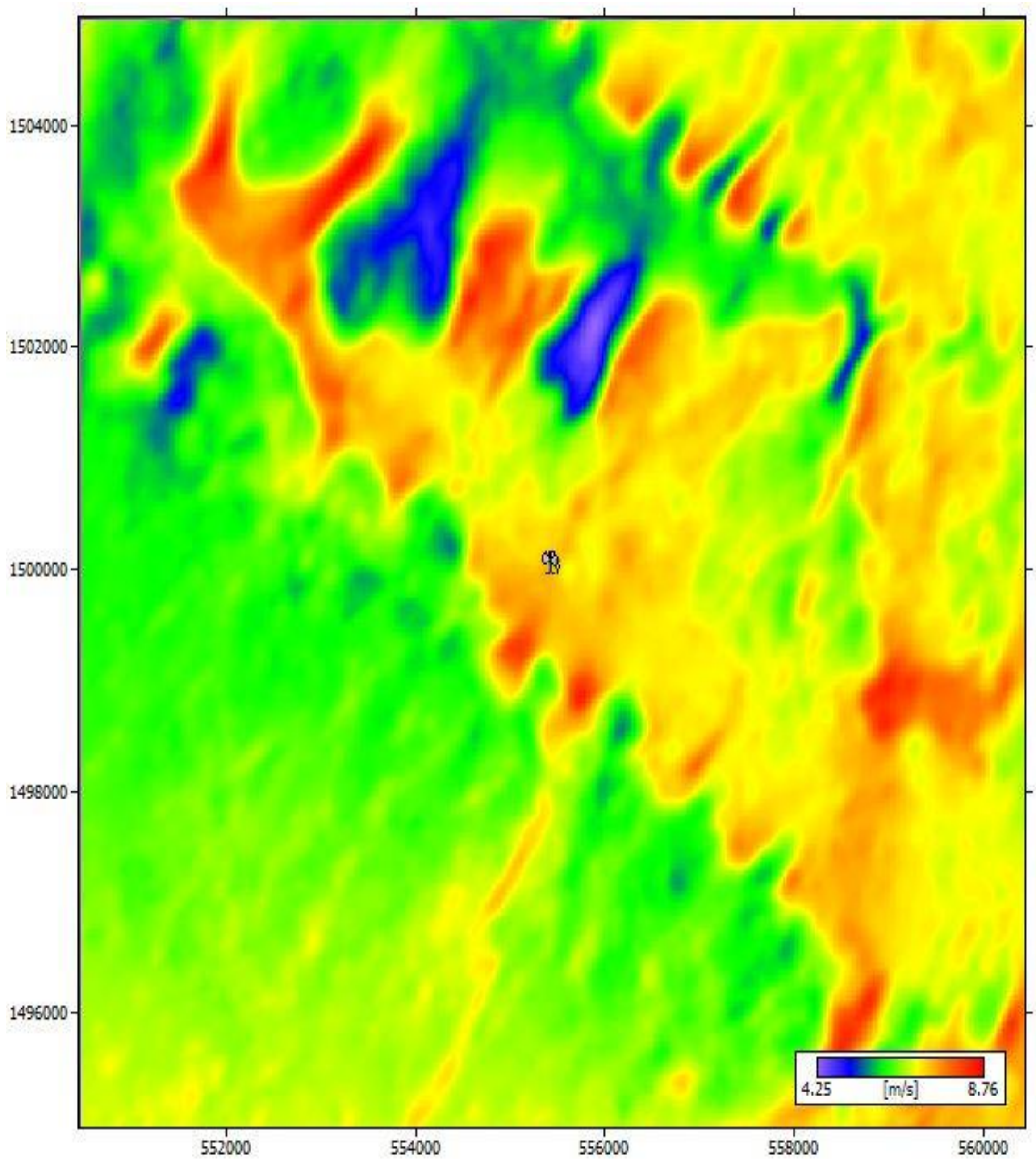


Figure 4.18 Wind resource grid showing mean wind speed of Mossobo-Harena Wind Farm at 98 m a.g.l.

