



**Ethiopian Institute of Architecture, Building Construction and City Development
(EiABC)**

**Wind-based Energy-Plus Aerodynamic Building Design for the City of Addis Ababa,
Ethiopia**

By

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I feel like bathos to take this opportunity in order to express the almighty of “GOD” and his mercies, love, strength, courage and faith donations throughout this work and in my life as a whole, in short words, nothing was possible without him.

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Abstract

Alternative energy is becoming increasingly important in today's society since it is less detrimental and damaging to the environment than fossil fuels. Wind energy, a viable renewable energy source in Ethiopia, has great potential, but its utilization in Addis Ababa's buildings is restricted, and the present infrastructure is failing to satisfy rising electrical demand owing to frequent outages and significant power distribution losses. This paper presents a study on the design of energy-plus aerodynamic buildings in Addis Ababa, Ethiopia. The objectives of the study were to: (1) identify potential sites for wind-based energy-plus buildings; (2) carve out the form of buildings responding to wind energy harvesting; and (3) design aerodynamic buildings. The study utilized primary and secondary data from various sources, including NASA, MapServer Ethiopia, EnergyPlus, the USGS Satellite Map, and the Global Wind Atlas. The GIS-based MCDM method is used to locate wind energy sites, while software-based CFD simulation optimizes the aerodynamic form of buildings for wind-based wind energy harvesting. Addis Ababa city has 80% potential for wind energy harvesting, with high wind speed areas, including the project site located in the main city center, suitable for wind-based energy-plus buildings. In this study, the wind-based energy-plus aerodynamic was designed to minimize drag and maximize lift, resulting in a significant reduction in energy consumption and maximization of wind energy harvesting. Finally, the optimized aerodynamic building form reduces wind force by 27.64% and can generate 2,776.65 MW per year by integrating small-scale wind turbines, demonstrating its potential for wind energy integration. This study contributes to showcase Addis Ababa's transition towards renewable energy by identifying potential energy sources in built environments and designing high-rise buildings with wind-based power generation concepts.

Keywords: Form Optimization, Aerodynamics, Wind Energy, Multi-Criteria Decision Making

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Acronyms and Abbreviations

AADMP	Addis Ababa Distribution Master Plan
AHP	Analytical Hierarchy Process
BAWT	Building Augmented Wind Turbine
BIWT	Building-Integrated Wind Turbine
BOA	Bank of Abyssinia
CBE	Commercial Bank of Ethiopia
CFD	Computational Fluid Dynamics
DEM	Digital Elevation Model
EEPCO	Ethiopian Electric Power Corporation
EPW	EnergyPlus Weather
EUI	Energy Use Intensity
GIS	Geographic Information System
GW	Gigawatt
GWEC	Global Wind Energy Council
Ha	Hectare
HAWT	Horizontal Axis Wind Turbine
KW	Kilowatt
LED	Light Emitting Diode
MCDA	Multi-Criteria Decision-Making Analysis
MCDM	Multi-Criteria Decision Making
MW	Megawatt
NASA	National American Satellite Agency
SEDA	Sustainable Energy Development Authority
UBL	Urban Boundary Layer
UCL	Urban Canopy Layer
VAWT	Vertical Axis Wind Turbine
WLC	Weighted Linear Combination
WPP	Wind Power Plants

CHEAPTER ONE

INTRODUCTION

1.1 Background Study

Globally, it is virtually impossible to imagine cities without high-rise buildings (Halis Günel & Emre Ilgin, 2014), which are the city's most famous landmark, a symbol of power and human ingenuity over nature, trust in technology, and national pride. The importance of skyscrapers in modern urban development is undoubtedly steadily increasing, despite the undeniable negative impact on the quality of life of the built environment (Neethi B. & Joby, 2018). Burj Khalifa in Dubai is currently the tallest building in the world with a height of 828m, and the next tallest building in the world is the Kingdom Tower with a height of 1000m (Samad & Kumar Jain, 2020). Around the world, increasing penetration of environmentally friendly energy sources is constantly encouraged to meet growing energy demand and minimize the use of hydrocarbon-based power plants (Nishimura & Kolhe, 2015).

Wind power, one of the sources of renewable energy, is sustainable and environmentally friendly. The related market is growing at a rate of about 20% each year. The most common application for the use of wind energy is in the construction of wind power plants. That is, arrays of large wind turbines in hills or coastal areas without constant turbulence. Despite their effectiveness, wind farms have one significant limitation due to the distance between farms, which are usually remote, and urban areas, which consume more than 70% of the world's energy demand. This long distance between producers and consumers causes significant energy losses during transmission and requires expensive transmission systems. To use wind energy more effectively in urban areas, power losses and costly networks need to be addressed appropriately (Park J. et al., 2015).

Rapid urbanization is causing cities to consume 70% of the world's energy, while buildings account for 48% of the energy used in air conditioning for thermal comfort (Javanroodi et al., 2020). Herewith, urban areas facing increasing energy consumption and rapid economic development require a balance between energy supply and demand (Lee et al., 2017). Wind power usage has surged by over 8.3% annually in recent years, with numerous skyscraper-based wind power generation systems being developed (Jung & Park J., 2017).

Integrating wind turbines into buildings and urban structures not only expands wind power capacity but also reduces transmission line load and losses, offers energy-efficient aesthetics, and can increase wind energy generation potential if integrated intelligently into building planning (Alanis Ruiz et al., 2021). To maximize wind power in densely populated areas, there is great potential for using urban wind energy to form power generation modules through distribution networks (Yang et al., 2016).

Ethiopia, a developing country, is grappling with increasing energy demand due to its reliance heavily on hydropower, providing only 1% of its total electricity supply, including geothermal, natural gas, solar, wind, coal, and diesel. The final report of the Urban Distribution Network and Expansion Project found that Addis Ababa's existing grid cannot meet the growing demand for electricity and it is characterized by frequent disruptions and high-power distribution losses (Assefa, 2015). Approximately 19% of losses in distribution systems occur due to a lack of capacity and equipment deterioration (Ethiopian Electric Power, 2018). Similarly, many studies proved that power outages can result in firms without backup generators losing about 15–30% of their potential production in Addis Ababa. In other years when power shortages were low, losses could be up to 10%. With rapid economic growth, Ethiopia is seeking more power plants to meet the high demand for electricity (Derbew, 2013). The country has invested heavily in the power sector over the last decade (about 40% of GDP), but the problem of power shortages has not yet been resolved (Hassen & Degu, 2019). Studies indicate that Ethiopia has potential for wind power, particularly for small turbines under 100 kW, which could generate over 10,000 MW of electricity.

Indeed, renewable energy, particularly wind energy, is crucial for city resilience and sustainability due to its reliability, cost savings, and economic feasibility. Distributed generation allows smaller turbines to be installed closer to consumers (Hemida et al., 2020) and interrelated with high-rise buildings where the wind with high speed is available (Zhou et al., 2017).

Therefore, wind energy is a potential sustainable and cost-effective renewable energy source, but Ethiopia's rapidly growing skyscrapers in Addis Ababa have not yet been utilized to expand its wind energy capacity, despite its potential for sustainable energy production. What is new is the introduction of wind-based treatments of limitless vertical developments and wind energy harvesting augmentations, both of need a sensitive integration.

1.2 Problem Statement

Power shortages are a significant obstacle to growth in developing countries, particularly in sub-Saharan Africa. Many enterprises report losing 47 hours of economic activity a month due to power shortages (Carlsson et al., 2018), similar to Ethiopian companies. To address these difficulties, there is an urgent need for new power systems generating distributed energy from renewable sources. Power outages in Ethiopia are becoming a common issue, lasting an average of eight hours on a normal day, making them a significant challenge in Addis Ababa, where people and businesses often consider them part of their lives. Ethiopia is developing wind power plants for large farms, but lacks practical guidelines and information on urban wind generation, and knowledge about wind resources in built environments is limited.

Furthermore, Addis Ababa's energy system is not keeping up with the Ethiopian economy's growth, urbanization, and future energy demand. There is no provision for embedded generation, such as wind energy harvesting and selling excess back to the grid. The number of skyscrapers under construction in Addis Ababa is increasing, with the Commercial Bank of Ethiopia's (CBE) headquarters and upcoming projects like the Bank of Abyssinia's (BOA) 60-story headquarters and 250-meter-high Mesob Tower consuming significant energy. Despite the suitable wind environment for power generation, there are no practical developments for wind energy harvesting in cities.

On the other hand, wind loads on high-rise buildings are influenced by atmospheric boundary layer wind, increasing with height in cities like Addis Ababa. Vertical expansion is often used to address this issue, but there is a gap in the design process and wind treatment, necessitating a creative method for tall buildings to address this issue. In Addis Ababa, the design of buildings' external shape and orientation is often influenced by architectural, functional, and site limitations rather than aerodynamic factors. Studies show that 33% of the 73 tallest buildings lack macro-level geometric modifications and 59% lack micro-scale modifications (Alaghmandan et al., 2013), possibly due to a lack of comprehensive design methods for wind-based form optimization.

Indeed, Addis Ababa's energy demand and power outage challenges require a long-term approach to exploring renewable and environmentally friendly energy options, considering their potential, and an alternative design methodology is required for the exponentially growing skyscrapers in the city.

1.3 Objectives

General Objective:

To identify suitable sites and design wind-based energy-plus aerodynamic building in Addis Ababa, Ethiopia.

Specific Objectives

1. To identify potential sites for wind-based energy-plus buildings.
2. To carve out the form of a building responding to wind energy harvesting.
3. To design aerodynamic buildings.

1.4 Scope

The study focuses on how wind energy sources are used to increase the energy demand of the city by locating and prioritizing the most urban wind energy potential sites in Addis Ababa city that fulfill the minimum standards for wind energy production and on how high-rise buildings of exponentially growing vertical developments should be designed to boost energy harvesting competence.

Thematically, this research is limited to urban wind energy and governing parameters to locate windy areas inside Addis Ababa City and to aerodynamic form optimization techniques to shape the building envisioned for wind power harvesting through wind-based simulations of influencing parameters. Spatially, the extent of this study is limited to the city of Addis Ababa, Ethiopia.

1.5 Significance

The research aims to demonstrate Ethiopian cities' transition towards renewable energy by identifying potential energy sources in built environments and designing high-rise buildings with wind-based power generation concepts, thereby enabling energy self-sufficiency through on-site power generation. The study highlights the potential of wind energy sources in Addis Ababa city, which can stimulate socio-economic development, reduce energy shortages, and create new employment opportunities.

Moreover, this paper presents additional information on renewable energy sources by identifying potential locations for urban wind power harvesting and the seizing of buildings for wind turbine integration so that local and national policymakers can design appropriate policies

and strategies for identifying the immediate resources of Addis Ababa. And also, it helps other cities and towns consider the available renewable energy sources in the area.

From an academic point of view, other researchers interested to studying in this thematic area can use it as a reference for related research.

1.6 Limitations

The research aims to better understand wind speed in Addis Ababa City by collecting daily, hourly data for years. However, this data is scarce and difficult to obtain. The study uses data from NASA metrological data, global wind atlas, and Meteoblue metrological data, with the last 30-year data that has been released for research. CFD simulations are limited by the accuracy of turbulence models, which may not capture all complex interactions in real-world flows due to simplifying flow assumptions.

1.7 Organization of the Paper

There are six chapters in this essay. The problem statement, study objective, fundamental research questions, significance of the study, scope, and study limitations are all included in the first chapter's introduction. The topic-related literature and a contextual review are covered in the second chapter. The third chapter covers the study's content and methodology, including a description of the study region, the data gathering process, and the data analysis process. The findings of the investigation and analysis are covered in chapter four. The topic of discussion is covered in chapter five. The sixth and last chapter is devoted to conclusions and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.0 Theoretical Review

2.1 Building Aerodynamics

Mankind has always built monumental structures for the gods, such as towering temples, pyramids, and cathedrals (Halis Günel & Emre Ilgin, 2014). Today's monuments, i.e., tall buildings, symbolize power, wealth, prestige, and fame. From years of effort to reach heaven at the Tower of Babel to Taipei 101, the tallest building in the world, the biggest challenge was to overcome the limits of nature with human ingenuity (Emre Ilgin, 2006). The habitability and comfort of the exterior of a building, which are influenced by urban conditions where atmospheric dynamics cause wind phenomena around the building, have received a great deal of attention from researchers in recent years (Gu et al., 2014). Pioneering work on building aerodynamics was carried out by Davenport (1971), who investigated the shape effects with the help of aerodynamic model tests (Samad & Kumar Jain, 2020).

Aerodynamic design is an approach that is incorporated into architectural design early in the project (Biswas & Peronto, 2020), which is taken as an effective way to reduce the wind load of a building. Aerodynamic architectural designs are implemented as part of the effects of wind on high-rise buildings, taking into account aspects such as building orientation, aerodynamic shape, floor plan changes, and aerodynamic tips (Hernandez & León, 2017).

Nowadays, the challenge of designing efficient high-rise buildings has changed dramatically. Traditional approaches to high-rise building structures in the past have limited the shape of buildings to mostly rectangular prisms, but today much more complex building shapes are being utilized. In addition, buildings planned and designed using advanced computer technology have little or no historic role modeling capabilities, so civil engineers come up with bold structural resolutions (Kovacevic & Dzidic, 2018). Therefore, increasing lateral stiffness against wind loads is beneficial for both structural adhesion and occupant comfort. To accomplish this task, a new trend in high-rise design practices is to improve the aerodynamics of the overall shape (Sev & Tuğrul, 2014).

2.1.1 Buildings Aerodynamic Classification

(Abdolhossein-Pour et al., 2013) stated that building forms can be categorized as bluffing or aerodynamic (streamlined) bodies, depending on the shape and direction of the flow. The body can be either bluff or aerodynamic, depending on how it is exposed to the wind. A flat plate is an aerodynamic object as the flow moves parallel to it and a bluff body when the angle of attack is about 15° to 90° as shown in Figure 2.1.

Bluff buildings are characterized by an easy and early separation of flow from the building surface. Bigger wakes behind the bluff bodies result in a larger pressure difference at the building surfaces. Thus, bluff geometries experience higher drag force induced by wind. Aerodynamic buildings are characterized by a very small separation. The thin front boundary layer remains attached to the surface (Abdolhossein-Pour et al., 2013).

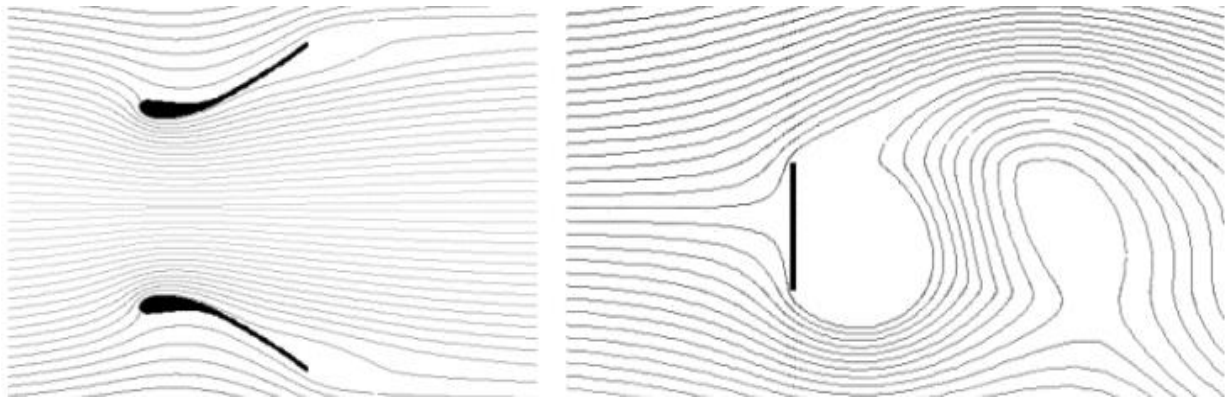


Figure 2.1: Flow pattern over an aerodynamic body (left) and a bluff body (right) in parallel flow (Abdolhossein-Pour et al., 2013).

2.1.2 Aerodynamic Modifications of High-Rise Buildings

The shape of a building has a great influence on the wind force acting on the building and the resulting movement. Careful adjustment of the components and shape of high-rise buildings can minimize wind stimulus and save considerable resources (Amin & Ahuja, 2010). Accordingly, a very important and effective design approach among these methods is the aerodynamic modification of buildings, such as the cross-sectional shape of the building and its corner geometry, the sculptural top of the building, and the modification of the horizontal and vertical openings of the building. By changing the pattern of flow around the building, aerodynamic changes in the shape of the building are crucial for the appropriate selection of building shape to mitigate wind reaction compared to the original building shape (Neethi B. & Joby, 2018).

A. Types of Aerodynamic Modifications

Various aerodynamic modifications can be made to the building to improve aerodynamic performance. To investigate this closely, researchers considered testing polygons with different numbers of sides, from squares to circles (Al Share, 2020). These changes can be categorized as minor or major modifications (Alaghmandan & Elnimeiri, 2013).

i. Minor Modifications

According to Asghari Mooneghi and Kargarmoakhar (2016), these modifications have little impact on the overall structure and architectural design of the building. Minor modifications include changing the corners of a building's cross-section, such as slot corners, bevel corners, corner depressions, and rounded corners, and changing the orientation of the building concerning the most common strong wind directions, which enables the improvement of the wind performance of tall buildings, as shown in Figure 2.2 (Sun, 2021).

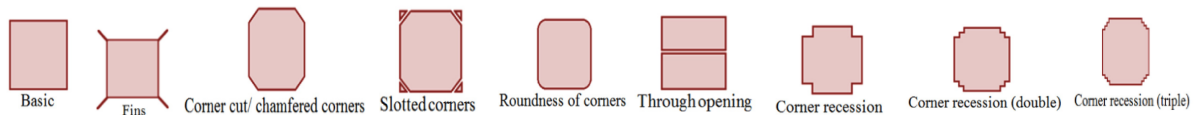


Figure 2.2: Minor aerodynamic modifications (Sun, 2021).

ii. Major Modifications

These changes have a significant impact on the structure and architectural design of the building. The most important modifications that can be used to achieve an aerodynamically favorable building shape are changes in the shape and height of the building, tapering, the introduction of upward openings, and twisting of the building, as shown in Figure 2.3 (Sun, 2021).

The tapering method was partially used to optimize the shape of the Burj Khalifa in Dubai, which has a stronger effect in the across-wind direction than in the along-wind direction (Halis Günel & Emre Ilgin, 2014). Rotating a building is very effective because the designer can assign the orientation of the building so that, in the worst case, the orientation does not match the direction of the strongest winds. In addition, the twisted building shape is effective in reducing the vibrations caused by the vortex by preventing simultaneous vortex emission along the height of the building (Asghari Mooneghi & Kargarmoakhar, 2016).

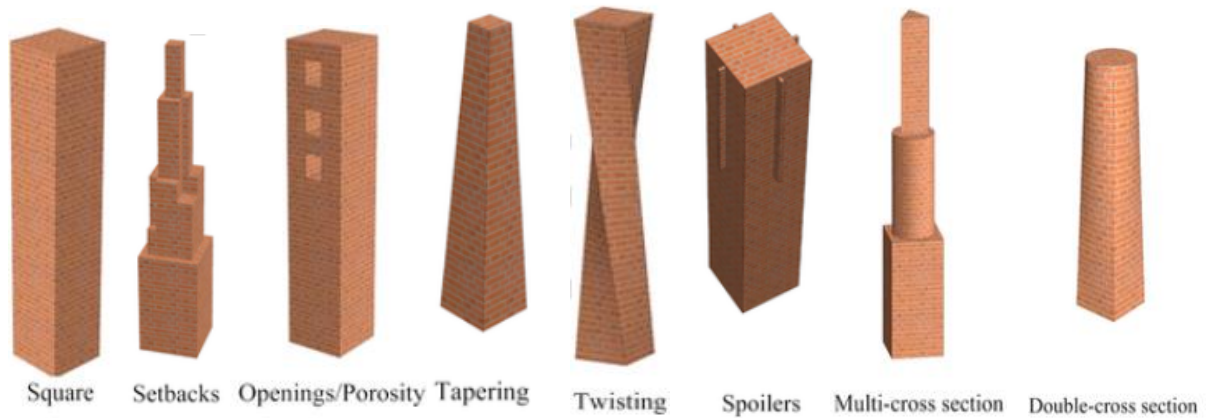


Figure 2.3: Major aerodynamic modifications (Jafari & Alipour, 2021).

2.1.3 Aerodynamic Shape Optimization

Aerodynamic optimization of building shape is an important factor in the design of mega skyscrapers (Samad & Kumar Jain, 2020). Aerodynamic optimization techniques are very attractive in today's competitive environment because they can reduce design cycle times by automating the design process (Mengistu & Ghaly, 2003). The goal of the aerodynamic optimization process is to determine the shape of the building that provides near-optimal wind behavior while meeting all other design requirements such as architectural constraints, energy harvesting, cost goals, construction considerations, etc. (Biswas & Peronto, 2020).

Shape Optimization Using Computational Fluid Dynamics (CFD)

Simulation-based optimization is an increasingly common calculation for designing a resource and energy-efficient building (Al-Najjar & Al-Azhari, 2021). Computational designers use parametric models with structural and environmental simulations automatically to detect high-performance design candidates and to notify further iterations of the design process (Spence et al., 2013). In addition to the development of computer and numerical computing technologies, computational fluid dynamics (CFD) has also made rapid progress. CFD technology includes fluid dynamics, computational methods, computer graphics, and many more. CFD simulation creates a computer model based on an architectural design scheme. This allows the CFD software to simulate the wind environment around and inside buildings and residential buildings, and wind speed and pressure simulation diagrams are created under natural aeration. Thus, the architect can modify the building design plan accordingly (Guo et al., 2015).

Computational fluid dynamics (CFD) is the best tool available nowadays to carry out a careful analysis of the wind flow around buildings (Toja-Silva et al., 2018). CFD aerodynamic shape

optimization has been used for many years in the aerospace and automotive industries, and recently there has been increasing interest in civil engineering structures, especially for high-rise buildings, to shape aerodynamic design (Muyl et al., 2002).

2.1.4 Design with Wind

Wind-inspired design has a long tradition, but its integration into the architectural design cycle is still a very recent practice (Singh & Aggarwal, 2020). Wind influences architecture by shaping built environments, causing zones with no wind or high-speed wind with turbulent flow. Studying individual wind characteristics helps create a sustainable and comfortable environment (Kabošová et al., 2020). In cities, the roughness of the surface of a building slows the flow of wind and tends to slow the wind as it protects the void space adjacent to the building from the wind, as shown in Figure 2.4.

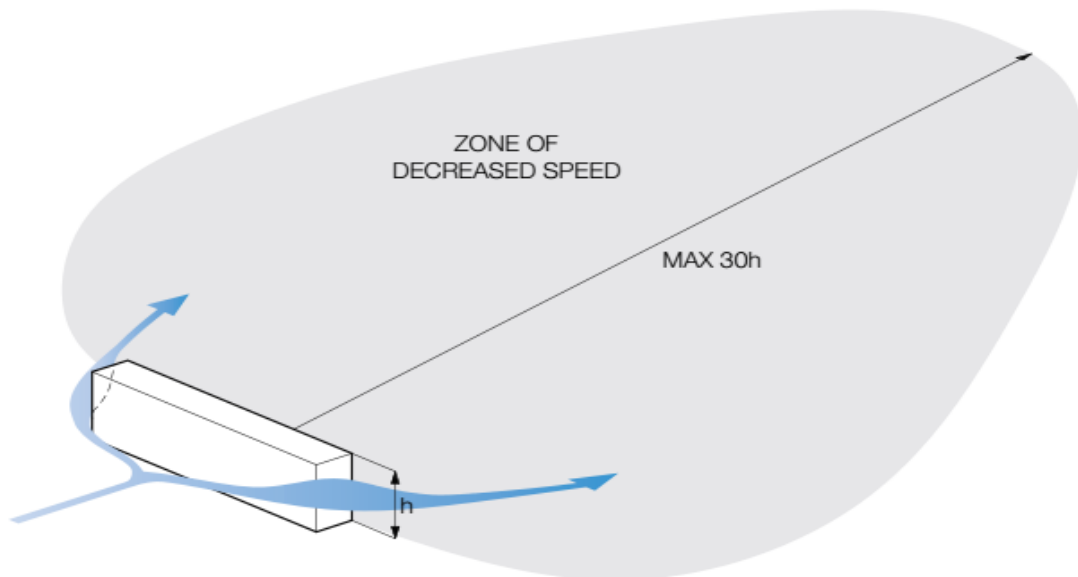


Figure 2.4: Buildings shield leeward spaces from the wind (Fleming, 2015).

However, the wind can interact with the building in a way that accelerates in the area. Buildings standing parallel to each other can form canals that increase the speed of the wind flowing between them (Figure 2.5); the wind accelerates around the corners of the building (Figure 2.6a) and through the openings of the building (Figure 2.6b); and the walls of tall buildings exposed to headwinds can direct the wind faster from the front of the building to the height of the street (Figure 2.7) (Fleming, 2015).

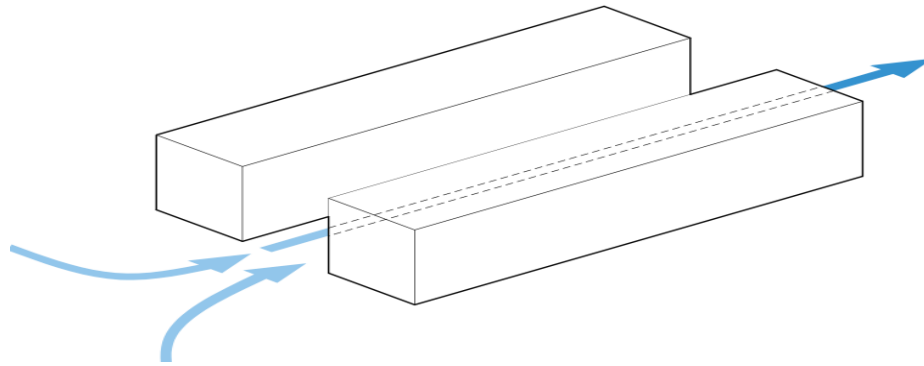


Figure 2.5: Wind is channeled and accelerated between buildings (Fleming, 2015).

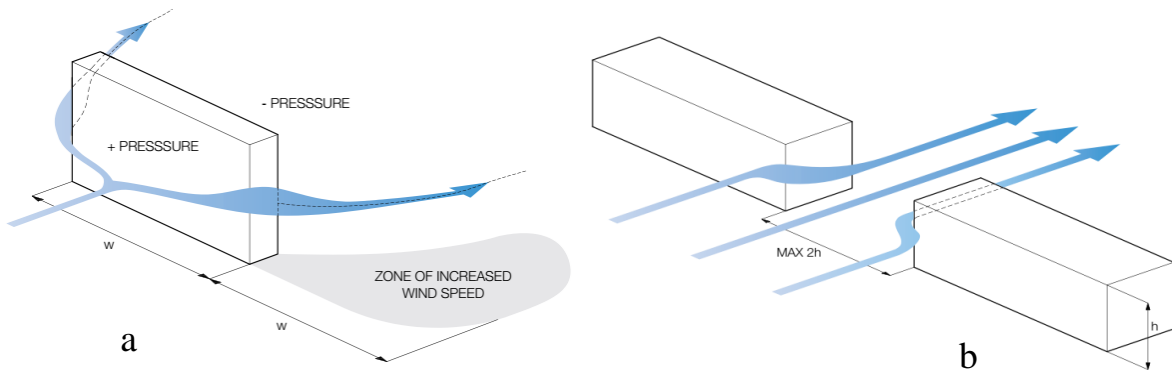


Figure 2.6: Wind accelerates around corners (a) and through openings between buildings (b) (Fleming, 2015).

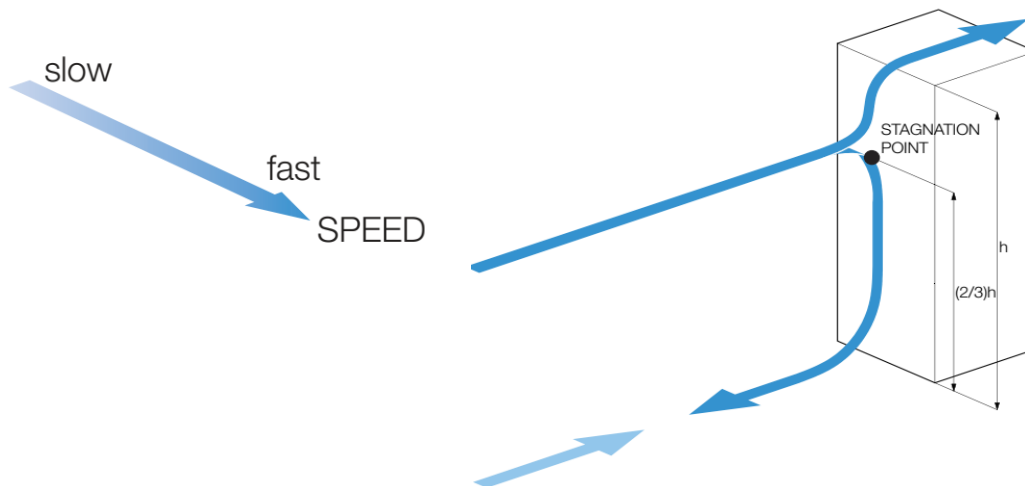


Figure 2.7: Tall buildings direct high-speed wind down to street level (Fleming, 2015).

Interactions of Wind and Architecture

Wind is one of the most obvious meteorological factors that significantly shapes the natural environment. In the architectural context, wind can ‘form’ the built environment (Kormaníková et al., 2018). Wind analysis of specific wind conditions at the design site contributes to the creation of a sustainable and comfortable building environment (Kabošová et al., 2020).

The magnitude and direction of wind flow are unevenly distributed around the world. Accordingly, the designs incorporating the wind can be aimed at different goals, depending on what kind of wind-architecture interaction is beneficial for the specific site: natural ventilation, pollutant dispersion, aerodynamic designs, pedestrian wind comfort, and wind energy harvesting, as shown in Figure 2.8 (Kabošová et al., 2020).

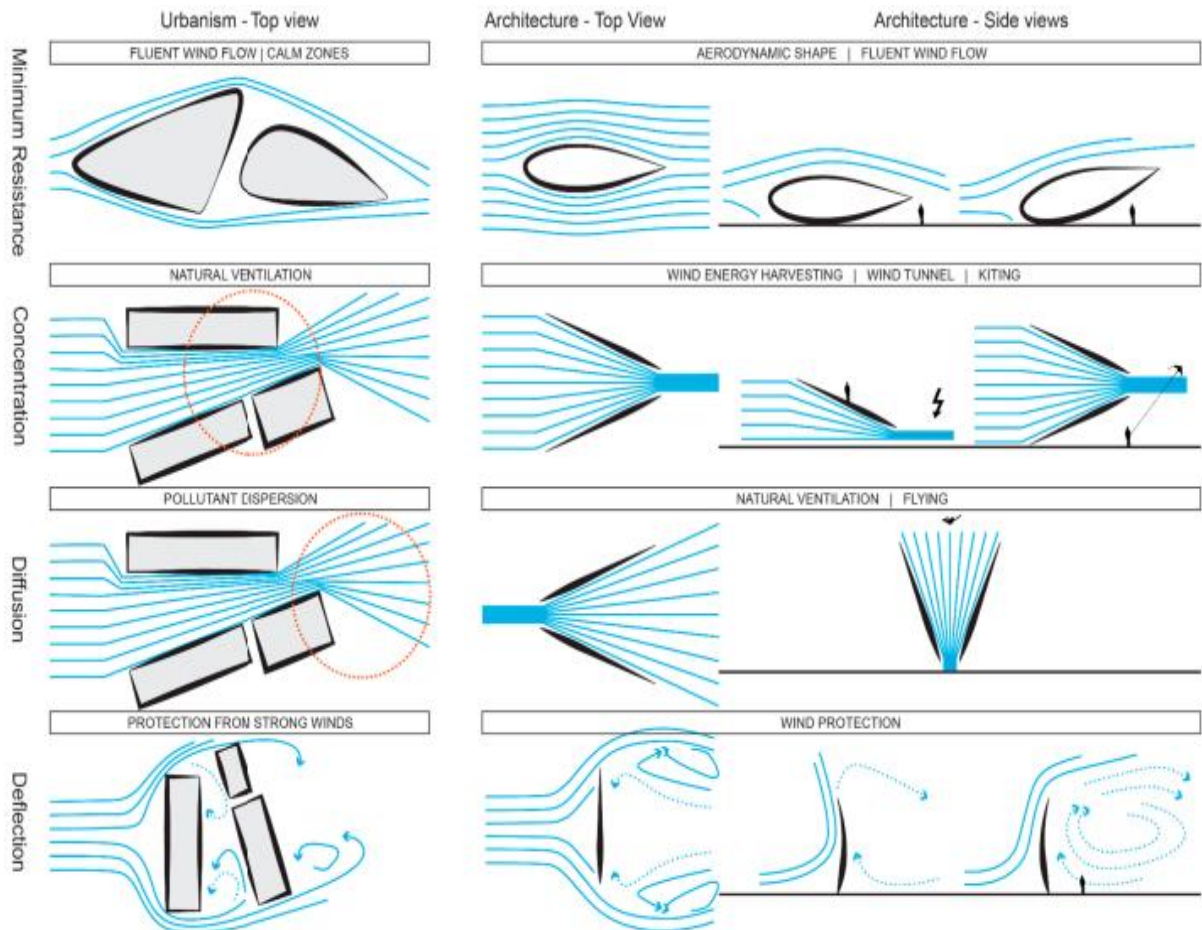


Figure 2.8: The reciprocal interactions of the urban layouts and shapes of the buildings with the wind (Kormaníková et al., 2018).

The influence of the wind conditions on the built environment can be predicted at the early stages of designing, through CFD simulations, to help understand the expected wind-architecture interactions, and, based on the results, the concept can be adjusted to be optimal for the specific design goal. Figure 2.9 shows the sample process, which can, in the future, lead to designing architecture by morphing its shape in the wind (Singh & Aggarwal, 2020).

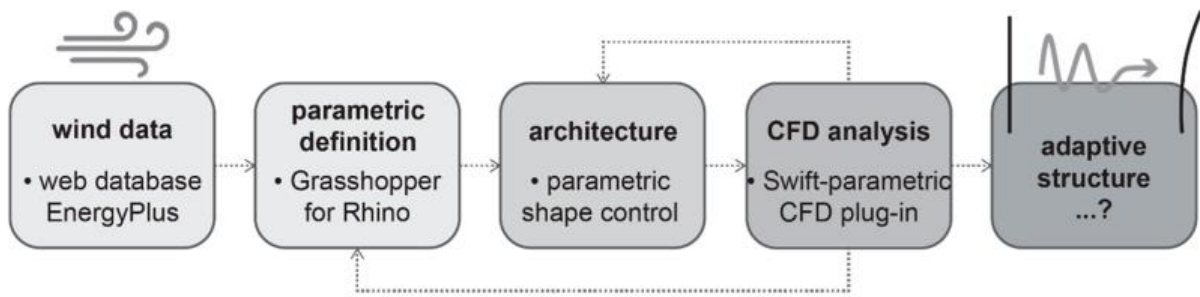


Figure 2.9: The design loop of creating wind-based architecture (Kabošová et al., 2020).

2.2 Energy-Plus High-Rise Buildings

High-rise buildings are becoming increasingly popular in developing countries due to population growth, urban space shortages, service collection, and company status. These buildings demand significant operational energy, necessitating ecological design and energy generation elements. Buildings that adapt to the natural environment are crucial for a better-built environment and future living needs (Alawi, 2018).

Energy-plus buildings are environmentally friendly structures whose design and construction are based on a practical and simple approach. Energy-efficient and water-efficient buildings have been shown to reduce operating costs by more than 50% with a well-integrated sustainable design concept (Alnaser, 2008). The town's most energy-plus skyscraper incorporates wind turbine technology, solar panels, LED lights, rainwater harvesting systems, and seawater-powered air conditioners, incorporating cutting-edge energy and water-saving technologies. The current green design shows that energy conservation measures can create efficient high-rise buildings (Al-Kodmany, 2018).

Engineers are increasingly focusing on aerodynamic forms and winds in skyscrapers, as they provide structural benefits, sustainable benefits, and enhance the symbolism of buildings. Wind-induced excitation in slim skyscrapers occurs due to vortex shedding, increasing wind speed, air pressure, and pulling force (Holmes, 2004).

Recent developments in wind energy for the urban environment have impacted several types of building integrated wind turbine projects. For example, the Strata SE1 in London (Figure 2.10) is a 43-story building with three 9m-diameter wind turbines at the top of the structure (Garcia et al., 2019). These wind turbines having three 5 blade, 9m diameter, 19kW custom turbines installed in its structure has an estimated energy production of 50MWh per year, enough to produce 8% of the tower's annual energy consumption (Dymock & Dance, 2013).



Figure 2.10: Building integrated wind turbines with horizontal axis (Strata SE 1, London). (Dymock & Dance, 2013)

Many researchers have run numerical simulations to equip wind turbines (or Building Integrated Wind Turbines (BIWT)) and estimate that the BIWT system will generate nearly 20% of the energy required for building operation.

Figure 2.11 shows another example of energy-plus high-rise building, World Trade Center found in Bahrain, a building integrated wind turbine project with a horizontal axis. The two towers are connected by three sky bridges, each holding a 225kW wind turbine. Each of these turbines is 29 meters in diameter and faces north, from which air from the Persian Gulf flows. The amount of energy harvested using the BIWT systems was almost 1100–1300 MWh per year which is 11–15% of the total consumed energy of the building (J. C. Park et al., 2019). The building design has been extended to achieve a channeling effect and increase wind speed. The sail-shaped buildings on both sides are designed to direct the wind through the gap so that the accelerated wind can pass through the turbine. This was confirmed by a wind tunnel test showing that the building produces an S-shaped flow. This causes wind that enters within a 45-degree angle to either side of the central axis to create a wind flow that remains perpendicular to the turbine. This greatly increases the potential for power generation (Haase & Löfström, 2015).



Figure 2.11: Building augmented wind turbine, horizontal axis (World Trade Center, Bahrain). (Haase & Löffström, 2015)

2.2.1 Wind-based Building Design Process

The geometry of a building significantly influences its airflow pattern, especially in taller buildings. Aerodynamic changes can transform this unstructured phenomenon into a large-scale concentrator effect, increasing wind power generation in tall buildings (Mertens, 2006).

1. Criteria Definition

The first step is to collect design criteria from various relevant areas, including geometric, functional/architectural, urban, and climatic areas. The parameters are then categorized into three categories based on their impact on building performance (Abdolhossein-Pour et al., 2013).

Variable Parameters: These affect airflow patterns across buildings' bodies and are typically associated with overall building geometries, corner modifications, or tower arrangements.

Constant Parameters: These include those influencing the building performance but not the building form itself.

Controlling parameters: These are design functional criteria, limiting the range of incremental changes found in variable parameters to assure that the result of 3D alternatives falls within allowable ranges for high-rise architecture.

2. Geometries and Tower Arrangement Classification

Footprint shapes of tall buildings fall into three classes, including basic bluff, complex bluff, and aerodynamic buildings (Abdolhossein-Pour et al., 2013). As shown in Figure 2.10, streamlining or corner modifications reduce turbulence noticeably and prevent early separation across buildings (Halis Günel & Emre Ilgin, 2014).

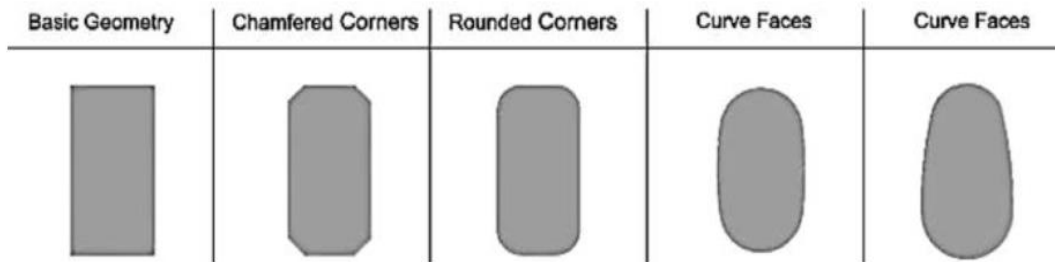


Figure 2.12: Corner modifications (Halis Günel & Emre Ilgin, 2014).

3. Prototype Definition

The third step in the wind turbine integration design process is prototype definition.

4. Optimization Processes

The final step is the optimization process on the algorithmic platform of building performance simulation (BPS)-based form generation, as shown in Figure 2.11. The major procedure sequences include raw data input, parametric model setup, optimization loop, accuracy control, and optimal output (Abdolhossein-Pour et al., 2013).

