

**GIS-BASED SITE SUITABILITY ANALYSIS FOR WIND AND SOLAR  
PHOTOVOLTAICS ENERGY PLANTS IN CENTRAL NORTH REGION, NAMIBIA**

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Klaudia Kamati .....  Date: .....17/04/2022.....

## **DECDICATION**

This work is dedicated to my supervisors with most sincere gratitude, Prof. Julian Smith, and Mr. Miguel Orti, for their unwavering support and guidance throughout this project, as well as to my mother and in memory of my father, who taught me that even the most challenging task can be completed if done one step at a time. Throughout my studies, I have also dedicated my work to Frans Shafuda in appreciation of his love, support, and encouragement.

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## **ABSTRACT**

Increasing urbanisation and population growth are making it difficult for governments to achieve sustainable development. Provision of clean energy is among the seventeen sustainable development goals, as it reduces reliance on fossil fuels. In recent years, Namibia has rapidly increased her reliance on sustainable energy. The renewable energy sources (RESs), including wind and solar energy, can be described as clean sources which have lesser negative environmental impact compared to conventional energy sources. Amongst the pressing challenges today is finding solutions on efficient solar and wind energy production. It is imperative to work out the optimum location of RESs before installing them. This can significantly improve performance and establishes the foundation for studying both solar and wind power in a site selection problem. This study aims to determine potential locations for wind and solar photovoltaic (PV) energy plants installation using one of the multi-criteria decision-making (MCDM) methods, the analytical hierarchy process (AHP), and a geographic information system (GIS) within the Central North Regional Electricity Distributor (CENORED) supply area. Combining GIS with MCDM results in a powerful technique for selecting potential sites, since GIS provides effective analysis, manipulation, and visualization of geospatial data, whereas MCDM provides consistent weighing of criteria. In the evaluations of the location: topographical, environmental, climatic and regulations constraints were considered as factors that may facilitate or hinder the deployment of solar-wind energy power plants. For solar PV energy plant, the highest potential areas are in the north-west, south-west and study area's southern regions, whereas for the wind power plant, only the northwest part is a highly suitable location for wind energy plants installation. These findings can be used to determine most favourable location of interest for solar PV and wind power plant development or to support the integration of electrical grid expansion and off-grid electrification strategies.

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## **ACRONYMS AND ABBREVIATIONS**

AHP	Analytic Hierarchy Process
CENORED	Central North Regional Electricity Distributor
CI	Consistency index
DEM	Digital Elevation Model
EIA	Environment Impact Assessments
EREDPC	Ethiopian Rural Energy Development and Promotion Centre
EMA	Environmental Management Act
GIS	Geographic information systems
GHG	Greenhouse gases
GP	Green Plan
GDP	Gross domestic product
IBA	Important bird areas
IPP	Independent Power Producer
MCDM	Multi-criteria decision making
MSB	Modified Single Buyer
NamPower	Namibia Power Corporation
NSA	Namibia Statistic Agency
NIRP	National Integrated Resource Plan
PV	Photovoltaic
PVOUT	Photovoltaic power output
RI	Random index
RED	Regional electricity distributors
RESs	Renewable energy sources
RES	Renewable energy system
SDGs	Sustainable development goals
SRTM	Shuttle Radar Topography Mission
SWERA	Solar and Wind Energy Resource Assessment program
UN	United Nation
UTM	Universal Transverse Mercator
WGS	World Geodetic System

# CHAPTER 1: INTRODUCTION

## 1.1 Background

Energy resources exist in various forms such as heat, electrical, mechanical, kinetic energy, and many others, and can be generated in many ways. The availability, affordability, and security of energy supply plays a significant role in human society (Nelson, 2014) and it is a prerequisite for industrial development, and sustainable economic growth (Bujac, 2011). Energy resources can be classified as non-renewable or renewable energy resources (Behal, et al., 2013). Non-renewable energy resources such as nuclear material and fossil fuels are removed from the earth and can be depleted (Nelson, 2014). These are accepted and established resources of energy. The associated energy production technology is highly advanced, and many coal and nuclear energy plants are in operation globally, supplying significant amounts of power to consumers *ibid*.

Since pre-industrial times, conventional fossil fuels have been used significantly (Goldemberg, 1998) and are said to be the source of numerous negative consequences such as glacier meltdown, global warming, seasonal variation, and natural disasters, resulting in an increase of serious environmental and atmospheric impacts (Intergovernmental Panel on Climate Change, 2019). This is primarily due to the emission of various greenhouse gases (GHG) – e.g., chlorofluorocarbons, nitrous oxide, methane, and carbon dioxide into the atmosphere through the combustion of conventional energy sources (Jaccard, 2005). Fossil fuels, specifically coal, necessitate extensive mining operations, leaving disturbed land that may be difficult or impossible to reclaim to usefulness. Coal combustion may disrupt and alter the earth's heat balance (Jaccard, 2005). These effects are said to have been initiated and accelerated by the industrialization process and increased energy demands. A lot of animals, humans, and plants have been harmed because of these impacts, and they face new challenges every day (Ei-Hinnawi, 1977; Colak, et al., 2020).

Furthermore, the energy demand is constantly escalating because of rapid human population growth, urbanization, and industrial development (Zhao & Zhang, 2017; Colak, et al., 2020). The International Energy Agency observes that the African continent, especially Sub-Saharan Africa, has the biggest population with no access to electricity (Avila, et al., 2017). Namibia falls into this group and her energy demand is fluctuating daily. Namibia's economic growth, combined with a greater emphasis on industrialization and a large-scale rural electrification program to bring electricity to remote areas, has led to a substantial rise in energy demand.

Because of these problems, several countries across the globe, including Namibia, have turned to integrated renewable energy sources (RESs) to supplement the current generation capacity of primary energy

resources. RESs are now widely regarded as capable of meeting a significant portion of the world's rising energy demand, ensuring a continuous energy supply, and reducing the negative impacts of fossil fuels (Wu, et al., 2015; Messaudi, et al., 2019). Under RESs production, power is produced from natural processes including geothermal, hydro, solar, wind, and tide which are natural, free, replenished, and widely available worldwide and in Namibia expect geothermal.

Namibia is fortunate to have an abundance of wind and solar resources that may be utilised to minimise the country's dependence on coal-fired energy plants while also reducing emissions of GHG from the usage of convectional sources of energy. Achieving energy sustainability in Namibia would therefore require investment in RESs like wind and solar energy. Namibia has enacted an energy policy with the aim to increase energy security, and enabling access to modern, environmentally clean, sustainable, and affordable energy services for all Namibian inhabitants (Republic of Namibia, 2017). Clean energy will be a key part of Namibia's innovative future energy policy. In this context, alternative energy sources are among the most important and undoubtedly clean energy sources used worldwide and in Namibia for energy production (Uyan, 2013; Colak, et al., 2020).

## **1.2 Problem Statement**

Currently, power utilities and electricity distribution companies (such as CENORED in Namibia) are facing a challenge of customers choosing alternate energy providers because the electricity tariffs have become exorbitant. Solar energy is a particularly appealing alternate. This has a negative impact on CENORED's cash flow because the more customers go 'off-grid,' the less the revenue generated, with the same operating cost. This will cause CENORED to increase the charges/tariffs to continue with infrastructure maintenance which will cause more customers to defect from the electricity grid. Therefore, CENORED needs to come up with strategies on how to solve this dilemma before it is too late; ignoring this could lead to retrenchment of employees, bankruptcy, and eventually unreliability of electricity supply. To overcome this challenge and reduce dependency on utilisation of conventional sources of energy which cause devastating environmental and atmospheric impacts (Intergovernmental Panel on Climate Change, 2019), CENORED needs to supplement its existing power generation capacity with RESs to be more sustainable and bring the tariff costs down. Therefore, the development of renewable energy is a critical part of the transition away from fossil fuels, cleaning the air and reversing the consequences of climate change. So, it is crucial that suitable areas be identified to develop and install wind and solar PV power plants. The use of GIS technology has been found to be a powerful and effective decision support tool for solving complex site selection issues for solar PV plants and wind farms (Moradi, et al., 2020; Noorallahi, et al., 2022; Colak, et al., 2020). A study using GIS application on selecting optimal sites for wind and solar PV energy plant installation across the study has not been published to the best of the researcher's knowledge.

### **1.3 Research Aim and Objectives**

The aim of the study to determine suitable locations for wind and solar PV energy for the establishment of renewable energy power plants in Namibia, particularly within CENORED's supply areas.

The following objectives have been established to achieve the study aim:

1. To find out which factors and criteria influence the suitability of a solar PV and wind power plant's site.
2. To identify an appropriate and effective spatial data analysis method for selection of optimal sites for renewable energy plants development.
3. To establish socio-economic and environmental constraints on the location of renewable energy production plants.
4. To establish suitable sites for wind and solar power plants within CENORED's supply areas using geographic information system (GIS), taking the previous objectives into consideration.

### **1.4 Research Questions**

- What factors and criteria influence the suitability of a wind and solar PV energy plant site?
- Which method of spatial data analysis is suitable to effectively identify optimal location for installing wind and solar PV energy plants?
- Where in the CENORED supply areas are the potential sites for the wind and solar PV power plant development?

### **1.5 Significance of the Study**

To address Namibia's electricity crisis, the government has expressly endorsed an increase of renewable energy. Recently the Government of the Republic of Namibia, has adopted a new market structure known as Modified Single Buyer which allows all individuals to install renewable energy power plants and sell power to utilities (Electricity Control Board, 2019). However, the location with the maximum solar resources and wind potential are not always viable sites for installing solar PV or wind energy. The selection of power plant sites is strongly linked to the plant's security, which must meet meteorological, geomorphological, environmental, economic, and societal requirements. Therefore, certain factors must be considered and investigated when choosing a location for this type of project, such as power plant location and how to maximize the energy plant's output while lowering costs. This study will provide a suitability assessment of different environmental, geomorphological, meteorological, and economic factors affecting solar and wind power plant projects. Additionally, it will show what could be implemented in the presence of different conflicting interests.

This research contributes significantly to land use planning at local, regional, and national levels, and it will be informative by making this information readily available to policymakers, investors and decision-makers who are interested in developing solar and wind power plant projects. Another important result of this study will be the production of potential locations for installing wind and solar PV power plants. Such maps can be an effective means of evaluating the suitability of potential solar PV and wind sites development because they can be a cost effective and visually powerful information source. In addition, this method seems to be the first time it has been applied within the study area based on what I have read in the literature.

## **1.6 Limitation of the Study**

Each research project has a few limitations. It is important to refine the focus of the study by briefly identifying various key areas that the present study will not cover. The current study has two significant limitations, and it is recognized that all of these factors contribute to the efficiency of wind and solar PV power plant installation, but they will not be explored in this study. Due to limited time in academic research in general and complex nature of modelling, this study does not explore the social factor and financial analysis factor to evaluate whether it is cost-effective to install solar and wind power plant during construction of the plants.

## **1.7 Research Outline**

The present study comprises of six chapters which are shortly described. The content in these chapters is outlined as shown in Figure 1.

Chapter one presents the research background, the research problem, the questions the study seeks to answer, aim, followed by research objectives and limitations of this study. This first chapter places the entire study into perspective.

Chapter two reviews important subjects that are core to the present research study (empirical evidence and theoretical contexts). This examines the available relevant literature associated with RESs, especially wind and solar, instead of conventional sources of energy because of their negative environmental impact. The types and impacts of wind and solar energy are introduced. In addition, the AHP and GIS methods are highlighted.

Chapter three presents Namibia's environmental law and regulations, environmental concerns as well as factors affecting both solar PV and wind farm site selection.

Chapter four describes the methodological approaches of the study in detail. It provides an overview of the research area, procedure for data collection, the data types, the data sources, and software. It describes

various spatial data analysis methods to achieve the purpose and study's objectives. It also elaborates on the pre- and post-processing of data in preparation for core analysis.

Chapter five discusses the outcomes of each of these analyses and their ramifications, as well as the specific details of each stage of analysis that was completed.

The final findings of the present study and their implications are summarized in Chapter six, based on the analysis done in Chapter four. The study's acknowledged limitations are discussed, as well as prospective future work recommendations. A discussion of potential research contributions concludes this chapter.

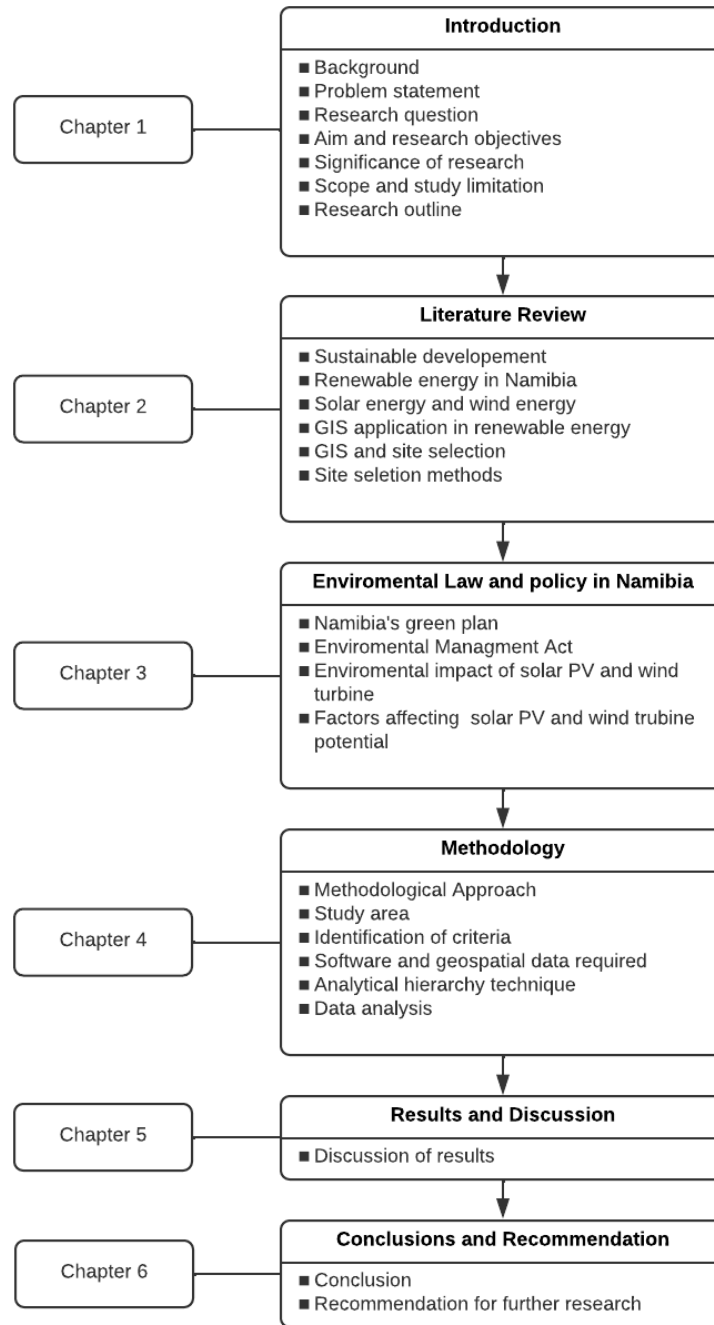


Figure 1: Simplified schema of the research outline

## **CHAPTER 2: LITERATURE REVIEW**

The preceding chapter presents the study's overview and its background. This chapter reviews a considerable number of previous literature studies conducted in areas related and relevant to this research. Under sustainable development, section 2.1. discusses climate change and sustainable energy. Section 2.2 provides the review of energy status in Namibia, and existing government policies that describes the alternative energy in Namibia, while section 2.3 explores GIS application in renewable energy. Section 2.4 provides a high-level overview for both solar PV and wind energy as well as factors and criteria to be considered and the degree to which these criteria will influence the selection of a site. In section 2.5, methods for implementing site selection are presented and compared. The concluding section of this chapter focuses on modelling solar radiation and wind speed. Evaluating solar PV and wind turbine potential is also discussed in section 2.6.

### **2.1 Sustainable Development**

The concept of sustainable development involves recognizing the world as a complex system of interconnected environmental, social, and political systems (Willis, 2016; Goniadia, 2015; Omer, 2008). Sustainable development is development that meets the necessity of the current generation while not compromising the future generation's ability to satisfy their own needs (Elliott, 2013; Hak, et al., 2016; Willis, 2016; Dikdar, et al., 2004). The United Nations (UN) drafted 17 sustainable development goals, which have been described as a to-do list for people and the planet, under the banner of Agenda 2030 (UN General Assembly, 2015). According to the United Nations General Assembly in 2015, the sustainable development goals (SDGs) are intended to build on the previous millennium development goals and to complete what the millennium development goals did not accomplish. These goals provide a blueprint for making the world a better and more sustainable place in the future by addressing global problems like climate change and environmental degradation. Among the goals of this study are to take immediate action to lower climate change's effects, to make sure urban areas and cities are more sustainable and resilient, and to guarantee affordable, reliable, and sustainable energy.

#### **2.1.1 Climate Change**

Global climate change is among the most difficult challenges the world faces today - and has been since the Industrial Revolution (Lau, et al., 2009). Climate change is characterised as a significant change in wind, temperature, snow, or rainfall patterns that lasts decades or longer. Both man-made and natural activities contribute to climate change (Karl, et al., 2009; Fahey, et al., 2017; Tester, et al., 2012; Lau, et al., 2009; Solangi, et al., 2011). Natural factors include the circulation of the ocean, volcanic activity, and orbit changes. Human activities include cutting down trees, dumping waste in landfill as well as burning fossil fuels.

However, there are those who dispute the climate change discourse. Climate change deniers oppose the notion that human activities contribute to changes in the Earth's climate or weather patterns and argue that natural processes are to be blamed (Lubke, 2022). Nevertheless, the public's scepticism of climate change trends is a major impediment to developing effective climate change legislation and policies. Majority of studies have focused on Anglo-American countries because they are the most prone to climate change denial and disengagement (Bjornberg, et al., 2017; Wong-Parodi & Feygina, 2020). It was argued that climate change denial has been articulated from the standpoint of preserving shared identities and values of salient social groups as well as claiming to justify political system and economic structures that offer desirable benefits *ibid*. Climate change unbelief covers both a categorical rejection of the fact of anthropogenic climate change and a lack of certainty about the anthropogenic origin of climate change (Lubke, 2022).

Energy generation is the economic activity in most countries that emits the most GHG into the atmosphere (Kiviyiro & Arminen, 2014; Dincer, 2011; Mohammed & Al-Bazi, 2021; Wang, et al., 2020). In response to these situations, the UN adopted the Kyoto protocol in 1997 and entered into force in 2005 (United Nation, 1998) and UN in 2015 established a framework known as the Paris Agreement. This is an agreement within United Nations Framework Convention on climate change dealing with GHG emissions. These are some international agreements that require all countries to set emissions-reduction pledges with the aim to combat the threat of climate change on a global scale and to curb the adverse effects of climate change (Kiviyiro & Arminen, 2014).

And yet carbon dioxide levels continue to rise in the atmosphere, heating the Earth at an alarming rate (Ahmed , et al., 2020). The evidence of climate change includes melting glaciers, changing precipitation pattern, rising sea level and responses by plants and animals such as shifting ranges (Crick, 2004; Lior, 2010). In response to the rising risk of climate change and its impact, a shift to renewable energy production is anticipated to effectively increase capacity to respond (Lima, et al., 2020).

### **2.1.2 Sustainable Energy**

Today, among the most popular pressing issues confronting societies is the generation and use of energy in a sustainable manner (Esen & Bayrak, 2017). According to Tester et al. (2012), sustainable energy is referred to as the combination of energy provision that addresses the needs of the present generations while also protecting the environment to meet the needs of the generations to come. Thirteen years ago, the global economy has grown at a rate of 3.3 percent per year over the last 30 years, while energy demand has increased at a rate of 3.6 percent (Gular, 2009). Over the last half-century, the global energy consumption has steadily increased, reaching approximately 23,900 terawatt-hours in 2019 (Alves, 2022) and it is predicted that worldwide energy consumption will rise by 39 percent in 2030 (International Energy Agency,

2021). Energy consumption is a key indicator of economic development and prerequisite for achievement of SDGs (Esen & Bayrak, 2017; Dincer, 2011). Therefore, energy shortage continues to impact on the achievement of the SDGs. Thousands of new power plants must be constructed to satisfy the required electricity demand. However, many countries are currently heavily reliant on fossil fuels, which will eventually be depleted, especially as energy demand rises (Imaran, 2018; Dincer, 2011; Martins, et al., 2018; Kannan & Vakeesan, 2016).

