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Development /EIABC/

Identifying potential wind energy harvesting sites for sustainable development of
Debere Berhan town, Ethiopia

By

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A Thesis submitted to the school of graduate studies of Addis Ababa University for the
partial fulfillment of the degree of Masters of Science in Urban Design and Development

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This Thesis is submitted to the School of Graduate Studies of Addis Ababa University in the Partial Fulfillment of the Requirements for the Degree of Master of Science in Urban Design and Development.

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Declaration

I, the undersigned, declare that this thesis prepared for the partial fulfillment of the requirements for the degree of Master of Science in Urban Design and Development entitled “**Identifying potential wind energy harvesting sites for sustainable development of Debere Berhan town, Ethiopia**” is my original work and has not been presented for a degree in any other university and that all sources of material used for the thesis have been duly acknowledged.

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Confirmation

This thesis can be submitted for examination with my approval as a university advisor.

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Abstract

In the modern world, renewable energy resources are a very important segment and critical input for the development of human life which provides energy for electricity. Renewable energy resources are naturally refilled by nature with short time such as wind, sunlight, and others, and have less impact on the environment. Site selection is an important step for the utilization of those renewable resources. The method of primary and secondary data analysis by using multi-criteria decision-making (MCDM) was used for site selection using ArcGIS as a tool. The potential sites for wind energy harvesting take into account four major groups (topographic, technical, environmental, and socio-economic aspects of wind farm development) and eight sub-criteria groups (slope, wind speed, distance from existing power lines, rivers, LULC, distance from urban areas, distance from roads, and wetland). All the layers and datasets are weighted and overlayed to determine weights of sitting criteria to select the best and feasible site according to their importance for the wind farm site selection. The most suitable areas both inside and around Debere Berhan town have been presented on the wind farm suitability map and windy map of Debere Berhan town. From the total study area around Debere Berhan town, 31.4 % is most suitable for wind energy harvesting which covers about 2,507.2 ha of land, and from this area, approximately the estimated energy is about 60.18 MW. Locations for urban wind energy also identified inside Debere Berhan town which covers about 189.2 ha of land in four different places and these areas can be used as building-integrated wind turbine (BIWT) for energy harvesting within the town and about 3.82 MW of energy is estimated from urban wind energy resource within Debere Berhan town. Finally, the urban design plan for the wind farm of Debere Berhan town is developed and mapped.

Keywords: Energy, Windfarm, Wind Speed, Debere Berhan town, Multi-criteria decision making

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Acronyms and Abbreviations

AHP	Analytical Hierarchy Process
ANRS	Amhara National Regional State
BIWT	Building-integrated wind turbine
CEI	Clean energy ideas
CSA	Central Statistical Agency of Ethiopia
DEM	Digital Elevation Model
EEPCO	Ethiopian Electric Power Corporation
GC	Gregorian calendar
GIS	Geographic information system
GW	Giga Watt
GWEC	Global Wind Energy council
HAWT	Horizontal axis wind turbine
LULC	Land use / Landcover
MCDM	Multi-criteria decision making
MW	Megawatt
NASA	National American Satellite Agency
SEDA	Sustainable Energy Development Authority
UHI	Urban heat island
VAWT	Vertical axis wind turbine
WLC	Weighted linear combination
WETO	Wind Energy Technology Office

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Energy is the most important factor for economic growth and the sustainable development of society especially to improve living conditions. Global energy demand increases rapidly as a result of the growth in population and the development of economies. Currently, fossil fuels are the major source of energy, and there are various environmental issues majorly atmospheric pollution, the greenhouse effect, and water pollution. Environmental impacts are minimized by the use of renewable energy sources. It is recognized that wind energy is a renewable energy source and it is clean, affordable, abundant by nature, and environmentally friendly (Oyedepo & Paul, 2012).

Cities play a major role in energy consumption. Only household consumption in cities with half of the world's population accounts for 67 – 76% of global energy use. Urbanization and the growth of megacities are directly linked to increased energy consumption. The highly increasing energy demand with less provision of renewable energy leads to the increasing use of fossil fuels which have a consequence for emission and environmental impact (Asarpota & Nadin, 2020).

Ethiopia has a total installed power generation capacity of around 4,238 MW. Hydroelectric power plants cover most of the electrical energy supply and it generates about 90% (3,807 MW). Additionally, 324 MW (7.65%), 7.3 MW (0.17%), and 99.17 MW (2.34%) are produced by wind, geothermal, and diesel power plants, respectively (Khan & Singh, 2017).

The city Debre Berhan is located in the central part of Ethiopia in the Semen Shewa Zone of the Amhara region about 130 km northeast of Addis Ababa. Emperor Zara Yaqob founded the city and was the early capital for his empire in 1454 (Amdetsion, 2016).

The present state of electricity supply in Debre Berhan town is that about 89% of the total energy demand of the town is satisfied by biomass fuels. According to Tadesse and Teketay (2018), their study shows that through multiple regression model suggested that, there is energy supply shortage for household consumption in the town and there is a continuous supply of biomass energy from rural areas nearby to Debere Berhan town. This shows that the majority of household in the town is dependent on biomass energy to meet their day-to-day energy demand for cooking and heating activities. The main reason for using biomass fuels as the main source of energy is because there is a big gap between energy supply and energy demand of the town and a shortage of reliable access to modern energy (Tadesse & Teketay, 2018).

The city, Debere Berhan attaining economic growth due to the emerging industrial development in the city. Because of this, there is a huge increase in energy demand in the city. Renewable energy sources are the solution to fulfill the increasing energy demand, by minimizing environmental pollution as well as supporting economic and industrial development of the city.

So, wind energy is considered as the most sustainable source for energy production. Energy generation from wind is described as one of the mature and cost-effective resources among different renewable energy technologies. But, even if Debere Berhan is at the high land, where wind energy is abundant, it has not been utilized to augment the availed hydroelectric energy now.

1.2 Problem statement

In Ethiopia, there is a shortage of electricity and power outages occur frequently. In Debere Berhan, the energy provision is very less when compared to the town demand because this power blackout occurs frequently especially in the dry season because the major source of electricity is only hydropower (Amdetsion, 2016).

In Debere Berhan town there is a high shortage of electricity within a different time interval, for example in night time from 7:30 Pm up to 9:30 Pm, there is a high shortage of electricity within

the town. During this time interval, the bulb has decreased light output (brownout or reduced voltage) because of shortage of power and it is difficult to use stove, oven, and large stove specifically used in Ethiopia called “injera mitad” during this time interval. This shows that the power generated is smaller than the power demand and sometimes power outages (temporary loss of power) occurs within the town.

Additionally, the road light infrastructure in Debere Berhan town is well constructed and fully completed but there is no light from those roadside bulbs. These bulbs are working well but due to the energy shortage in the town, these lights are not giving targeted functions for the people of the town. Almost all roadside lights are not giving function to the town due to the shortage of power within the town. Not only the roadside light but also many houses are constructed within the town and most of the new houses within the town didn’t get electricity supply until now due to high shortage of power within the town and kebele 07 and “Dashen” beer factory adjacent houses is a good example for this, in which these houses are constructed well and have no electricity supply.

The greater economic growth and rapid urbanization in Debere Berhan town make the energy demand increase constantly through increasing rate. Currently, in the town, there are additionally many new emerging industries and firms that vary from under construction up to finalizing stage, so there is an exponentially increasing rate of electricity demand in the town and it is the major challenge of the town. Because of this, Debere Berhan is significantly affected by a shortage of energy supply and power blackout.

The annual electricity consumption for medium developed countries is about 3,000 kwh annually (8.2 kwh) per capita and the high-income countries are about 6720 Kwh per capita (18.4 kwh daily) (Moss *et al.*, 2020). Unlike this, in Debere Berhan town, the average energy usage is 5 kwh

per household which is about 0.83 kwh per capita, which is very high gap with 8.2 kwh, with medium supply demand per capita (municipality, 2020). The supply and demand gap of energy in Debere Berhan leads to increased use of wood from forests and crop residues as a major energy source. There is only 25 MW of electricity supplied for Debre Berhan and the surrounding town from two stations (municipality, 2020), because of very low energy supply for the town about 89% of the people used fossil fuels as energy sources (Tadesse and Teketay, 2018).

This leads to environmental pollution and degradation. Additionally, air pollution associated with traditional fuel consumption is a major concern for health especially for children and women while using biomass energy for cooking. Debere Berhan town has a different potential for renewable energies in and around the town, but those renewable energy sources are not used as a power source for the town to minimize the challenge of blackout and energy shortage in the city.

To deal with the energy demand challenges of Debere Berhan town, a long-term perspective must be taken by examining various renewable and environmentally friendly energy options by understanding the potential of the town. As Debere Berhan town is located in highland it is expected that the city has greater wind energy potential. So, wind energy is considered as the most sustainable source for energy production in Debere Berhan, as an alternative because it is a renewable and clean energy source in supporting sustainable development.

1.3 Research Objective

1.3.1 General Objective:

To identify the potential sites for wind energy harvesting in and around Debere Berhan town, Ethiopia.

1.3.2 Specific objectives:

1. To identify potential wind energy harvesting sites in and around Debere Berhan town.
2. To investigate the suitability of the wind farms.
3. To develop urban design plan based on the suitability map.

1.4 Research Question

1. How to identify potential wind energy harvesting sites in and around Debere Berhan town?
2. How to investigate the suitability of the wind farms?
3. How to develop urban design plan based on the suitability map?

1.5 Scope

The research work zooms in on how wind energy sources are used to increase the energy demand of the city by locating and prioritizing the most wind energy potential sites in Debere Berhan town that fulfills the minimum standards for wind energy production.

Thematically this research is limited to wind energy, and related environmental parameters to locate windy areas inside and around Debere Berhan town and the neighboring administrative kebele boundaries in all directions from the town boundary.

1.6 Significance

This research shows how Ethiopian cities will be renewable cities by identifying the potential renewable energy sources. So that cities will be self-sustained in energy.

This study will benefit the people of Debere Berhan by indicating the available energy source at their door and surrounding areas. Hence it enhances their socio-economic development and even minimize the energy shortage and inspire potential companies and the municipality can open new employment opportunity for the citizens of the city.

Academically, this paper introduces additional information relating to renewable energy sources by identifying the potential sites for wind energy production, and also it is helpful for policymakers both at the local and national levels to consider the renewable energy sources for other cities and towns.

1.7 Limitations

For the decision of wind speed in Debere Berhan town, it is better to collect wind speed data daily for each hour, for many years is required. This kind of data is not collected and difficult to gain such kind of data in Debere Berhan town. So, this research uses the wind speed data from NASA metrological data, global wind atlas, and meteoblue metrological data that are released for researches, and the last 30-year wind speed data is used.

1.8 Organization of the paper

This paper is organized into six chapters. The first chapter is an introduction which includes a statement of the problem, objective of the study, basic research questions, significance of the study, scope, and limitation of the study. The second chapter deals with literature related to the topic and contextual review. The third chapter deals with the material and methods of the study that includes study area description, method of data collection, and method of data analysis. Chapter four is about the results of the analysis and the research. Chapter five is devoted to discussion. Finally, chapter six is devoted to conclusion and recommendations.

CHAPTER TWO: LITERATURE REVIEW

2.0 Theoretical Review

2.1 The role of renewables in cities energy use

Cities have a high energy consumption rate and they have the opportunity to provide sustainable energy service and increase the quality of life. Globally, the urban area covers more than half of the world population, as well as 65% of global energy demand and 70% of energy-related carbon emission is released by cities. Therefore, city planners and designers need to take action to meet the rising need of the population to maintain a healthy living environment. There is a potential to meet these energy demand goals by using abundant renewable energy sources. Because renewables offer low-cost energy supply and sustainable power sources (IRENA, 2016).

Energy efficiency is the primary focus of many cities. But the use of renewable energy sources is also required towards a sustainable energy system of a city. Renewables have many advantages in which reducing carbon emission, a clean source of energy, and affordability and additionally increases greater economic opportunities in cities (IRENA, 2016).

2.1.1 Priority areas in cities for renewable energy use

There are two main priority areas cities can accelerate uptake of renewable energy (IRENA, 2016).

i. Renewable energy in buildings

Most of the energy used by cities is consumed by commercial, residential, and public buildings, through cooling, heating, and different power appliances. There are many renewable sources cities can make supply energy consumption by buildings. For example, urban wind energy covers 33% of New Zealand building electricity needs (IRENA, 2016). *Figure 2.1* below demonstrates that Possible turbine placement based on wind flow acceleration on roof turbine, side façade, and between buildings.

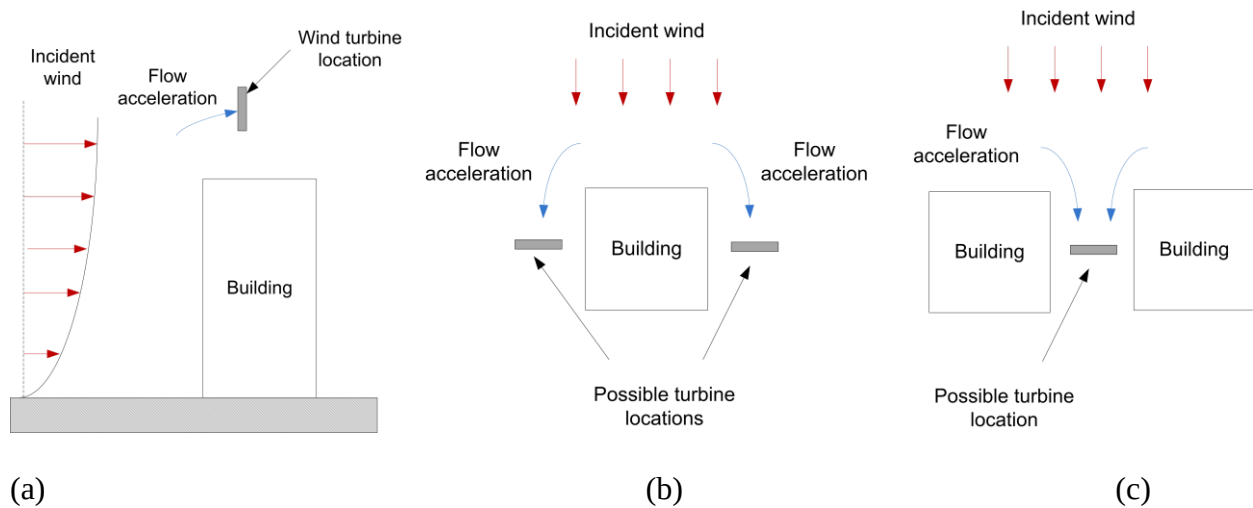


Figure 2.1; Possible turbine placement based on wind flow acceleration. (a) Roof turbine; (b) side façade turbine; (c) between buildings (Micallef & Bussel, 2018).

ii. Creating smart integrated urban energy systems

Cities not only consume energy but also produce sustainable energy sources. Particularly wind and solar can be used in cities as renewable energy sources. Currently, 5% of various renewable energy sources are used for global power generation. Currently, cities are increasingly implementing the micro-grid architecture. This allows for distributed energy generated (e.g., from rooftop small wind turbines) can provide electricity (IRENA, 2016).

While making the city, energy supply has never been taken into account as an issue in urban planning. This concept is changed, the vital role of energy efficiency makes energy supply, the key issue as an important part of urban designer's work. The crucial issue is creating a sustainable form of energy production by the use of renewable energy sources. Renewable energy sources are distributed and available anywhere. So, in the urban context, they need to be integrated into urban development to make a self-sustaining city (UN-HABITAT, 2018).

2.1.2 Urban wind resource

One of the major topics in urban wind energy is the urban wind resource. The presence of small and medium-scale wind turbines in the built environment is dependent on the urban microclimate. This section shows the overview of wind speed at different scales of flows in the urban environment. The area directly above the roof level is the urban canopy layer and urban boundary layer which is illustrated in *Figure 2.2* below. The wind speed area directly above the roof is affected by the presence of an urban zone (Micallef & Bussel, 2018).

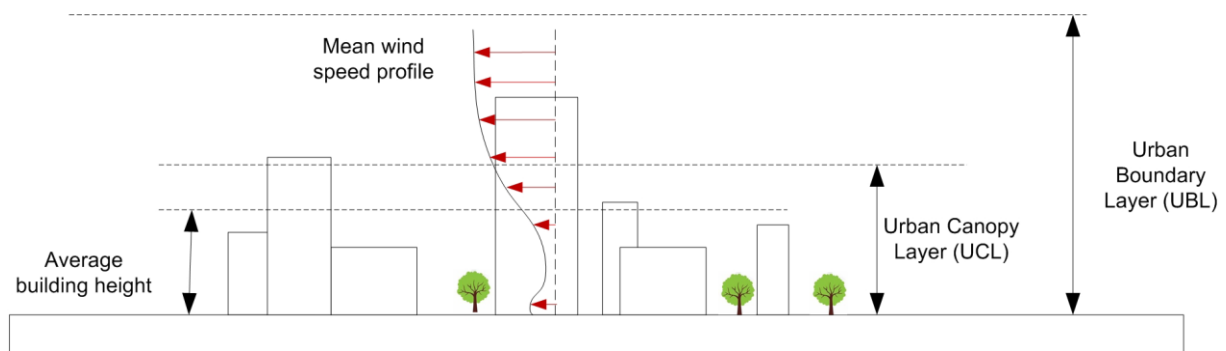


Figure 2.2; The urban wind profile (Micallef & Bussel, 2018)

2.1.3 Factors considered while designing building-integrated turbines

i. Height of building

The height of building should be above the general heights of the surrounding. The building should be highest of all other buildings so it gains maximum amount of wind pass (Purohit *et al.*, 2018).

Figure 2.3 shows height of building and surrounding buildings for better wind turbine placement.

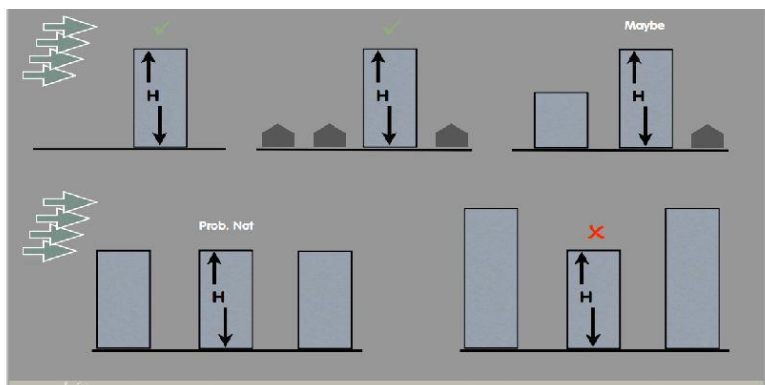


Figure 2.3; Height of Building and Surrounding Building (Purohit *et al.*, 2018)

ii. Orientation of the building

The building receives wind from all side, the turbine should be placed in the place where maximum wind pass. Tall buildings in urban areas work when they place isolated rather than placed in groups and long elevation facing dominant wind directions. *Figure 2.4* shows that wind passes as a result of the orientation of the building (Purohit *et al.*, 2018).

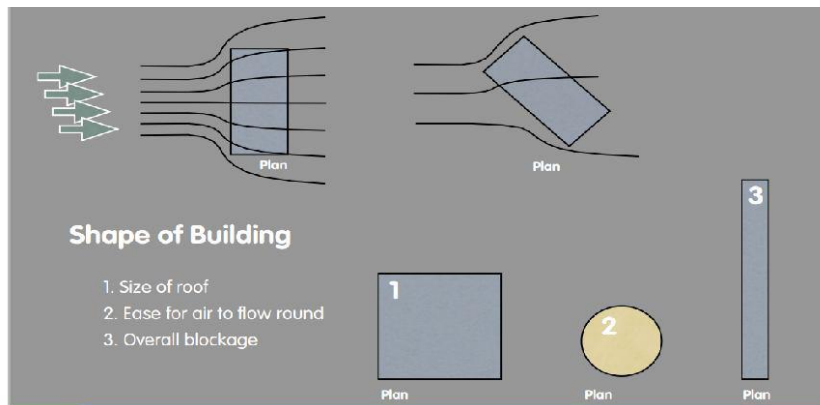


Figure 2.4; Orientation of building (Purohit *et al.*, 2018)

iii. Optimal turbine locations

Suitable Site assessment is a detailed process that includes both wind resource assessment and the evaluation of site characteristics. The site characteristics include, if the surrounding area of the site is not relatively flat, then the evaluation of topographic features is necessary. Additionally, the turbine should be upwind of any obstacles, nearby presence of large or small objects such as trees and buildings especially within 150 meters from the nearest obstacle and 9m above the highest obstacle (Exchange, 2021). *Figure 2.5* shows the obstruction of wind by a building.

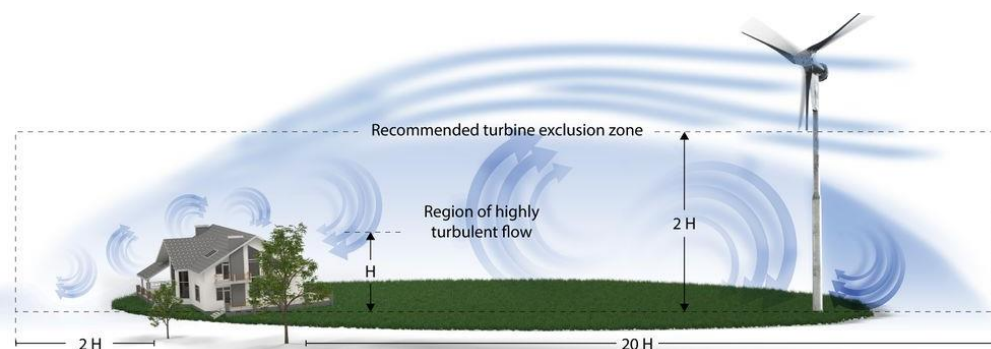


Figure 2.5; Obstruction of wind by a building or a tree of height (Exchange, 2021)

A building disturbs the prevailing winds and it might extend up to a distance of 20 times the height of the building. Therefore, in urban design wind turbines should be placed away from built urban areas to avoid the turbulence zone. If the turbine is placed in the disturbed zone the height should be at least twice the tallest building on the upwind side (Zeng, 2011).

iv. Impact of roof shape on wind speed

The wind potential above the roof of nine buildings with the same plane (12 x 30m) at a height of 20m with different roof shapes was tested by wang (2020) which includes a flat roof, gable roof, leeward roof, and dome-roof model. The height from the ground level of the planes is H=23, 24, 25, 26, 27, and 30m with different model of roof shape shown in *Figure 2.6* below. (Wang, 2020).

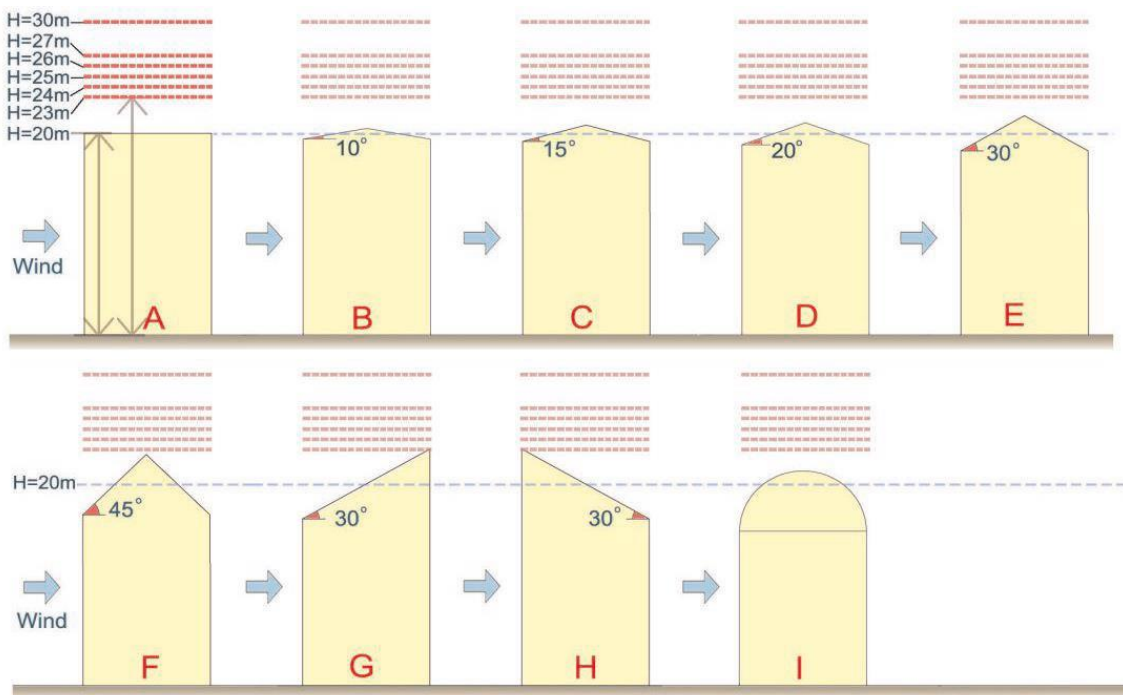


Figure 2.6; Different models of roof shapes vertical section (Wang, 2020)

The results of wind speed of model roof shapes are evaluated in *Figure 2.7* below. So, as we can see from *Figure 2.7* wind speed is higher in dome shape roof model, the flat roof and gable roof types up to 15 degrees have less impact on the prevailing wind and right-facing leeward roof model with 30 degrees has a greater impact on the prevailing wind (Wang, 2020).

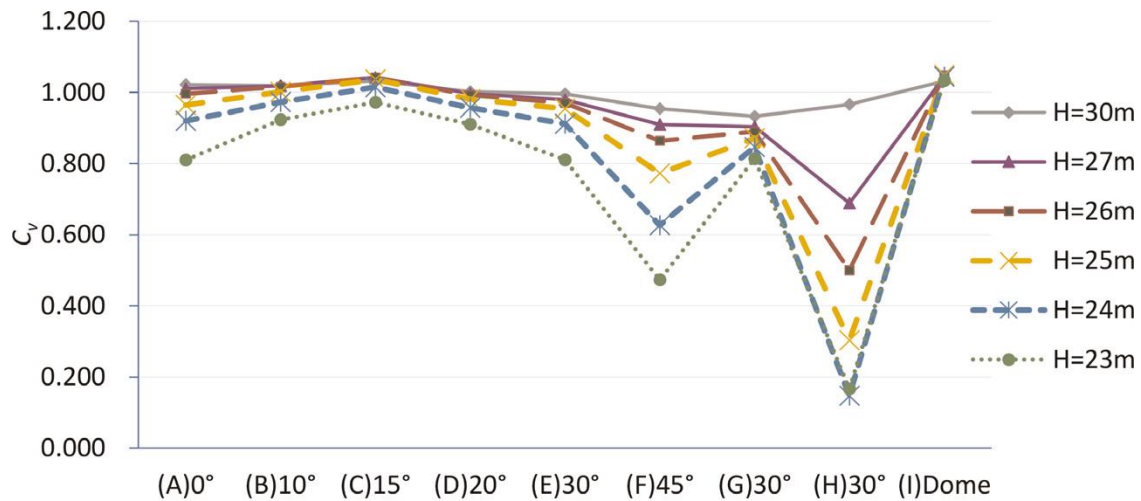


Figure 2.7; models of roof shape marked by the roof gradient (Wang, 2020)

2.1.4 Wind energy, urbanization, and cities

There is an idea of the ‘urban dimension’ which argues that more attention should be given to climate action strategies and energy policy. Urbanization and growth of megacities are directly associated with energy consumption and increase energy demand. About 75% of the energy generated throughout the world is consumed by cities. So, generating city-integrated energy could contribute to the economic, environmental, and social aspects of urban sustainability (Delponte & Schenone, 2020).

Renewable energies cover about 15% of the world's energy sources, and fossil fuels have satisfied a large part of the world's energy demand. The energy sector and energy sources cover two-thirds of global CO₂ emissions and the main drivers of climate change. In Latin America, which has a high degree of urbanization, 78 % of the population resided in urban areas in 2007, and in less developed countries like Africa and Asia, 40% of the population are living in cities. Although fossil fuels continue to be the main source of energy in cities which create serious pollution issues, and solution to mitigate more and more essential, many cities have a commitment to the renewable energy model. Copenhagen and Munich will obtain 100% of their electricity from renewable sources by the year 2025 and aspire to become carbon-neutral cities (Perea-Moreno & Hernandez-Escobedo, 2018).

The use of green energy in urban areas as a solution for the development of sustainable energy, both to meet growing energy demand in the cities and reduce greenhouse gases emission. Currently growing research trend related to small-scale wind energy generation. The installation of wind turbines in cities is a simple and eco-friendly technology because mini wind turbine has a low maintenance cost, reliable and very low environmental impact. It also works with low-intensity winds and does not need the creation of new electrical infrastructures (Perea-Moreno & Hernandez-Escobedo, 2018).

Urban wind energy is very important for power generation but it has also additional benefits such as ventilation, mitigation of the UHI effect, and pollution dispersion. In most of the countries based on urban wind characteristics, estimates the potential for urban electricity generation. Urban wind provides 33% of New Zealand residential building electricity needs with HAWTs and 40% with VAWTs in San Cataldo. There is also an additional example of existing urban wind projects. The world trade center in Bahrain uses three vertically arranged HAWTs, and providing 11 to 15 % of electrical energy needs, although the two VAWTs installed in Pearl River Tower in Guangzhou, China which provides 5% of its energy needs (Kammen & Sunter, 2016).

The Jiuquan wind power also known as Gansu Wind Farm is the world's biggest wind farm which contains 7,000 wind turbines and an installed capacity of 20 GW. The Jaisalmer wind park which is located in the Jaisalmer district of Rajasthan, India also generates 1.6 GW and is the biggest wind farm in India. Alta wind energy center can generate 1.55 GW which is located in Tehachapi, Kern County, California. Muppandal Wind Farm, India, Shepherds Flat Wind Farm, US, Roscoe Wind Farm, US also generates 1500MW, 845 MW, and 781.5MW, respectively (Unwin, 2019).

2.2 The evolution of wind energy

The wind is produced as a result of the movement of air due to atmospheric pressure gradients. The wind blows from greater pressure gradients to lower pressure gradients. The higher wind speed is present in higher pressure regions so, greater wind energy is obtained from those areas. The wind is generated due to different factors the most important factors are uneven solar heating of the earth's surface, local geographic condition, and the Coriolis effect due to the earth's self-rotation. Wind energy can be captured by wind energy converting technology (Tong, 2010).

Wind is used as a source of energy for many years. Since early recorded history, it has been used as an energy source for many ages. For the first time in history, a wind-driven wheel is used to power a machine. By 1000 AD; simple windmills in china are used for pumping seawater. In 1887 the first wind turbine built in Scotland, used to produce electricity and it is used to power the lighting in a cottage, thus make the first house in the world that has its electricity (Shahan, 2014).

Energy generated from wind power is blooming all over the world as a technological answer to environmental problems of the globe such as greenhouse gas emissions, fossil fuel depletion, environmental degradation, global warming, etc. *Figure 2.8* shows that wind power installed capacity in the world is increasing exponentially. In the last decades, the world wind energy capacity had a doubling time of only three years and no other energy technologies have ever grown at such a growth rate in the past (GWEC, 2019).

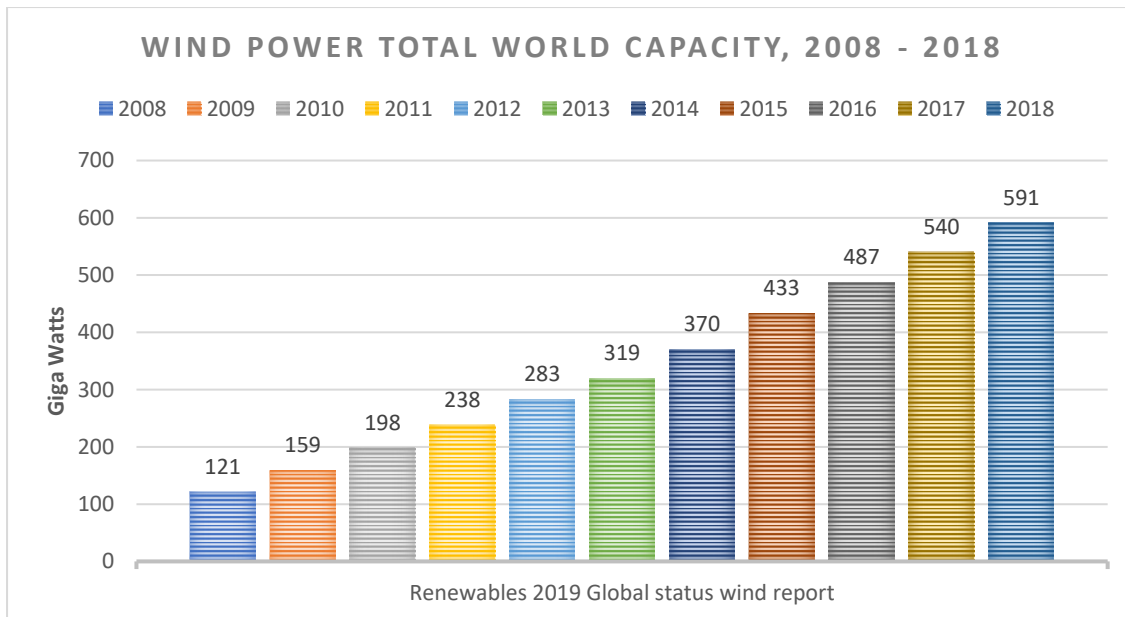


Figure 2.8; The growth rate of wind energy from 2008 to 2018 in the world (GWEC, 2019)

World researchers widely focus on pollution-free renewable energy sources. As a result, wind energy is the most suitable and least-cost source of energy. Wind energy is now widely used in most countries in the world and *Figure 2.9* shows the world wind energy capacity of the top ten countries (Saifullah *et al.*, 2016).

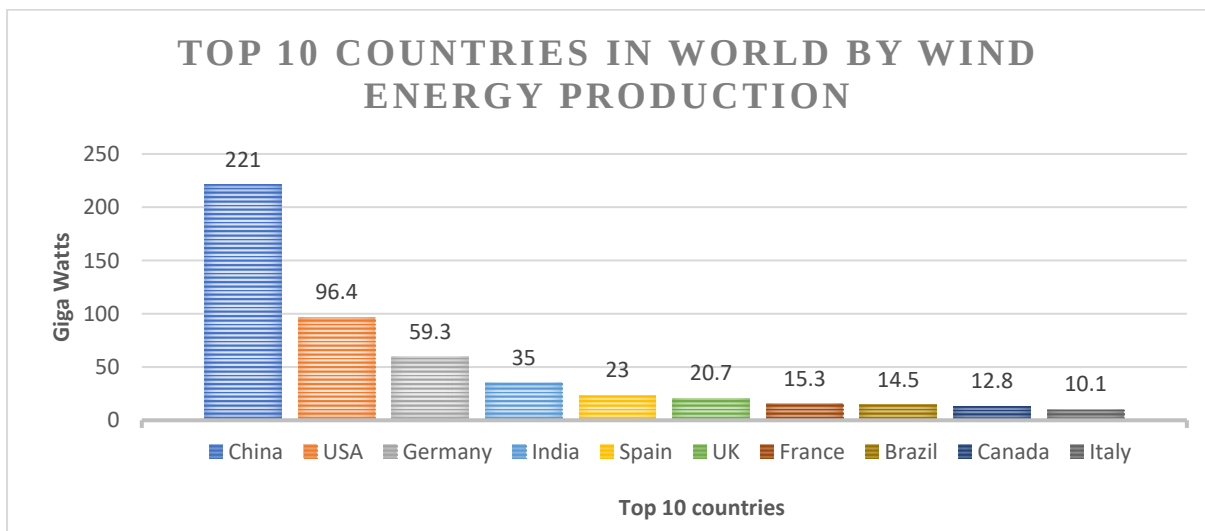


Figure 2.9; Top ten countries, the cumulative capacity of Wind Energy (unwin, 2019)

2.3 Technologies for harvesting wind energy

A wind turbine is an energy-converting machine that converts kinetic energy that presents in the wind to mechanical energy and finally turns to electrical energy. In the last decades, there is a remarkable advancement in wind turbine design with modern technological development (Tong, 2010).

Modern wind turbines come in various styles and sizes and are classified as horizontal (HAWT) and vertical axis wind turbines (VAWT) based on the rotating axis of rotor blades (Saad & Asmuin, 2014).

i. Horizontal axis wind turbine (HAWT)

Currently, most of the wind turbines are horizontal-axis type, which is the rotating axis of the blade is parallel to the prevailing wind. Horizontal axis wind turbines have advantages of high turbine efficiency, low cost per output power, minimum cut-in wind speeds, and high power density. *Figure 2.10* illustrates some examples of HAWT (Tong, 2010).



Figure 2.10; Examples of existing horizontal axis wind turbines (Stathopoulos et al., 2018)

ii. Vertical axis wind turbine (VAWT)

Vertical axis wind turbine rotates with a vertical axis that is perpendicular to the ground. Vertical axis wind turbine has the advantage of wind turbine accept the wind from any direction. Because

of the lower power efficiency of this kind of wind turbine currently, it covers a small percentage of wind turbines. *Figure 2.11* below shows some examples of VAWT (Mohammed *et al.*, 2014).



Figure 2.11; Examples of existing Vertical axis wind turbines (Stathopoulos *et al.*, 2018)

iii. Small-scale and Large-scale turbine classification

Wind power has an image of large wind turbines arranged together to form a wind farm. Small-scale wind turbines are mostly less than 50 kW and can be large as 250 kW in size and are typically designed for small commercial, residential, agricultural, and some industrial applications. The main difference between Small-scale and Large-scale turbine classification is summarized in *Table 2.1* below (Temesgen, 2011).

Table 2.1; Large-scale and small-scale wind turbines

No	Parameter	Small Scale	Large Scale
1	Mast height	≈10 m	>50 m
2	Blade length	5 – 8 m	20 – 50 m
3	Turbine rotation	Several hundred rpm	15 – 30 rpm
4	Rated power	< 100kw	1 – MW
5	Transmission Type	Direct driven	Gearbox
6	Application	Standalone / Grid connected	Grid-connected

Source, (Temesgen, 2011)

iv. Application of wind energy in urban area

The commonly used application for wind energy harvesting is to construct wind farms. Moreover, the effective utilization of wind energy is achieved in urban areas by building integrated wind turbines. The wind environment in an urban area is different from hilly or coastal areas. Wind speed in the urban area is generally less than the same height in hilly or coastal areas due to surface roughness caused by complicated building arrangements. *Table 2.2* describes the roughness length of various terrain types. On the other hand, the upper air in urban areas is not significantly affected by surface roughness (Jung *et al.*, 2015).

Table 2.2; Surface roughness lengths for various terrain types

Terran	Roughness length (m)
Cities, forests	0.7
Suburbs, wooded countryside	0.3
Villages, countryside with trees	0.1
Open farmland, few trees, and buildings	0.03
Flat grassy planes	0.01
Flat desert, rough seas	0.001

Source: (Micallef & Bussel, 2018)

The application of a building-integrated wind turbine (BIWT) system to buildings is to install many small-size wind turbines on the buildings instead of a few large-sized wind turbines. This kind of approach can be used with existing structures without any specific structural strengthening of the existing structure (Jung *et al.*, 2015). *Figures 2.12, 2.13, and 2.14* show building-integrated wind turbine possible locations.

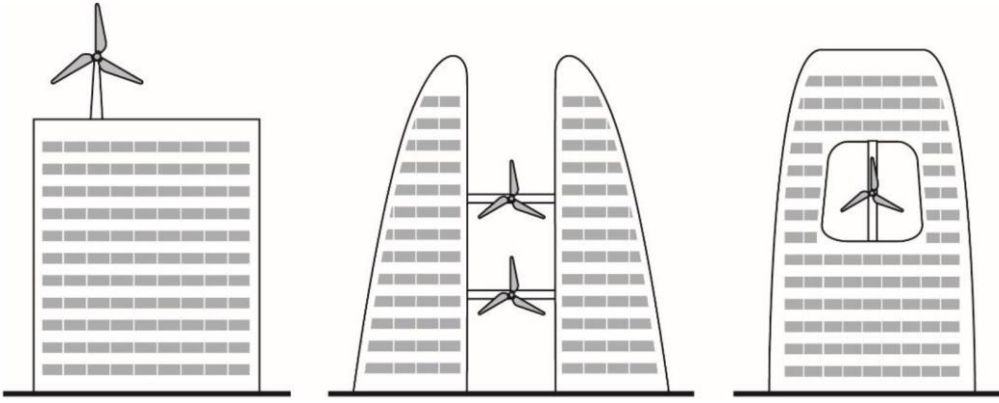


Figure 2.12; Building-integrated wind turbine system using wind turbines: three possible installation locations of large-sized wind turbines (Jung et al.,2015).