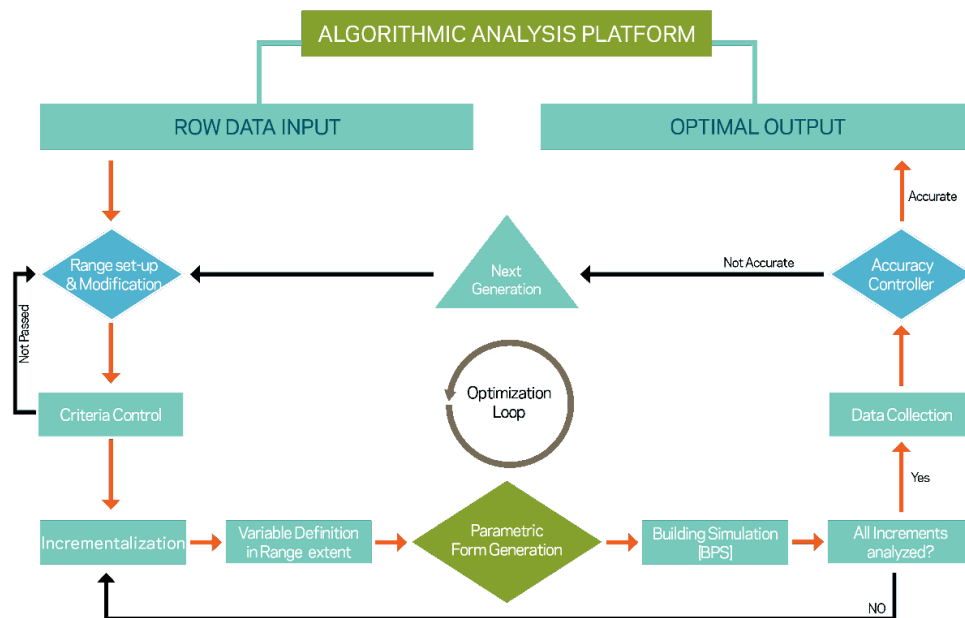


Figure 2.13: Flowchart of Algorithmic analysis platform (Abdolhossein-Pour et al., 2013).

2.3 Wind Energy

Wind power can play an important role in resolving current energy and environmental crises (Kasinatha Pandian Karpaga et al., 2007). Its environmental friendliness, increased profitability, compatibility of wind power with other land uses, and abundant wind resources make it a powerful option to meet future energy needs (Nasehi et al., 2016). Wind energy is currently the largest contributor to renewable energy sources (Rezaeiha et al., 2020), which is one of the less-impact forms of electricity generation in terms of the benefits outlined at the regional and global levels (Baffoe & Sarpong, 2016). The idea of integrating wind was born to improve the overall energy efficiency of the building. Turbines that build the hull are becoming more and more popular (Popovac, 2012).

Due to the rapid development of construction technology and the widespread use of high-strength materials, modern skyscrapers tend to be more flexible and more sensitive to wind excitement than previous buildings. This raises an important question: “How can wind power be harvested in high-rise buildings?” (Y. Li et al., 2020).

Compared to traditional energy sources, wind energy has many benefits and advantages. Unlike fossil fuels, which emit harmful gases, and nuclear power, which produces radioactive waste, wind power is a clean and environmentally friendly energy source (Tong Chong et al., 2012).

2.3.1 Nature of the Wind

Wind, caused by temperature differences, is the movement of air in the natural horizontal movement of the atmosphere. Vertical movement, known as current, is more significant in meteorology and engineering. The surface boundary layer for horizontal wind movement extends to a height where horizontal airflow is unaffected by ground effect, making it crucial to design how wind effects are perceived in this zone (Emre Ilgin, 2006).

The wind environment has a great influence on the human senses. In the outdoor environment where human activity takes place, the physical environment, about 1.5 meters above the ground, affects one's most direct senses. If the wind speeds in this area are within the appropriate range, people will be comfortable (Guo et al., 2015). Table 2.1 shows the different feeling levels of the human body that vary by wind speed. In general, when the outdoor wind speed is within the range of 1m/s~5m/s, it is believed to be the most comfortable environment for human beings.

Table 2.1: Wind speed and human body feeling (Zhou et al., 2017).

Wind speed range	Human body feeling
<1.0m/s	breezeless.
1.0~5.0m/s	comfortable.
5.0~10.0m/s	uncomfortable with movements affected.
10.0~15.0m/s	very uncomfortable with movement greatly affected.
15.0~20.0m/s	intolerable.
>20.0m/s	dangerous.

I. Variation of Wind Speed with Height

An important feature of wind is that its speed changes with altitude, as shown in Figure 2.12. Wind speed increases along a curve from zero to the ground's maximum distance, with the altitude at which speed doesn't increase being called the gradient height and the corresponding speed (Emre Ilgin, 2006). The height at which the wind speed is affected by the topography is called the atmospheric boundary layer (UKDiss, 2021).

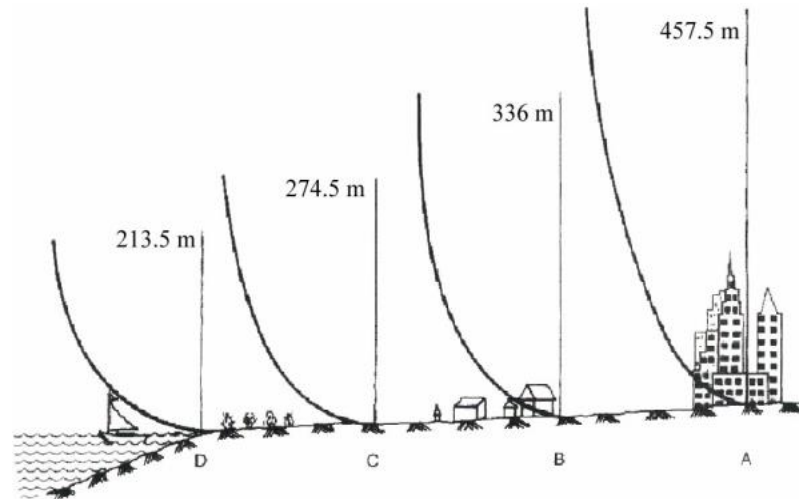


Figure 2.14: Variation of wind speed with height (Al-Quraan et al., 2016).

II. Turbulent and Dynamic Nature of Wind

The wind transfers some of its energy to the objects it encounters along the way. The unevenness of the terrain and the difference in ground clearance affect the turbulence of the wind. Wind loads associated with gusts or turbulence change rapidly, as opposed to average wind currents with static properties (Irshad, 2012). Furthermore, the movement of the wind is turbulent. Turbulence can be described as the movement of air at velocities above 0.9–1.3 m/s, resulting in the random movement of air particles in all directions (Emre Ilgin, 2006).

III. Vortex-Shedding Phenomenon

When a building is exposed to wind currents, the originally parallel lines of wind flow move on both sides of the building (Figure 2.13), and the forces generated on these sides are called vortices (Irwin et al., 2008).

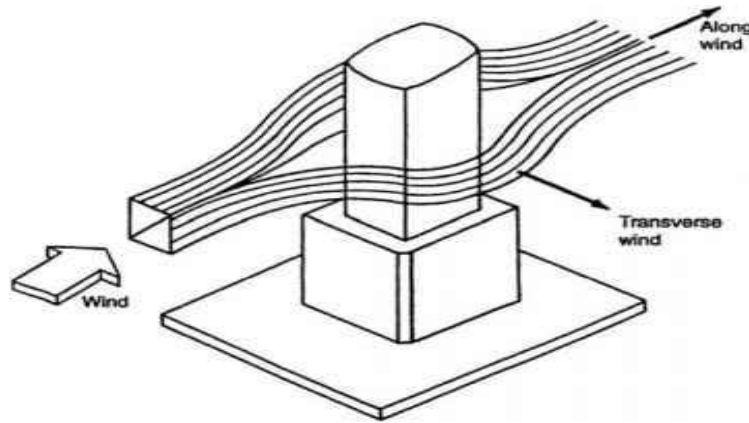


Figure 2.15: Simplified wind flow (Ilgin & Günel, 2007).

At low wind speeds, the vortices are shed symmetrically (at the same instant) on either transverse side of the building (Figure 2.14a), so the building does not vibrate in the opposite wind direction.

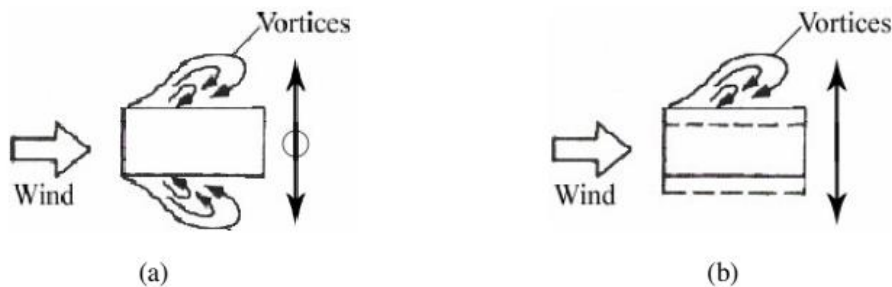


Figure 2.16: Vortices in different wind speed conditions: (a) vortices at low speeds of wind; (b) vortices at high speeds of wind (Sawant, 2017).

On the other hand, at higher wind speeds, the vortices are repelled from one side first and then from the other. This creates impulses in both the vertical and wind directions. Crosswind impulses are applied alternately to the left and then to the right. This type of emission, which causes structural vibrations across flows and winds, is known as vortex shedding, a well-known phenomenon in fluid mechanics (Emre Ilgin, 2006). Figure 2.14b schematically shows this phenomenon of alternating vortex shedding in a rectangular high-rise building.

2.3.2 Evolution of Wind Energy

Wind energy has been independently discovered and utilized in various parts of the globe since ancient civilizations thousands of years ago. As early as about 4000 B.C., the ancient Chinese were the first to attach sails to their primitive rafts. From the oracle bone inscription, the ancient Chinese scripted on turtle shells in the Shang Dynasty (1600 B.C.–1046 B.C.). At approximately 3400 BC, the ancient Egyptians launched their first sailing vessels, initially to sail on the Nile River and later along the coasts of the Mediterranean. Around 1250 BC, Egyptians built fairly sophisticated ships to sail on the Red Sea. Wind energy has been used as an energy source for ships and mills for hundreds of years (Zimmickas & Gecevicius, 2017). The wind-powered ships dominated water transport for a long time until the invention of steam engines in the 19th century (Tong, 2010).

Over time, the generation and utilization of wind energy, particularly the location of the rotor, have significantly shifted. The graph in Figure 2.15 attempts to illustrate this development, along with the importance assigned to the corresponding time for wind energy conversion (Beller, 2011).

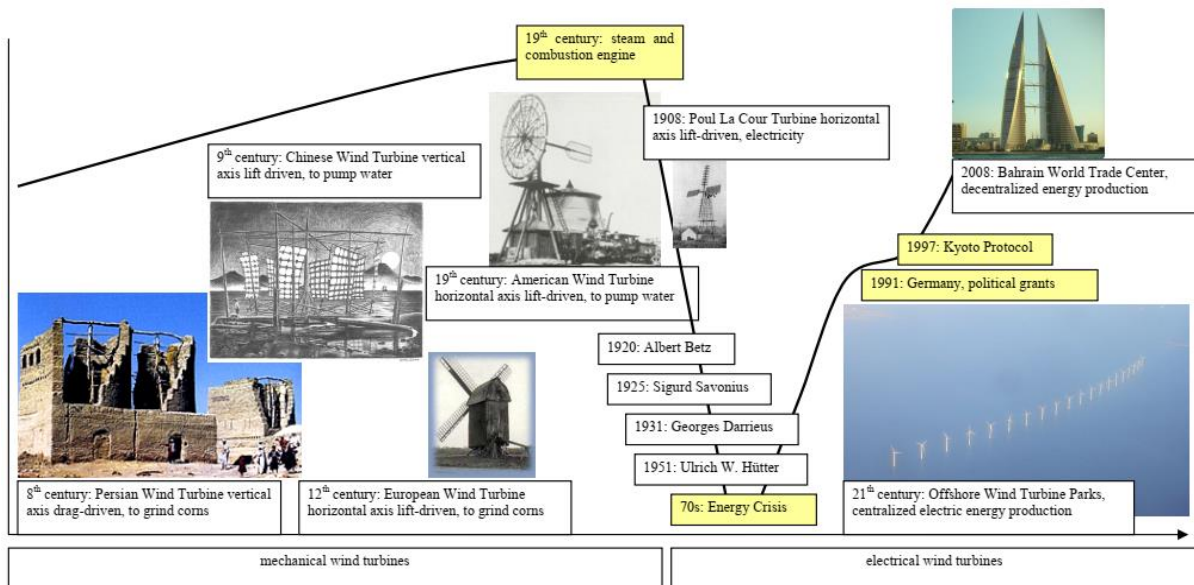


Figure 2.17: Historical development of wind energy applications and their importance with example turbines (Beller, 2011).

Since the 1970s, the wind industry has grown steadily, with smaller turbines initially used for residential purposes. Later, economies of scale led to larger turbines with outputs ranging from tens to megawatts. The third shift is underway today, installing wind turbines in a building or otherwise integrating them into a building (Wilson, 2021).

2.3.3 Wind Energy in Urban Areas

Urban wind energy is a niche of wind energy aimed at harvesting wind resources in a built environment (Vita et al., 2021). Limitations on the use of rural wind power plants have led to a gradual increase in interest in the direct use of wind energy in urban areas. However, the wind environment in urban areas is very different from that in hills and coastal areas (Wang et al., 2014). First, urban wind speeds are generally slower than those in hills or coastal areas of the same altitude due to the surface roughness caused by complex building arrangements. In addition, due to the limited space required to install many large wind turbines in urban areas, wind farms in such areas may not be considered a viable approach. On the other hand, the upper atmosphere in urban areas is not much affected by surface roughness, and special building arrangements, such as urban canyons and height differences between adjacent structures, often cause strong winds around the building. Therefore, high-rise buildings are considered to be candidates for wind energy use in urban areas (J. Park et al., 2015). 3 m/s is the minimum wind volume required to operate a wind power system on a high-rise building (J. H. Park et al., 2014).

In the current stage of the global energy crisis, the urban environment can play an important role as it is affordable, safe, and available. Research on the Urban Canopy Layer (UCL) and Urban Boundary Layer (UBL) was important. UCL is defined as the distance from the ground to approximately roof height, and UBL is a section affected by urban wind turbulence from above roof height (Tasneem et al., 2020). Figure 2.16 illustrates the wind speed profile of the city, including UBL and UCL, which are issues relevant to the generation of wind energy.

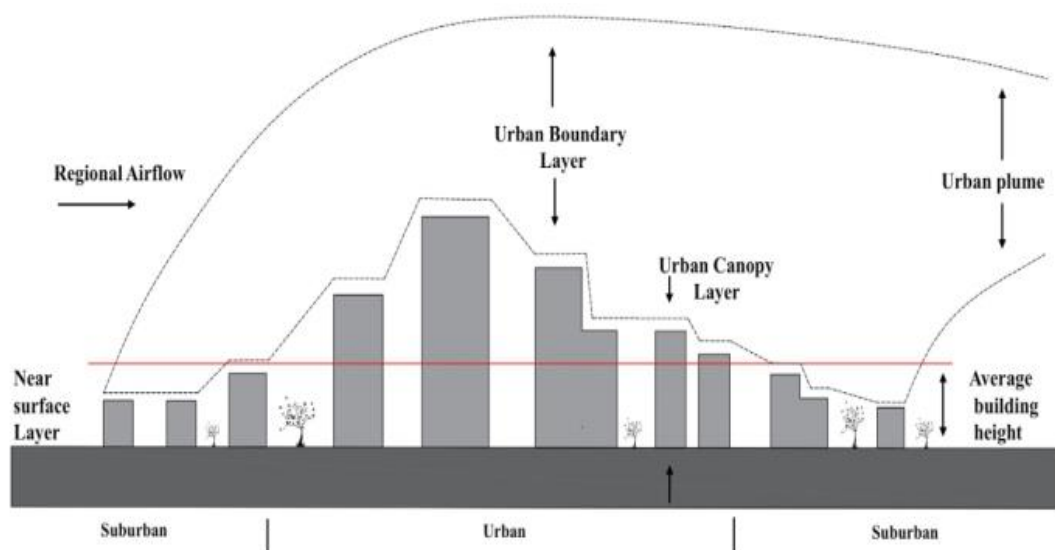


Figure 2.18: Wind profile in the urban area; UBL and UCL (Tasneem et al., 2020).

Urban wind energy can be generated by installing wind turbines on rooftops or standalone units, forming micro-power generation. The use of wind energy in buildings for distributed generation is growing due to the significant impact of wind speed on power generation. A slight increase in wind speed can significantly increase wind energy production (Al-Quraan et al., 2016). In addition, wind turbines can be fully integrated into the building's architectural design, inside or outside the façade of a building, or between corners or blocks. Figure 2.17 is a schematic diagram of three major types of urban wind energy harvesting systems (Rezaeiha et al., 2020). Researchers and developers are now using CFD models to determine the potential for turbines installed in buildings in urban areas. They found that even a small change in the location and height of high-rise buildings could have a dramatic impact on the performance of a city's wind farms (Tasneem et al., 2020).

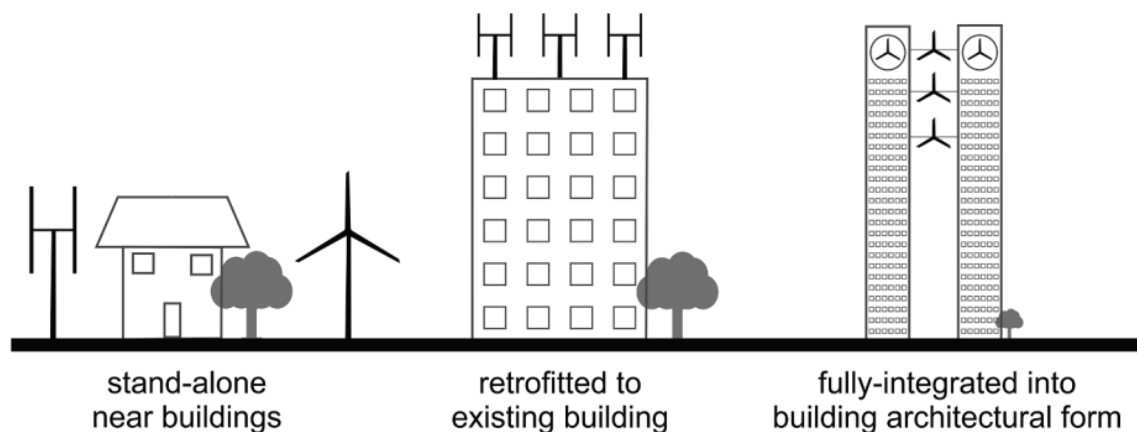


Figure 2.19: Categories of urban wind energy harvesting systems (Rezaeiha et al., 2020).

2.3.4 Suitable Site Selection Methods

Identifying suitable areas for wind development involves the analysis and consideration of criteria based on a combination of topographic, technical, environmental, and socio-economic factors (Athanasios, 2018). In addition, ensuring the optimal location for wind turbines in the built environment is important for efficient installations that hopefully maximize performance from unobstructed airflow (Dymock & Dance, 2013).

GIS-Based MCDM Suitability Analysis

The use of GIS-based multi-criteria decision-making (MCDM) analysis for the planning of wind energy harvesting sites gained significance in the early 2000s (Baseer et al., 2017). The tools used in energy planning and decision-making issues are best known as multiple-criteria decision analysis (MCDA) or multi-criteria decision support methods. MCDA tools help

decision-makers evaluate preferences and find the best compromises between different energy scenarios. Geographical Information Systems (GIS) analyze and combine geographic data to create powerful tools for decision-makers to make spatial decisions. GIS software is often associated with MCDA technology to correctly shape decision problems and identify, evaluate, and structure possible alternatives (Athanasios, 2018).

GIS-MCDA methodologies, as shown in Figure 2.18, are the most important part of MCDM analysis, which is the selection of various economic, planning, and ecological criteria, followed by using them as either restriction and/or evaluation factors to identify potential wind harvesting sites (Baseer et al., 2017).

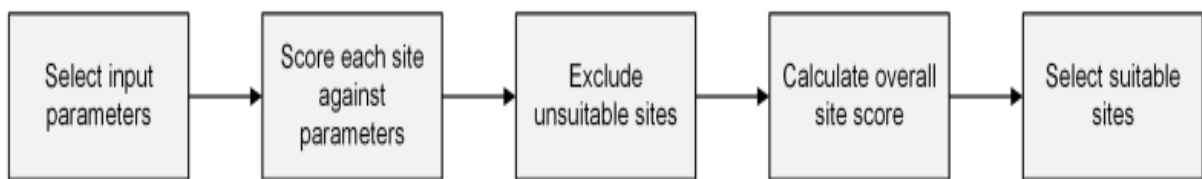


Figure 2.20: An overview of the typical structure of GIS-MCDA methodologies (Harper et al., 2017).

i. Evaluation Criteria

The evaluation of suitable areas for the expansion of wind harvesting is done by defining evaluation criteria. Their purpose is to assess the entire region based on the preferences of decision-makers (Taoufik & Fekri, 2021). This evaluation is made possible through a process called standardization, which is required to compare and combine criteria against various properties (distance, percentage, velocity, etc.). In the standardization process, score values are accredited according to criteria (Bobeck, 2017).

ii. Definitions of Evaluation Criteria

To analyze the suitability of potential locations for the development of wind harvesting sites, several factors divided into four groups: topographical, technical, ecological, and socio-economic factors, should be considered (Rehman et al., 2020).

Topographic Factors: slope

The slope is a criterion that denotes areas technically feasible for wind energy harvesting. For the proper development of wind energy, various slope grading's have to be proposed, where slopes above 25% are considered inappropriate for wind power generation (Szurek et al., 2014).

Technical factors: wind speed

Wind speed is one of the key factors in producing energy at a wind harvesting site in the built environment. Wind speeds above a certain value are essential for the production of wind energy (Idrizi et al., 2018).

Environmental factors: proximity to rivers

Distance from protected areas like rivers, including cultural heritage, is essential, and it is needed to have a minimum buffer distance of 40 to 60 m to protect the waterways (Chamanepour, 2017).

Socio-economic factors: distance to main roads and airports

Distance to main roads is important for the assessment of available wind energy harvesting sites. Being close to the road is a great advantage as to facilitate the transportation of elements from wind energy harvesting tools, such as wind turbine components (Bobeck, 2017). The distance between the wind turbine and the airport affects flight safety, and it is important to maintain a significant buffer from it (Idrizi et al., 2018).

iii. Evaluation Map Creation

Weights are assigned to the rating layer, and a rating map is created (one for each decision-maker). The evaluation map is created in two steps. In the first step, the weights calculated using AHP analysis are assigned to the evaluation layer. In the second step, the evaluation map is created using the weighted overlay technique, or the WLC is created using the GIS weighted overlay tool (Szurek et al., 2014).

iv. Final Suitability Map Creation

Final suitability maps are calculated based on the multiplication of each evaluation map with the constraint map. This is possible by using the raster calculator function on GIS. As shown in Table 2.2, suitability assessment classes are proposed by Höfer (2016).

Table 2.2: Suitability classes (Höfer et al., 2016).

Suitability	Value Score
High Suitability	8 - 10
Medium Suitability	5 - 7
Low Suitability	1 - 4
Not Suitable	0

2.4 Wind Energy Harvesting Technologies

2.4.1 Wind Turbines

A wind turbine is a popular name for a device that converts kinetic energy from the wind into electrical power (Heo et al., 2016). The aerodynamic design process for improved wind turbines continues to be the ultimate research and development goal for reducing wind energy costs (Khalil et al., 2017). Furthermore, wind turbines generate electricity in the field, avoiding transmission losses and the cost of individual connections to local distribution networks (Haase et al., 2014). Advancements in wind turbine technology have enabled the development of small and micro turbines in urban areas, driven by new technologies, construction advancements, and government financial incentives amid rising energy prices (Probala et al., 2016).

Options for the Integration of Wind Turbines

Wind turbine integrations can be organized by the types of devices, as shown in Figure 2.19, and categorized into three typologies: stand-alone wind turbines, retrofitting wind turbines onto existing buildings, and full integrations (Campbell et al., 2001).

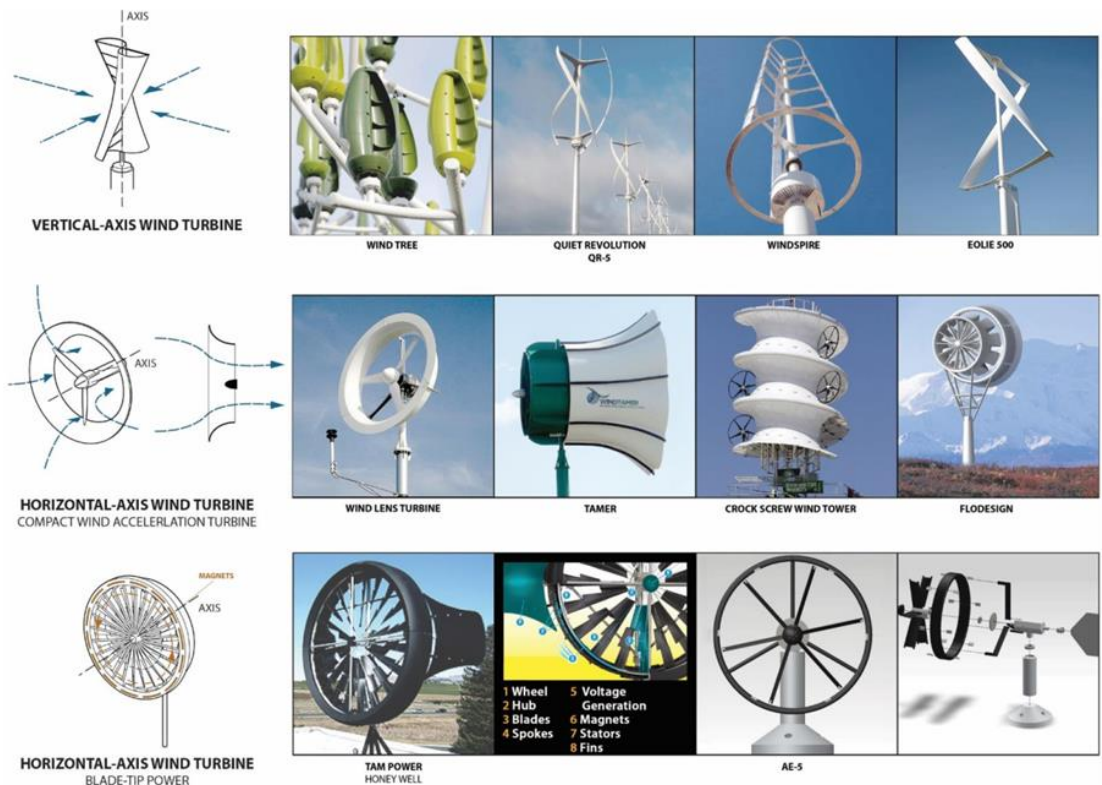


Figure 2.21: Different typologies of wind turbines (Serero et al., 2016).

Types of Urban Wind Turbines

Wind turbines can be categorized based on the axis of rotation and the performance of the turbine. Accordingly, they can be distinguished as rotary types: building-mounted wind turbines (BMWT), building integrated wind turbines (BIWT), and building augmented wind turbines (BAWT) (Haase & Löfström, 2015). It can also be categorized by rotor diameter (m) and axis of rotation. Wind turbines based on their axis of rotation can be divided into vertical-axis wind turbines (VAWT) and horizontal-axis wind turbines (HAWT) (Koç et al., 2017). Table 2.3 elaborates on a comparative analysis and advantages of urban wind turbines based on their type.

Table 2.3: Comparative analysis of urban wind turbines (Dilimulati et al., 2018).

	HAWT	VAWT (Lift based)	VAWT (Drag type)	H-Rotor
Advantages	<ul style="list-style-type: none"> • Higher efficiency • Most economical • Widely used in onshore and offshore applications 	<ul style="list-style-type: none"> • Less noise • High C_p • Less sensitive to turbulence • Lower bending stress 	<ul style="list-style-type: none"> • Low cut-in wind speed • Self-starting • Reduced vibration and noise • Reduced tower height • High reliability 	<ul style="list-style-type: none"> • Better efficiency
Disadvantages	Cannot perform well with: <ul style="list-style-type: none"> • The unpredictable change in wind direction • Low wind speed • Turbulent wind flow 	<ul style="list-style-type: none"> • Low starting torque • High production cost • Needs external power source 	<ul style="list-style-type: none"> • Poor efficiency • Torque varies with blade angle 	<ul style="list-style-type: none"> • High starting torque • Expensive to manufacture

Building Integrated Wind Turbines (BIWT)

Wind turbines integrated into buildings are becoming a popular green building technology, bringing power generation closer to consumers and reducing fossil fuel consumption, making them a new icon for green buildings (Sari & Kusumaningrum, 2014).

Today, interest in BIWT systems is growing significantly, considering introducing BIWT systems into their buildings. The BIWT system can be applied to high-rise buildings in two different ways. The first is to install one or more large wind turbines in a building. Wind turbines have four possible locations: (i) on the rooftop, (ii) between two adjacent buildings, (iii) inside a hole within a building, and (iv) integration into the building's skin (Arup et al., 2016). The second way to apply the BIWT system to a building is to install many small wind turbines in the building instead of some large wind turbines (J. Park et al., 2015). The optimal location of a wind turbine in a building depends on its ability to generate electricity for energy consumption. The shape of the building's roofs and the location of turbines also play a crucial role in maximizing wind energy potential (Sari & Kusumaningrum, 2014).

Factors to Keep in Mind While Designing Building Integrated Turbines

- A. Absolute Height of Building:** The height of the building above the general heights of surrounding buildings. The building should be the highest of all other buildings to gain the maximum amount of wind and pass through the turbine blades (Purohit et al., 2019).
- B. Orientation of the building:** Building orientation is an important factor for wind power generation through the installation of wind turbines into a tall building (Q. S. Li et al., 2013). Since the building receives wind from all sides, a turbine should be placed such that it lets in maximum wind. Tall buildings in urban areas work well when they are isolated rather than in groups and have long elevations facing dominant wind directions (Purohit et al., 2019).

When deploying wind turbines as a location-based renewable energy solution, wind-focused maneuvering is an important design factor that can significantly improve the potential operating performance of wind turbines (Bogle, 2011).

2.5 Contextual Review

2.5.1 Wind Energy in Africa

Wind energy's potential in Africa is recognized, with South Africa, Morocco, Egypt, and Ethiopia currently holding the largest share of wind energy production. Wind capacity has increased in Africa from 1997-2012, and it has grown tremendously since 2006, with a total capacity of over 2 GW by the end of 2012 (Mentis et al., 2015). Although there is a potential supply of wind energy in Africa and promising trends, the installed wind power capacity in Africa is only 0.4% of the global capacity. Africa and the Middle East added 821 MW of new wind capacity in 2020, bringing the region's total installed wind power capacity to over 7 GW. (Mukasa et al., 2013).

The African continent's wind resource potential exceeds 59,000 GW, meeting 250 times the continent's energy demand. South Africa installed 515 MW of new wind power capacity in 2020, boosting energy security, cost reduction, and socio-economic benefits (Pek, 2021).

Morocco's high electrification rate and Egypt's excellent wind resource potential make them self-sufficient. Morocco is focusing on renewable resources, while Egypt is building 750 MW of wind energy, with wind power being a key component. Ethiopia has a wind energy production capacity of over 320 MW but needs to increase annual power generation by 20–

25% due to its rural population and large population. Kenya's largest wind farm, the Lake Turkana project, has increased its capacity from 14 MW to 324 MW (Tiyou, 2016).

2.5.2 Wind Energy in Ethiopia

Ethiopia, situated in East Africa, has a population of over 110 million, with 83% residing in rural areas. With a diverse range of renewable energy sources like hydropower, wind, solar, geothermal, and biomass, the country is a significant contributor to the global energy landscape. (Mazengia, 2010). The country's total hydropower potential is estimated as 650,000 GWh per year; 25 percent of it (160,000 GWh per year) can be economically converted to electricity (Mekonnen, 2009), whereas the estimated exploitable potential for wind is 10 GW (Hailu & Kumsa, 2020).

Ethiopia's annual electricity demand increased from 1.6 TWh in 2000 to 9.5 TWh in 2014/2015. 55% of the population lives in areas covered by the grid, but less than 25% are connected to the grid. Ethiopia's continued economic growth will drive demand for electricity, which is projected to increase by about 10% annually in the medium term from the current peak daily demand of 1,900 MW (Ayalew, 2016). Figure 2.21 shows Ethiopian energy demand forecasting in different sectors.

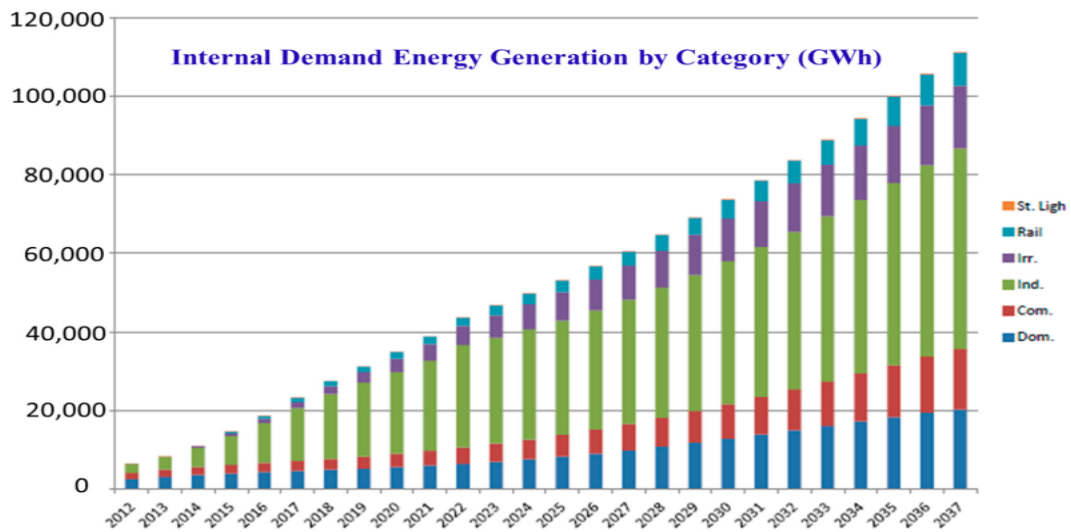


Figure 2.22: Ethiopian energy demand forecast in different sectors (Tiruye et al., 2021).

Ethiopia is one of the countries in Africa in which energy resources are underexploited; as evident from the past, significant energy demands are still met from traditional resources (Hailu & Kumsa, 2020). The country consumes around 40,000 GWh of energy, with 92% for consumer electronics, 4% for transportation, and 3% for industrial use. Bioenergy covers most of the

energy supply, with hydroelectric power generation accounting for 96% and wind energy for 4%. 11% of transportation energy is imported in the form of petroleum (Telfser et al., 2021). Table 2.4 shows the exploitable energy potential and currently exploited amount.

Table 2.4: Potential and exploited sources of energy in Ethiopia (Hailu & Kumsa, 2020).

No.	Source	Unit	Exploitable potential	Exploited amount	Percentage exploited (%)
1	Hydropower	GW	45	3.18	~17
2	Solar (day)	kWh/m ²	5.2		<1
3	Wind	GW m/s	1350	0.324	<1
4	Geothermal	GW	7	0.0073	<1
5	Wood	Million Ton	1120	560	50
6	Agricultural waste	Million Ton	15–20	~6	30
7	Biogas	Household	1–3 million	17869	<1

Ethiopia aims to meet 100% of its domestic energy demand with renewable energy by 2030, as part of the Climate Change-Resistant Green Economy Initiative. The National Electrification Program aims for 35% of the population to achieve universal access to off-the-grid solutions by 2024 (Smith, 2021). Presently, the country has installed three wind farms with a capacity of 324 MW. The Assela Wind Farm will be the fifth wind farm in the country after the Adama 1 Wind Farm, the Ashegoda Wind Farm, the Adama 2 Wind Farm, and the Aysha Wind Farm, which are currently under development. Ethiopia, a country rich in wind energy resources, is aiming to sustain economic growth and become a major energy exporter by diversifying electricity generation and utilizing this natural resource (Vergnet, 2016).

Ethiopian wind farms are still in their early stages, with suitable areas for grid-based power generation being those with wind densities of 300 W/m² and speeds of 6.5 m/s and above. Ashegoda, Adama I, and II wind farms have completed and have a total installed capacity of 324 MW (Evwind, 2018). Table 2.5 displays Ethiopia's wind turbine power generation capacity and future models. Wind power complements hydropower in Ethiopia due to the high availability of dry wind energy during dry periods, improving system reliability even during the dry period (Hailu & Kumsa, 2020).

Table 2.5: Existing and upcoming wind power plants (WPP) (CitiesAlliance, 2017).

No.	Project	Generating capacity (MW)	Annual Energy production (GWh)
<i>Connected to grid</i>			
1	Adama I WPP	51	157
2	Adama II WPP	153	479
3	Ashegoda WPP	120	450
	<i>Total</i>	<i>324</i>	<i>1,086</i>
<i>Upcoming project</i>			
4	Ayisha WPP	300	592
5	Messobo WPP	42	104
6	Assela WPP	100	197
7	Debre Birhan WPP	100	197
	<i>Grand Total</i>	<i>866</i>	<i>2,176</i>

Indeed, Ethiopia has an estimated 1.35 million MW of huge wind energy potential, and areas with moderate wind energy compatibility are also counted as having total wind energy potential (Tiruye et al., 2021). Figure 2.22 illustrates the average monthly wind speed at five different locations: Addis Ababa (09°02' N, 38°42' E, 2408 m); Mekele (13°33' N, 39°30' E, 2130 m); Nazret (08°32' N, 39°22' E, 1690 m); Debrezeit (08°44' N, 39°02' E, 1850 m); and Debre Markos (10°20' N, 37°43' E).

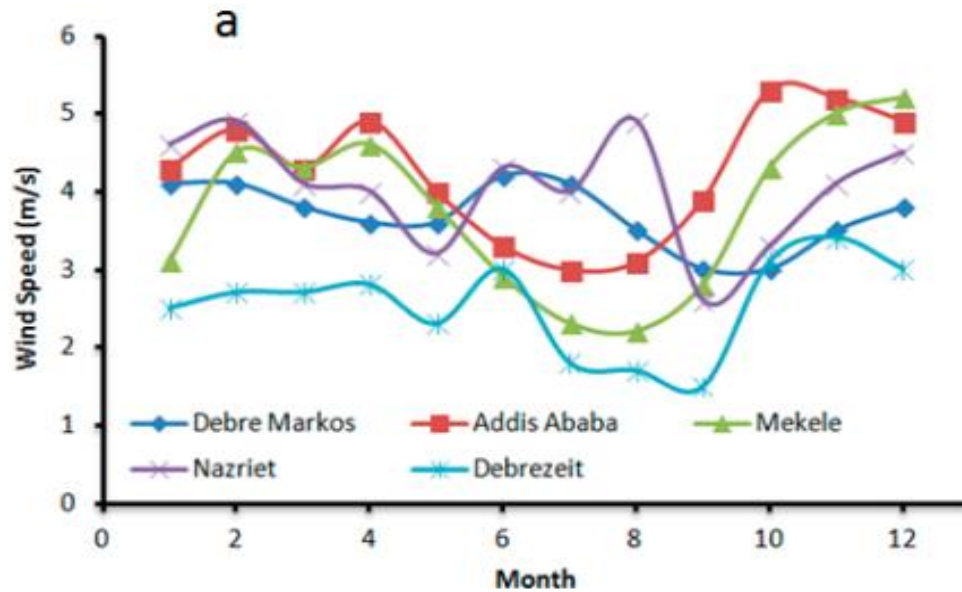


Figure 2.23: Monthly average wind speeds at the five locations (Tiruye et al., 2021).

Tolu (2021) identified 2,507.2 hectares of land around Debre Berhan town as most suitable for wind energy harvesting, generating 60.18 MW. Additionally, 189.2 hectares of land in the

town can be used for urban wind energy, with an estimated 3.82 MW of urban wind energy from building-integrated wind turbines.

2.5.3 Wind Energy in Addis Ababa

According to the Addis Ababa Distribution Master Plan (AADMP) prepared by the African Development Bank (AfDB) in 2015, Addis Ababa's electricity demand will continue to increase from 800 MW in 2014 to 3,576 MW in 2034 (Ethiopian Electric Power, 2018). Specifically, 1) insufficient capacity and deterioration of equipment cause a loss of about 19% of the distribution system; 2) a rapid increase in demand causes the capacity of transformers and distribution lines to become overloaded; and 3) deterioration due to the aging of equipment, frequent power outages, and voltage drops occur on the grid. For example, Addis Ababa experienced more than 20,000 power outages in 2017, for a total of more than 20,000 hours of power outages (NEWJEC Inc., 2018).

By increasing clean energy and considering different supply forms (which may or may not depend on the national grid), urban municipalities should augment a wide range of energy services and use them for production activities to increase and accelerate economic growth (CitiesAlliance, 2017). Degife & Sy (2020) considered the design and analysis of small wind turbines as an alternative power source for Addis Ababa's inhabitants, with an average power consumption of about 20 kWh and a design power of about 25.418 kWh, which is above average. Thus, the city's electricity consumption can be met as an alternative energy source. As the survey found, the average wind speed in Addis Ababa at 20m high is 8 m/s. After calculations and simulations, the design has been fully tuned to meet the average needs of the city's inhabitants, and the city of Addis Ababa often suffers from power outages, so the installation of small wind turbines is essentially desirable.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of Study Area

The study area, Addis Ababa City, is located on the plateau of central Ethiopia. It is between $8^{\circ}49'55.9''$ to $9^{\circ}5'53.8''$ North latitude and $38^{\circ}38'16.6''$ to $38^{\circ}54'19.5''$ East longitude. The city's height varies from 2,050 meters in the southern Akaki Plain to 3,000 meters on Mount Entoto in the north, indicating its diverse terrain and elevation. Addis Ababa's terrain is steep with typical volcanic features, with the central part being calm and hilly and the southern and eastern parts being flat (Ethiopian Electric Power, 2018). Addis Ababa, with an electricity access rate of 98%, faces frequent outages and interruptions, with an average of 42 weekly interruptions in January 2015. With 614 MW of demand in 2014, Addis Ababa accounted for 42% of the country's interconnected system peak load. Upgrades are needed to improve efficiency and reduce system losses, estimated between 20% and 22.7% (Ketema et al., 2015). The location map of the study area, Addis Ababa City, is shown in Figure 3.1 below.