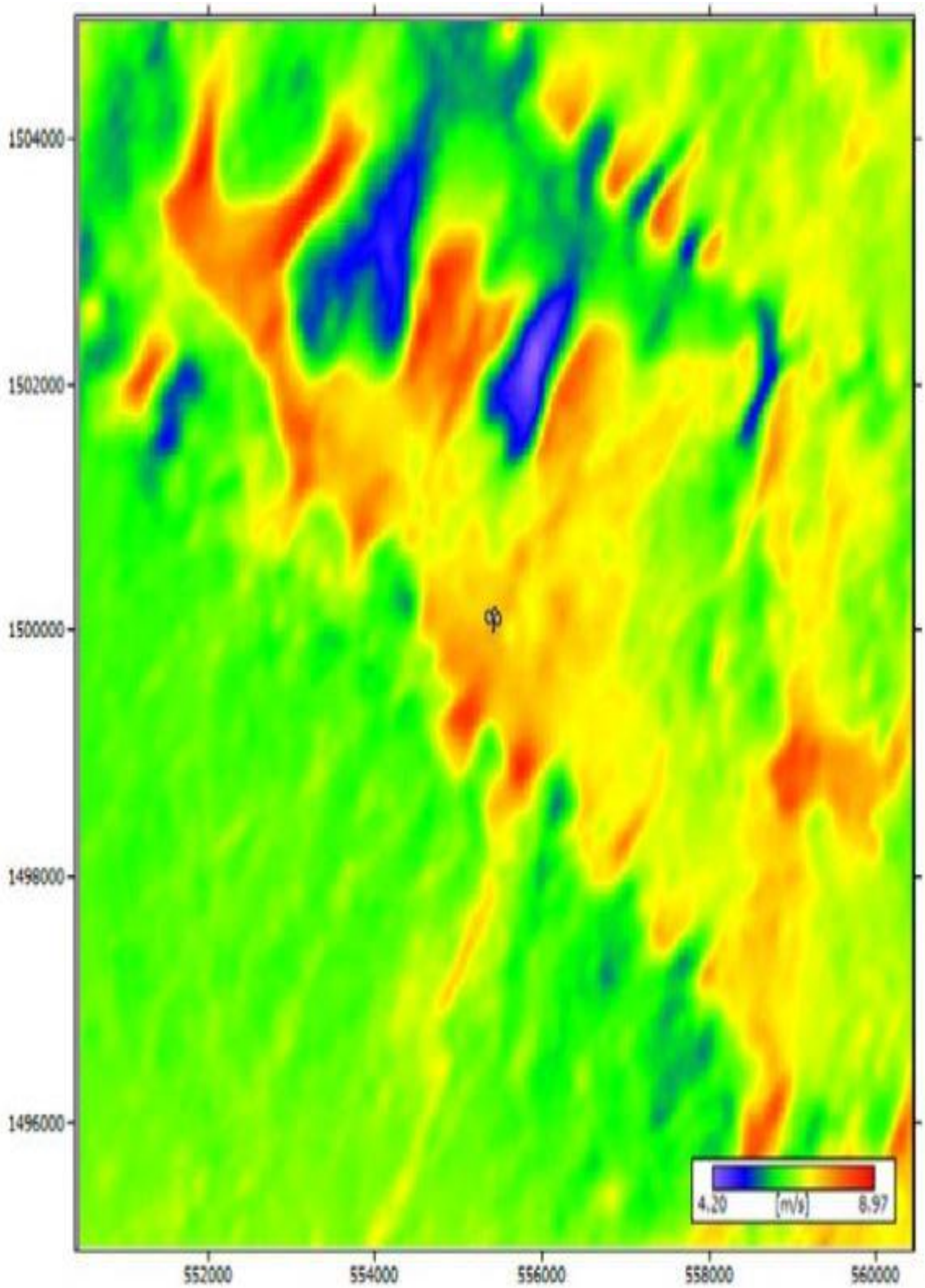


Figure 4.19 Wind resource grid showing mean wind speed of Mossobo-Harena Wind Farm at 98 m a.g.l. [74]

Power density

The minimum power density value of the study area at 98-meter a.g.l. was 57 w/m^2 whereas the maximum value was 536 w/m^2 which is the same as the result of [74].