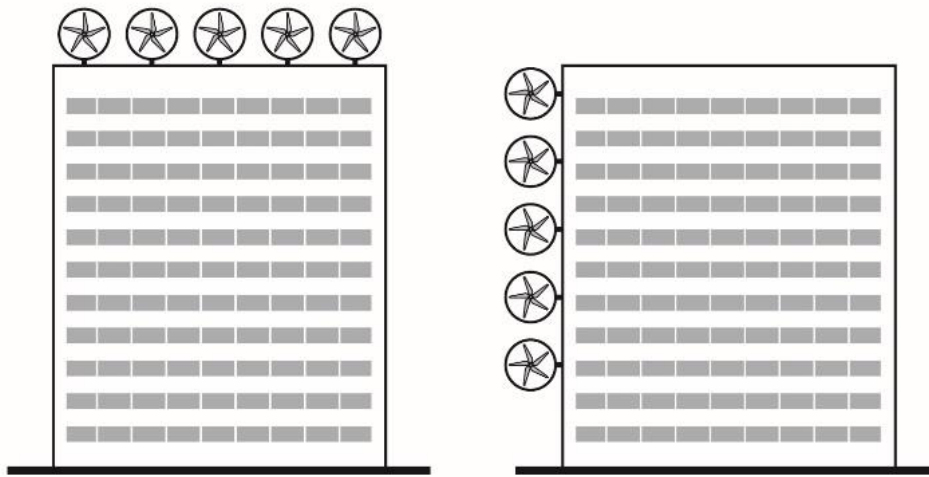


Figure 2.13; Building-integrated wind turbine system using wind turbines: two possible installation locations of small size wind turbines (Jung et al.,2015).

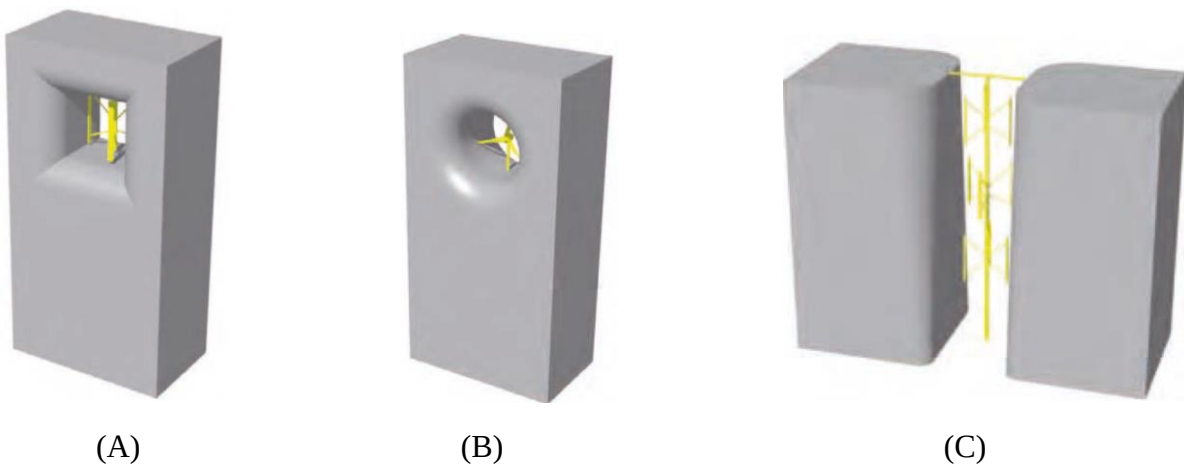


Figure 2.14; Building-integrated wind turbine system using wind turbines: three possible installation locations (A), Square within a building, (B) Circular within a building, (C) Between multiple buildings (Stankovic et al., 2009).

2.3.1 Components of the wind farm

The energy generated from wind is reported to be close to becoming self-sustaining.

Wind energy can be generated by a single wind turbine or several power generating units commonly called a wind farm. The wind farm has the following components

- wind turbines
- towers
- transformers
- internal access roads
- transformer station
- transmission system connecting the facility to the national grid (Talinli *et al.*, 2011).

The capacity for generating wind energy depends on the selected site for the wind farm. Inadequate site selection for the wind farm leads to lower energy generated than expected and increases maintenance cost etc. (Talinli *et al.*, 2011).

The decision of selecting appropriate sites for a wind farm is a complex study involving not only technical considerations but also environmental and social requirements.

i. Technical considerations for decision criteria

Many technical factors affect the decision making on selection potential sites for wind energy production includes,

- wind speed,
- land topography and geology,
- grid structure and distance
- turbine size (Talinli *et al.*, 2011)

ii. Environmental considerations for decision criteria

There are also environmental factors while selecting a site for wind farms which include

- visual impact, noise impact

- wildlife and endangered species

Wind energy is a renewable energy source and wind farms don't cause a reduction in natural resources because the only input is wind and no formation of emission during the energy production process. But wind turbines create noise while they are working, incompatible views of the region, and endangered species could be disturbed during the construction of large-scale wind farms (Saidur *et al.*, 2011).

iii. Social considerations for decision criteria

Many social factors directly affect the decision making of a site selection which include

- public acceptance
- distance from the residential area
- alternative land use options of the selected wind farm site

Public acceptance is important because wind farms have an impact on the environment and social effects. So, these effects must be considered to gain social acceptance while selecting an appropriate site for a wind farm. Distance from the residential areas has a vital role with minimum interface with social life during wind farm construction and operation (Talinli *et al.*, 2011). The criteria identification that influences the location of wind farms in the town is a vital process. The criteria can be classified into four major groups and summarized in *Table 2.3* below.

Table 2.3; Wind energy site selection criteria and description

Criteria	Description
Topographic	
Slope	While selecting a site for a wind farm, the slope is an important topographic factor in which it indicates construction-related challenges. Areas with a steep slope are less suitable for wind farm sites because of extra construction and maintenance costs. Slope more than 15 % is restricted in some studies, the restriction is related

	to the elimination of huge parts but up to 30% is assumed for the construction of wind farms (Athanasios, 2018).
Aspect	The direction of slope concerning wind direction is important for maximum utilization of wind potential. The direction of the slope should be toward the dominant wind blow on the location of the wind farm (Idrizi <i>et al.</i> , 2018).
Technical	
Wind speed	Wind speed is the most important factor to consider for a wind farm. Wind speeds greater than 3m/s are evaluated continuously up to 20 m/s If the speed is more than 20m/s, it will cause damage to equipment (Pamucar <i>et al.</i> ,2017).
Distance from power lines	The other issue to consider is the distance from power lines, it reduces the cost of construction of energy transmission infrastructure. While selecting potential sites it is better to consider the existing availability of electrical power lines (Idrizi <i>et al.</i> , 2018).
Environmental	
Rivers and lakes	Rivers and lakes are natural protected areas and the wind farm should exclude the buffer zones. For rivers, it is 500 m, for lakes, and water bodies it is 700 m away (Moradi <i>et al.</i> , 2017).
Land use/ Landcover	Land use is the most important factor to consider. Wind farms should be placed which have less impact on the existing land and must be located outside protected areas, wetlands, artificial surfaces, aquatic and forest areas (Pamucar <i>et al.</i> ,2017).
Socio-economic	

Distance from urban areas	Wind farms have negative impacts on the local population with relation to visual and noise disturbance, these lead to some setback distance from urban areas. To minimize those impacts, wind farms are located at the greatest possible distance from urban areas and the minimum distance from an urban area is at least 500m up to 1000 m or three times the height of the wind turbine (Athanasios, 2018).
Distance to roads and railways	Wind farm is not better located adjacent to roads because the transportation of massive turbines can be interrupting the existing road network. But the distance from roads or railways should be reduced to minimize the cost. The minimum distance of 500m should be kept from highway roads (Bili & Vagiona, 2018).

Wind farm site selection is intricate decision-making, which includes multiple criteria. Multi-criteria decision-making (MCDM) has a framework to analyze, survey, and solve such kinds of problems. Analytical Hierarchy Process (AHP) is one of the methods which is considered for MCDM. Analytical Hierarchy Process formulation of solution based on weight by considering the criteria of each problem (Moradi *et al.*, 2017).

2.3.2 Analytical Hierarchy process weights

For analyzing the site selection, a set of factors must be considered and, the criteria are classified into four major groups and eight sub-groups as shown in *Table 2.4* which includes Topographic, Technical, Environmental, and socio-economic factors (Izeiroski *et al.*, 2018).

Table 2.4; Factors and weight used in the analysis of suitability for wind farm development

No	criteria	Max/Min cut point criteria	Weight
Topographic (5%)			
1	Slope	<25%	5%
Technical (50%)			
2	Wind speed	>5 m/sec	40%
3	Distance from power lines	>500 m	10%
Environmental (20%)			
4	Distance from rivers and lakes	>500m	5%
5	Land use/ Landcover	>2000m of woodland, wetland, and natural protected areas	15%
Socioeconomic (25%)			
6	Proximity to an urban area	>1500m	15%
7	Proximity to village	>1000m	5%
8	Distance to roads	>250m	5%

Source: Izeiroski *et al.*, 2018

2.3.3 Characteristics of wind energy

Energy generated from wind is the other form of kinetic energy in the air as it flows. By using converting machines wind energy is converted to electrical energy.

i. Wind power

Kinetic energy is present in any object in motion for a given mass with rotational or translational speed. In moving air, the kinetic energy can be determined as shown in Equation (3.0).

$$E_k = \frac{1}{2} mv^2 \text{ -----(2.0)}$$

Where m is air mass,

v is the mean wind speed for a suitable period of time,

Wind power is obtained from differentiating kinetic energy in wind with time (Tong, 2010).

Wind power, P_W , is directly proportional to the density of air, ρ , the cube of wind speed, V^3 , and the swept area of the blade (A) which is represented as where r is the radius of the blade and summarized in the Equation (3.1) below.

$$P_W = \frac{1}{2} C_P \rho A V^3 \text{ -----(2.1)}$$

Where C_P , represents the efficiency of the turbine

ρ , represents the density of air

A represents swept area of the blade and V represents wind speed

The coefficient performance of the turbine, C_P , represents the efficiency of the turbine while converting wind power to mechanical power (power of the turbine). Equation (2.1) describes to gain higher wind power there must be high wind speed, and if the length of the blade is longer, it helps to get a larger swept area. So, increasing wind speed, the longer length of blades, and higher air density are directly affecting wind power (Temesgen, 2011).

2.3.4 Wind energy generating systems

The technology of wind energy was developed in the last three decades, as shown in *Figure 2.15* with increasing rotor dimension and use of efficient power electronics to increase the rotor speed.

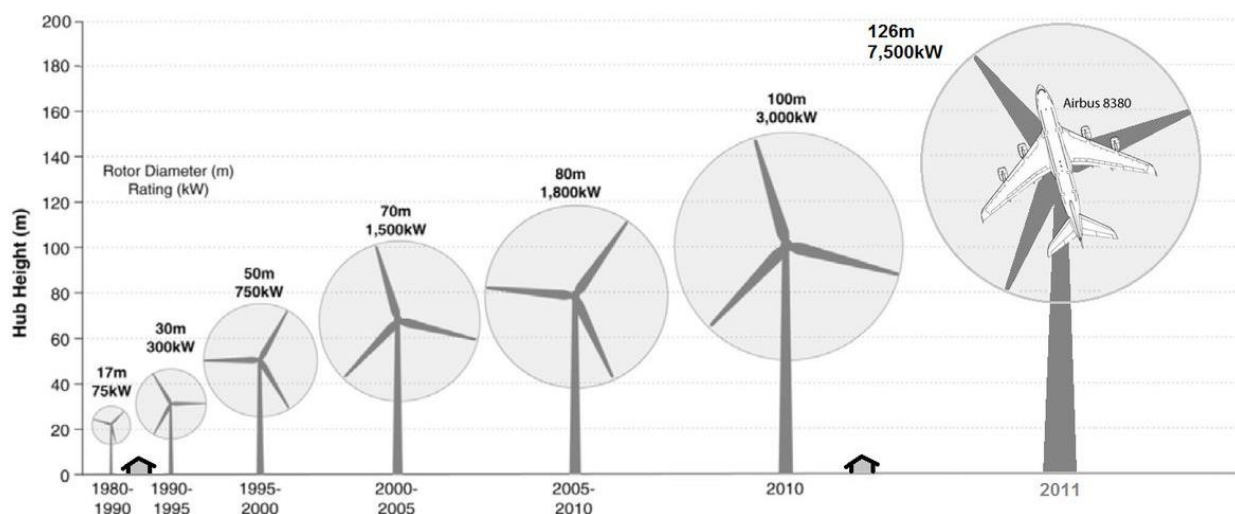


Figure 2.15; Evolution of wind turbine dimensions (David, 2016)

i. Wind Turbines

The wind turbine is used to produce electricity by using wind to drive an electrical generator. When wind passes through the blades it generates a turning force, the rotating blades turn the shaft which goes to the gearbox. The gearbox increases the rotational speed which is appropriate for the generator, which uses a magnetic field to convert the rotational energy into electrical energy (Anaya-Lara *et al.*, 2009).

After selecting a good wind site, several wind turbines are installed and called wind farm or wind park. Inside wind farm, wind turbines are installed in rectangular arrays. The number of wind turbines in a specific location depends on the size of the wind turbine and the rotor diameter. The recommended space for separating towers within a row is 3 – 5 times rotor diameter and 5 – 9 times between the rows (Gupta, 2015). *Figure 2.16* below shows optimum spacing between wind turbines.

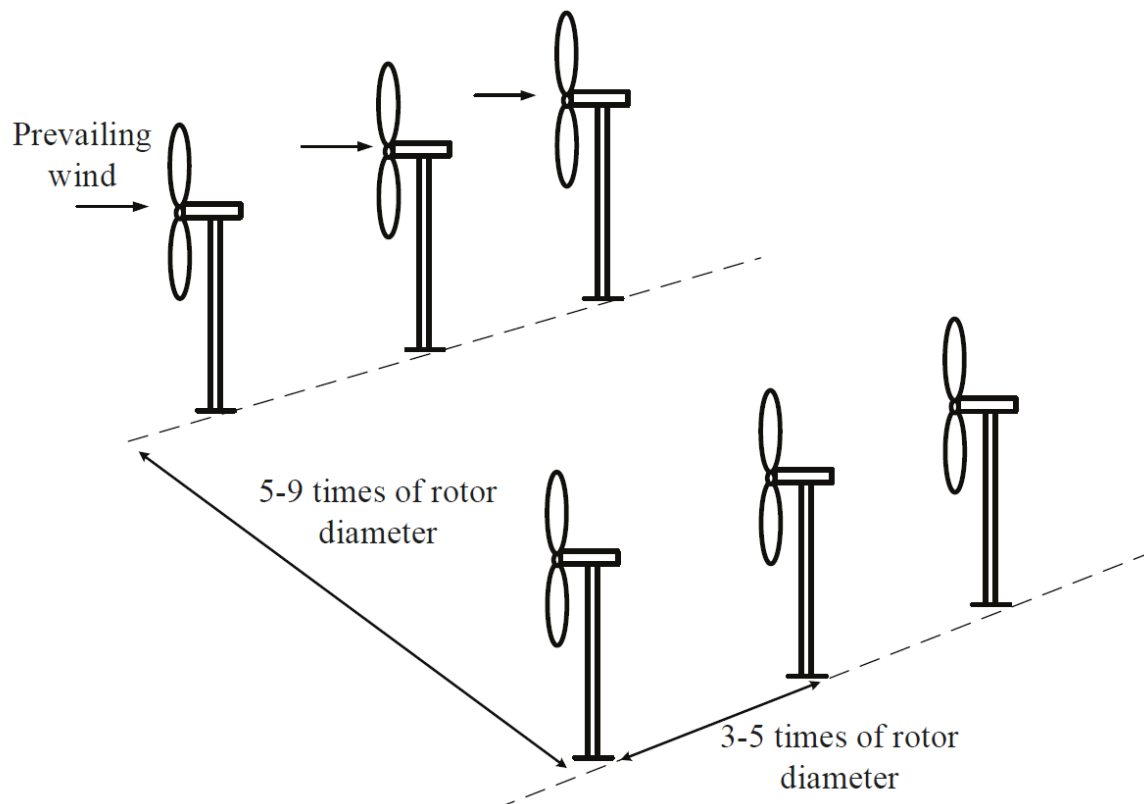


Figure 2.16; Optimum spacing of wind turbines within wind farm (Gupta, 2015)

ii. Blade swept area

The swept area refers to the area of the circle created by the blades as they sweep through the air. *Figure 2.17* illustrates the swept area of a wind turbine. The swept area of the blade is calculated as

$$A = \pi [(l + r)^2 - r^2] = \pi l (l + 2r) \text{ -----(3.2)}$$

Where A , is blade swept area

l is wind blades length

r is the hub radius

So, when doubling the wind blade length, the swept area is increased by 4 when $A \approx \pi l^2$.

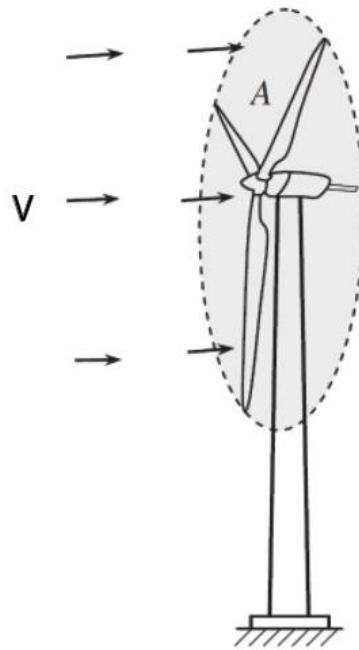


Figure 2.17; Swept area of wind turbine blades (Tong, 2010)

2.3.5 Advantages and challenges of wind Energy

Wind power is one of the fastest-growing energy sources throughout the world because it has many advantages.

i. Advantages of wind energy

Wind energy is cost-efficient: wind energy is one of the low-cost sources of energy available today. It is a fuel-free and minimum cost in relation to traditional energy sources (WETO, 2017).

Wind energy is clean: Energy generated from wind does not pollute the air like other energy sources. The most common types of energy sources like fossil fuels (coal, natural gas) can cause health problems and economic damages. Wind turbines are a clean source of energy and do not produce atmospheric emissions which causes greenhouse gases and acid rain (S.Han, 2019).

Wind energy is sustainable: Wind energy is derived from solar energy and it is caused by the heating of the earth's surface by the sun. So as long as the sun shines the wind is present and it is not finite (WETO, 2017).

ii. Challenges of wind energy

Wind power generation has various benefits and advantages but it has also some challenges that need to be addressed while power generation from wind. The challenges are originated from environmental influences to thermal management of wind turbines must be considered in the wind power generation and site selected for wind farm sites.

Impacts on the environment: Wind energy have negative and positive impacts on the environment. Energy generated from wind does not have pollutants but there is a significant negative impact on wildlife and human life such as noise and visual impact (Agarwal, 2016).

1. **Impact on wildlife:** Large-scale wind farm's impacts on wildlife can be categorized into two categories; direct and indirect impact. The direct impact is the wildlife mortality rate with direct collisions with the turbines. The indirect impact is habitat disruption (Saidur, *et al.*, 2011).
2. **Noise impact:** Noise pollution is the other critical environmental issue of wind energy; it leads to lower property value from the wind turbine within a certain radius (Lloyd, 2014).

3. **Visual impact:** Visual impact is mainly influenced by the color, layout, and shape of wind turbines. This problem is mostly focused on individual perception and it is difficult to measure. Arranging turbines in a simple and uniform row with light colors can improve people's perception and aesthetics of wind farms (CEI, 2019).

2.4 Contextual Review

2.4.1 Wind energy in Africa

The thinking about natural resources was changed after the energy crisis of the 1970s. It inspired environmental advocacy and seeds environmental awareness. In the 1970s petroleum exporting countries restricted the trade. The restriction created a shortage of gas and made gasoil more expensive. The way spaces were designed was changed and impacted by the energy crisis which includes interiors, illuminated with bright ceilings and fluorescent lamps, but electricity prices increased. So, facility managers removing lamps, lighting layouts, and damaging ballasts and fixtures. So, designers more utilizing task on lighting and sustainable energy sources and returning to daylighting strategies, and inspired sustainable environmental advocacy (Donof, 2016).

Renewable energy in the African continent is steadily growing. African countries have the best potential for wind power resources. The total installed wind energy in Africa and the middle east is above 6 GW. In the next five years, African countries are expected to increase new over 10.7 GW of energy from wind farms (GWEC, 2019).

The leading country in Africa, with high wind energy production, is South Africa, in which a total of 1.17 GW of wind energy has been built and south Africa is aiming to install 8.4 GW of wind energy capacity by 2030. Morocco and Egypt are positioned as the second and third high wind

energy-producing countries in Africa. Morocco currently has installed 870 MW and another 50 MW is under construction (Tiyou, 2016).

Morocco has a high electrification rate unlike sub-Saharan African countries that is about over 95%. So, the use of renewable resources in Morocco is seen as the way to help the country becoming for self-sufficient. Egypt has excellent wind resource potential, particularly Suez Gulf where an average speed of 10.5 m/s. Currently, Egypt has built about 750 MW of wind energy production. They have set a target of 4.3 GW of renewable energy in 2022 and wind energy is the vital part of these renewable energy developments and it will account for 2GW (Tiyou, 2016).

Ethiopia is positioned in the fourth rank and has installed capacity more than 320 MW of wind energy production capacity. Over 75 % of the country is not connected with the national grid and many populations are living in rural areas. Ethiopian energy requirements are huge and to meet this demand it needs to increase the electricity production by 20 – 25 % per year. Kenya is placed in the fifth position and the project Lake Turkana, this wind farm is the biggest in the continent and lift the country wind energy capacity from 14 MW to 324 MW and it is not completed yet (Tiyou, 2016). *Table 2.5* below illustrates the top 5 wind energy capacity countries in Africa.

Table 2.5; Top five wind energy capacity countries in Africa

Rank	Countries	Operational (MW)	Under construction (MW)
1	South Africa	1,170	840
2	Morocco	870	50
3	Egypt	750	0
4	Ethiopia	320	0
5	Kenya	14	310
	Total	3,124	1,200

Source: (Tiyou, 2016)

2.4.2 Wind Energy in Ethiopia

Wind is the flow of air across the earth's surface. Wind is created by differences in atmospheric pressure that force air to flow from higher pressure zones to lower pressure zones (SEDA, 2001). Wind energy is one of the promising sources of renewable energy, which is derived from solar energy. The generation of wind can be attributed to both global and local effects. On a global scale, the wind is created by the pressure difference due to unequal heating of the earth's surface by the sun or solar energy. Solar radiation covers a large area around the equator than the poles of the earth's surface, and it decreases from the equator to the poles because of high latitudes. The hot air rises from the equator and expands, while the cold air moves towards the equator from the poles. The winds blowing towards the equator from both the north and south poles get deflected due to the effect of the rotation of the earth. So, winds are the result of both pressure force and the earth's rotation (V, Pandey *et al.*, 2019).

Wind energy has a major role as a renewable source of energy supply, to meet the growing energy demand. Wind energy has been taken as a promising choice as a renewable energy source because it is abundant, clean, affordable, inexhaustible, and environmentally preferable. Wind energy has become the fastest growing renewable source of energy in both developing and developed countries throughout the world because of its advantages to environmental and sustainable energy development of society (Oyedepo & Paul, 2012).

Currently, in Ethiopia, 97 % of energy is gained from hydropower plants and only 15% of the population has access to electricity (EEPCO, Ethiopia Electric Power Corporation, 2011). According to the study of Ethiopian Electric Power Corporation (EEPCO) in October 2006, wind energy is considered as complementary to hydropower because in the rainy season there is low wind and high hydropower energy and vice versa.

Ethiopia has huge and various potentials of renewable energy resources. The estimated potentials that can be generated from wind is 10 GW. This source can be used as long-term energy potentials for both local industries, which are developing in Ethiopia as well as for international energy trade (Mengistu *et al.*, 2015). Currently, different wind farm project is underway in the country among these Ashegoda project having 8.5 m/s wind speed, Herna having 6.9 m/s and Nazaret having 9.3m/s is the major site for wind energy productions in Ethiopia (Temesgen, 2011).

In the past centuries wood, oil, coal, natural gas has been used as the main source of energy in Ethiopia. These energy sources are limited, finite, and have the consequence of long-term environmental pollution problems, this led countries to focus on clean and sustainable energy sources. Wind energy has become rapidly growing as one of the most cost-effective renewable sources of energy and it increases throughout the world (Asressa, *et al.*, 2013).

Ethiopia has huge potential and usage of hydropower and it is considerable however, it is necessary to mix broad renewable energy sources, because in the dry season when climate change occurs the precipitation level can diminish, in such cases Ethiopia characterized by an extremely low level of energy consumption, and low level of electric power generation. In such intervals, the energy usage is returned to fossil fuels which increased greenhouse gas emissions and environmental pollution. The energy demand of Ethiopia is challenged due to the factors like the population and economic growth of the country, increase of energy demand of 10 – 12% per annum due to rapid economic growth, and only near 14% of the population have access to electricity (Azemraw, 2014).

Ethiopia has an overall 120 MW of electric generating capacity from the Aysha II wind farm project. The wind farm project will have 48 turbines and each turbine has generating capacity of

2.5 MW. The construction of Aysha II was launched in June 2017 in Somali region of Ethiopia in which 700 km east of Addis Ababa.

Currently, Ethiopia is generating 324 MW of electricity from wind energy located in a different part of the country. These wind farms are Adama wind Farm which generated 51 MW, Adama II, and Ashegoda wind farms also generate 153 MW and 120 MW energy capacity, respectively. Adama wind farm is located 95 km southeast of Addis Ababa, the construction on the Adama wind farm is started in June 2011, and phase I was inaugurated in March 2012. After phase I in Adama, EEP signed another contract with Hydro china to add 153MW of capacity. Phase II additional capacity became available in 2015. Adama, I wind farm was the first operational wind farm in Ethiopia (Birru, 2019).

Ashegoda wind farm is located in the Tigray region near Mekelle, 780 km north of Addis Ababa and it generated 120MW of energy which includes 84 wind turbines. *Figure 2.18* illustrates currently operational wind farms in Ethiopia.



Figure 2.18; Operational wind farms in Ethiopia

2.4.3 Wind energy in Debere Berhan town

Wind resource in a specific location is a major driving factor for any wind energy project. Based on the general wind resource map of Ethiopia Debere Berhan have better wind resource potentials. Debere Berhan is the town in the central part of Ethiopia in which this study was conducted. The town faces greater economic growth and rapid urbanization. The high industrialization and economic development of the town lead to a continuous increase in power demand, because of this, the power system has faced frequent, widespread, and long-lasting blackouts (Tadesse & Teketay, 2018). So, this wind resource potential is of the town changed to energy, by the further study on the location to address the energy shortage of the town by sustainable energy supply.

Figure 2.19 below illustrates that there is a continuous increase in energy consumption and it is more than double within only 8 years in the town. These show that there is an outstanding continuous shortage of energy supply in the town with an increasing rate.

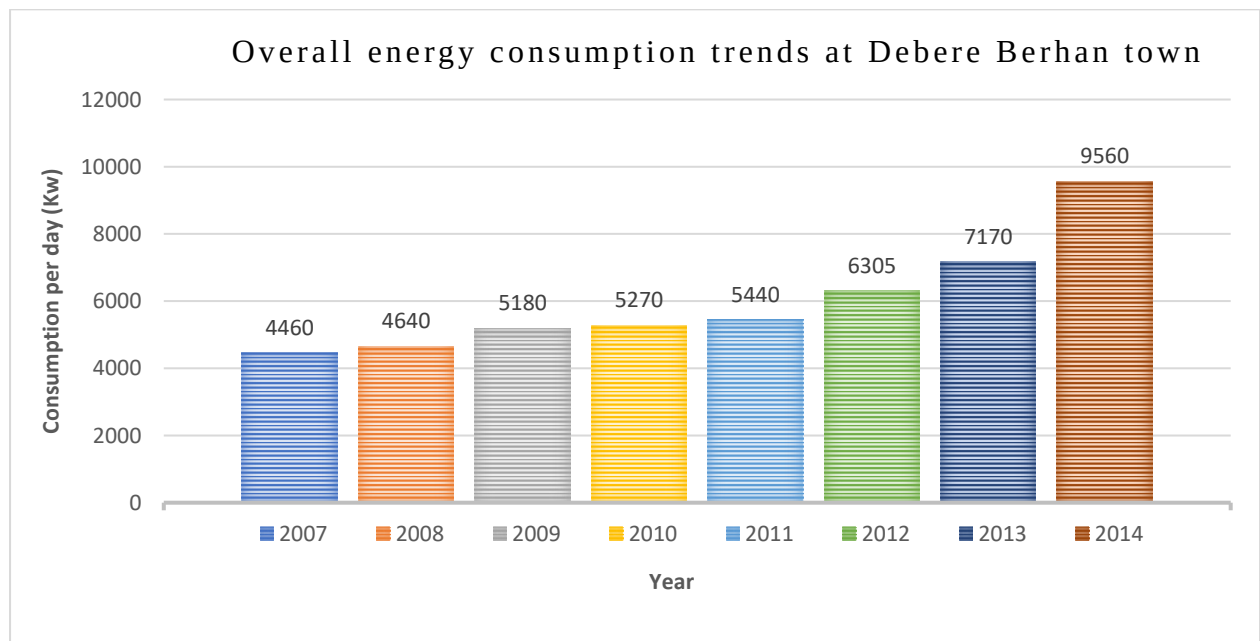


Figure 2.19; Overall Electric Consumption Trends at Debre Berhan town (EEPCO, 2014).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Study Area

The study was conducted in Debre Berhan town, North Shewa Administrative zone of Amhara national regional state that is about 130 kilometers northeast of Addis Ababa. The town is situated at an elevation of 2,840 meters and it is the early capital of Ethiopia. Debre Berhan town is located between latitude 9°39'4.79"N, longitude 39°30'45.78"E and latitude 9°41'34.02"N, longitude 39°33'17.40"E. Based on the national census conducted by the Central Statistical Agency of Ethiopia (CSA) in 2012, Debre Berhan town has a total population of 87,408 with growing by an average of about 4.5 percent per annum. The study area covers a total area of 8,010 ha.

According to Meteoblue climate diagrams based on 30 years of hourly model simulations, the town temperatures vary from 4 °C (the mean daily minimum for every month) the coldest month August to 20 °C (the mean daily maximum for every month) the hottest month April. The precipitation of the town is maximum at July and monthly average reaches up to 210mm and the minimum precipitation is recorded in November and December and the annual rainfall ranges between 800 to 1100mm. The location map of Debre Berhan town and the study area is shown in *Figure 3.1* below.

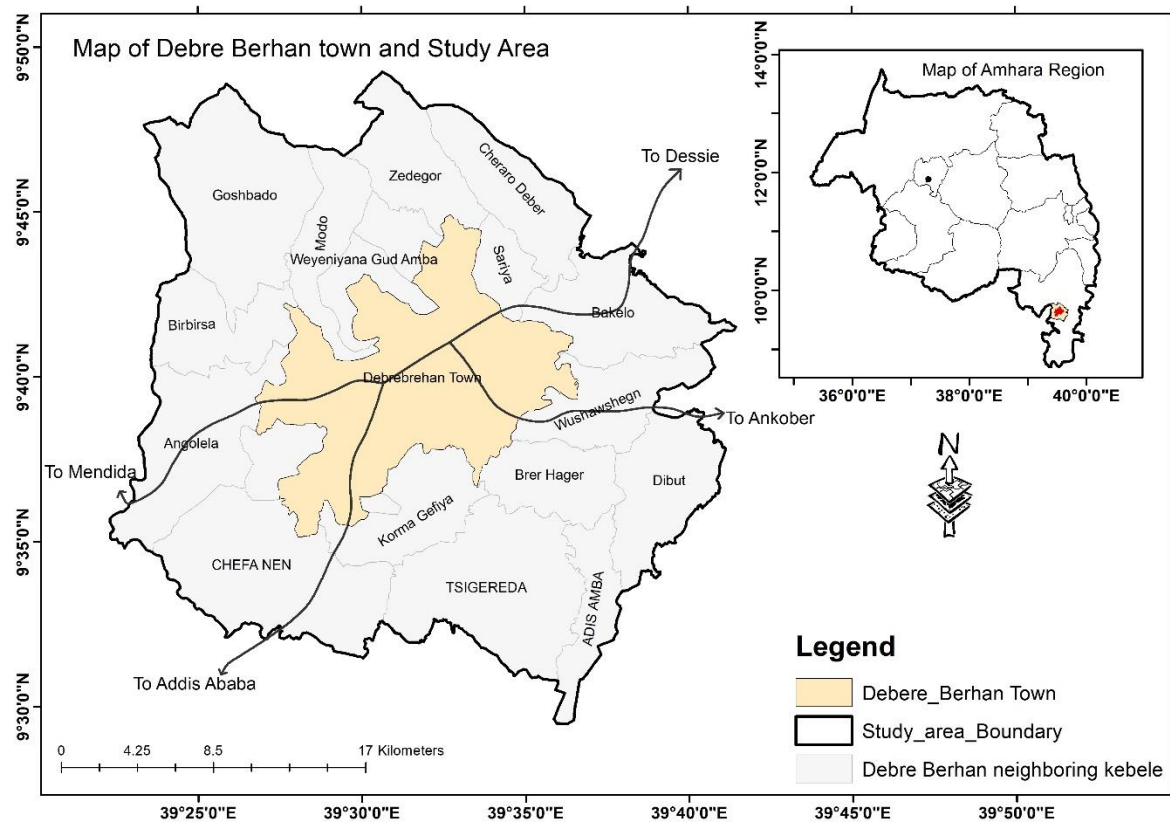
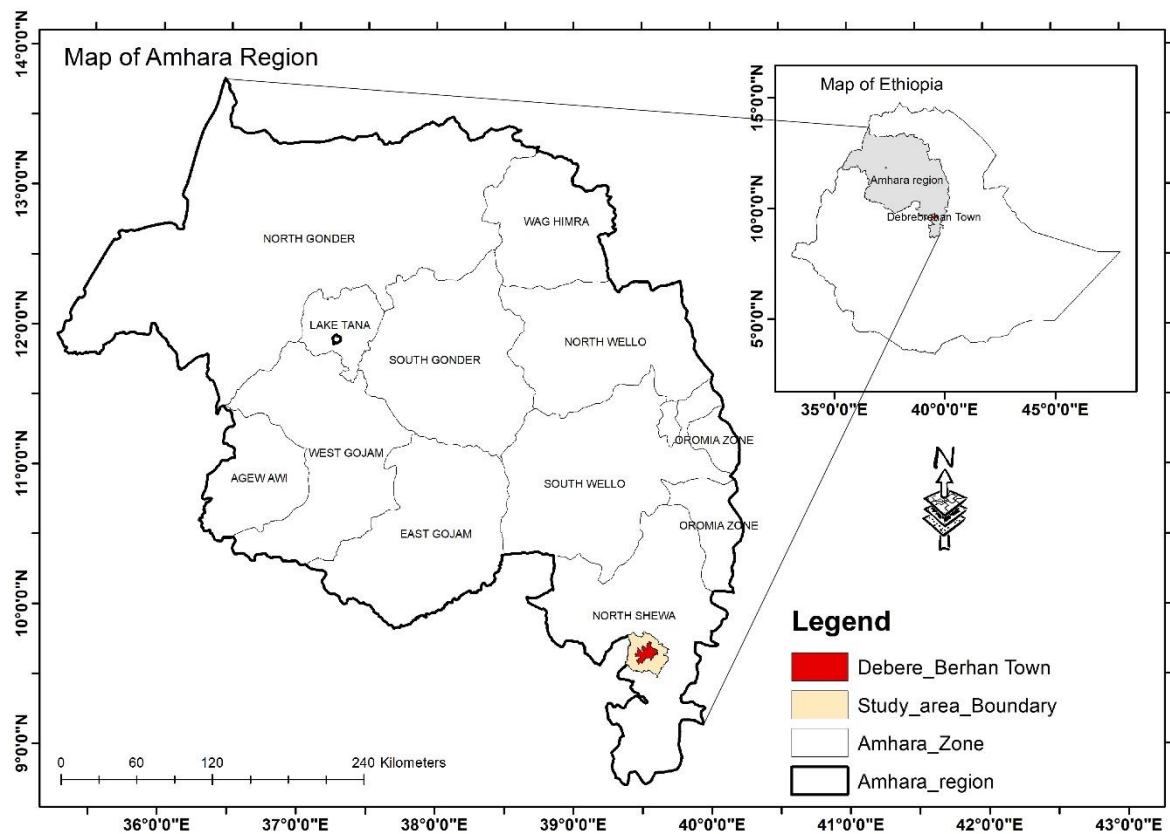


Figure 3.1; Location map of the study area (Mapcruzin, 2021)

3.2 Data types

There are different types of data used for this study in which the data are organized are qualitative data types, in which most of the data are non-numerical or the data collected are in the form of words and sentences. The types of data used for this study is based on the input for multi criteria decision making. The data types which include, DEM (digital elevation model) which helps to produce most of the spatial data used for this study which includes, slope, stream order and wetland. Additionally, windspeed, existing road network, land use / landcover, powerlines and exiting building network of spatial data which used for this study.

3.3 Data sources

The data was collected from both primary and secondary data sources. The primary data for this study was collected by site observation and in-depth interview. The secondary data sources which include municipality office of Debere Berhan town, books, journal articles, metrological stations data sources which was collected from NASA surface metrology, global wind atlas, and meteoblue metrology data and USGS satellite map earth explorer.

3.4 Method of data collection

The statical data for this study is a wind speed of 30-year data which is collected from NASA surface metrology, global wind atlas, and meteoblue metrology data. The spatial data for this study were collected from the digital elevation model (DEM) which helps to generate slope, wetland, rivers, etc. by ArcMap and QGIS desktop as a tool which is collected from the USGS satellite map earth explorer. Landsat imagery that helps generate Land use/ land cover (LULC) maps of the study areas by ArcMap remote sensing which is collected from USGS satellite map earth explorer. All other spatial data which are urban area, village, roads, and power lines will be done by digitization in ArcMap by editor tool to self-create shapefiles for this study. Maps, tables, and figures was used for the data presentation for this study.

3.5 Method of Analysis

The data collected for this study is based on spatial data for the input of MCDM. Multi-criteria decision making, which consists of procedures that include geographic spatial data and the weight of the decision-making criteria, and the manipulation of data according to decision criteria. This approach uses the ArcMap software in the management and processing of MCDM to combine the spatial information which includes wind speed, slope, distance from power lines, and other spatial data or criteria used for the study. *Table 3.1* shows the spatial data source, data analysis, and overall weight of each criterion.

3.5.1 Multi-criteria decision making (MCDM)

Multi-criteria decision making is an approach used to facilitate the consideration of multiple criteria by decision-makers MCDM is used to compare and evaluate multiple criteria often conflicting to make the best possible decision (Ryan & Nimick, 2019).

GIS-MCDM: Spatial problems involve many sets of feasible alternatives and multiple, conflicting, and incommensurate evaluation criteria. GIS-MCDM is a process that transforms and combines geographical data and value judgments to solve spatial problems (Ryan & Nimick, 2019).