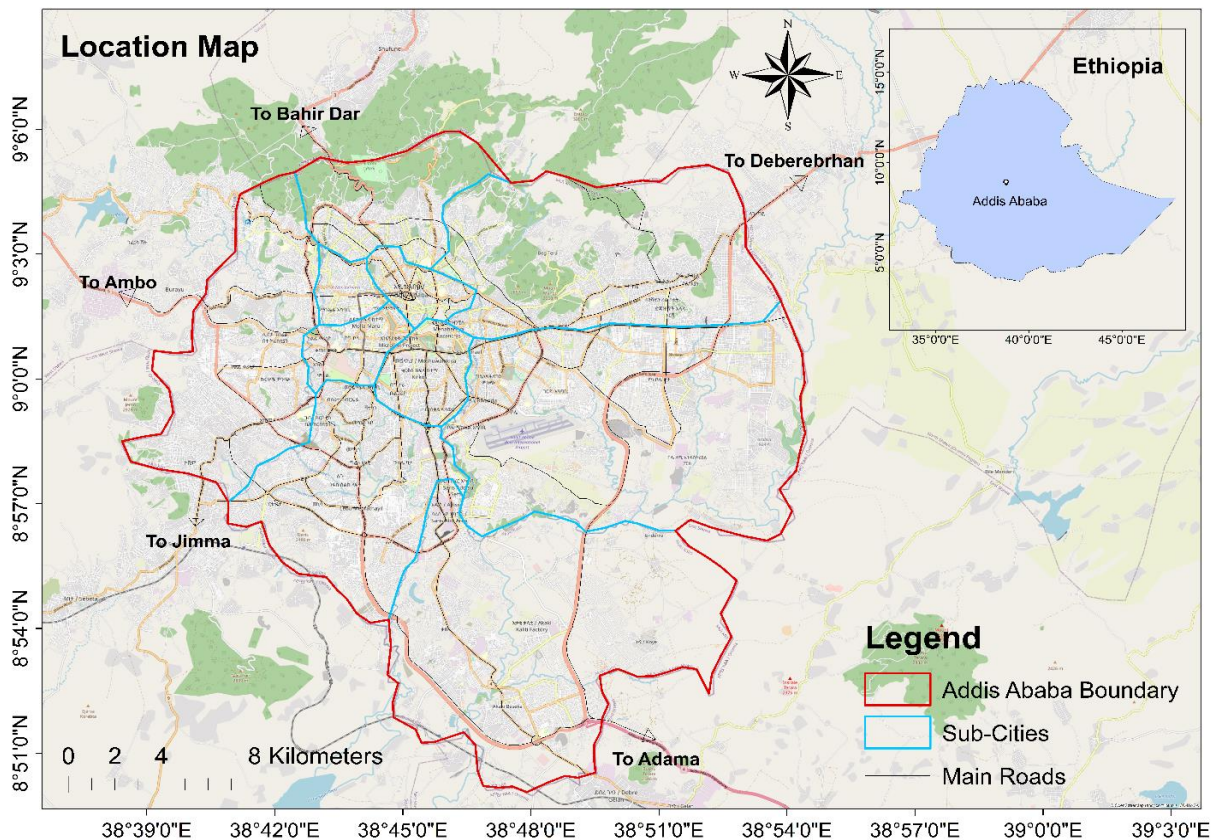


Figure 3.1: Location map of the study area.

3.2 Data Types

There are several types of data used in this study, and the data are qualitatively organized. Most data and non-numeric or collected data are in the form of annotations and illustrations. The data type used in this study is based on multi-criteria decision input. In addition, the data types include DEMs (Digital Elevation Models) that can be used to generate most of the spatial data used in this survey, such as slopes and stream orders. Furthermore, wind speeds, existing road networks, air traffic locations, and a building network of geospatial data are used.

3.3 Data Sources

Data was collected from both primary and secondary data sources. Key data from this study were collected through field observations and informational interviews. Secondary data sources include different Addis Ababa City Offices, books, journal articles, and metrology station data sources collected from NASA Surface Metrology, the Global Wind Atlas, EPW, MapServer Ethiopia, the USGS Satellite Map, Earth Explorers, and the Global Positioning System.

3.4 Method of Data Collection

Wind speed data, the statistical data for this study is collected from NASA's Surface Metrology, Global Wind Atlas, and Meteoblue Metrology Data. Spatial data from this study was collected from a Digital Elevation Model (DEM) that helps generate slopes and rivers streams. From ArcMap and QGIS desktops as a tool collected by the USGS Satellite Map Earth Explorer. USGS satellite map Landsat images that support the creation of maps for the study area by ArcMap remote sensing collected by the Earth Explorer and MapServer Ethiopia. EPW is used to collect additional wind data and ladybug tools, and all other spatial data such as urban areas, air traffic locations, light railways, etc. are created by digitizing with ArcMap using an editor tool. Maps, tables, and figures were used to present the data from this survey.

3.5 Method of Analysis

The analysis method that is developed in this study integrates both wind speed and aerodynamic form considerations into early design stages by pairing the GIS-based MCDM analysis method for siting locations with CFD software simulations for wind-based form-finding processes.

The data collected for this study is based on geospatial data from GIS-based MCDM inputs. Multi-criteria decision-making consists of steps that include weighting geospatial data and

decision criteria and manipulating the data according to the decision criteria. This approach uses ArcMap software to manage and process MCDM and combine spatial information, including wind speeds, gradients, distances from power lines, and other spatial data or criteria used in the survey.

In addition, CFD simulation software and parametric analysis are used to process output data from MCDM and wind speed data for further aerodynamic form optimization iterations.

3.5.1 Potential Sites for Wind Energy Harvesting in Addis Ababa City

Potential site selection for urban wind harvesting requires a balance of multiple objectives to be considered when determining the suitability of a particular area for a defined land use. Choosing the right project area involves a complex set of key elements from the fields of physical geography, demography, economics, policy, and environmental discipline (Bennui et al., 2007).

For this study, Geographic Information Systems (GIS) and Multi-criteria Decision Making (MCDM) techniques have been used in solving site selection problems. In addition, the Analytic Hierarchy Process (AHP) method is adopted to weight criteria used in multi-criteria decision-making processes.

A. Geographic Information Systems (GIS)

Geographic Information Systems (GIS) have proven to be computerized tools that help describe and manipulate space. Often described as a decision support system, there have been some supporting modules for site selection based on different regional situations and conflicting goals.

B. Multi-Criteria Decision-Making (MCDM)

The technique used in different approaches to decision analysis is known as multiple-criteria decision-making (MCDM). These methods contain explicit statements about decision-maker preferences. Such settings are represented by various sizes, weighting schemes, limits, goals, benefits, and other parameters. MCDM analyzes and supports decision-making through formal analysis of alternative options, their characteristics, characterization criteria, goals or specifications, and limitations. MCDM has been used to solve various site selection problems. MCDM results can be mapped to show the spatial extent of the best areas or the index of land suitability (Bennui et al., 2007).

C. The Analytical Hierarchy Process (AHP)

The most important factor in MCDM is to set weights on some criteria based on importance. Location decisions, such as the ranking of alternative municipalities, are typical multi-criteria decisions that require the prioritization of several criteria. Analytic Hierarchy Process (AHP) is a comprehensive, logical, and structural framework that allows analyzers to improve their understanding of complex decision-making by breaking down problems into hierarchical structures. By including all relevant decision criteria and their pairwise comparisons, decision-makers can determine conflicting goals. AHP allows decision-makers to model complex problems in a hierarchical structure that shows the relationships between goals, objectives, criteria, and alternatives (Solangi et al., 2018).

D. Steps used in GIS-MCDM

Step 1: Defining the problem, goal, or objective; Try to understand and define the problem as comprehensively as possible.

Step 2: Determine the criteria and constraints; Using a combination of experts' opinions and information from various sources. This could be acquired through discussions with experts in relevant fields, a survey of the literature, and the analysis of historical data.

Step 3: Transform the values into a relative scale; this allows for comparison between each of the criteria to represent the judgments and expert knowledge with meaningful numbers.

Step 4: Weight the importance of each criterion regarding the objective and in respect to each other.

Step 5: Combine, synthesize, and aggregate the layers or criteria together.

Step 6: Analyze and then validate the results.

ArcGIS has fantastic possibilities for storage, analysis, manipulation, management, and visualization of spatial facts, and MCDM affords a group of procedures and strategies for structuring selection problems, designing, evaluating, and prioritizing the selection criteria.

Table 3.1 specifies the spatial facts of supply and common weight. So, GIS-MCDM primarily based CFD simulation is a model proposed for this study as a scientific tool for rational decision-making for choosing suitable sites for wind harvesting.

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

No	Factors	Spatial Data Source	Analysis
Topographic (5%)			
1	Slope	DEM of Addis Ababa city from USGS EarthExplorer	ArcGIS Spatial Data Analysis
Technical (50%)			
2	Wind speed	NASA metrology agency Global wind atlas, EPW	ArcGIS, ArcMap
Environmental (20%)			
3	Distance from rivers	DEM of Addis Ababa city	ArcGIS
Socioeconomic (25%)			
4	Distance to main roads	MapServer Ethiopia	ArcGIS
5	Distance from airports	Humdata Digitize existing airport	ArcGIS ArcGIS Editor tool

Figure 3.2 illustrates GIS based MCDM wind harvesting site selection overall process.

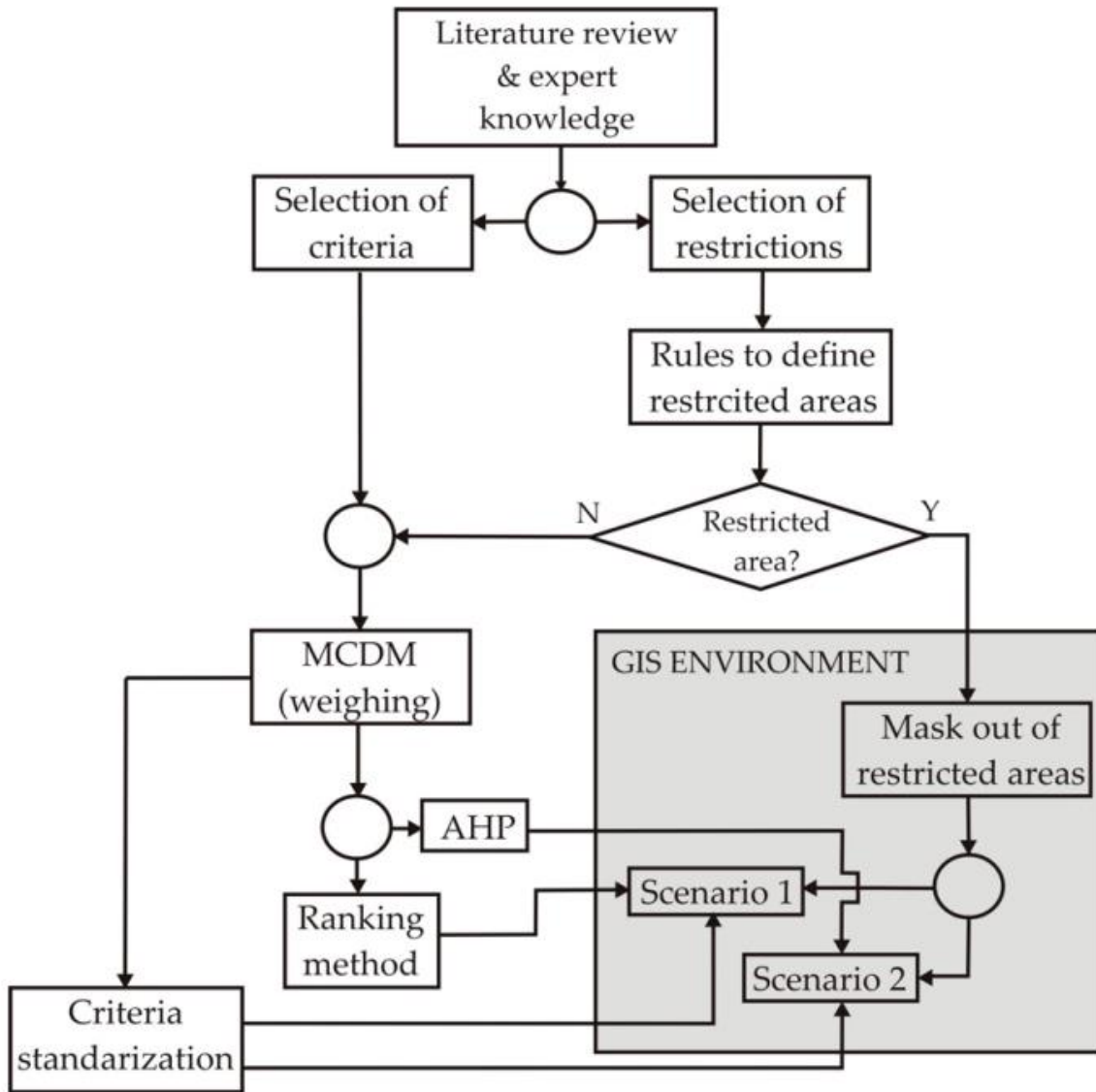


Figure 3.2: GIS based MCDM wind harvesting site selection overall process (Prieto-Amparán et al., 2021).

E. Investigation of the suitability of the wind farm

The investigation of suitability for a city wind harvesting site is done tremendously, defining and weighting every criterion with a specific impact or weight to choose a vicinity for wind harvesting locations. The standards and supply of statistics concerned with the MCDM are diagnosed and entered into ArcMap. The input data fed comes from different sources, as defined in Table 3.1, and the datasets are generally prepared in ArcMap in a raster or vector layout with a first-rate or spatial resolution. ArcMap is used to hold the transformation of thematic and spatial figures into virtual form (distance mapping, buffering, masking, mapping, map overlay, map sum, etc.).

3.5.2 Wind-Based Building Form Optimization

The basic purpose of calculating the effect of air parameters on mechanical performance (later to be electrical output) is to show the power generation sensitivity of a wind power generator to changes in air characteristics at arbitrary wind speed values. Likewise, the consistent aim of optimizing the building form based on the analyzed wind data is to maximize the revenues of power from building integrated wind farms, which poses a huge need for understanding the way wind turbines perform. Thus, in this study, the Computational Fluid Dynamics (CFD) simulation method is used to analyze the energy performance of the building to optimize its aerodynamic form accordingly.

I. Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics is a powerful analysis tool that is used to study the wind flow around a building. It simulates the flow of fluids, including wind, around an input model and produces numbers, graphics, and animations to convey this flow (Spence et al., 2013).

Computational fluid dynamics (CFD) is a method used to describe the movement of heat or liquid in and around a solid object over time. In this study, CFD was used to simulate wind, solving complex differential equations using a CFD code. The code divides the void space around the building model into smaller boxes, where the movement of the liquid is calculated using differential equations. Before performing the simulation, the simulation parameters, such as wind speed and direction, are entered (Bernardini, Spence, et al., 2015).

CFD programs are typically designed for engineering purposes but can also be used in architectural design stages. The method selects software that can be adapted for architectural use, and the best CFD program for this method is determined based on its performance.

Hence, Autodesk Forma, HKwind, and Butterfly Grasshopper plugins are the selected CFD programs to be used in this study, including Octopus and Galapagos parametric optimizers as building form analysis methods.

II. Optimization Process

Airflow patterns around a building are strongly influenced by the building's geometry. This is noticeable in buildings that are taller than the average urban area. By changing the shape of the building aerodynamically, this non-structural phenomenon can be turned into a large-scale

condensing effect, which can increase the amount of wind power generated by high-rise buildings.

Accordingly, to find the optimal solution for wind energy-generating buildings, the following steps are adopted in the optimization process:

Step 1: Criteria Definition: The criteria defined for this study are *variable parameters*, which include geometries, tower arrangements for single towers, and form modification using HKwind, Autodesk Forma, and Galapagos-Grasshopper.

Step 2: Footprint Geometry and Tower Arrangement: In this step, footprint shapes of tall buildings such as basic bluff, complex bluff, and airfoil geometries are investigated to get the optimal geometry and tower arrangement using Butterfly CFD, Autodesk Forma, and Octopus-Grasshopper.

Step 3: Prototype Definition: In this stage, optimized footprint geometry and tower arrangement are simulated to carve out elective prototypes of the building form responding to wind energy harvesting using HKwind, Autodesk Forma, and Octopus Multi-Objective Optimizer in Grasshopper.

Step 4: Performance Simulation: After the optimal building form is defined, this step simulates the performance of the building for wind turbine integration using Autodesk Forma. The major procedure sequences include raw data input, parametric model setup, optimization loop, accuracy control, and optimal output.

The overall method of this study's optimization process is summarized in Figure 3.3 below.

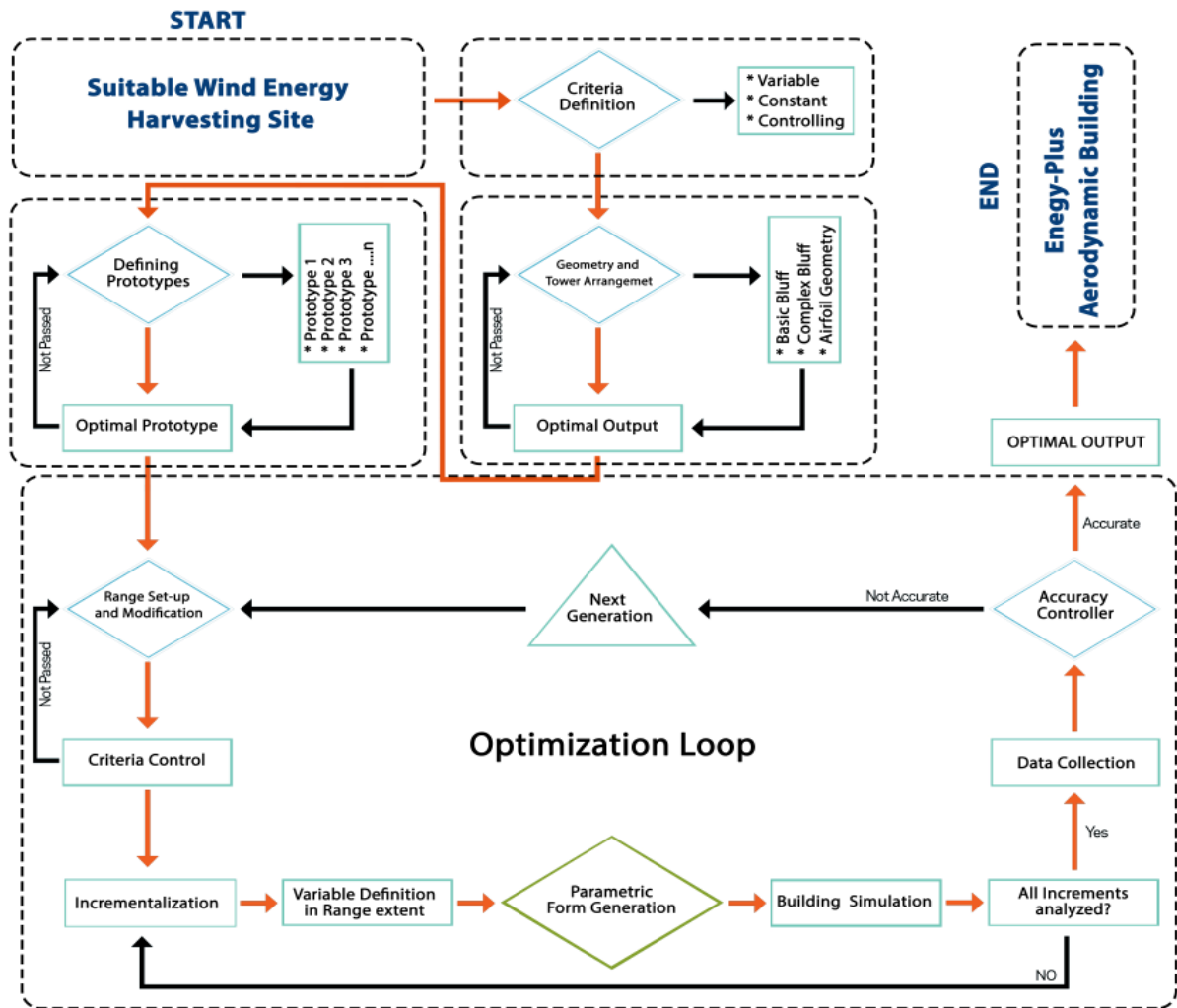


Figure 3.3: Flow chart of the energy-plus aerodynamic building form optimization process.

3.6 Research Design

Research design is a strategic approach that logically integrates study elements to address research issues. It serves as a roadmap for data collection, measurement, and analysis (Loru, 2020). Figure 3.4 illustrates the research design and procedure designed for this study.

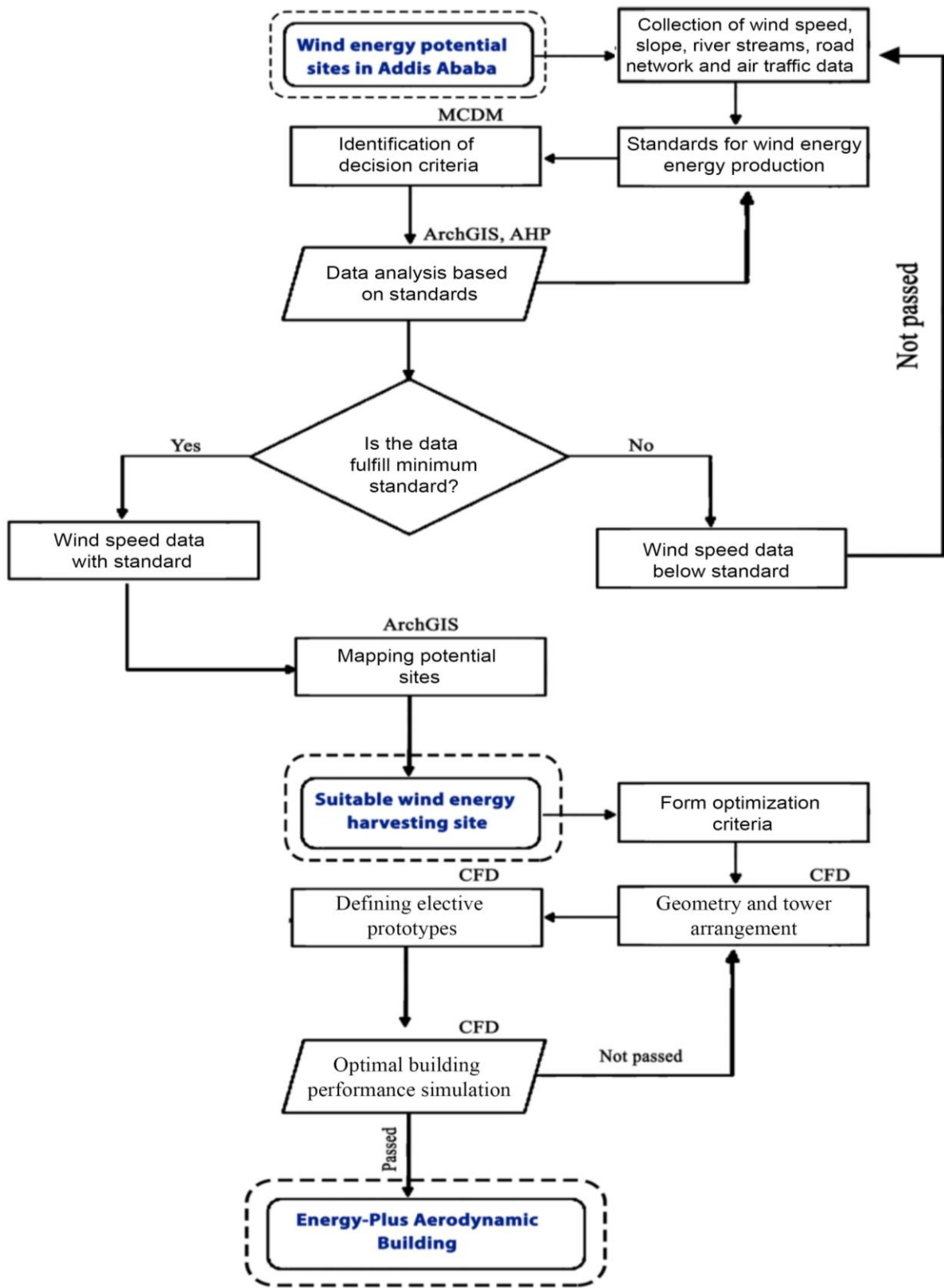


Figure 3.4: Research design and procedure.

3.7 Summary of methods

Methods, including data types used for this study, methods of data collection, and methods of data analysis, are summarized in Table 3.2 below.

Table 3.2: Summary of methodologies.

Specific Objective	Data type	Methods of data collection	Method of analysis
1. To identify potential sites for wind-based energy-plus building.	Wind speed, DEM and published documents	NASA Metrology Agency, MapServer Ethiopia, EnergyPlus, USGS Satellite Map and Global Wind Atlas	ArcGIS, MCDM and AHP to analyze suitable maps
2. To carve out the form of building responding for wind energy harvesting.	Wind speed and Suitability map	ArcGIS suitability map, EPW and NASA Metrology Agency	Autodesk Forma, Hkwind CFD simulation, Butterfly-Grasshopper CFD plugin, Octopus and Galapagos Grasshopper plugins to generate optimized building from
3. To design aerodynamic building.	Optimized building form	CFD simulated model from Rhinoceros + Grasshopper software	Rhinoceros, Lunch-box-Grasshopper Plugin, Heliotrope-Grasshopper Plugin and paneling tools for final building output

3.8 Analysis

3.8.1 Potential Sites for Wind Energy Harvesting in Addis Ababa City

The analysis of 30-year average wind speed data for the study area shows that the average minimum wind speed was recorded in August, which was 3.02 m/s, and the highest average wind speed was recorded in October, which was 5.18 m/s. As 3 m/s is the minimum wind volume required to operate a wind power system on a high-rise building (J. H. Park et al., 2014), the average 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. Figure 3.5 below provides an overview of the study area's 30-year data on yearly average wind speed. The Appendices 1 and 2, respectively, exhibit the 30-year inter-annual averages of wind speed data for Addis Abeba city for each month from 1991 to 2021 at heights of 10m and 50m.

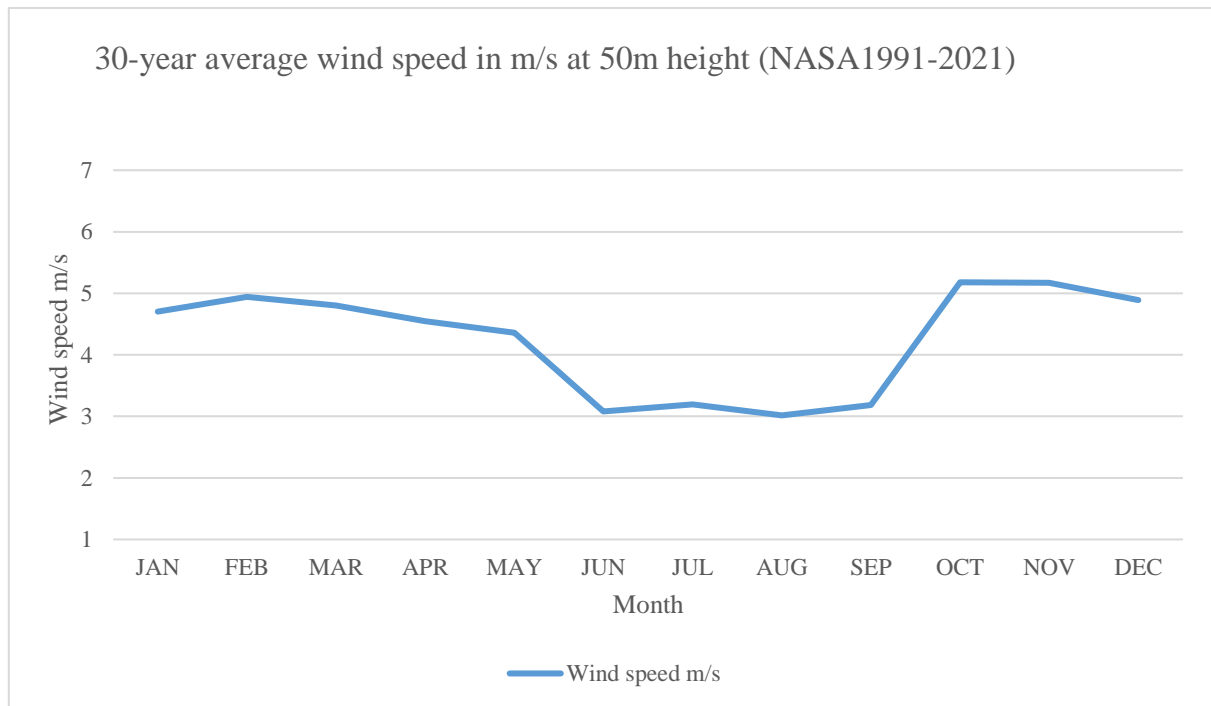


Figure 3.5: 30-year average wind speed in m/s at 50m (NASA 1991 - 2021).

The wind rose diagram, as shown in Figure 3.6, illustrates that the wind flow direction in Addis Ababa city is mostly blown from the east and east of the south-east.

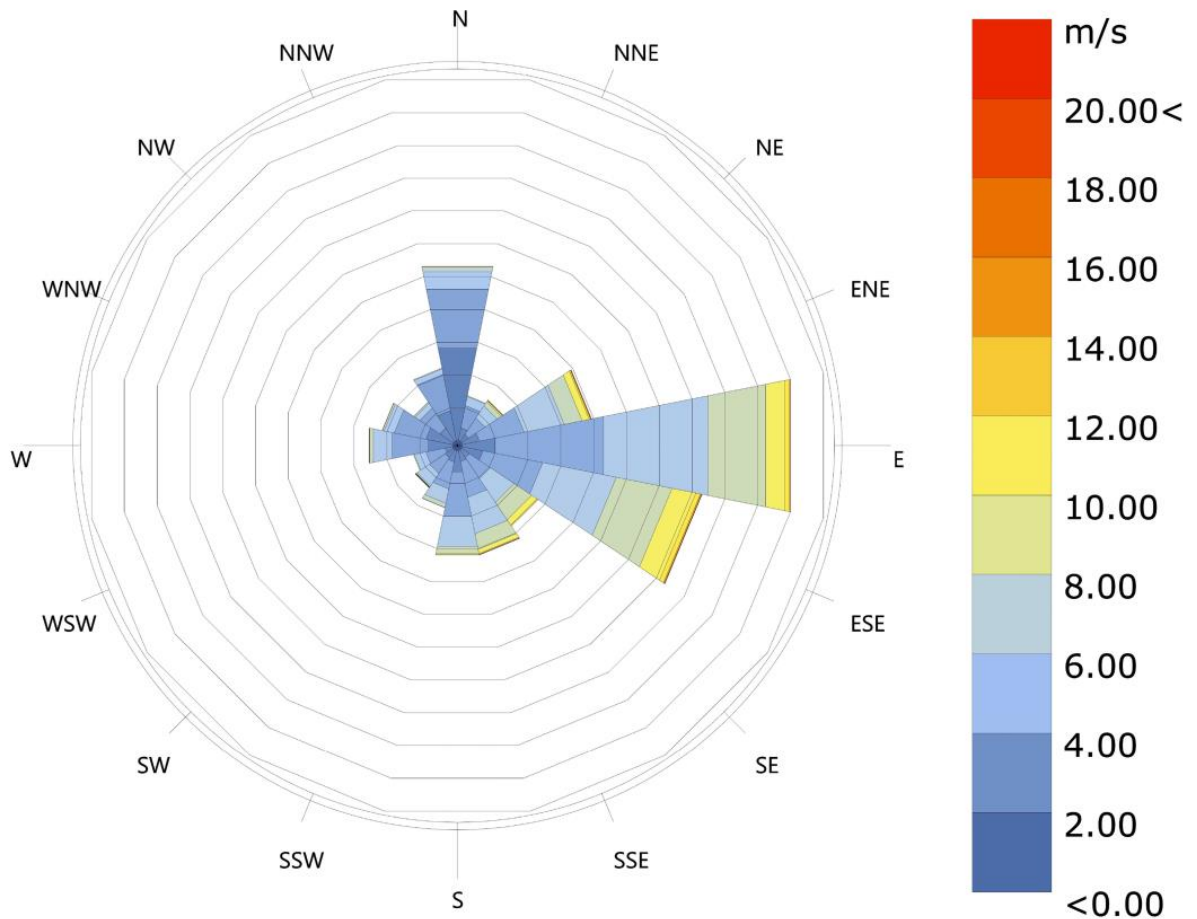
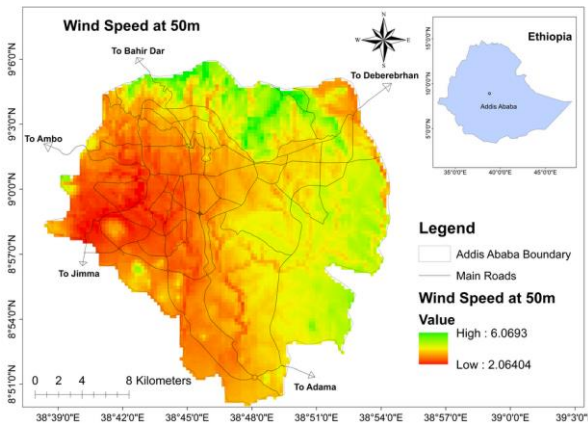
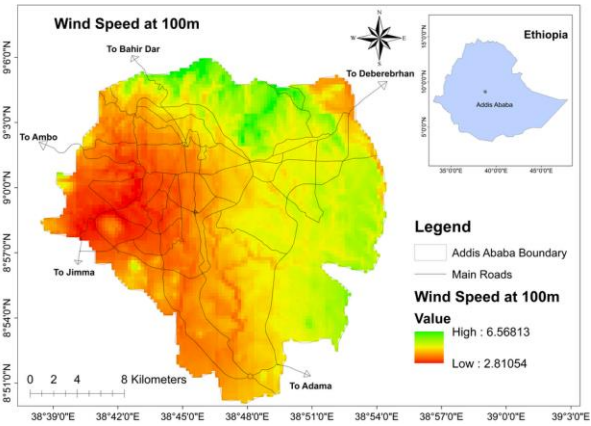


Figure 3.6: Wind rose diagram of the study area (EnergyPlus).

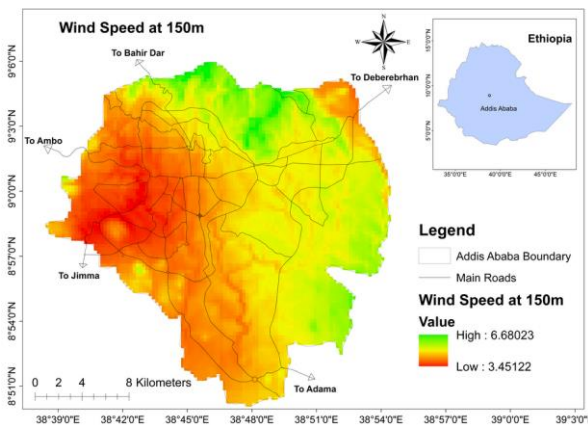
Altitude is one of the determinants for installing wind turbines. At higher altitudes, the wind speed increases, and at constant speeds, maximum energy harvesting from the wind is possible. Thus, velocities at 50m, 100m, 150m, and 200m are analyzed. The maximum wind speed is at 200m, which is equivalent to about 6.85 m/s. Figures 3.11 (a), (b), (c), and (d) display the maximum and minimum wind speeds in the study area at four different heights, as shown in Figure 3.7 below. The southeast and northeast parts of the study area are the best places to use wind energy.



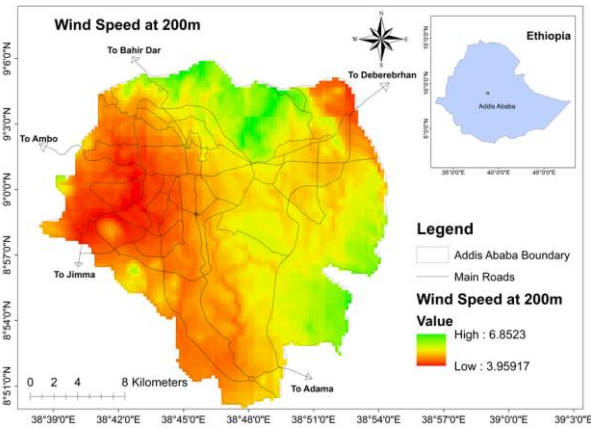
(a) at 50m



(b) at 100m



(c) at 150m



(d) at 200m

Figure 3.7: Windy areas in Addis Ababa at 50m, 100m, 150m and 200m.

3.8.2 Investigation of Wind Farm Suitability Using MCDM

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 were reclassified, the criteria values were normalized for comparison and weighting. 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 that minimizes the impacts of less importance for selecting windy areas, and with each layer assigned a suitability value. Finally, combine the weighted layers to select the best location for producing wind energy. Table 3.3 illustrates the criteria used for prioritizing wind energy harvesting sites.

Table 3.3: Criteria used for prioritizing wind energy harvesting sites.

No	Criterion	Parameters	Suitability	Value Score
1	Slope (%)	0-5	Very High	4
		5-10	High	3
		10-20	Moderate	2
		20-25	Low	1
		>25	Not suitable	0
2	Wind speed (m/s)	>6	Very High	4
		5-6	High	3
		4-5	Moderate	2
		3-4	Low	1
		<3	Not suitable	0
3	Distance from rivers (m)	>250	Very High	4
		150-250	High	3
		100-150	Moderate	2
		50-100	Low	1
		<50	Not suitable	0
4	Distance to main roads (m)	0-200	Very High	4
		200-500	High	3
		500-1000	Moderate	2
		>1000	Low	1
5	Distance to airports (m)	>6000	Very High	4
		4000-6000	High	3
		3000-4000	Moderate	2
		2500-3000	Low	1
		<2500	Not suitable	0

1. Slope Suitability

The slope map of the overall examined site illustrates that the maximum of the area is between 0 and 5 degrees, which is appropriate for wind energy harvesting. Most of the location with slope criteria appropriate for the wind farm is placed within the southern part of the studied site, and the slope map of the study area is shown in Figure 3.8 below.

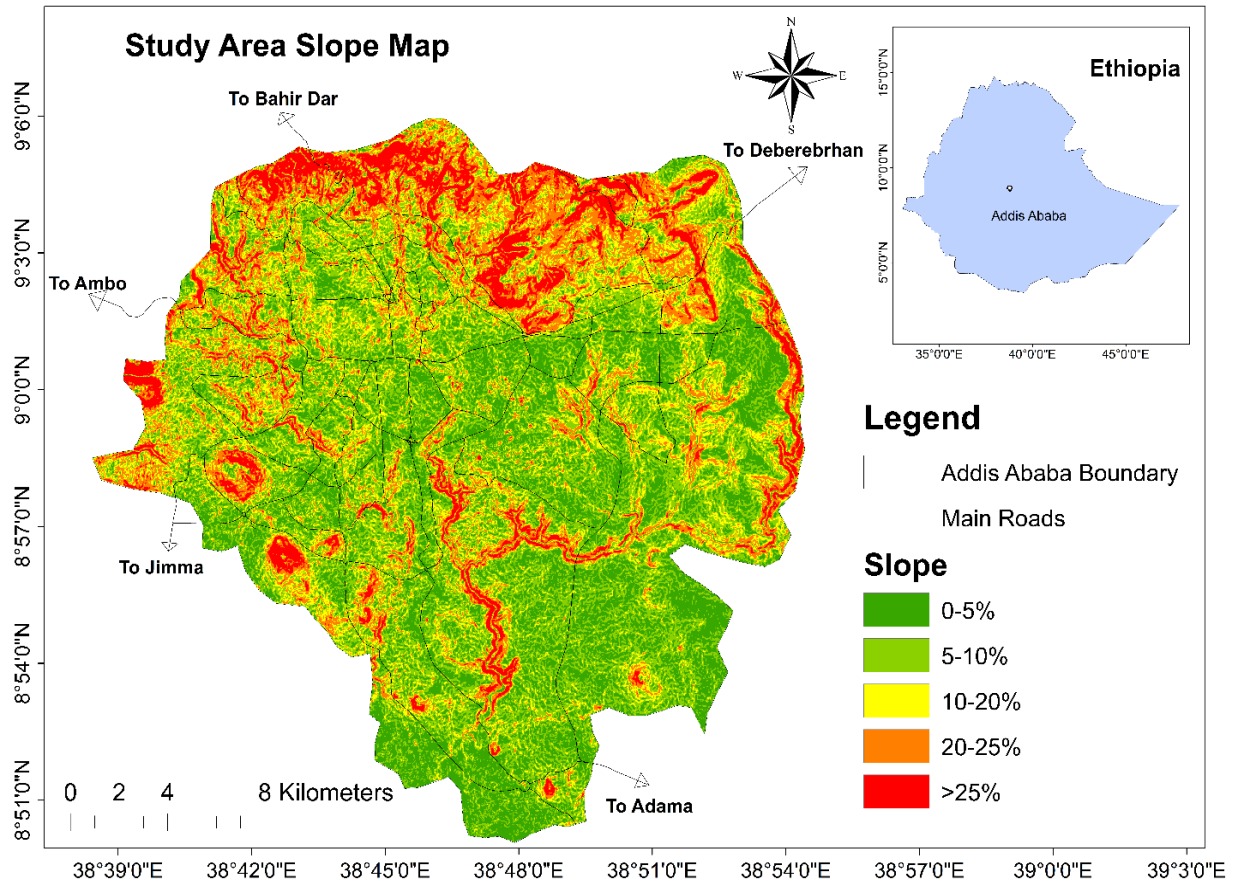


Figure 3.8: Slope map of the study area.