The consumption of conventional sources of energy was analysed for several European countries (Martins, et al., 2018). The analysis found that only Iceland and Sweden with fossil fuel energy consumption indicators below 40%, Iceland has a low consumption of fossil fuel energy, with a value less than 20%. The countries with the highest levels of fossil fuel energy consumption (more than 90%) are the Netherlands, Poland, and Cyprus (Martins, et al., 2018).

It became evident that further use of conventional sources of energy is not only unwise due to their depletion, as well as due to their consequences on both the environment and society (Martins, et al., 2018). The consumption of fossil fuels contributes significantly to soil pollution, air pollution, global warming, water pollution, and also causes socially negative impacts related to health issues and general quality of life of populations (Imaran, 2018; Tester, et al., 2012; Zheng, et al., 2015; Wang, et al., 2020). Achieving the solutions to environmental problems and energy supply challenge, it is important to employ sustainable energy technologies as shown in Figure 2. These appear to be among the most effective and efficient solutions considering the close relationship between sustainable development and sustainable energy (Omer, 2008; Mohammed & Al-Bazi, 2021).



Figure 2: Renewable energy derived from (National Integrated plan, 2016)

Use of renewable energy resources may decrease fossil fuel energy usage, improve energy security supply, and boost competitiveness of technology innovation in the RES sector (Martins, et al., 2019; Chul, 2010; Paoli, et al., 2008). Although any energy source has several potential environmental repercussions, it is feasible to model alternatives and determine which directions have the least impact on the environment. In today's world, sustainable energy systems are on the agenda, both for their environmental benefits and for their reliability for economic development (Omer, 2008; Mohammed & Al-Bazi, 2021). It has been determined that the generation and delivery of renewable energy may considerably enhance any country's economic growth. Globally, the United States is ranked second-highest in established wind energy capacity at 96.4 GW behind China with installed capacity of 221 GW (Unwin, 2019). United States wind power capacity additions progressed at a fast rate in 2018, with 7 588 MW of additional wind energy capacity installed in 2018 (Wiser, et al., 2018). Unfortunately, the United States is also among the world's largest energy consumers.

Iceland is leading the way with renewable energy by generating a significant proportion of energy using renewable sources (Hreinsson, 2008). The Icelandic power system is based almost 100% on RES including geothermal and hydroelectric power. In addition, Iceland has made the first proposal for 100% renewable energy in 1998. Germany is ranked the fourth-largest economy worldwide (Gray, 2017). According to McCarthy (2018), Germany generated sufficient renewable energy in the first six months of 2018 to energise every German household for the rest of 2018. In fact, the country managed to improve energy security by incorporating renewable energy, resulting in a decrease in energy imports (McCarthy, 2018). This energy shift has benefited Germany's local economy because it has generated more employment opportunities, and stimulated technology innovation (Progan AG and IAEW, 2014; Berlo , et al., 205). Similarly, renewable energy has enhanced German farmers' income by becoming energy producers and earning more profit from renewable energy sales (Hockenos, 2014). According to Hockenos (2014), farms located in Bavaria have 2 300 biogas plants and 465 000 Photovoltaics panels with a technical capacity of 10 400 MW equivalent to roughly 10 nuclear reactors, most of which are run by farmers.

In Africa, Morocco is a good example of reducing dependence on energy imports through the development of renewable energies. With increased energy exports of 67 percent and decreased imports of 93.5 percent in 2018 and 2019, Morocco became a renewable energy powerhouse (Booth, 2021). This can be ascribed to the country having installed the world's biggest solar plant called Noor Complex. The Noor Complex solar plant is estimated to have the capacity to provide enough electricity to power 1 000 000 households and significantly lower the usage of conventional sources of energy. Prior to adopting a more sustainable attitude, Morocco used to generate 97% of its energy from fossil fuels. Morocco is performing relatively well when it comes to climate action when compared with many countries, as its policies and commitments

are near compliance with reducing global temperatures by 1.5°C, according to Climate Action Tracker (Alami, 2021).

In light of these considerations, RES should be developed to meet the energy needs of current and future populations. It is possible to enhance energy security if each country, including Namibia, explores the potential for renewable energy. So long as renewables remain affordable, and the technology works and reliable, they can help boost energy security (Twidell & Weir, 2015).

## 2.2 Energy Production in Namibia

Throughout history, Namibia's economic activities have been shaped by energy. Namibia has three power stations, and they are the country's primary source of local energy generation capacity, namely Van Eck coal power station, Ruacana hydro-electric power station and Anixa diesel-powered power station (Nampower Annual Report, 2019). Figure 3 depicts Namibia's total primary energy supplies. The country has combined installed capacity of 459.50 MW, of which 347 MW is generated from hydro-electric power station in Ruacana, Kunene region, 90 MW from Van Eck coal-fired power station on the outskirts of Windhoek and 22.5 MW from Walvis Bay's Anixa diesel-powered power station (Nampower Annual Report, 2019). According to NamPower Annual Report of 2019, Namibia's largest power plant is the Ruacana hydroelectric power station, although variable flows of the Kunene River continue to affect its operation which has an impact on the generation capacity. Significantly lower river runoff was recorded in Namibia in 2017 and 2018 compared to the previous five years (Nampower Annual Report, 2019). This is a result of the drought condition facing the Southern African regions, and the dependence on seasonal run of the Kunene River stream. In response to this situation, Namibian Power Corporation (NamPower) could not rely on its energy source supply derived from Ruacana hydro-electric power station and was obligated to import electricity depending on the availability of water at the Ruacana power station to meet its electricity demands.

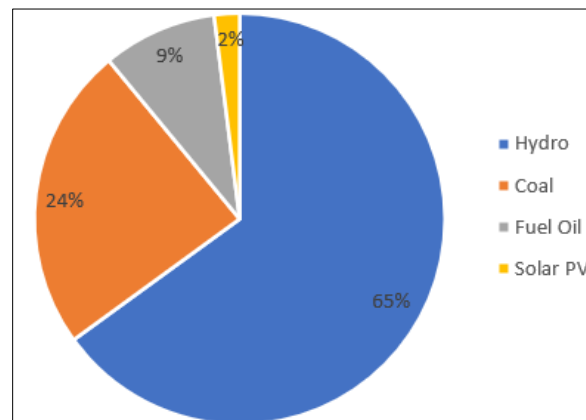


Figure 3: Namibia installed energy capacity of 2016 derived from National Integrated plan (2016)

As shown in Figure 4, Namibia is highly dependent on importing half of its electricity from the region through Southern Africa Power Pool (SAPP)'s long term bilateral agreements (PPAs) and short -term trade market to optimise and ensure that electricity demand is always met (Nampower Annual Report, 2018). The goal of SAPP is to provide dependable and cost-effective electricity supply to each SAPP member's consumers while remaining mindful of natural resource stewardship and environmental impact *ibid*.

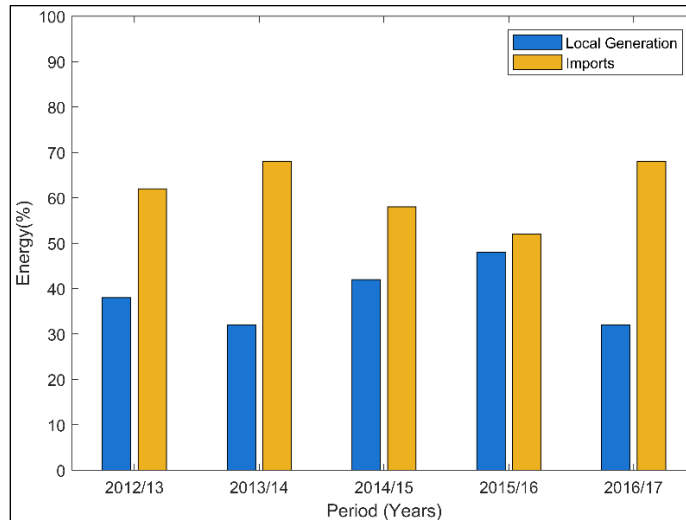


Figure 4: Contribution of local generation and imports in providing power from 2012-2017 derived from (Nampower Annual Report, 2019)

According to NamPower (2019), there are four long term bilateral agreements (PPAs), of which 200 MW contracted with ESKOM (South Africa), 300 MW non-firm contract with ESKOM (South Africa), 50 MW firm contract with ZESCO (Zambia) and 80 MW firm contract with ZPC (Zimbabwe). Per Namibia's National Energy Policy of 2017, Namibia imported 73% of its total energy requirement in 2014, while from June 2018 to July 2019 Namibia has imported 71.3% of electricity, thus exposing the country to the risk of import dependency. In acknowledge of these challenges, several strategies are currently being implemented and little advancement in utilising renewable energy has been made which are in line with the National Integrated Resource Plan (NIRP) and this is evident from Namibia's National energy policy of 2017. The commissioning of three new Independent Power Producer (IPP) solar PV energy plants of 5 MW each increased the country's local generation capacity, according to the NamPower 2017 report. InnoSun (Osona), HopSol (Grootfontein), and MetDecci (Karibib) are a few examples.

The commissioning of local IPPs would reduce Namibia's dependence on import electricity and this may lead to affordable tariffs in the end. Various solar PV and wind turbine installations have been constructed by government institutions and many private companies (Jadhav, et al., 2017). According to Jadhav et al. (2017), the National Breweries of Namibia installed 1.1 MW of roof-top solar PV system connected to the

grid. It comprises of 4 200 panels, making it one of the biggest roof-top solar projects in Africa. The system can meet 34% of the company's electricity needs. NamPower, the national power company, installed a grid-connected solar PV system with a capacity of 640 kW. The country could have seen a rise in the number of IPPs in the solar energy generation industry if there had been a policy allowing them to be paid for feeding additional power into the grid. However, the absence of a policy restricts the participation of investors. At Tsumkwe, in Namibia, a hybrid system of solar PV was commissioned in 2011. This is one of the most extensive systems of its kind (Juwi AG, 2011).

Solar and wind energy have been shown by various researchers and reports to have a significant output capacity over comparative areas. The primary topics of this study are wind and solar PV energy sources. As a result, the following sections go into detail about these two types of RESs, their potential, and applications in Namibia.

## **2.3 Solar Energy**

### **2.3.1 Solar energy system background**

Solar energy is among the ancient energy sources that has been used throughout history. Solar energy is transmitted to the earth as electromagnetic radiation, commonly known as insolation or incoming solar radiation (Foster, et al., 2009). The amount of insolation reaching a specific area on the surface of the Earth over a given period changes according to spatial, temporal, local, global, and meteorological factors (Seidlitz, et al., 2001; Gristey, et al., 2020). One of the earliest advancements in solar technologies was built by well-known French chemist Lavoisier in 1774 who built a 1 700° solar furnace in the 18th century (Kalogirou, 2013; Drake, et al., 2005). As the energy demand increases around the world, wide ranges of solar technologies have been constructed and operated such as solar Photovoltaic (PV) systems, passive solar design, concentrated solar power, and solar thermal heating system (Nwaigwe & Dintwa, 2019; Brower, 1992).

Solar PV systems generate electricity by using cells that take advantage of solar radiation. The solar PV system, indicated in Figure 5, is typically made up of a series of battery wires, devices, and collector panels that transform direct current energy into alternating current, which can then be used to energise household lights and appliances (REEP, 2013). Solar thermal electric plant or flat plate collector are used to generate electricity and hot water in solar thermal heating systems. Solar building may have active or passive systems. In a passive system the principle is to efficiently design the building so that it can harness sunlight. According to Tester et al. (2005), the primary distinction between passive and active systems is that in active systems a collector is used to capture solar energy. There are various solar PV system benefits highlighted by Solangi et al. (2011) regarding sustainability and environmental advantages of solar over

alternative energy sources. They are as follows: no depletion, no emissions of GHGs, acceleration of rural electrification, minimal maintenance costs, and diversification and energy security of energy supply, as well as increase of national and regional energy independence. However, there is much more to solar energy both in terms of set up as well as the types of solar energy. When installing a solar energy resource, it is important to achieve an accurate estimation of yearly global, monthly, daily irradiation reaching the surface of the Earth, specifically when determining the optimal location for placing the solar system (Hofierka & Kaňuk, 2009). The PV systems as stated earlier, is discussed further in the section that follows.

### **2.3.2 Photovoltaic (PV) Systems**

In United States of America in 1954 Chapin, Fuller, and Pearson developed the solar photovoltaic cells at Bell Labs to power everyday electrical equipment. In 1958 Mandelkorn, invented solar PV technology that has been used to generate power for space satellites, hence keeping them in orbit during their entire life span (Fraas, 2014). PV technology was first used in the space industry. PV cells have been made from a variety of semi-conductive materials, including cadmium telluride, copper indium diselenide, silicon, gallium arsenide and few other materials. Single and multi-crystalline silicon wafer technology is the most widely used today, accounting for more than 95 percent of the PV-industry (Messenger et al. , 2007).

PV systems comprise of solar PV modules mounted on the ground or on the rooftops depicted in Figure 5. These systems are operational when sun's rays strike a PV cell, negative charges (electron charges) are stimulated in a layer designed to readily give them up, resulting in an electric current. Through semiconductors, PV technologies convert direct current to electricity from solar irradiation.

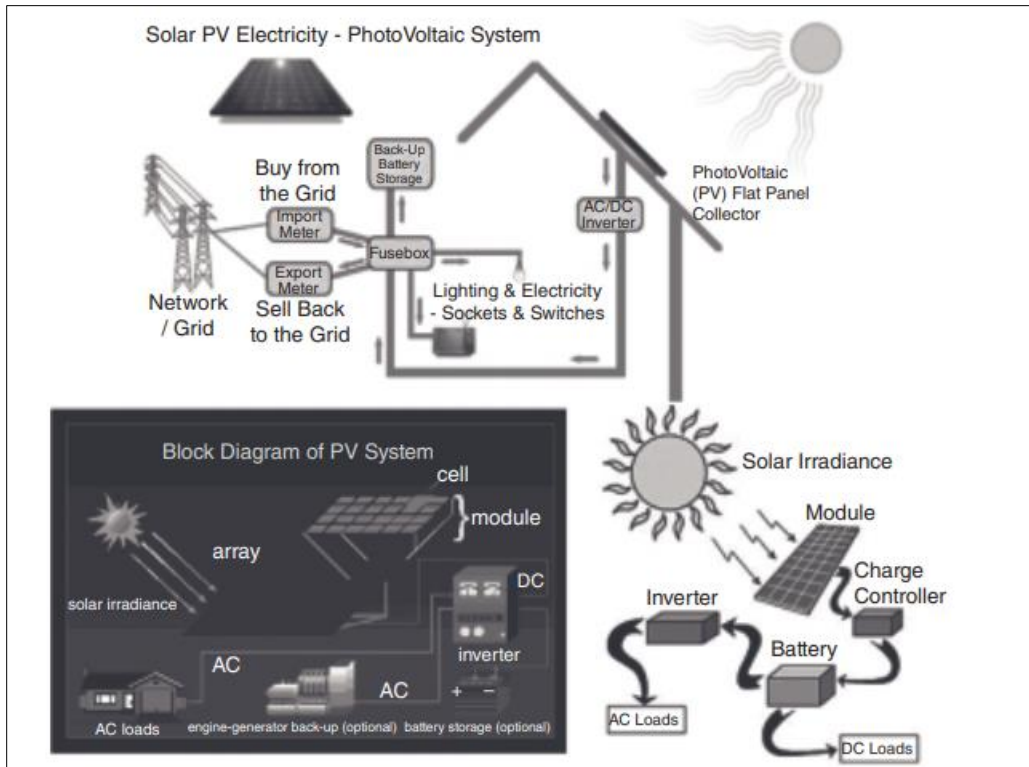


Figure 5: Illustration of ground-mounted and rooftop solar PV system (Strauch, et al., 2010)

The global PV systems market has expanded rapidly in recent years, encompassing both grid-connected and off-grid applications, making PV among the most rapidly RES technologies. Majority of countries in Europe have higher installed capacity of solar PV compared to wind and other RES because of the numerous advantage the PV technologies have over conventional energy converters (Dornan, 2011, Messenger et. al, 2007). Firstly, PV modules do not require a secondary source of energy, such as fuel, to function. Secondly since PV cells are solid-state devices that do not have moving parts, they barely require any maintenance thanks to their less complicated design and powerful functionality. Thirdly, they have unique quality of being completely scalable, which allows for the possibility to expand the system if the energy demand rises. PV technology is quite valuable in remote regions. PV system has the flexibility and versatility for developing systems for various regions, particularly off-grid applications in remote areas. Therefore, in the future, solar PV is expected to contribute significantly to global energy generation mix, which produce electricity directly from sunlight without creating any water or air pollution.

However, different PV system also have various drawbacks, the upfront cost of the PV system and its lifespan. In some instances, half of the service cost comes from maintenance and operation. According to Mala et al. (2009), frequently off-grid systems have difficulties with batteries. Therefore, batteries themselves could be costly, inefficient, and harmful to the environment. For example, Mala et al (2009)

found that faulty batteries were the main problem faced by customers. Remote areas are at risk for batteries accumulating in backyards, which has the potential to contaminate the ecosystem (Svantesson and Linder, 2012).

Furthermore, a system's lifetime and service cost may also be affected by its installation location's physical conditions (Svantesson and Linder, 2012). In humid and hot climates, for instance, the cost of maintenance and operation may contribute to half of the total service cost. Another potential disadvantage is that the installation of a PV system may have impact on the landscape of the surrounding environment. Lastly, PV arrays in the surrounding suburban communities may create visual or aesthetic issues (e.g., Aydin, 2009). Proper education and responsibility will increase the system's stability and durability, lowering costs. As a result, when using PV system, it is best to utilise PV energy immediately after it has been generated (Svantesson and Linder, 2012).

Numerous research has been conducted in the recent years on solar power. The studies mostly emphasise site selection, and effects of solar energy on the environment and the economy aspects. For instance, Yushchenko et al. (2018), assessed and selected the suitable location for solar concentrated power in West Africa. The locations were evaluated according to social constraint, topographical, legal and factors that might hinder solar energy development. Using their results, one can identify potential areas for solar generation deployment. Paoli et al. (2008) compared thermal and PV power plants with conventional energy systems. The study emphasised the energy efficiency and long-term viability of solar power technologies. Martins et al. (2018) conducted a feasibility study to evaluate the usage of solar PV power applications in Brazil for energy production. Solar PV potential was estimated by using Solar and Wind Energy Resource Assessment program (SWERA) database. According to the findings of the study, grid-connected PV systems can make a significant contribution to the capacity of the utility.

Other popular study areas include the economic and environmental viability of solar systems. Liu (2014) compared and investigated the economic viability of two kinds of systems: grid connected and islanded system, for lighting the streets in Hunnan Province, China. Their results showed that the two systems are economically feasible, and it will encourage the utilisation of solar PV in infrastructure. The study by Tsoutsos et al. (2005) gives an overview of the possible negative environmental effects of solar energy systems. Among the effects identified were visual and noise interference, soil and water contamination, energy consumption, and impacts on sensitive ecosystems or archaeological sites. A system to support environmental decision making for grid-connected PV energy plants sites selection was developed by Carrion et al. (2008). To identify optimal sites in a GIS environment, an analytical hierarchy process (AHP) and multi-criteria analysis were applied.

Also, numerous scholars examined the solar power potential in Namibia as well as solar power systems performance. For example, Okorie et al. (2018) conducted research to identify the highly suited locations in a particular region of Namibia for the solar energy plant utility development. Their analysis found that the potential of solar power plants in Namibia is incredibly significant and can contribute to energy self-sufficiency (Jadhav, et al., 2017). Geographically, Namibia is ideally situated for utilising solar energy because of high solar irradiation of 6.94 kW/m<sup>2</sup>/day on average of 2 500 kWh/m<sup>2</sup>/y (Fol & Ndhlukula, 2013). Wamukonya (2001) investigated potentials and social-economic impacts of rural electrification in Namibia. It was discussed that grid electrification costs are higher than the cost of providing solar home systems. An optimisation model built by Campana et al. (2016) was developed and validated with special consideration of life cycle costs and system reliability. Analyses indicated that the model is an excellent and powerful tool for optimal design of a solar home system. Briefly, solar PV energy can be used to minimise the usage of other energy sources that have more negative environmental effects. Using solar PV systems can have a positive contribution to achieving universal energy access and the SDGs.