3.5.2 Steps used in GIS-MCDM

- i. Determine the criteria
- ii. Transform the values and reclassify with meaningful numbers
- iii. Weight-based on the importance
- iv. Combine, synthesize and aggregate the criteria or layers together
- v. Analyze then validate the final results

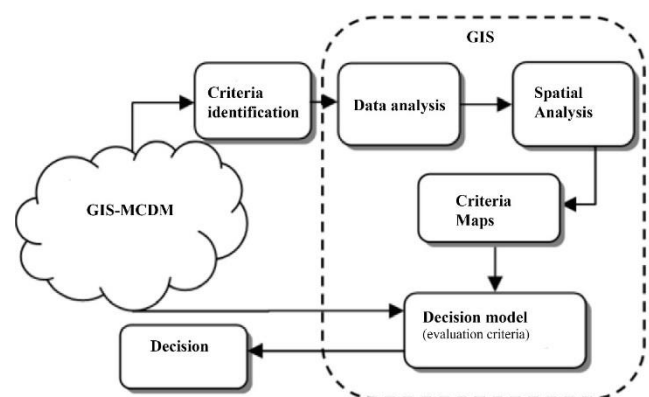


Figure 3.2; Integrated GIS-MCDM approach

ArcGIS has great opportunities for storage, analysis, manipulation, management, and visualization of spatial data, and MCDM provides a collection of procedures, techniques for structuring decision problems, designing, evaluating, and prioritizing the decision criteria. *Table 3.1* shows the spatial data source and overall weight. So, GIS-MCDM based ENVI-met simulation is a model proposed for this study as a systematic tool and rational decision-making for selecting locations for wind farms. *Figure 3.3* illustrates GIS-MCDM based wind farm site selection overall process.

Table 3.1; Spatial data sources and overall weights for each major attribute

No	Factors	Spatial Data Source	Analysis
Topographic (5%)			
1	Slope	DEM of Debere Berhan town From USGS satellite map	ArcGIS spatial data analysis
Technical (50%)			
2	Wind speed	NASA metrology agency Global wind atlas	ArcGIS
3	Distance from power lines	Digitize the existing lines	ArcGIS Editor tool, self-Digitize
Environmental (20%)			
4	Distance from rivers	Digital elevation model of Debere Berhan town	ArcGIS spatial data analysis
5	Wetland	DEM of Debere Berhan town	QGIS Desktop
6	Land use/ Landcover	Landsat with a recent timeline	Remote sensing (GIS)
Socioeconomic (25%)			
7	Proximity to urban area	Digitize the existing buildings	ArcGIS Editor tool
8	Distance to roads	Digitize the existing roads	ArcGIS Editor tool

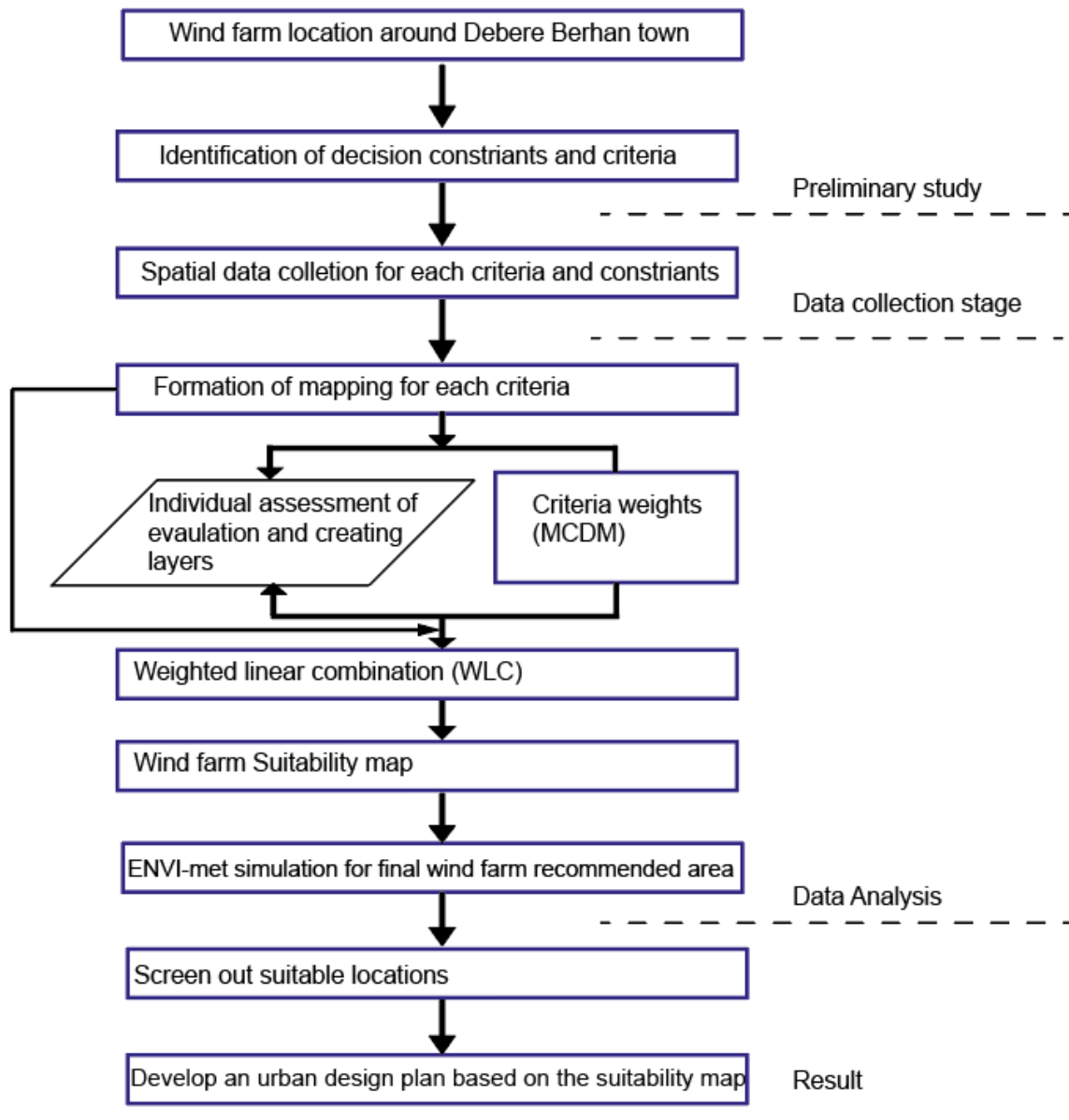


Figure 3.3; GIS-MCDM based wind farm site selection overall process

i. Identification of potential wind harvesting sites in and around Debre Berhan town

The first step for identifying windy areas is to collect wind speed data of the town and surrounding area. The wind speed data is collected from the national metrology agency, NASA surface metrology, meteoblue metrology data, and global wind atlas to make sure the data is more near to reality. The 30-yr data is collected from those sources at different heights and mapped by using ArcMap as a tool for mapping windy areas both within Debere Berhan town and the surrounding area.

ii. Investigation of the suitability of the wind farm

This step is the most significant process in which defining and weighting each criterion with a particular influence or weight to select a location for wind farms. The criteria and source of data involved in the MCDM are identified and they are entered into ArcMap. The input data come from different sources as described in *Table 3.1* and the datasets are usually organized in ArcMap in raster or vector format with a visible graphic quality or spatial resolution. ArcMap is used to carry the transformation of thematic and spatial data into digital form (distance mapping, buffering, mapping, map overlay, etc.).

The slope map of the overall study area illustrates that most of the area is between 0 – 5 degrees and it is suitable for the wind farm. Most of the area with slope criteria, suitable for the wind farm is located in the southern direction of the study area and the slope map of the study area is shown in *Figure 3.4* below.

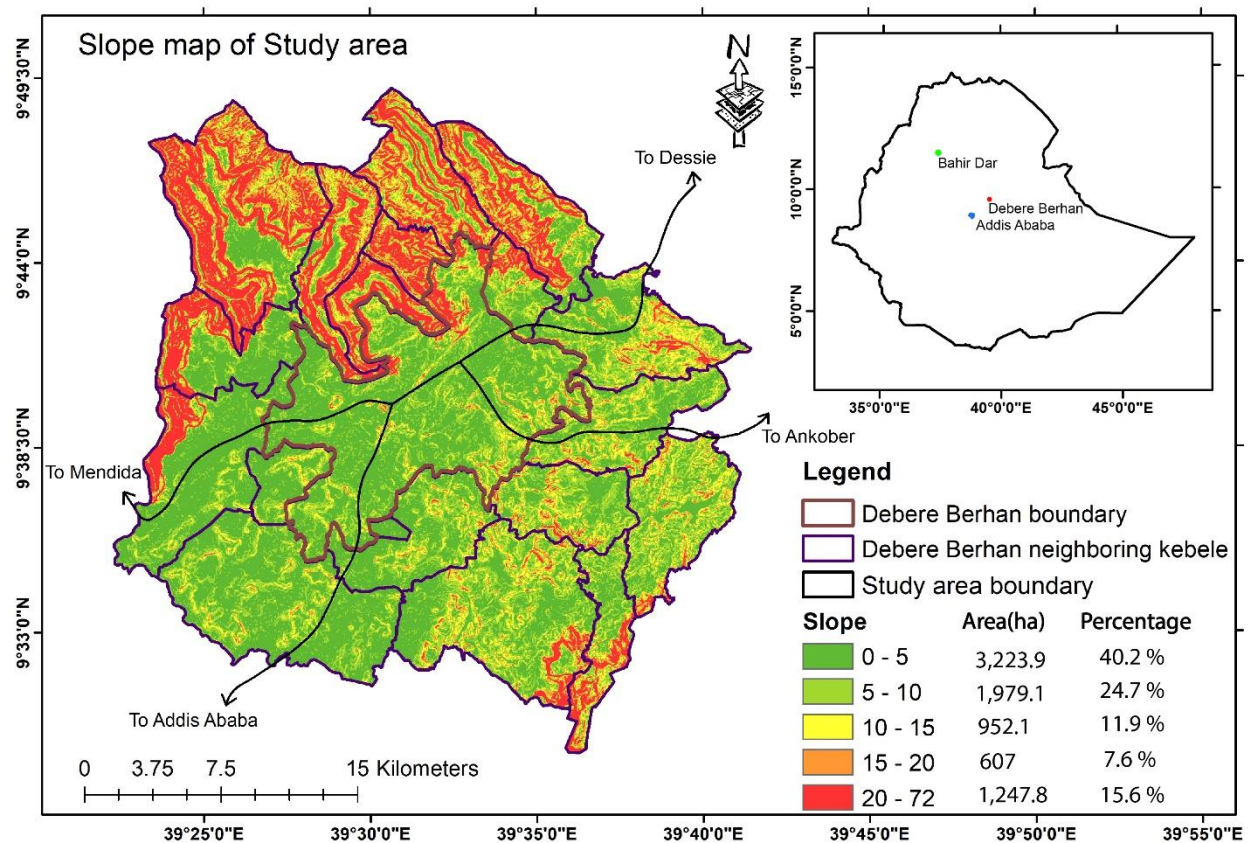


Figure 3.4: Slope map of the Study Area

Availability of existing electric lines in the study area is needed for the construction of new energy transmission infrastructure because it helps to reduce costs. If the location of the wind farm is far from the major existing lines of the town it will increase the cost of electric transmission infrastructure. *Figure 3.5* shows the major power infrastructure of the study area.

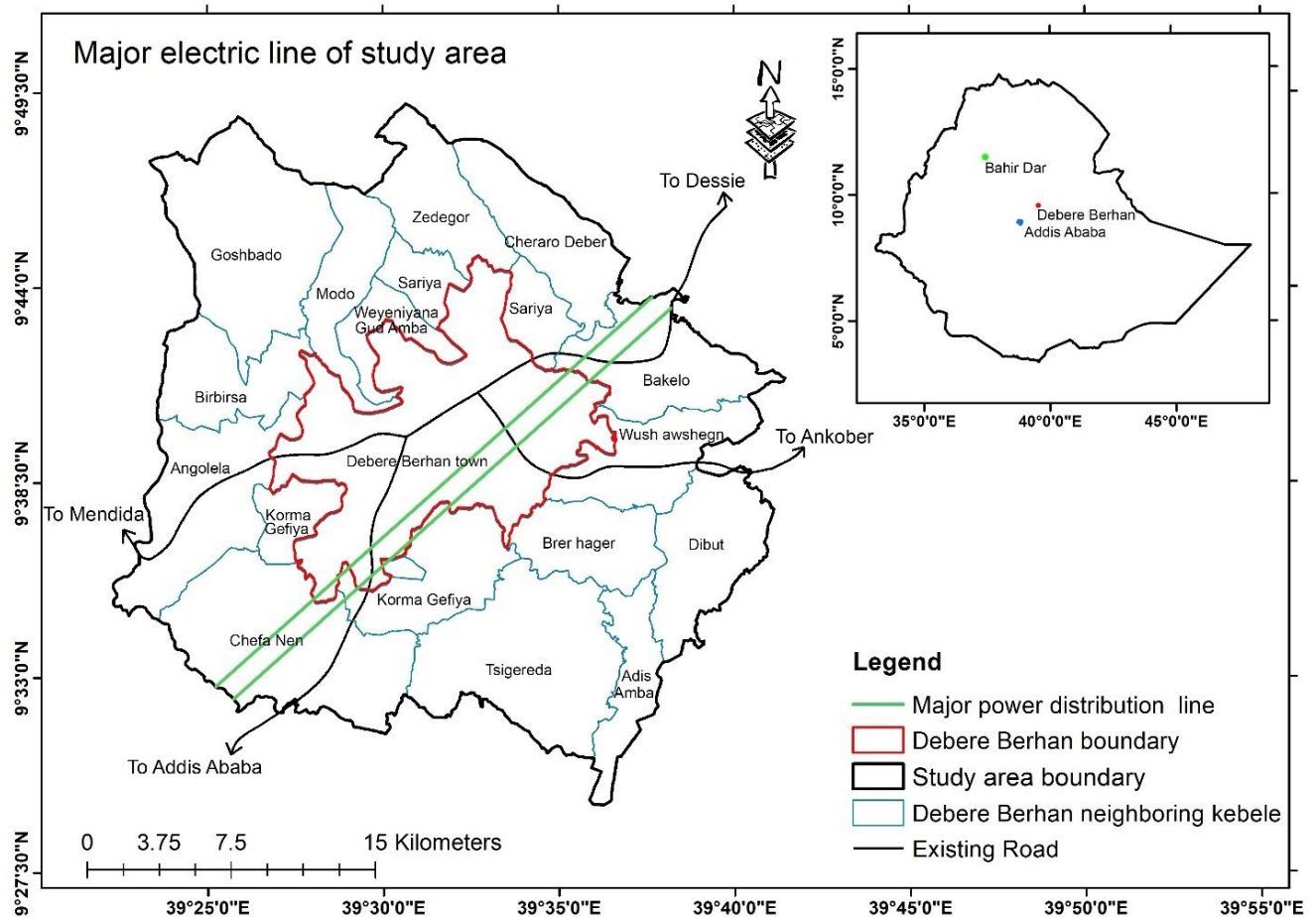


Figure 3.5: Major electric infrastructure of the study area

The buffer zone for the major river lines is also considered for wind farms. For this study, major river lines are extracted and rivers with grid code 4 (which is stand for the mainstream of the river) and above are considered for this study, and the overall river map of the study area is shown in *Figure 3.6* below. Most of the major river lines with grid code above 4 are located in the north and northwest direction of the study area.

Wetland- Map of the study area is identified and shown in *Figure 3.7* below. Wetland is one of the criteria used for wind farm site selection for this study area. As wetlands are natural protected areas wind farm is not directly located on wetland with high intensity.

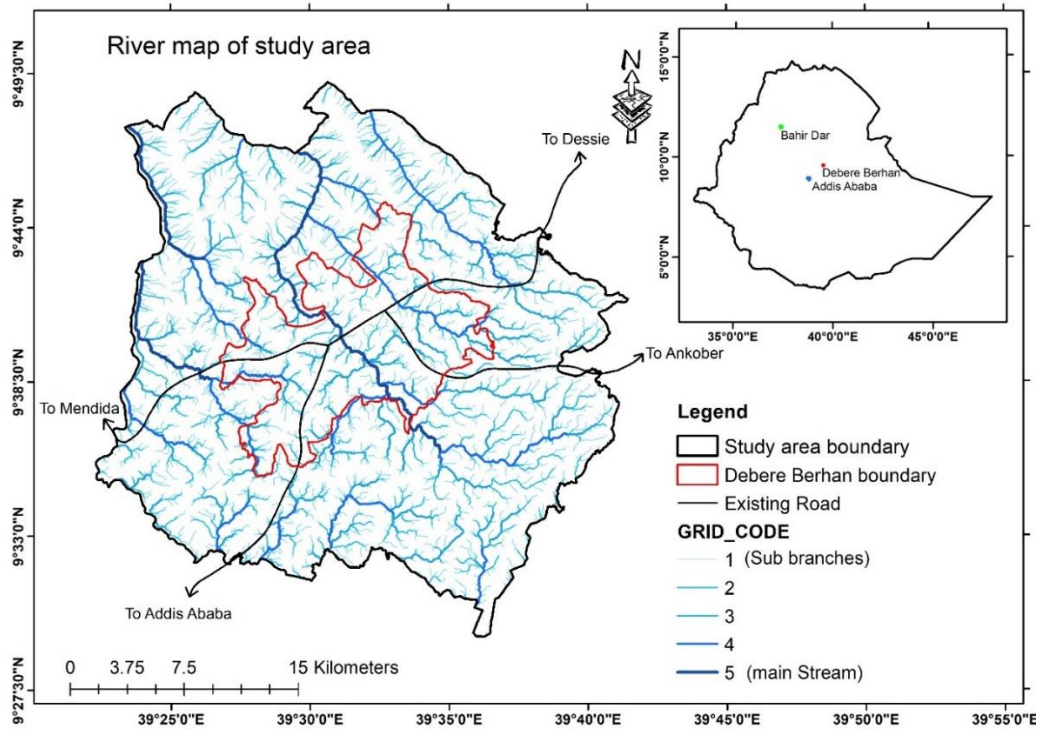


Figure 3.6; River map of the study area

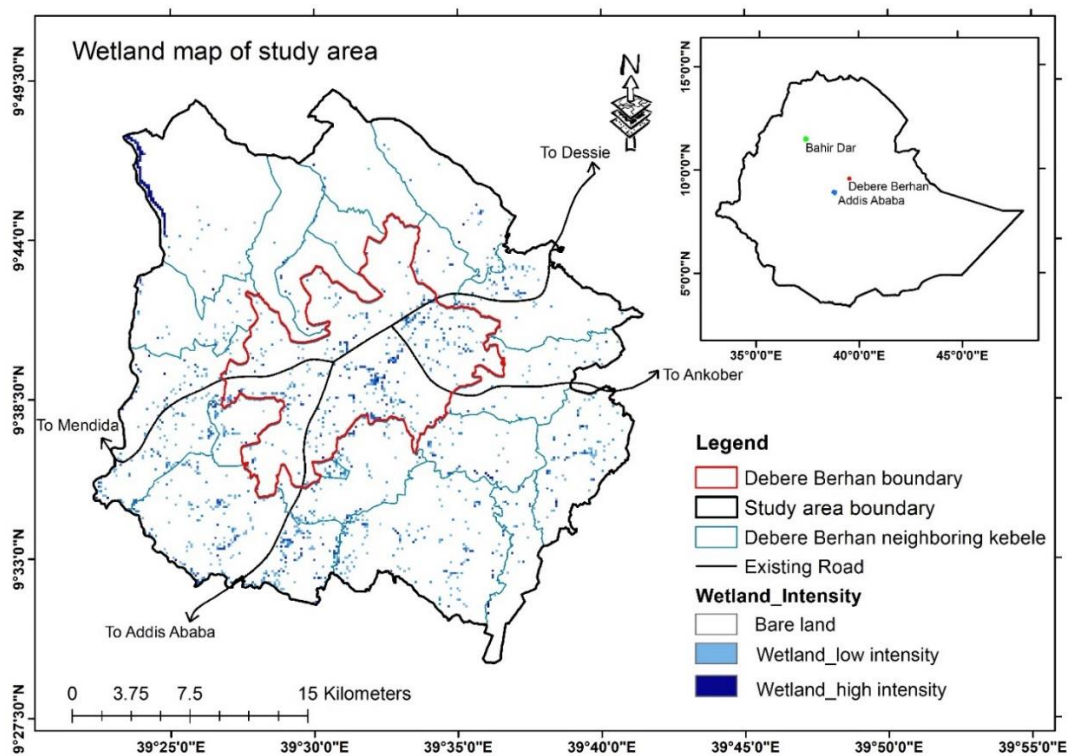


Figure 3.7; Wetland map of the study area

The land use land cover map of the study area identifies areas with buildings, forests, lakes, and bare land of the study area. Most of the study area is covered with bare land and it is mostly located in the southern part of the study area. The forest is located in the north and northwest of the study area. The land use land cover map of the study area is shown in *Figure 3.8* below and *Figure 3.9* illustrates existing building in the study area and most of the existing building is located in the central part of the study area. The existing road network of the study area shows that four major roads are going out from the study area. The existing road network of the study area is shown in *Figure 3.10* below.

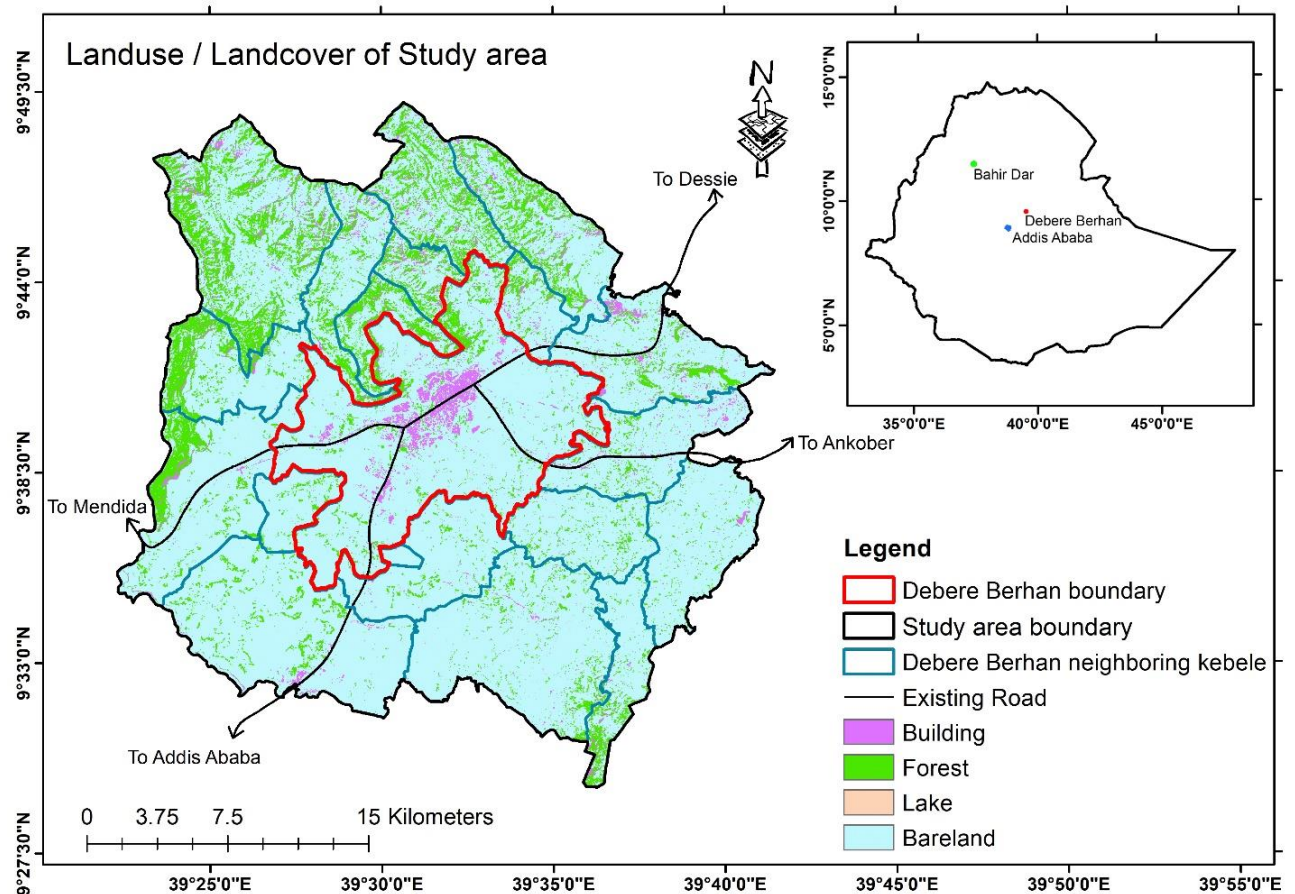


Figure 3.8: Land use / Landcover map of the study area

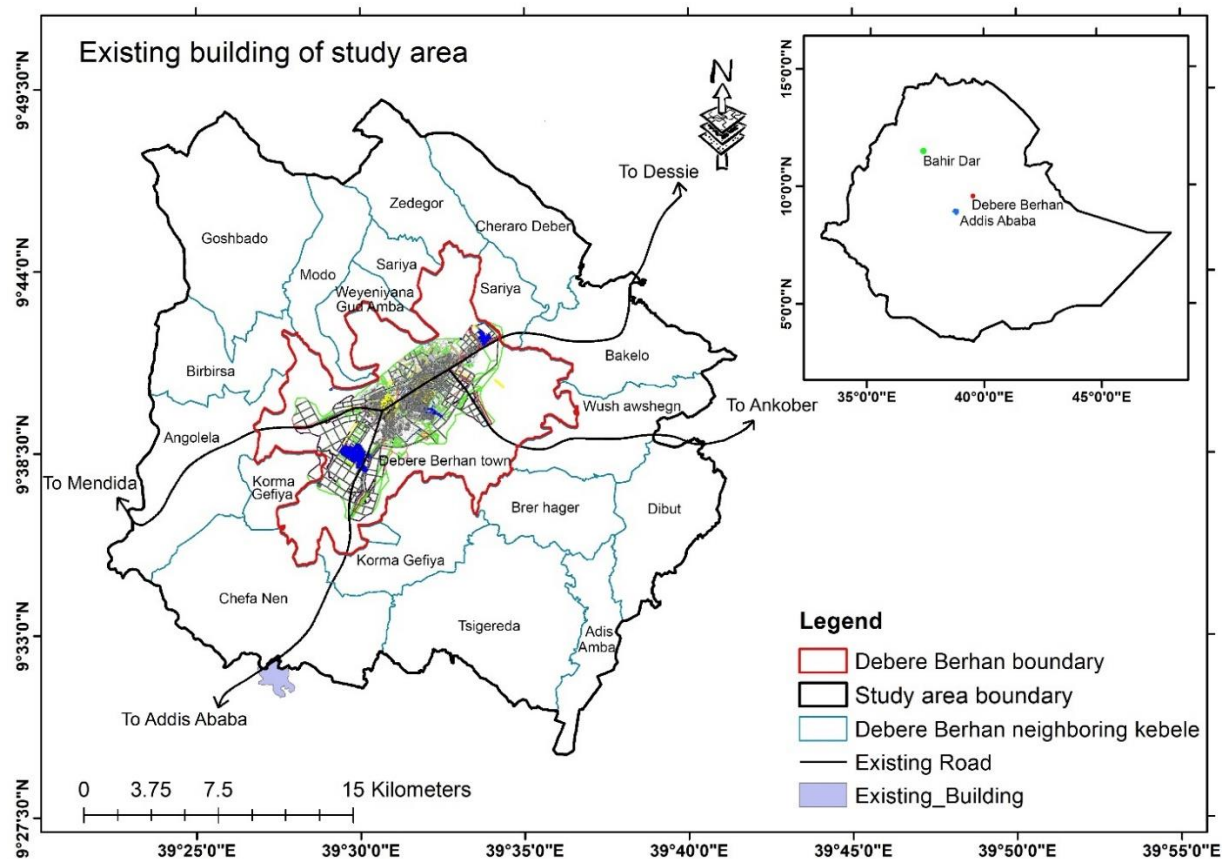


Figure 3.9: Existing map of the urban area

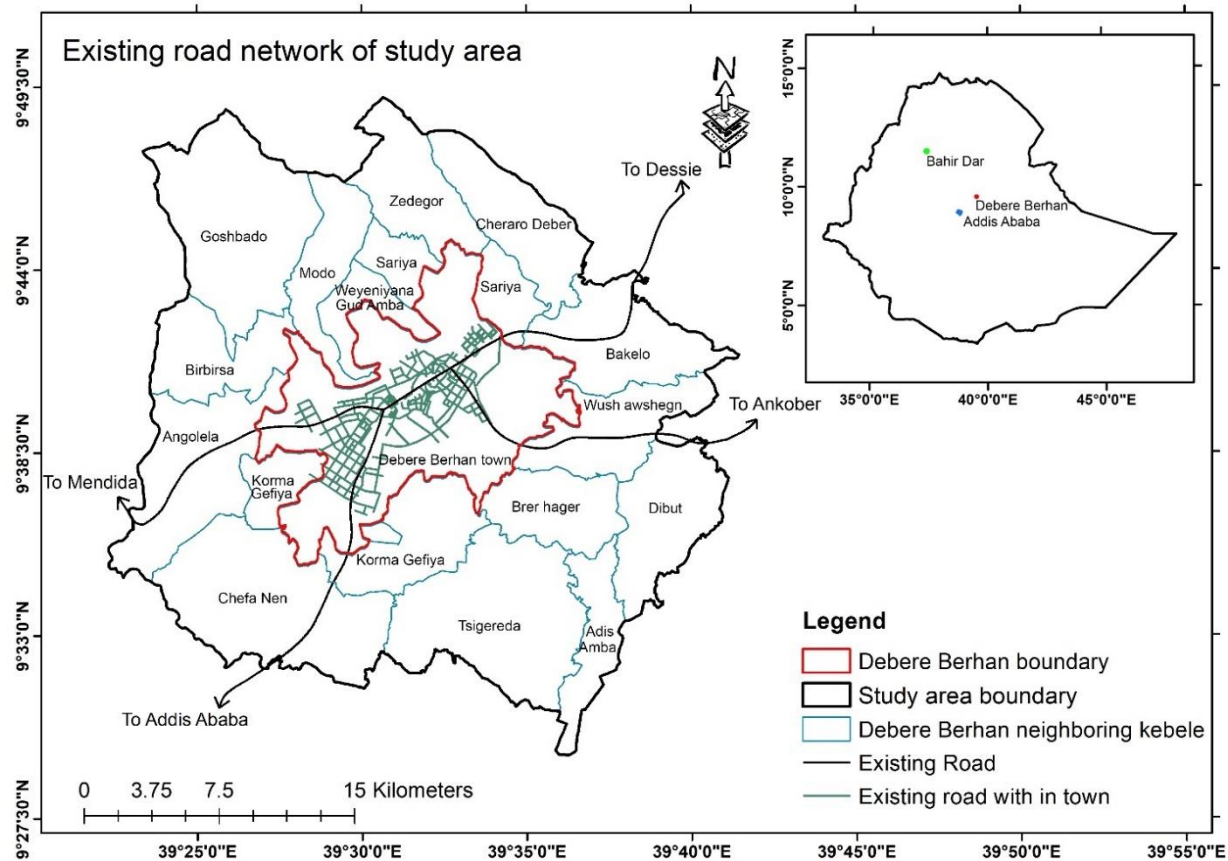


Figure 3.10: Map of the existing road network

The MCDM process includes prioritizing, in which the criteria and constraints will be presented on maps with different ArcGIS layers, and reclassified or transformed into units to be compared. Then weighting will be going on, by determining the weight coefficients of each criterion, and while solving, the criteria do not have the same degree of significance. As a result of applying a weighted linear combination (WLC), a wind farm suitability map is generated.

The soil type in the study area has an influence in the selection of the site for the wind farm, and in the study area, most of the area is covered by cambisols which cover about 53.9% of the study area and this type of soil has medium-textured and good structural stability. The soil map of the study area, in *Figure 3.11* below shows that leptosols and vertisols coverage about 45.5 % and 0.6 % respectively. Both soil types are suitable and have no that much effect on the structural stability of the wind farms. So, a wind farm can be built in all types of soil located in the study area.

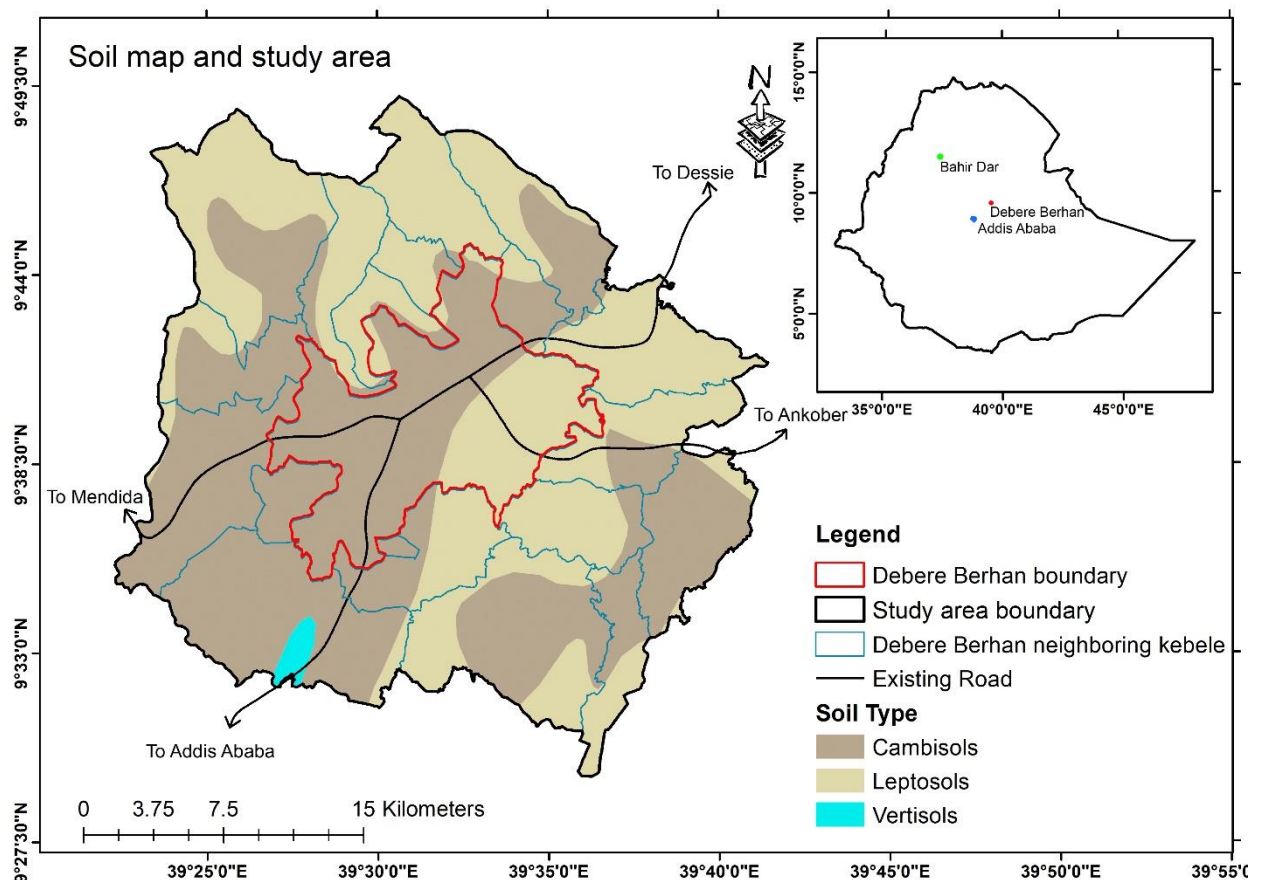


Figure 3.11; Soil map of the study area

After prioritizing the wind farm potential sites, screening-out of the most suitable sites is the final step to draw the suitability map based on logical (algebra) and they can have a value from Not suitable (1) up to very highly suitable (5), which could identify the most suitable locations for wind farms. Finally, the most suitable location for a wind farm is evaluated or measured by ENVI-met wind speed simulation software.

3.6 Research Design

Research design is the arrangement of an overall strategy that integrates relevant components of the study in a clear, purposeful, and logical way. It is a conceptual structure, roadmap, plan, and blueprint strategy of investigation to achieve answers for research questions. Research design is the heart of any study (Kothari, 2004). The research design and procedure is designed for the present study and shown in *Figure 3.12* below.

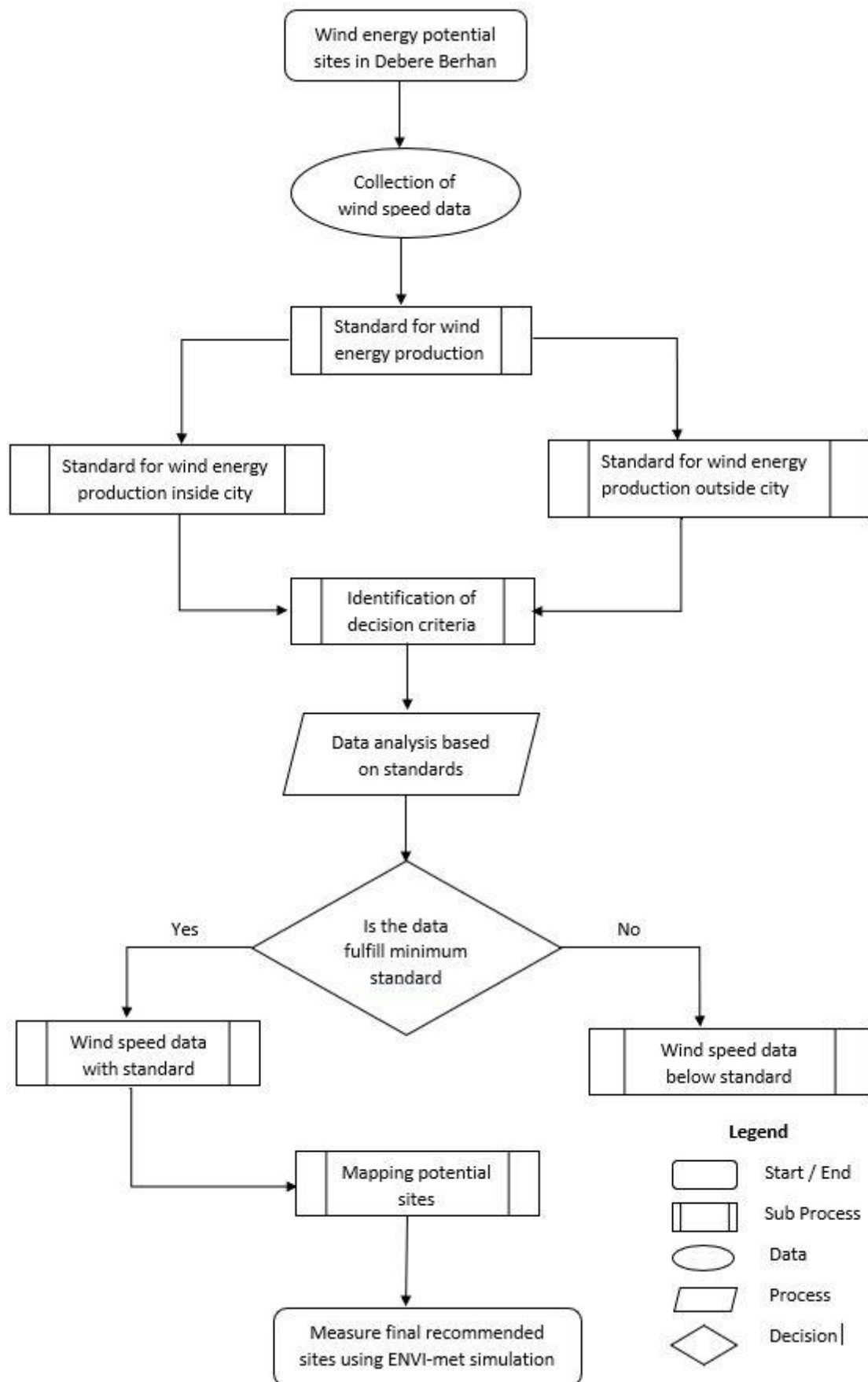


Figure 3.12: Research design and procedure

3.7 Summary of the methods

The methodology includes study area description, method of data collection, and method of data analysis and finally summarized in *Table 3.2* below.