Slope suitability analysis, as shown in Figure 3.9 and summarized in Table 3.4, shows that only 7.46% of the study area is not suitable for siting wind turbines, and 4.86% of the whole area is low suitable. On the other hand, 27.71%, which covers around 14,973 hectares is very high suitable for wind energy harvesting.

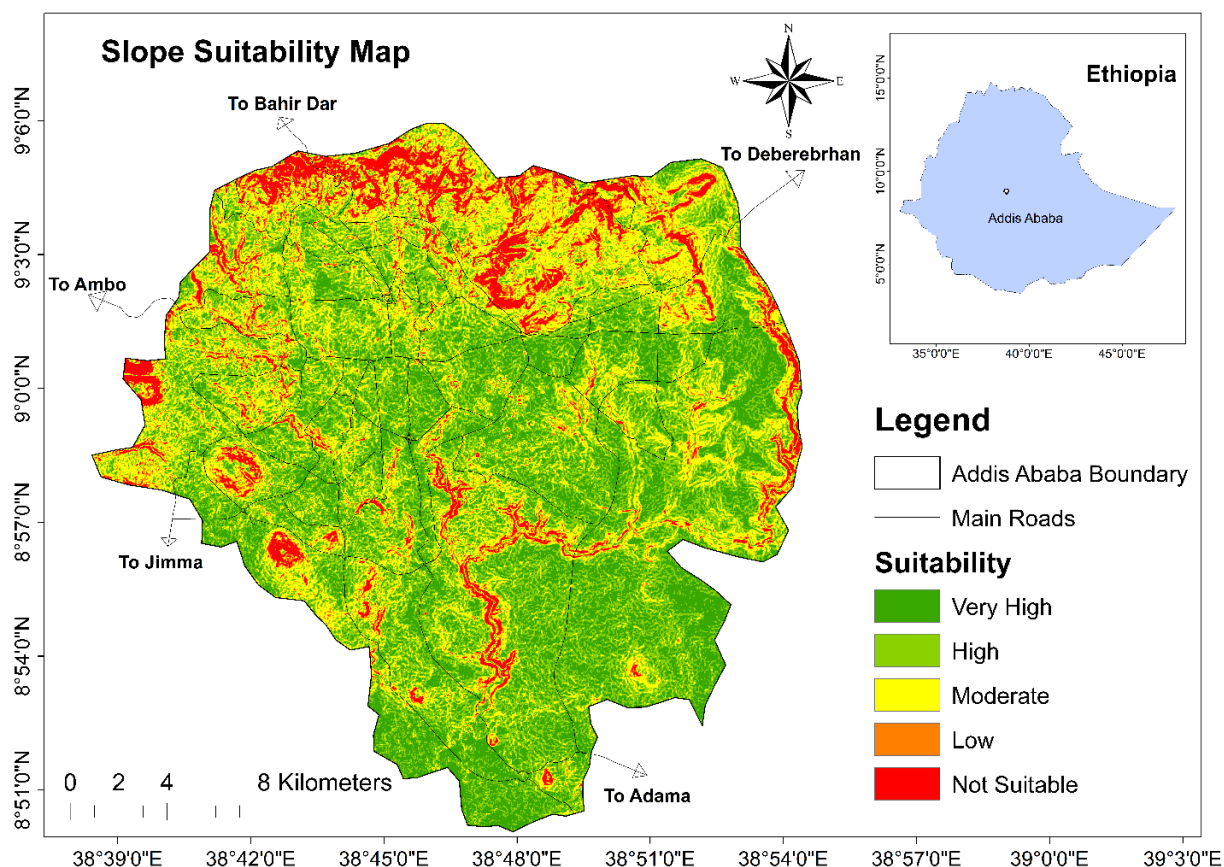







Figure 3.9: Slope suitability map.

Table 3.4: Summary of slope suitability.

Suitability	Rank	Color Code	Slope (%)	Area (ha)	Percentage
Very High	1		0-5	14973	27.71%
High	2		5-10	17888	33.18%
Moderate	3		10-20	14446	26.79%
Low	4		20-25	2624	4.86%
Not Suitable	5		>25	3980	7.46%

2. Wind Speed Suitability

In this study area, all extents met the standard for harvesting wind energy in built environments, which is >3 m/s. 14.70% of the area is low suitable for wind energy harvesting, whereas 80% of the whole area has more than 4 m/s wind speed under different suitability ranks. Moreover,

961 hectares of the study area are very high suitable, and 13,831 hectares from the whole extent are highly suitable for wind energy harvesting. Figure 3.10 and Table 3.5 shows the wind speed suitability map and its summary, respectively.

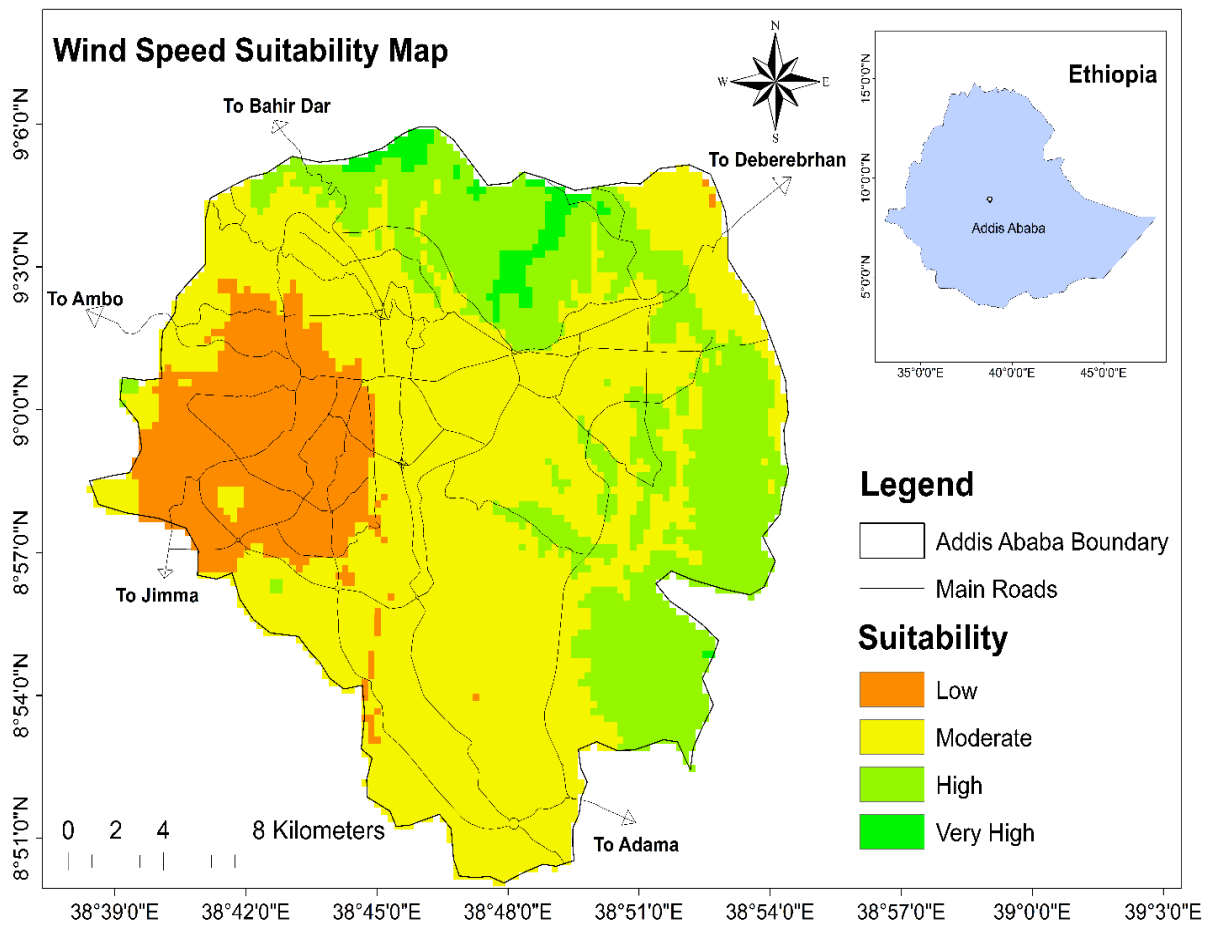






Figure 3.10: Wind speed suitability map.

Table 3.5: Summary of wind speed suitability.

Suitability	Rank	Color Code	Wind Speed	Area (ha)	Percentage
Very High	1		>6 m/s	961	1.78%
High	2		5-6 m/s	13831	25.67%
Moderate	3		4-5 m/s	31169	57.85%
Low	4		3.45-4 m/s	7914	14.70%

3. Proximity to River Lines Suitability

The buffer zone for the main river lines is likewise taken into consideration when selecting wind harvesting sites. For this study, main river lines are extracted and taken into consideration, and the general river map of the study area is shown in Figure 3.11 below.

Most of the main river lines are located on the western central sides of the north-south directions in the study area.

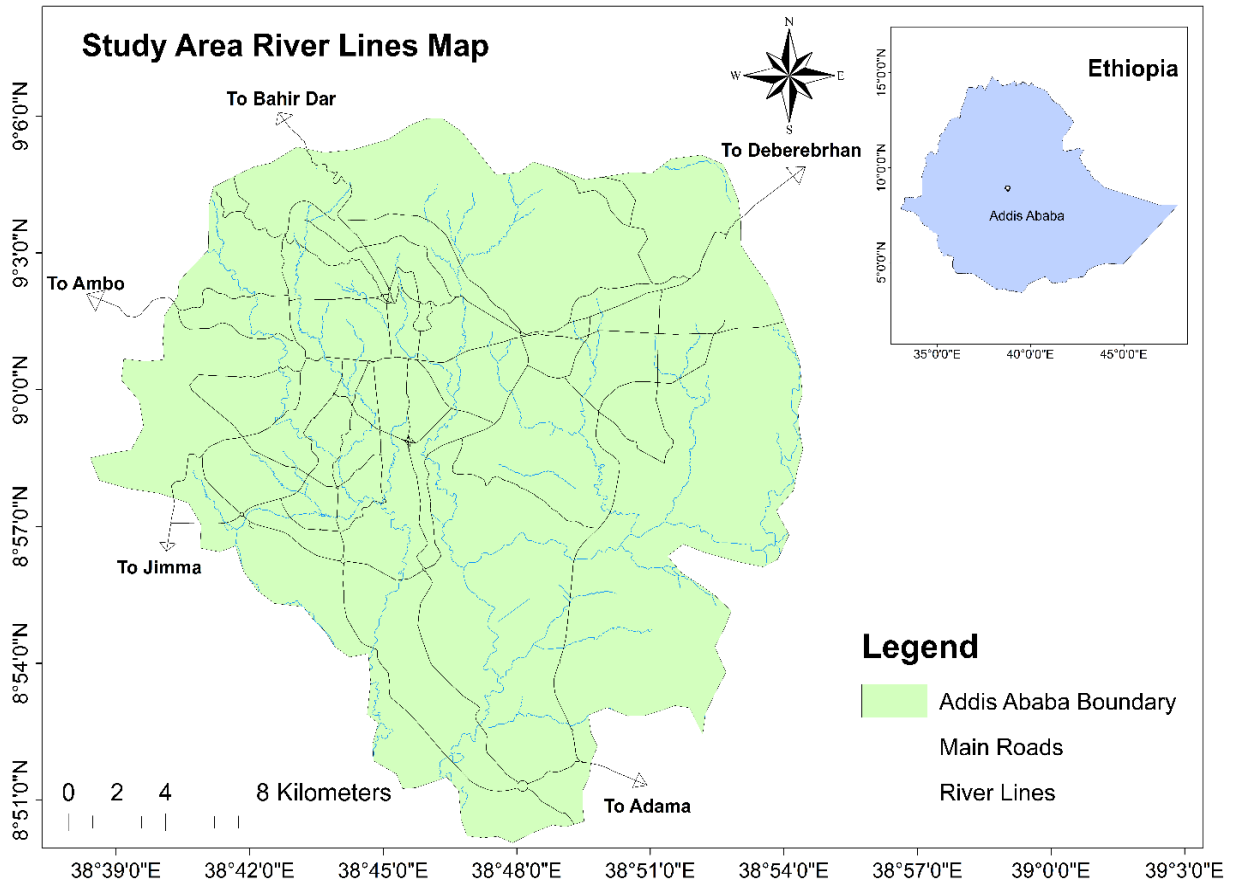


Figure 3.11: River map of the study area.

As rivers are naturally protected areas, the construction of wind harvesting sites should exclude the buffer zone from existing major river lines. Figure 3.12 and Table 3.6 show that 78.98% (72,583 hectares) of the study area is more than 250m away from river lines, which is very high suitable for siting wind farms.

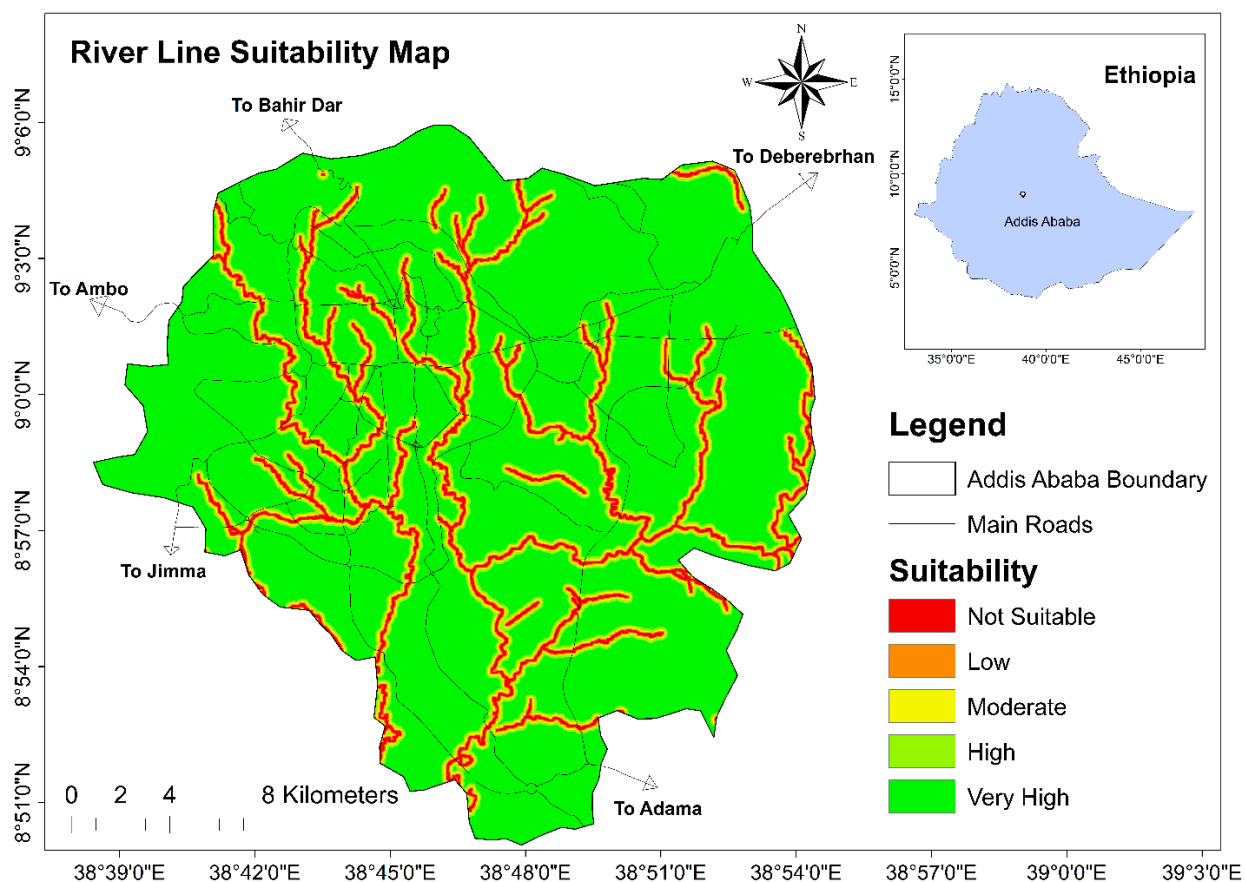







Figure 3.12: River line suitability map.

Table 3.6: Summary of river line suitability.

Suitability	Rank	Color Code	Distance (m)	Area (ha)	Percentage
Very High	1		>250	42583	78.98%
High	2		150-250	4100	7.60%
Moderate	3		100-150	2334	4.32%
Low	4		50-100	1870	3.46%
Not Suitable	5		<50	3025	5.64%

4. Proximity to Main Road Suitability

Road networks are another essential factor in wind farm development in that their proximity helps minimize the construction and maintenance costs of wind farms. It is therefore necessary that the distance between the proposed wind farm location and the road network be as low as

possible. In this study area, different categories of road networks are studied and presented in Figure 3.13 below.

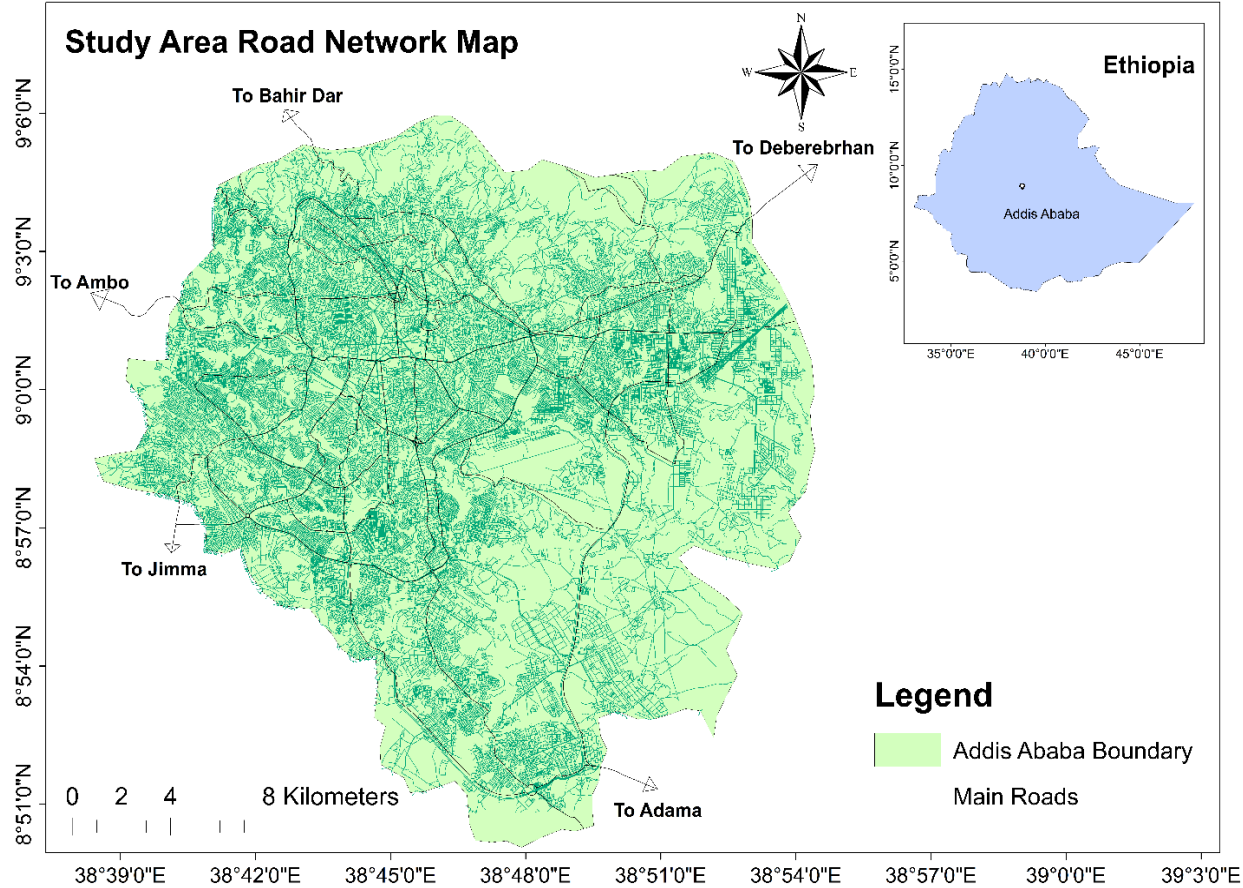


Figure 3.13: Existing road networks in the study area.

As shown in Figure 3.14 and summarized in Table 3.7 below, the study area under very high and high suitability is 0-500m close to the main road, which covers 23.22% (12,512 ha) and 25.73% (13,862 ha), respectively, which are considered to be the highest siting preferences.

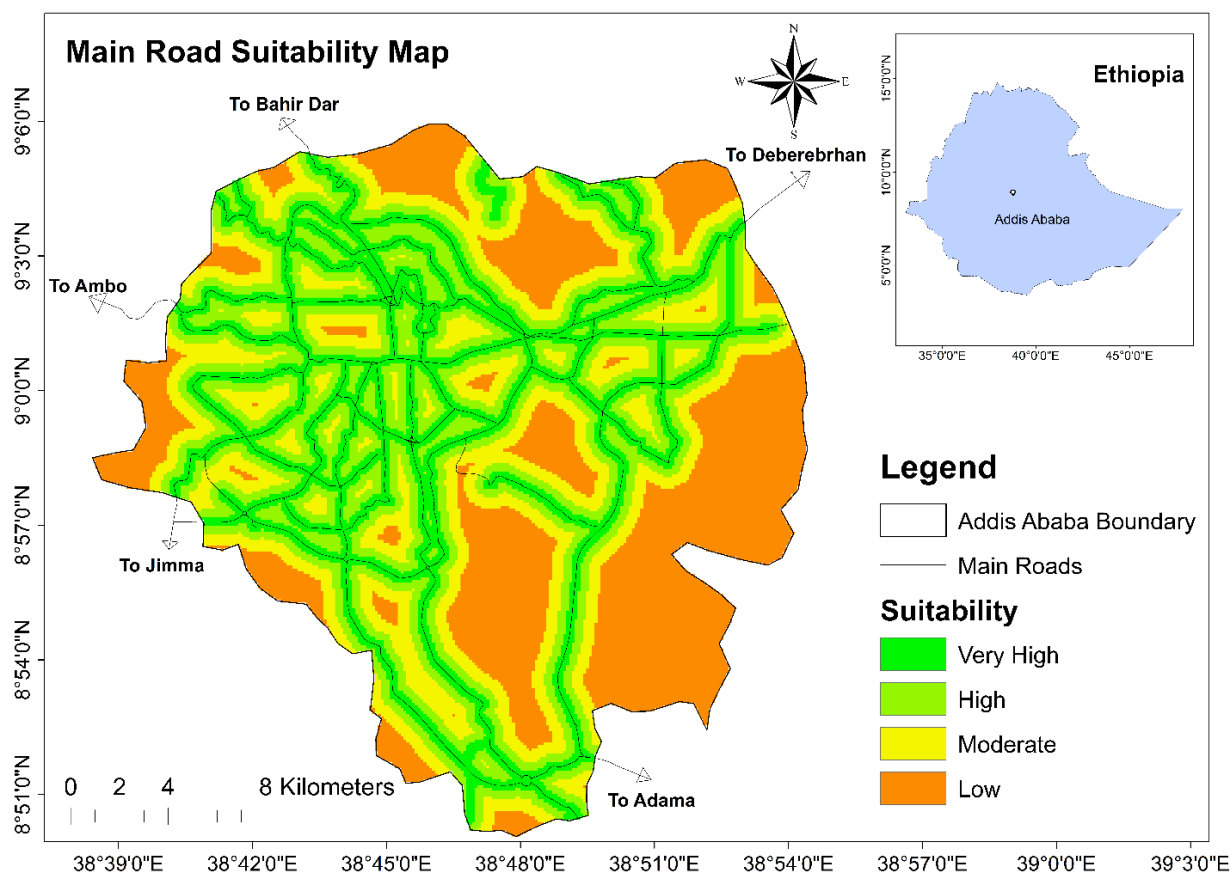






Figure 3.14: Existing road suitability map.

Table 3.7: Summary of existing road suitability.

Suitability	Rank	Color Code	Distance (m)	Area (ha)	Percentage
Very High	1		0-200	12512	23.22%
High	2		200-500	13862	25.73%
Moderate	3		500-1000	11158	20.71%
Low	4		>1000	16342	30.34%

5. Proximity to Air Traffic Suitability

Wind turbines are affected by flight paths and can lead to collisions, so care must be taken when installing a wind farm to ensure a reasonable distance from the airport. In addition, wind turbines can affect airport communications systems and navigation. It is recommended to offset

that a minimum distance of 3 km from major airports (Zalhaf et al., 2022). In the study area, as shown in Figure 3.15, there are two air traffic locations, which are Bole International Airport situated in Bole and Torhailoch Air Force landing at the Ministry of Defense compound.

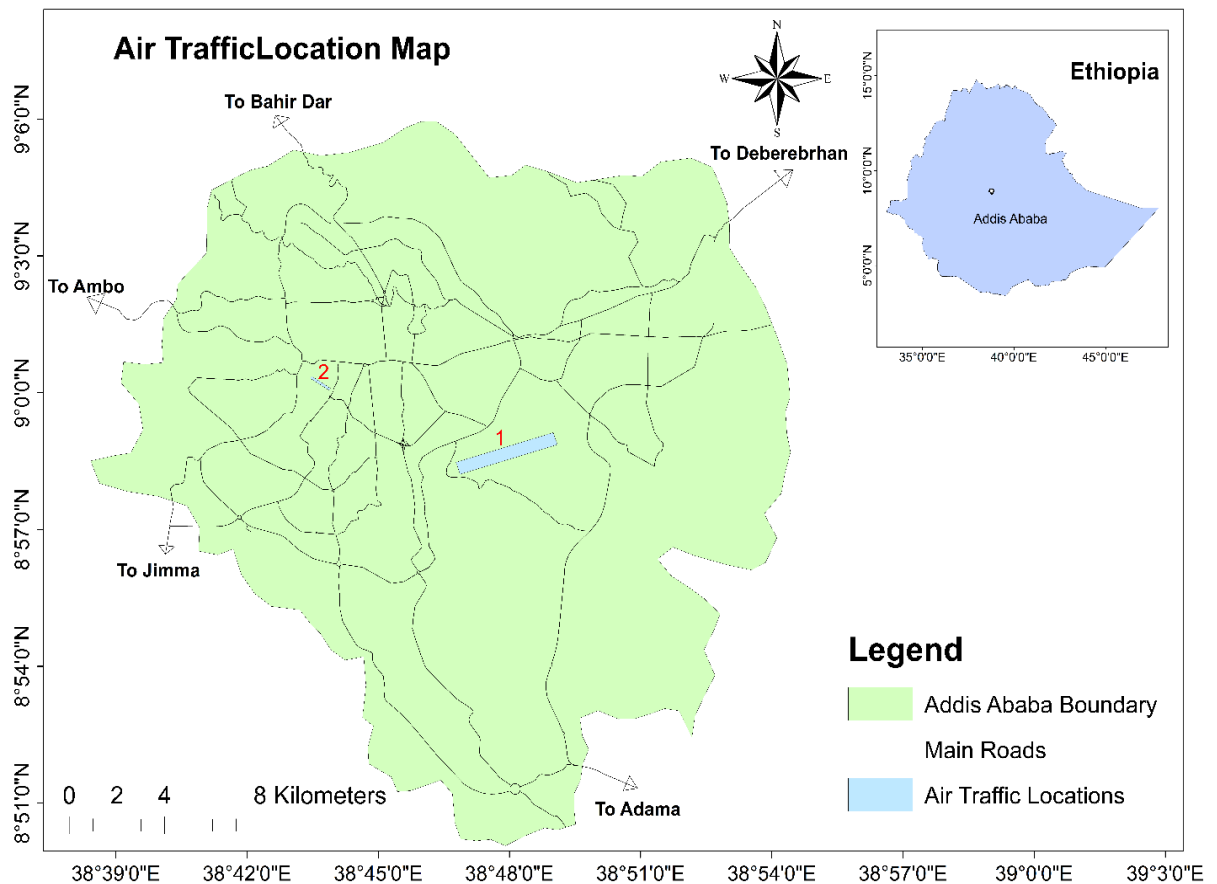


Figure 3.15: Air traffic locations in the study area.

Since wind turbines have a probable impact on communication systems and navigation in airports, proximity to air traffic is also analyzed as an influencing factor. Figure 3.16 and the summary of Table 3.8 show that 60.95% (32,875 ha) is more than 6 km, which enables it to be a very high suitable site for wind energy harvesting.

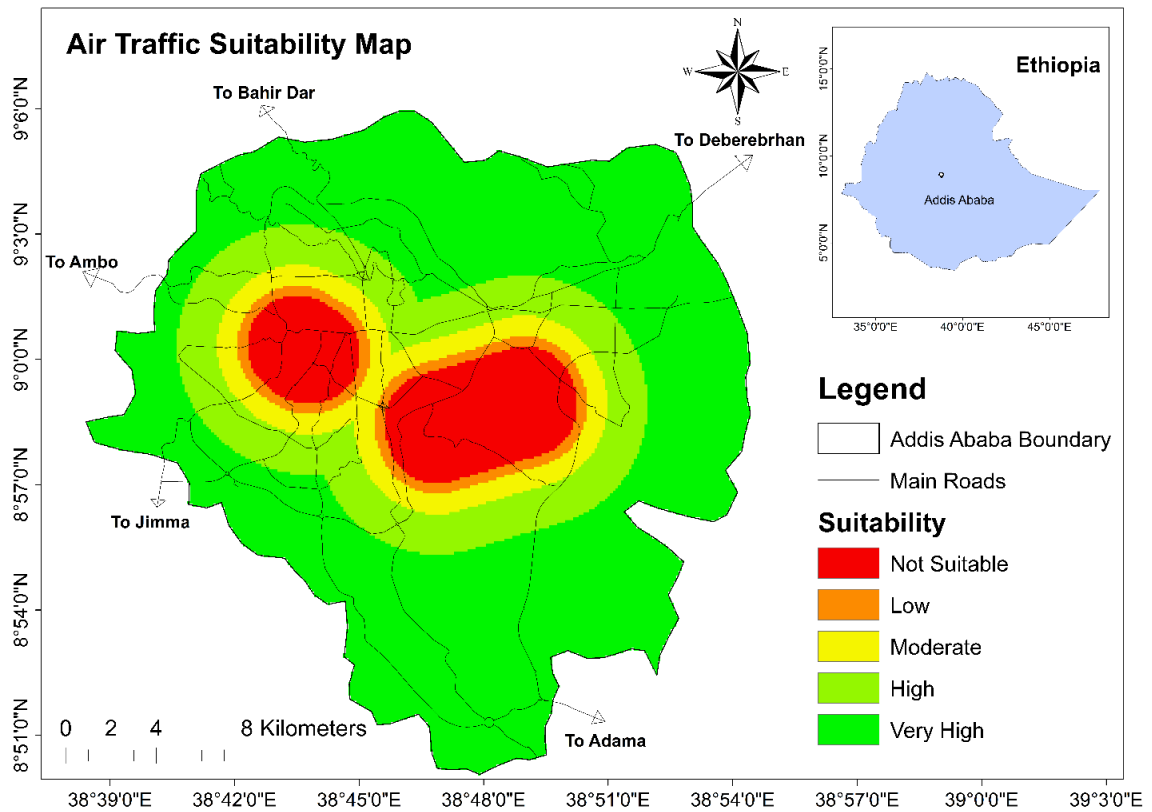







Figure 3.16: Air traffic suitability map.

Table 3.8: Summary of air traffic suitability.

Suitability	Rank	Color Code	Distance (m)	Area (ha)	Percentage
Very High	1		>6000	32875	60.95%
High	2		4000-6000	9379	17.40%
Moderate	3		3000-4000	4243	7.85%
Low	4		2500-3000	1831	3.40%
Not Suitable	5		<2500	5600	10.40%

3.8.3 Wind-Based Building Form Optimization

The proposed method for wind-based building form optimization in this study uses a genetic algorithm inspired by natural selection. It starts with a population of randomly generated building forms, evaluates their aerodynamic performance, and selects the best fit. The offspring are mutated and recombined, creating a new prototype until a high-fitting form is selected.

The analysis of specific project site locations and the building form optimization process is presented below.

1. Site Selection:

In this research, the project site was selected by referring to the overall suitability map, building height regulation, and newly developed land use plan of the city. Since vertical developments in the study area are booming in the main city center and becoming the center of business for the city and the country as well, the main city center of Addis Ababa was designated as a preferable zone for locating specific sites and experimenting with wind-based building form optimization. Figures 3.17 and 3.18 show the land use map and building height regulation in the main city center, respectively.

Main City Center Land Use Map

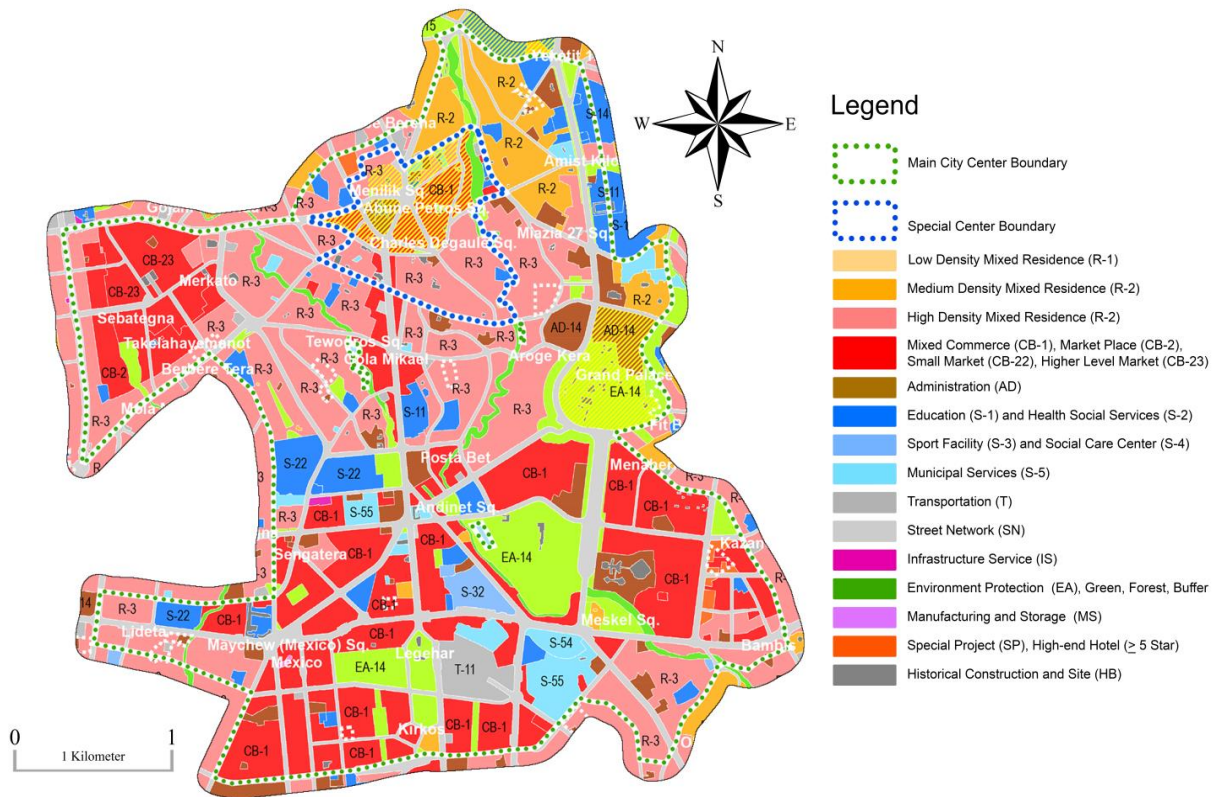


Figure 3.17: Main city center land use (Addis Ababa City Planning Project Office, 2022).

Main City Center Building Height Regulation

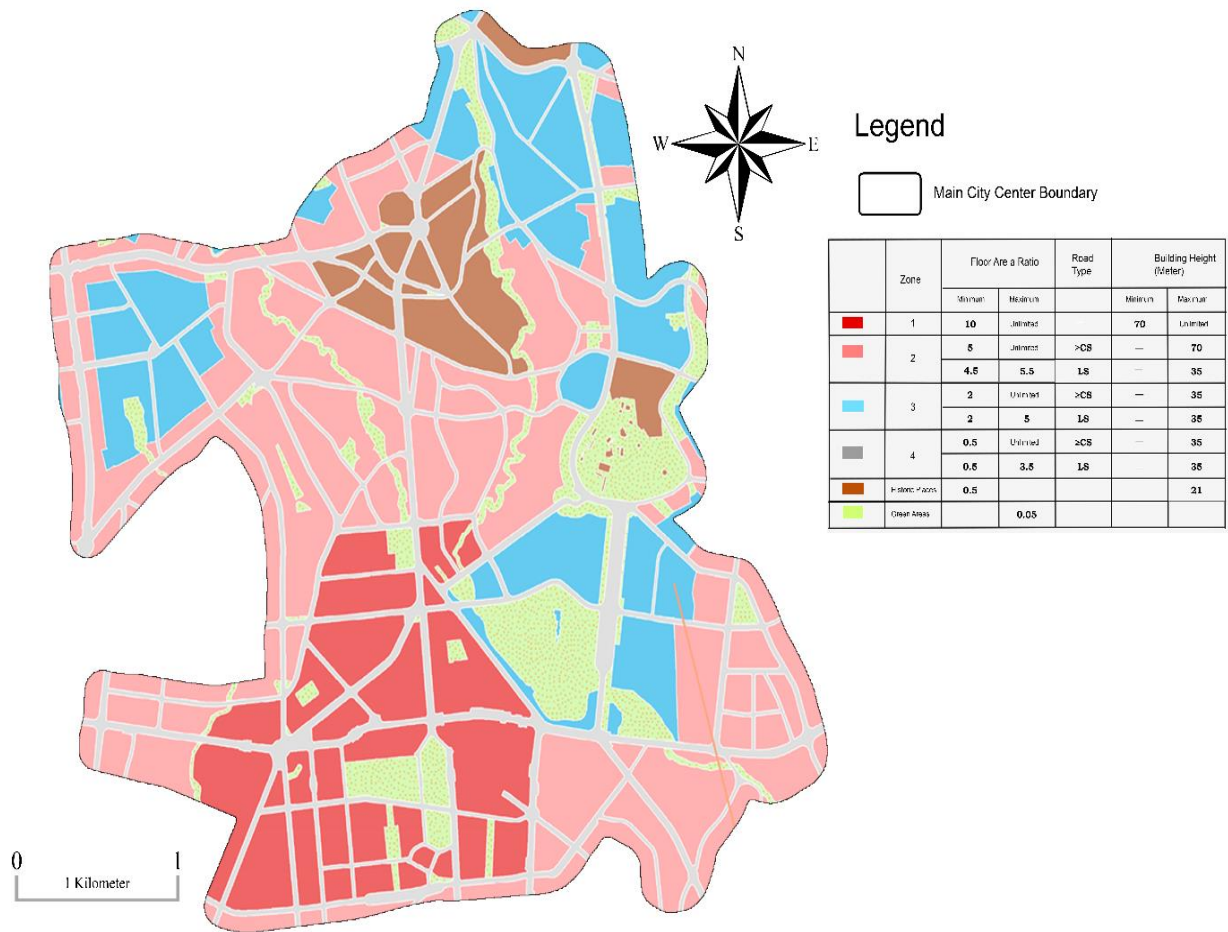


Figure 3.18: Main city center building height regulation (Addis Ababa City Planning Project Office, 2022).

As shown in Figure 3.19, highly suitable sites in the main city center were taken from the overall suitability map of the study area to overlay it with the land use map and building height regulation to locate the specific project site.