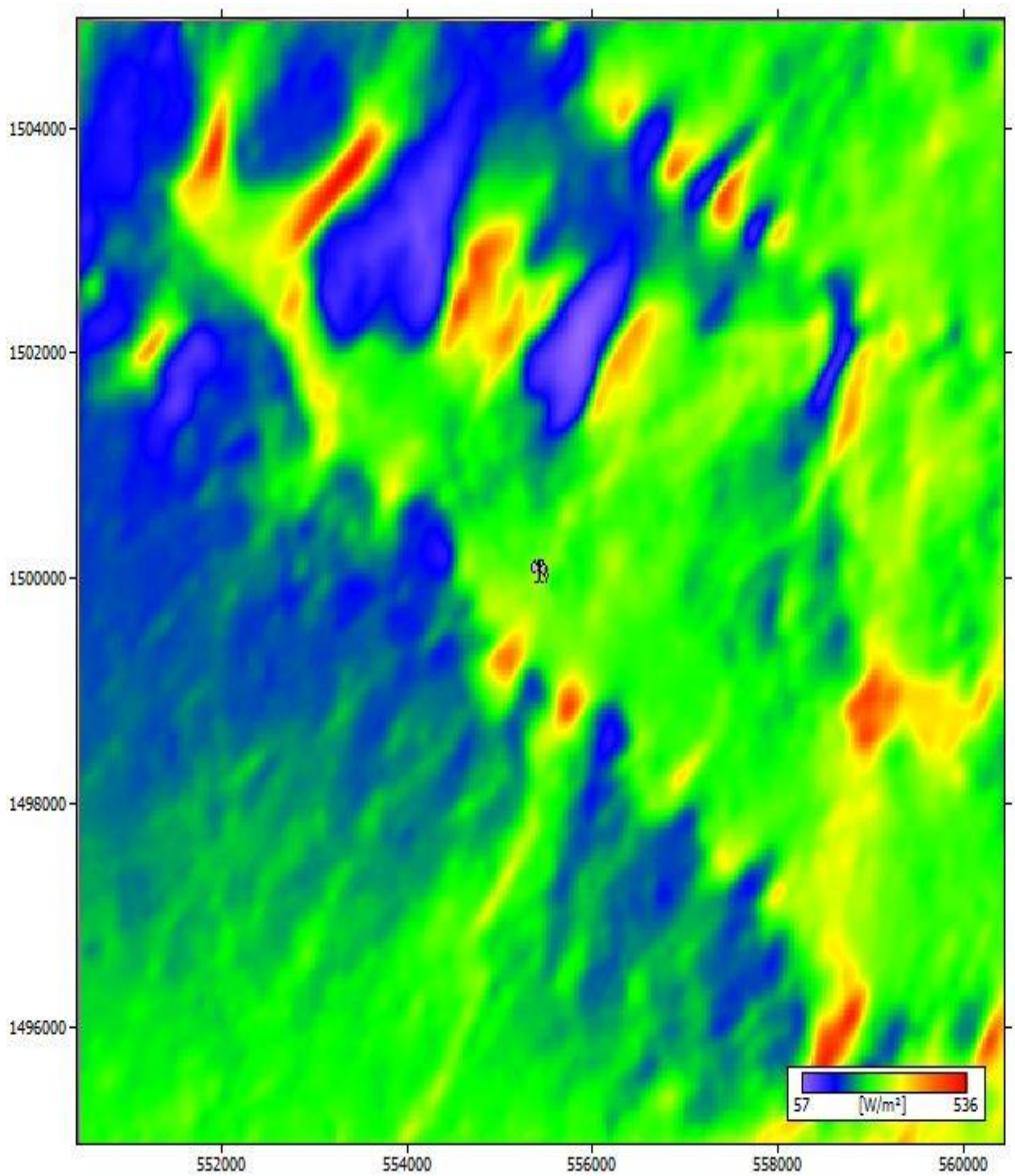


Figure 4.20 Wind resource grid showing power density of Mossobo-Harena Wind Farm at 98 m a.g.l.

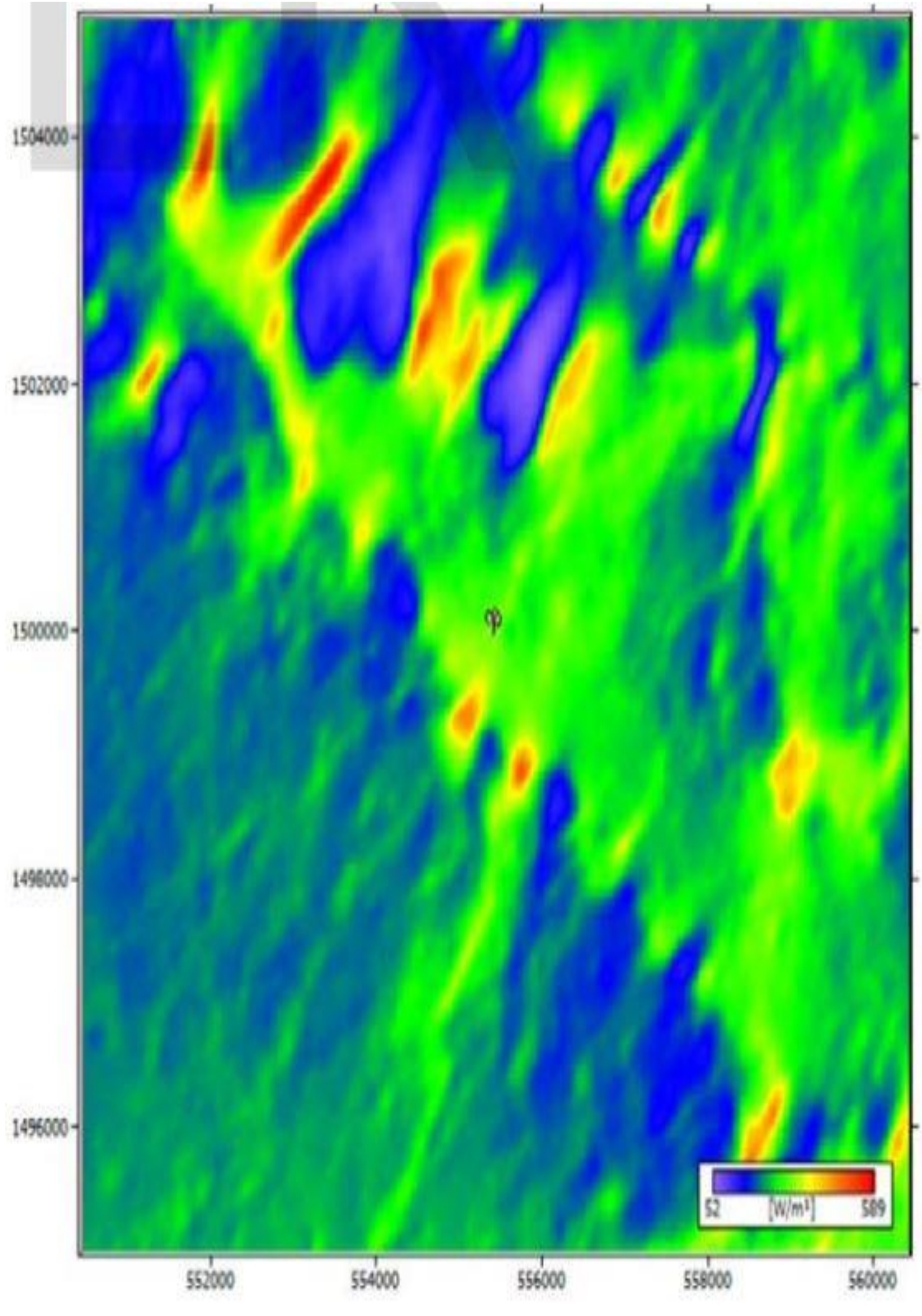


Figure 4.21 Wind resource grid showing power density of Mossobo-Harena Wind Farm at 98 m a.g.l. [74]