Table 3.2; Summary of the methodology

No	Specific Objective	Type of data	Methods of data collection	Analytical tool	Data Analysis
1	To identify windy areas in and around Debere Berhan town	Wind speed	NASA metrology agency, Meteoblue metrology data Global wind atlas	ArcGIS	ArcGIS based map showing windy sites
2	To prioritize windy areas among the identified windy areas	Wind Speed DEM LULC Published documents	USGS satellite map NASA metrology agency	ArcGIS	ArcGIS tool, MCDM, WLC to generate suitable location
3	Select the best, feasible site and estimate its potential	Suitability map	ArcGIS suitability map	ENVI-met	Measure the final recommended location

3.8 Analysis

3.8.1 Potential wind harvesting sites around Debre Berhan town

30-year average wind speed of the study area found at latitude $9^{\circ} 41' \text{ N}$ and longitude $39^{\circ} 32' \text{ E}$, shows that the mean minimum wind speed is recorded in August which is 3.8 m/s and the highest mean wind speed is recorded in both May and October which is 5.9 m/s. As the minimum criteria for wind energy production is 3.5 m/s (Pamucar *et al.*,2017), the mean wind speed of 30-year data shows that all months are suitable for wind energy production and the study area has high wind energy potential. The annual mean wind speed 30-year data of the study area is summarized in *Figure 3.13* below. The 30-year interannual averages of wind speed data in and around Debre Berhan town of each month from 1990 – 2019 at 10m and 50m height are shown in *appendix 2* and *3* and *appendix 4* and *5*, respectively.

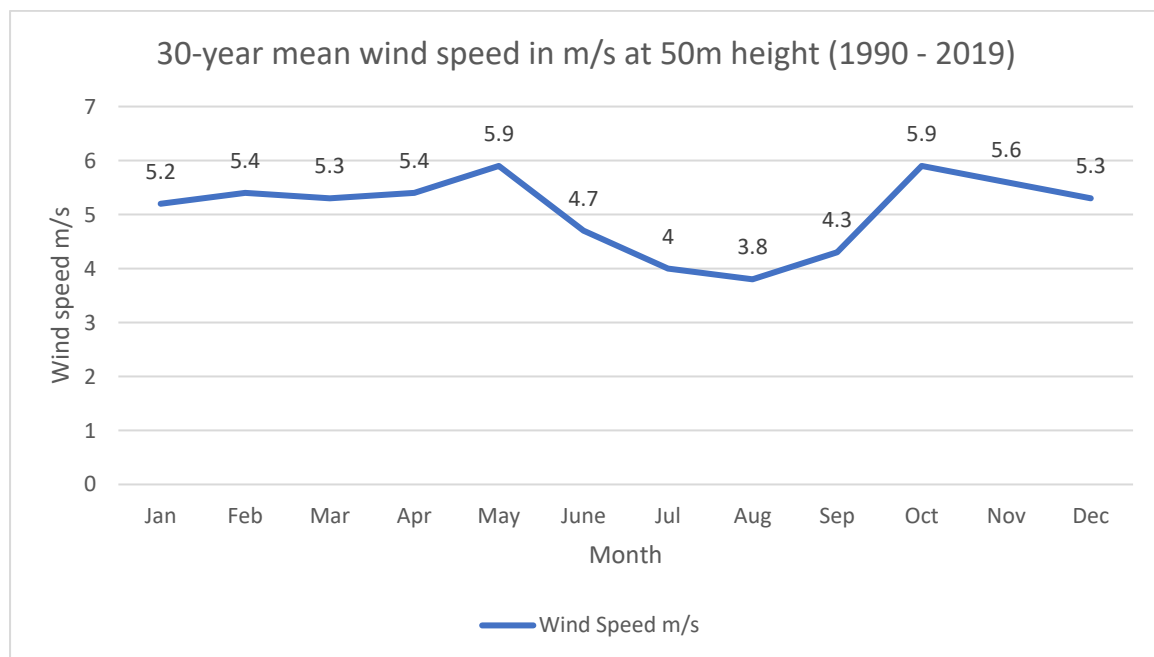


Figure 3.13; 30-year mean wind speed in m/s at 50m (NASA 1990 - 2019)

The wind rose in *Figure 3.14* shows that in the town the wind is mostly blown from the east-northeast (ENE) and west-southwest direction (WSW).

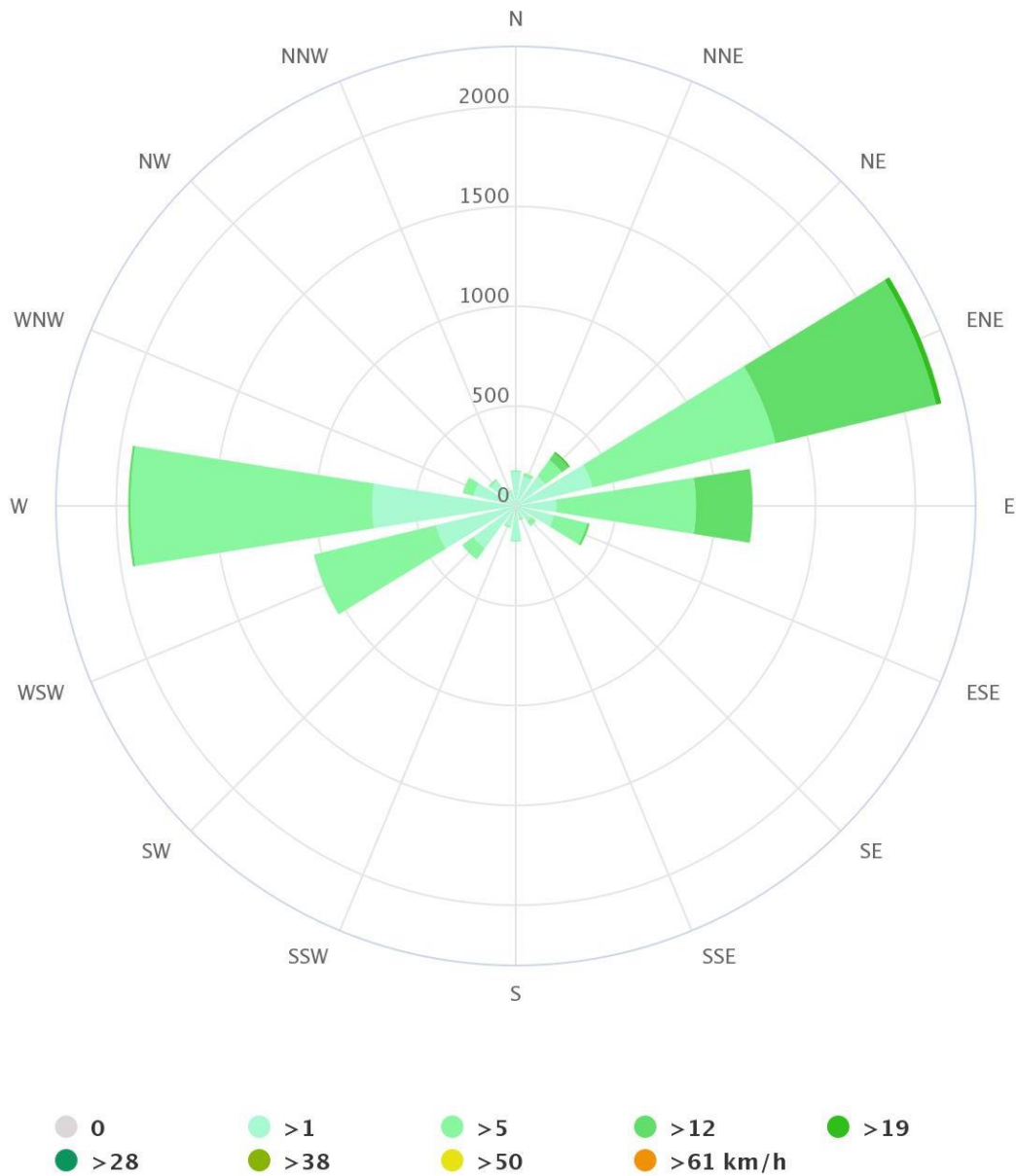


Figure 3.14; Wind rose diagram of the study area (meteoblue metrology data).

Height is one of the decisive factors for wind turbine installation. As height increases the wind speed increases and maximum energy harvesting for wind is possible since the speed is becoming steady. Thus, the speed at 50m, 100m, 150m, and 200m were analyzed. The maximum wind speed is at 200m, about 7.67m/s. *Figure 3.15* (a-d) shows the maximum and the minimum wind speed prevailing in the study area at four different heights identified below. The south and southwest parts of the study area are the most suitable locations for wind energy harvesting.

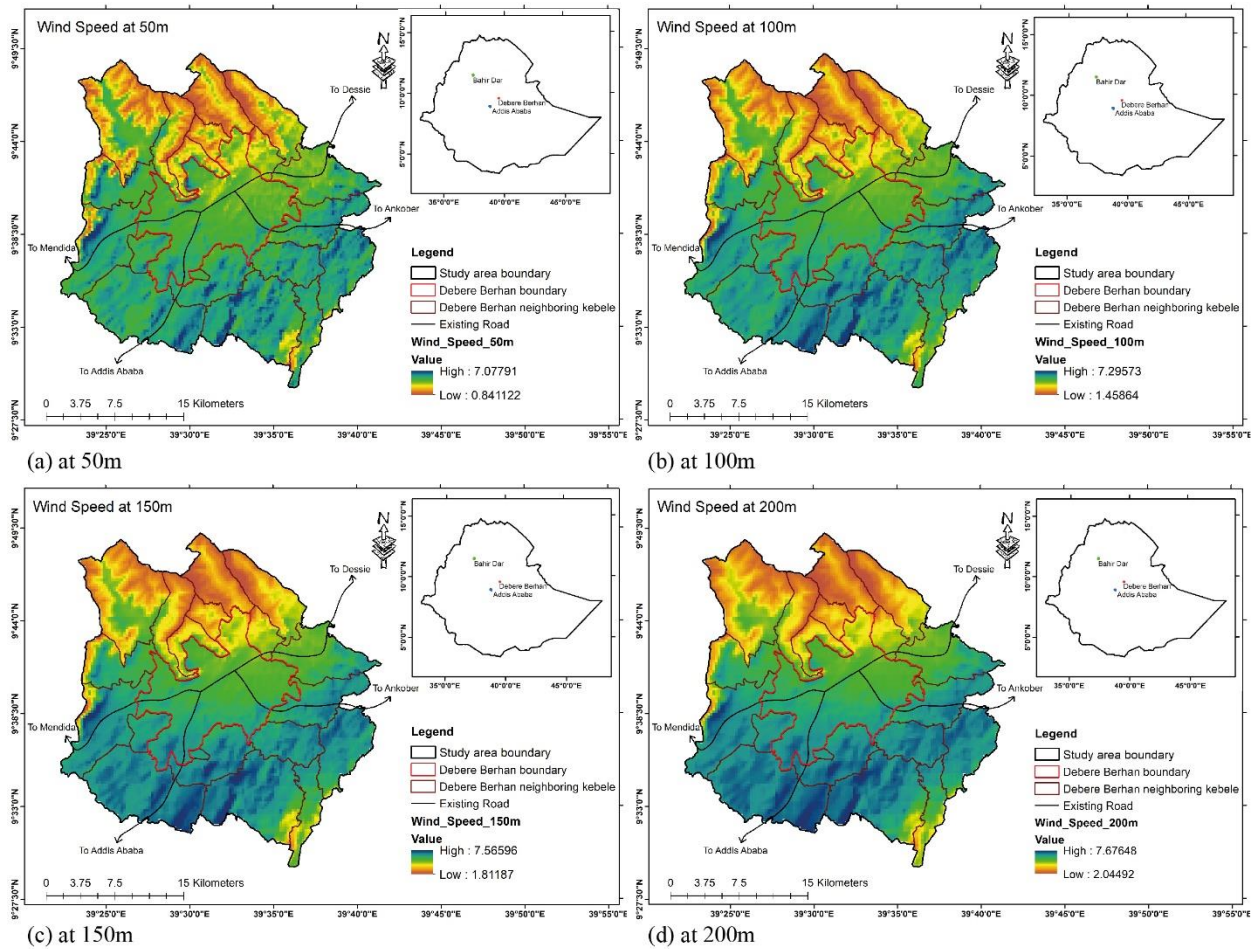


Figure 3.15: windy areas around Debre Berhan town at 50m, 100m, 150m, and 200m.

i. Potential wind harvesting sites within Debre Berhan town

For identifying windy areas within the Debre Berhan boundary, a similar wind speed mapping was done at 10m and 50m height as shown in *Figures 3.16* (a) and (b). Areas in the west, southwest, and southern part of the town boundary are found to be suitable for urban wind energy harvesting. Their speed is 5.6 m/s and 5.9 m/s at 10 and 50m height, respectively.

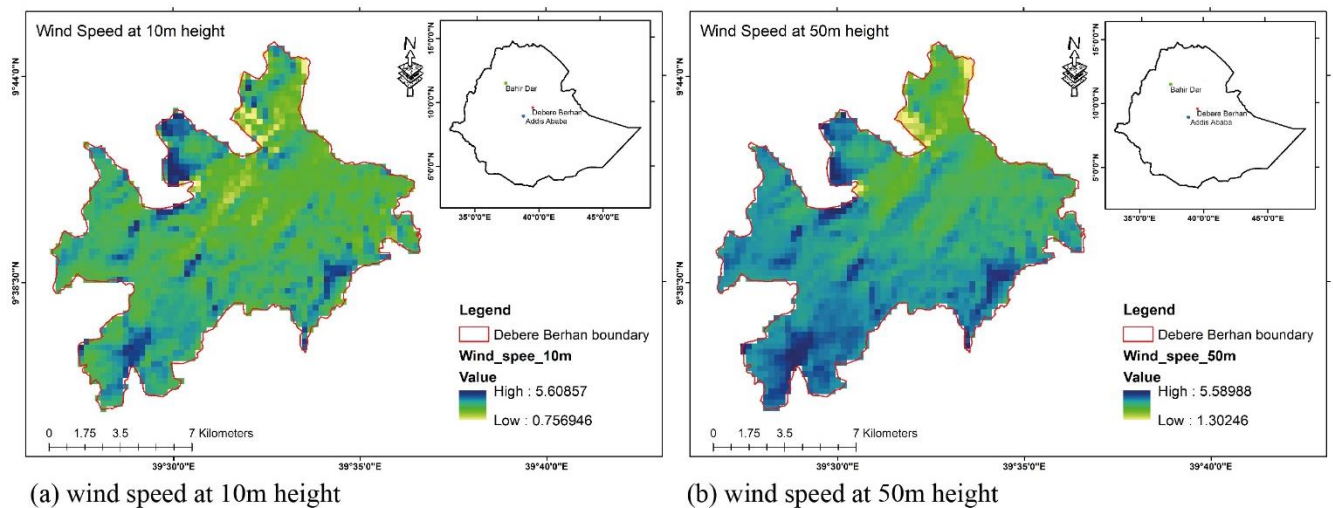


Figure 3.16: Windy areas inside Debere Berhan town

3.8.2 Investigate the suitability of the wind farms

There are many criteria used to prioritize the windy areas based on the restrictions, limitations, and potentials of the study areas. The criteria are classified and weighted based on the most important layers. Once the criteria are reclassified, criteria values were normalized for comparison and weighting.

3.8.2.1 Multi-criteria decision making (MCDM)

The weight of each layer is assigned in terms of importance in affecting the suitability of a potential site for wind energy harvesting. Following the layer weights, using a weighted linear combination (WLC) which minimizes the impacts of less importance for selecting windy areas, and with each layer assigned a suitability value. Finally, combine weighted layers and select the best locations for wind energy production.

As shown in *Table 3.3* below supported by the literature review on *Table 2.3*, (wind energy selection criteria and description) were identified, and the respective parameters were grouped and values assigned from best to least suitable and ranked from 5 to 1 accordingly for this study. For

each criterion, a separate suitability map is produced and layered one over the other based on each weight or influence to identify the best location for a wind farm around Debere Berhan town.

Table 3.3; Criteria used for prioritizing windy areas

No	Criteria	Parameters	Suitability	Rank
1	Slope (degree)	20 – 66.2	Very low	1
		15 - 20	low	2
		10 - 15	Moderate	3
		5 – 10	high	4
		0 – 5	Very high	5
2	Wind speed (m/s)	0 - 2	Very Low	1
		2 - 3	Low	2
		3 - 5	Moderate	3
		5 – 5.5	High	4
		5.5 - 9	Very High	5
3	Distance from power lines (m)	> 4000	Very low	1
		3000 - 4000	low	2
		2000 - 3000	Moderate	3
		1000 - 2000	high	4
		0 – 1000	Very high	5
4	Rivers and lakes (m)	0 - 100	Very Low	1
		100 - 200	Low	2
		200 - 250	Moderate	3
		250 - 300	High	4
		300 – 14,534	Very High	5
		Building	Very low	1
		Forest	Very low	1
		Lake, water bodies	Very low	1

5	Land use/Landcover (type)	Bare land	Very high	5
6	Distance from urban areas (m)	0 - 600	Very low	1
		600 - 1200	low	2
		1200 - 1800	Moderate	3
		1800 - 2400	high	4
		2400 – 14,534	Very high	5
7	Distance from roads (m)	0 - 100	Very low	1
		100 - 200	low	2
		200 - 250	Moderate	3
		250 - 300	high	4
		300 – 14,534	Very high	5
8	Wetland (intensity)	High intensity	Very low	1
		Low intensity	Moderate	3
		0 (none, bare land)	Very high	5

i. Areas relatively on flat land

As shown in *Figure 3.17* and *Table 3.4* below, 76.8% of the study area is suitable based on slope criteria as shown in *Table 2.3* in the literature review, however, 40.2% (3,224 ha) is the best flat land and it is considered as the most suitable location for the wind farm.

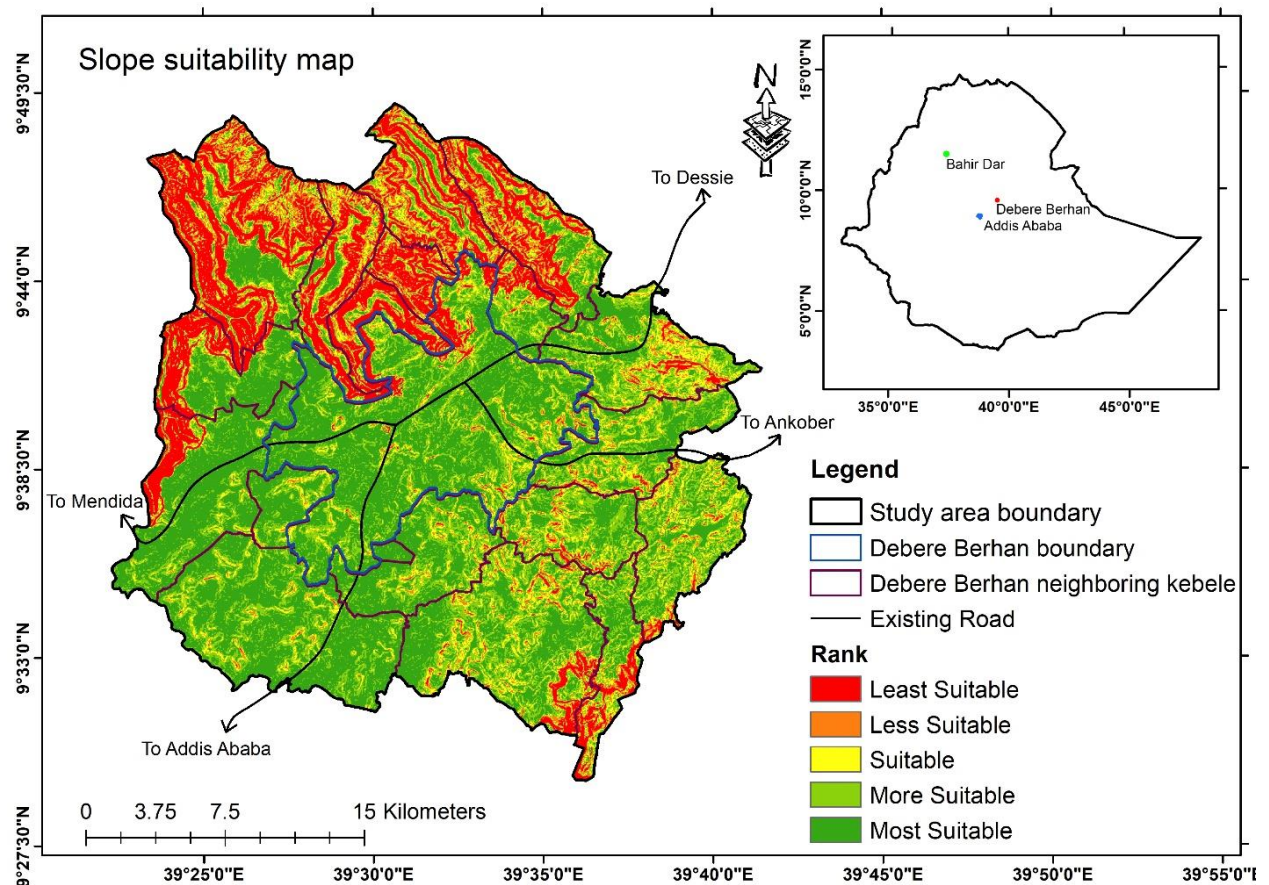


Figure 3.17; Slope suitability map

Table 3.4; Slope suitability area coverage and summary

Suitability	Rank	Colour Code	Area (ha)	Slope	percent
Least Suitable	1		1,248 ha	20 - 72	15.6 %
Less Suitable	2		607 ha	15 - 20	7.6 %
Suitable	3		952 ha	10 - 15	11.9 %
More Suitable	4		1,979 ha	5 - 10	24.7 %
Most Suitable	5		3,224ha	0 - 5	40.2 %

ii. Wind speed

Wind speed higher than 3.5 m/s is suitable for wind energy production (Pamucar *et al.*,2017). so, as shown in *Figure 3.18* and *Table 3.5*, about 89% (7,110.3 ha) of the area is suitable with wind

speed criteria but the 30.9 % (2,469.3 ha) of the total study area is most suitable, in which this area has a wind speed greater than 5.5 m/s.

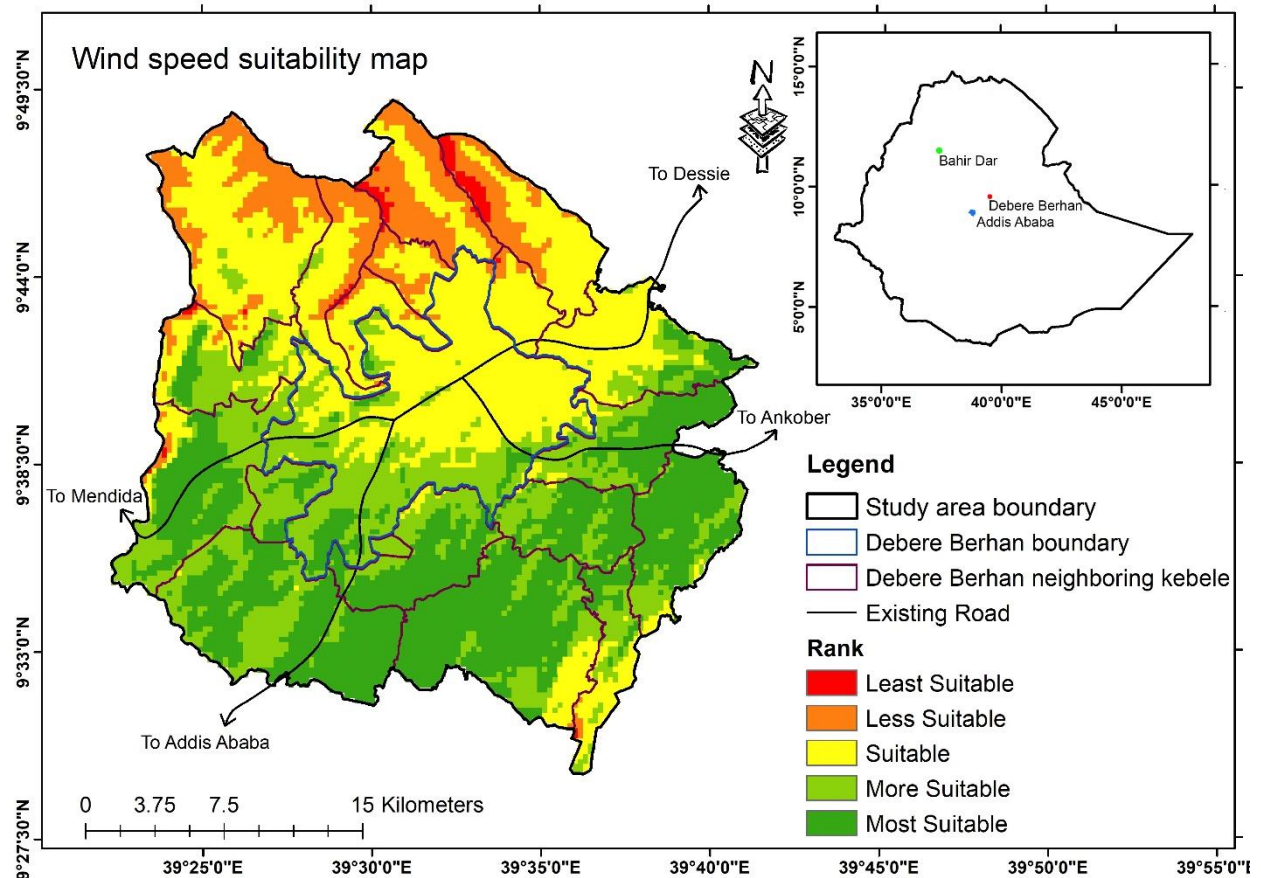


Figure 3.18; Wind speed suitability map

Table 3.5: Wind speed suitability area coverage and summary

Suitability	Wind Speed	Rank	Colour code	Area (ha)	percent
Least Suitable	0 – 2 m/s	1		69.4 ha	0.9 %
Less Suitable	2 – 3 m/s	2		815.7 ha	10.2 %
Suitable	3 – 5 m/s	3		2643.8 ha	33.1 %
More Suitable	5 – 5.5 m/s	4		1997.2 ha	25.0 %
Most Suitable	5.5 – 9 m/s	5		2469.3 ha	30.9 %

iii. Proximity to existing power grid line

The existing availability of power grid lines must be considered because it reduces the construction of new energy transmission infrastructure (Idrizi *et al.*,2018). *Figure 3.19* and *Table 3.6* show that only 12.5% (1,002.3 ha) of the study area is the most suitable area. But 27.2 % (2,178.8 ha) is a suitable area by existing power grid line criteria.

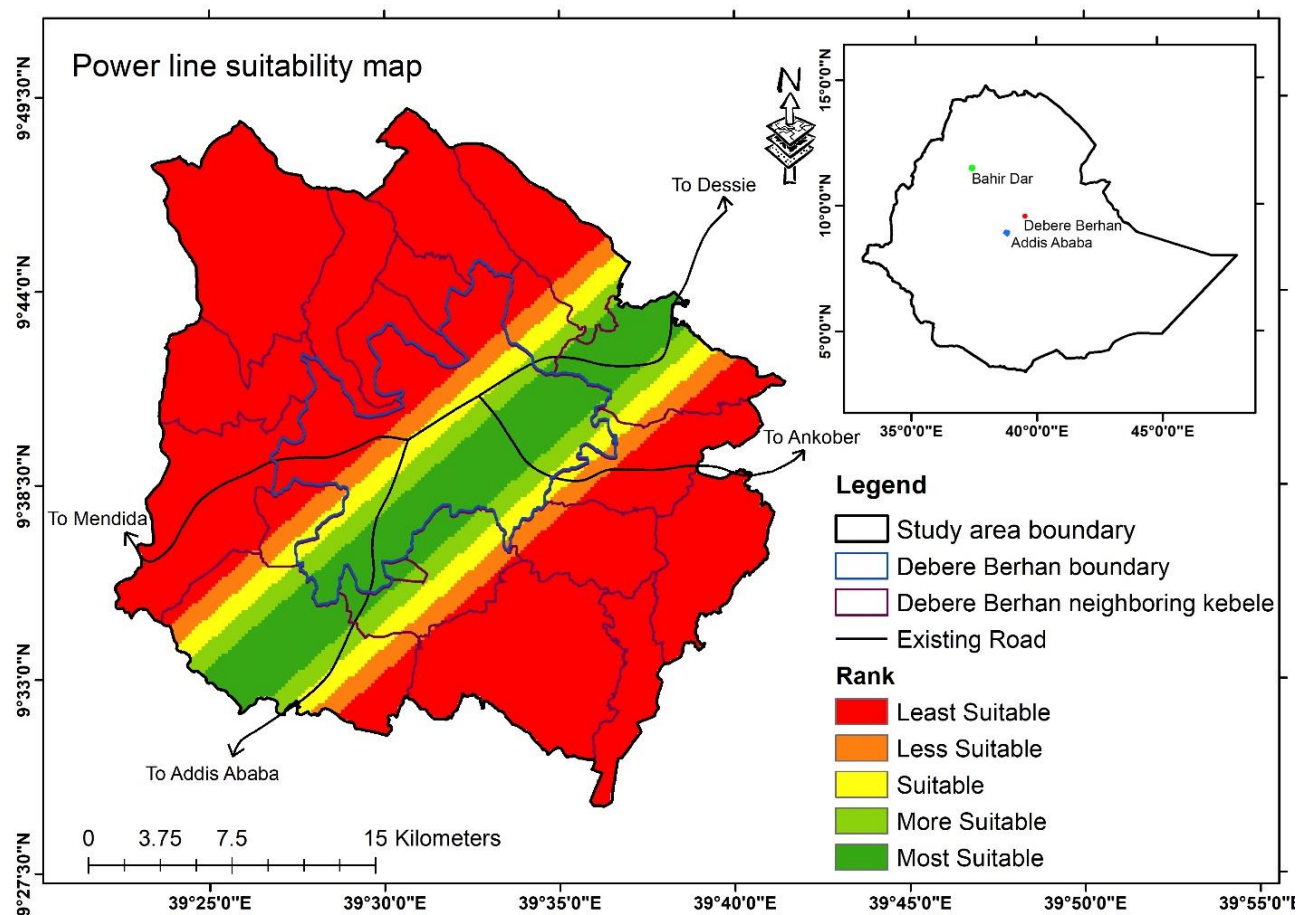


Figure 3.19: Existing power lines suitability map

Table 3.6: proximity to existing power grid line suitability area coverage and summary

Suitability	Power line dist.	Rank	Colour code	Area (ha)	percent
Least Suitable	>4000 m	1		5241.8 ha	65.5 %
Less Suitable	3000 – 4000 m	2		583.4 ha	7.3 %
Suitable	2000 – 3000 m	3		590.0 ha	7.4 %
More Suitable	1000 – 2000 m	4		586.5 ha	7.3 %
Most Suitable	0 – 1000 m	5		1002.3 ha	12.5 %

iv. Areas away from rivers

Rivers are natural protected areas and the construction of wind farms should include the buffer zone from existing major river lines (Moradi *et al.*, 2017). *Figure 3.20* and *Table 3.7* show that 84.1 % (6730 ha) of the study area is most suitable.

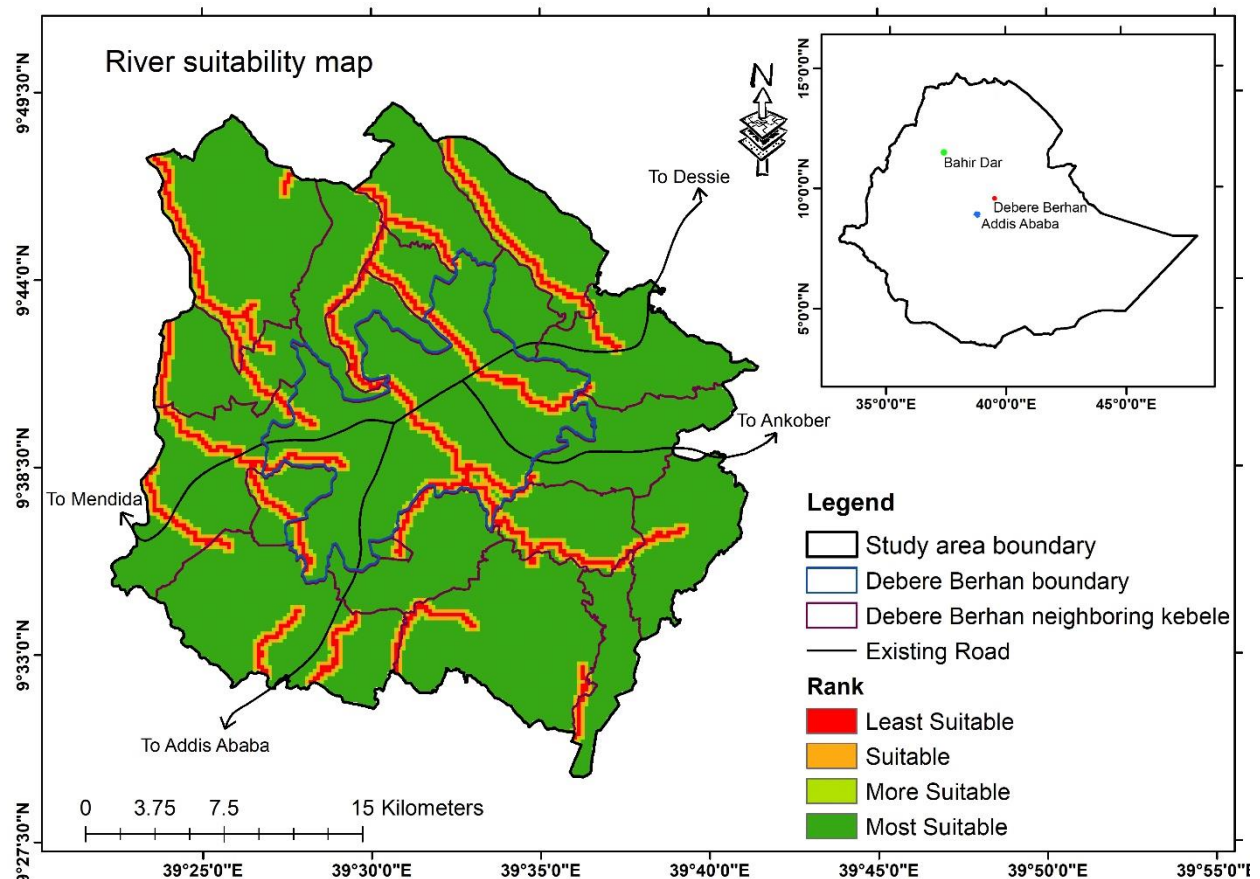


Figure 3.20; River suitability map

Table 3.7; Major river line suitability area coverage and summary

Suitability	River Dist.	Rank	Colour Code	Area (ha)	percent
Least Suitable	0 -100 m	1		440.2 ha	5.5 %
Suitable	100 – 200 m	3		579.3 ha	7.2 %
More Suitable	200 – 300 m	4		253.8 ha	3.2 %
Most Suitable	>300 m	5		6730.0 ha	84.1 %

v. Land use/ landcover

Land use is an important factor to consider and wind farms should be placed in areas with less impact on the existing land. *Figure 3.21* and *Table 3.8* show that the land types are classified as forest, lakes, buildings, and bare lands and about 83.1 % (6,657 ha) of the study area is bare land and it is considered as the most suitable area.

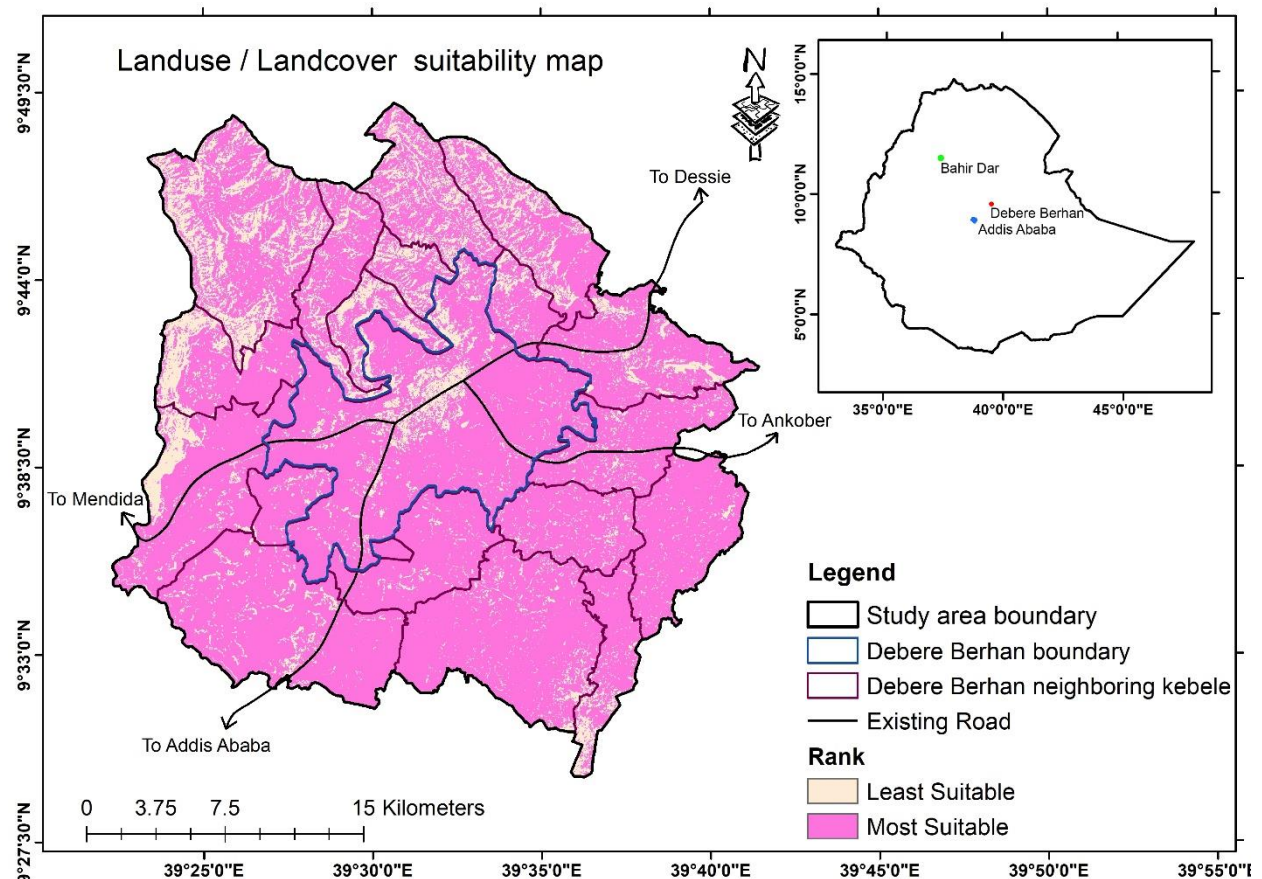


Figure 3.21; LULC suitability map

Table 3.8; LULC suitability area coverage and summary

Suitability	LULC	Rank	Colour Code	Area (ha)	Percent
Least Suitable	Forest, lakes,				
	buildings	1		1,354 ha	16.9 %
Most Suitable	Bare land	5		6,657 ha	83.1 %

vi. Distance from dense settlement area (urban area)

Wind farms have their own negative impact on the local population including visual and noise disturbance because of this it is recommended a setback distance from existing urban areas (Athanasios, 2018). Figure 3.22 and Table 3.9 show that 94.9 % (7,608.2 ha) of the study area is suitable and 89.9% (7,192.3 ha) is the most suitable area.