## **2.4 Wind Energy**

There is growing concern over the future global demand for energy and its environmental consequences. To alleviate these challenges, global communities are striving to identify and apply various energy-saving schemes and clean energy sources. The development of wind energy can contribute significantly to meeting future energy demand while also reducing environmental impacts to some extent. As a global source of clean energy, wind energy generation has considerable potential at present, as it is easily accessible and inexpensive, though diffuse, and producing no GHG during power generation. Tapping into wind energy will diminish reliance on non-renewable energy and assist in terms of decreasing GHG (Kim, et al., 2016; Noorallahi, et al., 2016; Munday, et al., 2011). Wind energy has been used since ancient times to provide mechanical power to pump water and grind grains, and the first proper wind turbines were created for electricity generation in 1887 (Mirza, et al., 2007).

Since the early 1970s, technology has gradually improved. Currently wind power is viewed as one of the cost-competitive and rapidly growing RES technologies worldwide (Latinopoulos & Kechagia, 2015). With modern wind power technologies, wind's kinetic energy can be transformed into useful forms such as electrical power and mechanical. The existing wind power technologies can be categorised into three types: off-grid standalone, distributed generation, and grid-connect wind farm systems. Each of these types is applicable to both offshore and onshore installations.

According to Bilgili, et al., 2011 (2011), there are different alternatives for wind power such as offshore and onshore. Offshore wind farms are installed in bodies of water where higher wind speeds are available

and should be attached to the seafloor, necessitating a more substantial supporting structure. They are more complex and expensive to construct and operate, according to most studies, due to the need for larger fortified foundation structures, submarine cables for power transmission, and specialised vessels for shipping and installation (Bilgili, et al., 2011). Onshore wind farms are installed on the land and generate energy with wind occurring in terrestrial locations. There are several factors to take into consideration as to which type of wind farm is chosen including geographical, political, and financial factors. For example, the wind speed and the wind direction can vary based on the characteristics of topography. Onshore wind power provides a much better choice than offshore due to actual costs of development and generation. Therefore, the most of wind energy projects have been developed onshore *ibid*.

A significant number of studies have been conducted over the past few years on wind energy and numerous researchers have emphasised and focused on various aspects of wind energy including site selection procedures, economic benefits of wind and environmental impacts. An example would be the study carried out by Morteza (2018) in the context of GIS system environment, the fuzzy AHP and Promethee approaches were utilised to determine feasible locations for wind energy plants in Lorestan, western Iran. According to their findings, approximately 7.38 % of Lorestan province's land area is well suited for the wind power plants development. The aim was to evaluate profitability and investment opportunities to some selected suitable sites of offshore wind farm in Puglia region. The study concluded that the use of enormous size turbine generators allows reducing of energy and increase the profitability of the wind farm.

A study by Ulgen and Hepbasli (2003) analysed the production of electricity from RESs energy plants located in Izmir, Turkey. A model for identifying wind, solar, and hybrid power resources was first created. After analysing the integration of hybrid energy on a daily, weekly, and monthly basis, a trend was identified. Renewable systems were found to be capable of contributing to more efficient utilisation of resources. Kim et al. (2016) developed methodologies for undertaking onshore wind energy site selection and evaluated potential onshore wind farm locations on Jeju Island, off the coast of South Korea. Noorollahi et al. (2016) investigated the feasibility of a wind farm in the western Iranian province of Markazi. Their findings were favourable for power generation, and 28 percent of the area studied has the potential for setting up large wind turbines. Munday et al. (2011) analysed economic development opportunities associated with the development of wind energy in rural Wales. Economic assessments were conducted, and their electrical energy costs were calculated. Latinopoulos and Kechagia (2015) proposed and implemented an integrated evaluation scheme by using GIS for identifying the potential sites for wind energy plants installation projects in Greece. An evaluation of suitability criteria was done in that study based on physical requirements and environmental constraints as well as human impact factors. Overall, harnessing wind to generate energy has less environmental consequences than conventional sources of

energy. Wind farms can therefore preserve ecosystems, minimise the consumption of convectional energy sources, and reduce the amount of carbon dioxide in the atmosphere.

## **2.5 Site Selection of Renewable Energy Sources Using GIS**

Prior to the wide accessibility of computational mapping tools, planners depended extensively on hand-drawn representations acquired from many sources, which were frequently exhibited at different scales. However, a single map is insufficient for assessing and selecting a site. A variety of factors and reliable sources of information must be reviewed to identify geographical relationships, cost-benefits, suitability, and implications. The application of GIS incorporates a comprehensive set of tools, people, procedures, and data that can assist with strategic planning and location selection for the intended purpose (Tomlison, 2007). GIS tools provide the capability of analysing, classifying, and categorising geospatial data, which is an important feature for location selection. GIS-based suitability analysis of land-use originates from hand-drawn overlay methods employed in the late 19th and early 20th centuries by American landscape architects (Malczewski, 2004).

Traditional observation methods of site selection involve costly and time-consuming routine field visit, often based on biased sampling schemes (Golmehar, 2009). Observing the earth's surface from ground level is difficult since features cover such vast areas over uneven topography. In these traditional studies, engineers selected a site based on their judgment, experience, and knowledge, but factors and criteria related to site selection are ignored (Kumar & Bansal, 2016). Throughout the years, using GIS for site selection has proven to be a cost-effective and highly dependable application to enhance the understanding of the real world through spatial modelling and site selection (Ehsan Golmehar 2009; Reis 2008; Yang et al. 2017). In site selection, the use of GIS entails weighing the needs of a planned facility against the advantages of potential sites. This procedure is a step toward maximising the benefits of project scope regarding the time, safety, quality, and expenditure. The primary goal is to integrate wind farm with solar PV systems while preserving the natural environment with the least amount of harm to the ecosystem.

GIS is a powerful scientific technique used to derive timely and accurate information. GIS is a computer system designed to collect, manage, store, visualise, and analyse geospatial data, that is, information tied to specific geographical areas on the surface of the Earth (Tomlison, 2007). In addition to enhancing and sometimes replacing traditional mapping techniques, GIS is capable of handling geospatial imagery of the Earth's surface derived from satellite applications, as well as geospatial data from survey records and administrative data. GIS is utilised in practically every field of study where location is involved, such as site selection, land management and planning, disaster management, environmental pollution, and natural resource management. The use of GIS is crucial in assessing RES since it approaches the problem by

incorporating all viable solutions. It has been used in numerous research concerning RES, most notably in mapping, measuring the quantity, and locating RES (Ghobadi & Ahmadipari, 2018; Al Garni & Awasthi, 2017; Voivontas, et al., 1998; Carl, 2014).

For example, Carl (2014) assessed the potential of solar modules installed on household rooftops in Kailua Kona, Hawaii. The study used LIDAR data with the support of GIS systems to determine the amount of solar PV energy that could be harnessed. The study concluded that the energy generation potentials for rooftop is approximately 190 000 000 kWh annually. AlGarni and Awasthi (2017) identified and evaluated potential locations for solar PV power plants in Saudi Arabia applying GIS and MCDM approach. Their study found that highly potential areas are situated in the north as well as in northwest of the country, following the pattern of the approximate range of the proximity to transmission network, main roads, and residential areas.

Most of the environmental effects of wind and solar PV energy technologies are directly related to RES's geographical area and can be addressed through proper location selection. Before implementing RES, a rigorous site selection analysis must be performed to prevent negative social and environmental implications. Therefore, GIS has become an indispensable tool in environmental management. Despite not being the only computer application associated with this field, it plays a critical role in the formulation of environmental policies and decisions (Goodchild, 2003). For engineers to understand the selected site's dependence on existing infrastructure, they need spatial information about the area. In the absence of GIS, such dependences are difficult to model. With the aid of GIS, one can analyse and visualise the impact of situating a proposed utility near the existing utilities or facilities. The growth of GIS accessibility opens new avenues and possibilities for researchers and construction professionals.

## **2.7 Multi-criteria Decision and GIS Techniques**

In Multi-Criteria Decision Making (MCDM) technique, and sustainable energy management are becoming increasingly popular, because of incorporating environmental, social, technical, and political factors in energy planning and development (Pohekar & Ramachandran, 2004). MCDM is a structured framework that is essential for analysing and supporting decisions concerning problems characterised by complex multiple objectives and criteria (Kahraman, 2008). It is difficult to make a decision when multiple criteria and conflicting factors have to be considered (Jankowski & Richard, 1994), therefore MCDM techniques provide solutions to decision challenges with multiple alternatives and can provide more dependable decisions for location selection (Pohekar & Ramachandran, 2004; Ligus & Peternek, 2018; Al Garni & Awasthi, 2017).

In MCDM problems, several factors are assessed simultaneously based upon priorities, constraints, and the preference of decision-makers (Ozdemir & Sahin, 2018). Different methods are developed for energy planning decisions and can be utilized in the decision-making process of MCDM (Pohekar & Ramachandran, 2004). Highlighting the importance of GIS, Garni and Awasthi (2017) and Ghobadi and Ahmadipari (2018) pointed out that the integration of the MCDM and GIS technologies has emerged as highly useful and a powerful tool for suitable site selection. Therefore, the approach can highlight spatial correlations between datasets as well as versatility in managing data at various levels of geospatial analysis. Therefore, GIS offers effective geographic data administration, analysis, and presentation, and MCDM allows for consistent criterion weighting. (Voivontas, et al., 1998; Yushchenko, et al., 2018). The integration of MCDM in GIS allows researchers to combine various methods to generate a better description of an issue for example, the fuzzy-AHP technique or approach using AHP-TOPSIS. These techniques aid to enhance decision-making qualities by making them more rational, explicit, and efficient (Pohekar & Ramachandran, 2004).

The fuzzy set method, analytic network process, weighted product method, weighted sum method, and AHP are widely used approaches. One of the most often utilised methods is the AHP approach (Ramanathan & Ganesh, 1995; Ghimire & Yeonbae, 2018; Uyan, 2013). It might be argued that AHP has been employed in a range of applications of different decision-making problems integrated with GIS environment and has been successful.

## **2.8 Analytical Hierarchy Process (AHP)**

In the 1970s, Saaty invented the AHP method, and it has been refined since then (Doorga, et al., 2019). The AHP method is based on a series of pairwise comparisons that consider the decision maker's perception and evaluation. It is simple to use because of its hierarchical structure and pairwise comparison, which enable users to assign different weights to each criterion and it has the ability to integrate quantitative and qualitative criteria into an unified decision framework (Ozdemir & Sahin, 2018; Wedley, 1990; Kaya & Kahraman, 2010; Saaty, 2008).

According to Saaty (2008), the AHP is useful for making multi-criteria decision involving risks, opportunities, benefits, and cost. For this reason, AHP techniques are widely used in various research, especially in the energy resources allocation, renewable energy planning and project planning, electric utility planning and transportation energy planning. An example would be the study carried out by Ghimire and Kim (2018), to identify the barriers for RES development in Nepal. The study identified twenty-two barriers based on the previous studies. This study used AHP methodology for ranking and estimating the barriers. Their analysis showed that most significant barrier types were policy, economic, and political. In 1995, Ramanathan and Ganesh carried out a study in Madras, India, based on energy resources allocation

incorporating qualitative and quantitative criteria. Their study developed an integrated model using AHP method and goal programming for tackling issues involving qualitative and quantitative criteria. Overall, the results of the analysis indicate the need to increase the efficiency of resource utilisation (Ramanathan & Ganesh, 1995).

In a recent study by Colak et al. (2020), an AHP-based GIS application was applied to establish the ideal areas for solar PV power plants in Turkey, Malatya province. The results indicated the best possible locations for solar PV energy plants. A similar study was carried out by Uyan (2013) in the Karapinar region of Konya, Turkey, where GIS and AHP were employed to determine potential locations for solar farms. In determining weighting criteria and evaluating importance, the AHP was used. A final index model was classified into four classes based on an equal interval classification, and they were high-suitable, moderate, low-suitable, and unsuitable. Their analysis indicated that 40% of some areas were considered unsuitable for solar PV plants installations, while 13 % was highly suitable for solar farm development.

In addition, some researchers have integrated different methods to address uncertainty in subjective judgments of decision makers and lack of information. For example, Ligus and Peternek (2018) suggested a MCDM model based on the integrated GIS-based AHP technique for evaluating and determining the most appropriate RES technologies development in Poland. Their results seem to be in line with a similar study conducted by Sun et al. (2016).

## **2.9 Chapter Summary**

The chapter presented a high-level review of the literature relevant to this research. In light of the previously discussed and reviewed literature, it is evident that various federal state and local governments are indeed committed to reducing GHG emissions and developing their energy sector sustainably. Using these studies, it has been concluded that GIS-based analysis can be used to calculate, estimate, and locate solar PV and wind power plants based on several factors. The literature reviewed serves as a basis for the methodology adopted in this research.

# **CHAPTER 3: ENVIRONMENTAL LAW AND SITE SELECTION FACTORS**

This chapter presents a brief background on the regulations that protect the natural environment in Namibia, ensuring that no harm is done by the practices used and applied on the environment. Numerous factors affecting wind and solar PV energy development are reviewed in this chapter.

## **3.1 Environmental Legislation in Namibia**

### **3.1.1 Background**

Namibian law is a result of various sources and reflects the history of the country, as shown in Figure 6. Section 1 of the Namibian Environment Environmental Management Act (EMA) defines environment as a complex of biotic, chemical, and physical factors such as living and non-living things, that act on an ecosystem or ecological community and ultimately determine their course and their way of survival (Rupper & Rupperl-Schlichting, 2011). Living things such as people and animals are directly dependent on the natural resource and ecosystems. Additionally, ecosystem provides intellectual stimulation, spiritual, aesthetic, and cultural.

Over the last few decades, concerns about the environment have been high because of the dependence of human activities resulting into altering nature and exhausting natural resources. In some extent, Namibia experiences quite a few environmental problems like those found in in the rest of sub-Saharan Africa. Some of these problems include land degradation and soil erosion, water management, climate change, waste, and pollution (Rupper & Rupperl-Schlichting, 2011). Therefore, environmental matters have become subject to multiple legislative processes to preserve the stability and quality of nature as well as sustaining natural resources. A definition of environmental law would be the collection of norms, procedures, rules, and institutional arrangements in common and civil law to protect the environment from damage and manage natural resources for sustainable development and intergeneration equity (Lazarus, 2004).

Environmental law is a comprehensive area of law that covers a broad variety of environmental matters including biodiversity, wetlands, air quality and waste management, agriculture, sustainability strategies, and alternative energy sources. These laws explain the significance of legal and non-legal measures for the consequence of such damage towards governments, private entities, individuals, and corporations (Rupper & Rupperl-Schlichting, 2011).

<b>Environmental Policies in Namibia</b>	
<b>Environment and Wildlife</b>	<b>Land</b>
Namibia's Environmental Assessment Policy	Land-use Planning: Towards Sustainable Development
Policy for Prospecting and Mining in Protected Areas and National Monuments	The National Land Use Planning Policy
National Policy on Human Wildlife Conflict Management	The National Land Policy
	The National Resettlement Policy
	The National Land Tenure Policy
<b>Water and Fisheries</b>	<b>Climate Change</b>
Water Supply and Sanitation Policy	Namibia's Climate Change Policy
The National Water Policy	
Namibia's Draft Wetland Policy	<b>Forestry</b>
Namibia's Aquaculture Policy – towards responsible development of aquaculture	Namibia Forestry Strategic Plan
	Development Forestry Policy
<b>Agriculture</b>	<b>Tourism</b>
The National Agricultural Policy	The Tourism White Paper
The National Drought Policy and Strategy	The Draft National Tourism Policy
The Regional Planning and Development Policy	The Community-Based Tourism Policy
The National Seed Policy	Revised Draft Tourism Policy
	<b>Biotechnology</b>
	Enabling the Safe Use of Biotechnology Policy

Figure 6: Most relevant environmental policies in Namibia (Rupper & Rupperl-Schlichting, 2011)

### 3.1.2 Namibia's Green Plan (GP)

Namibia's Green Plan (GP) was compiled in consultation with various non-government and government organisations by the Ministry of Wildlife, Conservation and Tourism. In 1992, Namibia's GP was first presented at the Rio Conference. The GP outlines legislations and policies, strategies, and recommendations for the key areas including environmental education for sustainable development, sustainable management of wildlife, tourism, and fisheries (Rupper & Rupperl-Schlichting, 2011). As a result, the GP has established the groundwork for a series of processes aimed at conserving and managing development resources. A few of the key outputs of the GP have been EMA No.7 of 2007, which establishes legal foundations for the protection of the environment in Namibia through integrated community-based natural management, environmental impact assessments (EIAs), and regional land use plans. The GP emphasises that environmental policies should be based on the precautionary principle and all major construction projects in the water sector, architecture sector and especially energy sector should always be preceded by EIA to prevent and minimise any potential negative environmental effects (Rupper & Rupperl-Schlichting, 2011). According to the GP, a clear precautionary principle should guide the implementation of environmental policies.

### **3.1.3 Environmental Management Act (EMA) No.7 of 2007**

The EMA is an essential environmental protection tool. This act establishes general principles for managing the environment and natural resources in accordance with Article 95 (1) of the Constitution. Among its objectives is to promote the coordinated and integrated management of the environment and to give statutory effect to Namibia's Environmental Assessment Policy. The Act includes administrative provisions such as the requirement of environmental assessments and issuing environmental clearance certificate (Republic of Namibia, 2007). An environmental clearance certificate is required for certain projects or activities that may influence the environment (Republic of Namibia, 2012). All activities requiring an environmental clearance certificate must adhere to the EIA regulations established in accordance with section 56 of the EMA 7 of 2007. Without an environmental clearance certificate, the following activities are prohibited including building of facilities for:

- ✓ Energy generation of electricity
- ✓ Transmission of electricity
- ✓ Construction and other activities within a catchment area
- ✓ The use of zoned open space and nature conservation to any other land use
- ✓ Forest activities including clearance of forest area, timber harvesting and deforestation

The environmental impact must be considered and affected and interested parties must be given the opportunity to participate in environmental assessments. Suitable location selection of solar PV and wind farm is a key concern for utility-scale projects because of the various factors affecting site selection, such as proximity to facilities, significance of climatic variables as well as the environmental presence considerations such as protected areas.

### **3.1.4 Environmental Impact of Solar PV and Wind Energy**

RESs may provide safe and clean power to industries and the public, but as with any man-made project, RESs development has environmental consequences such as changing landscape settings and land use. Most specific environmental matters associated with these systems are determined by the dimensions such as the nature and size of the projects, which generally result in a loss of amenity (Tsoutsos et al., 2005). PV systems, for example, during operation, no noise or chemical pollutants are emitted. Understanding these effects will allow for better mitigation and the development of more effective renewable energy policies (Wang & Wang, 2015).

### **(A) Solar PV Development**

These are concerned with the air pollutants produced during manufacturing, transportation, and after decommissioning, handling the waste from PV modules. Direct effects of PV systems, on the other hand, are related to visual effect and land use. The visual impact of PV systems is heavily influenced by their surroundings. The deployment of PV modules nearby a natural beauty area poses an unavoidable impact on the area's visual appeal. Additionally, there are further prohibition and restriction in accordance with Namibian Civil Aviation Act 6 of 2016 to provide regulations relating to the safety and security of airport (Republic of Namibia, 2020). For instance, there should not be any tree, infrastructure, or other object located on land or water that could pose a threat to aircraft operating in accordance with normal aviation practice. Upon large-scale PV system installation, the impact on land use will differ depending on the size of area covered, the land type (cultivable area may be negatively affected by large-scale installations), the distance from endangered ecosystems or places of natural beauty. Furthermore, lands used for agricultural purpose in Namibia are protected by the National Agricultural policy and Land use law. According to Namibia National Agriculture policy, agricultural areas must be protected to preserve the land's natural functions. The goal is to increase farm incomes as well as food security on a national and household level by maintaining or increasing agricultural productivity (Government of Namibia, 2015).

The environmental decision support system, designed by Carrion et al. (2008), assists grid-connected PV module site selection. Priority sites are identified using environmental, topography, technical, and climate factors. These factors are further subdivided into criteria; for example, there are two criteria in the environmental factor: land use and PV modules' aesthetic. Restrictions on land use, according to Carrion et al. (2008), are determined by legislation protecting the environment. Namibian environmental laws are associated with forestry land, protected zones, coastline, and wetlands. Any type of construction in a forest area is prohibited under Namibian forest regulations enacted in accordance with the Forest Act 12 of 2001. However, the Ministry of Environment and Forestry may permit development of defence infrastructure, telecommunications, and petroleum exploration on forestry land if these activities are necessary for public benefit (Republic of Namibia, 2015).