Chapter 5: Conclusion, Recommendations, and Future Works

5.1 Conclusion

The wind resource potential and economic analysis for generating electricity in the Dangla area were carried out in this thesis work. In this study, three years of wind data which were recorded at a height of 10-meter a.g.l. in 15 minutes interval, a vector map of the site which was generated by WAsP map editor, and Vestas V100-1.8 MW grid streamer wind turbine generator were used. The minimum and maximum wind speed of the study area were 0.12083 m/s and 9.96389 m/s respectively The mean wind speed and power density at a height of 10 m a.g.l. were 1.8 m/s and 9 w/m^2. The most frequent wind direction was also found to be 210° (i.e. the most prevailing wind direction was to the south-west direction).

The wind resource assessment was carried out using the Wind Atlas Analysis and Application Program (WAsP) and the results showed that the maximum wind speed was available around hills. The energy production of the wind farm is sensitive to the wind speed, height, type of wind turbine selected, and wake losses. The wind resource map was plotted at 10, 40, 80, and 100 m height a.g.l. but the wind farm was modeled at 80 m height. The net annual energy production of the study area at a turbine height of 80 m a.g.l. was found to be 282.726 GWh (or, 32.27 MW). The capacity factor of the farm was also found to be 9.54% which in turn indicates that the site is classified as lower potential.

The result of the economic analysis showed that the Vestas V100-1.8 MW Grid streamer wind turbine yields the highest cost of 396,547 birr/kW at the site. The economic analysis of the site was analyzed using the current price of electricity in Ethiopia and the price of electricity generated from the project. The result obtained showed that the Levelized cost of electricity was found to be 4.9 birr/kWh. Based on the results obtained, it is possible to conclude that the project is not feasible at the current price of electricity in Ethiopia and it will be feasible when the electricity price is more than 4.9 birr/kWh or the incentives given by the government and other organizations increases.

5.2 Recommendations

Based on the conclusions made above, the following recommendations are made.

- Data measuring instruments should be monitored and maintained regularly to avoid missing records and to decrease the uncertainties in measurement.
- The climate data should be recorded at hub height for the accuracy of the results.
- The renewable energy technologies should be encouraged by giving incentives to make them competitive in the market.
- The government should increased the price of electricity to enhance renewable energy investment in the country.
- Add meteorological masts to decrease wind flow uncertainties.

5.3 Future Works

The following future works are stated.

- It is better to include environmental analysis.
- It is better to check the results using other methods like WindPro, CFD, and other computational tools.

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Annexes

Annex I: Site results of Dangla Wind Farm

Site	Location [m]	Turbine	Elevation [m] a.s.l.	Height [m] a.g.l.	Air density [kg/m&sup3]	Net AEP [GWh]	Wake loss [%]
TS 001	(233800, 1236450)	V100-1.8 MW GS	1887.4	80.0	0.952	2.154	1.51
TS 002	(234100, 1237100)	V100-1.8 MW GS	1924.5	80.0	0.949	1.895	2.06
TS 003	(234874, 1237900)	V100-1.8 MW GS	1944.9	80.0	0.947	2.521	1.23
TS 004	(235400, 1238850)	V100-1.8 MW GS	1884.8	80.0	0.952	1.545	2.07
TS 005	(235671.4 ,1240142)	V100-1.8 MW GS	1997.3	80.0	0.943	1.740	3.58
TS 006	(235613.2 ,1241613)	V100-1.8 MW GS	2040.9	80.0	0.939	1.950	7.32
TS 007	(235148.1 ,1241995)	V100-1.8 MW GS	1957.6	80.0	0.946	2.220	4.30
TS 008	(235054.6 ,1242563)	V100-1.8 MW GS	1778.7	80.0	0.962	1.608	5.16
TS 009	(235502.9 ,1243000)	V100-1.8 MW GS	1776.8	80.0	0.962	1.557	8.24
TS 010	(236603.3 ,1234592)	V100-1.8 MW GS	2113.0	80.0	0.932	2.283	1.58
TS 011	(236904.1 ,1235097)	V100-1.8 MW GS	2256.9	80.0	0.920	2.988	2.63
TS 012	(237146.5 ,1235512)	V100-1.8 MW GS	2233.7	80.0	0.922	2.821	2.58
TS 013	(237334.3 ,1235992)	V100-1.8 MW GS	2194.9	80.0	0.925	2.600	2.19
TS 014	(237334.3 ,1236806)	V100-1.8 MW GS	2121.1	80.0	0.932	2.518	1.75
TS 015	(237313.4 ,1237536)	V100-1.8 MW GS	2194.1	80.0	0.925	2.960	2.25
TS 016	(237000.5 ,1238245)	V100-1.8 MW GS	2191.2	80.0	0.926	2.652	2.66
TS 017	(236833.7 ,1238912)	V100-1.8 MW GS	2128.3	80.0	0.931	2.072	3.82
TS 018	(237312.7 ,1240322)	V100-1.8 MW GS	2223.6	80.0	0.923	2.499	5.78
TS 019	(237327.5 ,1240827)	V100-1.8 MW GS	2244.8	80.0	0.921	2.257	9.86
TS 020	(236748.4 ,1240832)	V100-1.8 MW GS	2229.6	80.0	0.922	2.372	6.79