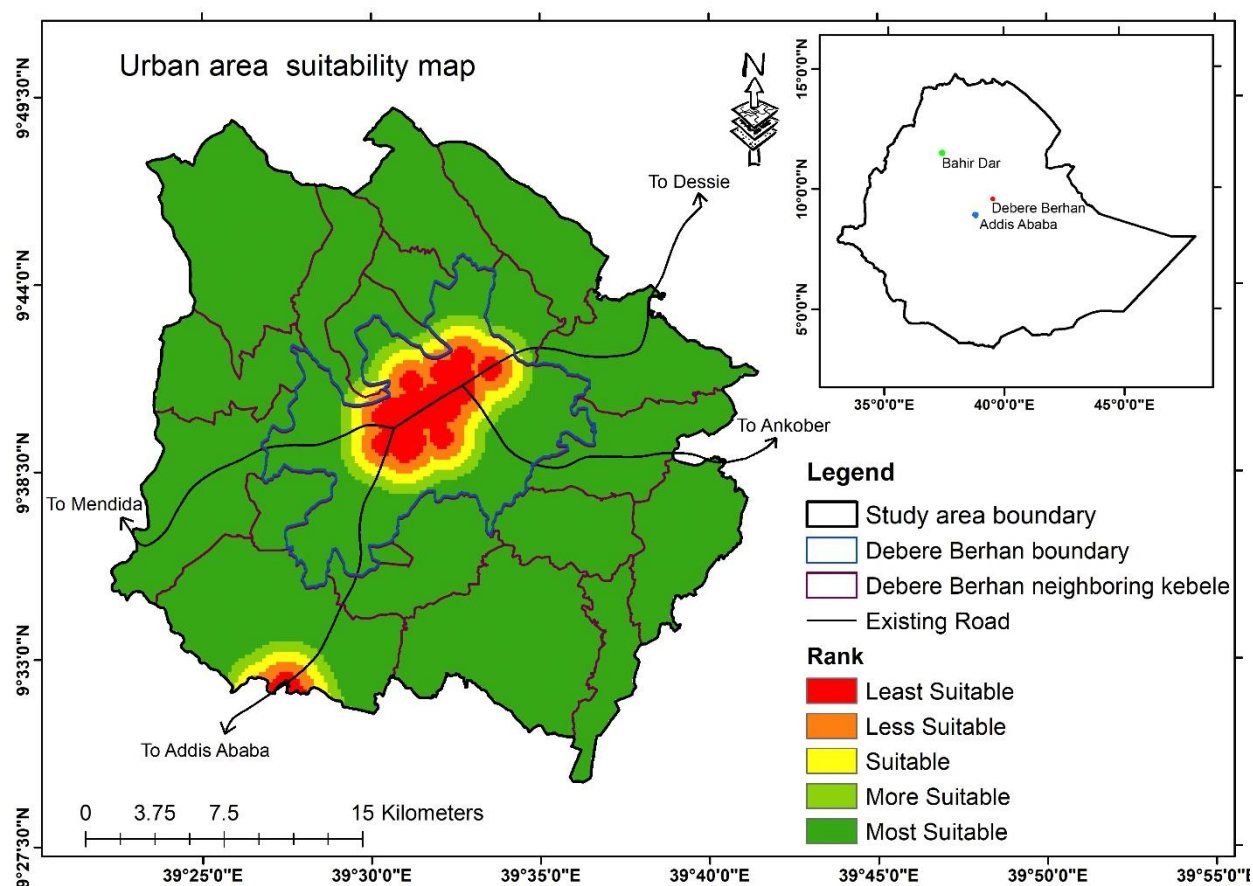


Figure 3.22; Urban area suitability map

Table 3.9; Urban area suitability area coverage and summary

Suitability	Urban Dist.	Rank	Colour Code	Area (ha)	percent
Least Suitable	0 – 600 m	1		222.0 ha	2.8 %
Less Suitable	600 – 1200 m	2		183.6 ha	2.3 %
Suitable	1200 – 1800 m	3		188.6 ha	2.4 %
More Suitable	1800 – 2400 m	4		227.3 ha	2.8 %
Most Suitable	> 2400 m	5		7,192.3 ha	89.7 %

vii. Proximity to existing roads

Wind farms must not locate to adjacent to roads and need some distance from the existing transportation networks (*Bili & Vagiona, 2018*). *Figure 3.23* and *Table 3.10* show 89% of the study area is the most suitable area based on road criteria.

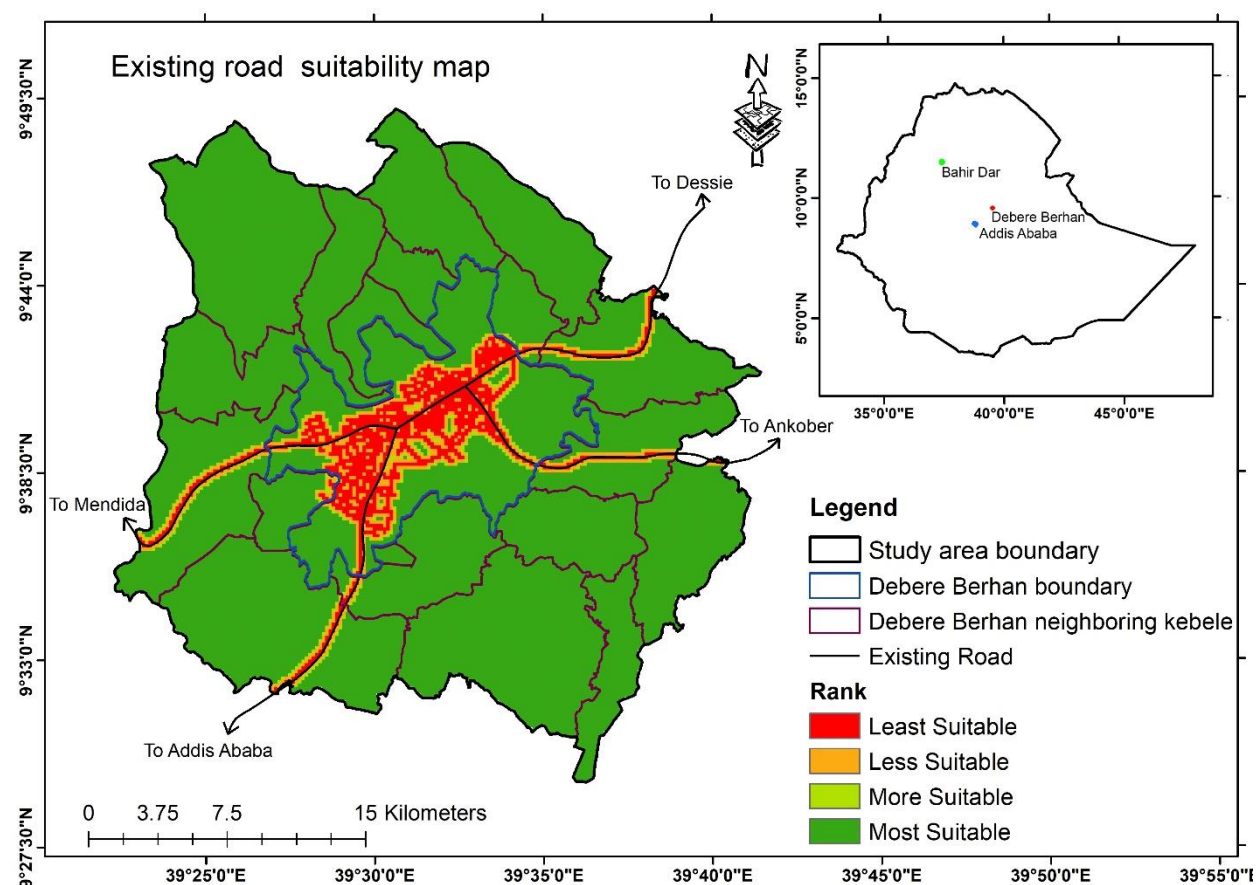


Figure 3.23; Road suitability map

Table 3.10; Road suitability area coverage and summary

Suitability	Road Dist.	Rank	Colour Code	Area (ha)	Percent
Least Suitable	0 – 100 m	1		479.1 ha	6.0 %
Less Suitable	100 – 200 m	2		309.5 ha	3.9 %
More Suitable	200 – 300 m	4		92.4 ha	1.2 %
Most Suitable	>300 m	5		7128.7 ha	89.0 %

viii. Proximity to wetland

Wetland is a natural protected area and wind farms should be placed in less impact on the existing land. *Figure 3.24* and *Table 3.11* illustrate that 98.4 % (7,878.7 ha) of land is the most suitable area.

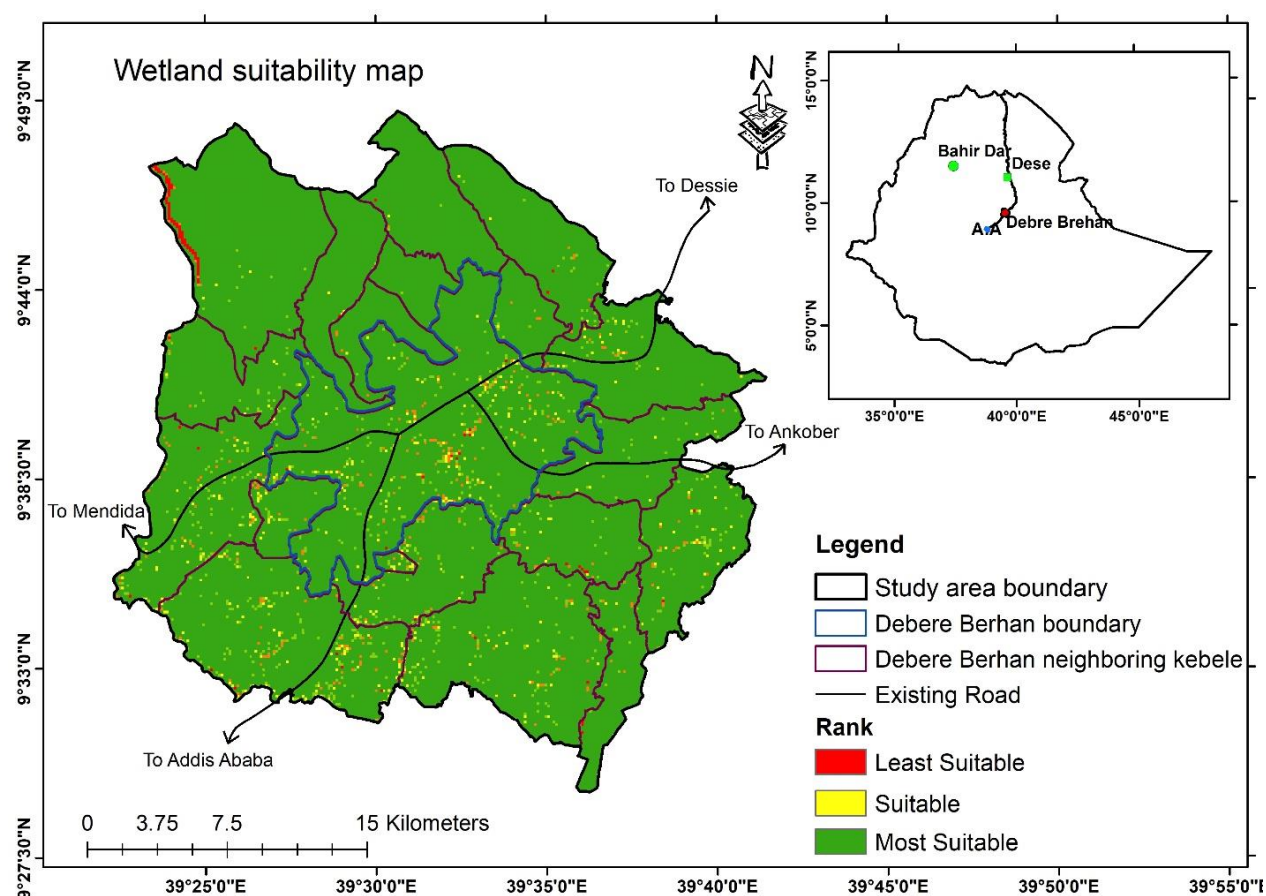


Figure 3.24; Wetland suitability map

Table 3.11; Wetland suitability area coverage and summary

Suitability	Wetland	Rank	Colour Code	Area (ha)	Percent
Least Suitable	High intensity	1		20.5 ha	0.3 %
Suitable	Low intensity	3		108.7ha	1.3 %
Most Suitable	Bare Land	5		7878.7 ha	98.4 %

To select the best and feasible site, the reclassified outputs (the suitability maps) of all the layers (slope, wind speed, distance from power lines, rivers, LULC, distance from urban areas, distance from roads, and wetland) were overlayed using ArcGIS to find the combined effect.

As shown in *Table 3.12* supported by literature described in *Table 2.3*, for each parameter the share of influence of each is assigned out of 100% and normalized. Even if all layers are much required for wind farm feasible site selection, all layers are not equally important for suitability model, so each layer is to be weighed (WLC) in which giving the most important datasets in the model with a higher percentage influence (weight) than the others.

Table 3.12; Suitability percentage and weight

Suitability Criteria	Percent influence	Percentage normalized
Slope	5%	0.05
Wind speed	40%	0.40
Distance from power lines	10%	0.10
Distance from rivers	5%	0.05
Land use / Landcover	15%	0.15
Proximity to urban areas	15%	0.15
Proximity to roads	5%	0.05
Wetland	5%	0.05
Total	100	1

Slope, distance from the river, distance from roads, and wetland all layers have an influence of 5 percent (0.05). Wind speed influences 40 percent (0.40). Both land use/landcover and proximity to urban areas influence 15 percent (0.15) and distance from power lines have an influence of 10 percent (0.10) on the final result (output model).

3.8.2.2 Investigate the suitability within the town

The larger wind turbines and the increased wind speed led to higher energy output. When wind speed doubles the energy output increases up to eight times, however some studies with small wind turbines in New Zealand have found the increment is linear. When wind speed doubles, the energy produced also increased by double. So, wind speed has a direct impact on electricity generation capacity. In general, a minimum wind speed of 2m/s is required to start rotating most of the small wind turbines and 3.5 m/s is the cut-in speed, and turbines start generating power. The maximum power is generated in wind speed from 10m/s - 15m/s and 25m/s is a maximum, and the turbine stopped or braked and which is considered as cut-out speed (Branz, 2020). According to Branz (2020), the wind speed within Debera Berhan town is reclassified as 3.5 m/s is the cut-in speed for wind speed suitability and illustrated in *Figures 3.25 and 3.26* and at 10m and 50m height, respectively.

As shown in *Table 3.13*, only 0.7 % (10.4 ha) of the study area is the most suitable location at 10m height. However, 22.1 % (323.2 ha) of the study area is suitable and can generate electricity from those locations.

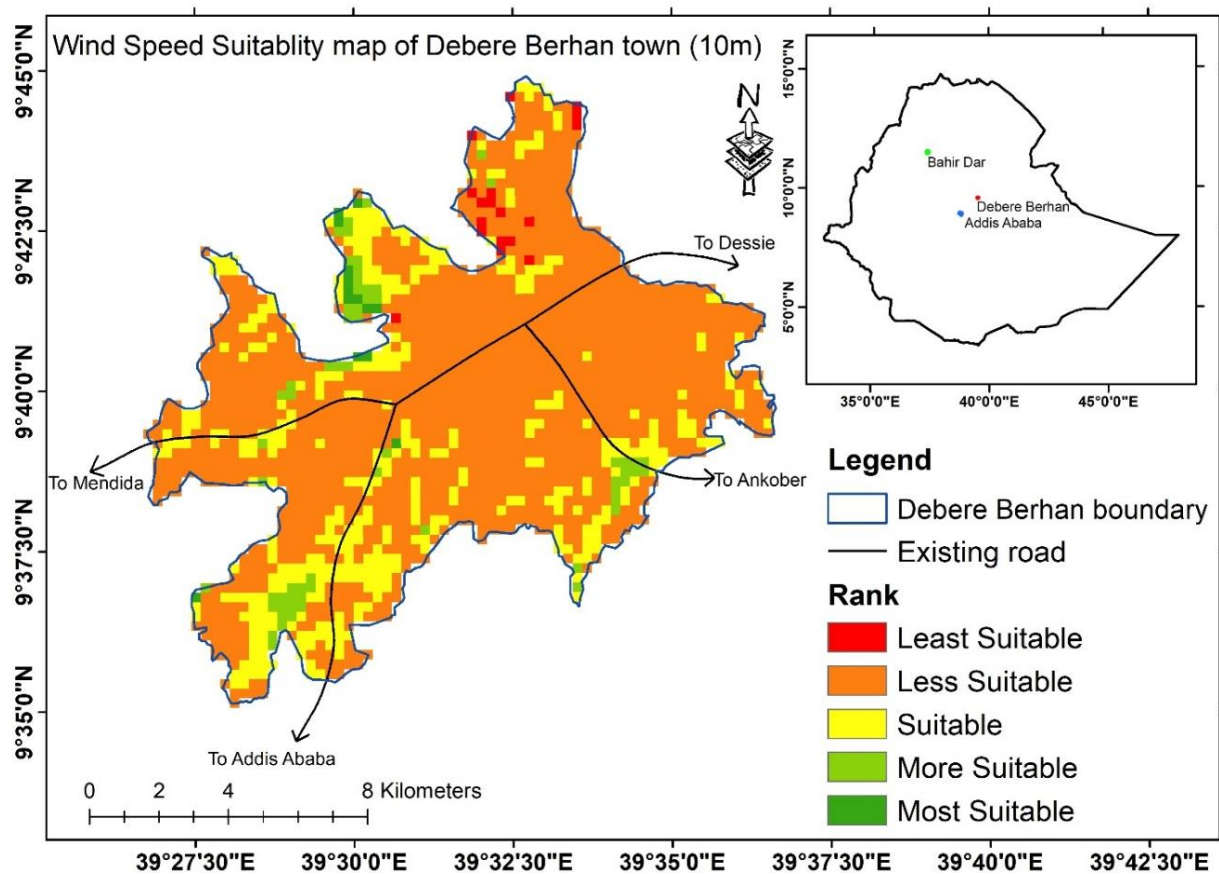


Figure 3.25; Wind speed suitability map in Debere Berhan town (10m height)

As shown in *Table 3.13* and *Table 3.14*, from the building-integrated wind farm summary, at 10m height 77.9 % of the Debere Berhan is unsuitable areas, however, at 50m height, only 8.9 % of Debere Berhan town is unsuitable areas. So, at 50m height, there is a good potential for urban wind energy.

Table 3.13; Wind speed suitability inside Debere Berhan town summary (10m height)

Suitability	Wind Speed (10m)	Rank	Colour code	Area (ha)	Percent
Least Suitable	0.7 m/s – 2.0 m/s	1		11.6 ha	0.8 %
Less Suitable	2.0 m/s – 3.5 m/s	2		1,124.8 ha	77.1 %
Suitable	3.5 m/s – 4.0 m/s	3		266.2 ha	18.2 %
More Suitable	4.0 m/s – 4.5 m/s	4		46.6 ha	3.2 %
Most Suitable	4.5 m/s – 5.6 m/s	5		10.4 ha	0.7 %

Figure 3.26 and Table 3.14 show that 13 % (189.2 ha) of Debere Berhan town is most suitable but 91.1% (1,328.3 ha) of the town is suitable for a building-integrated wind farm at 50m height.

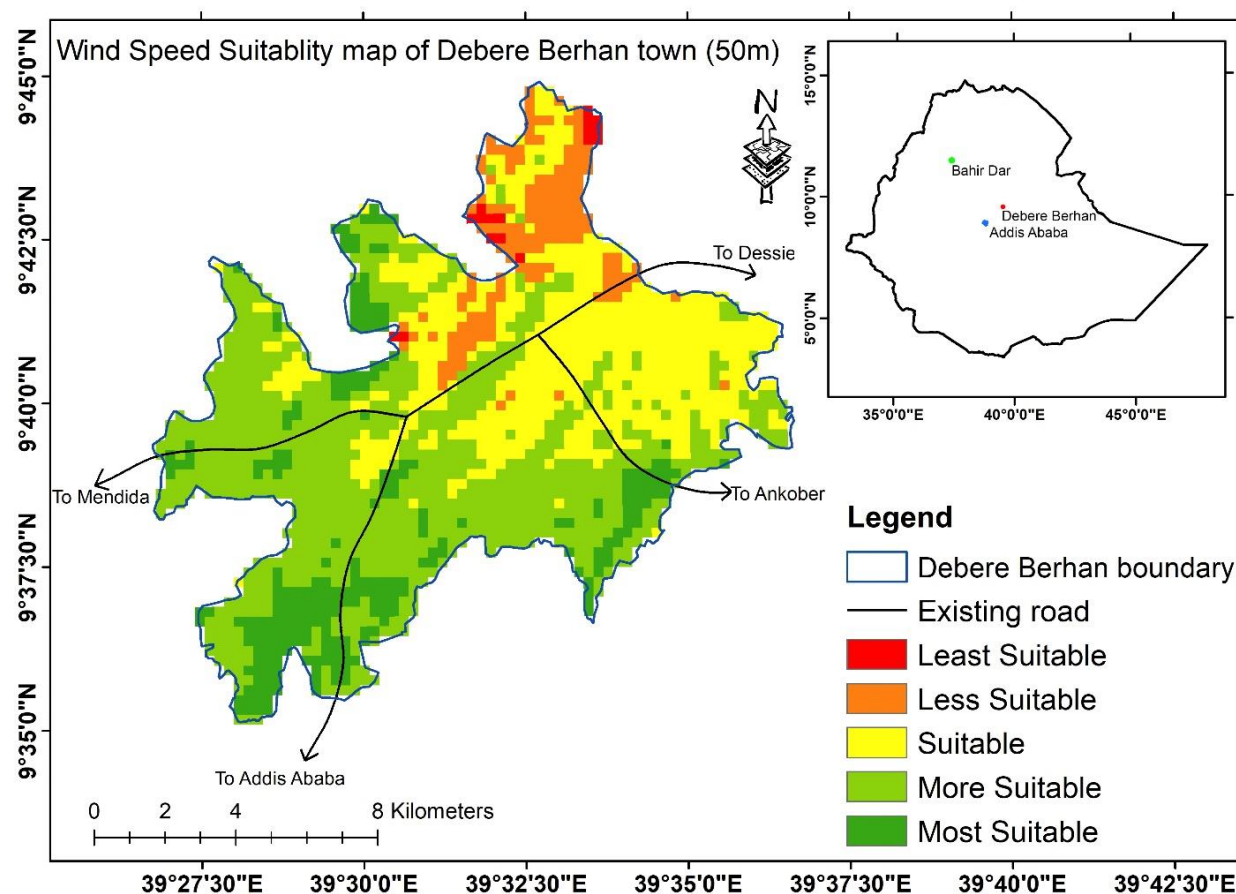


Figure 3.26; Wind speed suitability map in Debere Berhan town (50m height)

Table 3.14; Wind speed suitability inside Debere Berhan town summary (50m height)

Suitability	Wind Speed (50m)	Rank	Colour code	Area (ha)	Percent
Least Suitable	1.3 m/s – 2.0 m/s	1		12.3 ha	0.8 %
Less Suitable	2.0 m/s – 3.5 m/s	2		118.9 ha	8.1 %
Suitable	3.5 m/s – 4.0 m/s	3		442.1 ha	30.3 %
More Suitable	4.0 m/s – 4.5 m/s	4		697.0 ha	47.8 %
Most Suitable	4.5 m/s – 5.89 m/s	5		189.2 ha	13.0 %

CHAPTER FOUR: RESULTS

4.1 Potential wind energy harvesting sites in and around Debere Berhan town

The multi-criteria analysis with eight input layers is analyzed, and the result has shown in *Figure 4.1* and *Table 4.1* that 2,507.2 ha (31.4%) of the study areas is found to be the most suitable for harvesting wind energy. More suitable areas cover 3,921 ha (49.2%) from the total study area. The most suitable areas are dispersed in the south, southwest, and southeast of the study area, namely Tsigereda kebele, Chefa Nen kebele, Dibut kebele, and korma Gefiya kebele have the most suitable locations with a higher percentage of coverage for wind farm development. Additionally, Angolela, Adis Amba, Brer Hager, and Wush Aweshegn kebeles have the most suitable locations with lower percentages coverage for wind farm.

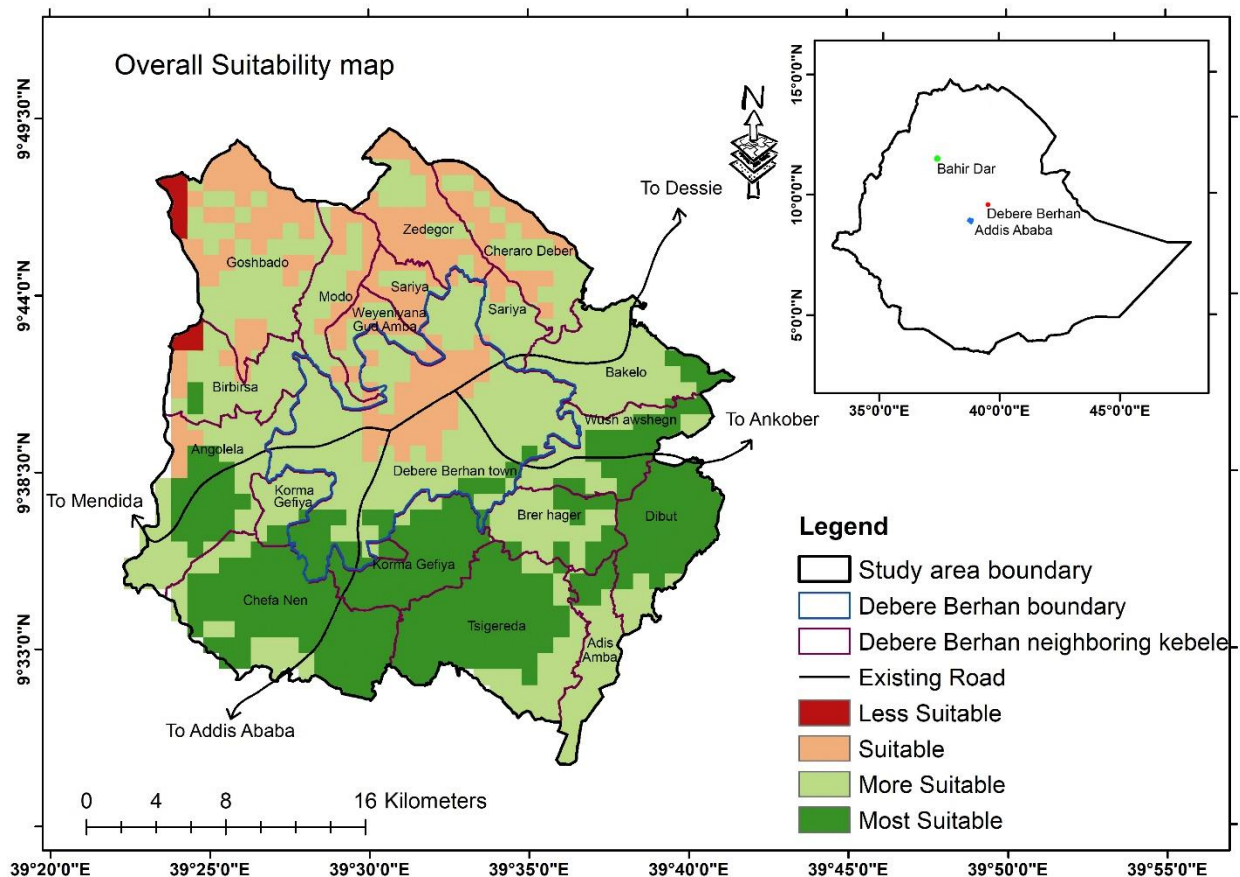


Figure 4.1: Suitability result for wind farm

Table 4.1: Suitability result summary

Suitability	Rank	Colour code	Area (ha)	Percent
Less Suitable	2		35.6 ha	0.4 %
Suitable	3		1509.3 ha	18.9 %
More Suitable	4		3921.0 ha	49.2 %
Most Suitable	5		2507.2 ha	31.4 %

4.2 Investigate the suitability of the wind farms

i. Peri-urban area

To select the best, feasible site inside the study area, it is to screen out the most suitable areas from the overall suitability map. Most of the areas that cover 31.4 % (2502.7 ha) of the study area are most suitable locations for peri-urban wind energy harvesting as shown above in *Table 4.1* and *Figure 4.2* below because Debere Berhan town and location around the town have high wind speed value because of this it has a best potential area for wind energy harvesting. The overall procedure of multi-criteria decision making and model builder map is shown in *appendix 18*.

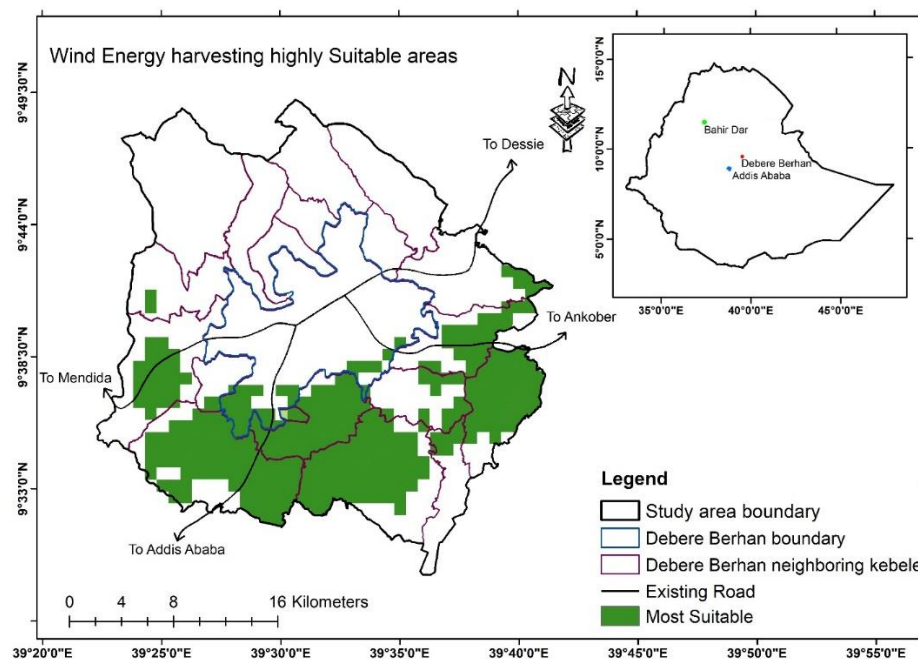


Figure 4.2; Best and feasible site for wind energy harvesting

The wind direction in the study area is mostly blown within the range of $240.5^{\circ} - 255.6^{\circ}$ and *Figures 4.3 and 4.4* show the direction of the wind, in which the dominant wind flows from east to west direction and the secondary dominant windblown with range $265.1^{\circ} - 275.8^{\circ}$.

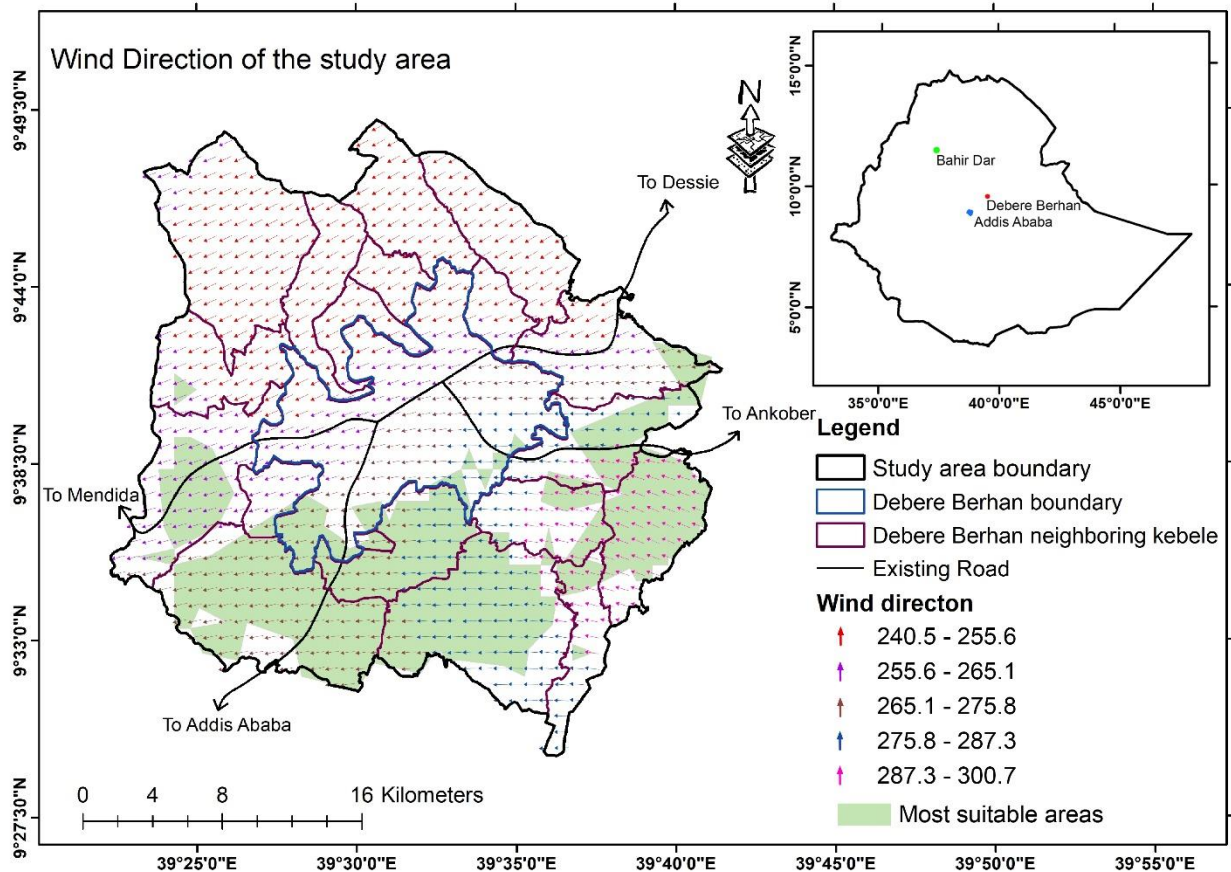


Figure 4.3: Wind direction map of the study area

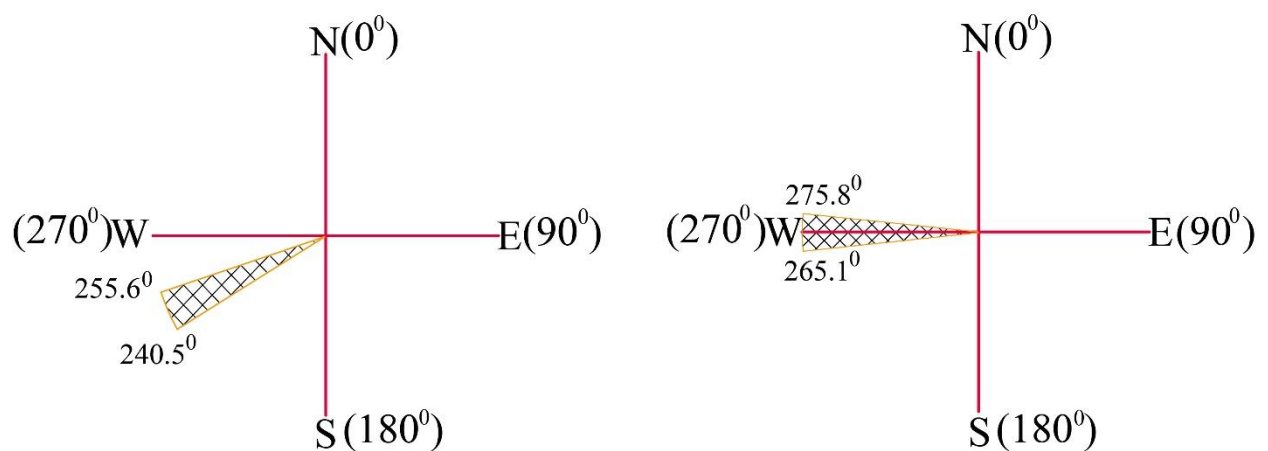


Figure 4.4: Major wind-blown directions $240.5^{\circ} - 255.6^{\circ}$ and $265.1^{\circ} - 275.8^{\circ}$, respectively

ii. Inside the town

The best and feasible site inside Debere Berhan town is identified, and screen out is performed the most suitable areas from the overall suitability map, inside the town and 13% (189.2 ha) of Debere Berhan town is the most suitable location or best site for urban wind energy harvesting illustrated in *Figure 4.5* below.

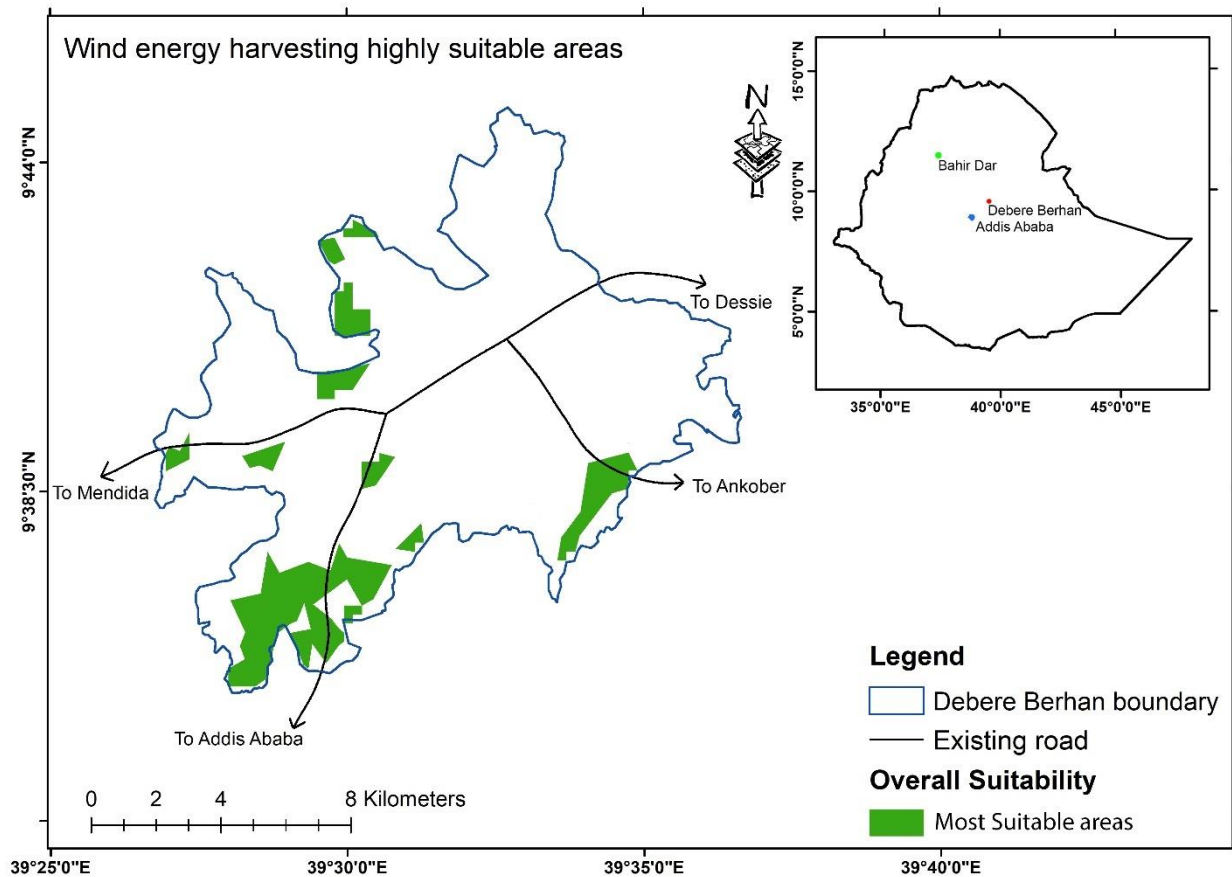


Figure 4.5; Best and feasible site for wind energy harvesting inside the town

The wind direction within Debere Berhan town is mostly blown within the range of 261.0° - 267.3° which is the dominant wind flows from east to west direction and the secondary dominant wind direction blown is from 267.3° – 273.3° . The wind direction map of Debere Berhan town is shown in *Figures 4.6* and *4.7* below.