Like forestry land, constructions at protected areas like national parks are prohibited by the law in Namibia (Republic of Namibia, 2021).. In accordance with National Parks Legislation, structures that adversely impact habitats are not permitted to be built in national parks because these areas must be protected. The only structures that may be built are for management, visitors, and research purposes. In addition, the Environmental Legislation and international conservation agreements identify national protected zones to protect the natural resources and hinder degradation of the environment. Only structures that are compatible with nature are permitted in these environmentally sensitive areas *ibid.*

Another negative impact of solar PV systems on the environment is the release of poisonous and dangerous compounds. Because PV modules include poisonous and hazardous components, irregular plant operations may result in toxic pollutants being discharged within the surroundings. Nevertheless, appropriate site selection that considers the organisms in the surrounding areas might reduce the hazards (IEA, 1998). Wetlands, which have significant ecological importance and biodiversity, should therefore be considered during PV system site selection. Wetland legislation requires at least a 500 m – 2000 m buffer zone to maintain the ecological and physical qualities of these places (Colak, et al., 2020; Noorallahi, et al., 2022; Noorallahi, et al., 2022; Sadeghi & Karimi, 2017).

Other solar energy technologies, including solar thermal electricity and solar thermal heating, must also consider visual intrusion and land use effects. Additionally, solar thermal systems create power by using cooling water. During thermal discharges, this could pollute water supplies, because coolant water comprises molten salts or liquid water, its dissemination could pose a health risk (IEA, 1998). Because solar PV systems are examined in depth in this thesis, alternative solar energy sources are not discussed further.

### **(B) Wind Power Plant Development**

The development of wind farms causes various environmental impacts. These impacts, as shown in Figure 7, include impacts on animal habitats (especially bat and bird collisions), electromagnetic interference, safety concerns, noise pollution and visual impact (Wang & Wang, 2015). Wind energy's environmental implications are applied in the present research to ascertain the environmental acceptability of alternative location for installation of wind energy. Hence, the environmental consequences are discussed in depth in the paragraphs that follow.

Although wind power is thought to be environmentally favourable, its development has been linked to fatal bird and bat collisions with turbine blades. Birds have been observed and recorded to be among the most common casualties of wind turbine accidents around the world (Erickson, et al., 2014). In the United States, the Fish and Wildlife Service estimates that wind turbine blades kill between 140,000 and 500,000 birds each year (Reve, 2020). Light from wind energy plants attracts birds, causing an increase in the number of birds flying across wind energy plants and being susceptible due to collisions with wind turbine blades. According to Morrison and Sinclair (2004), the wind turbine's whirling blades create a blurred image in the eyes of birds, which birds interpret as safe to fly through, resulting in collision of birds. Therefore, wind energy installations must be situated at a specific distance away from bird migration routes to avoid bird collisions. To avoid interference with nature conservation areas, wind energy plants must be placed at minimum of 500 metres away from them (Yue and Wang, 2006). In addition, Clarke (1991) suggests that wind energy plants be located at a distance of at least 300 meters from bird habitats. Some safeguards can also be put in place to protect and reduce the incidence of bird and bat deaths caused by wind turbines. For

examples, avian radars system technology in Texas was developed to detect and prevent fatal collisions of birds in the area: when there is a potential danger of birds being struck by turbines, the system will stop them (Goldenberg, 2009).

Another effect of wind turbine on habitat is noise pollution which is defined as unwanted sound (Rogers, et al., 2000). According to Wang and Wang (2015), wind turbines generate noise mainly in two ways: aerodynamic and mechanical noise. The aerodynamic sound is produced by interaction of turbines blades with the air, while the mechanical sound is produced by the gearbox and generators (Wang & Wang, 2015; Leung & Yang, 2012; Eja, 2010; Torrance & Goff, 2009; Nazir, et al., 2020). Wind turbine noise pollution is a combination of the two. Efforts have been made to reduce mechanical noise effectively, so it is no longer considered to be as significant as aerodynamic noise (Wang & Wang, 2015). Eja (2010) explored the relationship between the sound levels produced by wind turbine and neighbour's health and well-being. Their analysis found that those who were irritated by the presence of wind turbines were more likely to suffer from stress symptoms such as headaches (Eja, 2010). In addition, the operating of wind turbines causes sleep disturbances – noise is most likely reducing the sleep quality of neighbours and causes hearing loss (Linowes, 2019).

Even though there are some guidelines and regulations regarding acceptable noise levels that are based on community perceptions, it is difficult to establish a common noise pressure level principle (Wrixon et al., 1993). Various authorities have varying noise criteria, and one outlines the requirement that wind energy plants should be at least 400 meters from nearby habitats (IEA, 1987). Torrance and Goff (2009) recommend locating wind turbines at least 2 kilometres away from residential areas. Moreover, several authorities, including Tester et al. (2005), and Yue (2006), agreed that wind energy plants must be positioned at least 500 meters from nearby habitats to prevent any safety concerns. Wind farms, according to Parry and Baban (2001), should be positioned at least 2 000 metres away from major cities. For safety considerations, Voivontas et al. (1998) proposed at least 1 000 meters distance from settlements, and the same principles apply for minimising visual intrusion.

Other wind turbine side effects include the visual impact, which varies depending on the individual. The visual impact is the most difficult to assess (Leung & Yang, 2012). There are various characteristics of wind developments that may cause visual and landscape effects, such as the turbine (colour, material, number, size, and height), substation building, transmission lines, grid connection, and anemometer masks (Jaber, 2013). Ramirez-Rosado et al. (2008) mentioned that wind energy is creating a positive image of clean energy, implying that some individuals may consider wind farms to be pleasant with amazing views, while others may believe that wind farms have a detrimental impact on metropolitan landscape.

Even though some significant accidents have occurred, wind energy has a strong safety record, with the majority of the incidents resulting from management failure or lack of compliance with standards governing safety (Wrixon et al., 1993).

Wind power in Vietnam was analysed by Nguyen (2007), a buffer zone of 2 000 meters surrounding the city centre was unsuitable for wind energy installation due to concerns about visibility and safety. Furthermore, wind turbines contribute to electromagnetic interference by dispersing electromagnetic waves from telecommunication equipment and navigation (IEA, 2003). Even though wind energy can interfere with radio and television signals in a radius of two to three kilometres around the biggest installation, wind power systems' electromagnetic interference is being reduced by line-of-sight microwave satellites and cable networks (IEA, 1987).

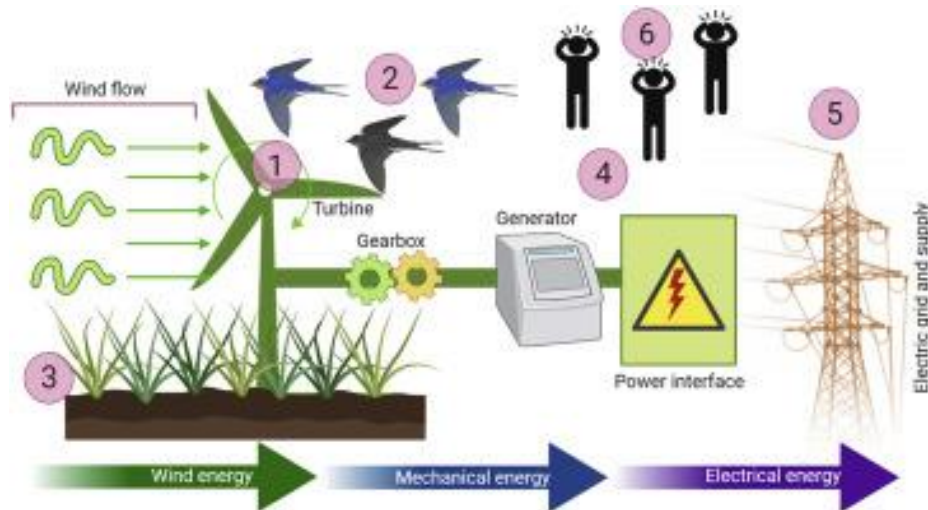


Figure 7: Diagrammatic depiction of wind energy generation and its environmental implications, (1) noise and visual, (2) bird collisions, (3) soil erosion and deforestation, (4) tower lightning, (5) electromagnetic, and (6) neighbouring neighbourhoods, source: (Nazir, et al., 2020).

## 3.2 Other Factors Affecting Site Selection of Wind Farm and Solar PV Potential

### 3.2.1 Demand and Supply Factor

Research on energy systems focuses largely on supply-side innovations, but less attention is given to end-of-use energy efficiency technologies (which could reduce energy consumption as a percentage of gross domestic product (GDP)). Researchers found that demand-side management impedes the development of new RESs in scenarios with a low growth in energy consumption because of issues with energy efficiency. Before deciding on a suitable site for RESs, the appropriate size of RES can be estimated by

analysing the potential energy demand production capacity of regional areas. Sorensen used GIS approach in 2001 to map solar resources utilising satellite datasets and incorporate them with power demand modelling based on energy demand intensity and population density. In some studies, the analysis of energy demand is solely based on GDP growth rates. For instance, Sambo (2008) examined Nigerian electricity demand by categorising it into four GDP-based scenarios: the Reference Scenario is 7 % GDP growth; the High Growth Scenario is 10% GDP growth; the Optimistic Scenario is 11.5 % GDP growth; and the Optimistic Scenario II is 13 % GDP growth. The demand of energy can also be calculated using precise economic and social factors. Ethiopian Rural Energy Development and Promotion Center (EREDPC), for example, evaluated the demand for national energy based on consumption in agriculture, household, services sectors, transportation, and industry in 2007 (Zenebe, 2007). Using the domestic sector as an example, the energy consumption was calculated based on the amount of time spent lighting, electric appliances, and refrigeration. EREDPC established assumptions about each sector's and subsector's general growth rate to forecast future energy consumption. Even though this method covers all sectors, the prediction still requires validation with past energy consumption data.

Aside from analysing energy demand, potential changes in the supply of energy must be considered. Mulherin (2011), for example, applied a GIS-based approach to estimate rooftop PV panel's potential energy production for homeowners. Using LiDAR data, each rooftop's solar radiation was calculated with dormers and chimneys excluded. The electricity cost of installing PV panels and the financial costs were then compared to assist each household in deciding where to install them. According to the outcomes of their study, energy potential supplies must be more accurately assessed, particularly at micro-scale levels, because rooftops structures can affect the power generation capacity and PV system performance. PV system performance is crucial to the potential supply of solar energy, but there are also other influencing factors that must be considered.

### **3.2.2 Slope**

To deploy RESs, several physical factors must be considered. These involve the orientation of the land surface and land surface gradient, as well as surrounding obstacles. Steeper slope and rough terrain are among the factors to consider in the development of solar and wind energy plants (Anwarzai & Nagasaka, 2017; Brewer, et al., 2015; Krewitt & Nitsch, 2003; Ali, et al., 2019). If the slope requirement is not met, excavation and filling in those areas result in both cost and time losses. According to Ali et al. (2019), steep slope is not recommended for wind and solar development, there are many demerits like risks including significant cost of constructing roads to the site, and more investment is required for power facilities installation, such projects are not preferable due to low economic feasibility. Furthermore, the challenging topography necessitates good wind turbine and solar PV performance, despite the high infrastructure costs.

A site with a flat surface topography is more favourable since the lesser the slope or flatter the slope of the site, the better the site is for construction. Hence, it is preferable to select the sites with lower gradient or slope.

Carrion et al. (2007) conducted research in Andalusia on the necessity of integrating terrain gradients in their analysis of optimal sites for PV grid-connected systems. The research revealed that areas with more than a 2% slope could result in shadow effects from the panels themselves, whereas Charabi and Gastli (2011) conducted a similar investigation and discovered that sites with a graded slope of 5% or higher may result in effects of shadow. This is especially troublesome in installations with multiple rows of PV modules. Noorollahi et al. (2016) used a MCDM support system for wind farm site selection. Their research discovered that potential sites for wind farm were limited to mountainous regions with slopes  $\leq 15\%$ . A similar study carried out by Xu et al (2020), regarding location selection for wind energy plants utilising MCDM and GIS approach in Wafangdian, China, showed that an appropriate site is restricted to a gradient with  $\leq 15\%$ . Their study concluded that the central region of Wafangdian is distinguished by extreme wind speed, which is advantageous to power output. However, the steep terrain raises the construction costs for installing wind turbines.

In Bravo's (2007) study, a maximum slope of 7% was selected for southeast and southwest oriented land surfaces. Obstacles can reduce PV installations' solar exposure. Ambient trees, for example, may obstruct incoming solar radiation (Reijenga and Ruoss, 2005). As a result, when determining a site's suitability, only unshaded areas should be considered when calculating average sun exposure (Wiginton et al., 2010). According to Carrion et al (2007), areas with crops and vegetation are unsuitable for PV grid-connected stations. Topographic shading, structural shading, and vegetative shading, according to Voegtle et al. (2005), should be considered in both the rooftop PV and ground-mounted PV site selection processes. As a result, topographic aspect and gradient must be considered.

### **3.2.3 Aspect (Orientation)**

Aspect is the indication of geographic direction of the surface at a given point (Smith, 2020; Writer, 2020), in which the slope surface is facing, which is also known as exposure or slope direction. Aspect has a strong influence on the solar illumination on a surface (Buckley, 2019). The aspect of the terrain is another significant consideration for wind and solar PV energy development plants that depend on slopes, shown in Figure 8, and it determines how much solar radiation a solar PV panel array can absorb (Verbyla, 2002). It is critical to ensure that the solar modules are oriented in the correct direction and have an optimum tilt to maximise energy generation since they are exposed to the most intense solar irradiation (Doorga, et al., 2019). Some solar modules track the sun's ray, whereas others are fixed in their angle.

The standard rule for solar modules placement in the southern hemisphere is that solar modules should be oriented true north while in the northern hemisphere, true south (Sandy, 2020). In 2018, Doorga carried a study on modelling solar PV potential for tropical islands in Mauritius in the southern hemisphere. It was suggested that the land surface facing the geographic north must be prioritised because it receives more sunlight throughout the year than the land facing other directions (Doorga, et al., 2019). This is because the south side of the slopes is typically shaded in the southern hemisphere, whilst the northern side absorbs more sun's energy as the slope is tilted toward the sun (Albert & Salas, 2007).

When the sunlight strikes Earth's surface perpendicularly, the solar PV power plant will generate the most power. The direction with the highest solar exposure is prioritised among the nine different directions (N, NE, NW, E, SE, S, SW, and W) for installing solar PV modules. In 2017, Hassan and Anjali conducted a study to assess potential areas for solar PV utility-scale project. According to their findings, a south-facing slope with a slope angle of less than 5 degrees was the optimal orientation for Solar PV site installation.

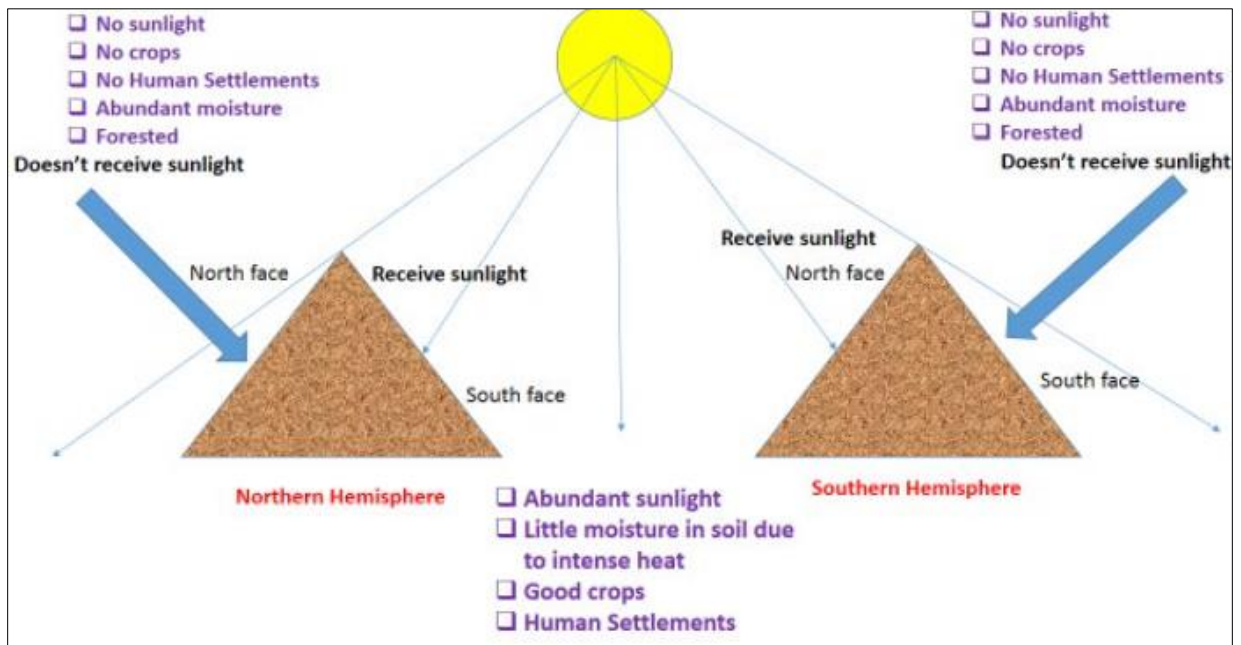


Figure 8: The differential in sunlight irradiation between slopes facing North and South (PMF IAS, 2018).

### 3.2.4 Solar Radiation

As illustrated in Figure 9, the amount of solar power absorbed at certain area on the Earth's surface is determined by a variety of factors that affect solar radiation as it travels through the atmosphere such as angle of the sun, humidity, evaporation, air temperature, topography and other surface features and then is intercepted as absorbed, diffuse, direct and reflected isolation components (Shetaee & Sabziparavar, 2007; Jacovides, et al., 2006; Fu & Helios, 2000). It is significant to understand the amount of solar irradiation reaching the Earth's surface, as solar PV depends on it (Fu & Helios, 2000). Therefore, the amount of

incoming solar irradiation plays a major role and determines how much power a PV panel can produce. To maintain long-term viability in meeting energy demands, solar installation locations must be able to provide sufficient power supply. Solar irradiation was regarded as the most important selection criterion in many wind and solar energy research studies (Uyan, 2013; Zoghi, et al., 2017; Colak, et al., 2020; Gastli & Charabi, 2010; Sanchez-Lozano, et al., 2015).

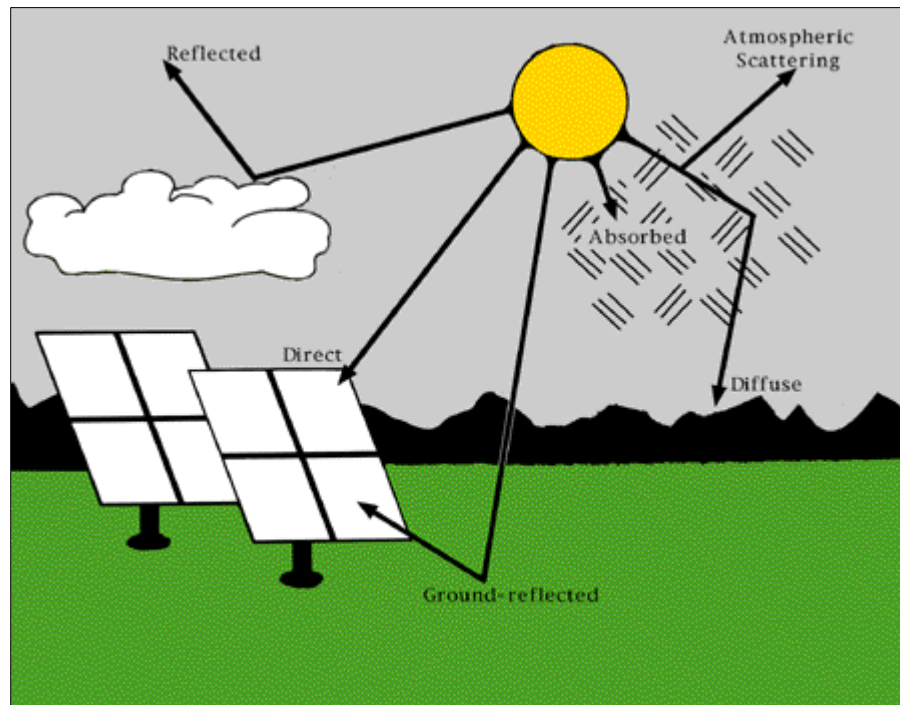


Figure 9: Different components of incoming solar radiation source ( Anderson, et al., 2015)

### 3.2.5 Air Temperature

Air temperature is one of the main factors that should be considered because cell temperature has a substantial effect on solar cell performance. As the ambient temperature rises, solar modules temperature increases, and the current output of the module increases exponentially while the voltage output decreases linearly. Therefore, high air temperatures have an adverse effect on the efficiency of solar modules systems (Adeeb, et al., 2019; Almarshoud, 2016; Popovici, et al., 2015). The solar power plant's operational environment is defined by the temperature of the air (World Bank Group, 2019). Amelia et al. (2011), investigated the impact of air temperature on PV modules output performance. Their research discovered that when PV modules were heated to 25°C, the most efficiency energy output was 15.43 %, however when PV modules temperature increased to 65°C, performance dropped by 12.27 %. Meanwhile, at temperatures of 55 °C, 45 °C, and 35 °C, the efficiency increased to 13.08 %, 13.88 %, and 14.66 %, respectively. Researchers in Dhahran, Saudi Arabia, found that the PV modules efficiency decreased by around 11% the as the temperature of the PV modules increased from 38°C to 48°C (Gherboudj & Ghedira, 2016).