Highly Suitable Sites in the Main City Center

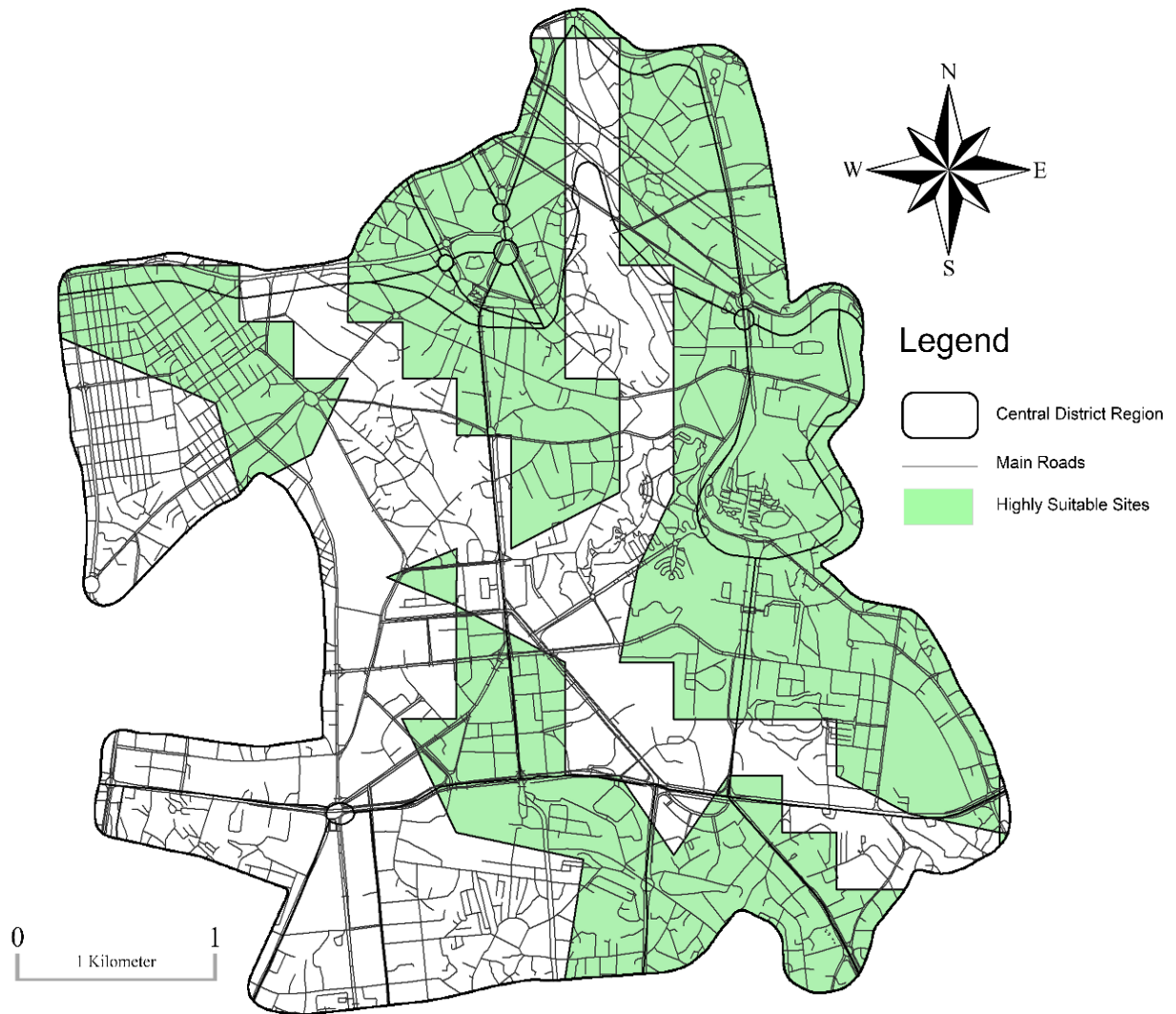


Figure 3.19: Highly suitable sites for the main city center.

Wind energy is a clean and renewable source of energy that can help reduce greenhouse gas emissions and improve air quality. However, the development of wind farms in urban areas can harm protected areas, such as wetlands, forests, parks, public areas, and historic sites. Accordingly, a preferable land use map is produced by excluding protected areas in the main city center. Since wind energy has harvesting potential with the increase in height of the building, the unlimited height zone of the main city center is selected as a prior experimental area. Figure 3.20 illustrates preferable and excluded land uses for wind energy harvesting in an unlimited height zone of the main city center.

Land Use Map of Unlimited Height Zone

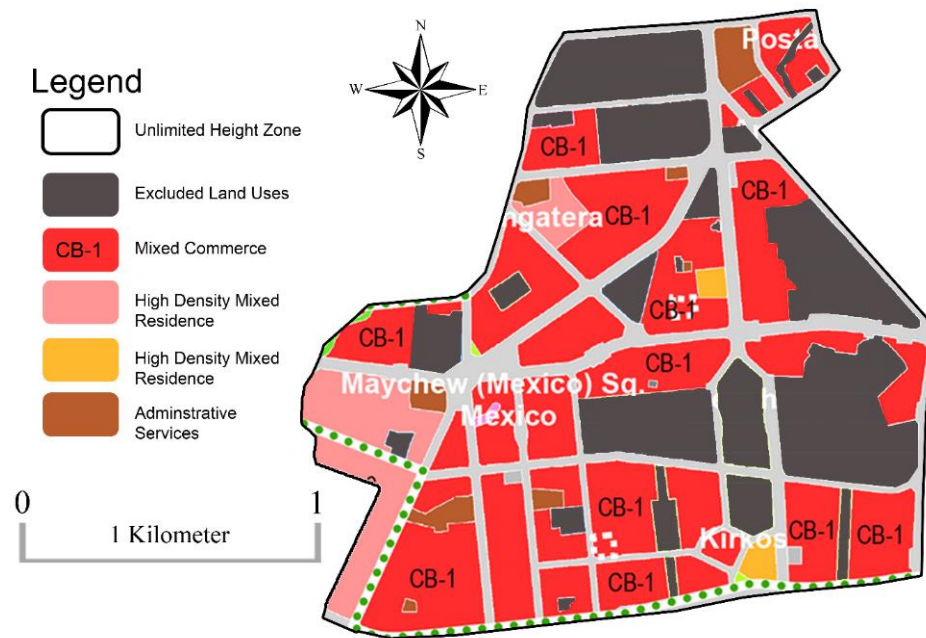


Figure 3.20: Land use map of an unlimited height zone.

By overlaying the preferable land uses of an unlimited height zone with highly suitable sites, desirable wind energy harvesting sites are identified, as shown in Figure 3.21 below.

Suitable Sites of Unlimited Height Zone

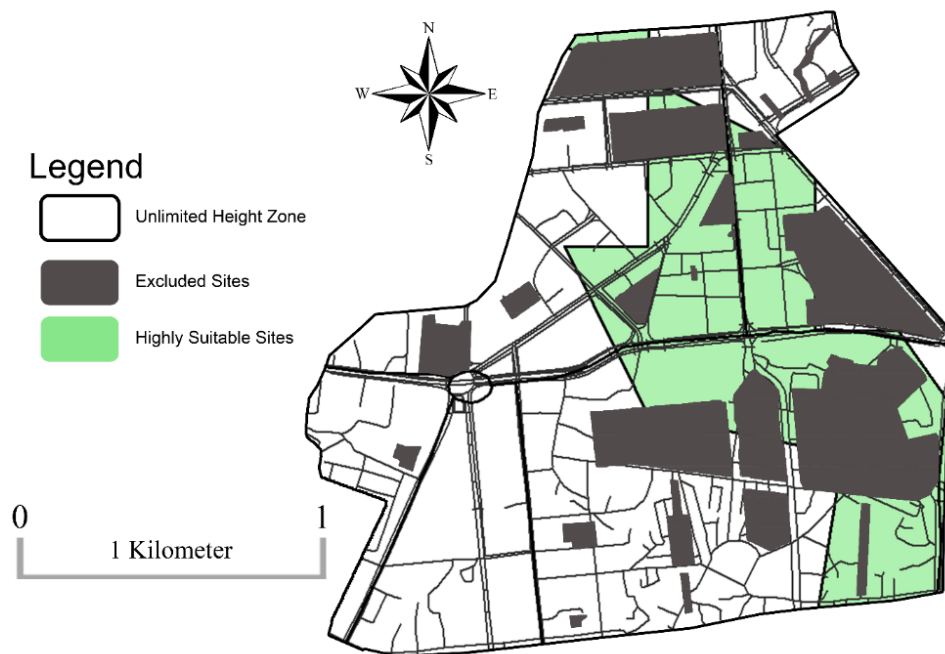


Figure 3.21: Suitable sites within an unlimited height zone.

The project site, as shown in Figure 3.22, located near the newly built CBE headquarters building, is set to be selected from suitable sites in the city center's unlimited height zone. The project site, which covers 9,500 square meters, is located where the Ethiopia Hotel is situated and is set to be replaced by a new high-rise building with more than 70 meters of height under the redevelopment plan of the Addis Ababa City Planning Project Office.

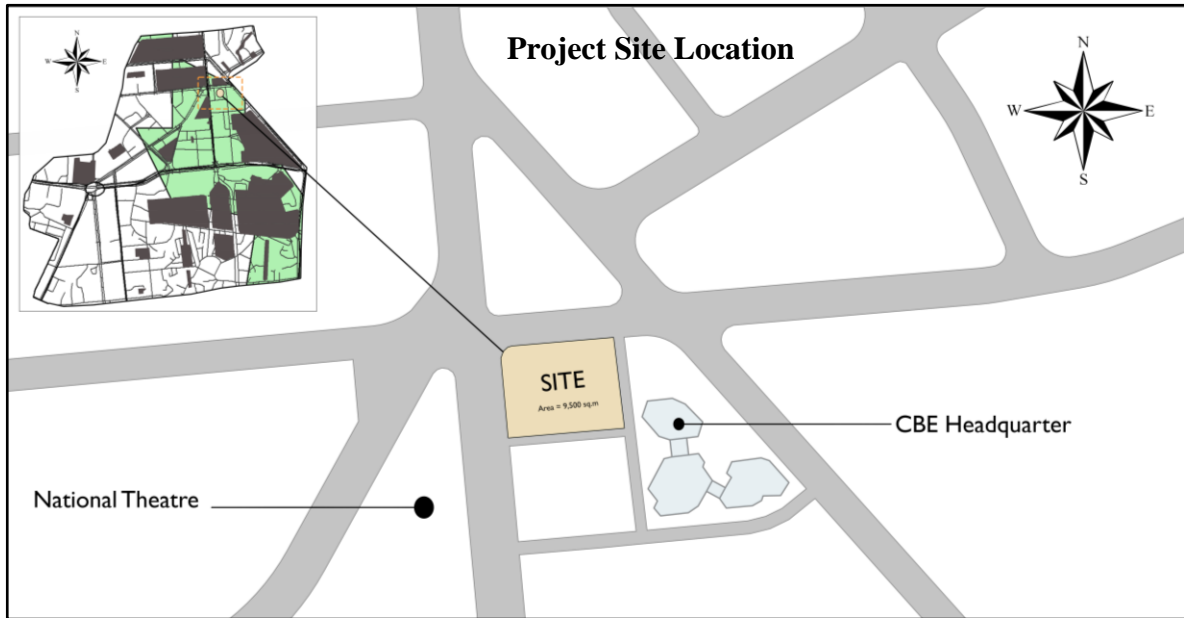


Figure 3.22: Project site location.

2. Building Form Optimization Process:

Step 1: Criteria Definition: The criteria defined for this research are *variable parameters*, which include geometries determined by footprint geometry type, corner modification, extrusion, rotation, twist, and tower modification for a single tower. These parameters are elements that influence airflow patterns in buildings, often linked to overall building geometries, corner modifications, or tower arrangements.

This research examines variable parameters affecting airflow patterns, focusing on specific factors and their impact on overall building geometry and layout.

Step 2: Footprint Geometry and Tower Arrangement: In this step, three different footprint shapes of tall buildings with airfoil geometries are investigated to get the optimal geometry and tower arrangement. This paper only investigates single towers with an airfoil shape in aerodynamic building forms. For this research, three different footprint geometries, namely rectangular (Figure 3.23), triangular (Figure 3.25), and circular geometry (Figure 3.27), which

are illustrated below with their corresponding script definitions, are basic experimental geometries applied in the discovery process of optimized aerodynamic shape.

As shown in Figures 3.24, 3.26, and 3.28, the wind simulation analysis of rectangular, triangular, and circular geometry shows their different interactions with the flow of wind. Their wind simulation analysis map is presented below consecutively.

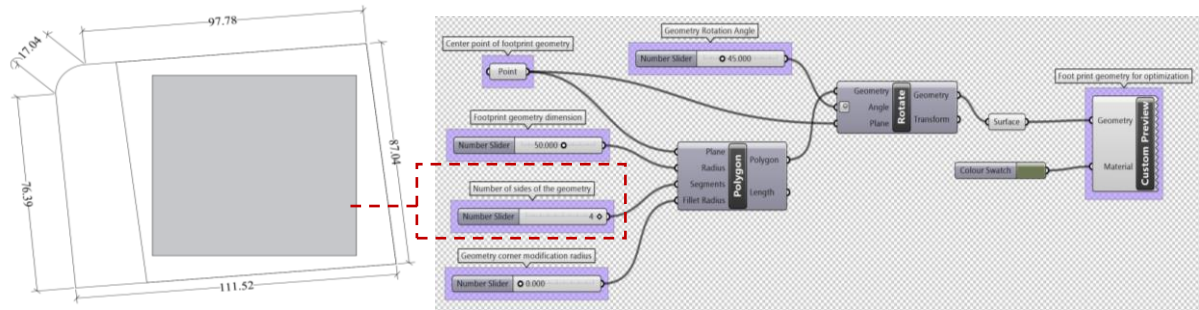


Figure 3.23: Rectangular footprint geometry and its script definition.

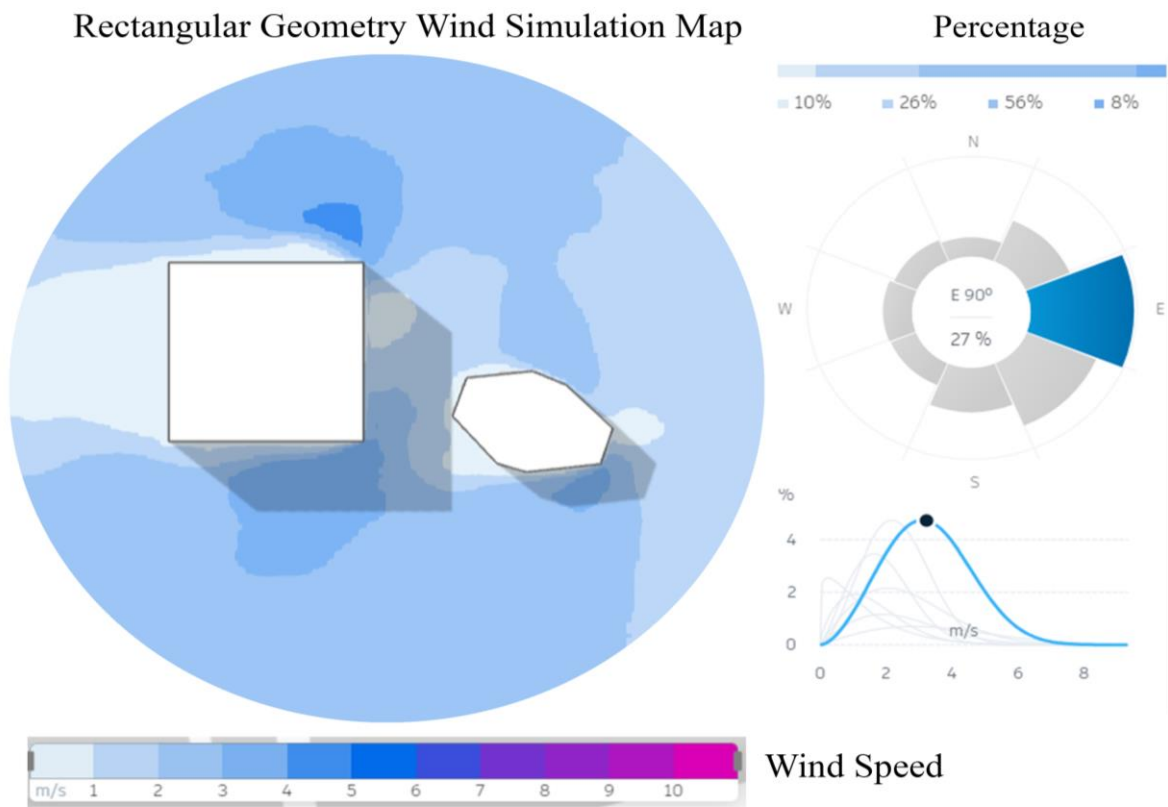


Figure 3.24: Rectangular geometry wind simulation map.

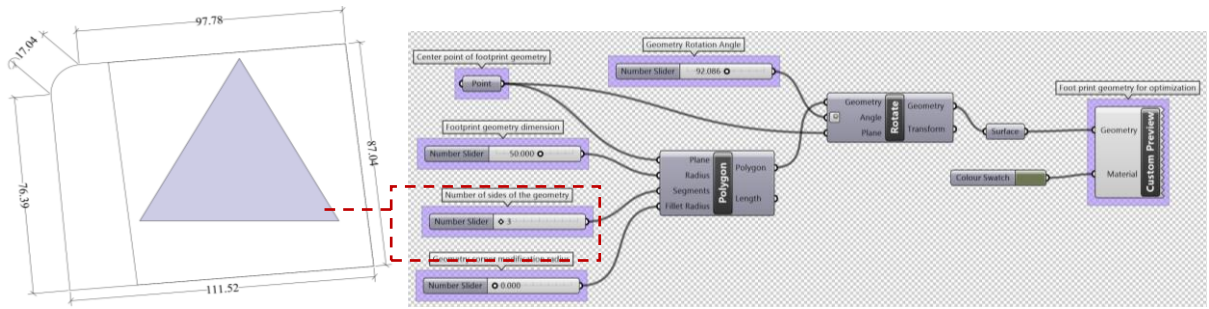


Figure 3.25: Triangular footprint geometry and its script definition.

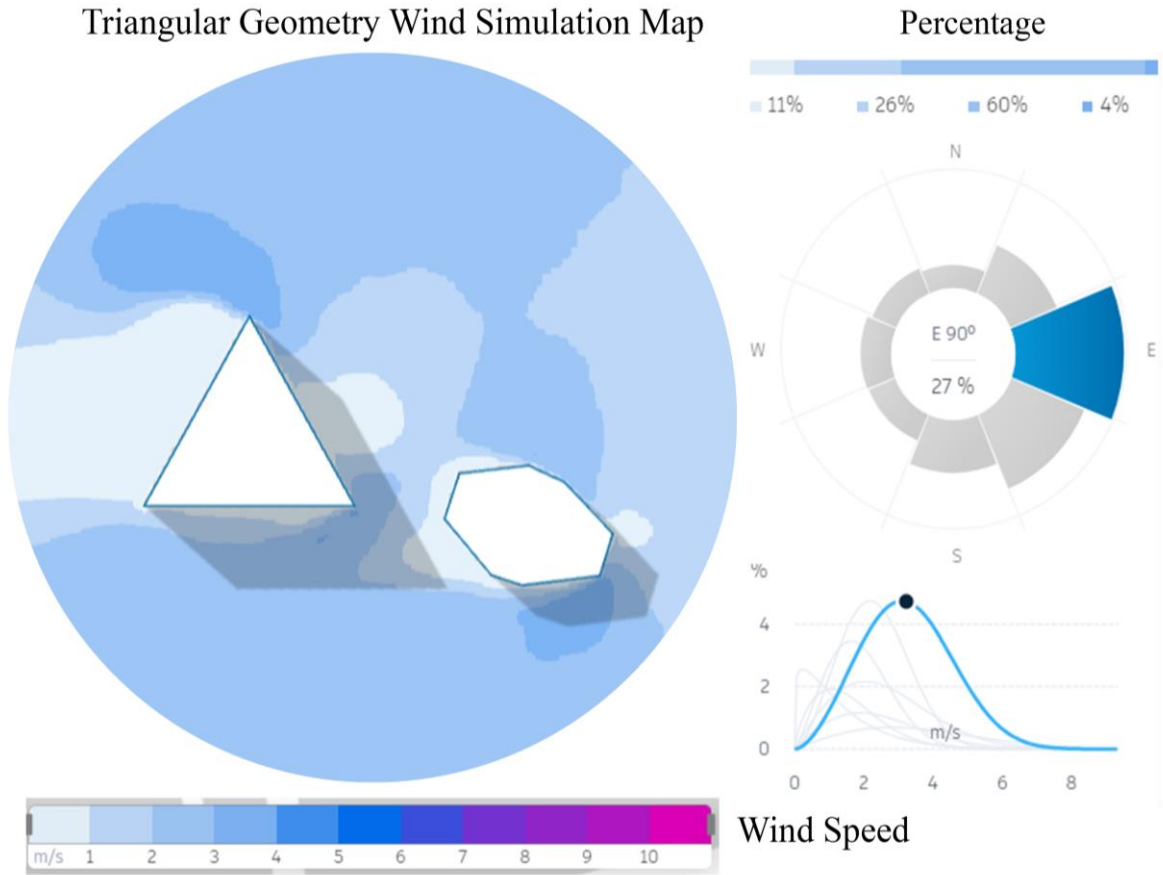


Figure 3.26: Triangular geometry wind simulation map.

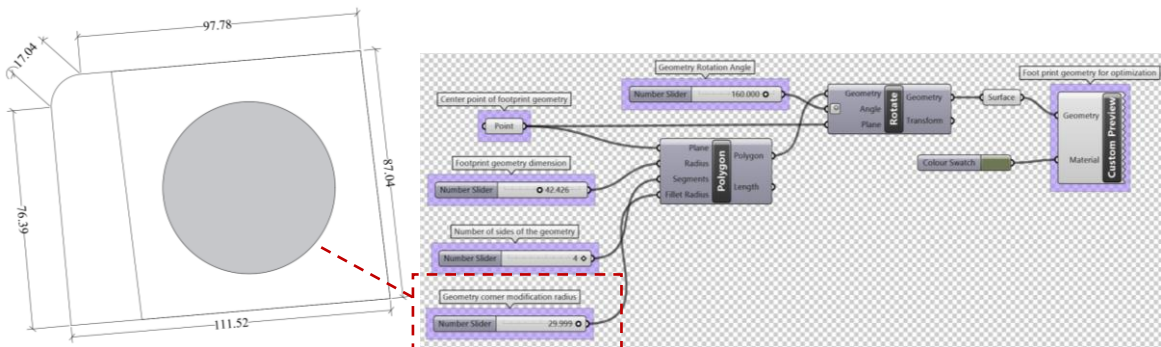


Figure 3.27: Circular footprint geometry and its script definition.

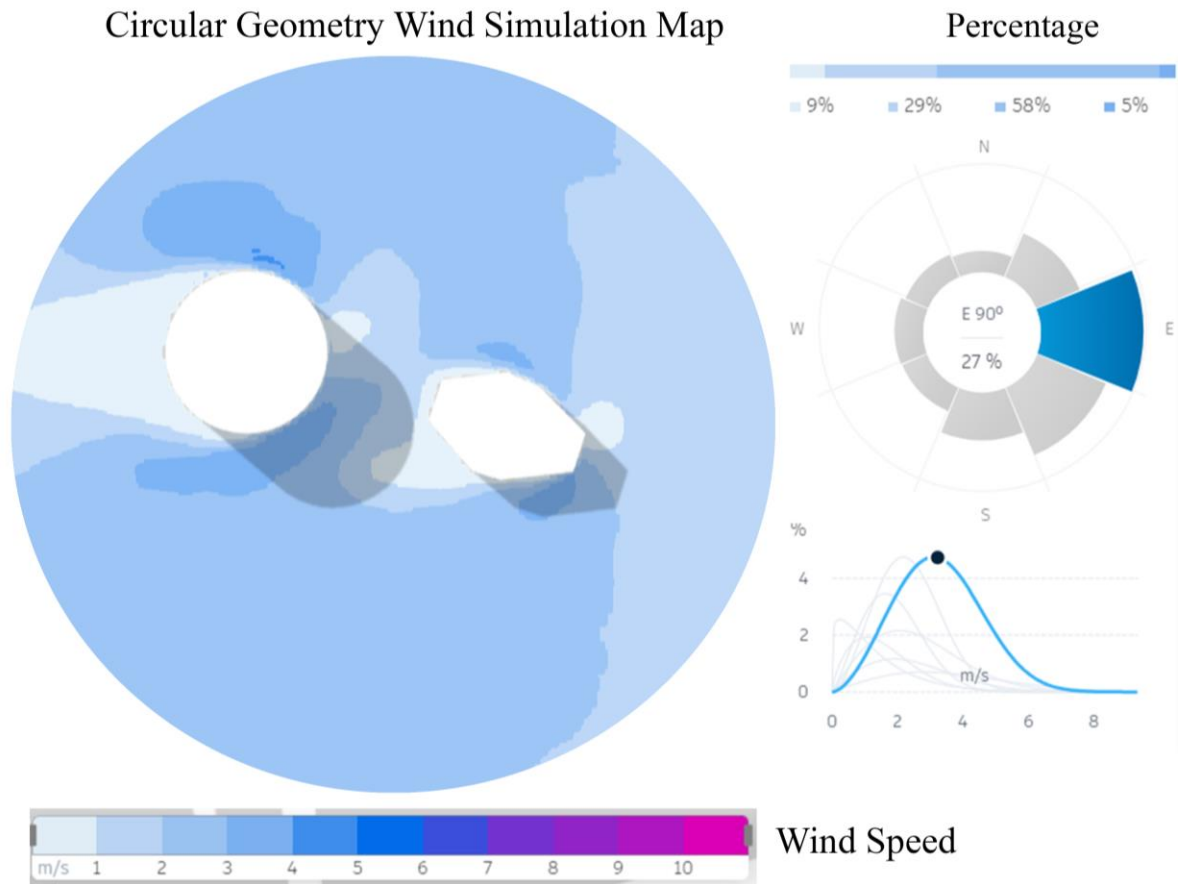


Figure 3.28: Circular geometry wind simulation map.

Step 3: Prototype Definition: In this stage, optimized footprint geometry and tower arrangement were simulated to carve out the building form responding to wind energy harvesting. This study analyzed more than three hundred different prototypes through wind-based simulation to discover the most efficient and optimized prototype for wind energy harvesting. This optimization was done by using computational fluid dynamics (CFD) in Grasshopper plugins in Rhinoceros software, namely Butterfly, Hkwind, and Octopus multi-objective optimizers. The analysis is done by modeling the flow of air around the prototype and calculating the forces acting on it to compare different options and optimize the prototype for better performance.

Figure 3.29 highlights the process of aerodynamic building form optimization. Initially, optimized building geometry was inserted in the optimization loop, and controlling parameters were defined to determine the building form based on the wind flow. Rhinoceros, octopus-grasshopper, and CFD simulation plugins are used to simulate the aerodynamic form.

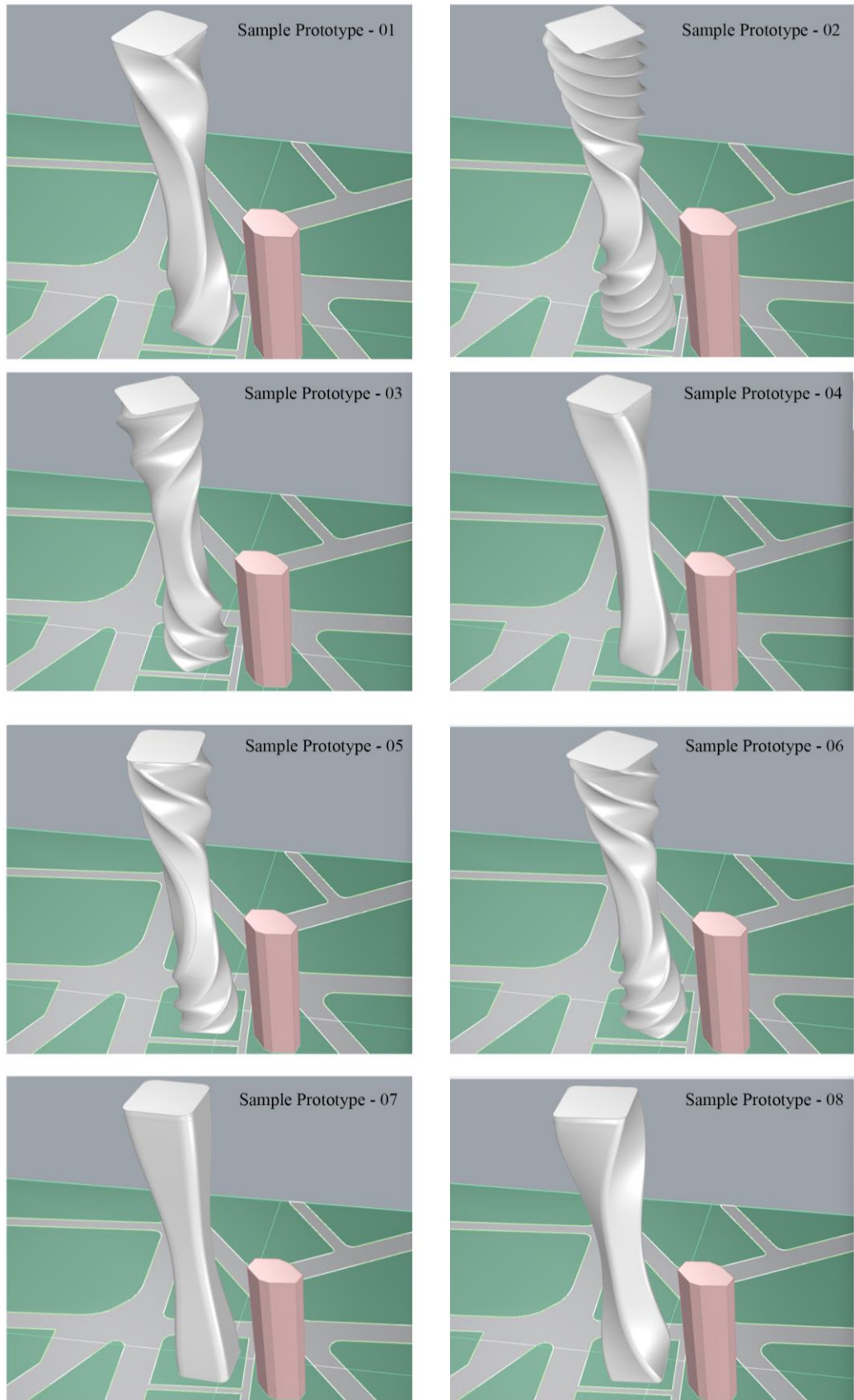


Figure 3.31: Sample prototypes tested in aerodynamic form optimization.

Step 4: Performance Simulation: After the optimal building form is defined, this step simulates the performance of the building for wind turbine integration. The major procedure sequences include raw data input, parametric model setup, optimization loop, accuracy control, and optimal output.

In this research, the optimal building form performance is simulated using Autodesk Forma CFD software coupled with Rhinoceros and Butterfly-Grasshopper plugins. The performance simulation is taken at every five-floor interval, and the analysis shows that all simulations from the ground floor to the hundredth-floor level have more than 90% values of average wind speed ranging from 3 m/s to 6 m/s. Performance simulation of the optimized aerodynamic form at different floor levels is presented from Figure 3.32 to Figure 3.42 below.

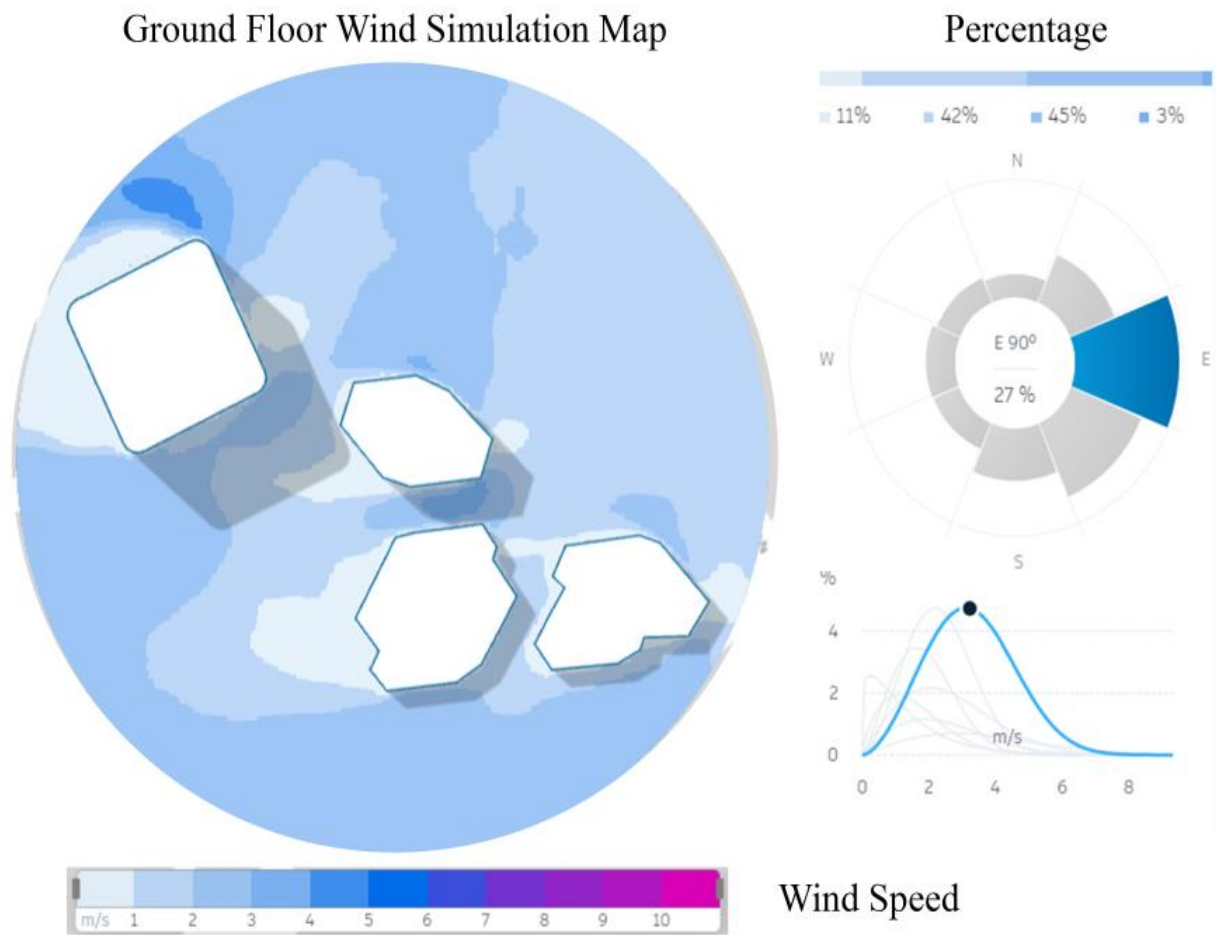
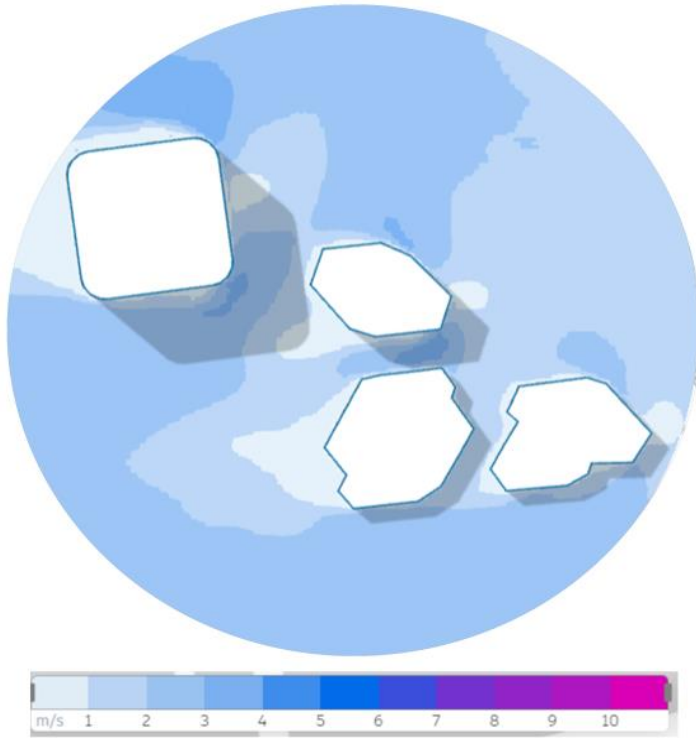
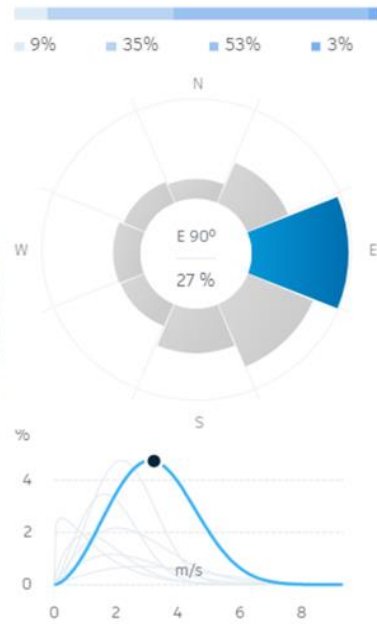


Figure 3.32: Ground floor simulation map.

Fifth Floor Wind Simulation Map

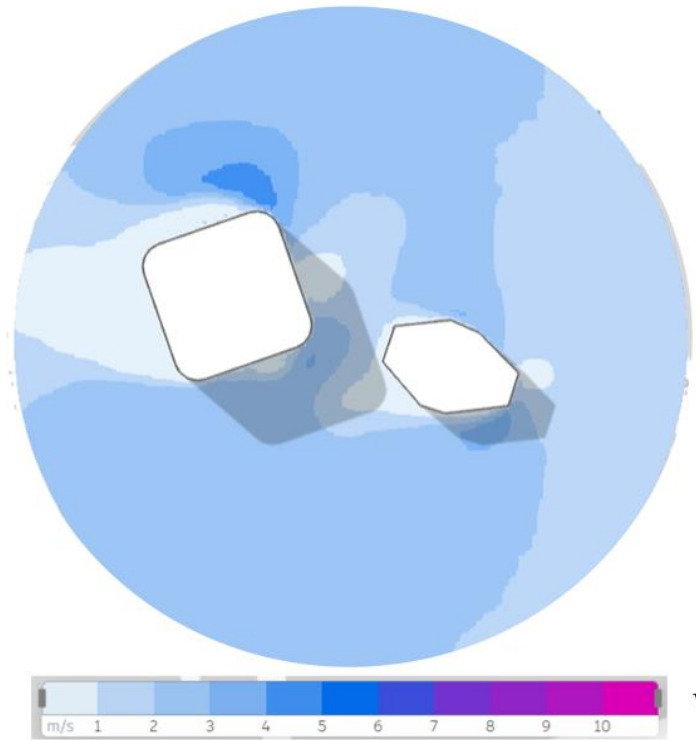


Percentage

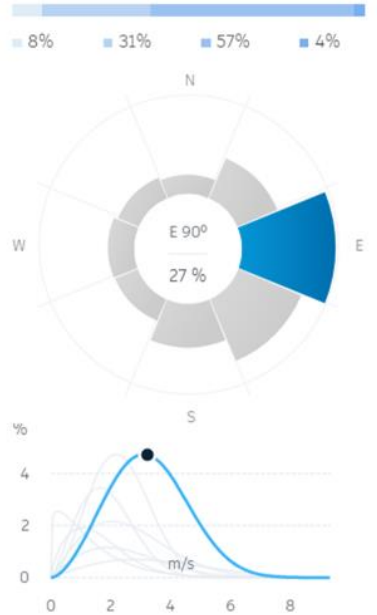


Wind Speed

Tenth Floor Wind Simulation Map



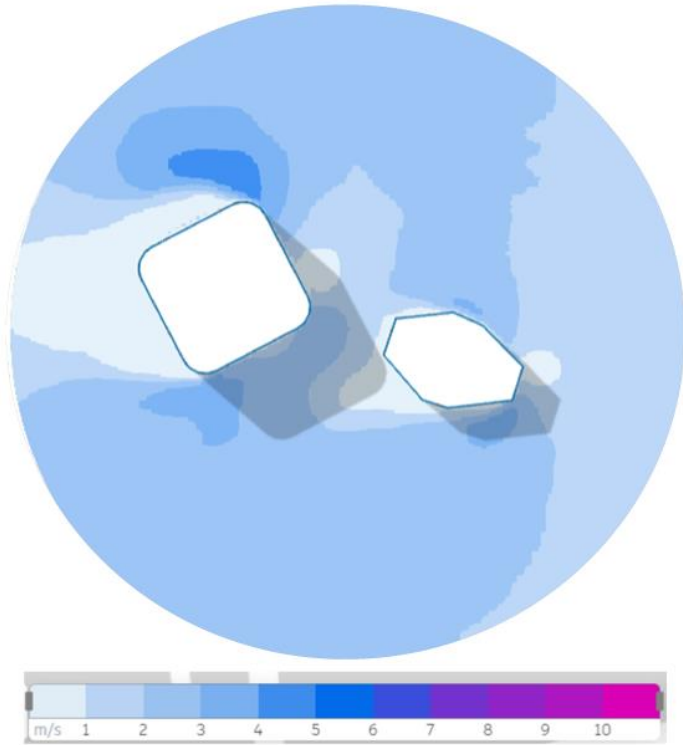
Percentage



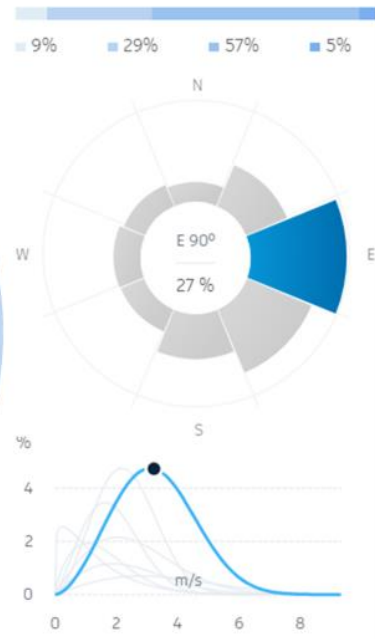
Wind Speed

Figure 3.33: Fifth and tenth floor simulation map.