TS 021	(237100.5 ,1241277)	V100-1.8 MW GS	2291.8	80.0	0.917	2.877	5.80
TS 022	(237058.1 ,1241701)	V100-1.8 MW GS	2283.8	80.0	0.918	2.753	8.30
TS 023	(236700, 1242000)	V100-1.8 MW GS	2314.8	80.0	0.915	3.078	8.37
TS 024	(236421.7 ,1242287)	V100-1.8 MW GS	2171.9	80.0	0.927	2.259	7.94
TS 025	(237157.4 ,1242950)	V100-1.8 MW GS	2183.0	80.0	0.926	2.565	5.30
TS 026	(237293.3 ,1243420)	V100-1.8 MW GS	2173.8	80.0	0.927	2.621	7.26
TS 027	(237795.8 ,1243682)	V100-1.8 MW GS	2122.7	80.0	0.932	1.971	6.76
TS 028	(237767, 1244112)	V100-1.8 MW GS	2077.2	80.0	0.936	2.292	8.95
TS 029	(238301.3 ,1243884)	V100-1.8 MW GS	2157.5	80.0	0.929	2.113	9.72
TS 030	(237885.7 ,1244686)	V100-1.8 MW GS	1896.0	80.0	0.951	1.743	8.23
TS 031	(237212.9 ,1245042)	V100-1.8 MW GS	1846.7	80.0	0.956	2.416	2.10
TS 032	(236747.8 ,1245685)	V100-1.8 MW GS	1751.3	80.0	0.964	2.051	1.57
TS 033	(239033.5 ,1244339)	V100-1.8 MW GS	2058.9	80.0	0.937	1.661	7.52
TS 034	(239340, 1244855)	V100-1.8 MW GS	1934.8	80.0	0.948	1.964	7.46
TS 035	(239468.4 ,1245358)	V100-1.8 MW GS	1863.6	80.0	0.954	2.387	4.48
TS 036	(239521.9 ,1245925)	V100-1.8 MW GS	1768.4	80.0	0.963	2.071	3.75
TS 037	(241234.6 ,1241834)	V100-1.8 MW GS	2053.2	80.0	0.938	1.361	7.04
TS 038	(240973.8 ,1242290)	V100-1.8 MW GS	2082.8	80.0	0.935	1.742	5.90
TS 039	(240995.6 ,1242769)	V100-1.8 MW GS	2059.5	80.0	0.937	1.825	6.04
TS 040	(241039, 1243312)	V100-1.8 MW GS	2047.1	80.0	0.938	1.462	7.62
TS 041	(241017.3 ,1243964)	V100-1.8 MW GS	2012.6	80.0	0.941	1.251	9.18
TS 042	(241343.3 ,1244551)	V100-1.8 MW GS	2068.9	80.0	0.936	1.818	6.36
TS 043	(242060.5 ,1244811)	V100-1.8 MW GS	1973.7	80.0	0.945	1.222	6.29
TS 044	(242473.4 ,1245659)	V100-1.8 MW GS	1819.4	80.0	0.958	0.992	8.52
TS 045	(243457.8 ,1247068)	V100-1.8 MW GS	1834.3	80.0	0.957	1.239	4.39

TS 046	(244051.8 ,1247582)	V100-1.8 MW GS	1854.2	80.0	0.955	1.257	6.61
TS 047	(244606.2 ,1247622)	V100-1.8 MW GS	1857.8	80.0	0.955	0.888	9.34
TS 048	(245041.8 ,1247820)	V100-1.8 MW GS	1893.4	80.0	0.952	1.091	9.83
TS 049	(245635.8 ,1247661)	V100-1.8 MW GS	1927.1	80.0	0.949	1.043	6.10
TS 050	(246071.5 ,1247859)	V100-1.8 MW GS	1966.0	80.0	0.945	1.452	7.33
TS 051	(246705.1 ,1248097)	V100-1.8 MW GS	1945.1	80.0	0.947	1.245	4.21
TS 052	(247180.3 ,1248770)	V100-1.8 MW GS	1906.3	80.0	0.951	1.216	5.73
TS 053	(247813.9 ,1248810)	V100-1.8 MW GS	1983.0	80.0	0.944	1.103	8.49
TS 054	(248487.6 ,1249186)	V100-1.8 MW GS	2059.2	80.0	0.937	1.388	6.37
TS 055	(248631.4 ,1249732)	V100-1.8 MW GS	2028.9	80.0	0.940	1.533	6.15
TS 056	(248500.3 ,1250154)	V100-1.8 MW GS	1970.9	80.0	0.945	1.494	4.40
TS 057	(248325.6 ,1250532)	V100-1.8 MW GS	1990.3	80.0	0.943	1.291	6.56
TS 058	(248150.9 ,1250940)	V100-1.8 MW GS	2026.8	80.0	0.940	1.323	6.94
TS 059	(248078.1 ,1251362)	V100-1.8 MW GS	2080.5	80.0	0.935	1.601	7.13
TS 060	(248165.5 ,1251814)	V100-1.8 MW GS	2052.0	80.0	0.938	1.631	6.73
TS 061	(248372.4 ,1252169)	V100-1.8 MW GS	2023.6	80.0	0.940	1.555	6.85
TS 062	(248806.1 ,1252440)	V100-1.8 MW GS	2039.8	80.0	0.939	1.528	9.14
TS 063	(249470.6 ,1252190)	V100-1.8 MW GS	2115.0	80.0	0.932	1.258	13.44
TS 064	(249985.3 ,1252600)	V100-1.8 MW GS	2104.3	80.0	0.933	1.266	9.69
TS 065	(249854.3 ,1253080)	V100-1.8 MW GS	2084.6	80.0	0.935	1.368	10.14
TS 066	(249825.2 ,1253619)	V100-1.8 MW GS	2028.2	80.0	0.940	1.664	8.78
TS 067	(249388.4 ,1254085)	V100-1.8 MW GS	1980.7	80.0	0.944	2.933	2.79
TS 068	(249097.2 ,1254536)	V100-1.8 MW GS	1844.6	80.0	0.956	2.311	2.12
TS 069	(248986.9 ,1254947)	V100-1.8 MW GS	1717.0	80.0	0.967	1.585	1.55
TS 070	(250217.5 ,1253648)	V100-1.8 MW GS	2115.7	80.0	0.932	1.537	15.44