However, it is also critical to choose the best solar modules technology for a certain location based on its average air temperatures. Adeeb, et al. (2019) carried out a study on the impact of air temperature on the performance of various solar cell technologies. Their study concluded that thin-film solar panels were found to be less impacted by temperature, with temperature coefficients of -0.109 % for Poly-crystalline and -0.0984 % for Mono-crystalline technologies. These findings can be used in the preliminary design stages, such as selecting the solar modules system to be deployed in a certain area (Al Garni & Anjali, 2018). In Namibia, the yearly average temperature is 20.6°C, with monthly average temperatures ranging from 16°C (June and July) to 24°C (November to March) (World Bank Group, 2021). The lower air temperature in Namibia with annual average temperature 20.6°C and annual average high solar irradiation 6.7 kWh /m<sup>2</sup> indicates optimal condition for high-power productivity.

### **3.2.6 Wind Speed**

In wind power development, wind speed is a critical evaluation criterion and a prevalent technical indicator (Xu, et al., 2020). According to Shoaib et al. (2019), a reliable estimate of wind potential for site under study requires a thorough understanding of its wind characteristics. These give reliable wind energy estimates of site selection for wind farms installation and efficient planning (Shoaib, et al., 2019; Adaramola, et al., 2014).

For this reason, it has motivated researchers worldwide to conduct studies utilising short- and long-term wind speed data by developing appropriate mathematical methods and distribution to model measured speed data (Shoaib, et al., 2019). There are factors for example, pressure, air temperature, topography, and heights that affects the wind speed variability (Shoaib, et al., 2019). The wind speed and direction can change depending on these factors. High wind speeds indicate abundant wind resources which can effectively increase energy production. High scores are obtained by increasing wind speeds within the proper range. Wind speed increases with height, and since the turbine is mounted on the tower, the taller the tower, the more power will be produced. Even though wind availability is not the only factor contributing to the locating of wind farms, it is the most significant criterion given the most weight in prior studies.

### **3.2.7 Socio-Economic Aspects**

The proximity to utilities ensures adequate accessibility, economic feasibility, and decreasing infrastructure construction costs while avoiding negative environmental implications (Al Garni & Awasthi, 2017; Noorallahi, et al., 2016; Janke, 2010; Baseer, et al., 2017). Furthermore, reducing the distance to power lines is a cost-effective way to evade the hefty construction cost of new electrical grid while also diminishing energy loss in the transmission line. A certain number of research consider sites that are farther away from urban areas to be best suited for RESs energy development plant to reduce unfavourable

environmental effects on metropolitan development (Colak, et al., 2020; Sadeghi & Karimi, 2017; Kocabaldir & Yucel, 2020; Uyan, 2013). On the other hand, some studies have found that locations close to urban areas have significant economic benefits (Ishugah, et al., 2014; Dehshri & Dehshiri, 2022). A screening of the study area could eliminate locations that are infeasible for RESs power plants installation to achieve more reliable decision outcomes. The GIS will be utilised to exclude unfavourable areas that prevent such facilities from being deployed. When multiple criteria are considered, it is difficult to make decisions. Multiple factors can influence complex decisions, such as those presented in Table 1. Therefore, multicriteria decision analysis methods have been developed to assist with difficult, conflicting judgments and complex decisions considering those criteria.

Table 1: The criteria used to select solar PV and wind energy sites.

Variables/Criteria	Wind energy	Solar PV	References
Slope	✓	✓	(Kocabaldir & Yucel, 2020)
Aspect	X	✓	(Sendy, 2020; Doorga, et al., 2019; Wiguna, et al., 2016)
Solar irradiation	X	✓	(Ali, et al., 2019; Anwarzai & Nagaska, 2017)
Air temperature	X	✓	(Habib, et al., 2020; Kereush & Perovych, 2017; Popovici, et al., 2015; Ramachandra, et al., 2011; Amelia, et al., 2016)
Wind speed	✓	X	(Gorsevski, et al., 2013; Noorallahi , et al., 2016; Latinopoulos & Kechagia, 2015; Moradi, et al., 2020)
Distance from roads	✓	✓	(Noorallahi , et al., 2016; Shorabeh, et al., 2019; Moradi, et al., 2020; Mierswiak & Calka, 2017; Sadeghi & Karimi, 2017; Uyan, 2013)
Distance from power lines	✓	✓	(Colak, et al., 2020; Dawod & Mosaad, 2016)
Distance to urban areas	✓	✓	(CNdV Africa Planning and Design, 2006)
Distance from the protected areas	✓	✓	(Uyan, 2013; Sadeghi & Karimi, 2017)
Distance to waterbodies	✓	✓	(Arnette & Zobel, 2011; Sadeghi & Karimi, 2017)
Distance to forestry areas	✓	✓	(Sliz-Szkliniarz & Vogt, 2011)
Distance from airport	✓	X	(CNdV Africa Planning and Design, 2006)
Distance to IBA	✓	X	(Diaz & Soares, 2020; CNdV Africa Planning and Design, 2006)
Distance to agricultural land	✓	✓	(Gasparovic & Gasparovic, 2019)

### **3.3 Chapter Summary**

Chapter three covered the detailed environmental concerns involved in the development of solar and wind energy through environmental regulations. Other factors that could affect the installing of RES were also identified and discussed in depth. Table 1 summarises the criteria considered by previous studies for solar and wind energy plant site selection.

## **CHAPTER 4: METHODOLOGY**

The chapter is structured as follows: section 4.1 provides the description of the study area, while section 4.2 presents the identified site selection factors and criteria considered for wind farm and solar PV energy plants development for the study. Section 4.3 and 4.4 highlight the software's relevant information, data source, and data formats that is selected for the study. In Section 4.5, the method adopted for the study is presented and comprehensively explained for solar PV and wind turbines site selection. Therefore, the chapter provides all the processes required to determine suitable sites of installing solar and wind energy plants.

### **4.1 Introduction**

Having reviewed numerous studies on the necessity to adopt RESs in lieu of conventional sources of energy, as well as the methods of extracting and analysing the solar PV and wind turbine, it is now important to determine which methods are most appropriate in achieving the study aim. This study presents a GIS-based approach for identifying the potential areas within CENORED's supply areas and evaluating the potential suitability for the construction of wind and solar PV energy plants. Sites selection for wind farms and solar PV energy is an important activity because of the consideration of various factors that make the plant technologically and economically viable, while at the same time assuring maximum environmental protection. This study will provide recommendations and essential information to the CENORED company, the investors, the researchers, the politicians, the students, and the public on preliminary site selection of solar and wind energy development. Numerous factors and variables were considered while determining the methodology to adopt, including the selection of software and the availability of datasets for the study. The flowcharts depicted in Figure 10 outline the study's proposed methodologies.

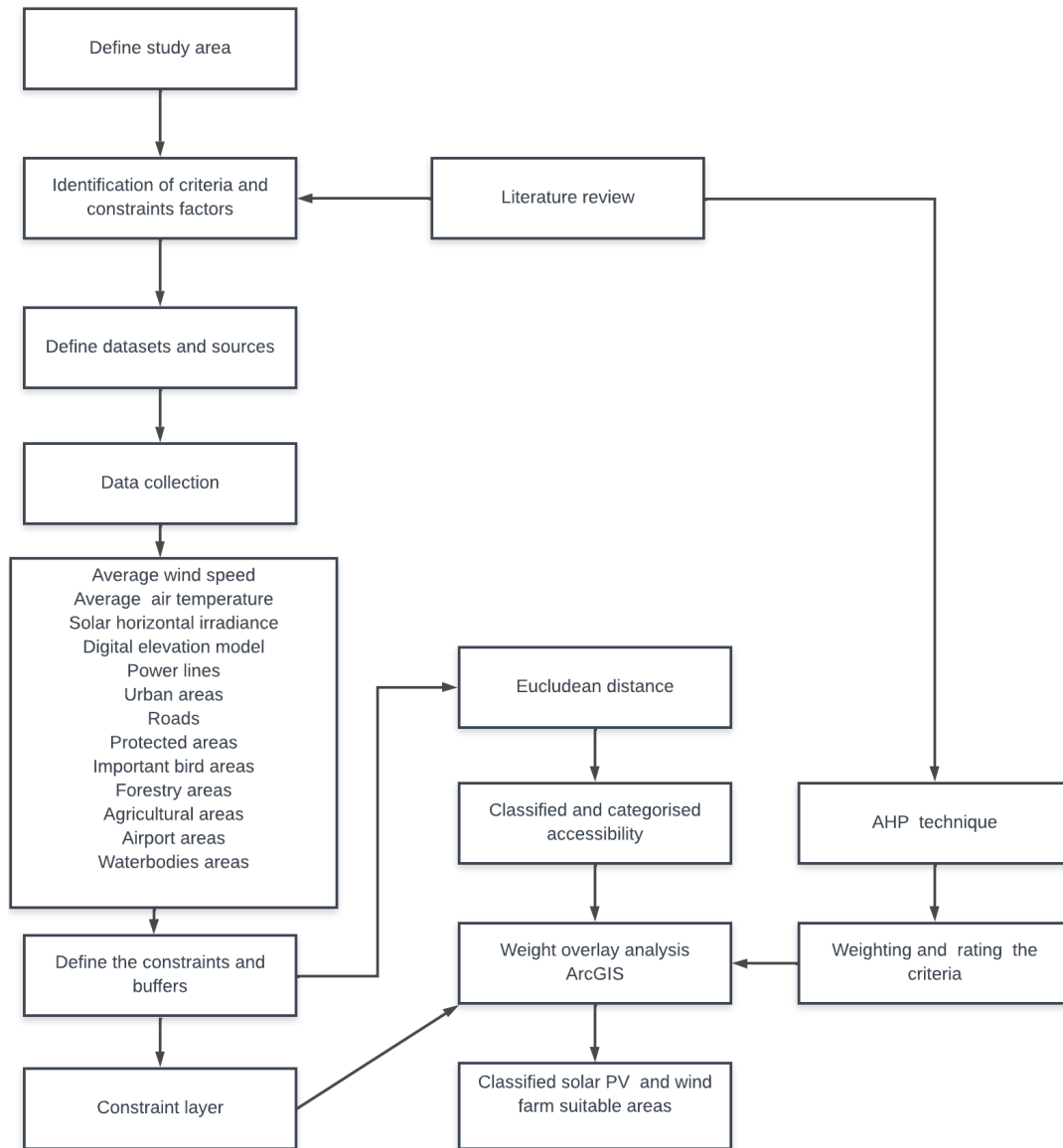


Figure 10: The methodological framework of the solar PV and Wind turbine site selection

## 4.2 Study Area

CENORED's supply area is situated in Namibia's Central North region. It covers Otjozondjupa and Kunene regions and recently incorporated the Omaheke region of Namibia (see

Figure 11). This region is characterised by highly mountainous areas and significant summer drought. Approximately 80% of the study area is covered by vegetation, mainly shrubland. Normally, rain falls from October to March, sometimes extending into April and early May. The heaviest rains occur from January to March. Different parts of the research area receive different amounts of rainfall. Otavi district receives relatively high rainfall compared to other areas, averaging between 450 mm and 600 mm annually. As a result of good rainfall, the area offers good commercial farming opportunities for grain and maize, and hence, it is known as the Maize Triangle. Across the study area, the average minimum yearly temperature is 11.0°C, while the average maximum temperature per year is 24.0°C. The study area has a lot of sun hours, with an average of 3 605 hours of sunlight per year, an average of 9.9 hours of sunlight per day, and an annual average solar irradiance ranging from 1953.36 kWh/m<sup>2</sup>/yr to 2465.44 kWh/m<sup>2</sup>/yr. There is the greatest potential for solar energy within the region. The coastal region of the study area has good wind resources, with wind speeds of 10 m/s or more, resulting in wind energy potential. CENORED distributes energy to more than 40 000 customers in this region, which includes numerous urban areas, villages, settlement areas, and farms in central-northern Namibia, with a surface area of about 120 000 km<sup>2</sup>.

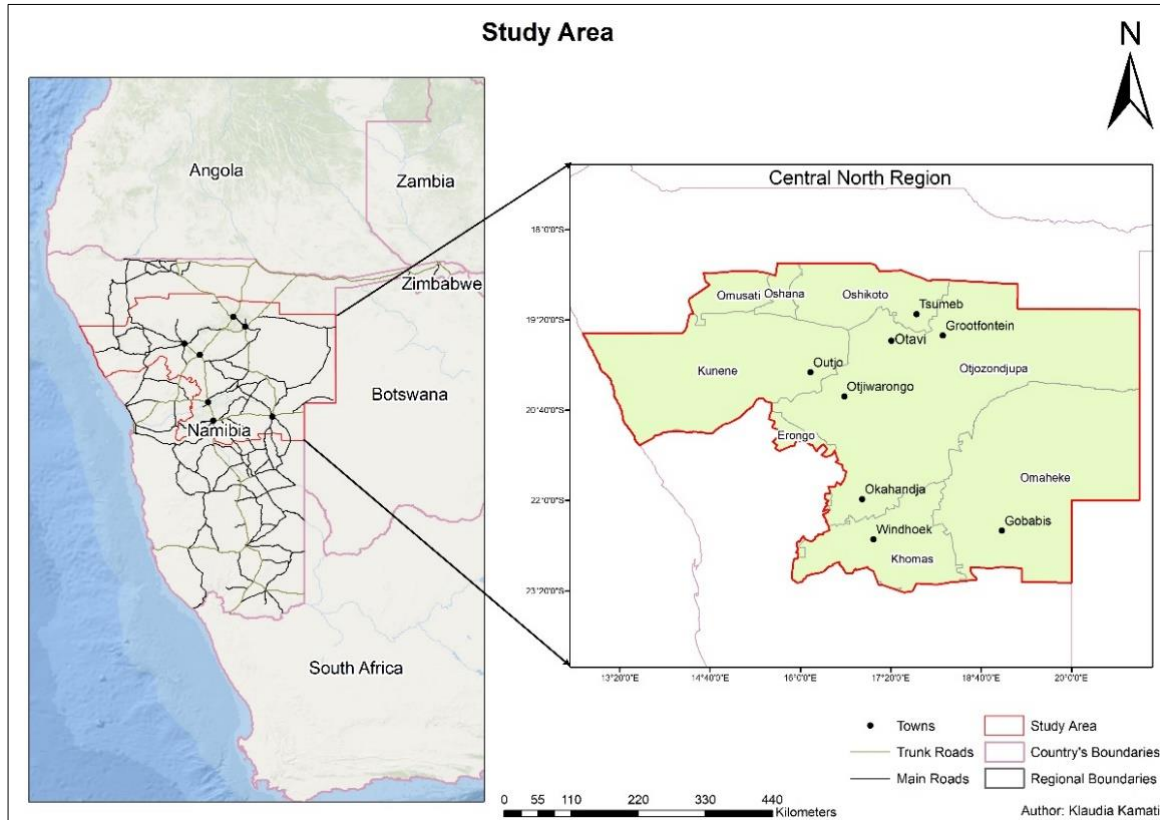


Figure 11: CENORED supply area

### 4.3 Identification of Criteria

First the study identifies and defines a set of factors that impact the sites selection for wind and solar PV energy plants development. A factor is anything that helps or hinders the suitability or effectiveness of a particular alternative for an activity being considered. A thorough review of literature, current Namibia environmental guidelines, legislations, and laws is used to identify the factors associated with solar and wind energy development. The factors considered for location selection are climatic, environmental, economic, and geomorphologic. Each factor is subdivided into criteria and fourteen criteria were considered in this study. The criteria were thoroughly examined for their characteristics, benefits, and implications for wind and solar PV energy plants development. Detailed explanations of these criteria can be found in Chapter 3. Figure 12 depicts a hierarchy of factors and criteria of solar PV and wind energy plants considered in the present study.

This study's dataset is divided in two categories: constraints and criterion variables. The constraint variables are employed to determine sites that are not suitable for RESs plant installation, whilst the criterion variables are used to evaluate the suitability of potential sites by identifying low and high suitability values for energy plant development. Environmental regulations associated with airports, noise management,

forest areas, agricultural lands, protected areas including wetlands, national parks, important bird areas (IBA) and waterbodies are investigated. By using these regulations, environmental objectives can be determined, which then are quantified using a variety of criteria.

It should be emphasised that some criteria can be identified based on energy policies, preferred technology, site characteristics, and country-specific requirements. New criteria can be simply incorporated into the evaluation using the proposed methodology, provided that the required dataset is readily accessible for the analysis. The criteria including topography, wind speed, air temperature, roads, proximity to the urban areas, power grid access, and solar irradiance will be integrated into MCDM approach to generate solar PV and wind energy suitable sites.

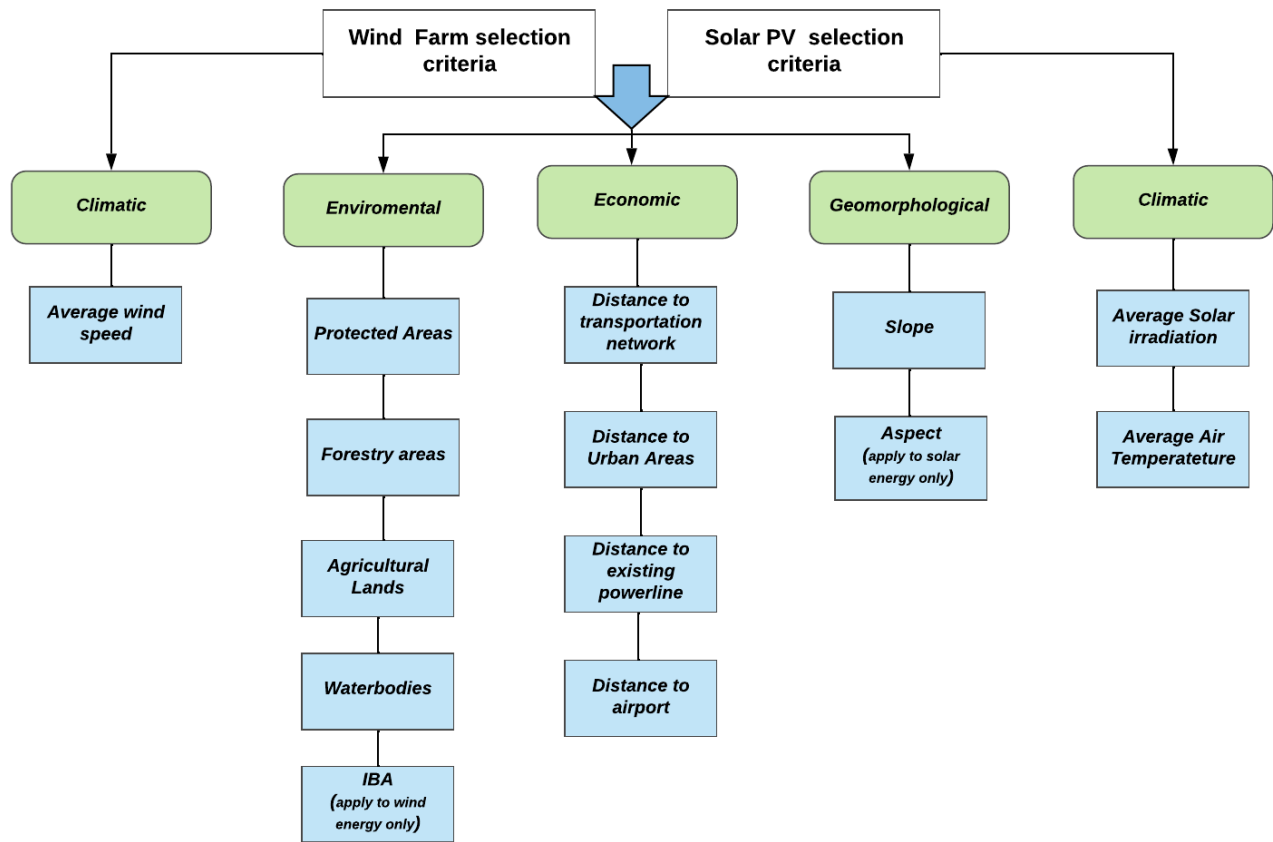


Figure 12: Site selection factors and criteria for solar and wind energy plant installation

#### 4.4 Software

ArcGIS 10.8.1 version is used throughout the whole process to prepare, analyse, and manipulate the data by applying various operations on the collected geospatial data, because the variety of tools within ArcMap provide users with the ability to convert layers to new formats, analyse data using geoprocessing tools, and integrating layers together to better understand landscape patterns. This software provides a unified approach to working with geographic information. Microsoft excel is specifically used for factor criterion weighting and analysing the attribute data.