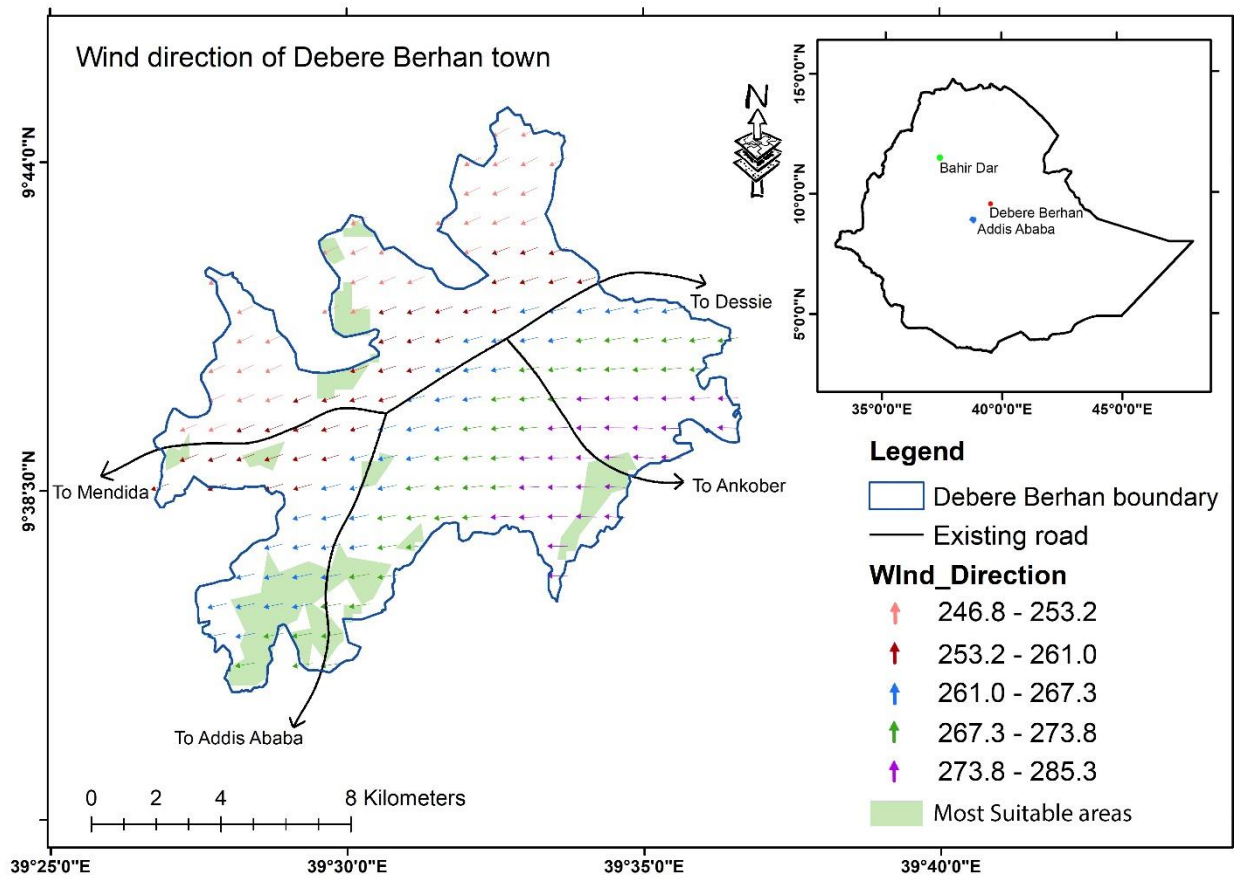


Figure 4.6: Wind direction of Debere Berhan town

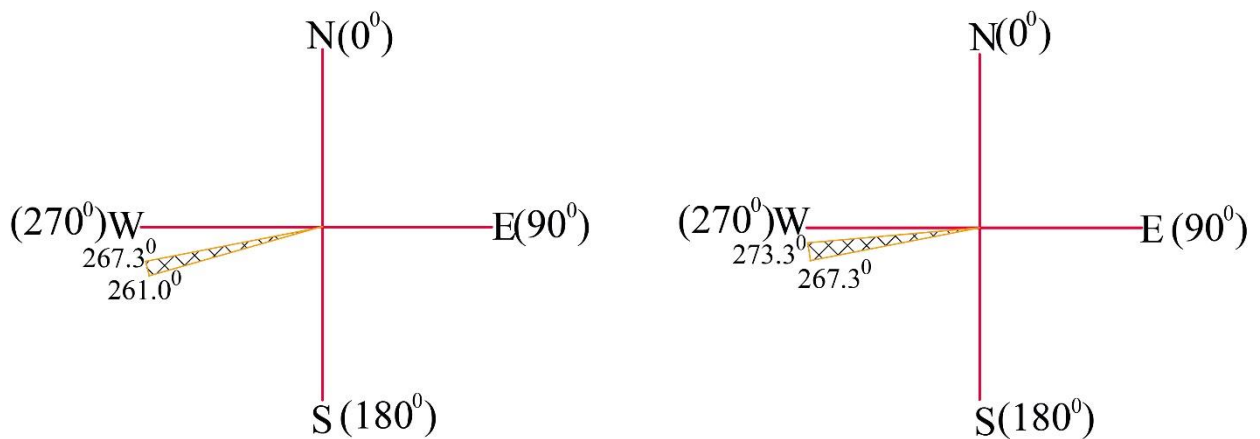


Figure 4.7: Major wind-blown directions 261.0°- 267.3° and 267.3° – 273.3°, respectively

A feasible wind energy harvesting site inside Debere Berhan town is identified. There are ten different locations identified as shown in *Figure 4.5* above and from those ten urban wind energy potential sites four-station are selected to make wind speed simulations based on the presence of the existing building in the potential sites. The selected four stations have buildings and located in

a different part within the town boundary and illustrated in *Figure 4.8* below and the simulation results are shown from *Appendix 6 - 17*.

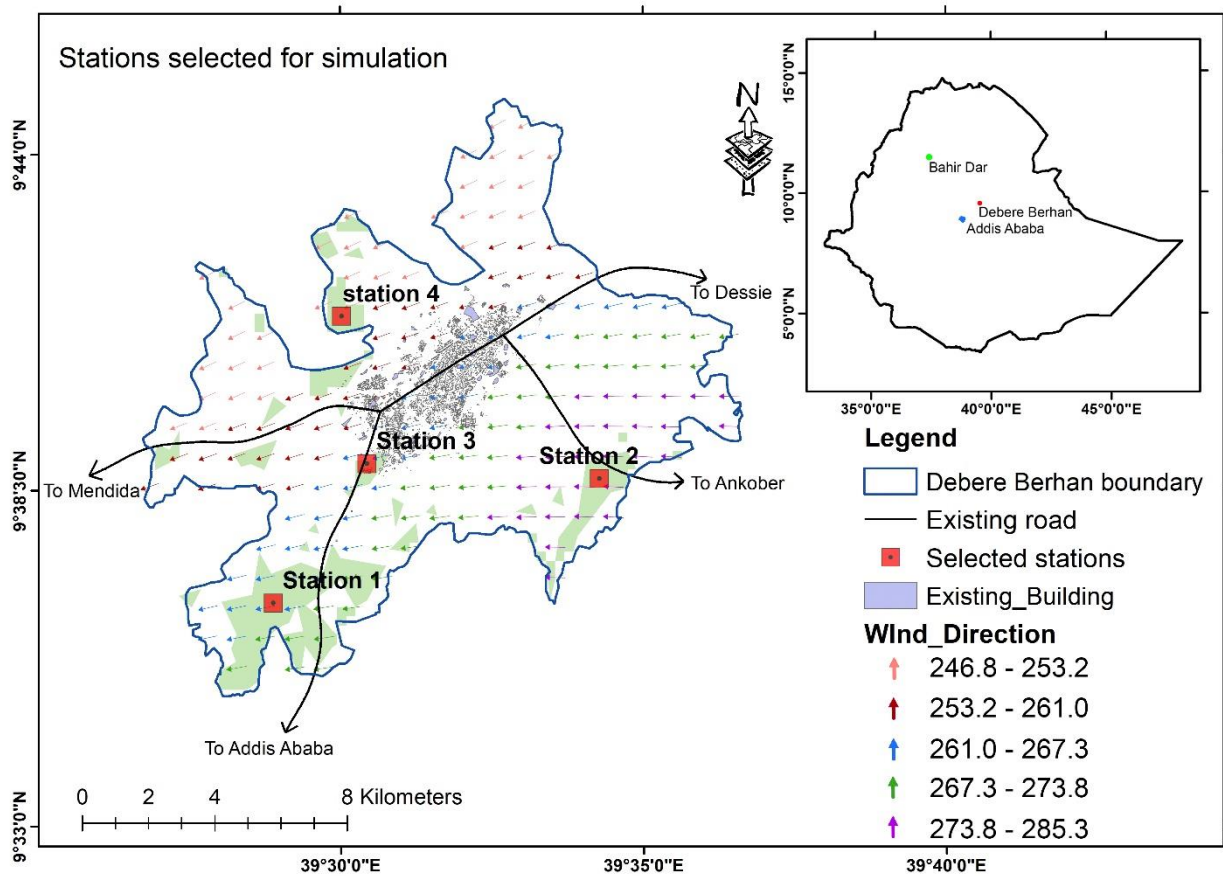


Figure 4.8: Selected stations for simulation

Wind speed simulation for potential sites for urban wind energy harvesting (stations) located within Debere Berhan town is done with ENVI-met simulation and the output is shown from *Appendix 6 - 17* at a different time in four potential locations.

4.2.1 Investigate the feasibility of the wind farms

i. The estimated energy production

The wind resource assessment from 30-year data shows that at 80m height the mean wind speed at the proposed locations (most suitable locations) is about 6.59 m/s, in which at the proposed 80m height, the wind speed is between 5.5 and 7.68 m/s, with an average of 6.59m/s. The net annual energy production is 60.18MW from 2,507.2 ha of land.

ii. Access to the site

Transportation of massive turbines to the most suitable areas for construction of wind farm, there is an existing access road to the selected locations for wind farms because the most suitable locations for wind farms is near to the major route from Addis Ababa to Dessie.

iii. Environmental impact assessment

The wind farm locations have very little impact on the existing environment because of the suitability analysis and the MCDM methods could identify and screen out such kinds of challenges. So, based on the environmental impact, wind farms have very little impact on the existing environment.

iv. Social impact assessment

The main social factors regarding the construction of wind farms are the displacement of residents on the locations of the wind farm and 2.4 km buffer from the locations of most suitable areas. So, this problem is also identified on the main criteria for wind farm site selection, and the wind farm site is located away from the dense settlement and urban areas. Because of this, there is no impact on the existing urban settlement. Despite, there are positive socio-economic benefits for the peoples of Debre Berhan town it which it inspires the social and economic development of the society by increasing the quality of life and additional direct and indirect job opportunities for the people of Debre Berhan town.

v. Wind farms power output

There is a high electricity supply shortage in Debre Berhan town and this is the main challenge of the town in which most of the people of Debre Berhan town used traditional source of energy and also currently high additional demand of electricity because of industrial and economic development within and around the town of Debre Berhan. Currently, two substations distribute

25 MW of electricity for Debre Berhan and the surrounding town which is very less when compared to the town demand, results in about 89% of the peoples forced to use traditional sources of energy. The current study investigates that 60.18 MW of electricity is generated from the wind farm and 3.28 MW from building-integrated wind farms. So, this is a big opportunity for the community of Debere Berhan in which is in high demand of electricity.

vi. Wind farm cost analysis

There is a rule of thumb to analyze the wind turbines are economical, that are directly associated with the wind resource within the construction site. Wind turbines are economical if the wind speed is greater than 5.5 m/s at the hub height of the turbine (Stankovic *et al.*, 2009). In this study the minimum criteria for wind speed are 5.5m/s. So, the study area has cost benefits from the wind turbines.

The overall conclusion of the suitability study is that the project of the wind farm is highly desirable according to with accessibility of the project site, environmental, social, and economic dimensions of development of society in which it has high positive impacts.

4.2.2 Energy generated from the wind farm

The energy generated from the wind farm around Debere Berhan town for the most suitable areas is calculated in the excel sheet and a single HAWT with a rotor diameter of 80 m generates 1,029,655 kWh energy annually.

So, a single HAWT with a rotor diameter of 80 m generates 1,029,655 kWh energy annually, which equals 2.821 MWh energy generated per day.

Megawatts (MW) = Megawatt hours (MWh) / Hours (h)

Megawatts (MW) = 2.821 MWh / 24 h = 0.12MW electricity production from single 80 diameter wind turbine.

According to Gupta, (2015) presented in the literature review, the recommended space for wind turbine spacing, for separating towers within a row is 3 – 5 times rotor diameter and 5 – 9 times between the rows.

So, the rotor diameter = 80m

Distance with in a row = $3 * 80\text{m} = 240\text{m}$

Distance between rows = $5 * 80\text{m} = 400\text{m}$

Area of single turbine (A_t) = $\frac{1}{2} (240\text{m} * 400\text{m})$

Area of single turbine (A_t) = 48,000 m² for 80m rotor diameter.

Number of turbines (N_t) = total land area / area of single turbine = 25,072,000 m² / 48,000m²

Number of turbines (N_t) = 501.5

Energy total = Number of turbines * energy generated from a single turbine

Energy total = 501.5 * 0.12 MW

Energy total = **60.18 MW** energy generated from the wind farm

4.2.3 Energy generated from urban wind energy

The energy generated from the urban wind energy within Debera Berhan town for the high potential areas is calculated in the excel sheet and a single VAWT with a rotor diameter of 7m generates 6,496 kwh energy annually which equals 6.496 Mwh.

According to Gupta, (2015) presented in the literature review, the recommended space for wind turbine spacing, for separating towers within a row is 3 – 5 times rotor diameter and 5 – 9 times between the rows.

So, the rotor diameter = 7 m

Distance within a row = $3 * 7 \text{ m} = 21\text{m}$

Distance between rows = $5 * 7 \text{ m} = 35\text{m}$

Area of single turbine (A_t) = $\frac{1}{2} (21\text{m} * 35\text{m})$

Area of a single turbine (A_t) = 367.5 m^2 for 7m rotor diameter.

Number of turbines (N_t) = total land area / area of single turbine = $1,892,000 \text{ m}^2 / 367.5 \text{ m}^2$

Number of turbines (N_t) = 5,148.3

Energy total = Number of turbines * energy generated from a single turbine

Energy total = $5148.3 * 6.496 \text{ MWh}$

Energy total = 33,443.4 MWh energy generated from the wind farm

To change from MWh to MW, it should be divided by the number of hours.

33,443.4 MWh energy is generated annually and to change it to daily it is divided by 365 days.

$33,443.4 \text{ MWh} / 365 = 91.63 \text{ MWh}$ energy generated per day

Megawatts (MW) = Megawatt hours (MWh) / Hours (h)

Megawatts (MW) = $91.63 \text{ MWh} / 24 \text{ h} = \mathbf{3.82 \text{ MW}}$ electricity production from the urban wind energy.

4.3 To develop an urban design plan based on suitability maps

The land-use plan is designed and mapped for wind farm development around Debera Berhan town based on the standard. There is a buffer distance of 350 m from each turbine to another turbine, in which the minimum distance for 80m rotor diameter is 240 m (three times the rotor diameter) and the maximum distance is 400 m (5 times the rotor diameter) (Gupta, 2015). According to their location of highly suitable areas, the wind farm locations are divided into four

major stations in which all of them have arranged wind turbines based on the standard for wind farm buffer zone. The land-use plan for the wind farms is illustrated in *Figure 4.9* below.

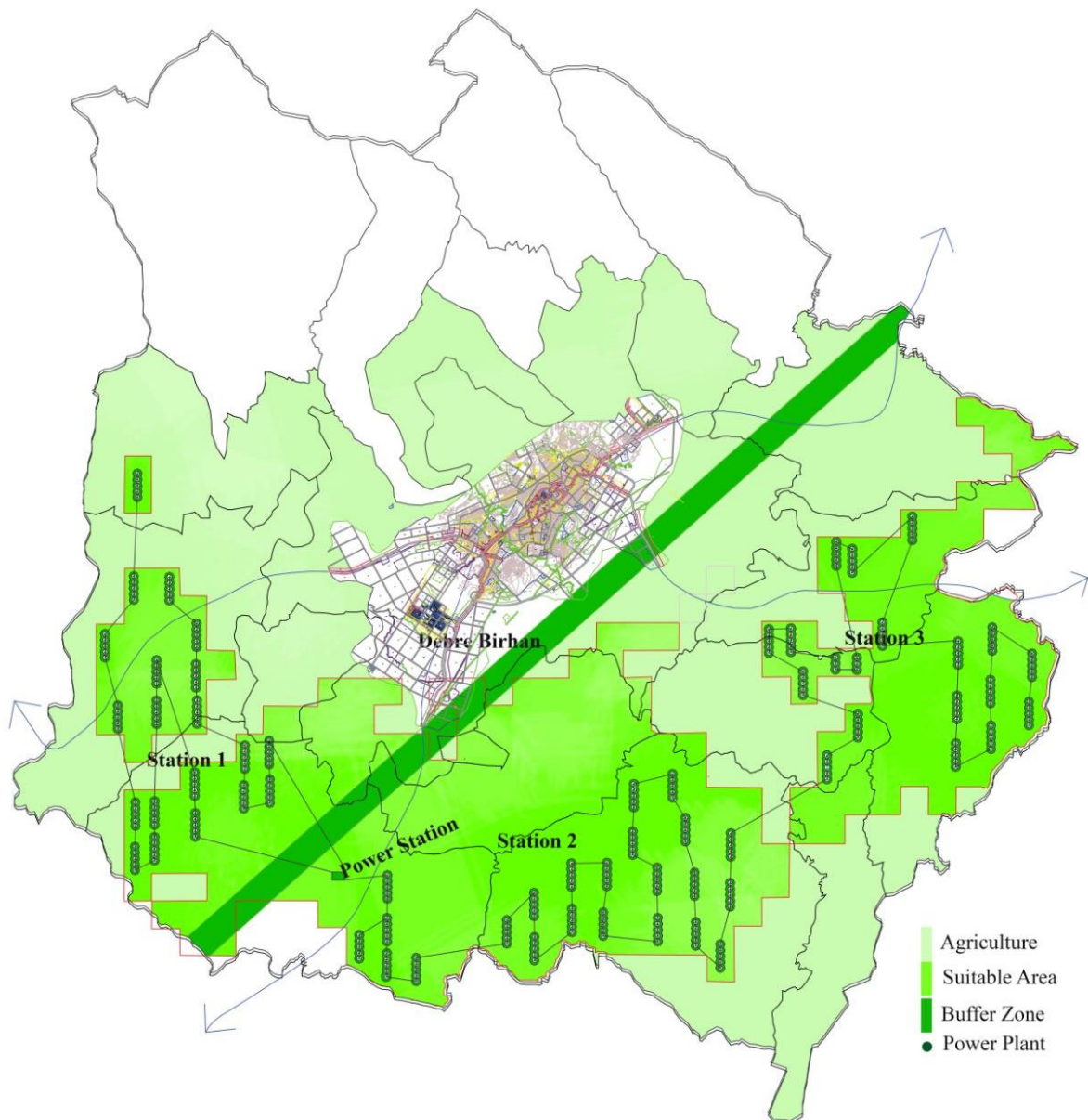


Figure 4.9; Wind farm land-use plan for highly suitable areas

There is also a buffer zone from each wind turbines which restrict any development and infrastructure within a 150m radius from each turbine and it is shown in red color in *Figure 4.10* below, and also within 450m radius from each turbines only road infrastructure is permitted and any other urban developments are restricted in those areas that are shown in the detailed wind farm map in dark green in the *Figure 4.10* below.



Figure 4.10; Detailed wind farm landuse plan

CHAPTER FIVE: DISCUSSION

5.1 Potential wind energy harvesting sites in and around Debere Berhan town

i. peri-urban area

The windy areas around Debere Berhan town are identified at 50m, 100m, 150m, and 200m. the result of wind speed in the study area is higher and more than expected. So, for this study wind speed above 5.5 m/s is used as the minimum criteria for wind speed for selecting wind energy potential sites around the town as one criterion. Because there is high wind speed is present more than expected, this study uses wind speed criteria more than the standard to select the most effective sites for wind energy harvesting. As most of the studies for wind farm site selection use the minimum criteria for wind speed is 3 m/s – 3.5 m/s.

According to Gigović *et al.*, (2015) In the study for wind farm site selection in the case of Vojvodina, Serbia, the study used as the minimum criteria for wind speed is 3.5m/s and the study rank most suitable sites for the wind farm in which wind speed greater than 3.5 m/s with no prioritizing. So according to Gigović *et al.*, (2015) study wind speed with 3.5 m/s and any wind speed above 3.5m/s has an equal opportunity to be selected for wind farm site.

The main result of this study identifies wind energy harvesting sites and the idea of the “urban dimension” of development goals which argues that more attention should be given to climate action strategies and energy policy. So, Integration of wind energy potential sites with the structure plan of Debere Berhan town is very necessary, because there is a potential to meet this energy demand by using abundant renewable energy sources. City planners and designers need to take action while making the future structure and land-use plan of the town by excluding these renewable energy areas, to meet the rising need of the population and to maintain a healthy living environment. This study identifies wind energy harvesting sites for Debere Berhan town and this

study is a big opportunity for the town in which it can be easily integrated with the future plan of the town.

ii. Within urban area

Windy areas and wind speed within Debere Behan town are decreased when compared with the peri-urban area. This is because the roughness length is increased when the proximity to urban areas is increased. Most of the areas around Debere Berhan town are bare land and bare land has very low roughness length while compared with cities and villages. So the roughness length of the built structures leads to minimizing the wind speed within the city. Because of less wind speed when compared from the peri-urban area the minimum criteria used for urban wind energy is 4.5 m/s as the most suitable location for urban wind energy, while still, the minimum standard for urban wind energy is 3 m/s as Pamucar *et al.*, (2017) states in their study.

According to Zeng, (2011) in his study on the integration of renewable energy with urban design, the study identifies the effective ways of combining renewable energy with urban development. The research by Zeng, (2011) has shown that urban form and building height has a significant impact on wind energy output. In this study in most of the locations within the urban area were equal in building height and this might be some drawback for high suitable locations, but for some buildings with higher height is a good opportunity to generate electricity from building-integrated wind turbines.

5.2 Investigate the suitability of wind farms

The result of the suitability map shows that the most suitable areas for wind farm development are located in the southern part of the study area, this is a big opportunity for the manufacturing industries of the town because most of the manufacturing sites are also located in the southern part of the town which is shown in the structure plan of Debere Berhan town, in which the energy is accessed with low utility infrastructure cost. Additionally, the suitability result of the wind farms

has the potential to be linked to the existing structure plan of Debre Berhan town, because of better access to the town, low infrastructure cost because the wind farm location is near to the manufacturing site of the town plus near to existing major power grid line of the town, less environmental impact on the existing land in which most of the high suitable areas is sitting on bare land.

In the case of building-integrated wind turbines, ten different locations are identified within Debre Berhan town. The height of buildings in these locations should be the highest of all other surrounding buildings to get maximum wind speed and higher energy output. The building height regulations in those (highly suitable locations) locations should be considered for better energy output. So wind turbines in urban context need to be integrated into structures designed and constructed this means greater electricity could be generated with small space in the top of buildings.

5.3 Develop urban design plan based on suitability maps

The final result of this study shows that 60.18 MW of energy is estimated from the 2,507.2 ha of land. In this study 31.4% (2,507.2 ha) of land is most suitable from the total study area, this shows the site has the best potential for wind farm development, but in Gigović *et al.*, (2015) study only 5% (32,000 ha) from the total study is the most suitable location for the wind farm.

This study includes the buffer distance between wind turbines and other any developments is about 450 m. The buffer distance is from any residential or other land-use variables including commercial and recreational areas. According to Weimar, (2011) in his study the buffer distance from wind turbines for both high-density residential areas and low-density area is 160m in which the standard for low-density development residential is 500m and for high-density development, it is 800m which is the developments.

CHAPTER SIX: CONCLUSION AND RECOMMENDATION

6.1 Conclusions

Energy consumption is increasing at a high rate throughout the world. Energy generating from renewable energy sources is one of the most possible ways for sustainable energy development. Wind energy has a major role as a renewable source of energy supply, to meet the growing energy demand. Because of this, the use of wind as a source of energy increased significantly throughout the world. For proper utilization of energy from wind needs to select an appropriate location for wind energy production.

The present study investigates that wind energy harvesting sites within and around Debere Berhan town, Ethiopia, and 2,507.5 ha of land is identified for wind farm development and ten different locations that cover 189.2 ha identified for urban wind energy harvesting. The energy generated from the wind farm is 60.18 MW, with an estimated annual production of 527.2 GWh, and from urban wind energy, 3.28 MW (annually 28.7 GWh) energy is generated.

The wind farm suitability study is highly desirable according to with accessibility of the project site, environmental, social, and economic dimensions of development of society in which it has high positive impacts. The urban design plan for wind farms for the high potential area is also identified and mapped in this study in which it can encourage the sustainable development of the town.

6.2 Recommendation

This study revealed potential wind energy harvesting sites within and around Debere Berhan town. Based on the main findings of this study the wind energy potential locations are identified, both within and around Debere Berhan town, but the wind speed data for this study is used from different international metrological data, that are released for research. It is better to check further by measuring the actual wind speed with an anemometer at Debere Berhan for greater assurance.

The future land use plan of Debere Berhan town should exclude the renewable energy resources of the very high potential area as identified, to encourage sustainable development of the town as well as to minimize the electricity challenges of the town. Additionally, urban wind energy is dependent on specific local factors which include the planning system. So, designers and planners should include sustainable energy generation methods or a sustainable design in a site orientation, building shape which can affect the energy output of building-integrated wind turbines and energy generation at a specific location.

Integration of renewable energy with urban design is much important to create a self-sustaining city. Additionally, urban form, the orientation of the building, height of the building, roof shapes have a significant impact on combining urban wind energy with urban development. So, all these factors should be considered while making urban design and developments.

Wind turbines should be arranged at the edge of windy urban open spaces and it is a useful principle for urban wind energy design. Such places include natural wind corridors like rigid lines or canyons. Additionally, the edge of the parks and the windward urban edge facing the prevailing winds. In such open space, standalone wind turbines are enable to be incorporated.

Implementation of sustainable and renewable energy sources like wind energy should be encouraged by city administrators, in order to meet the need for clean and secure renewable energy sources, the potential of wind energy is explored that fits the urban environment. A wide range of options is possible and several successful projects can be carried out. From those options, large-scale wind turbines with blade diameter 80m or above and building-integrated wind turbines can be used.

Ethiopian national metrology agency should measure the renewable energy sources like wind and solar data etc. for a long time (30 years and above) and the data should be given free for local researchers and should make the data easy to access for all local researchers on renewable energy sources.

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Appendix

Appendix 1: Publishable manuscript

Identifying potential wind energy harvesting sites for sustainable Debere Berhan town, Ethiopia

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Abstract

In the modern world, the use of renewable energy resources is a very important segment and critical input for the development of human life which provides energy generation for electricity. Renewable energy resources are naturally refilled such as wind, sunlight, and others, and have less impact on the environment. Site selection is an important step for the utilization of those renewable resources. The method of multi-criteria decision-making (MCDM) is used for site selection as a tool for wind energy. The potential sites for wind energy harvesting take into account four major groups (topographic, technical, environmental, and socio-economic aspects of wind farm development) and eight sub-criteria groups (slope, wind speed, distance from existing power lines, rivers, LULC, distance from urban areas, distance from roads, and wetland). All the layers and datasets are weighted and overlayed to determine weights of sitting criteria to select the best and feasible site according to their importance for the wind farm site selection.

Keywords: Energy, Windfarm, ArcGIS, Debere Berhan town, multi-criteria decision making

1.0 Introduction

Energy is the most crucial concern for economic growth and the sustainable development of society specially to improve living conditions. Global energy demand increases rapidly as a result of the growth in population and the development of economies. Currently, fossil fuels are the major source of energy, and there are various environmental issues majorly atmospheric pollution, the greenhouse effect, and water pollution. Environmental impacts are minimized by the use of renewable energy sources (Oyedepo & Paul, 2012).

Ethiopia has huge and various potentials of renewable energy resources. The estimated potentials from wind is 10 GW. This source can be used as long-term energy potentials for both local industries, which are developing in Ethiopia as well as for international energy trade (Mengistu *et al.*, 2015).

The city, Debre Berhan attaining economic growth due to the emerging industrial development in the city. Because of this, there is a huge increase in energy demand in the city. Renewable energy sources are the solution to fulfil the increasing energy demand, by minimizing environmental pollution as well as supporting the economic and industrial development of the city. Energy generation from wind is described as one of the mature and cost-effective resources among different renewable energy technologies. But, even if Debre Berhan is at the high land, where wind energy is abundant, it has not been utilized to augment the available hydroelectric energy now.

1.1 Problem statement

In Ethiopia, there is a shortage of electricity and power outages occur frequently. Debre Berhan is a town in Ethiopia in which this study conducted and, in the town, there are many existing residential houses and industrial firms. In the town, the energy provision is very less when compared to the town demand because this power blackout occurs frequently especially in the dry season because the major source of electricity is only from hydropower (Amdetsion, 2016).

In Debre Berhan town there is a high shortage of electricity within different time interval, for example in night time from 7:30 Pm up to 9:30 Pm, there is a high shortage of electricity within the town. During this time interval, the bulb has decreased light output (brownout or reduced voltage) because of shortage of power and it is difficult to use stove, oven and large stove specifically used in Ethiopia called “injera mitad” during this time interval. This shows that the

power generated is smaller than the power demand and sometimes power outages (temporary loss of power) occurs within the town.

Additionally, the road light infrastructure in Debere Berhan town is well constructed and fully completed but there is no light from those roadside bulbs. These bulbs are working well but due to the energy shortage in the town, these lights are not giving targeted functions for the people of the town. Not only the roadside light but also many houses are constructed within the town and most of the new houses within the town didn't get electricity supply until now due to high shortage of power.

2.0 Theoretical review

2.1 Wind energy, urbanization, and cities

Renewable energies cover about 15% of the world's energy sources, and fossil fuels have satisfied a large part of the world's energy demand. The energy sector cover two-thirds of global CO₂ emissions and main drivers of climate change. (Perea-Moreno & Hernandez-Escobedo, 2018). The criteria can be classified into four major groups and summarized in *Table 2.1* below.

Table 2.1: Wind energy site selection criteria and description

Criteria	Description
Topographic	
Slope	Areas with a steep slope are less suitable for wind farm sites because of extra construction and maintenance costs. (Athanasios, 2018).
Technical	
Wind speed	Wind speeds greater than 3m/s are evaluated continuously up to 20 m/s, if it is more than 20m/s, it will cause damage to equipment (Pamucar <i>et al.</i> ,2017).

power lines	The other issue to consider is the distance from power lines, it reduces the cost of construction of energy transmission infrastructure (Idrizi <i>et al.</i> , 2018).
Environmental	
Rivers and lakes	Rivers and lakes are natural protected areas and the wind farm should exclude the buffer zones (Moradi <i>et al.</i> , 2017).
Land use/ Landcover	Land use is the most important factor to consider. Wind farms should be placed which have less impact on the existing land and must be located outside protected areas, wetlands, artificial surfaces, aquatic and forest areas (Pamucar <i>et al.</i> , 2017).
Socio-economic	
Distance from urban areas	Wind farms have negative impacts on the local population with relation to visual and noise disturbance, these lead to some setback distance from urban areas. (Athanasios, 2018).
Roads and railways	Wind farm is not better located adjacent to roads because the transportation of massive turbines can be interrupting the existing road network (Bili & Vagiona, 2018).

Wind farm site selection includes multiple criteria. Multi-criteria decision-making (MCDM) has a framework to analyze, survey, and solve such kinds of problems (Moradi *et al.*, 2017). For analyzing the site selection, a set of factors must be considered and, the criteria are classified into four major groups and eight sub-groups as shown in *Table 2.2* below.

Table 2.2: Factors and weight used in the analysis of suitability for wind farm development

No	criteria	Max/Min cut point criteria	Weight
Topographic (5%)			
1	Slope	<25%	5%
Technical (50%)			
2	Wind speed	>5 m/sec	40%

3	Distance from power lines	>500 m	10%
Environmental (20%)			
4	Distance from rivers and lakes	>500m	5%
5	Land use/ Landcover	>2000m of woodland, and natural protected areas	15%
Socioeconomic (25%)			
6	Proximity to an urban area	>1500m	15%
7	Distance to roads	>250m	5%

Source: Izeiroski *et al.*, 2018

3.0 Materials and Methods

3.1 Study Area description

The study is conducted in Debre Berhan town; it is a town located north of the Shewa zone Amhara region that is about 130 kilometres northeast of Addis Ababa. The town is located with an elevation of 2,840 meters and it is the early capital of Ethiopia. Debre Berhan town is located between latitude 9°39'4.79"N, longitude 39°30'45.78"E and latitude 9°41'34.02"N, longitude 39°33'17.40"E. The study area covers a total area of 8010 ha.

The location map of Debre Berhan town and the study area is shown in *Figure 3.1* below.

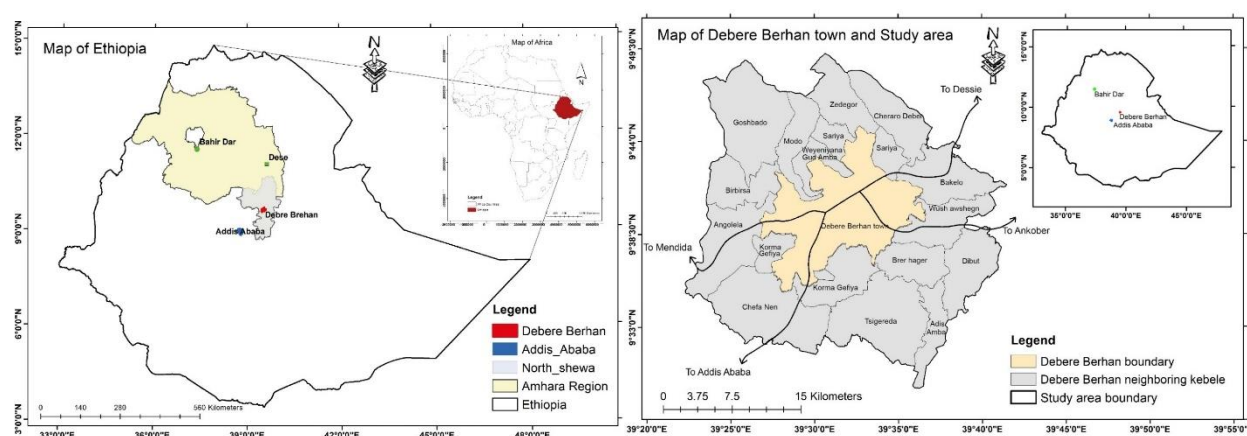


Figure 3.1: Location map of Ethiopia, Debre Berhan town and study area

3.2 Method of Analysis

The data sources and analysis tools are outlined in *Table 3.1* below

Table 3.1: Spatial data sources and overall weights for each major attribute

No	Factors	Spatial Data Source	Analysis
Topographic (5%)			
1	Slope	DEM of Debere Berhan town from USGS satellite map	ArcGIS spatial data analysis
Technical (50%)			
2	Wind speed	NASA metrology agency Global wind atlas	ArcGIS
3	Distance from power lines	Digitize the existing lines	ArcGIS Editor tool, self-Digitize
Environmental (20%)			
4	Distance from rivers	Digital elevation model (DEM) of Debere Berhan town	ArcGIS spatial data analysis
5	Wetland	DEM of Debere Berhan town	QGIS Desktop
6	Land use/ Landcover	Landsat with a recent timeline	Remote sensing (GIS)
Socioeconomic (25%)			
7	Proximity to urban area	Digitize the existing buildings	ArcGIS Editor tool
8	Distance to roads	Digitize the existing roads	ArcGIS Editor tool

The MCDM process includes prioritizing, in which the criteria and constraints will be presented on maps with different ArcGIS layers, and reclassified or transformed into units to be compared. Then weighting will be going on, by determining the weight coefficients of each criterion, and while solving, the criteria do not have the same degree of significance. As a result of applying a weighted linear combination (WLC), a wind farm suitability map is generated.

After prioritizing the wind farm potential sites, screening-out of the most suitable sites is the final step to draw the suitability map based on logical (algebra) and they can have a value from Not suitable (1) up to very highly suitable (5), which could identify the most suitable locations for wind farms. Once the criteria are reclassified, criteria values were normalized for comparison and weighting.

3.3 Multi-criteria decision making (MCDM)

The weight of each layer is assigned in terms of importance in affecting the suitability of a potential site for wind energy harvesting. For each criterion, a separate suitability map is produced and layered one over the other based on each weight or influence to identify the best location for a wind farm around Debera Berhan town.

i. Areas relatively on flat land

As shown in *Figure 3.2*, 76.8% of the study area is suitable based on slope criteria, however, 40.2% (3,224 ha) is the best flat land and it is considered as the most suitable location for the wind farm.

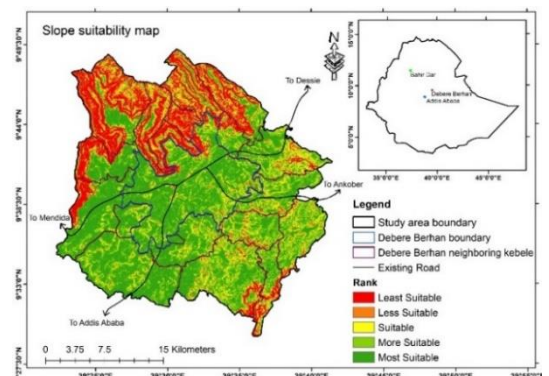


Figure 3.2: Slope suitability map

ii. Proximity to wetland

Wetland is a natural protected area and wind farms should be placed in less impact on the existing land. *Figure 3.3* illustrate that 98.4 % (7,878.7 ha) of land is the most suitable area.

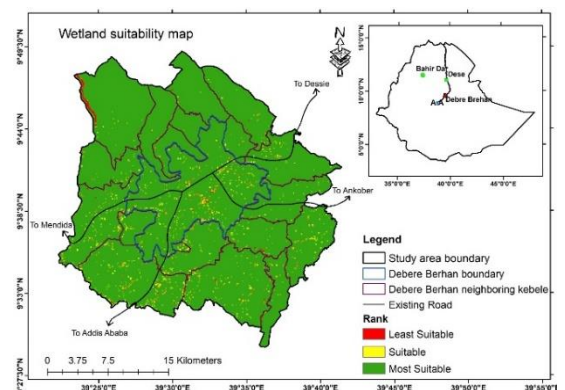


Figure 3.3: Wetland suitability map

iii. Wind speed

Wind speed higher than 3.0 m/s is suitable for wind energy production (Pamucar *et al.*,2017). So, as shown in *Figure 3.4*, about 89% (7,110.3 ha) of the area is suitable with wind speed criteria but the 30.9 % (2,469.3 ha) of the total study area is most suitable, in which this area has a wind speed greater than 5.5 m/s.

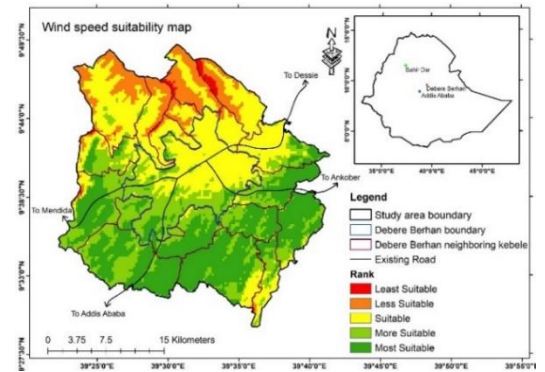


Figure 3.4: Wind speed suitability map

iv. Proximity to existing power lines

The existing availability of power grid lines must be considered because it reduces the construction of new energy transmission infrastructure (Idrizi *et al.*,2018). *Figure 3.5* show that only 27.2 % (2,178.8 ha) is a suitable area by existing power grid line criteria.