Fifteenth Floor Wind Simulation Map

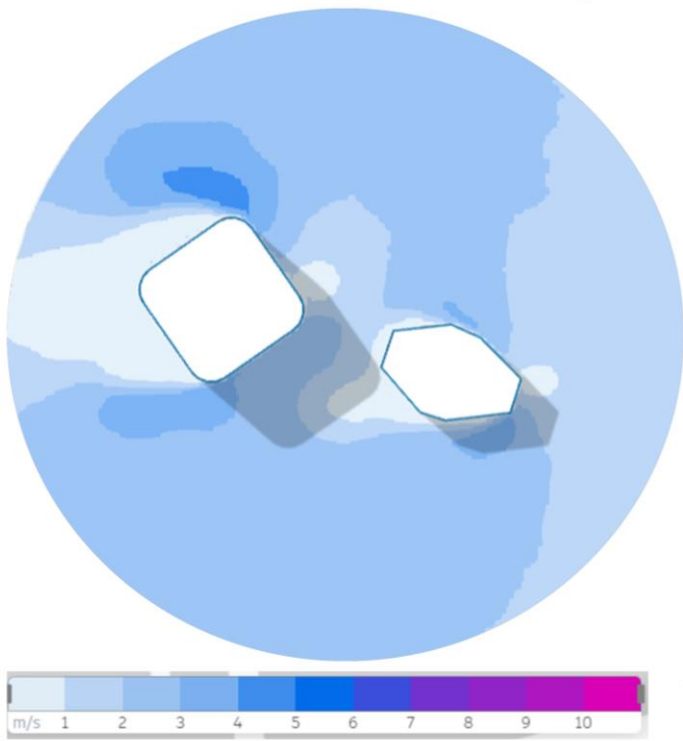


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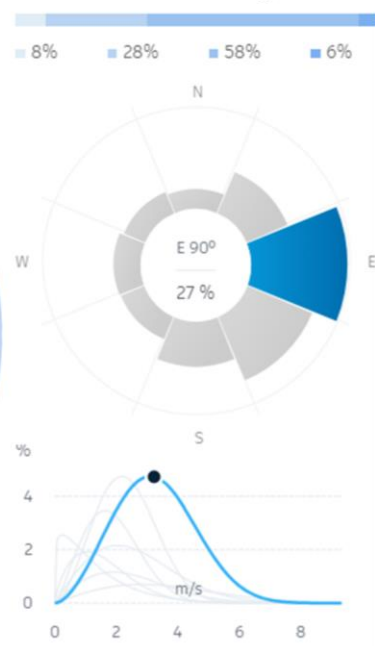


Wind Speed

Twentieth Floor Wind Simulation Map



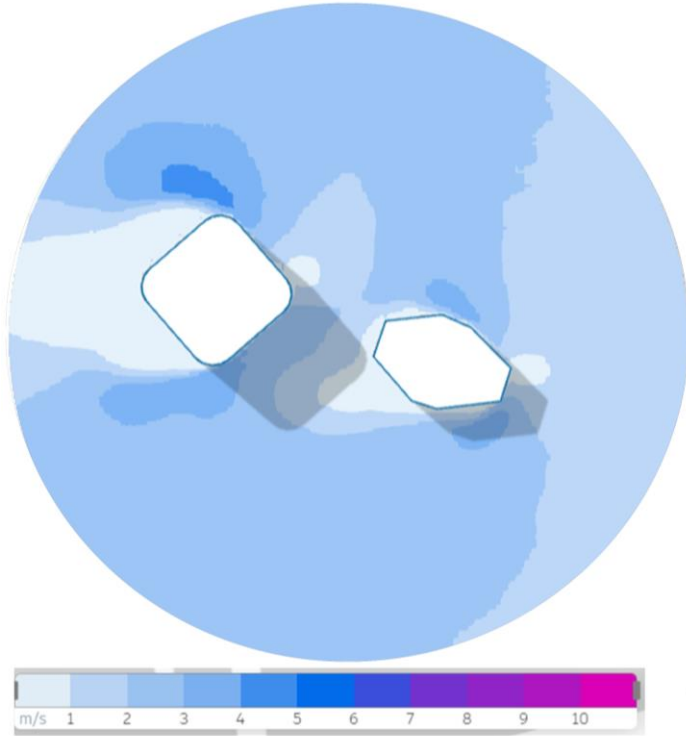
Percentage



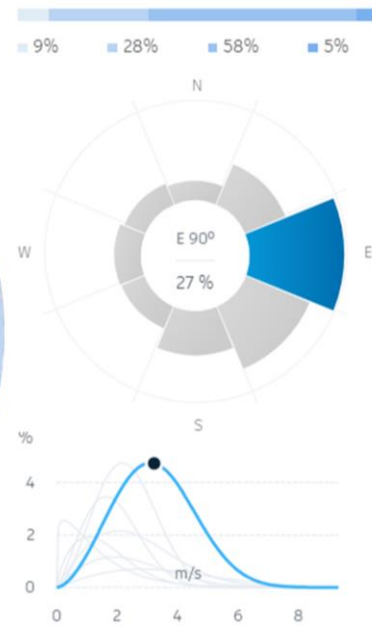
Wind Speed

Figure 3.34: Fifteenth and twentieth floor simulation map.

Twenty-fifth Floor Wind Simulation Map

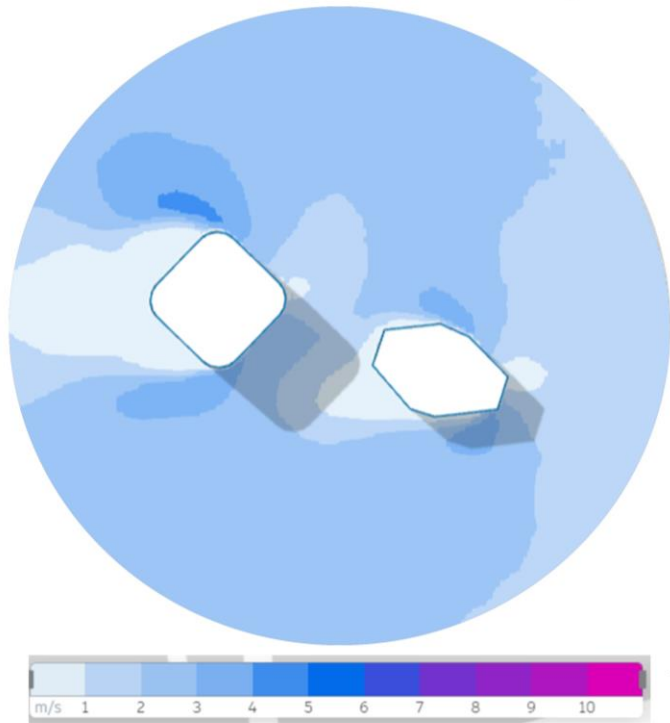


Percentage

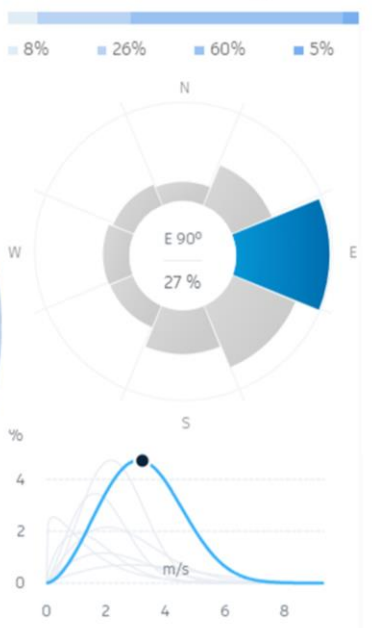


Wind Speed

Thirtieth Floor Wind Simulation Map



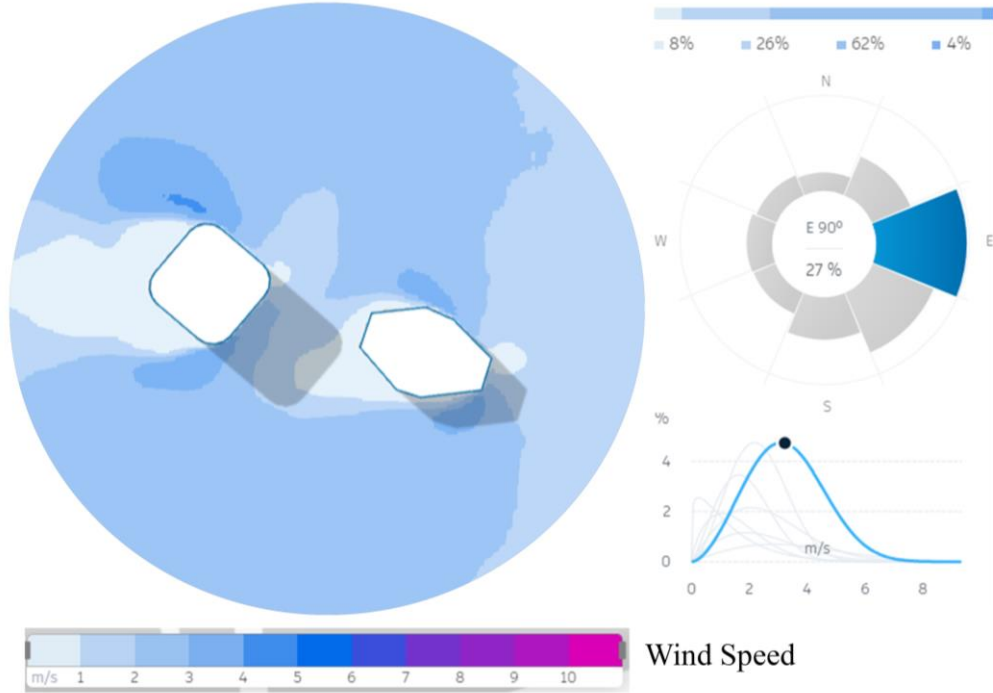
Percentage



Wind Speed

Figure 3.35: Twenty-fifth and Thirtieth floor simulation map.

Thirty-fifth Floor Wind Simulation Map



Fortieth Floor Wind Simulation Map

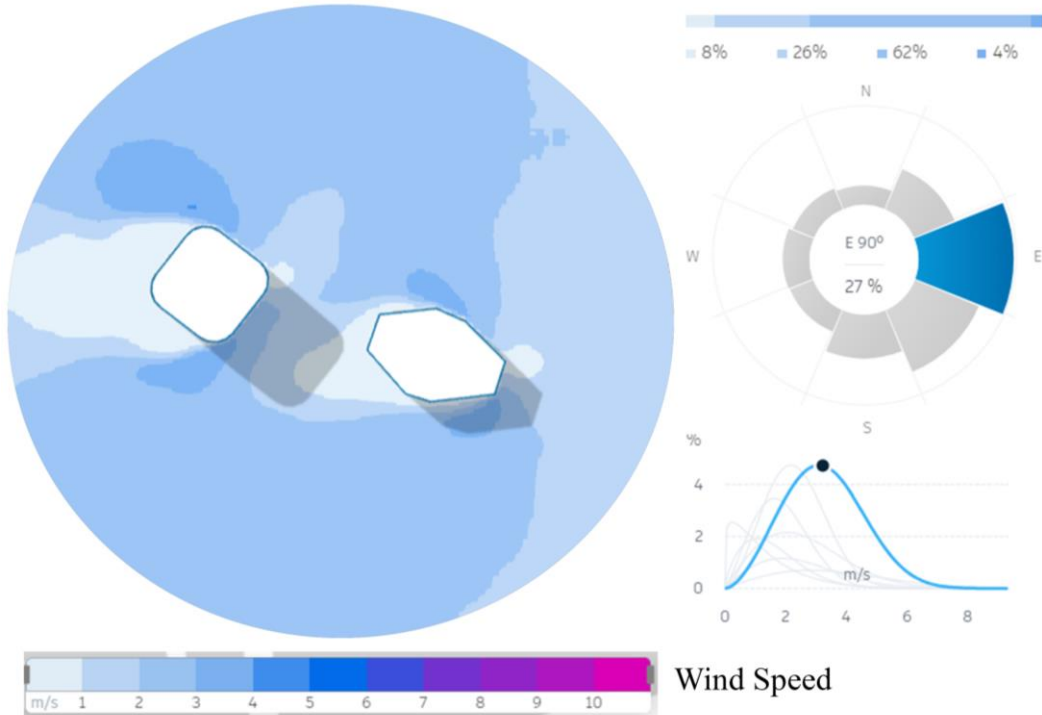
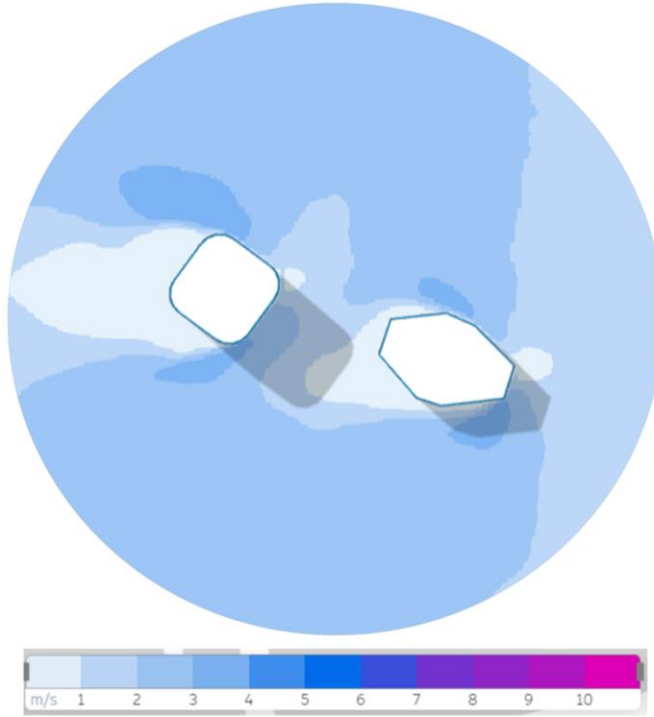
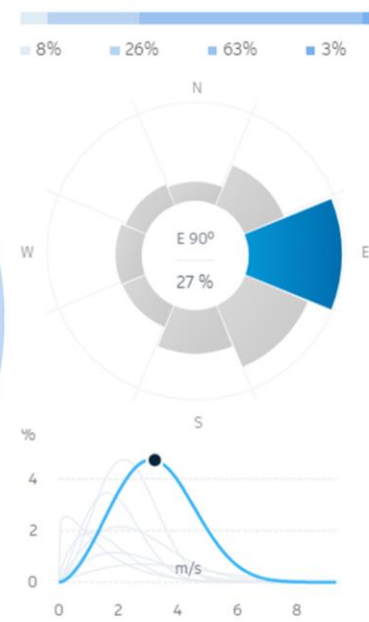


Figure 3.36: Thirty-fifth and Fortieth floor simulation map.

Forty-fifth Floor Wind Simulation Map

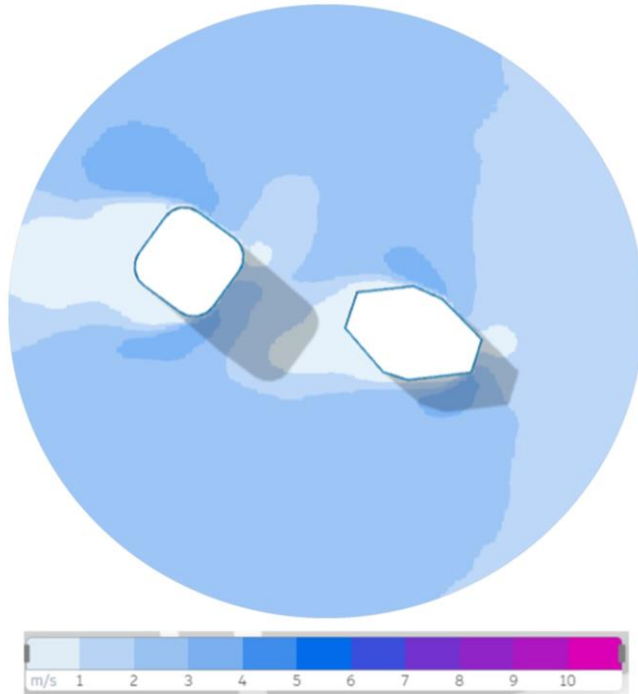


Percentage

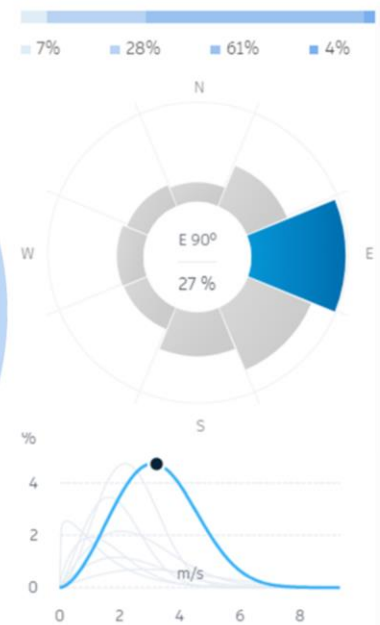


Wind Speed

Fiftieth Floor Wind Simulation Map



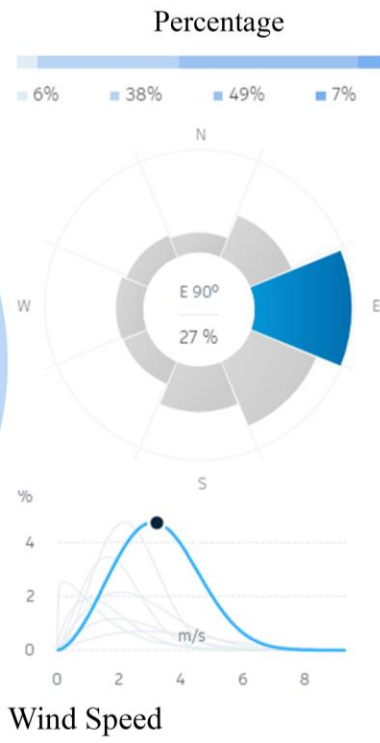
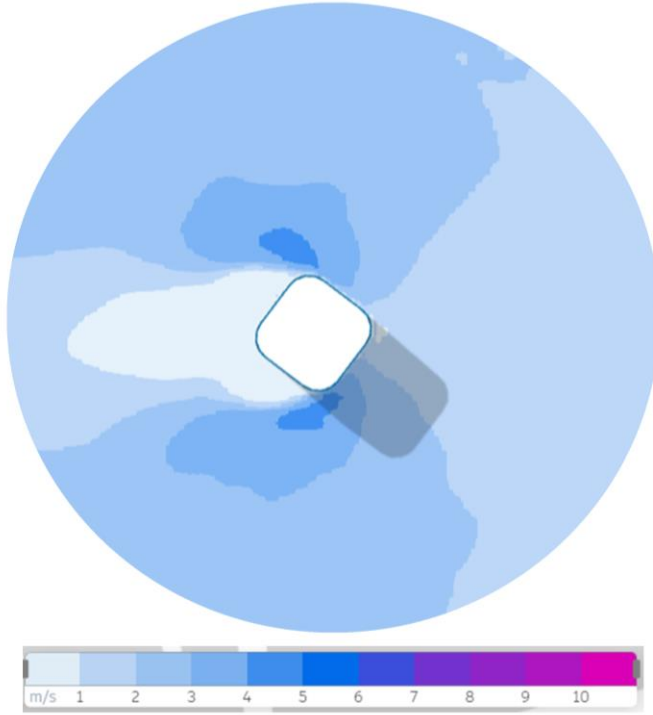
Percentage



Wind Speed

Figure 3.37: Forty-fifth and fiftieth floor simulation map.

Fifty-fifth Floor Wind Simulation Map



Sixtieth Floor Wind Simulation Map

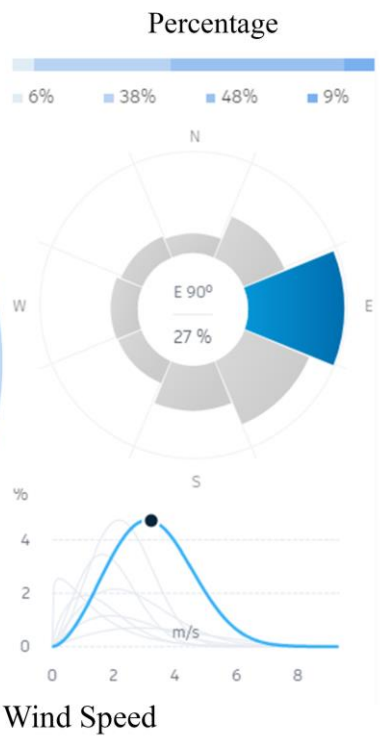
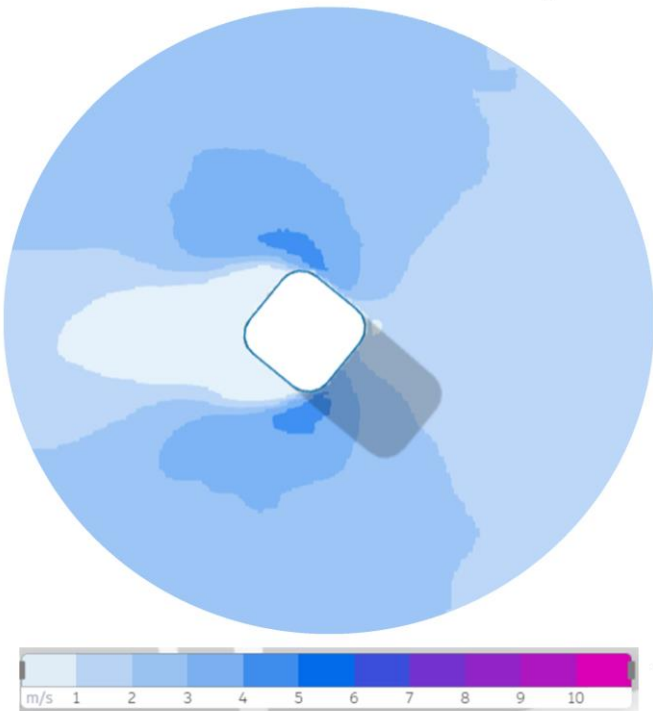
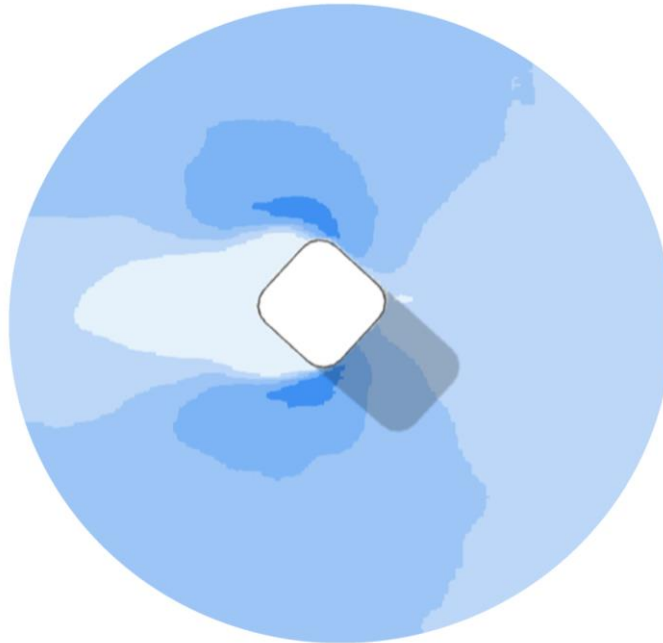
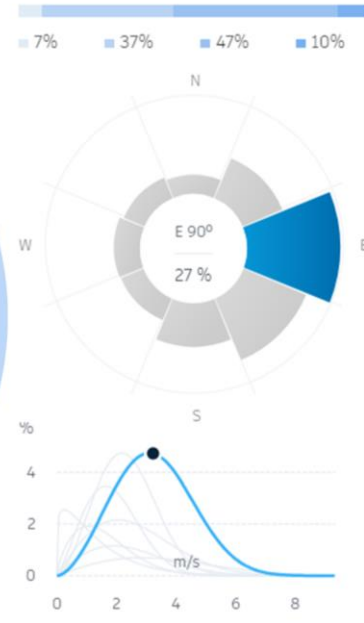


Figure 3.38: Fifty-fifth and sixtieth floor simulation map.

Sixty-fifth Floor Wind Simulation Map

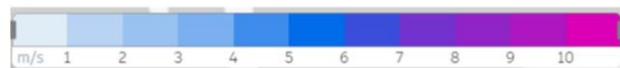
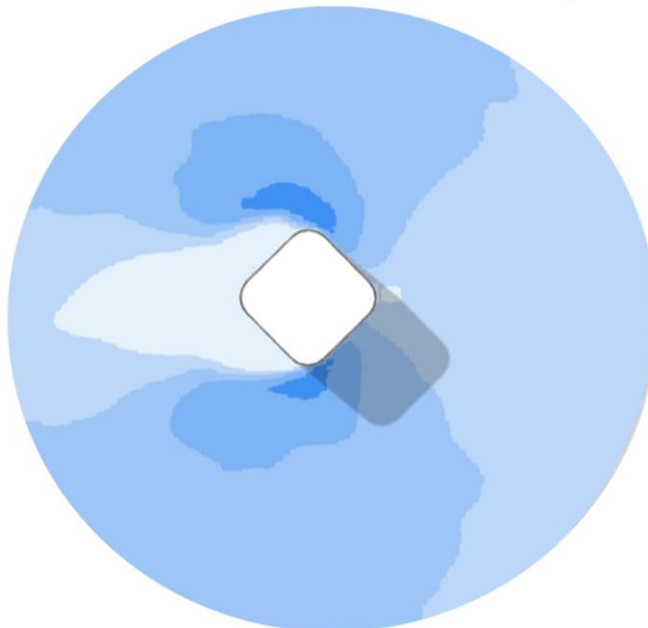


Percentage

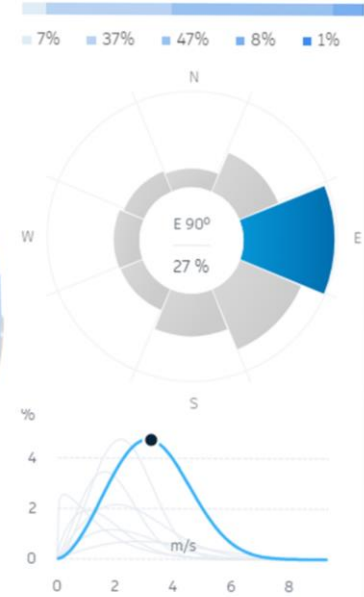


Wind Speed

Seventieth Floor Wind Simulation Map



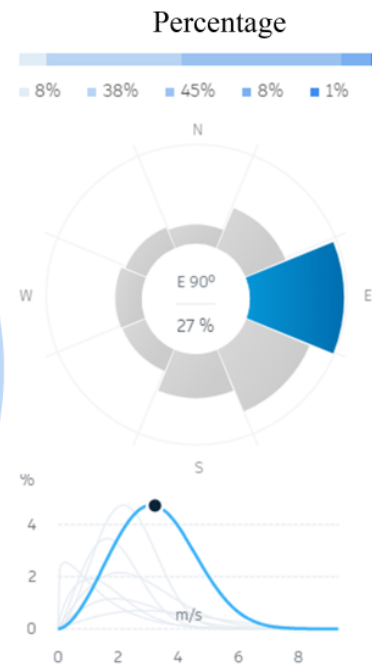
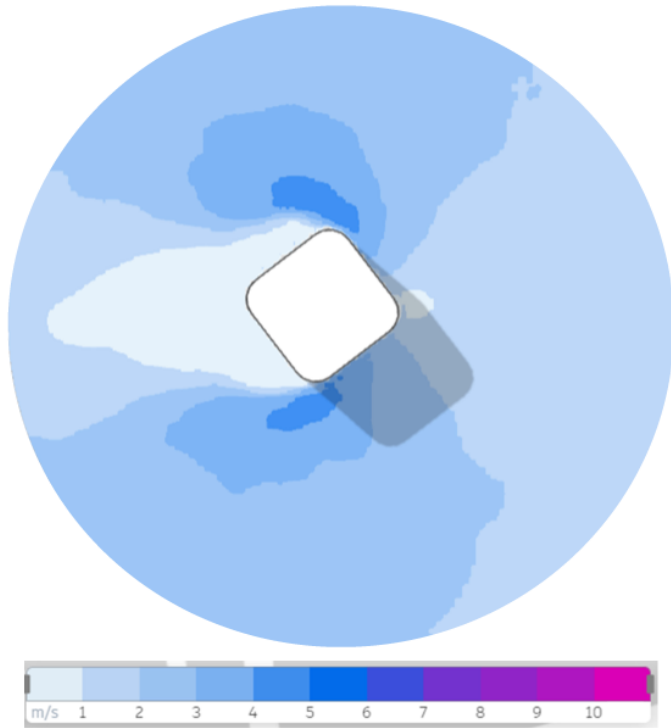
Percentage



Wind Speed

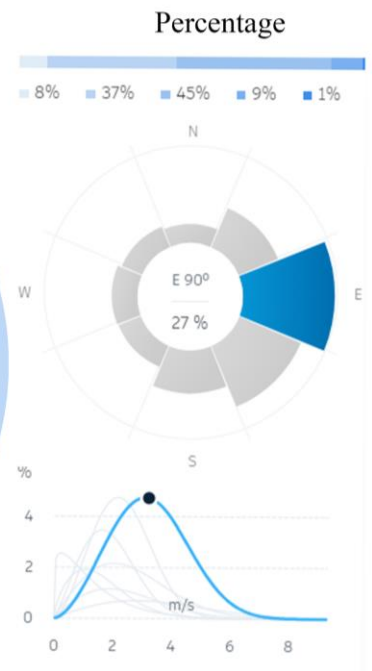
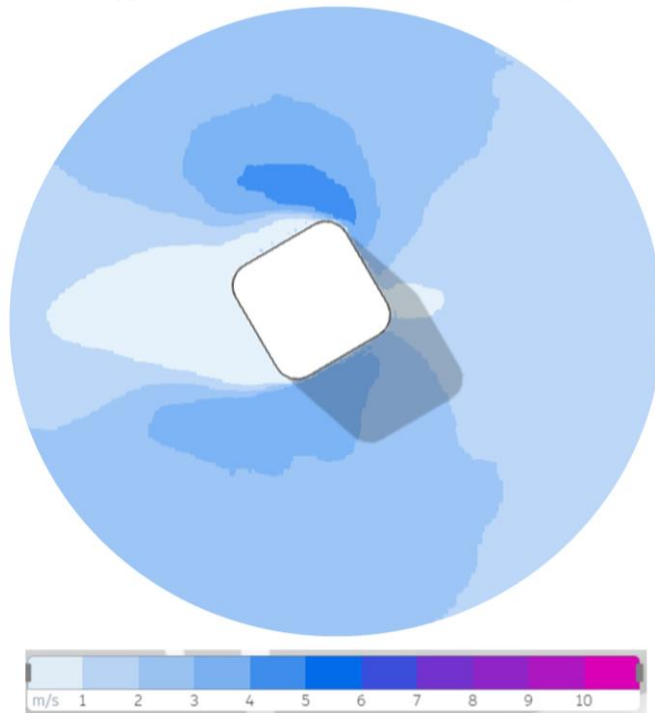
Figure 3.39: Sixty-fifth and seventieth floor simulation map.

Seventy-fifth Floor Wind Simulation Map



Wind Speed

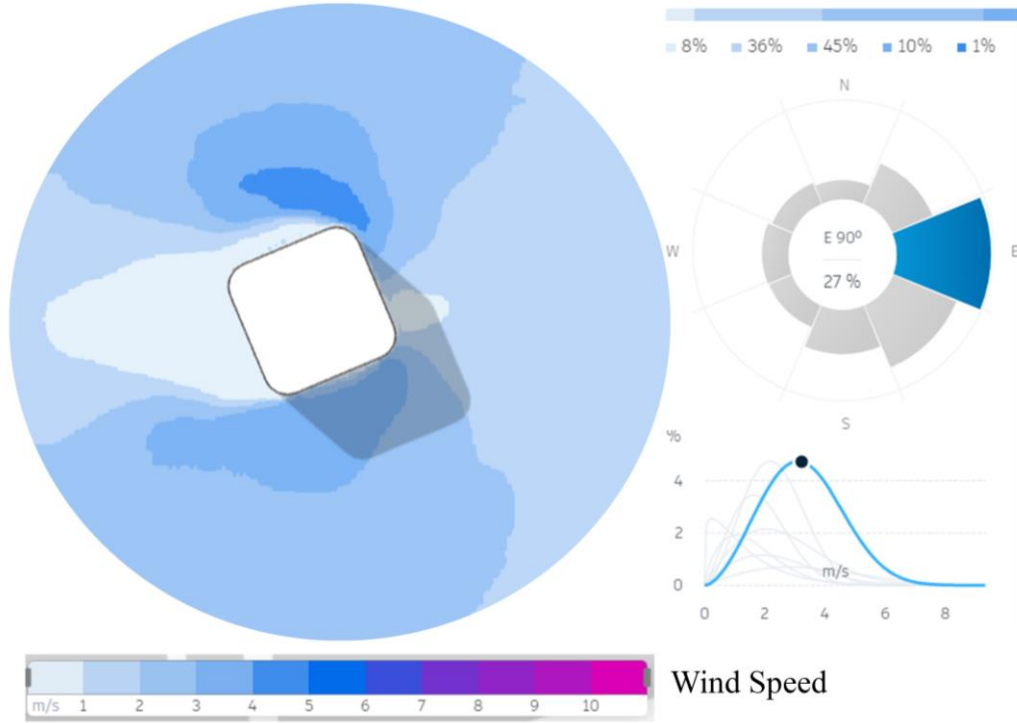
Eightieth Floor Wind Simulation Map



Wind Speed

Figure 3.40: Seventy-fifth and Eightieth floor simulation map.

Eighty-fifth Floor Wind Simulation Map



Nintieth Floor Wind Simulation Map

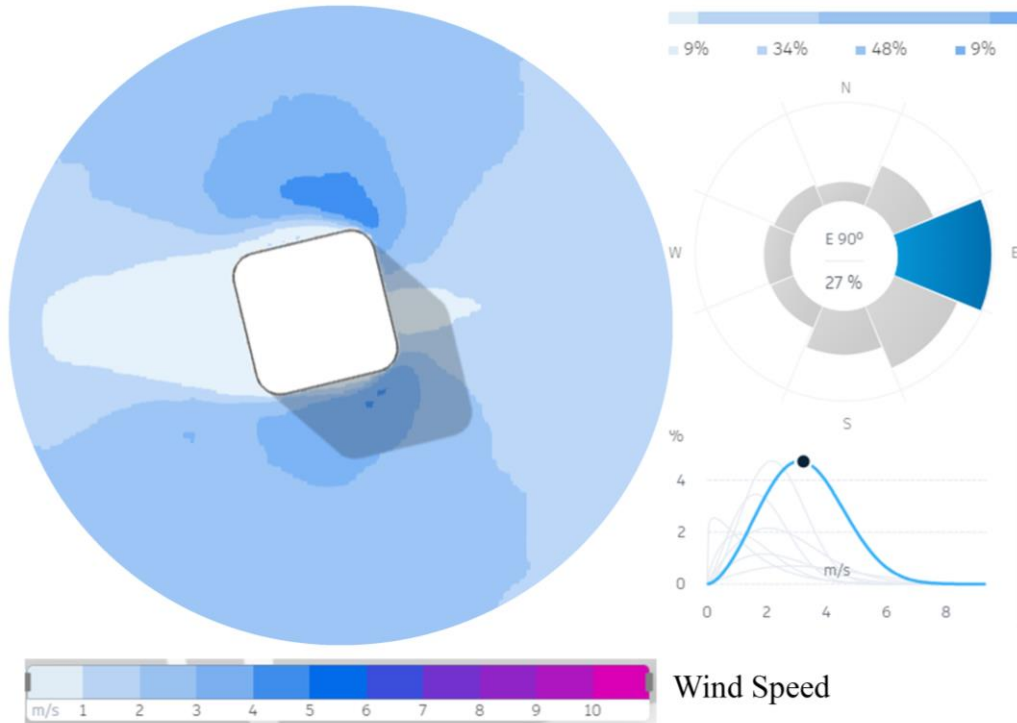
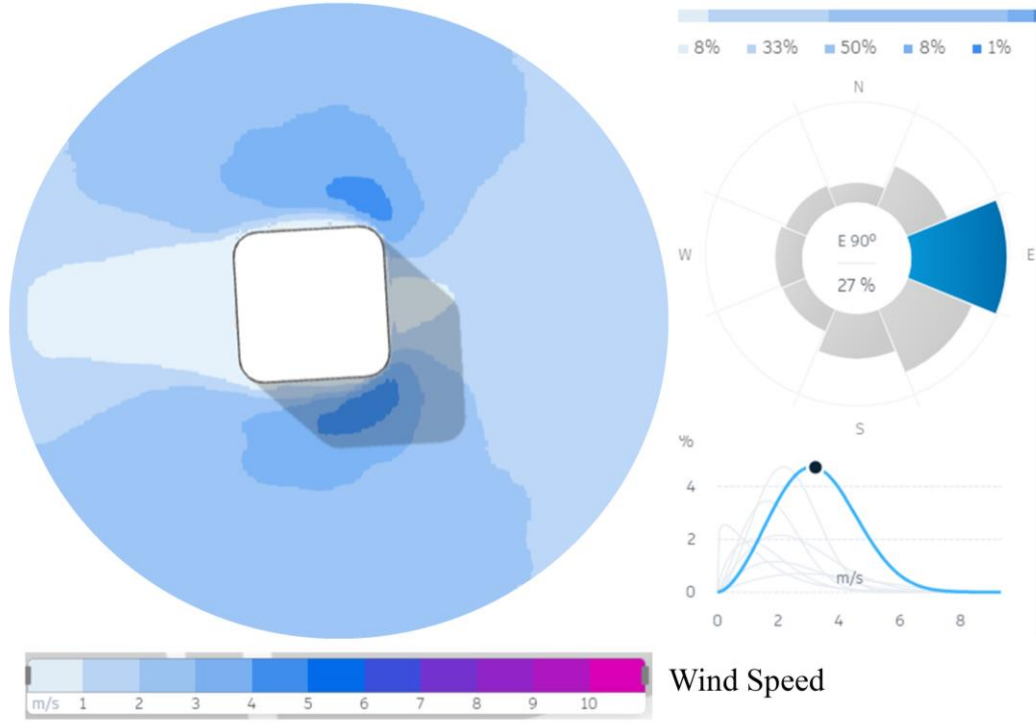


Figure 3.41: Eighty-fifth and ninetieth floor simulation map.

Ninty-fifth Floor Wind Simulation Map



Hundredth Floor Wind Simulation Map

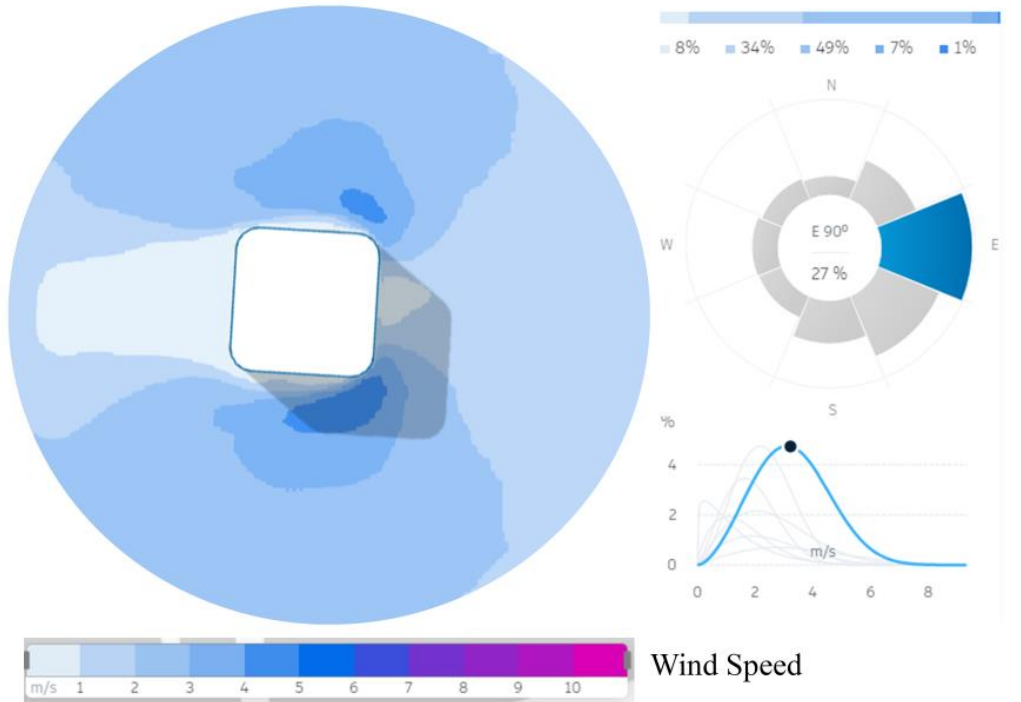


Figure 3.42: Ninety-fifth and hundredth floor simulation map.

3.8.4 Energy-Plus Aerodynamic Building Design

In this research, the optimized building form is used to design an energy-plus aerodynamic building. The optimized form is tested through CFD simulation to verify that the optimized form has reduced the wind loads on the building and improved its energy efficiency. Rhinoceros software and different grasshopper plugins like Lunch-Box, Heliotrope, and other parametric tools were used for simulation and modeling. The final script definition of the building is attached in Appendix 5.