#### 4.5 Data Source, Data Types, and Data Formats

The source of data influences the quality of data utilised in any analysis. Therefore, it is critical to explore and verify the attributes, the feature geometry, and metadata for each dataset to determine whether the data will be useful for analysis. Metadata is a document that helps the user to ascertain the reliability and accuracy of data. In addition, metadata also helps to support good decision making and cost saving because it clarifies why, who, how when or if the spatial information needs to be updated (ESRI, 2002). The use of

inaccurate or missing data will generate inaccurate outputs. From a quality assurance perspective, all collected datasets are loaded onto ArcMap Software to convert to appropriate data standards, formats, projections and ensure all layers are compatible.

The raw datasets used in this study were obtained through different sources and have different spatial reference including open sources, government agencies and related literature. Verifying and integrating the data first involved checking the geographic projections of obtained datasets. This was accomplished in ArcMap by inspecting the properties from the ArcCatalog. All the acquired datasets are projected to the same Projected Coordinate System which is Namibia LO 17 system. Namibia's co-ordinate system was developed using the Transverse Mercator Projection also referred to as the Guass Conformal (Polytechnic of Namibia, 2015). The LO 17 is used for medium and large-scale engineering surveys and topographic mapping, and this was appropriate for the study area. Having projected data makes it easier to perform a variety of integrated analytical processes, such as overlaying data layers and calculating distance because linear units are meters. As shown in Table 2, the collection of data is an incredibly challenging process because it involves collecting multiple datasets from various organisations, particularly in different formats, in high-quality and accurate, as well as up-to-date dataset.

GIS spatial data are primarily classified into two different data types namely: vector (discrete) and raster (continuous) data. Vector data uses sequential vertices or points to represent data. Each vertex contains x and y coordinates. Vector data depict longitude and latitude using polygons, lines, and points to represent the features on the Earth's surface. Whereas raster data made up of a matrix of pixels arranged into columns and rows in which every pixel is associated with a value that represents specific information on the Earth's surface.

Various file formats are also available for storing information within each of these types (vector and raster). The file formats are standard of encoding GIS data into a computer file, which can then be read by GIS software on the computer. Among the most popular vector data formats includes, Keyhole Markup Language (KML), Geomedia, Shapefiles (SHP), Vector Product Format (VPF), GeoJSON, and others with SHP being the most used for desktop GIS projects. While raster information is stored in ESRI Grid, IMG, PNG, JPEG, and GeoTIFF, of which the most extensively used file format in GIS software environment is GeoTIFF.

The GIS desktop applications commonly use the SHP and KML file formats, but some web applications generally use the GeoTIFF file format. The SHP and KML data file formats are used for vector analysis in this study, whereas GeoTIFF is used for raster analysis.

Table 2: Data used in this study

Description	Data type	Coordinate	Resolution	Data provider
DEM)	Raster	WGS84	30 m	USGS Earth Explorer
Air temperature	Raster	WGS84	30 arc-sec	Global Solar Atlas
Solar Radiation	Raster	WGS84	9.0 arc-sec	Global Solar Atlas
Wind Speed	Raster	WGS84	250 m	Global Wind Atlas
Agricultural	Raster	UTM	10 m	European Space Agency Sentinel-2 imagery
IBA	Vector	WGS84	-	Birdlife International portal
Roads	Vector	UTM	-	Namibia Statistic Agency (NSA)
Forestry	Vector	UTM	-	NSA
Protected areas	Vector	UTM	-	NSA
Airport	Vector	UTM	-	NSA
Power line	Vector	WGS84	-	CENORED
CENORED boundary	Vector	WGS84	-	CENORED

#### 4.6 Proximity Analysis for solar PV and wind Power Plant Development

Table 3 presents a summary of threshold requirements for constraint factors that impact an area's suitability for developing solar power plants. This section presents the proximity analysis for wind and solar PV energy plant in the present study.

Table 3: Constraints involved in installing solar PV and wind power plants

Environmental (Constraints Areas)	Distance from Water bodies (m)	$\leq 500$ $>500$	Unsuitable Suitable	(Arnette & Zobel, 2011; Sadeghi & Karimi, 2017)
	Distance from Protected Areas (m)	$\leq 500$ $>500$	Unsuitable Suitable	(Uyan, 2013; Sadeghi & Karimi, 2017)
	Distance from Urban Areas (m)	$\leq 500$ $>500$	Unsuitable Suitable	(CNdV Africa Planning and Design, 2006)
	Distance from Forestry Areas (m)	$\leq 100$ $>100$	Unsuitable Suitable	(Sliz-Szkliniarz & Vogt, 2011)
	Distance from IBA	$\leq 1000$ $>1000$	Unsuitable Suitable	(Villacreses, et al., 2017)
	Distance from Airfield with Rader	$\leq 25\ 000$ $> 25\ 000$	Unsuitable Suitable	(CNdV Africa Planning and Design, 2006)

Distance from Local Airfield	≤ 2 500 > 2 500	Unsuitable Suitable	(CNdV Africa Planning and Design, 2006)
Distance from Agricultural Land	≤ 100 >100	Unsuitable Suitable	(Gasparovic & Gasparovic, 2019)

#### 4.6.1 Proximity to Protected Areas

According to the Environmental Management Act of 2007 of Namibia, Solar PV and Wind Farm should be developed away from environmental protected areas such as national parks or inhabited areas as well as areas of historical importance. An appropriate buffer distance of 500 m needs to be maintained to protect environmentally sensitive areas (Uyan, 2013; Sadeghi & Karimi, 2017). The buffer is relevant because the construction of solar PV and wind farm power plants may possibly lead to unfavourable effects on threatened species. ArcMap’s buffer tool was applied to generate the buffer zone of 500 m from protected areas as shown in Figure 13.

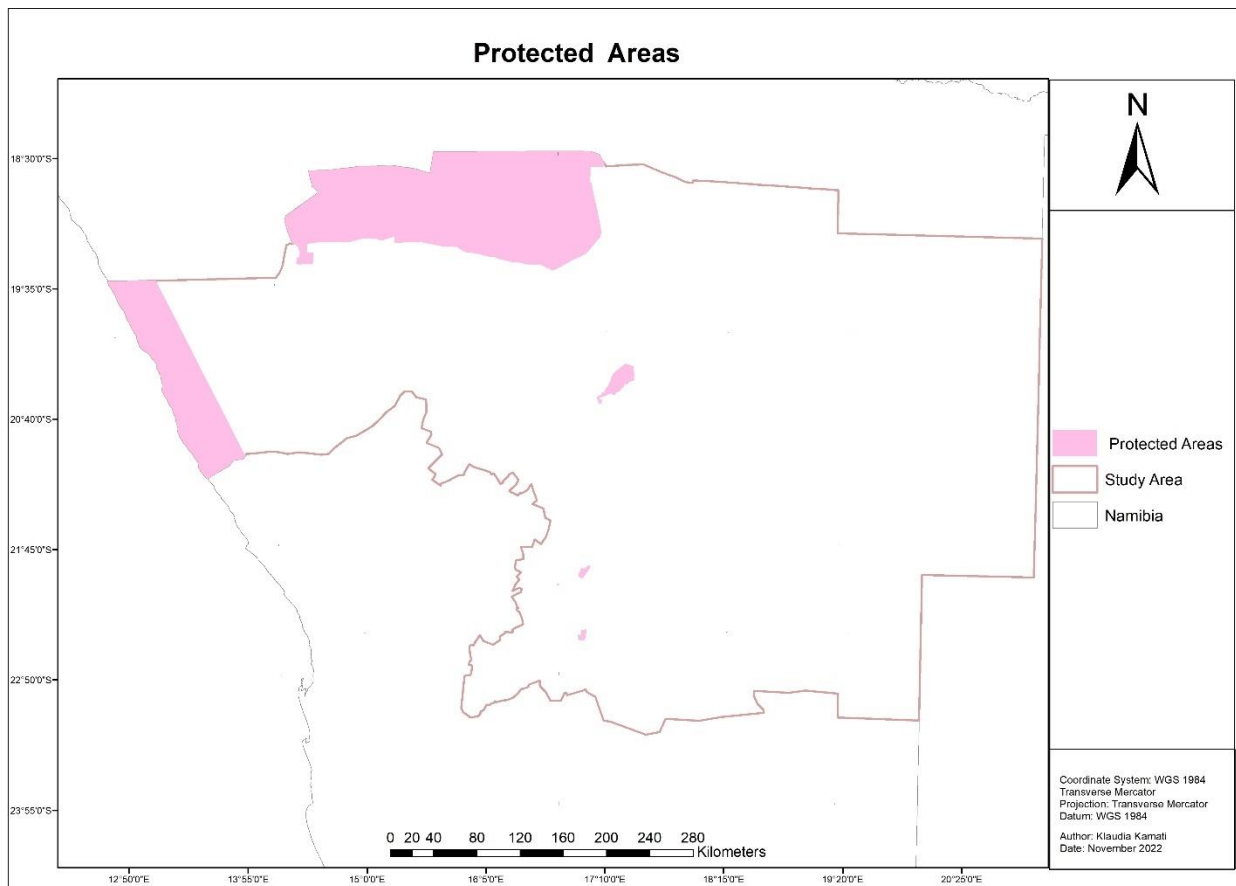


Figure 13: Buffered protected areas

#### **4.6.2 Distance to Urban Areas**

Economically, installing solar PV power plants and wind farms close to the consumer is advantageous. Nevertheless, considering the future expansion and development, it is necessary to specify a buffer distance (Colak, et al., 2020; Sadeghi & Karimi, 2017; Kocabaldir & Yucel, 2020; Uyan, 2013). According to Colak, Memisoglu, & Gercek, (2020); Sadeghi & Karimi, (2017); and Uyan, (2013, 2017), the location of a solar PV energy facility must be 500m away from metropolitan areas. The establishment of solar PV facilities near metropolitan areas may have a negative impact on population growth rates and dispersion (Uyan, 2013). Wind farm societal effects, such as noise nuisance, visual intrusion, and aesthetics, are frequently cited as important constraints for wind development projects (Xu, et al., 2020; Latinopoulos & Kechagia, 2015; Sadeghi & Karimi, 2017; Noorallahi , et al., 2016; Khanna, 2021; CNdV Africa Planning and Design, 2006; Villacreses, et al., 2017; Gigovic, et al., 2017). There are certain standards and procedures for determining acceptable noise levels that are based on community perception. Residents' approval must be addressed in sites selection, as some visual and noise impact are unavoidable once the wind turbines are operating. Noorallahi, et al., (2016), Sadeghi & Karimi, (2017), Ramirez-Rosado et al. (2008); Yue (2006), suggested that wind energy plants must be situated at a minimum distance of 500 m away from nearby urban areas to avoid safety concerns. In the current study, an 800 m buffer zone was used according to CNdV Africa Planning and Design, (2006) (see Figure 14).

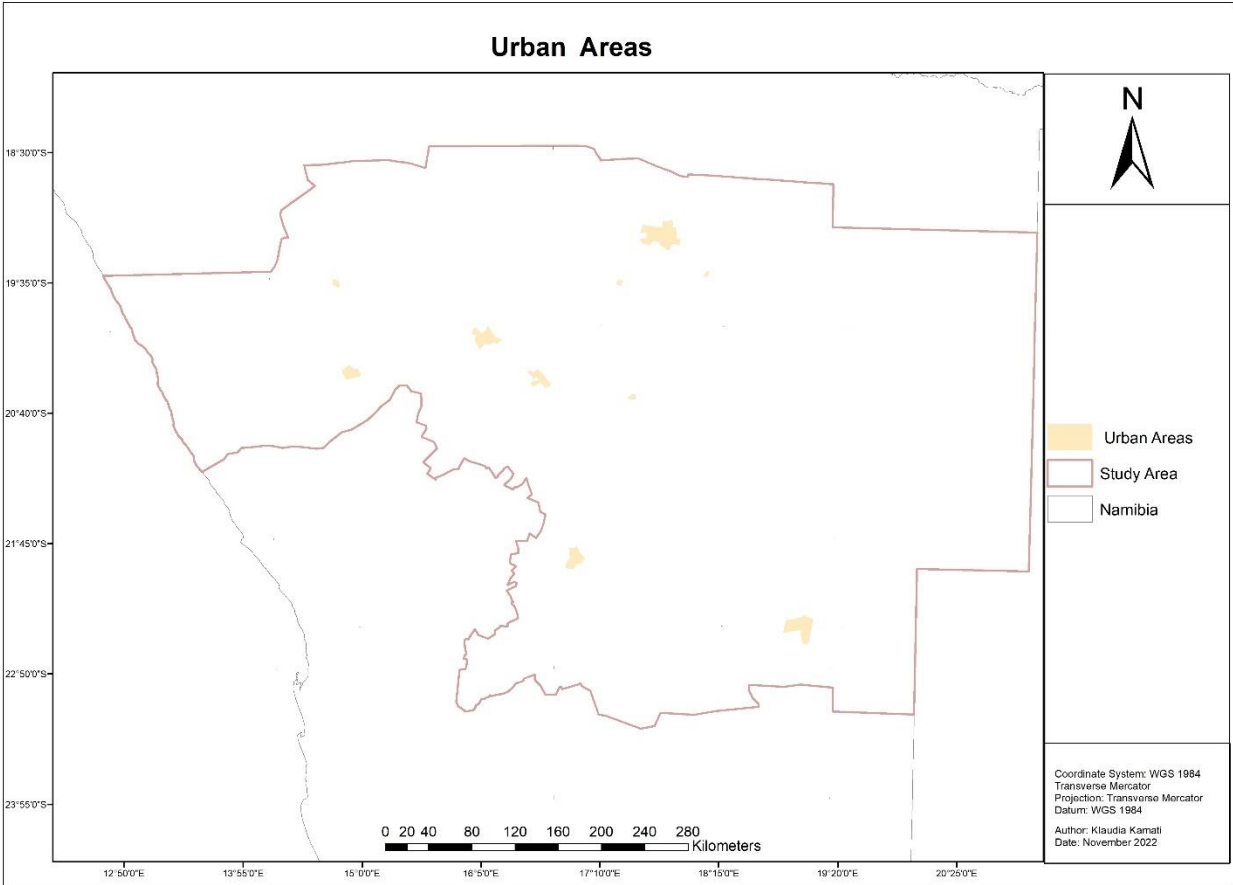


Figure 14:Buffered urban areas

#### 4.6.3 Distance to Water Source Areas

For the purpose of avoiding any undesirable consequences of water overflow during rainy periods, RESs plants should not be installed close to waterbodies (Colak, et al., 2020; Noorallahi, et al., 2022; Noorallahi, et al., 2022; Sadeghi & Karimi, 2017). In the present study, a 500m buffer zone from waters source areas was considered as constraint for wind and solar PV energy plant development. The buffer tool in ArcMap was used to perform the analysis. In this context, water source dataset within CENORED supply area was obtained from Namibia statistics Agency shown in Figure 15.

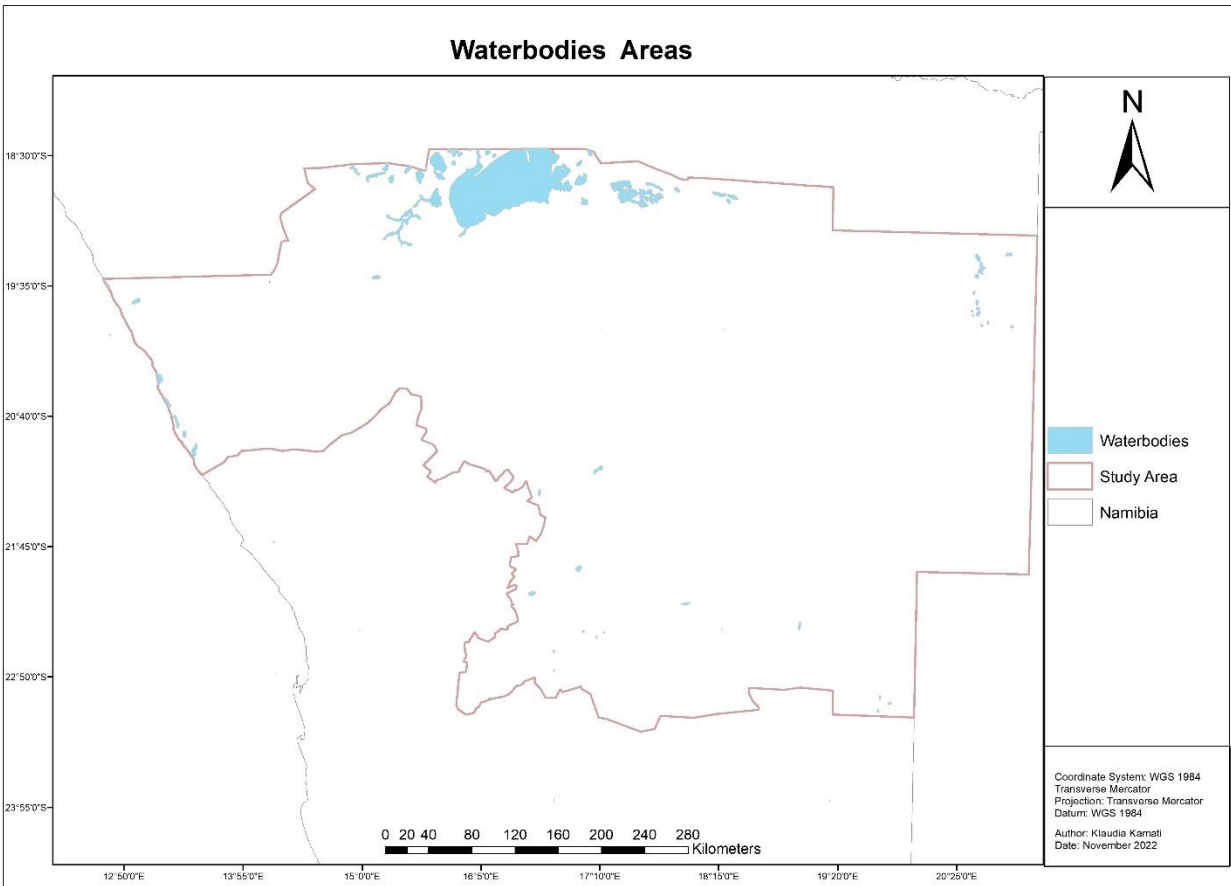


Figure 15: Buffered Waterbodies

#### 4.6.4 Distance to Important Bird Areas (IBA)

Birdlife International developed a project called the IBA to recognise and protect the most important bird areas in every country, worldwide. The goal of the project is to identify and safeguard a network of bird habitats that are critical to the survival of bird and bats populations across their entire ranges. Previous studies discovered that wind energy plants located in unfavourable geographic areas might pose negative effects on birds and bats, such as possibility of habitat destruction and rise in mortality rate (Latinopoulos & Kechagia, 2015; Xu, et al., 2020; Van-Haaren & Vasilis, 2011). Wind energy plants should, however, be positioned outside IBA to ensure the preservation of ecological and natural values, lessen bird collisions, and decrease noise impacting fauna. It is generally observed that bird migration occurs along settled migration routes. Wind turbines situated along these routes will significantly affect bird migration.