TS 071	(250627.8 ,1253812)	V100-1.8 MW GS	2108.9	80.0	0.933	1.515	11.62
TS 072	(251133.7 ,1253784)	V100-1.8 MW GS	2114.6	80.0	0.932	1.355	9.10
TS 073	(251516.6 ,1253784)	V100-1.8 MW GS	2114.0	80.0	0.932	1.167	9.17
TS 074	(252022.5 ,1253976)	V100-1.8 MW GS	2121.3	80.0	0.932	1.323	7.44
TS 075	(252692.6 ,1254208)	V100-1.8 MW GS	2135.7	80.0	0.930	1.270	6.20
TS 076	(253184.9 ,1254714)	V100-1.8 MW GS	2159.2	80.0	0.928	1.396	6.05
TS 077	(253600.8 ,1254894)	V100-1.8 MW GS	2180.8	80.0	0.926	1.410	5.95
TS 078	(253560, 1255462)	V100-1.8 MW GS	2095.9	80.0	0.934	1.638	6.90
TS 079	(253450, 1255873)	V100-1.8 MW GS	1981.4	80.0	0.944	1.327	7.34
TS 080	(254043.1 ,1255051)	V100-1.8 MW GS	2242.1	80.0	0.921	1.237	14.87
TS 081	(254453.7 ,1255115)	V100-1.8 MW GS	2289.8	80.0	0.917	1.349	14.27
TS 082	(254832.8 ,1255525)	V100-1.8 MW GS	2293.6	80.0	0.917	1.796	6.82
TS 083	(255022.3 ,1256031)	V100-1.8 MW GS	2243.6	80.0	0.921	1.840	4.06
TS 084	(255186.2 ,1256522)	V100-1.8 MW GS	2225.9	80.0	0.923	1.930	2.63
TS 085	(253963.2 ,1234230)	V100-1.8 MW GS	2342.3	80.0	0.913	1.897	2.18
TS 086	(253711.4 ,1234700)	V100-1.8 MW GS	2283.1	80.0	0.918	1.829	2.08
TS 087	(253929.6 ,1235204)	V100-1.8 MW GS	2246.0	80.0	0.921	1.666	2.84
TS 088	(254100, 1235640)	V100-1.8 MW GS	2222.5	80.0	0.923	1.723	3.42
TS 089	(253946.4 ,1236009)	V100-1.8 MW GS	2169.3	80.0	0.927	1.640	1.94
TS 090	(258862.8 ,1234262)	V100-1.8 MW GS	2339.0	80.0	0.913	1.194	3.08
TS 091	(258568.6 ,1234804)	V100-1.8 MW GS	2330.1	80.0	0.914	1.523	3.25
TS 092	(258450, 1235345)	V100-1.8 MW GS	2312.9	80.0	0.915	1.897	3.14
TS 093	(258500, 1235800)	V100-1.8 MW GS	2306.0	80.0	0.916	1.876	3.86
TS 094	(258650, 1236210)	V100-1.8 MW GS	2250.8	80.0	0.920	1.505	4.55
TS 095	(264000, 1234600)	V100-1.8 MW GS	2395.4	80.0	0.908	1.108	5.16