The examinations of the CFD simulation showed that the wind force is reduced by up to 27.64% after the form is optimized. The wind force simulation results of the aerodynamic building before and after optimization are attached in Appendices 3 and 4, respectively.

Figure 3.43 illustrates the site plan for the energy-plus aerodynamic building.

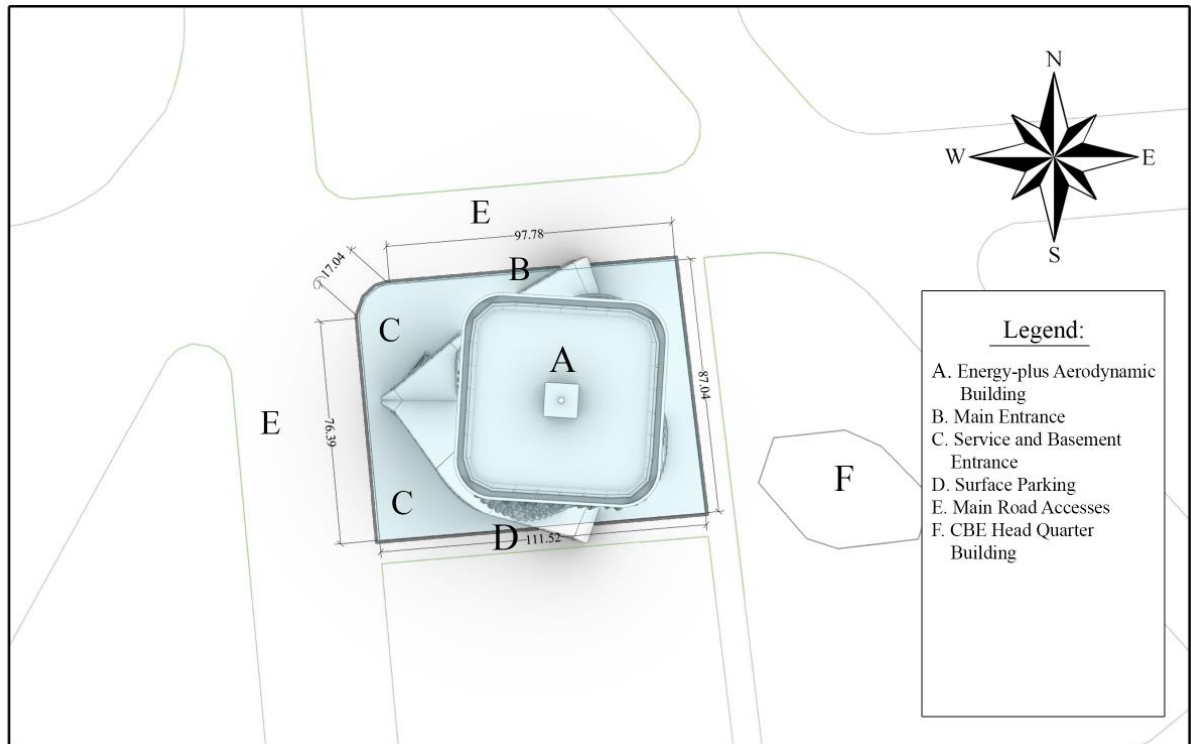


Figure 3.43: Site plan of an energy-plus aerodynamic building.

The aerodynamic building will have different functions since it is located in the main city center of Addis Ababa. The vertical functional zoning of the building is presented in Figure 3.44 below.

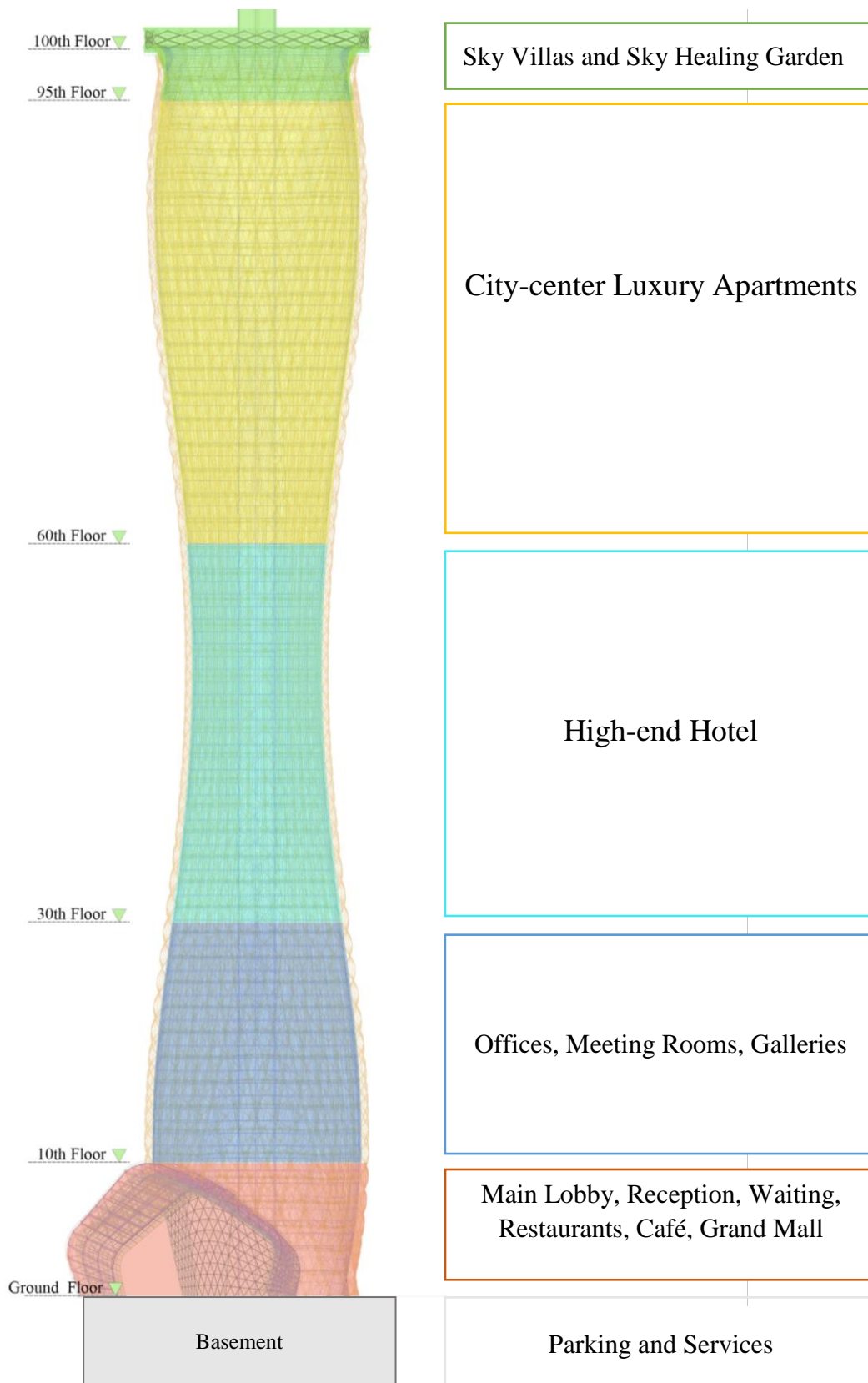


Figure 3.44: Energy-plus aerodynamic building vertical zonings.

Figure 3.45 illustrates the central core and slab structure, main diagrid structure, and wind energy-generating façade structure of the aerodynamic building.

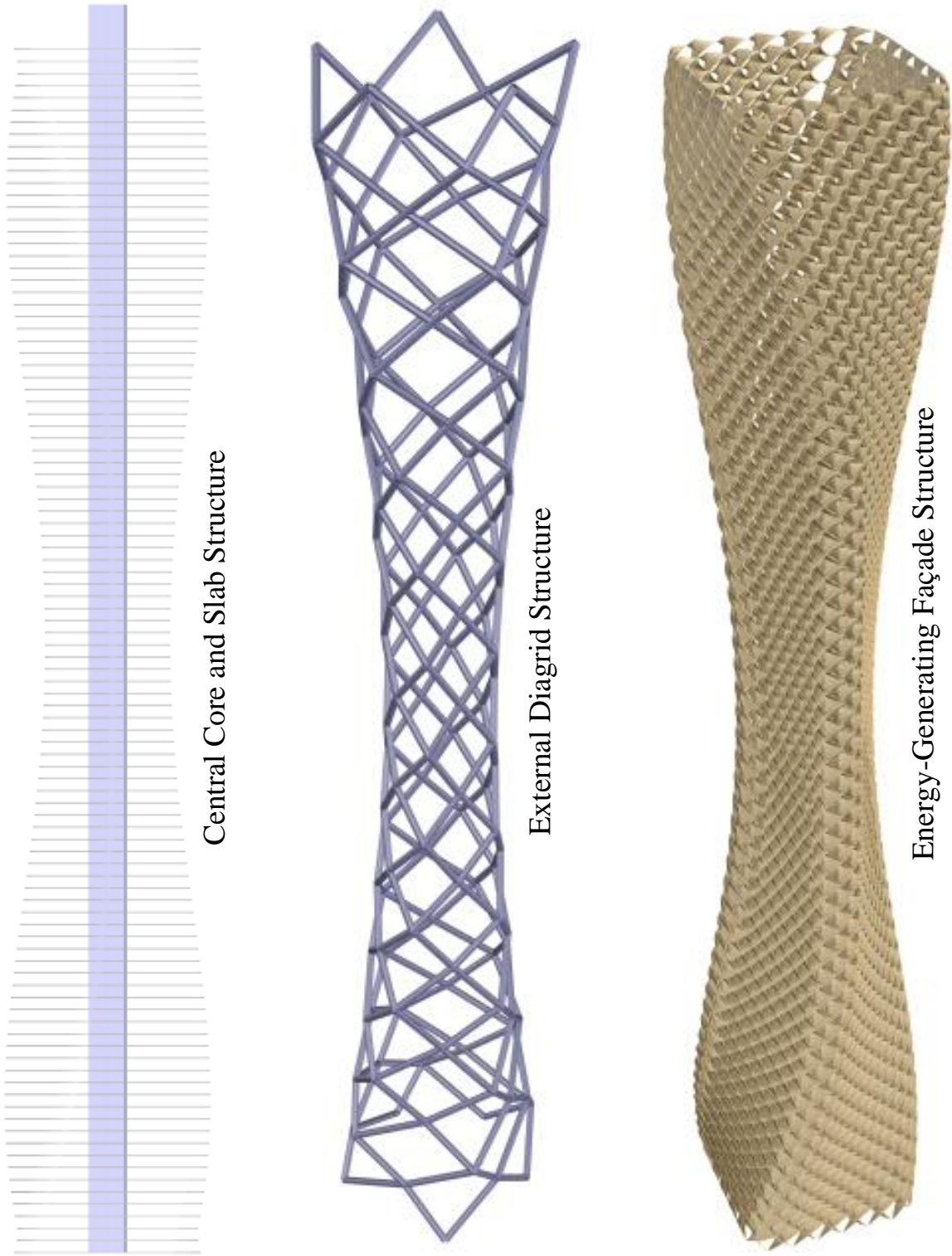


Figure 3.45: Different structural elements of the aerodynamic building.

Figure 3.46 displays the preliminary 3D visualizations of an energy-plus aerodynamic building.



Figure 3.46: 3D visualizations of energy-plus aerodynamic building.

The study explores the use of micro-wind turbines on aerodynamic building envelopes, highlighting their advantages over larger ones. These turbines are more affordable, environmentally friendly, flexible, and can enhance energy efficiency. The study uses horizontal-axis wind turbines (HAWTs), which are more effective in converting wind energy into electricity. The aerodynamic building will have 4,140 small-scale wind turbines with a 1.5-meter rotor diameter installed from the tenth floor to the hundredth floor. Fifty percent of the building's envelope will be used as an energy-generating surface for installing wind turbines. Figure 3.47 shows details of a wind generator and its structure.

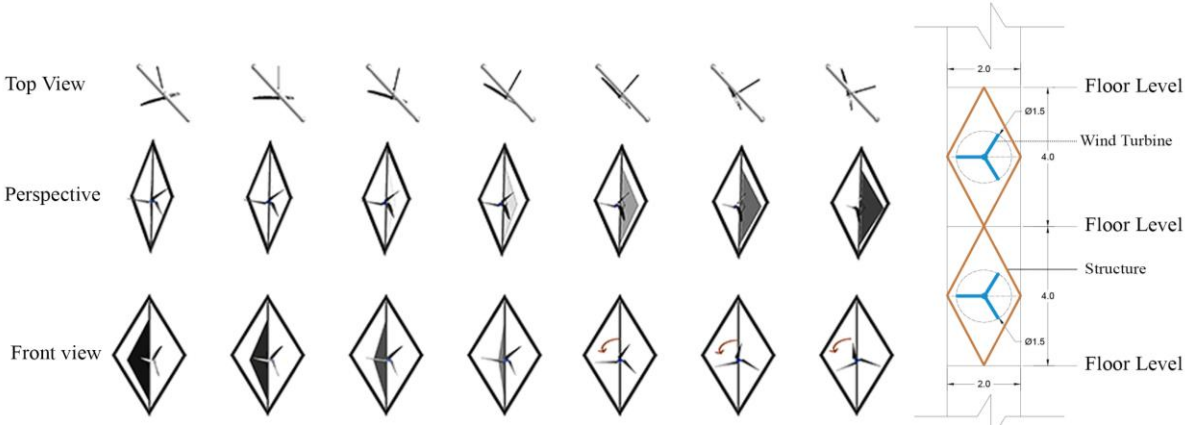


Figure 3.47: Integrated wind generator and its structure.

According to levels of Canadian Wind Energy Association (2016), small-scale wind turbine blades generally range from 1.5 to 3.5 meters in diameter and, at the ideal wind speed, generate 0.5 to 10 kW. Based on this reference, if the 1.5m long wind turbine produces an average amount of 5.25 kW per day, then by taking 35% of the generator's efficiency, the aerodynamic building will generate 2,776.65 MW per year.

Figure 3.48 shows the energy-generating surface of the aerodynamic building.

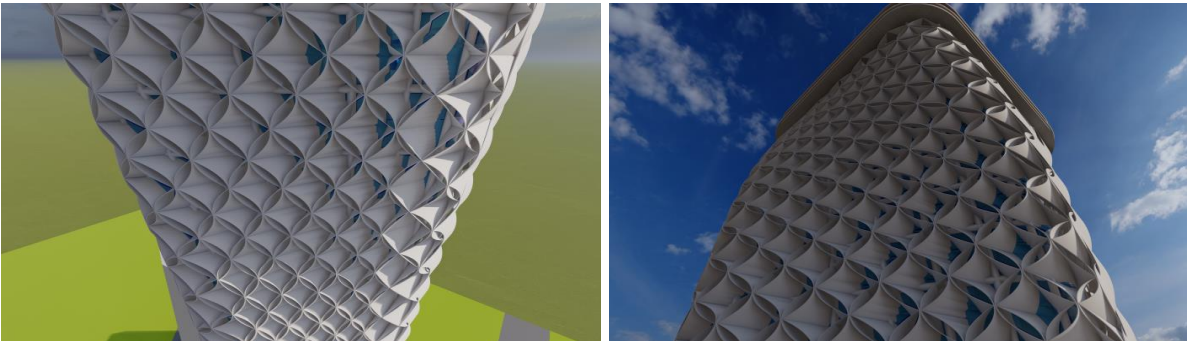


Figure 3. 48: Energy generating facade.

CHAPTER FOUR

RESULTS

4.1 Results

4.1.1 Potential Sites for Wind Energy Harvesting in Addis Ababa City

After analyzing five influencing layers using the GIS-based Multi-Criteria Decision-Making method, the overall overlaid result shows that around 80% of the study area has an above-moderate ranking of suitability. As shown in Figure 4.1 and summarized in Table 4.1, 32,079 hectares of the study area are highly suitable for wind energy harvesting, and 799 hectares are very high suitable for wind energy harvesting. On the other hand, only 3.17% of the whole site, which covers the Torhailoch area, Lideta area, Coca and Abinet area, Around Mexico Square, Bolie Airport area, and other sites of Addis Ababa City, are not suitable for wind energy harvesting, whereas 0.15% of the total extent has low suitability. Sites of high and very high suitability mostly cover the eastern, southern, and northeastern parts of the study area, in addition to different places in the central part of the city.

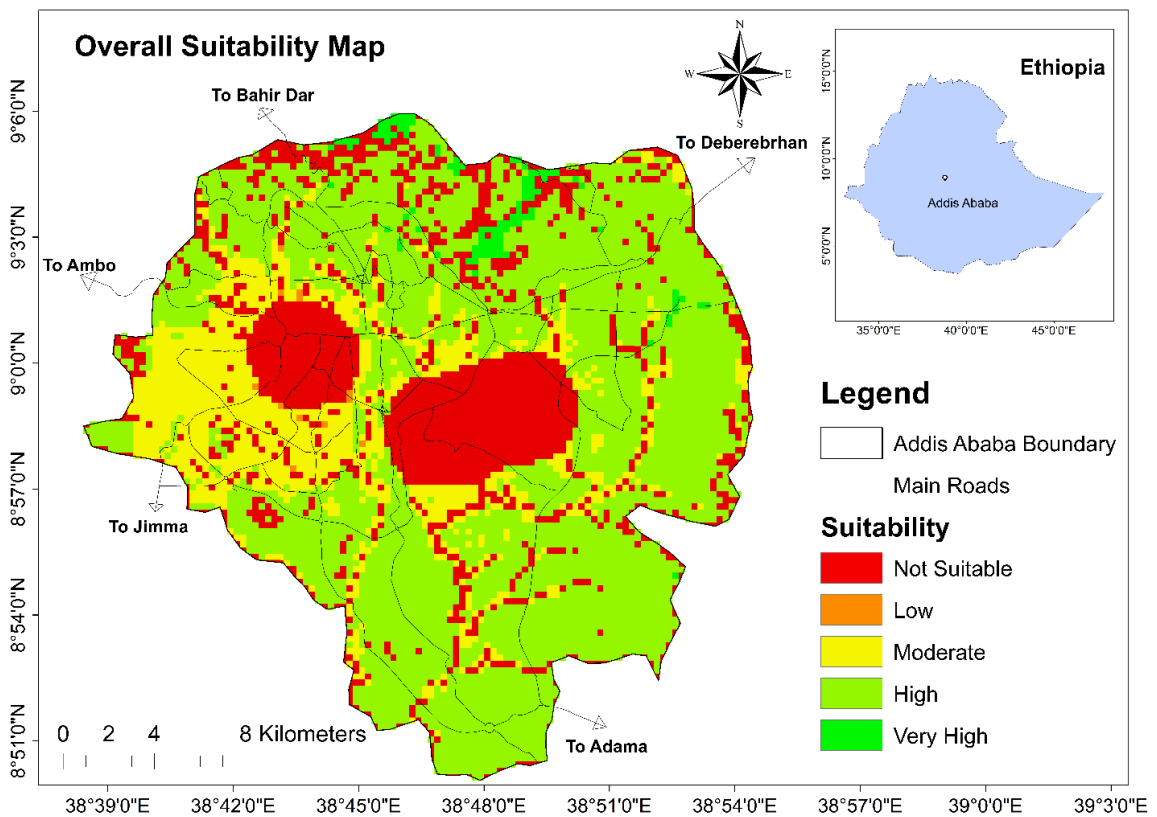







Figure 4.1: Suitability results of potential wind energy harvesting sites.

Table 4.1: Summary of overall suitability results.

Suitability	Rank	Color Code	Area (ha)	Percentage
Very High	1		799	1.50%
High	2		32079	59.95%
Moderate	3		9343	17.45%
Low	4		83	0.15%
Not Suitable	5		11,215	20.95%

4.1.2 Wind-Based Building Form Optimization

After simulations of three basic geometries performed using Galapagos optimizer in the grasshopper and Butterfly CFD to parametrize the optimization with the simulation output to maximize wind energy harvesting potential, the results of the optimized geometry show that it has a rotated square shape, which applied a minor aerodynamic modification technique of roundness of corner, and it has an improved performance simulation. Figures 4.1 and 4.2 show the results of optimized geometry and its performance simulation, respectively.

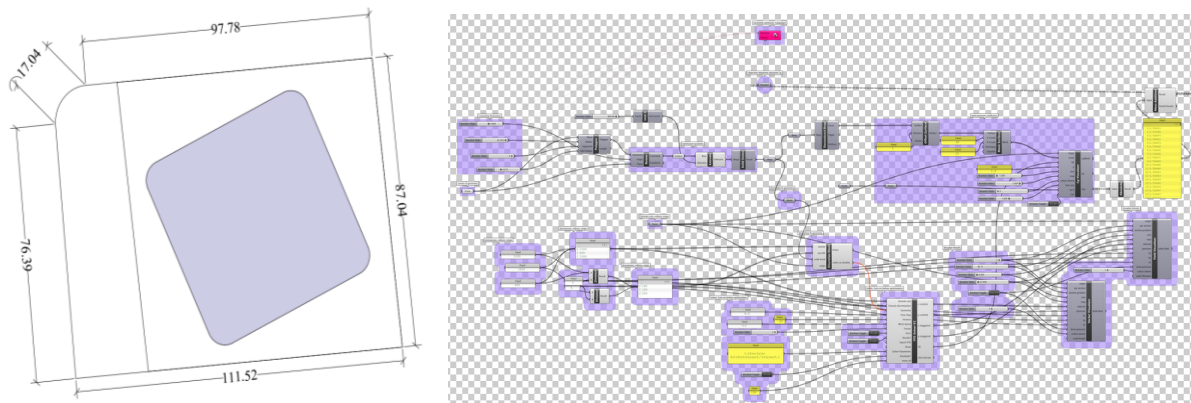


Figure 4.2: Results of optimized wind-based building geometry and its script definition.

Optimized Geometry Wind Simulation Map

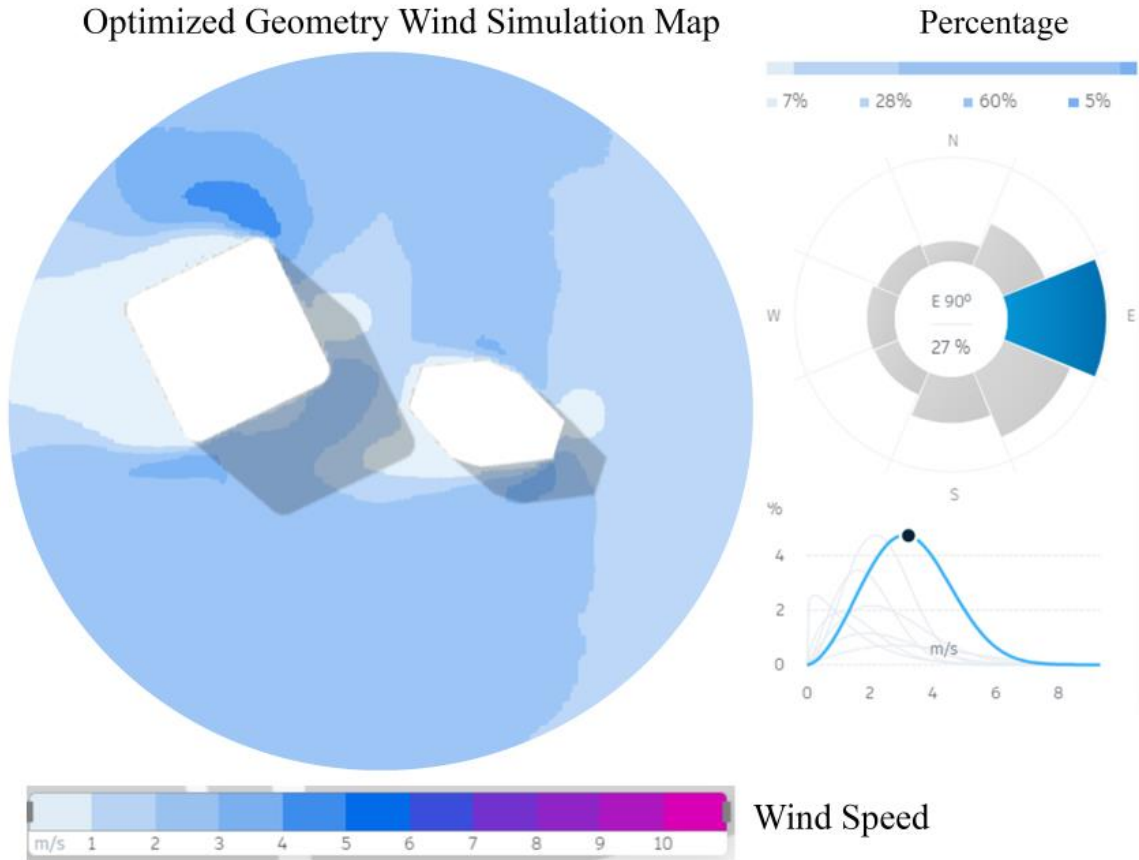


Figure 4.3: Results of an optimized geometry wind simulation map.

Similarly, the study tested several different building forms using the Octopus Multi-Objective Optimizer in the grasshopper and the Hkwind CFD simulation to parametrize the optimization with the simulation output to carve out the form of the building to maximize wind energy harvesting potential. The results showed that the method was able to find a building form that applied the twisting modification technique, and the output significantly reduced 27.64% of wind loads and improved the aerodynamic performance of the building. The result was also able to find aesthetically pleasing building form. Figures 4.4 and 4.5, respectively, presented the optimized aerodynamic form and results of the optimized form wind simulation, which was prioritized from 388 prototypes.

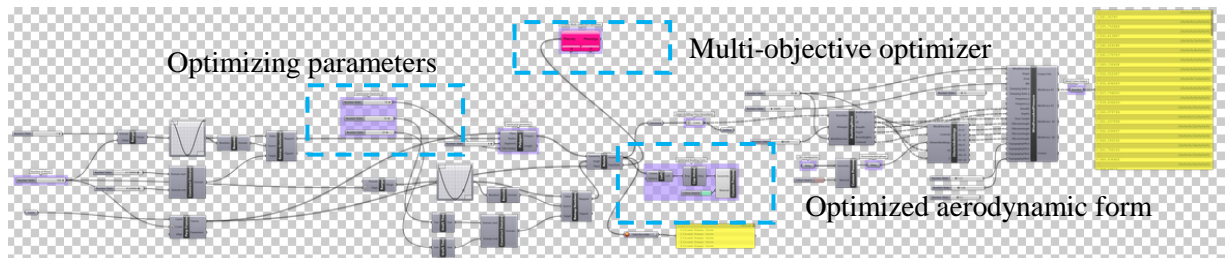


Figure 4.4: Optimized aerodynamic form script definition.

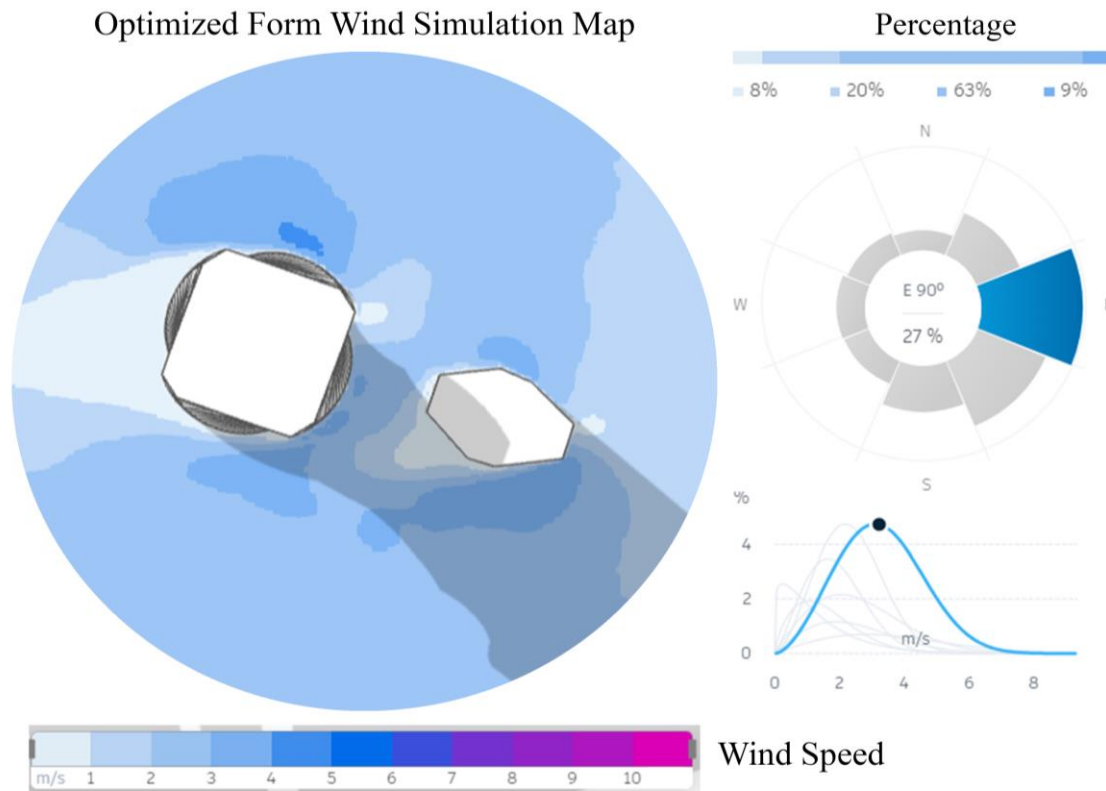


Figure 4.5: Results of an optimized form wind simulation.

4.1.3 Energy-Plus Aerodynamic Building Design

The results of the energy-plus aerodynamic building show that the optimized building form enables to reduction of wind force by up to 27.64%, and the integration of wind energy into the aerodynamically optimized building form enables it to generate 2,776.65 MW per year by installing a 1.5-meter rotor diameter small-scale wind turbines.

Energy Use Intensity (EUI) is a widely accepted indicator for comparing building energy performance. According to Melo (2023), the annual EUI for electricity, based on data from 3060 fully electric-powered buildings, shows a median of 185 kW h/m², dividing buildings into low and high energy intensive categories. Residential and educational buildings are low energy intensive (approximately 90-120 kW h/m²), while hotel and retail service categories are highly energy intensive (approximately 260-300 kW h/m²). Hospital and office buildings are slightly below the median (approximately 160 – 170 kW h/m²).

This study examines an aerodynamic building with 40 floors for hotel and retail, 20 for office, and 40 for residential use, covering an approximate floor area of 3,050m². The aerodynamic building is estimated to use an approximate 52,460 MW of energy annually.

CHAPTER FIVE

DISCUSSION

5.1 Potential Sites for Wind Energy Harvesting in Addis Ababa City

The study identifies windy areas in Addis Ababa City at 50m, 100m, 150m, and 200m, revealing higher wind speed results suitable for urban wind turbine integration. So, for this study, wind speed above 3.5 m/s is used as the minimum criterion for wind speed for selecting wind energy potential sites within the city as a determining criterion in addition to slope, river lines, road networks, and air traffic locations. As most of the studies for wind energy harvesting site selection use the minimum criteria for wind speed of 3 m/s–3.5 m/s, J. H. Park et al. (2014) also established 3 m/s as the minimum wind speed requirement for wind energy harvesting sites in built environments. Accordingly, numerous sites in the city are ideal for wind turbine integration, as they have an average annual wind speed of over 3 m/s, meeting the standard requirements for built environments. Some of these sites are located in the major city core, a vertically infinite zone.

On the other hand, the revised master plan of Addis Ababa City released by the Addis Ababa City Planning Project Office in 2022, which has over 80% potential wind energy harvesting sites, failed to consider this resource despite the city's overwhelming high-rise buildings with indefinite height regulations.

Addis Ababa, a city with over 20,000 power outages per year, as reported in a survey by NEWJEC Inc. (2018), could benefit from integrating wind turbines in its buildings. This would diversify the city's energy mix, reduce its reliance on fossil fuels, conserve resources, and reduce greenhouse gas emissions, thus mitigating climate change and reducing power outages.

Indeed, the findings of this study are useful for policymakers and planners evaluating the growth of wind energy in Addis Ababa. The research evaluates possible wind harvesting site locations and assesses the environmental and socioeconomic implications of wind energy development. The report also emphasizes the importance of thorough planning and coordination to ensure that wind energy growth in Addis Ababa is sustainable and beneficial to all stakeholders.

5.2 Wind-Based Building Form Optimization

The shape of a building significantly impacts wind force and movement, and careful adjustment of components and shape can minimize wind stimulus and save resources in high-rise buildings according to Amin & Ahuja (2010). Similarly, the findings of this study indicate that wind-based building form modification can be a potential way to lower building energy use. The experimented technique discovered an aerodynamic building design that greatly lowers wind loads by 27.64% which can be a promising lesson for the city of Addis Ababa, which is growing exponentially with limitless heights. The optimized building underwent minor modifications to round corners, while major modifications included twisting, according to Asghari Mooneghi & Kargarmoakhar's (2016) aerodynamic classification.

The proposed method for building form optimization also has limitations, including being computationally expensive, based on a simplified wind environment model, requiring specialized knowledge, the possibility of adverse effects on aesthetics, and the potential for severe effects on daylighting. Despite these limitations, the study suggests a wind-based building form optimization method that uses optimization algorithms and computational fluid dynamics (CFD) to automatically find the best shape for reducing a structure's aerodynamic response. As mentioned similarly by Bernardini & Bobby (2015), this method overcomes the difficulty of predicting changes in aerodynamic behavior with geometry, making it cost-effective and potentially allowing for more exploration of the search space, which is a promising approach to reducing energy consumption in buildings, indicating its potential for future research.

5.3 Energy-Plus Aerodynamic Building Design

The study reveals that energy-plus aerodynamic buildings can reduce energy consumption and greenhouse gas emissions by harvesting wind energy. Based on the calculation referring to the Canadian Wind Energy Association (2016) wind turbine levels, the proposed building can produce 2,776.64 MW of wind energy annually, reducing its energy consumption by 5.29%. This is due to the building's annual energy consumption of 52,460 MW, calculated via the annual energy consumption classification of buildings per floor area by Melo (2023), which can be offset by the wind energy harvested. So, this study exposes that energy-plus aerodynamic buildings are feasible, cost-effective, and can be implemented in various climates, with these findings having significant implications for future building design.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

In conclusion, the increasing demand for renewable energy and progress in energy-independent building designs have led to significant investigation into humanizing wind power technologies in built environments. Similarly, this study discovered that Addis Ababa City has significant potential for wind energy harvesting. Numerous sites with an average annual wind speed of over 3 m/s, meeting standard requirements for built environments, are ideal for wind turbine integration. Some of these sites are located in the major city core, indicating a significant wind resource for wind energy harvesting.

Rapid urbanization is causing a large amount of the world's energy consumption, with buildings accounting for 48% of that, so balancing supply and demand is crucial for urban areas. Wind power usage has increased by 8.3% annually, and integrating wind turbines with high-rise buildings in Addis Ababa could diversify the city's energy mix, reduce reliance on fossil fuels, solve power shortages, and save resources. However, challenges include protecting sensitive areas and ensuring wind harvesting sites are compatible with the city's urban development plans.

In addition, this paper introduced an innovative method of an energy-plus aerodynamic building design for carving out building forms that can respond optimally to urban environments and are highly energy efficient. These wind-based design methodologies, which use CFD simulations intended for guiding building design, started with early-stage developments of significant geometric modifications. The results of the study prove that the aerodynamically optimized building can reduce wind loads by 27.64% and harvest 2,776.65 MW of wind energy per year by integrating small-scale wind turbines, which can reduce its annual energy use by 5.29%.

6.2 Recommendation

- The study identified potential wind energy harvesting sites in a city using international metrological wind speed data but recommends measuring actual wind speed with an anemometer for confirmation.
- The future master plan revision for Addis Ababa city should consider potential wind energy harvesting sites and their renewable energy resources to promote sustainable development and minimize electricity challenges.
- The study highlights the complexity of wind-based aerodynamic building design, highlighting the need for efficient processing capacity and higher resources, and recommends prior assessment for research capacity and achievability.
- Urban wind energy's success relies on local factors, requiring sustainable design in site orientation, building shape, and energy output of building-integrated wind turbines.
- The integration of renewable energy into buildings is crucial for a self-sustaining city. Factors like wind speed, building orientation, height, and shapes influence this integration. City administrators should promote sustainable energy sources like wind energy for clean and secure energy.
- The study suggests integrating wind-based energy systems with other sustainable building strategies like solar panel systems to enhance energy efficiency.
- The study also recommends further research on the design of energy-plus aerodynamic buildings in Addis Ababa, including:
 - Investigating the effects of wind speeds and directions,
 - Exploring the effects of different building materials and construction techniques, and
 - Assessing the economic and environmental impacts of these buildings.

These recommendations aim to improve the performance and sustainability of an energy-plus aerodynamic building design in Addis Ababa.

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Appendix

Appendix 1: Publishable manuscript

Wind-based Energy-Plus Aerodynamic Building Design for the City of Addis

Ababa, Ethiopia

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Abstract

This paper presents a study on the design of energy-plus aerodynamic buildings in Addis Ababa, Ethiopia, focusing on wind energy as a viable renewable energy source. The study aims to identify potential sites for wind-based energy-plus buildings, carve out the form of buildings responding to wind energy harvesting, and design aerodynamic buildings. The research uses primary and secondary data from sources like NASA, MapServer Ethiopia, EnergyPlus, the USGS Satellite Map, and the Global Wind Atlas. The GIS-based MCDM method is utilized to identify wind energy sites, while software-based CFD simulation optimizes the aerodynamic form of buildings for wind-based wind energy harvesting. The study found that Addis Ababa has 80% potential for wind energy harvesting, with high wind speed areas suitable for wind-based energy-plus buildings. The optimized aerodynamic building form reduces wind force by 27.64% and can generate 2,776.65 MW per year by integrating small-scale wind turbines.

Keywords: Form Optimization, Aerodynamics, Wind Energy, Multi-Criteria Decision Making

1. Introduction

Globally, it is virtually impossible to imagine cities without high-rise buildings (Halis Günel & Emre Ilgin, 2014), which are the city's iconic landmarks, while skyscrapers' importance in urban development is increasing despite their negative impact on built environment quality (Neethi B. & Joby, 2018). Rapid urbanization is causing cities to consume 70% of the world's energy, while buildings account for 48% of it (Javanroodi et al., 2020). Herewith, urban areas facing increasing energy consumption and rapid economic development require a balance between energy supply and demand (Lee et al., 2017). Wind power usage has surged by over 8.3%

annually in recent years, with numerous skyscraper-based wind power generation systems being developed (J.-C. Park et al., 2017).

Ethiopia faces increasing energy demand due to reliance on hydropower, with its existing grid struggling to meet demand in Addis Ababa, causing frequent disruptions and high power losses (Assefa, 2015). Approximately 19% of losses in distribution systems occur due to a lack of capacity and equipment deterioration (Ethiopian Electric Power, 2018). With rapid economic growth, Ethiopia is seeking more power plants to meet the high demand for electricity (Derbew, 2013). The country has invested heavily in the power sector over the last decade (about 40% of GDP), but the problem of power shortages has not yet been resolved (Hassen & Degu, 2019).

Hence, wind energy is a sustainable and cost-effective renewable energy source, but Ethiopia's rapidly growing skyscrapers in Addis Ababa haven't utilized its potential. New wind-based treatments and wind energy harvesting augmentations require careful integration.

1.1 Problem Statement

Power shortages hinder growth in sub-Saharan Africa, causing businesses to lose 47 hours of economic activity a month (Carlsson et al., 2018). To address this, Ethiopia needs new power systems generating renewable energy. Power outages in Addis Ababa are becoming a significant challenge. Ethiopia is developing wind power plants, but lacks practical guidelines and knowledge about urban wind generation. Knowledge about wind resources in constructed environments is limited compared to rural areas. Furthermore, Addis Ababa's energy system is inadequate for the Ethiopian economy's growth, urbanization, and future energy demand. There's no provision for embedded generation like wind energy harvesting. The increasing number of skyscrapers in Addis Ababa consumes significant energy, and despite wind environments being suitable, there's no practical development for wind energy harvesting in cities.

On the other hand, wind loads on high-rise buildings in cities like Addis Ababa increase with height, requiring vertical expansion. However, there is a gap in design and wind treatment, leading to a lack of creative methods for tall buildings. Studies show that 33% of the 73 tallest buildings lack macro-level geometric modifications and 59% lack micro-scale modifications (Alaghmandan et al., 2013). Indeed, to address energy demand and power outage challenges, a long-term approach to renewable energy options is needed, and an alternative design methodology is needed for the city's growing skyscrapers.

2. Theoretical Review

2.1 Building Aerodynamics and Wind Energy

Aerodynamic design is an approach that is incorporated into architectural design early in the project (Biswas & Peronto, 2020), which is taken as an effective way to reduce the wind load of a building. Aerodynamic architectural designs are used to mitigate wind effects on high-rise buildings, considering factors like building orientation, aerodynamic shape, floor plan changes, and aerodynamic tips (Hernandez & León, 2017).

Aerodynamic optimization of building shape is an important factor in the design of mega skyscrapers (Samad & Kumar Jain, 2020). Simulation-based optimization is an increasingly common calculation for designing a resource and energy-efficient building (Al-Najjar & Al-Azhari, 2021). Computational fluid dynamics (CFD) is the best tool available nowadays to carry out a careful analysis of the wind flow around buildings (Toja-Silva et al., 2018). CFD aerodynamic shape optimization is increasingly being utilized in civil engineering structures, particularly high-rise buildings, to improve aerodynamic design (Muyl et al., 2002). The wind-based building design process includes: (1) criteria definition; (2) geometries and tower arrangement classification; (3) prototype definition; and (4) optimization processes (Abdolhossein-Pour et al., 2013). Wind impacts architecture by shaping built environments, causing zones with no wind or high-speed turbulent flow. Studying individual wind characteristics helps create sustainable and comfortable environments (Kabošová et al., 2020) while the geometry of a building also significantly impacts airflow patterns, particularly in taller buildings, which can be transformed into a large-scale concentrator effect, increasing wind power generation (Mertens, 2006).