As a result, the bird's habitat and birds' migration routes are ineligible for installation of large wind power facilities. For this study, a 1000 m buffer zone from IBA-identified areas was considered as a constraint for wind energy development only (Diaz & Soares, 2020; CNdV Africa Planning and Design, 2006). African-Eurasian Bird Migration Atlas is being developed under the auspices of Convention on Migratory Species

as part of the Global Animal Migration Atlas by the European Union of Bird Ringing (EURING). However, the EURING is currently planned to publish the Atlas online in Spring 2022 (EURING, 2021; European Union of Bird Ringing, 2020). Due to lack of bird's migratory routes dataset only IBA datasets were used in this study. IBA dataset was obtained from Birdlife International portal in KML file format and was then converted to Shapefile format in ArcMap. ArcMap's buffer tool was then then applied to generate the buffer zone of 1 000 m from the IBA-identified regions as shown in Figure 16.

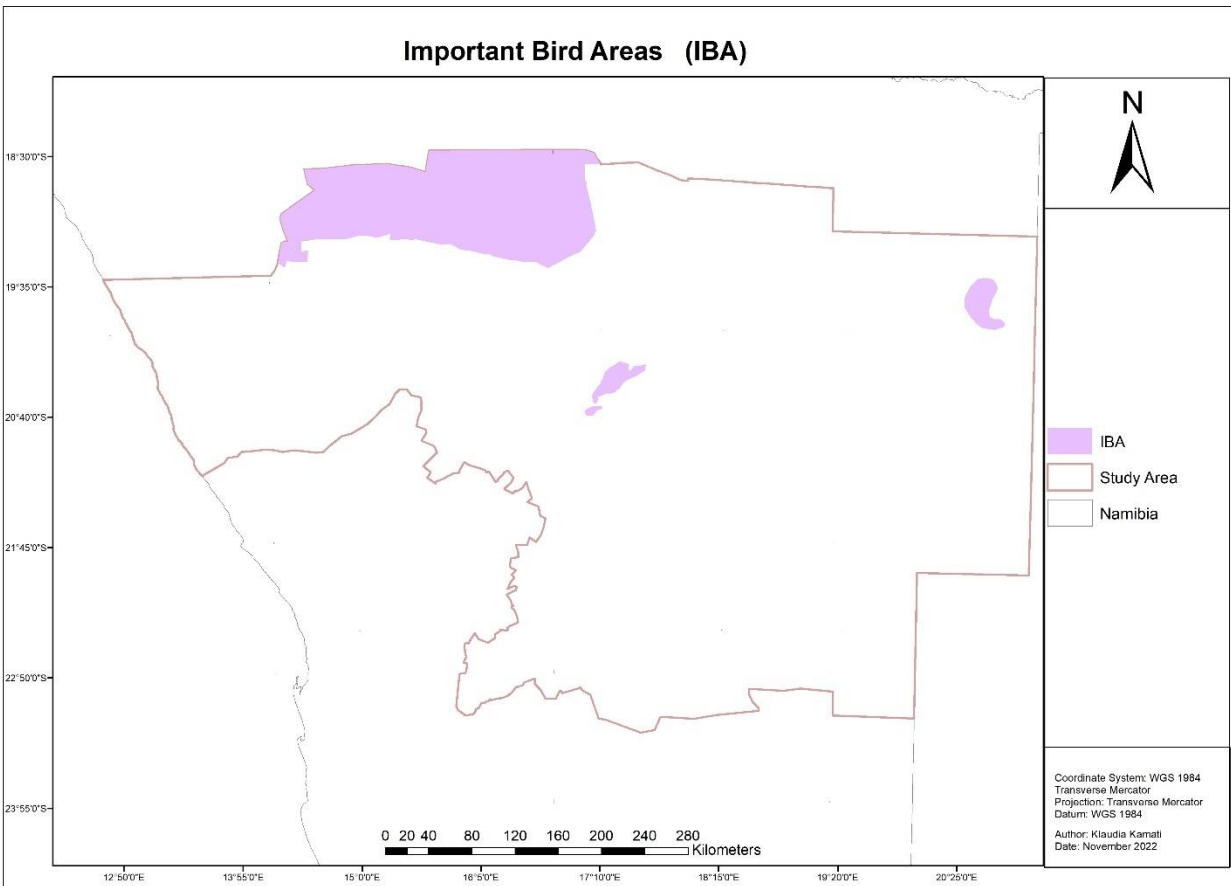


Figure 16: Proximity to IBA

#### 4.6.5 Proximity to Airfield

As wind turbines are at such a height that they can affect navigation, airports are among the most important factors to consider when identifying the optimal sites for wind energy plants. The aim is to address safety concerns, as when airports are built without allowing buildings and other obstructions to be built nearby (Young, 2018). It is important to take safety into account when choosing a wind site near an airport, because wind turbines generate electromagnetic interfere with the surveillance radar signals used to control traffic at airports (Ali, et al., 2019). Areas adjacent to wind farms are inaccessible to aircraft. Therefore, the wind farm locations should be 25 000 m away from airports' primary with radar, 15 000 m from military airports,

and at least 2 500 m from local airports (CNdV Africa Planning and Design, 2006; Noorallahi , et al., 2016; Tercan, et al., 2020).The current study, areas within 25 000 m from international airport with radar were deemed unacceptable and were eliminated from further evaluation according to the literature. ArcMap’s buffer tool was then utilised to create the buffer zone of 25 000 m from the Airfield with Radar and 5 000 m from local airfield as shown in Figure 17. However, a larger set-back distance was chosen in this study to ensure safe operation even in the event of an airfield expansion.

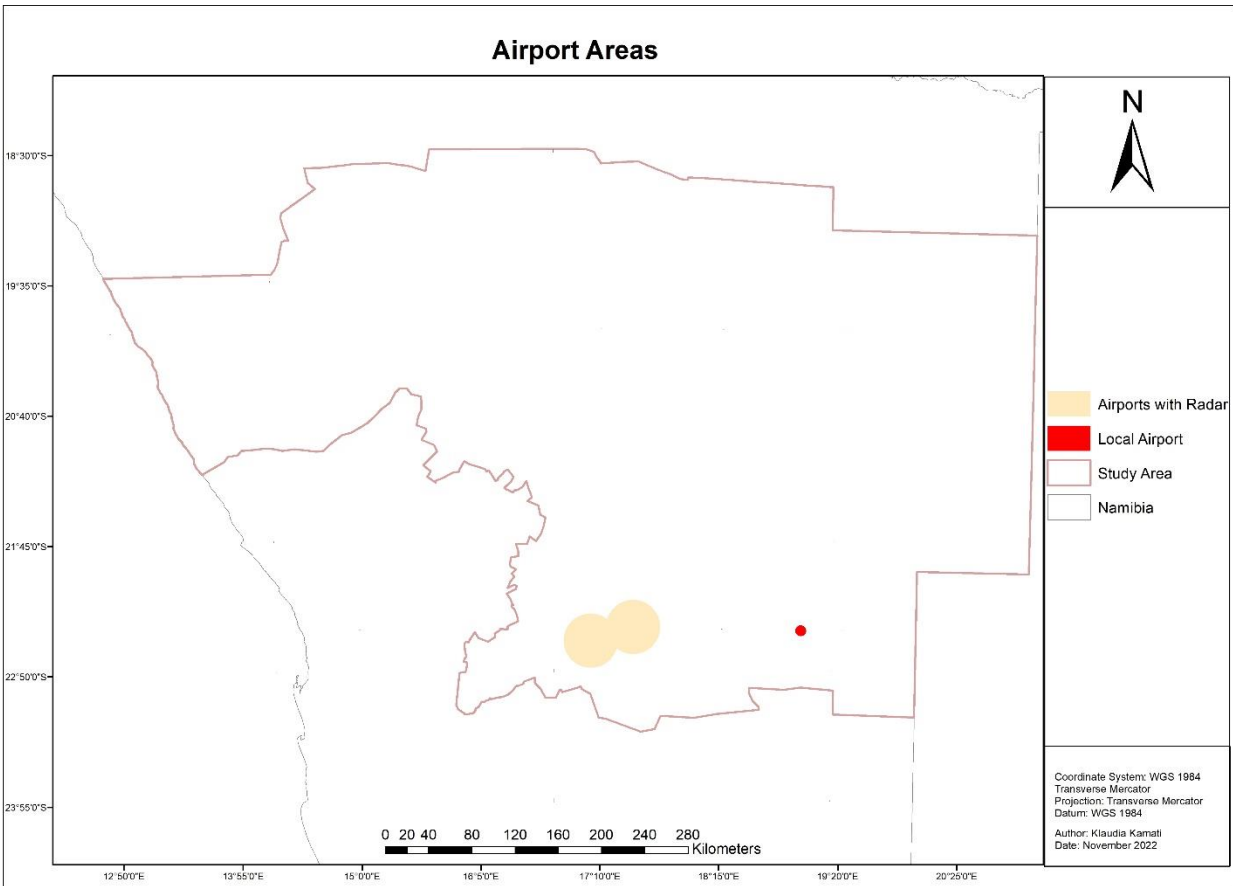


Figure 17: Proximity to airfield areas

#### 4.6.6 Distance to Agricultural and Forestry Areas

The Namibian government has established policies to protect agricultural lands and forestry areas. For this reason, these legislative barriers were considered, whereby agricultural land and forestry areas were excluded regardless of their other characteristics. As a constraint parameter in identifying suitable areas, a 100 m buffer zone around agricultural land and forestry areas in this study was used to distance potential areas from restricted areas, based on previous study (Gasparovic & Gasparovic, 2019). A landcover and land use GeoTIF raster file with 10 m resolution was derived from ESA Sentinel-2 imagery. Agricultural land was extracted from this raster file using select tool to extract agriculture class. As shown in Figure 18,

agricultural areas predominate in the study area's central region while forestry areas are situated on the northeast.

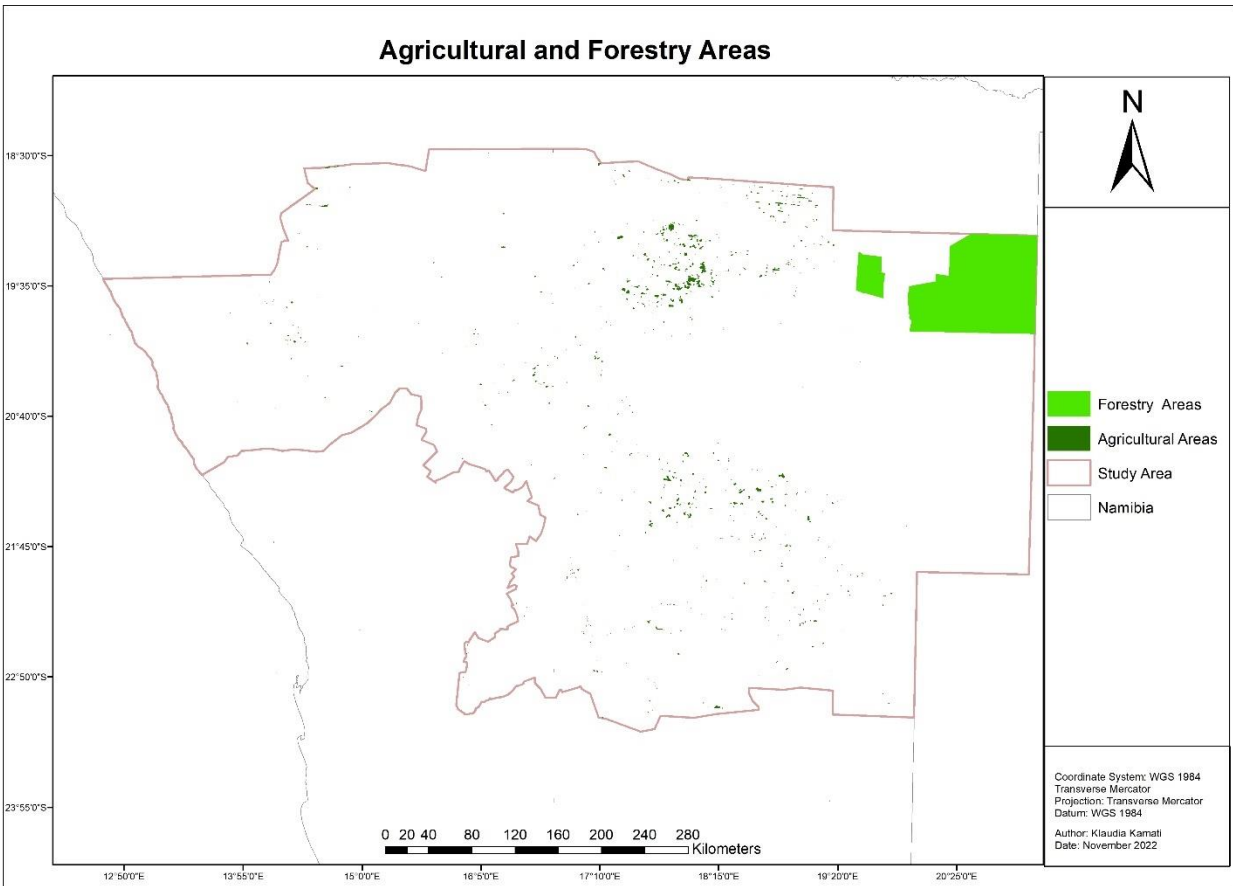


Figure 18: Agricultural lands and forestry areas

#### 4.6.7 Constraint Areas

A constraint is used to narrow down the options being explored, excluding places that are not desired in any way or are deemed undesirable. In addition, in the multi-criteria processing stage, forestry areas, agriculture, water bodies, metropolitan areas, IBA, and protected areas have been imposed as limits. Union analysis tool in ArcMap was used to combine these layers into a single composite layer and preserving all input features' boundary and attributes with all the necessary buffers as shown in Figures 16 - 22. The Erase tool was used to eliminate all constraint areas and Merge tool was used to combine the study area with erased constraint layer and assigned binary values 1 and 0. A binary of one indicates the possible PV power plant development, and zero shows the presence of limitation, indicating that the PV power plant cannot be developed. Polygon to raster function was used to convert polygon features to a raster dataset. Restricted areas are indicated in grey colour while the feasible areas are shown in dark green colour in Figure 19. The constraint areas apply to both solar and wind energy plant development.

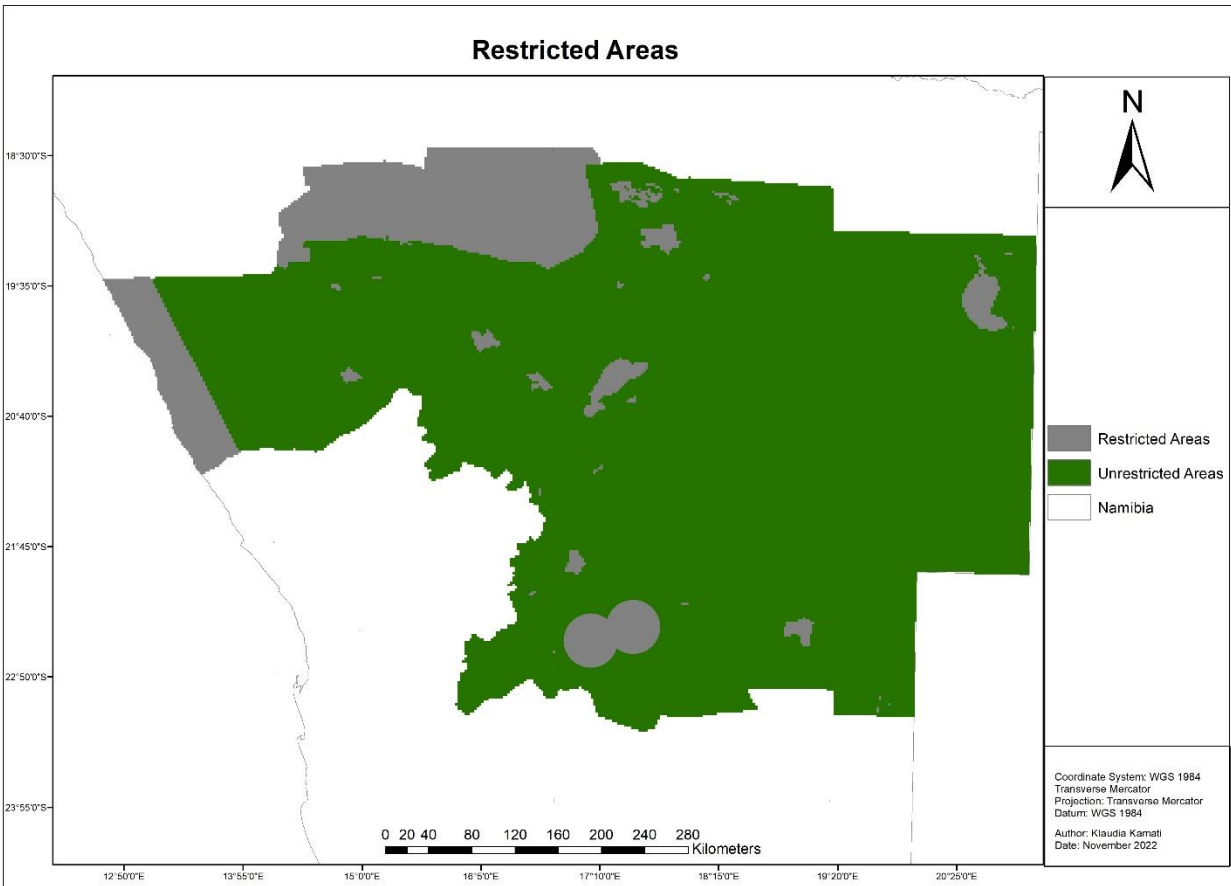


Figure 19: Restricted vs Unrestricted Areas

## 4.7 Data Processing

For this purpose, numerous vector, and raster layers like DEM of CENORED along with average solar radiation data, average wind speed data, average air temperature, road data, power line and land use data were used. In locating the solar PV and wind energy power plants, all analyses were conducted using ArcMap software (desktop version), from the company Esri® to perform a site-suitability analysis. Numerous datasets should be pre-processed. Projection and transformations were used for datasets projection. ArcGIS techniques such as Aspect, slope performed over the DEM data was utilised to generate aspect, and slope raster map. An aspect technique determines which direction the slope is facing. The values of each cell in the output raster represent the compass direction the surface faces at that location (Esri, 2016). In degrees, it is measured clockwise from 0 (due north) to 360 (once again due north). The slope tool determines how steep each cell of a raster surface is. Low slope values indicate flatter terrain and high slope values indicate steeper terrain. The slope raster can be expressed in degrees or percent (percent rise) (Esri, 2016). In the present study, the slope was calculated in percent because the percent rise can be easier understood if the rise is divided by the run and multiplied by 100.

For this study, the GIS methods to be employed require vector data to be converted to raster formats, making it easier to reclassify during further data processing. The reclassification technique reclassifies or convert cell values to alternative values. To reclassify by ranges of values, the reclassify tool requires the lower and upper bounds for the existing values on the input raster, as well as the alternative value to assign to the range of values. Any value in the original raster that falls within the specified range of values will be assigned the alternative value associated with that range (Esri, 2022). For example, when a range of 1 to 10 is associated with the criterion identified as 4, and a range of 10 to 20 is associated with the criterion identified as 3, the pixels of value 10 are assigned to the criterion 4 and pixels of value more than 10 are assigned to the criterion 3.

Euclidean distance tool was applied to calculate the distance from each cell in the road raster layer and powerlines raster and buffering excluded zones. Based on the straight-line distance, the Euclidean distance technique describe each cell's relationship to a source or set of sources. The Euclidean distance technique measures the distance between each cell in the raster to the nearest source (Esri, 2021).

All datasets were reclassified before performing weighted overlay operation. In the weighted overlay approach, average solar irradiation, average wind speed, aspect, slope, average air temperature, powerline, and road data are the input rasters. AHP method was applied as influence factor for each layer. Finally, using the weighted overlay method, various classes of suitable locations were discovered and segregated. To smooth the result, the vectorisation tool in ArcMap was utilised. Vectorisation converts raster data models to vector data models. It will be smoothed out the polygons so that they form simpler shapes. Smoothing is performed in such way that the polygons have the fewest number of segments while maintaining as near to the original raster cell boundaries as possible (Esri, 2022).