TS 096	(264361.2 ,1235041)	V100-1.8 MW GS	2404.8	80.0	0.907	1.181	7.17
TS 097	(264296.1 ,1235822)	V100-1.8 MW GS	2361.1	80.0	0.911	1.161	7.18
TS 098	(264572.6 ,1236582)	V100-1.8 MW GS	2334.7	80.0	0.913	1.075	7.83
TS 099	(262734.6 ,1235419)	V100-1.8 MW GS	2374.9	80.0	0.910	1.436	4.05
TS 100	(262584.6 ,1235963)	V100-1.8 MW GS	2407.5	80.0	0.907	1.592	3.88
TS 101	(262828.4 ,1236882)	V100-1.8 MW GS	2400.4	80.0	0.908	1.437	4.26
TS 102	(262800, 1237576)	V100-1.8 MW GS	2384.8	80.0	0.909	1.267	6.35
TS 103	(262059.4 ,1238101)	V100-1.8 MW GS	2352.8	80.0	0.912	1.652	3.24
TS 104	(261608.3 ,1238684)	V100-1.8 MW GS	2264.8	80.0	0.919	1.244	3.44
TS 105	(261492.2 ,1239074)	V100-1.8 MW GS	2272.6	80.0	0.919	1.401	3.38
TS 106	(261294.4 ,1239683)	V100-1.8 MW GS	2229.6	80.0	0.922	1.058	4.01
TS 107	(261250.8 ,1240178)	V100-1.8 MW GS	2234.6	80.0	0.922	1.204	3.88
TS 108	(260591.5 ,1241399)	V100-1.8 MW GS	2246.5	80.0	0.921	1.050	9.67
TS 109	(259991.2 ,1241714)	V100-1.8 MW GS	2232.0	80.0	0.922	1.001	7.77
TS 110	(260005.6 ,1242378)	V100-1.8 MW GS	2322.0	80.0	0.914	1.117	14.53
TS 111	(259481.5 ,1242393)	V100-1.8 MW GS	2316.0	80.0	0.915	1.325	8.03
TS 112	(259417, 1243077)	V100-1.8 MW GS	2254.8	80.0	0.920	1.148	7.38
TS 113	(260179.6 ,1242816)	V100-1.8 MW GS	2293.4	80.0	0.917	1.019	15.79
TS 114	(260532.3 ,1242565)	V100-1.8 MW GS	2314.5	80.0	0.915	0.941	19.63
TS 115	(261095, 1242898)	V100-1.8 MW GS	2275.1	80.0	0.918	0.952	14.90
TS 116	(261590.5 ,1243395)	V100-1.8 MW GS	2246.1	80.0	0.921	0.962	10.23
TS 117	(262030, 1244400)	V100-1.8 MW GS	2194.8	80.0	0.925	1.022	7.15
TS 118	(261402.6 ,1241991)	V100-1.8 MW GS	2264.8	80.0	0.919	0.901	13.01
TS 119	(256194.8 ,1242279)	V100-1.8 MW GS	2230.3	80.0	0.922	1.651	7.49
TS 120	(256113.1 ,1242583)	V100-1.8 MW GS	2295.7	80.0	0.917	1.903	7.91

TS 121	(255990, 1242850)	V100-1.8 MW GS	2303.3	80.0	0.916	1.839	7.88
TS 122	(255762, 1243267)	V100-1.8 MW GS	2276.8	80.0	0.918	1.530	11.09
TS 123	(255371.3 ,1243633)	V100-1.8 MW GS	2265.4	80.0	0.919	1.159	12.38
TS 124	(254878.4 ,1243768)	V100-1.8 MW GS	2256.3	80.0	0.920	1.084	10.46
TS 125	(255710, 1244192)	V100-1.8 MW GS	2274.8	80.0	0.918	0.901	15.38
TS 126	(256015, 1243710)	V100-1.8 MW GS	2273.7	80.0	0.918	0.927	18.86
TS 127	(253583.3 ,1242978)	V100-1.8 MW GS	2191.4	80.0	0.926	1.133	16.98
TS 128	(253612.4 ,1243371)	V100-1.8 MW GS	2275.5	80.0	0.918	1.385	16.81
TS 129	(253699.8 ,1243736)	V100-1.8 MW GS	2380.9	80.0	0.909	1.730	14.53
TS 130	(253399.5 ,1244120)	V100-1.8 MW GS	2424.2	80.0	0.906	1.541	13.23
TS 131	(252973.3 ,1244509)	V100-1.8 MW GS	2415.6	80.0	0.906	1.350	13.33
TS 132	(253270, 1245174)	V100-1.8 MW GS	2439.3	80.0	0.904	1.717	9.21
TS 133	(253305.8 ,1245610)	V100-1.8 MW GS	2341.0	80.0	0.913	1.205	10.81
TS 134	(252823.2 ,1246104)	V100-1.8 MW GS	2247.7	80.0	0.921	1.019	8.77
TS 135	(252288.2 ,1244194)	V100-1.8 MW GS	2363.1	80.0	0.911	1.307	12.83
TS 136	(251965, 1243975)	V100-1.8 MW GS	2328.8	80.0	0.914	1.231	13.05
TS 137	(251618.6 ,1243518)	V100-1.8 MW GS	2295.2	80.0	0.917	1.316	15.81
TS 138	(251489.4 ,1243080)	V100-1.8 MW GS	2208.6	80.0	0.924	1.134	20.61
TS 139	(252587, 1243375)	V100-1.8 MW GS	2224.8	80.0	0.923	1.091	19.86
TS 140	(252371.6 ,1242775)	V100-1.8 MW GS	2143.3	80.0	0.930	1.010	20.12
TS 141	(252092.6 ,1242228)	V100-1.8 MW GS	2104.8	80.0	0.933	1.114	13.36
TS 142	(251235, 1241138)	V100-1.8 MW GS	2106.7	80.0	0.933	1.345	11.15
TS 143	(250968.2 ,1240868)	V100-1.8 MW GS	2083.7	80.0	0.935	1.223	7.80
TS 144	(249597.8 ,1242075)	V100-1.8 MW GS	2104.0	80.0	0.933	1.534	7.72
TS 145	(249492, 1242428)	V100-1.8 MW GS	2160.4	80.0	0.928	1.756	8.39