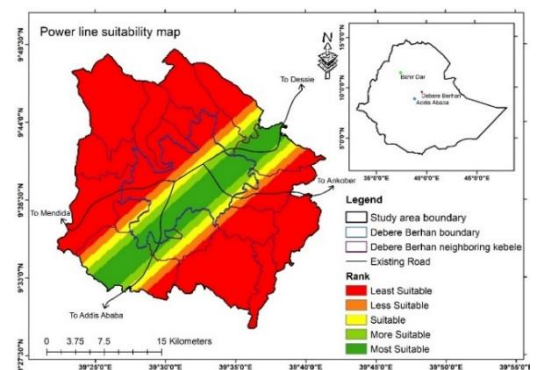


Figure 3.5: power lines suitability map

v. Areas away from rivers

Rivers are natural protected areas and the construction of wind farms should include the buffer zone from existing major river lines (Moradi *et al.*, 2017). *Figure 3.6* shows that 84.1 % (6730 ha) of the study area is most suitable.

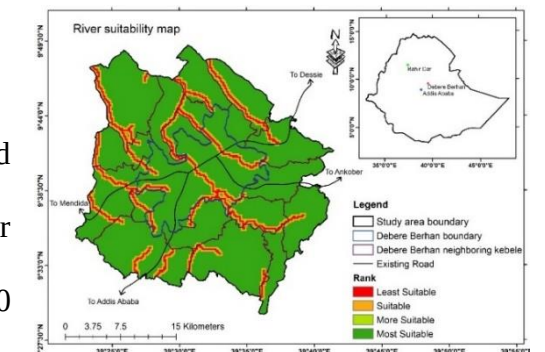


Figure 3.6: River suitability map

vi. Land use/ landcover

Wind farms should be placed in areas with less impact on the existing land. *Figure 3.7* shows that the land types are classified as forest, lakes, buildings, and bare lands and about 83.1 % (6,657 ha) of the study area is bare land and it is considered a the most suitable area.

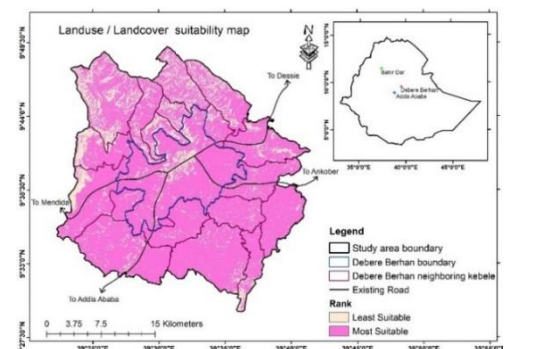


Figure 3.7: LULC suitability map

vii. Distance from dense settlement area

Wind farms have their own negative impact on the local population including visual and noise disturbance because of this it is recommended a setback distance from existing urban areas (Athanasios, 2018). Figure 3.8 show that 89.9% (7,192.3 ha) is the most suitable area.

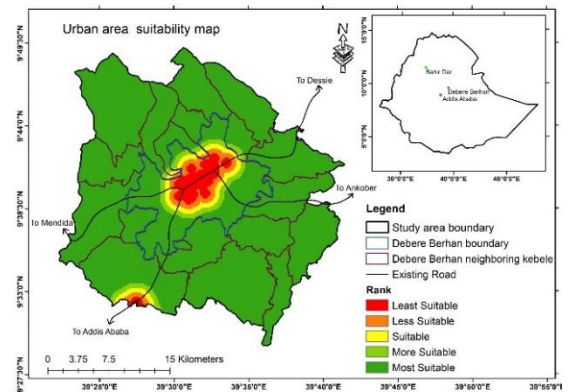


Figure 3.8: Urban area suitability map

viii. Proximity to existing roads

Wind farms must not locate to adjacent to roads and need some distance from the existing transportation networks (Bili & Vagiona, 2018). Figure 3.9 show 89% of the study area is the most suitable area based on road criteria.

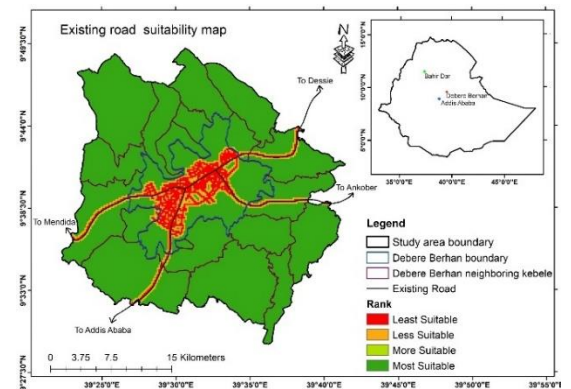


Figure 3.9: road suitability map

4.0 Results

The multi-criteria analysis with eight input layers is analyzed, and the result has shown in Figure 4.1 that 2,507.2 ha (31.4%) of the study areas is found to be the most suitable for harvesting wind energy.

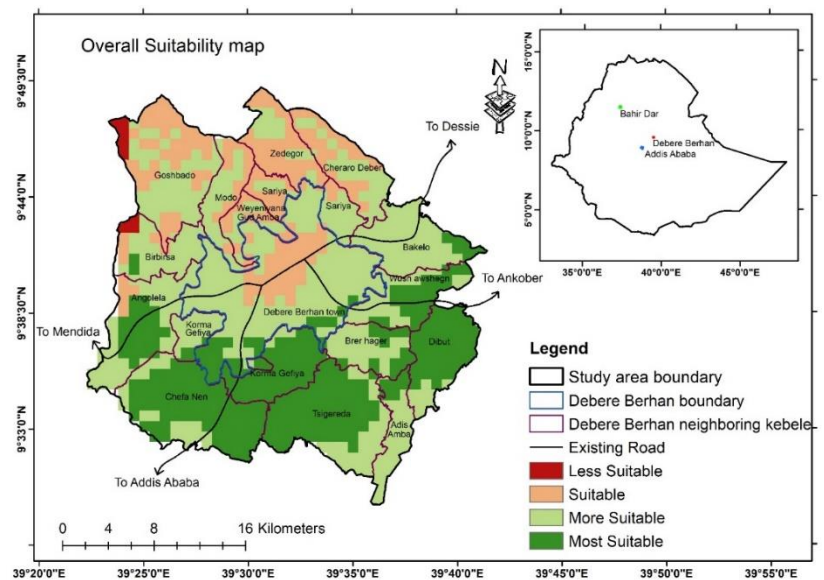


Figure 4.1: Suitability result for wind farm

4.1 Energy generated from the wind farm

The energy generated from the wind farm around Debera Berhan town for the most suitable areas is calculated. The total high potential area of land is 2,507.2 ha (25,072,000 m²).

A single horizontal axis wind turbine (HAWT) with a rotor diameter of 80m generates 1,029,655 kWh energy annually with 6.4m/s wind speed, which equals 2.821 MWh energy generated per day. According to Gupta, (2015), the recommended space for wind turbine spacing, for separating towers within a row is 3 – 5 times rotor diameter and 5 – 9 times between the rows.

Area of single turbine (A_t) = 48,000 m² for 80m rotor diameter.

Number of turbines (N_t) = total land area / A_t = 25,072,000 m² / 48,000m² = 501.5

Energy total = Number of turbines * energy generated from a single turbine

Energy total = 501.5 * 0.12 MW = **60.18 MW** energy generated from the wind farm

5.0 Discussion

The windy areas around Debera Berhan town are identified at 50m, 100m, 150m, and 200m. the result of wind speed in the study area is higher and more than expected. So, for this study wind speed above 5.5 m/s is used as the minimum criteria for wind speed for selecting wind energy potential sites. Because there is high wind speed is present more than expected, this study uses wind speed criteria more than the standard to select the most effective sites for wind energy harvesting. As most of the studies for wind farm site selection use the minimum criteria for wind speed is 3 m/s – 3.5 m/s.

The final result of this study shows that 60.18 MW of energy is estimated from the 2,507.2 ha of land. This shows that in every 41.6 ha of land there is 1MW energy is generated, not only with 80m rotor diameter but also at any size of rotor diameter 1MW energy is generated from 41.6 ha because when the rotor diameter is changed, the number of turbines also changed which results very near or equal energy generated output. In this study 31.4% (2,507.2 ha) of land is most suitable from the total study area, this shows the site has the best potential for wind farm development.

6.0 Conclusion

The present study investigates that wind energy harvesting sites within and around Debre Berhan town, Ethiopia, and 2,507.5 ha of land is identified for wind farm development. The energy generated from the wind farm is 60.18 MW, with an estimated annual production of 527.2 GWh. GIS-based multi-criteria decision-making method is used to select the most suitable locations for the wind farm around Debre Berhan town and the model can be applied for selecting other locations for similar projects. The weight linear combination (WLC) model is used in this study used to determine the weight or importance of each layer or criteria. The WLC is used, to sum up, based on their weight to identify the final suitable location for the wind farm.

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Appendix 2: Mean wind speed within Debere Berhan town at a 50-meter height from 1990 – 2019, Interannual Averages

Location: Latitude: 9°40'35.64"N Longitude: 39°31'58.83"E (NASA, 2020).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1981	5.42	5.59	4.3	3.52	4.77	4.72	3.67	3.81	3.4	4.73	5.32	5.31
1982	4	3.84	4.41	4.19	5.08	4.22	4.01	3.26	3.68	4.78	4.47	4.64
1983	4.72	4.06	4.53	4.18	3.59	3.84	4.03	4.25	3.15	4.44	4.9	5.42
1984	5.51	6.17	5.93	6.51	4.75	3.81	3.69	3.09	3.85	5.43	5.22	5.28
1985	4.95	5.75	5.77	4.09	4	3.79	3.21	3.8	3.91	5.24	5	5.25
1986	5.48	4.74	4.45	3.82	4.6	4.27	3.79	3.72	3.71	5.02	5.01	4.89
1987	5.54	5.01	3.79	3.77	4.46	3.34	3.66	3.51	4.04	5.18	5.37	5.33
1988	5.14	4.45	5.4	4.3	6.41	4.58	4.3	3.34	3.37	4.69	4.82	5.07
1989	5.38	4.92	4.51	3.66	5.03	4.67	4.37	3.35	3.64	5.04	5.3	4.5
1990	4.93	3.53	4.01	4.2	4.96	4.6	3.63	3.35	3.55	5.42	5.31	5.31
1991	5.11	4.42	4.26	5.13	6.55	4.49	3.69	3.06	3.63	5.18	5.11	5.01
1992	4.5	4.07	4.41	4.73	5.29	4.54	3.49	3.31	3.77	5	5.09	5.26
1993	5.07	4.83	5.17	3.8	4	3.71	3.52	3.34	3.52	4.98	5	5.17
1994	5.5	5.66	4.94	5.34	5.51	3.5	3.77	3.09	3.67	5.42	5.5	5.31
1995	5.65	4.39	4.75	4.07	5.69	5.22	3.66	3.51	3.77	5.75	5.36	4
1996	4.21	5.28	4.13	3.88	4.38	3.5	4.13	3.55	3.28	4.72	4.71	4.86
1997	4.87	5.71	4.96	4.67	5.62	4.87	3.48	3.6	4.71	5.29	4.42	4.71
1998	4.45	4.38	4.51	4.46	5.03	5.05	4.24	3.98	3.49	4.15	4.8	5.03
1999	5.06	5.61	4.38	5.61	5.67	4.65	3.9	3.23	3.75	4.39	5.4	5.36
2000	5.31	5.5	5.65	5.45	5.41	4.82	4.33	4.55	4.04	5.46	5.71	5.31
2001	5.29	5.42	4.08	5.42	4.91	4.54	3.85	5.22	4.5	5.7	5.66	5.33
2002	4.92	5.4	4.24	5.47	5.07	4.54	4.13	3.75	4.68	6.31	5.9	5
2003	4.93	5.03	5.2	5.02	6.69	5.11	4.35	4.3	4.18	5.89	5.67	4.98
2004	4.41	5.63	5.24	4.19	6.16	4.63	4.38	4.43	4.37	6.15	5.92	5.23
2005	4.78	5.33	4.84	5	4.33	4.93	5.03	4.02	4.24	5.71	5.48	5.22
2006	5.22	4.76	4.1	4.63	5.8	4.52	3.7	3.96	3.88	5.52	5.21	5.39

2007	5.11	4.49	5.21	4.74	5.07	4.97	3.7	3.32	3.7	5.48	6.02	5.56
2008	5.38	6.12	6.23	6.03	5.76	4.69	4.46	3.53	3.83	5.36	4.7	4.97
2009	4.68	5.03	5.57	5.48	6.61	5.29	4.56	3.7	3.9	4.67	5.19	4.41
2010	5.45	4.1	4.14	4.13	4.44	4.64	4.57	4.48	3.51	5.16	4.63	4.46
2011	4.78	5.91	5.27	4.68	5.1	4.28	4.67	4.04	4.08	6.55	5.6	5.77
2012	5.54	6	5.55	4.97	6.88	5.22	4.47	3.41	3.42	5.63	5.45	5.38
2013	5.55	5.87	5.09	4.39	4.6	4.2	5.36	3.48	3.74	4.58	4.99	4.83
2014	5.05	4.82	5.09	5.32	5.17	5.01	4.04	3.19	3.71	4.9	5.42	5.36
2015	5.52	5.61	5.7	6.59	5.72	4.44	4.07	4.05	4.45	6.07	5.72	5.11
2016	4.38	5.45	4.63	4	4.11	4.35	3.8	3.82	3.63	4.66	5.05	5.65
2017	5.42	5.02	4.69	5.28	4.64	5.09	4.19	3.74	3.86	5.19	5.34	5.31
2018	5.41	4.95	5.05	4.26	5.34	4.45	4.26	3.79	4.58	5.39	4.9	5.14
2019	5.79	5.21	4.59	4.02	5.18	4.81	4.04	3.55	3.35	5.04	5.31	4.86

Appendix 3: Mean wind speed within Debere Berhan town at a 10-meter height from 1990 – 2019, Interannual Averages

Location: Latitude: 9°40'35.64"N Longitude: 39°31'58.83"E (NASA, 2020).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1982	3.5	3.6	3.99	3.72	4.66	3.7	3.37	2.75	3.33	4.15	3.96	4.04
1983	4.14	3.57	3.78	3.52	3.29	3.36	3.22	3.2	2.99	3.91	4.25	4.76
1984	5.01	5.76	5.08	5.8	4.27	3.19	2.98	2.89	3.56	4.81	4.43	4.75
1985	4.51	5.17	5.04	3.76	3.69	3.53	2.93	2.92	3.61	4.67	4.06	4.52
1986	4.83	4.09	4.03	3.24	4.18	3.63	3.29	3.02	3.45	4.54	4.5	4.4
1987	4.89	4.3	3.42	3.51	4.04	3.01	2.97	3.05	3.72	4.6	4.64	4.67
1988	4.71	3.8	4.7	3.81	5.85	4.25	3.43	2.92	3.09	4.18	4.31	4.58
1989	4.88	4.46	3.91	3.28	4.63	4.28	3.33	2.93	3.33	4.43	4.67	3.8
1990	4.38	3.3	3.79	3.72	4.51	4.28	3.1	2.84	3.27	4.85	4.47	4.82
1991	4.59	4.04	3.89	4.66	5.83	3.97	3.1	2.74	3.33	4.7	4.35	4.57
1992	4.04	3.6	3.81	4.23	4.84	4.04	2.84	2.7	3.46	4.48	4.45	4.7
1993	4.55	4.32	4.6	3.48	3.6	3.35	2.86	2.91	3.18	4.43	4.5	4.53
1994	4.82	5.08	4.31	4.8	5.08	3.18	3.07	2.63	3.33	4.93	4.94	4.96
1995	5.07	3.99	4.07	3.71	5.13	4.69	3.04	3.03	3.46	5.2	4.72	3.56
1996	3.73	4.52	3.75	3.57	3.94	2.86	3.07	3.03	3.05	4.28	4.17	4.17
1997	4.06	5.11	4.31	4.3	5.18	4.24	3.02	3.12	4.26	4.56	4.05	4.38
1998	4.1	3.72	3.97	3.71	4.6	4.46	3.13	3.09	3.03	3.69	4.45	4.62
1999	4.38	5.07	3.93	5.1	5.14	4.1	3.03	2.81	3.37	4	4.91	4.67
2000	4.84	5.04	5.15	4.92	4.96	4.4	3.46	3.74	3.5	4.9	5.03	4.59
2001	4.61	4.75	3.62	4.87	4.39	3.81	2.87	4	4.08	5.14	5.13	4.67
2002	4.6	4.75	3.75	4.92	4.42	4.15	3.46	3.2	4.19	5.63	5.15	4.39
2003	4.44	4.71	4.7	4.32	6.04	4.48	3.45	3.61	3.64	5.31	5.06	4.63
2004	3.98	5	4.69	3.81	5.58	4.02	3.59	3.58	4.06	5.52	5.36	4.68
2005	4.28	4.81	4.44	4.22	3.84	4.45	3.87	3.49	3.86	5.04	5.02	4.89
2006	4.76	4.38	3.79	4.08	5.32	3.96	3.18	3.16	3.39	4.91	4.59	4.94
2007	4.51	4.18	4.74	4.23	4.65	4.12	2.95	2.84	3.18	5.03	5.41	5.21

2008	4.84	5.51	5.45	5.45	5.32	4.25	3.7	2.85	3.43	4.87	4.31	4.45
2009	4.26	4.56	4.88	4.99	6.01	4.92	3.59	3.17	3.58	4.27	4.64	3.77
2010	4.69	3.4	3.78	3.75	3.9	3.98	3.56	3.21	3.27	4.73	4.15	3.81
2011	4.14	5.25	4.63	4.39	4.63	3.87	3.7	3.39	3.55	5.93	5.05	5.35
2012	5.09	5.64	5	4.4	6.22	4.62	3.43	2.66	3.03	5.06	4.77	4.75
2013	4.95	5.28	4.14	4.05	4.21	3.63	3.86	2.85	3.31	4.11	4.59	4.14
2014	4.41	3.93	4.49	4.75	4.76	4.44	3.37	2.85	3.3	4.51	4.89	4.57
2015	5.11	4.96	5.14	6.06	5.28	4.03	3.33	3.45	4.02	5.49	5.27	4.69
2016	3.84	4.85	4.26	3.52	3.85	3.84	3.1	3.16	3.3	4.24	4.51	5.28
2017	5.08	4.6	4.05	4.94	4.32	4.72	3.44	3.13	3.57	4.73	4.88	4.7
2018	4.71	4.48	4.42	3.93	4.97	3.95	3.33	2.93	4.2	4.96	4.45	4.83
2019	5.33	4.63	4.2	3.75	4.82	4.47	3.52	2.75	2.99	4.65	4.87	4.3

Appendix 4: Mean wind speed around Debere Berhan town at a 10-meter height from 1990 – 2019, Interannual Averages

Location: Latitude: 9°40'35.64"N Longitude: 39°31'58.83"E (NASA, 2020).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1990	4.4	3.22	3.85	3.93	4.57	3.71	3.38	3.24	3.4	5.06	4.65	4.94
1991	4.51	4.29	4.17	4.81	5.97	4.02	3.58	2.74	3.38	4.94	4.44	4.55
1992	4.09	3.39	3.94	4.45	4.78	3.99	3.43	3.3	3.41	4.62	4.64	4.91
1993	4.56	4.32	4.68	3.84	3.66	3.42	3.2	3.14	3.33	4.58	4.73	4.59
1994	4.82	5.16	4.39	4.94	5	2.97	3.59	3.18	3.46	5.41	5.22	5.18
1995	5.23	4.02	4.47	3.97	5.35	4.61	3.69	3.52	3.58	5.44	4.82	3.83
1996	3.98	4.82	3.72	3.81	3.82	2.94	3.51	3.14	2.92	4.5	4.53	4.27
1997	4.22	5.15	4.58	4.19	4.73	3.97	3.07	3.12	4.4	4.31	3.74	4.11
1998	4.06	3.65	4.09	3.96	4.52	4.28	3.65	4.03	3.35	3.69	4.65	4.68
1999	4.44	5.04	4.1	5.4	5.18	4.13	3.52	3.01	3.56	3.86	5.09	4.82
2000	4.79	5.08	5.29	4.91	4.72	4.2	3.99	4.53	3.66	4.91	5.19	4.61
2001	4.84	4.75	3.52	4.85	4.32	3.7	3.46	5.04	4.18	5.26	5.08	4.59
2002	4.91	4.79	3.74	5.08	4.61	3.86	3.89	3.62	4.31	5.87	5.33	4.56
2003	4.52	4.67	4.56	4.43	6.16	4.46	3.89	4.02	4.01	5.56	5.15	4.82
2004	4.1	5.17	4.9	3.72	5.68	4.25	4.09	4.03	4.29	5.65	5.45	4.81
2005	4.51	4.95	4.49	4.55	3.76	4.45	4.24	3.89	3.96	5.25	5.07	4.87
2006	4.69	4.5	3.74	4.02	5.05	3.92	3.61	3.89	3.97	5.32	4.67	4.88
2007	4.56	4.21	4.85	4.27	4.51	4.03	3.57	3.11	3.32	5.22	5.52	5.29
2008	4.84	5.83	5.76	5.64	5.06	4.05	4.01	3.23	3.53	5.11	4.27	4.48
2009	4.28	4.63	5.01	4.98	5.97	4.85	4.28	3.7	3.77	4.32	4.73	3.8
2010	4.68	3.54	3.75	3.65	3.75	3.81	4.13	4.01	3.3	5.12	4.46	4.1
2011	4.25	5.37	4.8	4.53	4.62	3.65	4.2	3.63	3.73	6.24	5.26	5.56
2012	5.27	5.78	5.33	4.49	6.14	4.6	3.87	3.13	3.23	5.37	5.04	4.92
2013	5.16	5.43	4.32	4.11	4.22	3.46	4.35	3.24	3.57	4.58	4.69	4.31
2014	4.59	4.11	4.7	4.86	4.61	4.46	3.7	3.14	3.67	4.7	5.23	4.73
2015	5.24	5.14	5.37	6.42	5.42	3.97	3.5	3.83	3.99	5.71	5.4	4.81

2016	3.94	4.98	4.52	3.7	3.81	4.15	3.8	3.53	3.59	4.63	4.85	5.25
2017	5.14	4.57	4.21	5.2	4.46	4.5	3.68	3.69	3.62	4.85	5.06	4.8
2018	4.79	4.63	4.81	3.91	4.83	3.96	3.92	3.37	4.31	5.22	4.56	5.11
2019	5.36	4.75	4.25	3.98	4.98	4.04	3.38	3.19	3.16	4.94	5.17	4.54

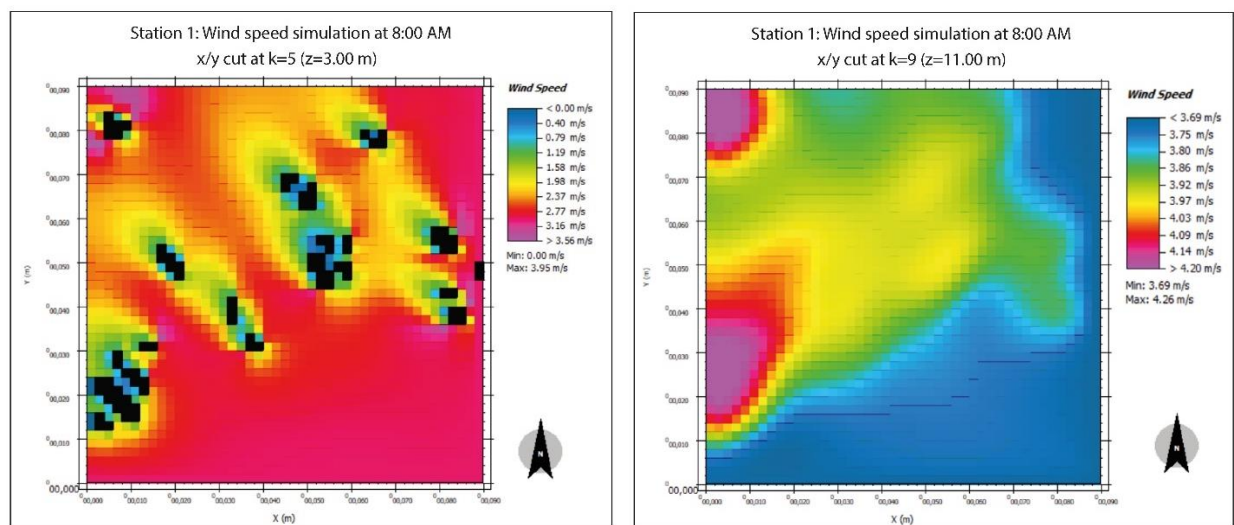
Appendix 5: Mean wind speed around Debere Berhan town at a 50-meter height from 1990 – 2019, Interannual Averages

Location: Latitude: 9°40'35.64"N Longitude: 39°31'58.83"E (NASA, 2020).

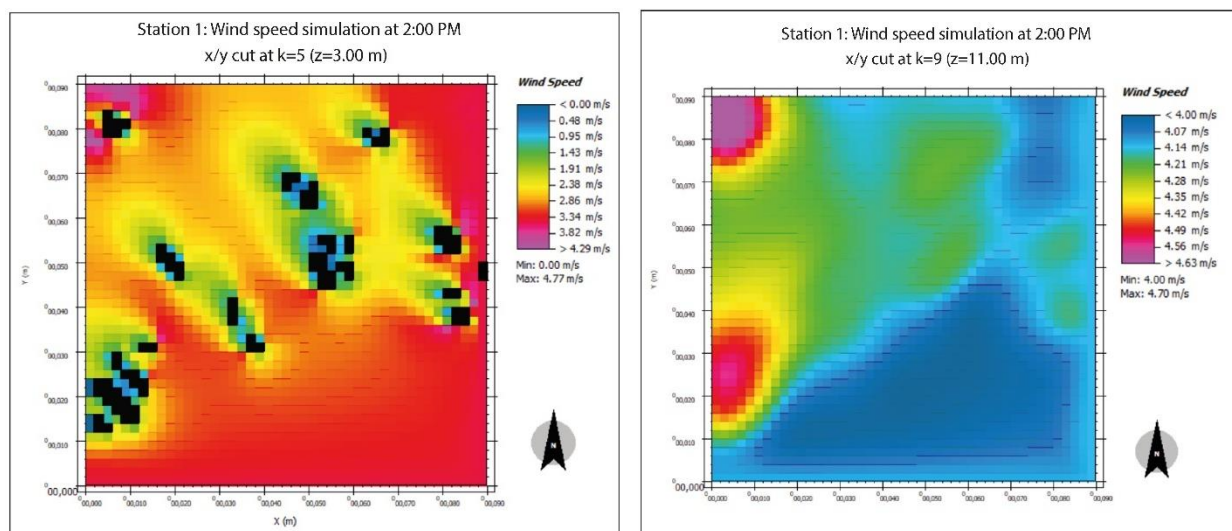
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1990	5.34	4.1	4.98	4.34	5.42	4.27	3.64	3.58	4.01	6.32	5.22	5.74
1991	5.51	4.84	4.91	6.75	7.94	4.93	3.67	3.39	4.3	5.8	4.91	5.32
1992	4.82	4.23	5.19	5.26	5.99	4.38	3.54	3.83	4.28	5.35	5.51	5.65
1993	5.37	5.21	5.8	4.43	4.75	3.88	3.77	3.61	3.92	5.77	5.41	5.5
1994	5.42	5.44	4.91	5.83	6.5	3.6	3.78	3.18	4.3	6.46	5.67	5.92
1995	5.73	4.88	5.42	4.71	6.25	5.43	3.85	3.61	4.25	6.39	5.18	4.79
1996	4.72	5.34	5.11	4.7	5.11	3.75	4.01	3.76	3.98	5.39	5.19	4.84
1997	4.6	6.13	5.28	5.17	6.25	5.41	3.35	3.82	5.17	5.81	5.38	5.48
1998	5.09	4.53	5.06	4.8	5.25	5.14	4.22	4.23	3.87	4.79	5.29	5.24
1999	4.9	6.11	4.77	6.18	6.21	4.61	3.79	3.24	4.14	4.73	5.9	5.21
2000	5.53	5.73	6.07	6.1	5.76	4.42	4.25	4.72	3.98	5.43	5.86	5.2
2001	4.51	5.45	4.21	6.13	5.08	4.17	3.91	5.33	4.6	5.86	5.86	5.59
2002	5.19	5.48	4.64	6.57	5.04	4.59	4.23	3.75	4.87	6.71	5.98	5.03
2003	4.99	5.46	5.75	5.28	7.18	4.84	4.49	4.52	4.09	6.18	6.06	5.65
2004	4.66	5.5	5.24	4.69	6.57	4.22	4.32	4.12	4.59	6.7	6.29	5.33
2005	4.98	5.85	5.37	5.28	4.96	5.08	4.69	4	4.59	5.76	5.9	5.82
2006	5.56	5.33	4.46	4.84	6.39	4.58	3.6	3.89	4.15	5.61	5.48	5.6
2007	5.1	4.88	5.7	5.51	5.51	4.97	3.55	3.19	3.79	6.42	6.63	6.05
2008	5.78	6.19	6.2	7.05	6.42	4.65	4.12	3.37	4.35	5.68	5.04	4.9
2009	4.7	5.48	5.77	6.14	7.18	5.83	4.14	3.57	4.61	5.09	5.51	4.35
2010	5.14	3.94	4.93	4.65	4.56	4.61	4.58	4.27	4	5.94	4.88	4.22
2011	4.63	5.97	5.44	5.58	5.49	4.2	4.45	3.99	4.28	6.66	5.26	5.91
2012	5.85	6.7	5.76	4.93	7.37	5.14	4.03	3.37	4.08	6.27	5.22	5.25
2013	5.37	6.18	4.93	4.83	5.15	4.11	4.64	3.81	4.41	5.03	5.26	4.48
2014	4.66	4.2	5.65	6.33	6.15	5.32	4.06	3.35	4.14	5.66	5.74	5.09
2015	5.53	5.67	6.28	6.82	6.18	4.88	3.97	3.73	4.92	6.62	6.22	5.17

2016	4.35	5.57	5.46	4.49	5.13	4.74	3.93	4.06	4.35	5.44	5.55	6.5
2017	5.88	5.59	5.16	6.36	5.43	5.83	4.26	3.81	4.66	5.98	5.45	5.23
2018	5.08	5.15	5.28	4.55	5.92	4.66	3.84	3.53	5.54	6.15	5.83	5.57
2019	6.46	5.71	5.09	4.82	5.95	5.29	3.87	3.54	3.63	6.29	5.81	4.95

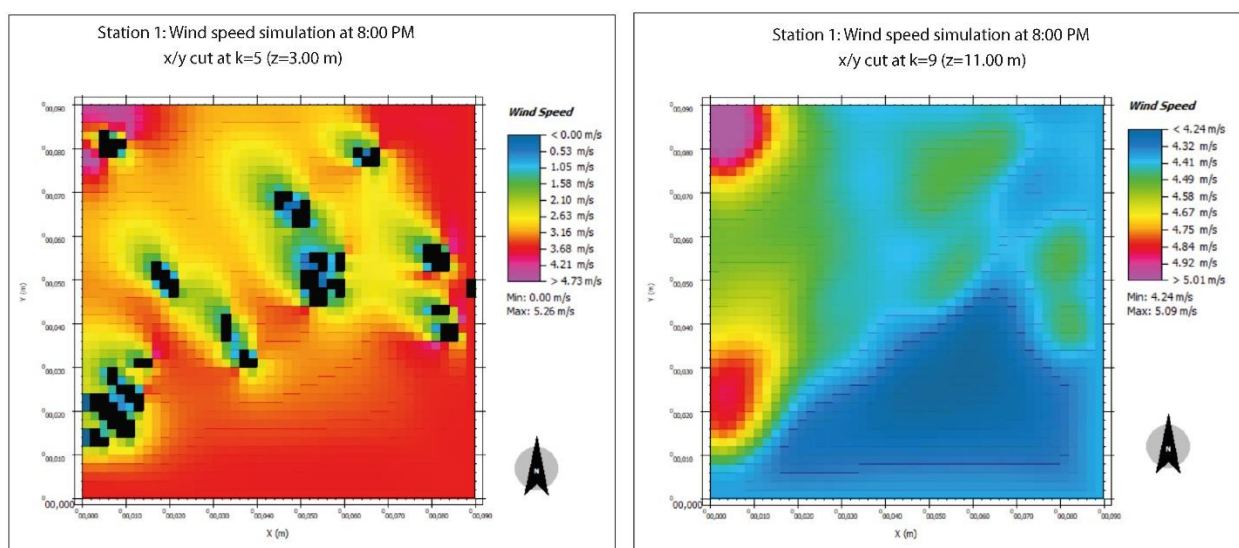
Appendix 6: Wind speed simulation at 9°36'20.65"N lat. and 39°28'51.68"E longitude (St. 1)



Wind speed simulation at 8:00 AM at 3m and 11m height respectively (Station 1)



Wind speed simulation at 2:00 PM at 3m and 11m height respectively (Station 1)

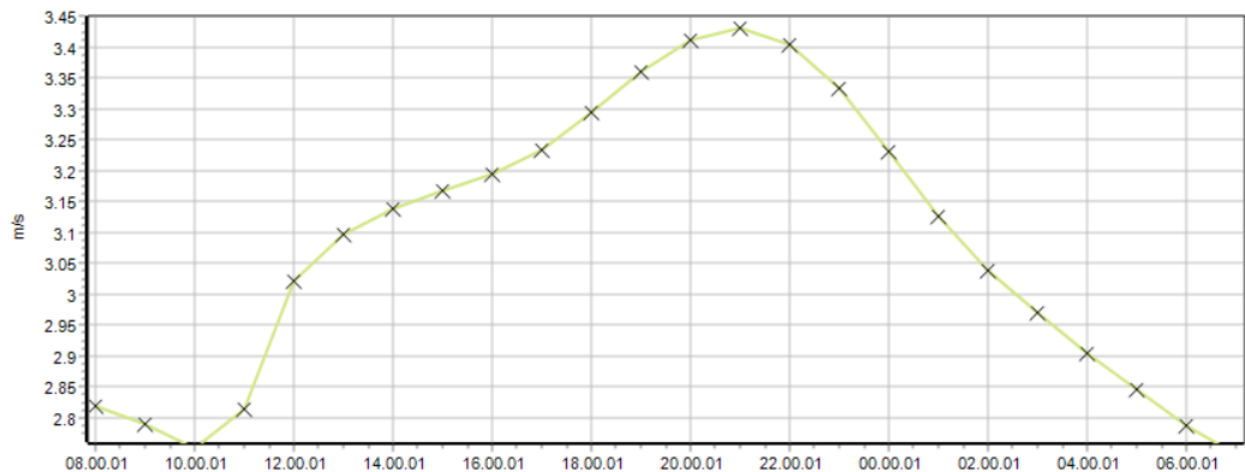


Wind speed simulation at 8:00 PM at 3m and 11m height respectively (Station 1)

Appendix 7: ENVI-met simulation output wind speed data and graph at 9°36'20.65"N latitude
and 39°28'51.68"E longitude at 3m height (station 1)

Date	Time	Wind Speed (m/s)	Relative Humidity (%)
23.06.2018	08.00.01	2.7323	71.988
23.06.2018	09.00.01	2.7132	69.924
23.06.2018	10.00.01	2.6867	67.625
23.06.2018	11.00.01	2.7317	63.851
23.06.2018	12.00.01	2.8999	60.57
23.06.2018	13.00.01	2.971	56.917
23.06.2018	14.00.01	3.0188	53.338
23.06.2018	15.00.01	3.0572	50.506
23.06.2018	16.00.01	3.0923	48.385
23.06.2018	17.00.01	3.1336	49.609
23.06.2018	18.00.01	3.1886	51.737
23.06.2018	19.00.01	3.2493	54.239
23.06.2018	20.00.01	3.3014	56.772
23.06.2018	21.00.01	3.3303	58.589
23.06.2018	22.00.01	3.3258	60.129
23.06.2018	23.00.01	3.2867	61.625
24.06.2018	00.00.01	3.2201	62.848
24.06.2018	01.00.01	3.1466	64.189
24.06.2018	02.00.01	3.0833	65.665
24.06.2018	03.00.01	3.0319	67.143
24.06.2018	04.00.01	2.9831	68.645
24.06.2018	05.00.01	2.9403	70.152
24.06.2018	06.00.01	2.8976	70.735
24.06.2018	06.59.59	2.8638	68.117

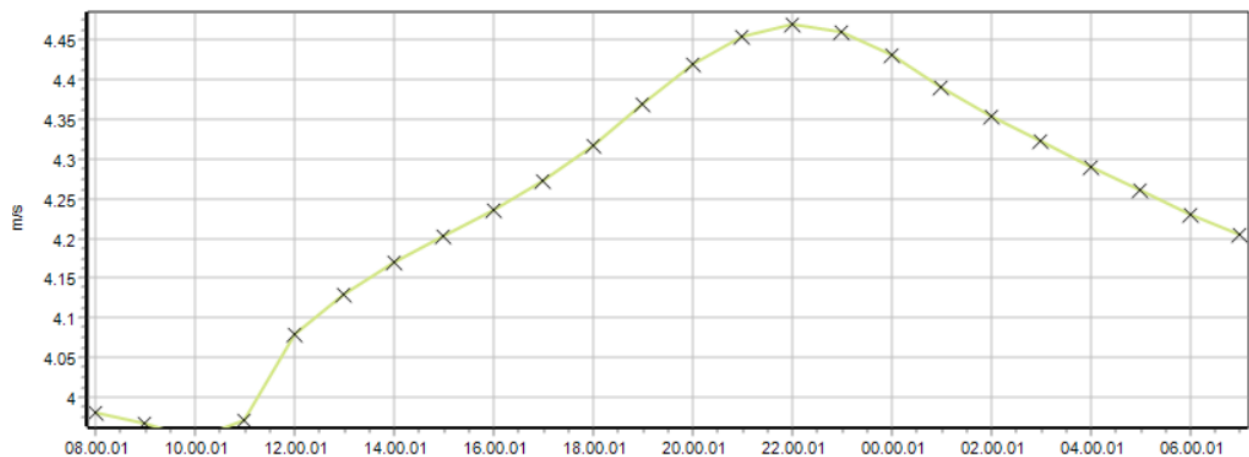
Graph of wind speed output from ENVI-met simulation at 3m height (Station 1)



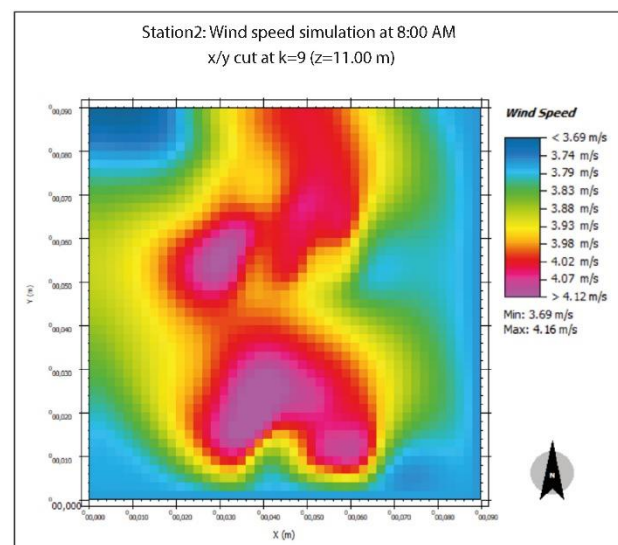
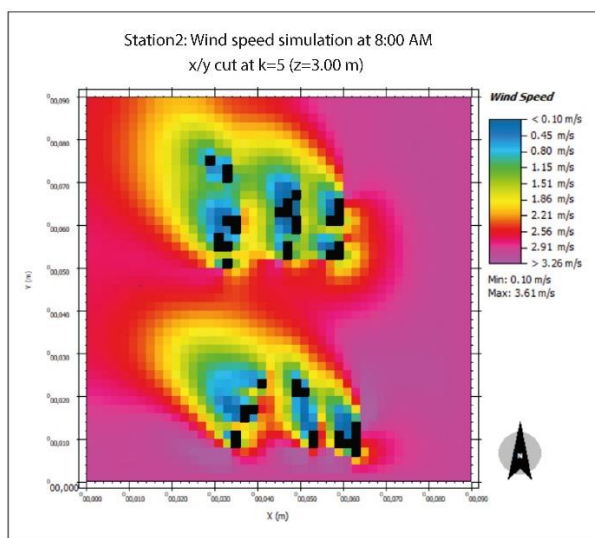
Appendix 8: ENVI-met simulation output wind speed data and graph at 9°36'20.65"N latitude
and 39°28'51.68"E longitude 11m height (station 1)