Wind power can play an important role in resolving current energy and environmental crises (Kasinatha Pandian Karpaga et al., 2007). Since the 1970s, the wind industry has grown steadily, with smaller turbines initially used for residential purposes, then larger ones, and now integrating them into buildings. (Wilson, 2021). The idea of integrating wind was born to improve the overall energy efficiency of the building. Turbines that build the hull are becoming more and more popular (Popovac, 2012). High-rise buildings are considered to be candidates for wind energy use in urban areas (J. Park et al., 2015). 3 m/s is the minimum wind volume required to operate a wind power system on a high-rise building (J. H. Park et al., 2014).

Identifying suitable areas for wind development involves the analysis and consideration of criteria based on a combination of topographic, technical, environmental, and socio-economic factors (Athanasios, 2018). The use of GIS-based multi-criteria decision-making (MCDM) analysis for the planning of wind energy harvesting sites gained significance in the early 2000s (Baseer et al., 2017). Multiple-criteria decision making (MCDM) is a powerful tool used in energy planning and decision-making, combining Geographical Information Systems (GIS) with MCDM technology to analyze and combine geographic data, enabling accurate problem-solving and alternative structure. (Athanasios, 2018). The evaluation criteria for wind harvesting expansion are defined to assess the entire region based on the preferences of decision-makers (Taoufik & Fekri, 2021). This evaluation is made possible through standardization process, which is required to compare and combine criteria against various properties (distance, percentage, velocity, etc.). In the standardization process, score values are accredited according to criteria (Bobeck, 2017).

Weights are assigned to the rating layer, and a rating map is created (one for each decision-maker). The evaluation map is created in two steps. In the first step, the weights calculated using AHP analysis are assigned to the evaluation layer. In the second step, the evaluation map is created using the weighted overlay technique, or the WLC is created using the GIS weighted overlay tool (Szurek et al., 2014). Finally, suitability maps are calculated based on the multiplication of each evaluation map with the constraint map. This is possible by using the raster calculator function on GIS, based on suitability assessment classes of Höfer (2016).

3. Materials and Methods

3.1 Description of Study Area

The study area, Addis Ababa City, situated on the central Ethiopian plateau, has a diverse terrain and elevation, with a height ranging from 2,050 meters in the southern Akaki Plain to 3,000 meters on Mount Entoto. Despite an electricity access rate of 98%, Addis Ababa experiences frequent outages and interruptions, with an average of 42 weekly interruptions (Ethiopian Electric Power, 2018).

Figure 3.1 shows location map of the study area.

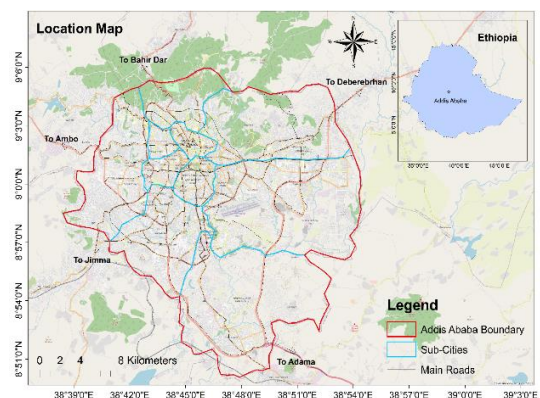


Figure 3.49: Location map of the study area.

3.2 Method of Analysis

The analysis method that is developed in this study integrates both wind speed and aerodynamic form considerations into early design stages by pairing the GIS-based MCDM analysis method for siting locations with CFD software simulations for wind-based form-finding processes. Table 3.1 specifies the spatial facts of supply and common weight.

Table 3.9: Spatial data sources and overall weights for each major attributes.

No	Factors	Spatial Data Source	Analysis
Topographic (5%)			
1	Slope	DEM of Addis Ababa city from USGS EarthExplorer	ArcGIS Spatial Data Analysis
Technical (50%)			
2	Wind speed	NASA metrology agency Global wind atlas, EPW	ArcGIS, ArcMap
Environmental (20%)			
3	Distance from rivers	DEM of Addis Ababa city	ArcGIS
Socioeconomic (25%)			
4	Distance to main roads	MapServer Ethiopia	ArcGIS
5	Distance from airports	Humdata Digitize existing airport	ArcGIS ArcGIS Editor tool

The investigation of suitability for a city wind harvesting site is done tremendously, defining and weighting every criterion with a specific impact or weight to choose a vicinity for wind harvesting locations. Computational Fluid Dynamics (CFD) simulation method is used to analyze the energy performance of the building to optimize its aerodynamic form accordingly. Methods, including data types used for this study, methods of data collection, and methods of data analysis, are summarized in Table 3.2 below.

Table 3.10: Summary of methodologies.

Specific Objective	Data type	Methods of data collection	Method of analysis
4. To identify potential sites for wind-based energy-plus building.	Wind speed, DEM and published documents	NASA Metrology Agency, MapServer Ethiopia, EnergyPlus, USGS Satellite Map and Global Wind Atlas	ArcGIS, MCDM and AHP to analyze suitable maps
5. To carve out the form of building responding for wind energy harvesting.	Wind speed and Suitability map	ArcGIS suitability map, EPW and NASA Metrology Agency	Autodesk Forma, Hkwind CFD simulation, Butterfly-Grasshopper CFD plugin, Octopus and Galapagos Grasshopper plugins to generate optimized building from
6. To design aerodynamic building.	Optimized building form	CFD simulated model from Rhinoceros + Grasshopper software	Rhinoceros, Lunch-box-Grasshopper Plugin, Heliotrope-Grasshopper Plugin and paneling tools for final building output

3.3 Investigation of Wind Harvesting Sites Suitability Using MCDM

The process involves assigning weights to each layer based on their importance in determining the suitability of a wind energy site. A weighted linear combination is used to minimize the impact of less importance on windy areas, and the weighted layers are combined to select the optimal location for wind energy production.

3.3.1 Slope Suitability

Slope suitability analysis, as depicted in Figure 3.2 shows that only 7.46% of the study area is not suitable for siting wind turbines, and 4.86% of the whole area is low suitable. On the other hand, 27.71%, which covers around 14,973 hectares is very high suitable for wind energy harvesting.

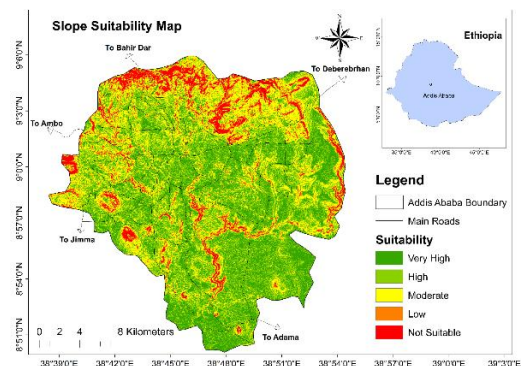


Figure 3.50: Slope suitability map.

3.3.2 Wind Speed Suitability

The study area meets wind energy harvesting standards, with 14.70% of the area being low-suitable, and 80% having wind speeds over 4 m/s. 961 hectares are highly suitable, and 13,831 hectares are highly suitable, with 961 hectares being very high-suitable as shown in Figure 3.3.

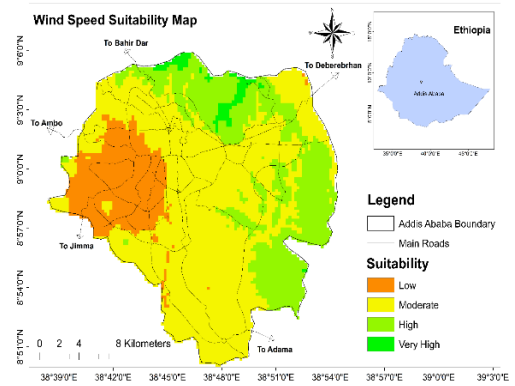


Figure 3.51: Wind speed suitability map.

3.3.3 Proximity to River Line Suitability

As rivers are naturally protected areas, the construction of wind harvesting sites should exclude the buffer from existing major river lines. Figure 3.12 show that 78.98% (72,583 hectares) of the study area is more than 250m away from river lines, which is very high suitable for siting wind farms.

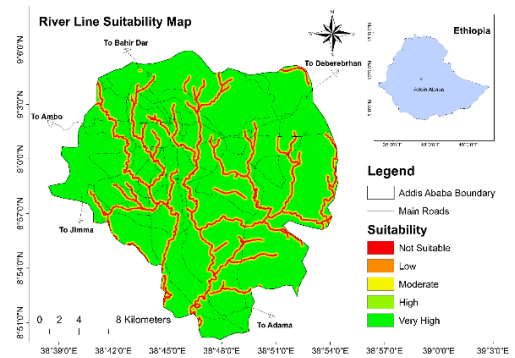


Figure 3.52: River line suitability map.

3.3.4 Proximity to Main Road Suitability

As shown in Figure 3.14, the study area under very high and high suitability is 0-500m close to the main road, which covers 23.22% (12,512 ha) and 25.73% (13,862 ha), respectively, which are considered to be the highest siting preferences.

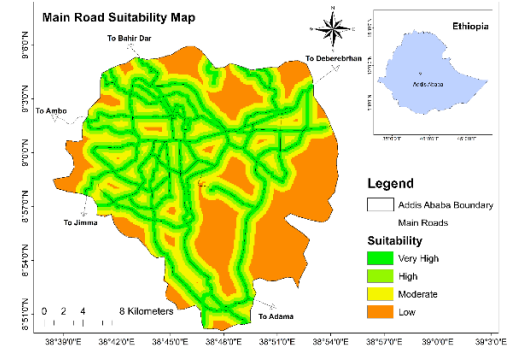


Figure 3.53: Existing road suitability map.

3.3.5 Proximity to Main Road Suitability

The study reveals that proximity to air traffic, specifically 60.95% of the 32,875 hectares of land, is a significant factor in the potential impact of wind turbines on airport communication systems and navigation, making it an ideal site for wind energy harvesting as shown in Figure 3.6.

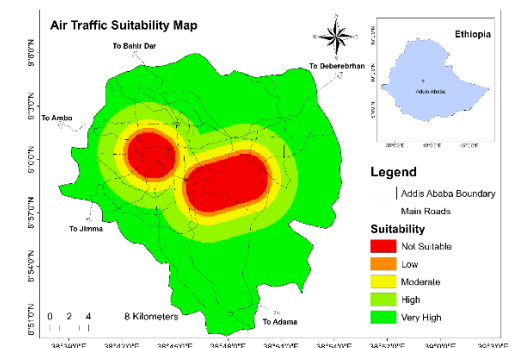


Figure 3.54: Air traffic suitability map.

3.4 Wind-Based Building Form Optimization

The project site, covering 9,500 square meters plot area, is located near the CBE headquarters building and is set to replace the Ethiopia Hotel with a new high-rise building having over 70 meters height. The site is chosen from suitable sites within the city's unlimited height zone, based on suitability maps, building height regulations, and land use plans.

3.4.1 Building Form Optimization Process:

Step 1: Criteria Definition: This research uses variable parameters, such as footprint geometry type, corner modification, extrusion, rotation, twist, and tower modification for a single tower, to influence airflow patterns in buildings.

Step 2: Footprint Geometry and Tower Arrangement: In this step, this paper investigates three different footprint shapes of tall buildings with airfoil geometries for optimal geometry and tower arrangement. The research focuses on single towers with an airfoil shape in aerodynamic building forms, using rectangular, triangular, and circular geometries as experimental geometries. The wind simulation analysis reveals the distinct interactions between rectangular, triangular, and circular geometry and wind flow, as depicted in Figures 3.15.

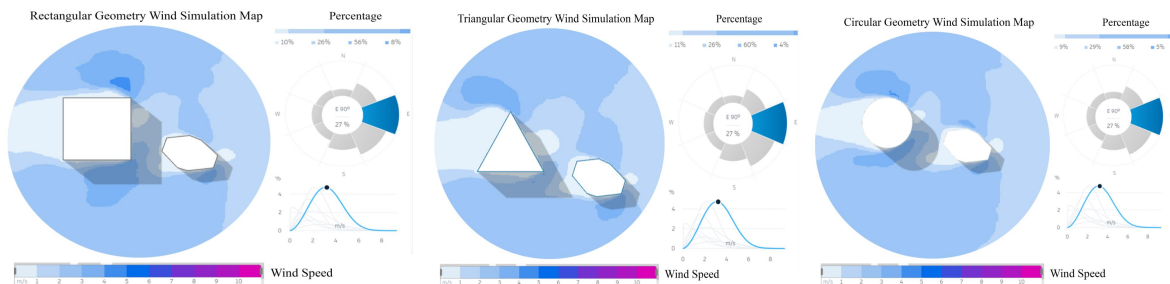


Figure 3.55: Wind simulation map of rectangular, triangular and circular geometries.

Step 3: Prototype Definition: In this stage, the study simulated footprint geometry and tower arrangement for wind energy harvesting, analyzing 388 prototypes using wind-based simulation. The most efficient prototype was found using computational fluid dynamics in Grasshopper plugins in Rhinoceros software. The analysis involved modeling air flow and calculating forces to compare options and optimize performance.

Step 4: Performance Simulation: After the optimal building form is defined, the research simulates the performance of the optimal building form for wind turbine integration using Autodesk Forma CFD software, Rhinoceros, and Butterfly-Grasshopper plugins. The simulation is conducted at every five-floor interval, and the analysis reveals that all simulations

from the ground floor to the hundredth-floor level have over 90% average wind speed values ranging from 3 m/s to 6 m/s.

3.5 Energy-Plus Aerodynamic Building Design

The research utilizes an optimized building form for an energy-plus aerodynamic building, tested through CFD simulation, using Rhinoceros software and grasshopper plugins for simulation and modeling. The CFD simulation revealed that the form's optimization can reduce wind force by up to 27.64%.

The study explores the use of micro-wind turbines in aerodynamic buildings, highlighting their affordability, environmental friendliness, and energy efficiency. It plans to install 4,140 small-scale turbines, utilizing 50% of the building's envelope as an energy-generating surface. Figure 3.47 shows details of a wind generator and its structure.

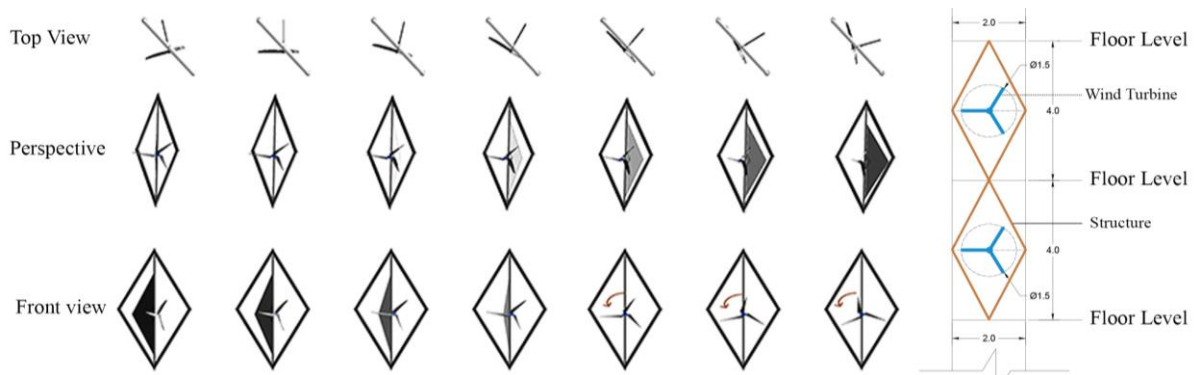


Figure 3.56: Integrated wind generator and its structure.

According to levels of Canadian Wind Energy Association (2016), small-scale wind turbine blades generally range from 1.5 to 3.5 meters in diameter and, at the ideal wind speed, generate 0.5 to 10 kW. Based on this reference, if the 1.5m long wind turbine produces an average amount of 5.25 kW per day, then by taking 35% of the generator's efficiency, the aerodynamic building will generate 2,776.65 MW per year. Figure 3.48 shows 3D visualizations of energy-plus aerodynamic building and its energy-generating facade.



Figure 3.57: Energy generating facade.

4. Results

4.1 Potential Sites for Wind Energy Harvesting in Addis Ababa City

The study area, analyzed using GIS-based Multi-Criteria Decision-Making method, shows 80% suitability for wind energy harvesting. 32,079 hectares are highly suitable, while 799 hectares are very high. Only 3.17% of the site is not suitable, and 0.15% has low suitability, shown in Figure 4.1.

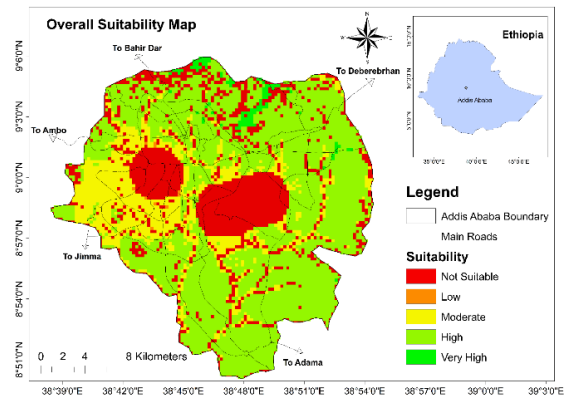


Figure 4.6: Suitability results of potential wind energy harvesting sites.

4.2 Wind-Based Building Form Optimization

The optimization of three basic geometries using Galapagos optimizer in grasshopper and Butterfly CFD was performed to maximize wind energy harvesting potential. The optimized geometry, with a rotated square shape and minor aerodynamic modification, improved performance simulations. In addition, the study utilized the Octopus Multi-Objective Optimizer in grasshopper and the Hkwind CFD simulation to optimize building forms for wind energy harvesting. The method found a twisting modification technique that reduced wind loads by 27.64% and improved aerodynamic performance. The optimized aerodynamic form were prioritized from 388 prototypes. Figures 4.2 show the results of optimized geometry and building form performance simulations.

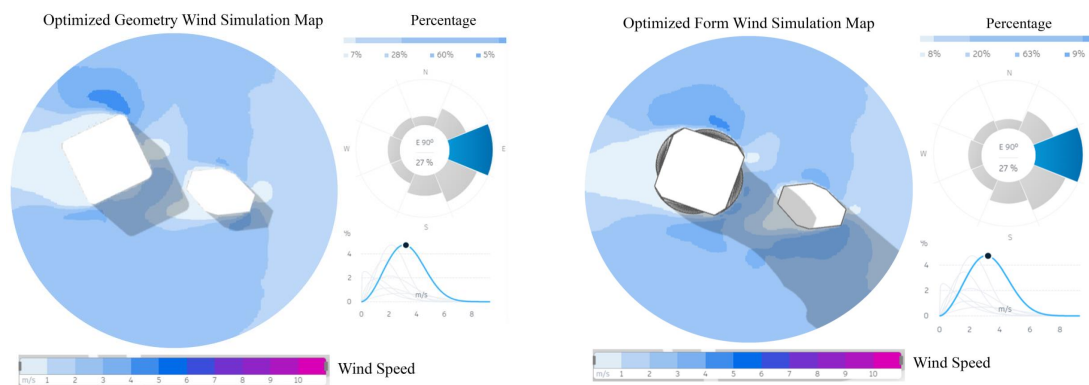


Figure 4.7: Results of an optimized geometry and aerodynamic building form wind simulation map.

4.3 Energy-Plus Aerodynamic Building Design

The results of this study reveals that an energy-plus aerodynamic building can reduce wind force by 27.64% and generate 2,776.65 MW per year by integrating wind energy through small-scale wind turbines. The building, with 40 floors for hotel and retail, 20 floors office, and 40 floors for residential use, uses an approximately 52,460 MW of energy annually.

5. Discussion

5.4 Potential Sites for Wind Energy Harvesting in Addis Ababa City

The study identifies windy areas in Addis Ababa City with wind speeds above 3.5 m/s as suitable for urban wind turbine integration, meeting standard requirements for built environments. However, the revised master plan of Addis Ababa City, which has over 80% potential wind energy harvesting sites, failed to consider this resource. The city could benefit from integrating wind turbines in its buildings, diversifying its energy mix, reducing reliance on fossil fuels, conserving resources, and reducing greenhouse gas emissions.

The shape of a building significantly impacts wind force and movement, and careful adjustment can minimize wind stimulus and save resources in high-rise buildings. This study suggests that wind-based building form modification can lower energy use. An aerodynamic building design significantly lowers wind loads by 27.64%, promising lessons for Addis Ababa's growing city. The method has limitations, including computational cost, requiring specialized knowledge, and potential adverse effects on aesthetics and daylighting. However, a wind-based building form optimization method using optimization algorithms and computational fluid dynamics (CFD) can find the best shape for reducing a structure's aerodynamic response. This method is cost-effective and could lead to more exploration of search space, indicating potential for future research.

The study reveals that energy-plus aerodynamic buildings can reduce energy consumption and greenhouse gas emissions by harvesting wind energy. The proposed building can produce 2,776.64 MW of wind energy annually, reducing its energy consumption by 3.29%. This is due to the building's annual energy consumption of 52,460 MW, which can be offset by wind energy. This study highlights the feasibility and cost-effectiveness of energy-plus aerodynamic buildings.

6. Conclusion

In conclusion, the increasing demand for renewable energy and advancements in energy-independent building designs have led to a study on wind power technologies in built environments. Addis Ababa City has significant potential for wind energy harvesting due to its numerous sites with an average annual wind speed of over 3 m/s. Balancing supply and demand is crucial for urban areas, and integrating wind turbines with high-rise buildings could diversify the city's energy mix, reduce reliance on fossil fuels, solve power shortages, and save resources. However, challenges include protecting sensitive areas and ensuring compatibility with urban development plans. An innovative energy-plus aerodynamic building design method was introduced, reducing wind loads by 27.64% and harvesting 2,776.65 MW of wind energy per year, which can reduce its annual energy use by 5.29% by integrating small-scale wind turbines.

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Appendix 2: Mean wind speed within Addis Ababa city at a 10m height from 1991 to 2021.

Location: Latitude: 8° 49`55.9" to 9°5`53.8" N and

Longitude: 38°38`16.6" to 38°54`19.5" E (NASA, 2022).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1991	3.64	3.33	3.39	4.27	4.56	2.51	2.03	1.67	2.17	3.51	3.18	3.31
1992	3.41	3.01	3.66	3.2	3.41	2.16	2	2.32	2.2	3.2	3.57	3.8
1993	3.72	3.49	3.81	2.94	2.73	1.73	2.05	1.83	1.88	3.38	3.66	3.61
1994	3.28	3.45	3.32	3.53	3.66	1.58	2.34	1.97	2.37	4.02	3.43	3.81
1995	3.52	3.19	3.34	2.89	3.6	2.65	2.21	2.05	2.34	3.73	2.98	3.45
1996	3.27	3.32	3.32	3.02	2.8	1.87	2.1	1.89	2.08	3.43	3.5	3
1997	2.98	4.23	3.54	2.9	3.22	2.48	1.74	1.89	2.63	3.04	3.24	3.52
1998	3.55	2.73	3.51	2.97	2.85	2.3	2.47	2.69	2.09	2.64	3.5	3.48
1999	3.3	4.07	2.76	3.83	3.08	2.27	2.24	1.84	2	2.57	3.77	3.23
2000	3.59	3.88	4.1	3.45	2.73	2.04	2.48	2.65	1.97	2.91	3.45	3.19
2001	2.73	3.57	2.74	3.73	2.55	2.19	2.48	3.03	2.38	3.34	3.45	3.72
2002	3.48	3.58	2.97	3.91	2.55	2.25	2	1.95	2.28	3.99	3.66	3.37
2003	3.28	3.59	3.84	2.94	3.66	2.34	2.51	2.52	1.98	3.79	3.75	3.65
2004	3.06	3.52	3.41	2.67	3.61	2.14	2.33	2.32	2.23	3.67	3.72	3.43
2005	3.23	3.88	3.29	3.09	2.36	2.48	2.59	2.29	2.31	3.28	3.62	3.84
2006	3.77	3.5	2.69	2.77	3.43	2.2	1.99	2.16	2.15	3.3	3.34	3.28
2007	3.31	3.15	3.84	3.3	2.98	2.44	2.12	1.76	1.95	3.84	4.05	3.79
2008	3.84	3.95	3.74	4.38	3.23	2.25	2.31	1.75	2.35	3.28	2.96	3.08
2009	2.88	3.66	3.61	3.66	3.8	2.73	2.22	1.97	2.41	3.14	3.49	2.73
2010	3.02	2.26	3.07	2.83	2.37	2.02	2.39	2.56	2.03	3.68	3.23	2.73
2011	3.09	3.69	3.59	3.45	2.83	1.86	2.41	2.2	2.17	3.84	3.01	3.48
2012	3.91	4.45	3.96	2.45	3.81	2.32	2.29	1.89	1.92	3.76	3.23	3.3
2013	3.2	3.92	2.67	2.27	2.42	1.87	2.69	2.02	2.24	3.11	3.3	2.7
2014	2.93	2.57	3.63	3.97	3.27	2.6	2.05	1.76	2.41	3.33	3.49	2.98
2015	3.37	3.59	4.22	4.01	3.29	2.44	1.94	1.9	2.43	3.84	3.66	3.4
2016	2.91	3.48	3.66	2.26	2.72	2.25	2.32	2.16	2.29	3.45	3.52	3.97
2017	3.8	3.73	3.45	4.31	2.92	2.48	2.08	2.02	2.32	3.57	3.44	3.15
2018	2.89	3.43	3.24	2.3	3.06	1.98	2.16	2.04	2.81	3.64	3.78	3.55
2019	4.06	3.95	3.65	3.04	3.56	2.15	1.8	2.05	1.86	3.7	3.55	2.96
2020	3.19	3.88	3.1	3.06	2.98	1.91	2.6	2.18	2.12	3.31	3.52	3.45
2021	3.31	3.27	4.4	3.56	3.11	2.59	2.95	2.03	2	3.53	3.77	3.63

Appendix 3: Mean wind speed within Addis Ababa city at a 50m height from 1991 to 2021.

Location: Latitude: 8° 49`55.9" to 9°5`53.8" N and

Longitude: 38°38`16.6" to 38°54`19.5" E (NASA, 2022).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1991	5.2	4.58	4.75	6.06	6.36	3.45	2.94	2.34	3.09	5.24	4.75	4.8
1992	4.81	4.11	5.22	4.46	4.79	2.92	2.86	3.36	3.19	4.85	5.38	5.59
1993	5.19	4.85	5.4	4.14	3.82	2.38	2.97	2.56	2.69	5.12	5.47	5.31
1994	4.74	4.69	4.63	5	5.02	2.23	3.3	2.83	3.48	6.05	5.12	5.55
1995	4.94	4.38	4.71	4.01	5.03	3.58	3.14	2.98	3.38	5.7	4.41	5.02
1996	4.61	4.63	4.7	4.16	3.89	2.63	3.05	2.75	2.94	5.13	5.21	4.34
1997	4.14	5.99	4.86	4.02	4.43	3.5	2.43	2.69	3.91	4.58	4.82	5.16
1998	5	3.85	4.95	4.18	3.96	3.25	3.57	3.95	3.03	3.95	5.2	5.05
1999	4.74	5.95	3.7	5.16	4.23	3.15	3.2	2.59	2.9	3.8	5.64	4.8
2000	5.16	5.45	5.7	4.83	3.73	2.84	3.56	3.8	2.8	4.36	5.2	4.57
2001	3.59	5.01	3.71	5.23	3.57	3.08	3.59	4.4	3.48	5.01	5.05	5.33
2002	4.83	4.98	4.02	5.45	3.52	3.16	2.84	2.77	3.32	5.99	5.31	4.64
2003	4.43	4.91	5.37	4.2	5.09	3.21	3.57	3.63	2.86	5.76	5.57	5.24
2004	4.22	4.76	4.69	3.75	5.09	2.94	3.4	3.36	3.19	5.55	5.47	4.87
2005	4.48	5.52	4.57	4.33	3.33	3.43	3.7	3.28	3.37	4.95	5.35	5.54
2006	5.32	4.9	3.74	3.86	4.81	3.19	2.8	3.05	3.12	5.04	5.02	4.81
2007	4.71	4.44	5.45	4.6	4.13	3.45	3	2.49	2.83	5.71	6.14	5.56
2008	5.54	5.49	5.3	6.16	4.44	3.08	3.34	2.43	3.31	4.89	4.34	4.52
2009	4.1	5.27	5.07	5.15	5.31	3.79	3.12	2.77	3.43	4.66	5.16	3.97
2010	4.26	3.15	4.21	3.99	3.35	2.83	3.43	3.72	2.92	5.56	4.83	3.88
2011	4.37	5.27	5.09	4.88	3.94	2.62	3.41	3.16	3.11	5.91	4.37	5.03
2012	5.5	6.31	5.55	3.5	5.35	3.16	3.29	2.73	2.75	5.66	4.88	4.88
2013	4.63	5.55	3.66	3.24	3.36	2.64	3.88	2.89	3.2	4.59	4.98	3.88
2014	4.11	3.57	5.12	5.66	4.52	3.62	2.9	2.45	3.43	4.96	5.28	4.35
2015	4.73	5.09	6.03	5.49	4.51	3.36	2.77	2.67	3.51	5.91	5.45	4.92
2016	4	4.78	5.19	3.12	3.8	3.15	3.33	3.09	3.3	5.18	5.28	5.86
2017	5.42	5.23	4.92	6.11	4.05	3.4	3.01	2.83	3.3	5.3	5.19	4.6
2018	4.02	4.85	4.44	3.16	4.29	2.73	3.11	2.85	4.05	5.48	5.62	5.16
2019	5.83	5.38	5.08	4.28	4.94	2.93	2.57	2.9	2.62	5.55	5.41	4.38
2020	4.45	5.3	4.15	4.27	4.16	2.64	3.73	3.17	3.09	4.93	5.27	5.09
2021	4.7	4.47	6.22	4.89	4.3	3.55	4.21	2.91	2.88	5.23	5.6	5.27

Appendix 4: Wind forces along East-direction before aerodynamic building optimization.

Location of Floors	Wind Force (KN)	Location of Floors	Wind Force (KN)
{0;0;0;0;0;0;0}	307.626788	{0;0;0;32;0;0;0}	202.253874
{0;0;0;1;0;0;0}	317.121538	{0;0;0;33;0;0;0}	197.018991
{0;0;0;2;0;0;0}	324.548592	{0;0;0;34;0;0;0}	191.693133
{0;0;0;3;0;0;0}	329.931833	{0;0;0;35;0;0;0}	186.341803
{0;0;0;4;0;0;0}	333.318361	{0;0;0;36;0;0;0}	181.026165
{0;0;0;5;0;0;0}	334.776295	{0;0;0;37;0;0;0}	175.802986
{0;0;0;6;0;0;0}	334.392434	{0;0;0;38;0;0;0}	170.724637
{0;0;0;7;0;0;0}	332.269817	{0;0;0;39;0;0;0}	165.839139
{0;0;0;8;0;0;0}	328.525235	{0;0;0;40;0;0;0}	161.190235
{0;0;0;9;0;0;0}	323.286741	{0;0;0;41;0;0;0}	156.817499
{0;0;0;10;0;0;0}	316.691191	{0;0;0;42;0;0;0}	152.756455
{0;0;0;11;0;0;0}	308.881849	{0;0;0;43;0;0;0}	149.038709
{0;0;0;12;0;0;0}	300.006093	{0;0;0;44;0;0;0}	145.692085
{0;0;0;13;0;0;0}	290.213234	{0;0;0;45;0;0;0}	142.740745
{0;0;0;14;0;0;0}	279.652477	{0;0;0;46;0;0;0}	140.205317
{0;0;0;15;0;0;0}	268.471042	{0;0;0;47;0;0;0}	138.102989
{0;0;0;16;0;0;0}	256.81245	{0;0;0;48;0;0;0}	136.447597
{0;0;0;17;0;0;0}	244.814994	{0;0;0;49;0;0;0}	135.249679
{0;0;0;18;0;0;0}	232.610387	{0;0;0;50;0;0;0}	134.51652
{0;0;0;19;0;0;0}	226.023498	{0;0;0;51;0;0;0}	134.252153
{0;0;0;20;0;0;0}	229.343208	{0;0;0;52;0;0;0}	134.457349
{0;0;0;21;0;0;0}	231.490943	{0;0;0;53;0;0;0}	135.129576
{0;0;0;22;0;0;0}	232.547157	{0;0;0;54;0;0;0}	136.262932
{0;0;0;23;0;0;0}	232.596324	{0;0;0;55;0;0;0}	137.848061
{0;0;0;24;0;0;0}	231.725735	{0;0;0;56;0;0;0}	139.872036
{0;0;0;25;0;0;0}	230.02438	{0;0;0;57;0;0;0}	142.318243
{0;0;0;26;0;0;0}	227.581909	{0;0;0;58;0;0;0}	145.166227
{0;0;0;27;0;0;0}	224.487709	{0;0;0;59;0;0;0}	148.391548
{0;0;0;28;0;0;0}	220.83006	{0;0;0;60;0;0;0}	151.965615
{0;0;0;29;0;0;0}	216.695412	{0;0;0;61;0;0;0}	155.855526
{0;0;0;30;0;0;0}	212.167747	{0;0;0;62;0;0;0}	160.023911
{0;0;0;31;0;0;0}	207.32805	{0;0;0;63;0;0;0}	164.428791

Location of Floors	Wind Force (KN)	Location of Floors	Wind Force (KN)
{0;0;0;64;0;0;0;0}	169.023451	{0;0;0;83;0;0;0;0}	243.772491
{0;0;0;65;0;0;0;0}	173.756343	{0;0;0;84;0;0;0;0}	255.702244
{0;0;0;66;0;0;0;0}	178.571032	{0;0;0;85;0;0;0;0}	267.285684
{0;0;0;67;0;0;0;0}	183.406177	{0;0;0;86;0;0;0;0}	278.379148
{0;0;0;68;0;0;0;0}	188.195581	{0;0;0;87;0;0;0;0}	288.833049
{0;0;0;69;0;0;0;0}	192.868291	{0;0;0;88;0;0;0;0}	298.49347
{0;0;0;70;0;0;0;0}	197.34878	{0;0;0;89;0;0;0;0}	307.203966
{0;0;0;71;0;0;0;0}	201.557211	{0;0;0;90;0;0;0;0}	314.807539
{0;0;0;72;0;0;0;0}	205.409785	{0;0;0;91;0;0;0;0}	321.148811
{0;0;0;73;0;0;0;0}	208.819184	{0;0;0;92;0;0;0;0}	326.076331
{0;0;0;74;0;0;0;0}	211.695122	{0;0;0;93;0;0;0;0}	329.445036
{0;0;0;75;0;0;0;0}	213.944997	{0;0;0;94;0;0;0;0}	331.118815
{0;0;0;76;0;0;0;0}	215.474645	{0;0;0;95;0;0;0;0}	330.973155
{0;0;0;77;0;0;0;0}	216.189217	{0;0;0;96;0;0;0;0}	328.897832
{0;0;0;78;0;0;0;0}	215.994151	{0;0;0;97;0;0;0;0}	324.799605
{0;0;0;79;0;0;0;0}	214.79625	{0;0;0;98;0;0;0;0}	318.604869
{0;0;0;80;0;0;0;0}	212.504863	{0;0;0;99;0;0;0;0}	310.26221
{0;0;0;81;0;0;0;0}	219.410904	{0;0;0;100;0;0;0;0}	309.821894
{0;0;0;82;0;0;0;0}	231.632766		

Appendix 5: Wind forces along East-direction after aerodynamic building optimization.

Location of Floors	Wind Force (KN)	Location of Floors	Wind Force (KN)
{0;0;0;0;0;0;0}	241.35747	{0;0;0;32;0;0;0}	211.267501
{0;0;0;1;0;0;0}	235.793424	{0;0;0;33;0;0;0}	207.810464
{0;0;0;2;0;0;0}	235.613907	{0;0;0;34;0;0;0}	204.441212
{0;0;0;3;0;0;0}	240.664348	{0;0;0;35;0;0;0}	201.178368
{0;0;0;4;0;0;0}	245.170703	{0;0;0;36;0;0;0}	198.039432
{0;0;0;5;0;0;0}	249.132438	{0;0;0;37;0;0;0}	195.040766
{0;0;0;6;0;0;0}	252.552387	{0;0;0;38;0;0;0}	192.197596
{0;0;0;7;0;0;0}	255.436583	{0;0;0;39;0;0;0}	189.524
{0;0;0;8;0;0;0}	257.794055	{0;0;0;40;0;0;0}	187.032915
{0;0;0;9;0;0;0}	259.636633	{0;0;0;41;0;0;0}	184.736144
{0;0;0;10;0;0;0}	260.978724	{0;0;0;42;0;0;0}	182.644357
{0;0;0;11;0;0;0}	261.837094	{0;0;0;43;0;0;0}	180.767102
{0;0;0;12;0;0;0}	262.230637	{0;0;0;44;0;0;0}	179.112815
{0;0;0;13;0;0;0}	262.180152	{0;0;0;45;0;0;0}	177.688826
{0;0;0;14;0;0;0}	261.708103	{0;0;0;46;0;0;0}	176.501367
{0;0;0;15;0;0;0}	260.838402	{0;0;0;47;0;0;0}	175.555585
{0;0;0;16;0;0;0}	259.59618	{0;0;0;48;0;0;0}	174.855537
{0;0;0;17;0;0;0}	258.007568	{0;0;0;49;0;0;0}	174.404205
{0;0;0;18;0;0;0}	256.099489	{0;0;0;50;0;0;0}	174.20349
{0;0;0;19;0;0;0}	253.899456	{0;0;0;51;0;0;0}	174.254215
{0;0;0;20;0;0;0}	251.435376	{0;0;0;52;0;0;0}	174.556122
{0;0;0;21;0;0;0}	248.735372	{0;0;0;53;0;0;0}	175.107866
{0;0;0;22;0;0;0}	245.827607	{0;0;0;54;0;0;0}	175.907011
{0;0;0;23;0;0;0}	242.740128	{0;0;0;55;0;0;0}	176.950018
{0;0;0;24;0;0;0}	239.500718	{0;0;0;56;0;0;0}	178.232236
{0;0;0;25;0;0;0}	236.136761	{0;0;0;57;0;0;0}	179.747888
{0;0;0;26;0;0;0}	232.67512	{0;0;0;58;0;0;0}	181.490062
{0;0;0;27;0;0;0}	229.142027	{0;0;0;59;0;0;0}	183.45069
{0;0;0;28;0;0;0}	225.562988	{0;0;0;60;0;0;0}	185.620543
{0;0;0;29;0;0;0}	221.962692	{0;0;0;61;0;0;0}	187.989209
{0;0;0;30;0;0;0}	218.364943	{0;0;0;62;0;0;0}	190.545087
{0;0;0;31;0;0;0}	214.792596	{0;0;0;63;0;0;0}	193.275375

Location of Floors	Wind Force (KN)	Location of Floors	Wind Force (KN)
{0;0;0;64;0;0;0;0}	196.166061	{0;0;0;83;0;0;0;0}	254.60312
{0;0;0;65;0;0;0;0}	199.201919	{0;0;0;84;0;0;0;0}	256.094823
{0;0;0;66;0;0;0;0}	202.366513	{0;0;0;85;0;0;0;0}	257.232809
{0;0;0;67;0;0;0;0}	205.642197	{0;0;0;86;0;0;0;0}	257.990132
{0;0;0;68;0;0;0;0}	209.010131	{0;0;0;87;0;0;0;0}	258.34089
{0;0;0;69;0;0;0;0}	212.450299	{0;0;0;88;0;0;0;0}	258.260453
{0;0;0;70;0;0;0;0}	215.941535	{0;0;0;89;0;0;0;0}	257.725701
{0;0;0;71;0;0;0;0}	219.461557	{0;0;0;90;0;0;0;0}	256.71526
{0;0;0;72;0;0;0;0}	222.987017	{0;0;0;91;0;0;0;0}	255.209742
{0;0;0;73;0;0;0;0}	226.493549	{0;0;0;92;0;0;0;0}	253.191988
{0;0;0;74;0;0;0;0}	229.955845	{0;0;0;93;0;0;0;0}	250.647302
{0;0;0;75;0;0;0;0}	233.347725	{0;0;0;94;0;0;0;0}	247.563689
{0;0;0;76;0;0;0;0}	236.642231	{0;0;0;95;0;0;0;0}	243.932073
{0;0;0;77;0;0;0;0}	239.811731	{0;0;0;96;0;0;0;0}	239.746518
{0;0;0;78;0;0;0;0}	242.828034	{0;0;0;97;0;0;0;0}	235.004428
{0;0;0;79;0;0;0;0}	245.662517	{0;0;0;98;0;0;0;0}	235.464969
{0;0;0;80;0;0;0;0}	248.286273	{0;0;0;99;0;0;0;0}	241.309823
{0;0;0;81;0;0;0;0}	250.67026	{0;0;0;100;0;0;0;0}	241.397178
{0;0;0;82;0;0;0;0}	252.785472		

Appendix 6: Final script definition of wind-based aerodynamic building.