TS 146	(249817.2 ,1242612)	V100-1.8 MW GS	2187.7	80.0	0.926	1.715	10.05
TS 147	(250118.9 ,1242819)	V100-1.8 MW GS	2167.4	80.0	0.928	1.235	12.23
TS 148	(250739, 1242581)	V100-1.8 MW GS	2180.0	80.0	0.927	1.425	17.24
TS 149	(250714.9 ,1242948)	V100-1.8 MW GS	2212.3	80.0	0.924	1.302	16.67
TS 150	(250793.2 ,1243473)	V100-1.8 MW GS	2263.8	80.0	0.919	1.344	14.06
TS 151	(249919.9 ,1243876)	V100-1.8 MW GS	2193.2	80.0	0.925	1.122	12.18
TS 152	(249574.6 ,1244113)	V100-1.8 MW GS	2204.8	80.0	0.924	1.424	8.88
TS 153	(248285, 1243546)	V100-1.8 MW GS	2124.8	80.0	0.931	1.693	5.17
TS 154	(249480, 1244624)	V100-1.8 MW GS	2174.8	80.0	0.927	1.382	8.89
TS 155	(248580.9 ,1244735)	V100-1.8 MW GS	2094.3	80.0	0.934	1.155	7.84
TS 156	(249280, 1245161)	V100-1.8 MW GS	2158.1	80.0	0.928	1.477	7.81
TS 157	(249423.7 ,1245668)	V100-1.8 MW GS	2118.4	80.0	0.932	1.360	8.21
TS 158	(249213.1 ,1246018)	V100-1.8 MW GS	2088.5	80.0	0.935	1.295	7.16
TS 159	(249086.5 ,1246477)	V100-1.8 MW GS	2036.1	80.0	0.939	1.091	7.55
TS 160	(248893.8 ,1247032)	V100-1.8 MW GS	1993.5	80.0	0.943	1.048	7.78
TS 161	(246154.4 ,1246986)	V100-1.8 MW GS	2004.8	80.0	0.942	1.228	10.13
TS 162	(246004.2 ,1246403)	V100-1.8 MW GS	1982.1	80.0	0.944	1.113	7.69
TS 163	(250483.6 ,1247907)	V100-1.8 MW GS	2094.0	80.0	0.934	1.060	11.94
TS 164	(250865.2 ,1247809)	V100-1.8 MW GS	2114.4	80.0	0.932	0.963	18.25
TS 165	(250900.5 ,1248552)	V100-1.8 MW GS	2116.8	80.0	0.932	1.022	13.66
TS 166	(251696, 1248675)	V100-1.8 MW GS	2170.7	80.0	0.927	0.891	18.27
TS 167	(251998.1 ,1249177)	V100-1.8 MW GS	2214.8	80.0	0.924	1.061	19.09
TS 168	(251186.1 ,1249297)	V100-1.8 MW GS	2155.6	80.0	0.929	0.875	20.46
TS 169	(250669.8 ,1249077)	V100-1.8 MW GS	2103.3	80.0	0.933	0.943	14.85
TS 170	(251295.8 ,1249708)	V100-1.8 MW GS	2159.6	80.0	0.928	0.942	19.52

TS 171	(251010.5 ,1250031)	V100-1.8 MW GS	2114.9	80.0	0.932	0.949	15.57
TS 172	(250564.1 ,1249763)	V100-1.8 MW GS	2065.6	80.0	0.937	0.839	14.14
TS 173	(252590, 1251473)	V100-1.8 MW GS	2227.9	80.0	0.922	0.965	11.05
TS 174	(249546.9 ,1251498)	V100-1.8 MW GS	2080.5	80.0	0.935	1.065	12.61
TS 175	(253194.8 ,1251792)	V100-1.8 MW GS	2284.8	80.0	0.918	1.156	10.71
TS 176	(253894.9 ,1252476)	V100-1.8 MW GS	2300.0	80.0	0.916	1.259	8.80
TS 177	(254035.5 ,1253518)	V100-1.8 MW GS	2264.8	80.0	0.919	1.171	8.97
TS 178	(254887.7 ,1252976)	V100-1.8 MW GS	2264.8	80.0	0.919	1.032	11.24
TS 179	(254268.6 ,1251132)	V100-1.8 MW GS	2224.8	80.0	0.923	0.973	10.26
TS 180	(254406.4 ,1250315)	V100-1.8 MW GS	2284.8	80.0	0.918	1.255	8.07
TS 181	(255093.8 ,1249780)	V100-1.8 MW GS	2244.8	80.0	0.921	0.985	9.92
TS 182	(255174.3 ,1249314)	V100-1.8 MW GS	2272.4	80.0	0.919	1.017	9.48
TS 183	(255622, 1248567)	V100-1.8 MW GS	2329.5	80.0	0.914	1.313	8.79
TS 184	(255692.8 ,1249051)	V100-1.8 MW GS	2340.2	80.0	0.913	1.130	14.88
TS 185	(256303.2 ,1249189)	V100-1.8 MW GS	2325.4	80.0	0.914	1.047	16.39
TS 186	(256745.5 ,1249160)	V100-1.8 MW GS	2294.8	80.0	0.917	1.010	17.11
TS 187	(256901.1 ,1250655)	V100-1.8 MW GS	2234.8	80.0	0.922	1.166	8.04
TS 188	(257407.8 ,1247843)	V100-1.8 MW GS	2272.5	80.0	0.919	1.026	8.06