Date	Time	Wind Speed (m/s)	Relative Humidity (%)
23.06.2018	08.00.01	4.0145	67.353
23.06.2018	09.00.01	3.9982	66.003
23.06.2018	10.00.01	3.9775	64.618
23.06.2018	11.00.01	4.0072	62.224
23.06.2018	12.00.01	4.1198	60.365
23.06.2018	13.00.01	4.172	58.323
23.06.2018	14.00.01	4.2102	56.201
23.06.2018	15.00.01	4.2435	54.15
23.06.2018	16.00.01	4.2754	52.031
23.06.2018	17.00.01	4.3124	52.58
23.06.2018	18.00.01	4.3612	53.662
23.06.2018	19.00.01	4.4162	54.906
23.06.2018	20.00.01	4.4674	56.175
23.06.2018	21.00.01	4.5036	57.372
23.06.2018	22.00.01	4.5176	58.555
23.06.2018	23.00.01	4.5067	59.757
24.06.2018	00.00.01	4.4742	60.967
24.06.2018	01.00.01	4.4339	62.198
24.06.2018	02.00.01	4.3969	63.465
24.06.2018	03.00.01	4.3651	64.729
24.06.2018	04.00.01	4.3328	66.023
24.06.2018	05.00.01	4.3029	67.328
24.06.2018	06.00.01	4.2714	68.586
24.06.2018	06.59.59	4.2458	67.444

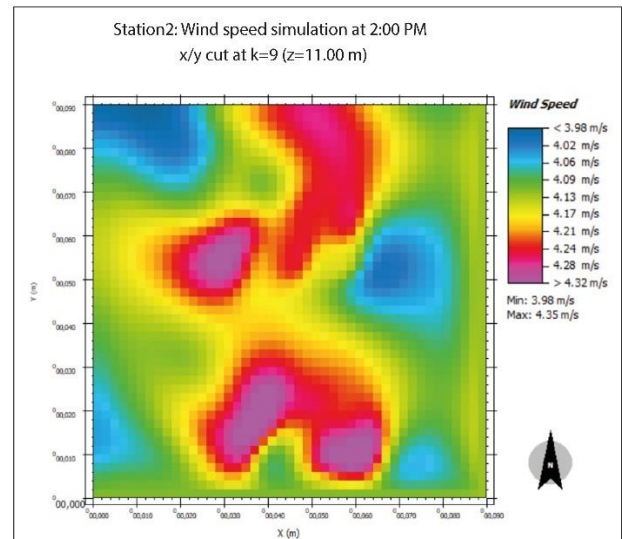
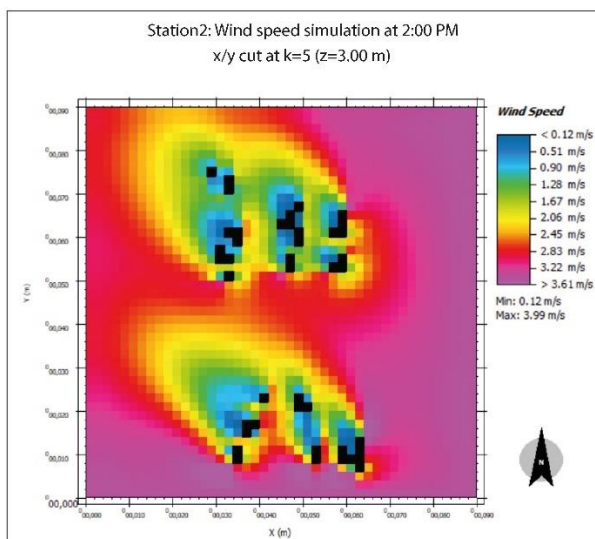
Graph of wind speed output from ENVI-met simulation at 11 m height (Station 1)



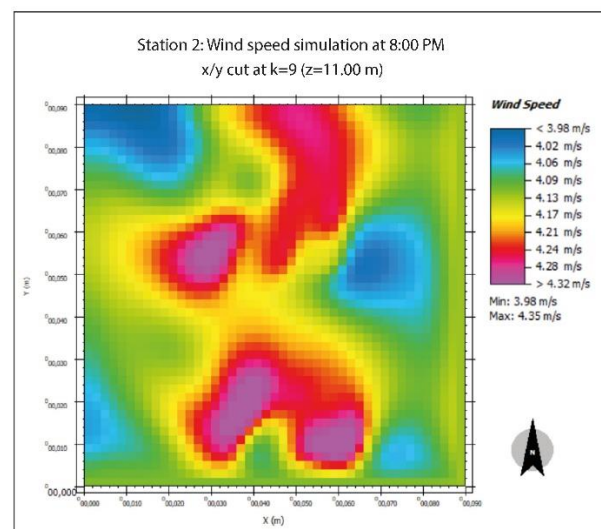
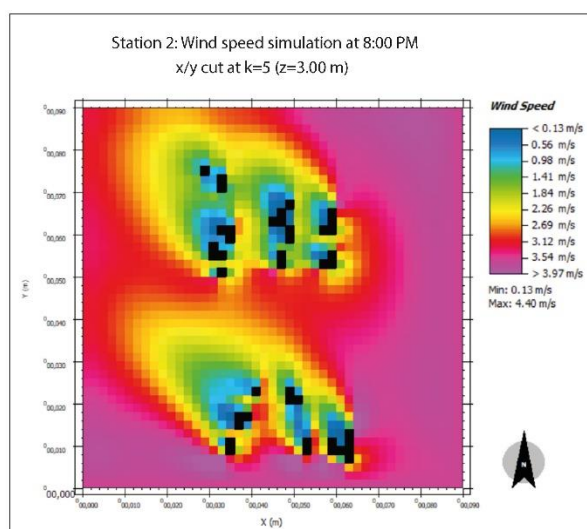
Appendix 9: Wind speed simulation at 9°38'41.99"N lat. and 39°34'31.93"E longitude (St. 2)



Wind speed simulation at 8:00 AM at 3m and 11m height respectively (Station 2)



Wind speed simulation at 2:00 PM at 3m and 11m height respectively (Station 2)

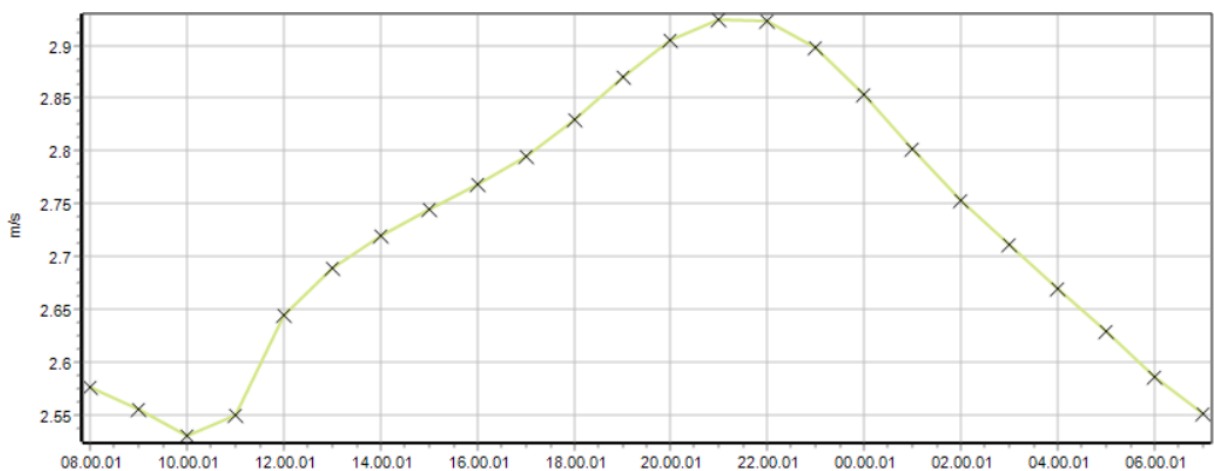


Wind speed simulation at 8:00 PM at 3m and 11m height respectively (Station 2)

Appendix 10: ENVI-met simulation output wind speed data and graph at 9°38'41.99"N latitude
and 39°34'31.93"E longitude at 3m height (station 2)

Date	Time	Wind Speed (m/s)	Relative Humidity (%)
23.06.2018	08.00.01	2.5772	71.575
23.06.2018	09.00.01	2.5562	69.511
23.06.2018	10.00.01	2.5308	67.304
23.06.2018	11.00.01	2.5497	63.678
23.06.2018	12.00.01	2.6447	60.558
23.06.2018	13.00.01	2.6897	57.11
23.06.2018	14.00.01	2.7204	53.69
23.06.2018	15.00.01	2.7455	50.912
23.06.2018	16.00.01	2.7685	48.676
23.06.2018	17.00.01	2.7948	49.905
23.06.2018	18.00.01	2.8302	51.952
23.06.2018	19.00.01	2.87	54.362
23.06.2018	20.00.01	2.9049	56.726
23.06.2018	21.00.01	2.9244	58.497
23.06.2018	22.00.01	2.9225	60.042
23.06.2018	23.00.01	2.8975	61.533
24.06.2018	00.00.01	2.8529	62.789
24.06.2018	01.00.01	2.8014	64.177
24.06.2018	02.00.01	2.7537	65.664
24.06.2018	03.00.01	2.7117	67.154
24.06.2018	04.00.01	2.6699	68.663
24.06.2018	05.00.01	2.6302	70.18
24.06.2018	06.00.01	2.5868	70.826
24.06.2018	06.59.59	2.5513	68.304

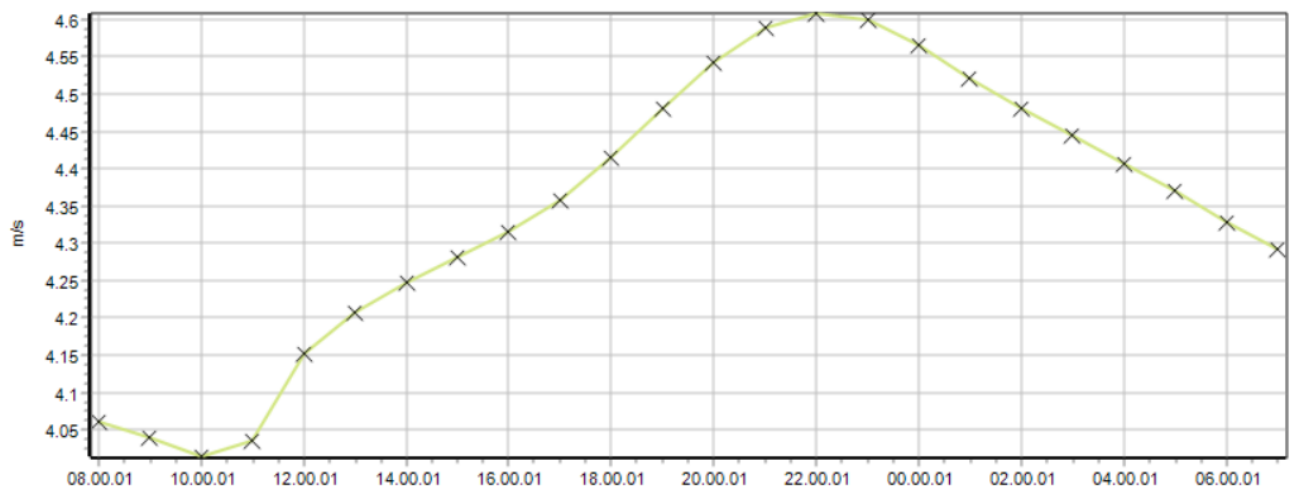
Graph of wind speed output from ENVI-met simulation at 3m height (Station 2)



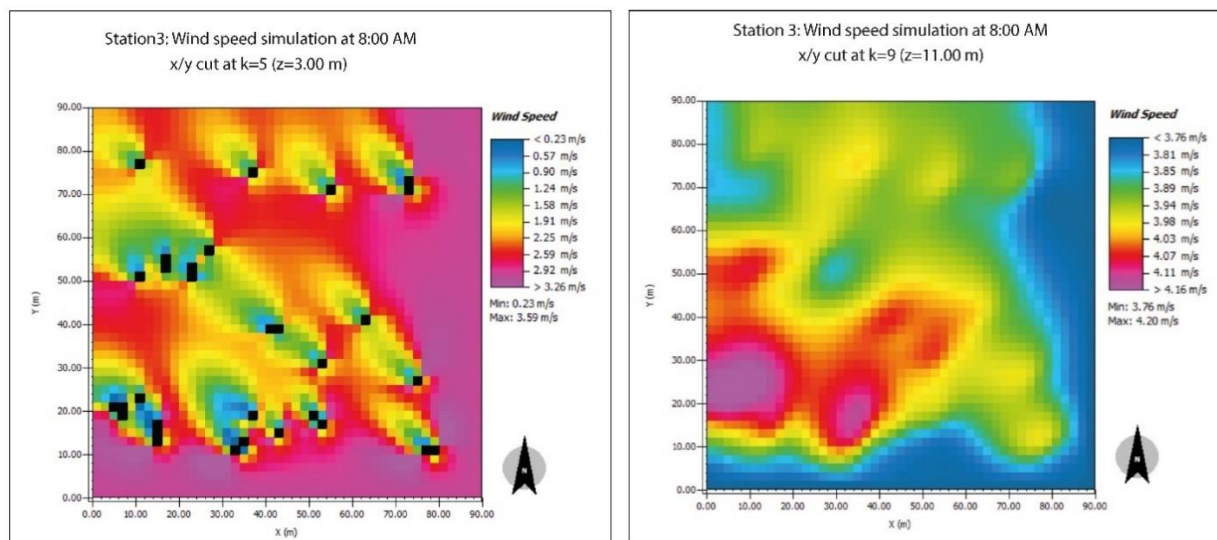
Appendix 11: ENVI-met simulation output wind speed data and graph at 9°38'41.99"N latitude
and 39°34'31.93"E longitude at 11 m height (station 2)

Date	Time	Wind Speed (m/s)	Relative Humidity (%)
23.06.2018	08.00.01	4.0605	67.854
23.06.2018	09.00.01	4.0404	66.445
23.06.2018	10.00.01	4.0143	65.015
23.06.2018	11.00.01	4.0364	62.476
23.06.2018	12.00.01	4.1511	60.463
23.06.2018	13.00.01	4.2071	58.289
23.06.2018	14.00.01	4.2474	56.017
23.06.2018	15.00.01	4.2823	53.87
23.06.2018	16.00.01	4.3161	51.761
23.06.2018	17.00.01	4.3583	52.337
23.06.2018	18.00.01	4.4155	53.507
23.06.2018	19.00.01	4.4809	54.873
23.06.2018	20.00.01	4.5428	56.251
23.06.2018	21.00.01	4.5884	57.503
23.06.2018	22.00.01	4.6081	58.735
23.06.2018	23.00.01	4.5989	59.985
24.06.2018	00.00.01	4.5651	61.224
24.06.2018	01.00.01	4.5216	62.503
24.06.2018	02.00.01	4.4808	63.827
24.06.2018	03.00.01	4.4447	65.149
24.06.2018	04.00.01	4.4071	66.503
24.06.2018	05.00.01	4.3706	67.867
24.06.2018	06.00.01	4.3286	69.073
24.06.2018	06.59.59	4.2929	67.683

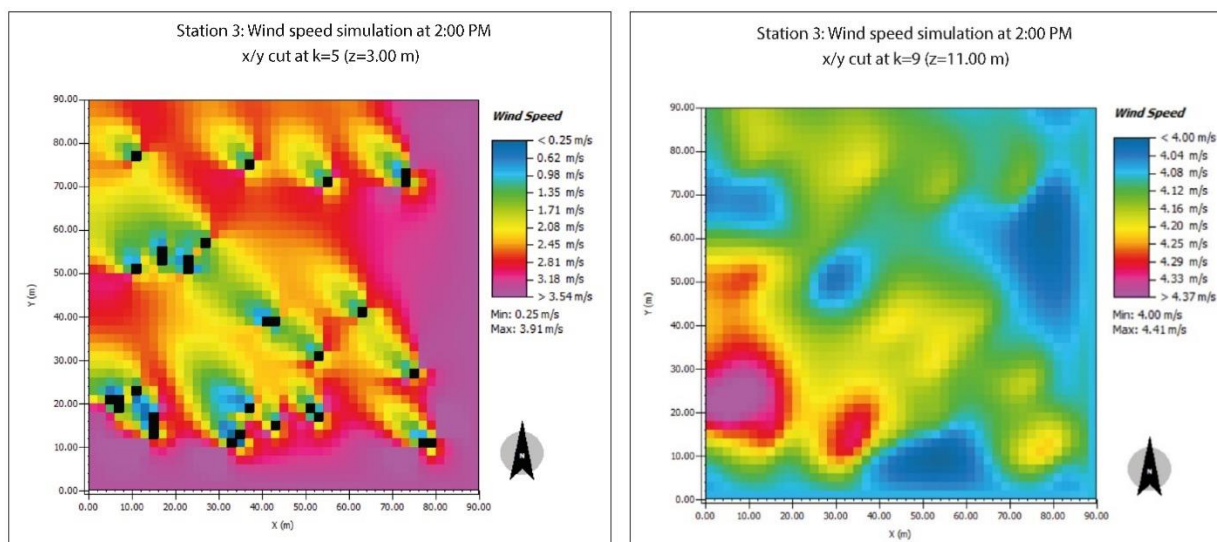
Graph of wind speed output from ENVI-met simulation at 11 m height (Station 2)



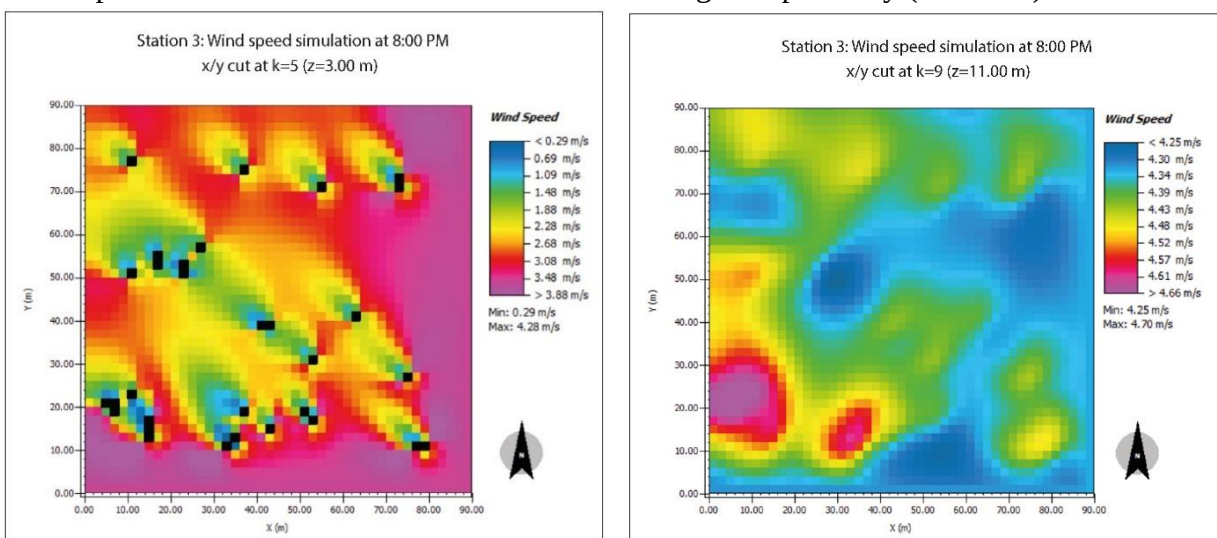
Appendix 12: Wind speed simulation at 9°38'53.46"N lat. and 39°30'26.45"E longitude (St. 3)



Wind speed simulation at 8:00 AM at 3m and 11m height respectively (Station 3)



Wind speed simulation at 2:00 PM at 3m and 11m height respectively (Station 3)

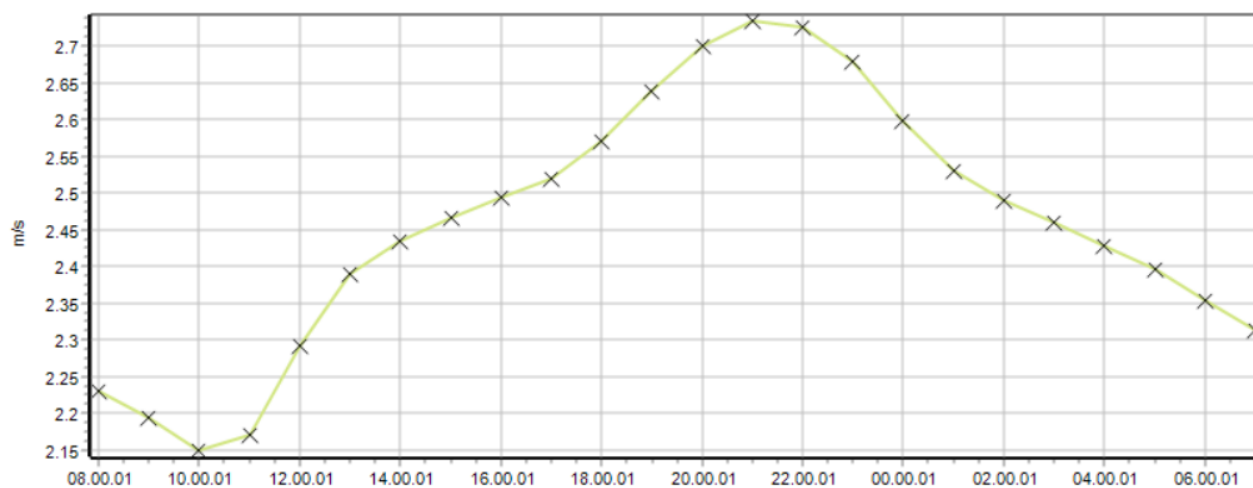


Wind speed simulation at 8:00 PM at 3m and 11m height respectively (Station 3)

Appendix 13: ENVI-met simulation output wind speed data and graph at 9°38'53.46"N latitude
and 39°30'26.45"E longitude at 3m height (station 3)

Date	Time	Wind Speed (m/s)	Relative Humidity (%)
23.06.2018	08.00.01	2.4158	72.076
23.06.2018	09.00.01	2.3938	70.137
23.06.2018	10.00.01	2.3641	67.92
23.06.2018	11.00.01	2.383	64.244
23.06.2018	12.00.01	2.4806	60.954
23.06.2018	13.00.01	2.5576	57.384
23.06.2018	14.00.01	2.5925	53.826
23.06.2018	15.00.01	2.616	50.951
23.06.2018	16.00.01	2.6339	48.754
23.06.2018	17.00.01	2.6522	49.758
23.06.2018	18.00.01	2.6909	51.825
23.06.2018	19.00.01	2.7453	54.374
23.06.2018	20.00.01	2.7958	56.959
23.06.2018	21.00.01	2.8246	58.761
23.06.2018	22.00.01	2.8211	60.292
23.06.2018	23.00.01	2.7845	61.757
24.06.2018	00.00.01	2.722	62.917
24.06.2018	01.00.01	2.6669	64.244
24.06.2018	02.00.01	2.6343	65.68
24.06.2018	03.00.01	2.6097	67.123
24.06.2018	04.00.01	2.5868	68.599
24.06.2018	05.00.01	2.5624	70.08
24.06.2018	06.00.01	2.53	70.482
24.06.2018	06.59.59	2.499	67.987

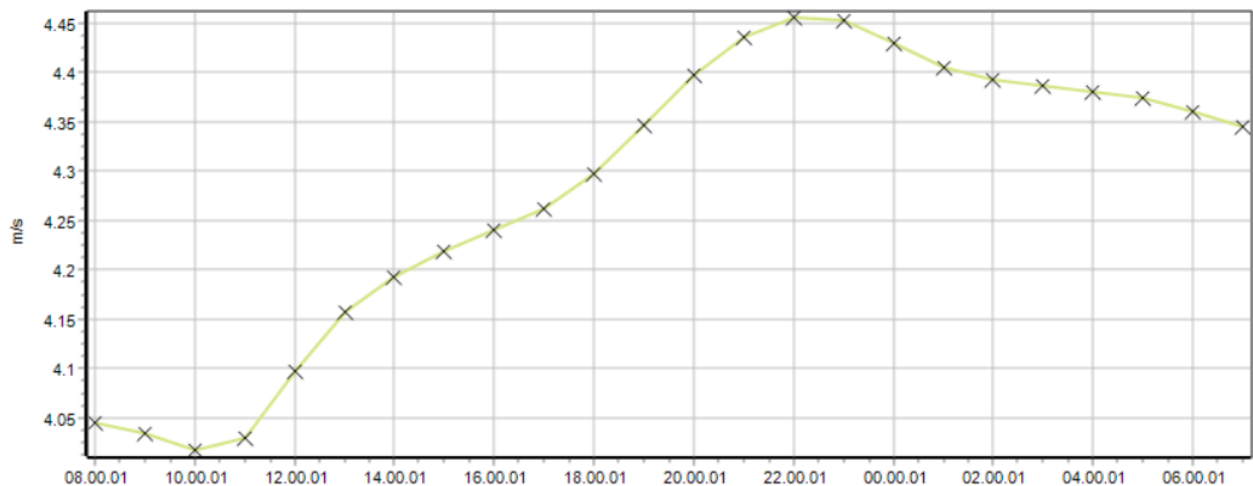
Graph of wind speed output from ENVI-met simulation at 3m height (Station 3)



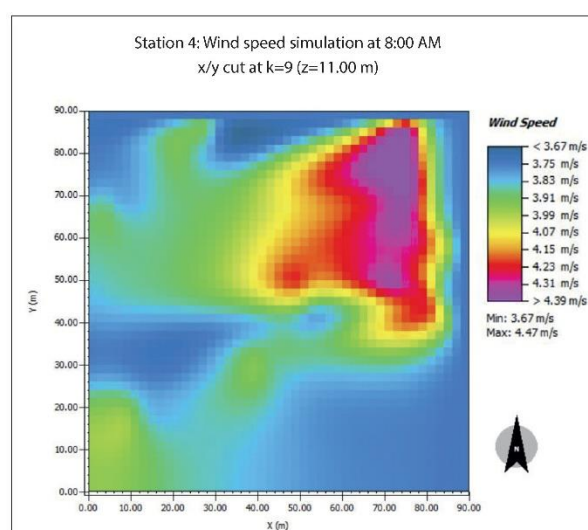
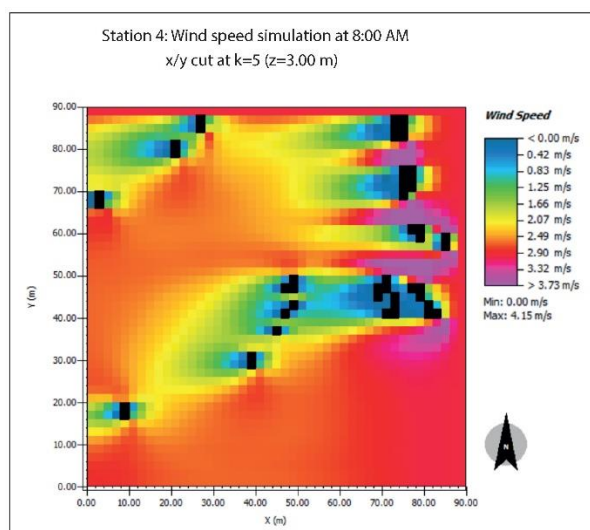
Appendix 14: ENVI-met simulation output wind speed data and graph at 9°38'53.46"N latitude
and 39°30'26.45"E longitude at 11 m height (station 3)

Date	Time	Wind Speed (m/s)	Relative Humidity (%)
23.06.2018	08.00.01	4.0455	67.338
23.06.2018	09.00.01	4.034	66.027
23.06.2018	10.00.01	4.0171	64.674
23.06.2018	11.00.01	4.029	62.253
23.06.2018	12.00.01	4.0965	60.406
23.06.2018	13.00.01	4.1578	58.41
23.06.2018	14.00.01	4.1923	56.304
23.06.2018	15.00.01	4.2186	54.241
23.06.2018	16.00.01	4.2407	52.074
23.06.2018	17.00.01	4.2622	52.587
23.06.2018	18.00.01	4.2973	53.662
23.06.2018	19.00.01	4.3461	54.903
23.06.2018	20.00.01	4.3967	56.169
23.06.2018	21.00.01	4.4363	57.37
23.06.2018	22.00.01	4.4558	58.558
23.06.2018	23.00.01	4.4527	59.762
24.06.2018	00.00.01	4.4295	60.98
24.06.2018	01.00.01	4.4053	62.211
24.06.2018	02.00.01	4.3932	63.467
24.06.2018	03.00.01	4.3864	64.731
24.06.2018	04.00.01	4.3807	66.039
24.06.2018	05.00.01	4.3736	67.356
24.06.2018	06.00.01	4.3607	68.641
24.06.2018	06.59.59	4.3456	67.5

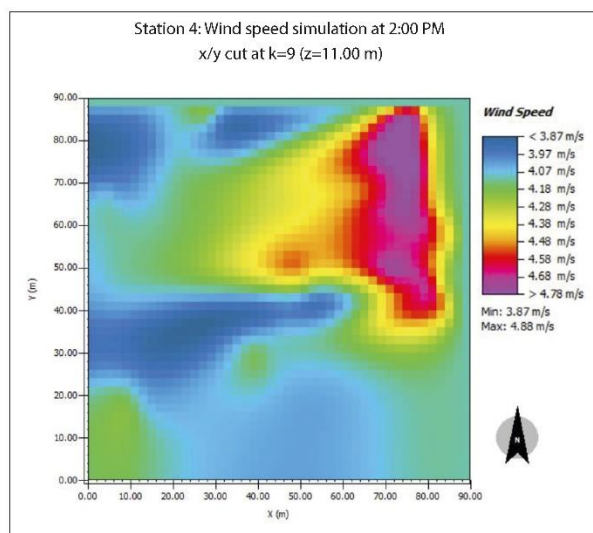
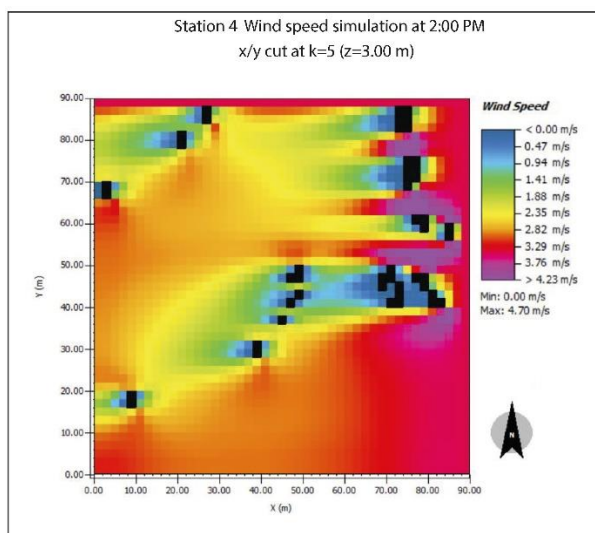
Graph of wind speed output from ENVI-met simulation at 11 m height (Station 3)



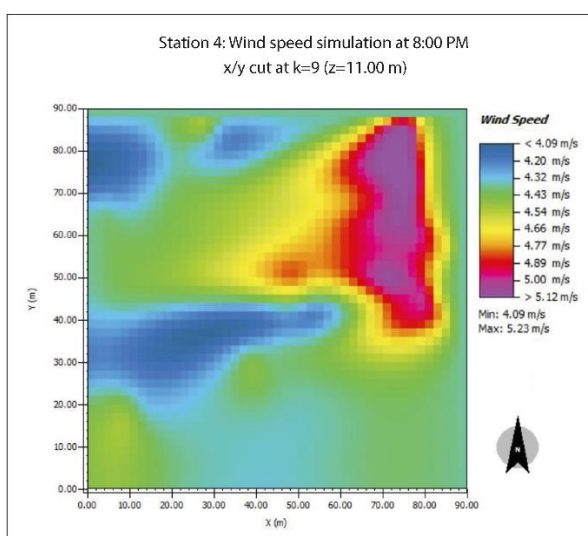
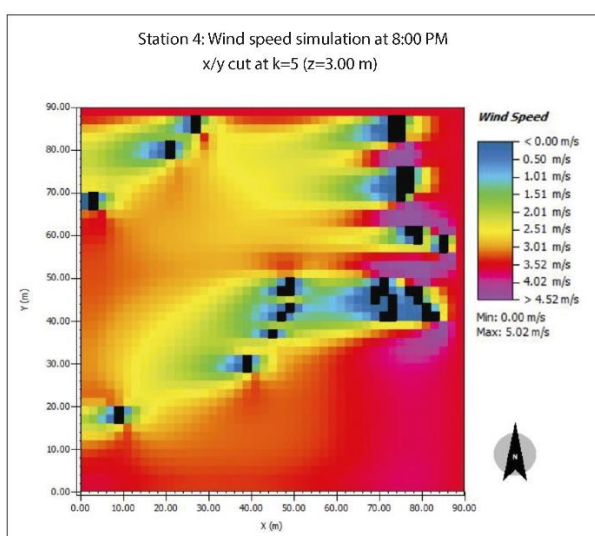
Appendix 15: Wind speed simulation at 9°41'30.98"N lat. and 39°30'16.80"E longitude (St. 4)



Wind speed simulation at 8:00 AM at 3m and 11m height respectively (Station 4)



Wind speed simulation at 2:00 PM at 3m and 11m height respectively (Station 4)

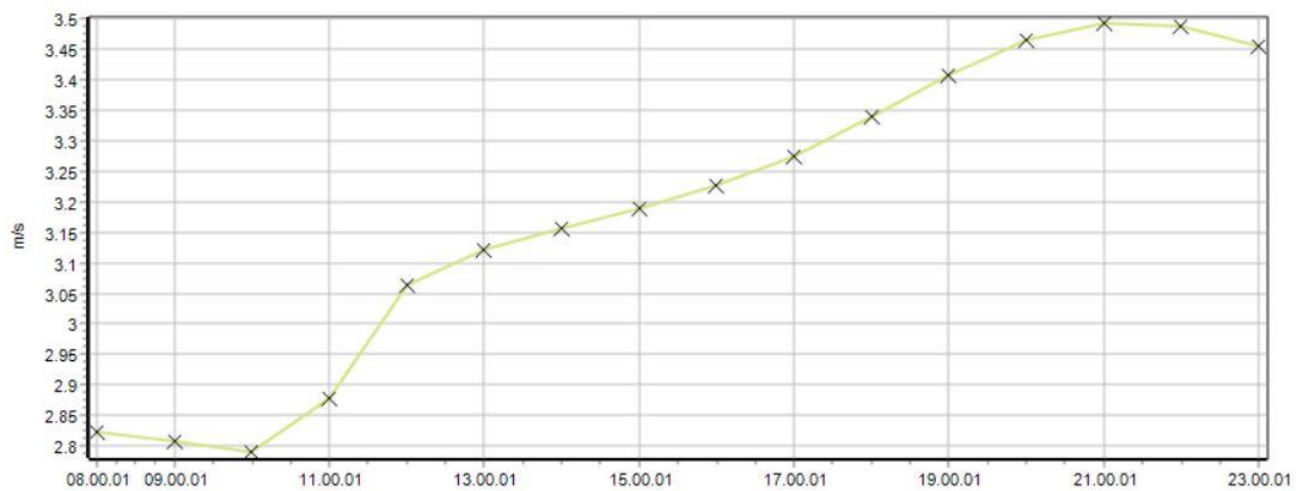


Wind speed simulation at 8:00 PM at 3m and 11m height respectively (Station 4)

Appendix 16: ENVI-met simulation output wind speed data and graph at 9°41'30.98"N latitude
and 39°30'16.80"E longitude at 3m height (station 4)

Date	Time	Wind Speed (m/s)	Relative Humidity (%)
23.06.2018	08.00.01	2.8224	70.258
23.06.2018	09.00.01	2.8081	68.259
23.06.2018	10.00.01	2.7906	66.313
23.06.2018	11.00.01	2.8775	62.984
23.06.2018	12.00.01	3.0628	60.24
23.06.2018	13.00.01	3.1211	57.248
23.06.2018	14.00.01	3.1566	54.221
23.06.2018	15.00.01	3.1904	51.619
23.06.2018	16.00.01	3.2259	49.32
23.06.2018	17.00.01	3.2734	50.534
23.06.2018	18.00.01	3.3392	52.344
23.06.2018	19.00.01	3.4084	54.381
23.06.2018	20.00.01	3.4644	56.384
23.06.2018	21.00.01	3.4925	57.964
23.06.2018	22.00.01	3.4876	59.43
23.06.2018	23.00.01	3.4538	60.877

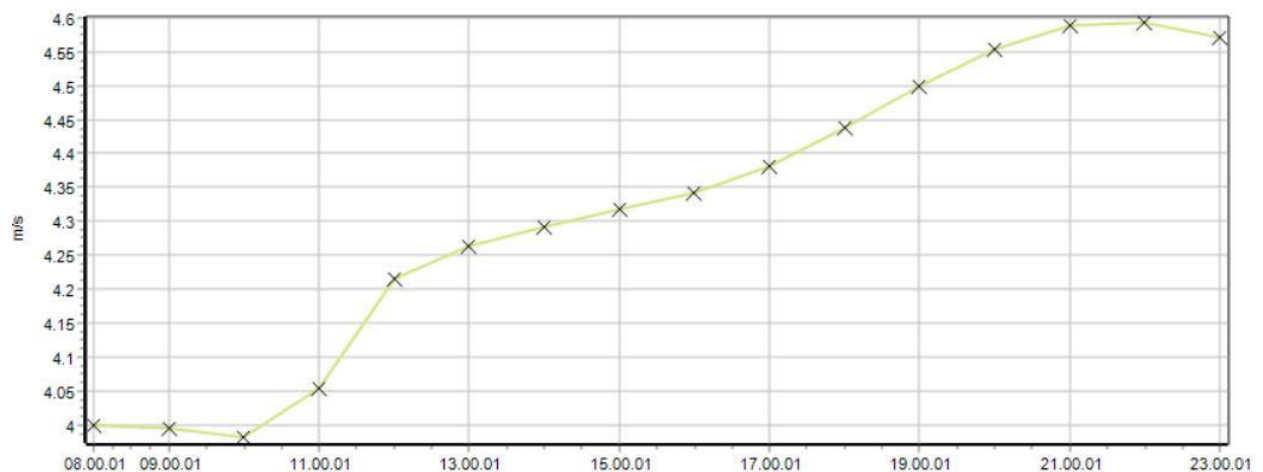
Graph of wind speed output from ENVI-met simulation at 3m height (Station 4)



Appendix 17: ENVI-met simulation output wind speed data and graph at 9°41'30.98"N latitude
and 39°30'16.80"E longitude at 11 m height (station 4)

Date	Time	Wind Speed (m/s)	Relative Humidity (%)
23.06.2018	08.00.01	3.9998	67.384
23.06.2018	09.00.01	3.9951	66.013
23.06.2018	10.00.01	3.9818	64.662
23.06.2018	11.00.01	4.053	62.226
23.06.2018	12.00.01	4.2156	60.336
23.06.2018	13.00.01	4.2641	58.301
23.06.2018	14.00.01	4.2927	56.162
23.06.2018	15.00.01	4.3179	54.087
23.06.2018	16.00.01	4.343	51.947
23.06.2018	17.00.01	4.3813	52.505
23.06.2018	18.00.01	4.4372	53.605
23.06.2018	19.00.01	4.4991	54.868
23.06.2018	20.00.01	4.5535	56.164
23.06.2018	21.00.01	4.5879	57.38
23.06.2018	22.00.01	4.5932	58.586
23.06.2018	23.00.01	4.5709	59.807

Graph of wind speed output from ENVI-met simulation at 11 m height (Station 4)



Appendix 18: Model builder map for MCDM