The restricted areas along with their buffers are identified and excluded from the analysis. For suitability analysis, environmentally sensitive/protected land, urban areas, forestry lands, waterbodies, airport, and IBA were selected as restriction criteria. The entire process for restricted areas has been shown in Figure 20.

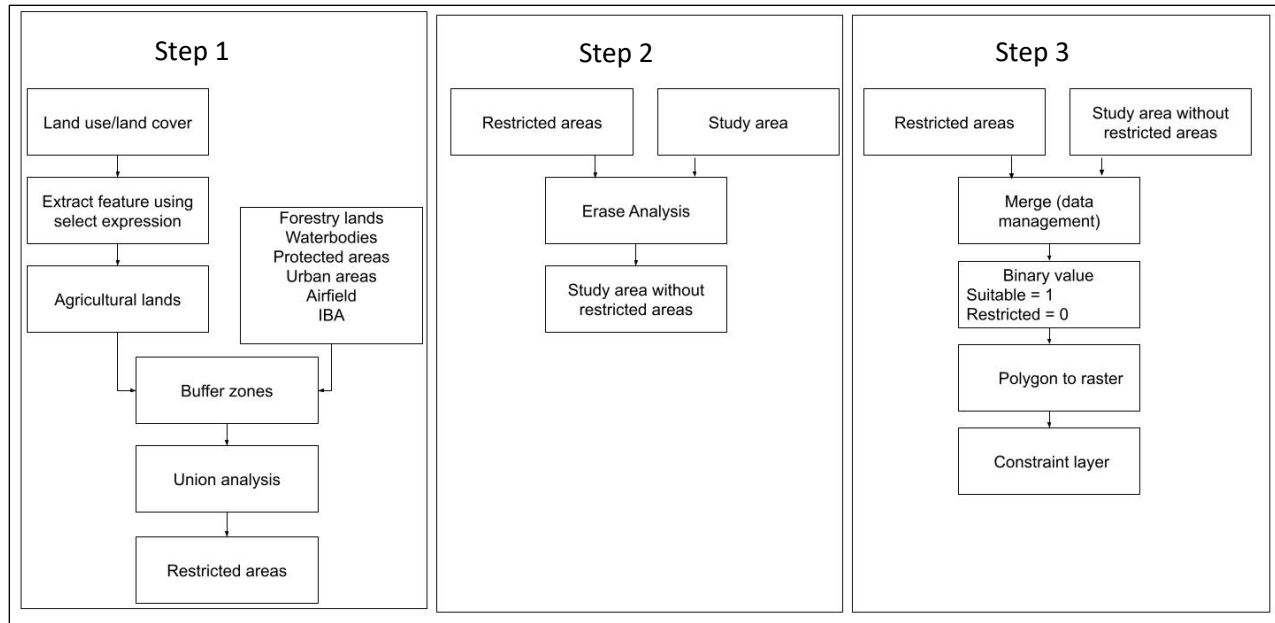


Figure 20: Constraint process

## 4.8 Weighted Overlay

One of the most common approaches to overlay analysis is the weighted overlay method, and it is used to handle multi-criteria problems including suitability analysis and site selection. A Weighted Overlay approach makes it possible to calculate and perform a multiple-criteria analysis between sets of raster layers. This tool only accepts input integer raster layers. Therefore, continuous floating raster layers must be converted to integers. The default evaluation scales range from one to nine, with one being the barely suitable and nine being the highly suitable. In the case where input raster has already been reclassified to a common measurement scale using the Reclassify tool, it is critical to choose an evaluation scale corresponds to the reclassified raster layers. Each raster layer input might be given a percentage influence or weighted. All raster layers must have a total influence of 100 percent.

## 4.9 Geodatabase

An ArcGIS geodatabase is a central location where collection of multiple types of geographic datasets are stored either in a common folder file system, or in a multi-user relational database management system. Data on the spatial locations and shape of geographical features is kept in a geodatabase as polygon, lines, points, pixels, or triangulated irregular network. A geodatabase is more than a collection of datasets. It has the capability of storing, managing, retrieving, and representing geographic datasets. In general, there are three kinds of geodatabases such as files, personal databases, or enterprise databases. For this study, an ArcGIS file geodatabase is created in ArcCatalog in preparation for the analysis. LO 17 spatial reference

system was chosen to match the data to be stored in it. The data that could be kept in the geodatabase is validated, integrated, and modified before being imported into the geodatabase. To make sure that every stage of the analysis is well-organised and streamlined, each dataset is stored under matching datasets.

#### **4.10 Analytical Hierarchy Process**

As outlined in Chapter 2, AHP is based on a hierarchical framework constructed through mathematical pairwise comparison and can be used for organising and making complex decisions in economic models. AHP is among the most preferred and used approach in literature to establish optimal sites for wind and solar PV energy plants installation. AHP is the mostly widely used MCDM technique that is implemented within GIS, which defines weights for criteria and can deal with inconsistent judgments.

With a high degree of reliability and flexibility, AHP may be the effective approach in working with intricate decision-making challenges and making accurate predictions of priorities (Colak, et al., 2020; Dawod & Mosaad, 2016; Asakereh, et al., 2017; Hassan & Anjali, 2017; Sadeghi & Karimi, 2017). AHP is a procedure in which each criterion is assigned a level based on a pair-wise comparison in the matrix to determine the relative weights of each. The matrix presents the judgment matrix by comparing the significance of each relative element and by calculating the weight of each index in relation to the general objectives, thus simplifying the decision-making process. The pairwise comparison matrix is generated based on relevant literature, using a numerical scale of degrees, the process judgment of pairwise comparisons is made by using the sequence values of 1 (Equal importance) to 9 (Extreme importance). In prior studies, the AHP approach and GIS tools were utilised to address site selection challenges. AHP technique is applied in the current research to analyse the selection of solar and wind farm sites by generating and evaluating useful alternative solutions. It reduces any possible error that may occur during multi-criteria evaluation and can deal with inconsistent judgments. Based on Saaty (1980), the fundamental principles of AHP can be summarised in the phases as shown in Figure 21.

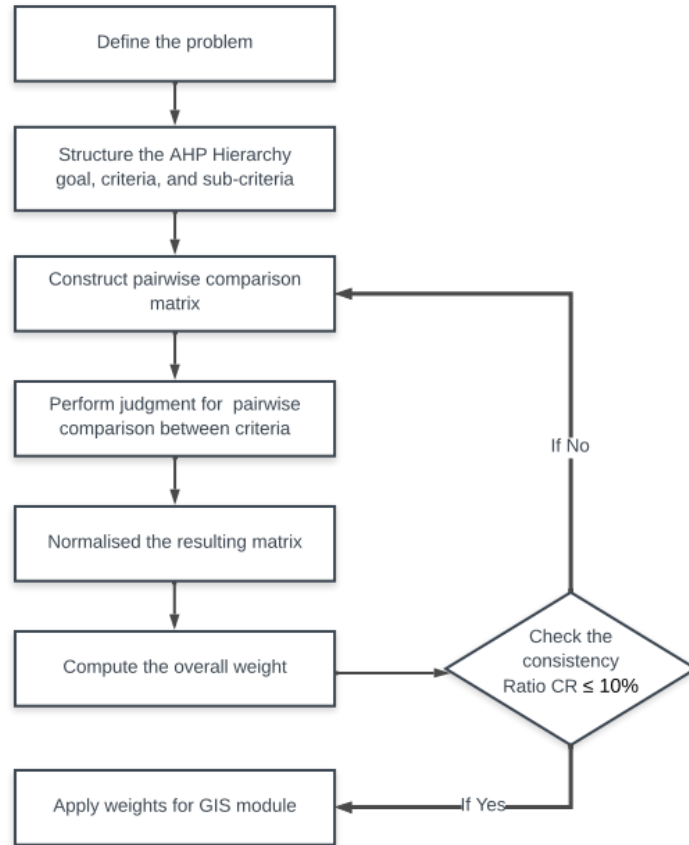


Figure 21: The AHP method's steps

The following are the important steps in identifying the optimal sites for solar PV plant deployment using AHP technique: In the AHP process, the first stage is to structure the decision problem as a hierarchy by identifying the main aim (selecting the ideal locations for PV energy plants), and criteria. In Figure 14, the decision problem was structured into a hierarchical model, with the goal representing the top level, which is to choose the optimal sites for installing PV utility-scale plants. In the second level, the decision criteria are listed. As indicated in Table 4, the pairwise comparisons of the criteria are determined on a numerical scale from one to nine depending on the importance of each criterion, as proposed by Saaty (1980).

Table 4: Pairwise comparisons on a relative scale

Importance scale of criteria $j$ to criteria $k$	Equivalent linguistic Judgment
1	The importance of criteria $j$ and $k$ is equal
3	The importance of criteria $j$ is slightly higher than that of criteria $k$
5	The importance of criteria $j$ is moderately more than of criteria $k$
7	The importance of criteria $j$ is stronger than of criteria $k$
9	The importance of criteria $j$ is extremely more than of criteria $k$
2,4,6,8	Intermediate values

The second important step is to generate the pairwise comparison matrix. The pairwise comparison matrix (M) is the square matrix (n x n), where n is the number of criteria. Each cell  $a_{jk}$  of matrix (M) represents the comparison values between the  $j^{\text{th}}$  (row) criteria relative to the  $k^{\text{th}}$  (column) criterion. If the cell  $a_{jk} > 1$ , the  $j^{\text{th}}$  criteria is more important than the  $k^{\text{th}}$  criteria and vice versa.

The next step is to derive the normalised pairwise comparison matrix after constructing the preceding pairwise comparison matrices to get the priority (weights) of each criterion. The sum of each column in a normalised pairwise comparison matrix (M) must equal to 1. This may be derived by calculating  $s_{jk}$  for each cell in the matrix (M) using equation 1.

$$s_{jk} = \frac{a_{jk}}{\sum_{j=1}^n a_{jk}} \quad 1$$

To determine the overall weight vector ( $W_j$ ) equation 2 was used. The criteria weight vector  $W_j$  is calculated by averaging across rows to obtain the relative weights. Where: m is the number of values in the row.

$$W_j = \frac{\sum_{j=1}^n s_{jk}}{m} \quad 2$$

Finally, a consistency ratio (CR) needs to be computed for the matrix to assess the consistency of the experts' judgement. The degree of consistency in the analysis is considered acceptable if the  $CR \leq 10\%$ . If  $CR > 10\%$ , the judgments must be revised to identify and correct the source of the inconsistency; therefore, to provide an acceptable level of consistency, CR value should be always  $\leq 10\%$  according to Saaty (1980). CR is given by equation 3 below.

$$CR = \frac{CI}{RI} \quad 3$$

With:  $CI = (\lambda_{\max} - n)/(n - 1)$  where  $\lambda_{\max}$  is the maximum Eigen value of the comparison matrix and  $n$  is the size of the matrix. RI represents values of random consistency index depending on the number of criteria  $n$  considered in ( $M$ ). The RI value, according to Saaty (1980), is shown in Table 5.

Table 5: Random consistency index values (RI)

$n$	1	2	3	4	5	6	7	8
$RI$	0	0	0.58	0.90	1.12	1.24	1.32	1.41

## 4.11 Chapter Summary

The methodology applied in the present study is described in detail in this chapter. Section 4.1 provided an overview of the entire methodology, 4.2 shows the study area, section 4.3 presents the identified criteria, the list of the hardware and software used in the processing of the dataset input was presented in Section 4.4, materials and datasets used were discussed in Section 4.5, proximity analysis for RESs installation were presented in Section 4.6 while section 4.7, 4.8, 4.9, and 4.10 examined the methods used in each phase. Therefore, this allows the data to be analysed in the next Chapter by applying the methodologies adopted in this chapter.

## CHAPTER 5: RESULTS AND DISCUSSION

As described in the preceding chapter, data manipulation and pre-processing lay the groundwork for the actual analysis needed to accomplish the study's objectives. The data required for the present study was identified, assembled, and prepared as discussed in Chapter 4. It is evident from literature review that putting together data obtained from various sources to identify suitable areas for renewable energy plants is a lengthy process. Based on the applied methodology, the study's primary finding is a standard map for optimal locations for wind turbine and solar PV energy plants. This chapter provides a comprehensive and in-depth analysis of the data in the present research, based on the approach that has been explained in Chapter 4. Potential locations for solar PV energy plants as well as wind energy are identified in Section 5.1 and 5.2, respectively. In this Chapter the results presented are discussed considering the research's objectives.

### 5.1 Solar PV Power Plant

The following table presents threshold requirements for factors influencing the suitability of an area for solar energy plants development. Please keep in mind that the solar irradiation data and the air temperature data within the study areas do not have values starting from 0. The rest of the section presents the analysis and results for site selections pertaining to these factors and constraints.

Table 6: Factors involved in installing solar PV systems

Factors	Criteria	Classes	Suitability	References
Topographical	Slope (°)	0 – 1.73 1.73 – 2.8 2.8 – 5.7 >5.7	Highly suitable Moderately Suitable Barely Suitable Unsuitable	(Kocabaldır & Yücel, 2020)
	Aspect (°)	0 - 22.5 and 337.5 - 360 22.5 - 67.5 and 292.5 - 337.5 67.5 - 90 and 270 - 292.5 90 – 270	Highly Suitable Moderately Suitable Barely Suitable Unsuitable	(Sendy, 2020; Doorga, et al., 2019; Wiguna, et al., 2016)
Climatic	Solar Irradiation (kWh/m <sup>2</sup> /d)	1 953.36 – 2 153.5 2 153.5 – 2 263 2 263 – 2 465.44	Barely Suitable Moderately Suitable Highly Suitable	(Ali, et al., 2019; Anwarzai & Nagaska, 2017)
	Temperature (°C)	14.7 – 17 17 - 20 20 - 24.1	Highly Suitable Moderately Suitable Barely Suitable	(Habib, et al., 2020; Kereush & Perovych, 2017; Popovici, et al., 2015;

				Ramachandra, et al., 2011; Amelia, et al., 2016)
Economic	Distance from Roads (m)	0 – 100 100 – 5000 5000 - 20000 >20000	Barely Suitable Highly Suitable Moderately Suitable Unsuitable	(Noorallahi , et al., 2016; Shorabeh, et al., 2019; Moradi, et al., 2020; Mierswiak & Calka, 2017; Sadeghi & Karimi, 2017; Uyan, 2013)
	Distance from Power lines (m)	0 – 5000 5000 - 10000 10000 - 20000 >20000	Highly Suitable Moderately Suitable Barely Suitable Unsuitable	(Colak, et al., 2020; Dawod & Mosaad, 2016)

### 5.1.1 Digital Elevation Model

The Shuttle Radar Topography Mission (SRTM) delivered a free DEM with spatial resolution level of 3 arc seconds at near global coverage (USGS , 2016). SRTM DEM dataset was downloaded for free from USGS Earth Explorer via National Map Seamless Data distribution provided by United States Geological Survey (USGS). Under the data sets tab, Digital Elevation > SRTM > SRTM 1-ArcSecond Global was selected. The Mosaic to New Raster tool in ArcMap was used to mosaic multiple DEM tiles into a new single DEM dataset. The DEM was then clipped to CENORED area using Extract by mask tool from ArcMap to extract the cells of raster that correspond to the areas defined by a mask. As shown in Figure 22, there were few data voids in the SRTM DEM dataset circled in blue colour that need to be filled before data processing. Void occurs when there are no points collected within the area represented by a pixel in the resultant raster and often caused by water bodies, class type selection or exclusion. Elevation void fill function in ArcMap was utilised to generate values where holes or no-data exist in the DEM (Ling, et al., 2007; ESRI, 2016). The DEM was projected from WGS84 coordinate system to a suitable projection LO 17 using Raster projection tool from ArcMap. The DEM was applied to create aspect and slope raster.

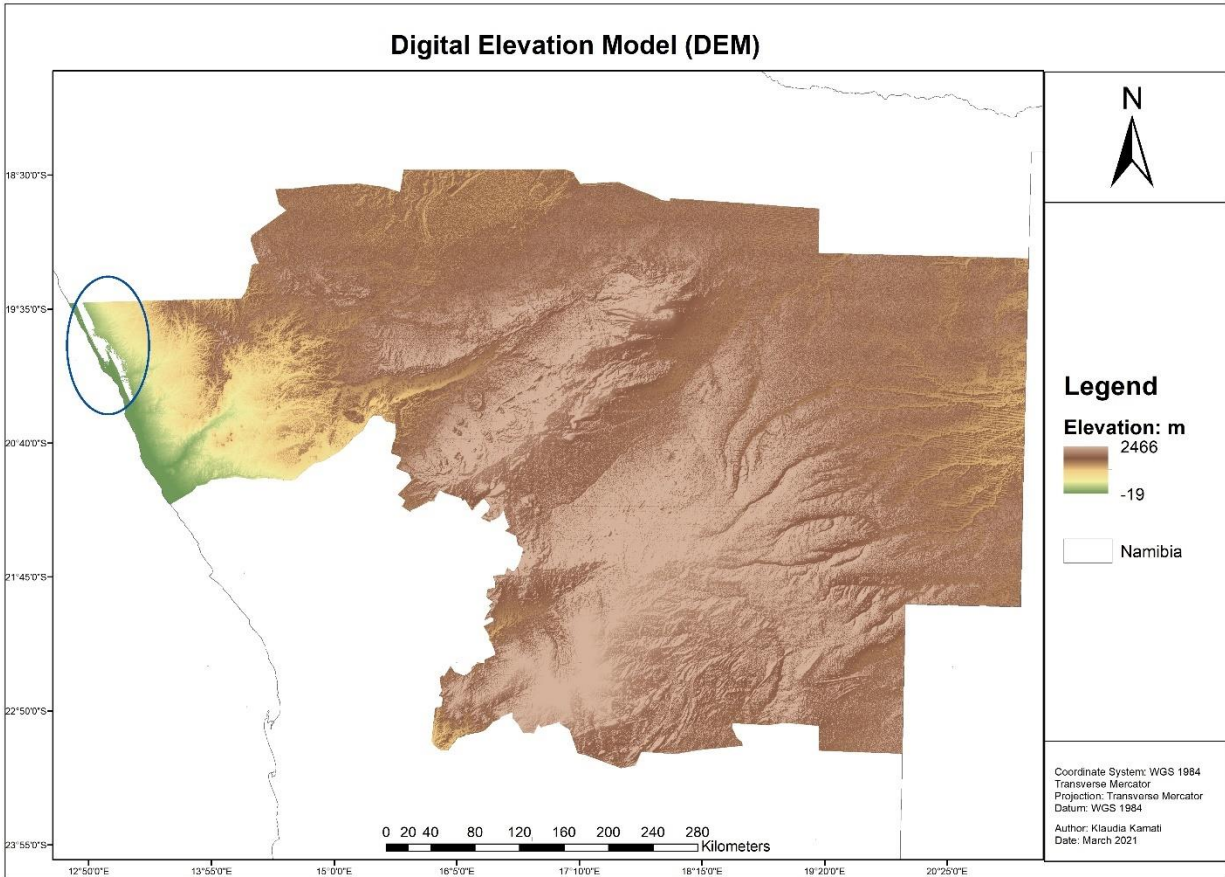


Figure 22: DEM of CENORED supply area

### 5.1.2 Slope of Terrain

The slope is a critical criterion for construction as it is essential in evaluating the economic feasibility of the project which is largely influenced by the accessibility of the construction site and ease of transportation during construction. The excavation or filling of the area becomes time consuming and costs more when the land does not meet the slope requirement (Colak, et al., 2020; Uyan, 2013; Hassan & Anjali, 2017; Uyan, 2017). Areas with mild slopes or flat areas will aid in avoiding the high construction costs associated with high slopes areas. Areas with steeper slopes are unsuitable for RESs energy plant development projects because of low economic viability. The slope raster shown in Figure 16 below was generated from the clipped DEM. A slope raster in degrees was created using ArcMap's slope tool, by selecting the degree measurement for the output, whereby a Z-factor default value of 1 was used. The slope of CENORED ranges from 0 to 53.4633° which can be seen in Figure 23. The DEM appears to have no artifacts, but the slope generated appears to have a few artefacts or strips circled in blue colour. As part of the projecting of the DEM, different resampling methods were utilised including bilinear and cubic convolution methods (ESRI, 2017) to reduce or eliminate the artifacts, despite the efforts the result remained unchanged. It is

possible that there is an inherent pattern to the DEM data introduced during creation *ibid*. The generated slope was used in both the solar PV and wind power plant site selection analyses.

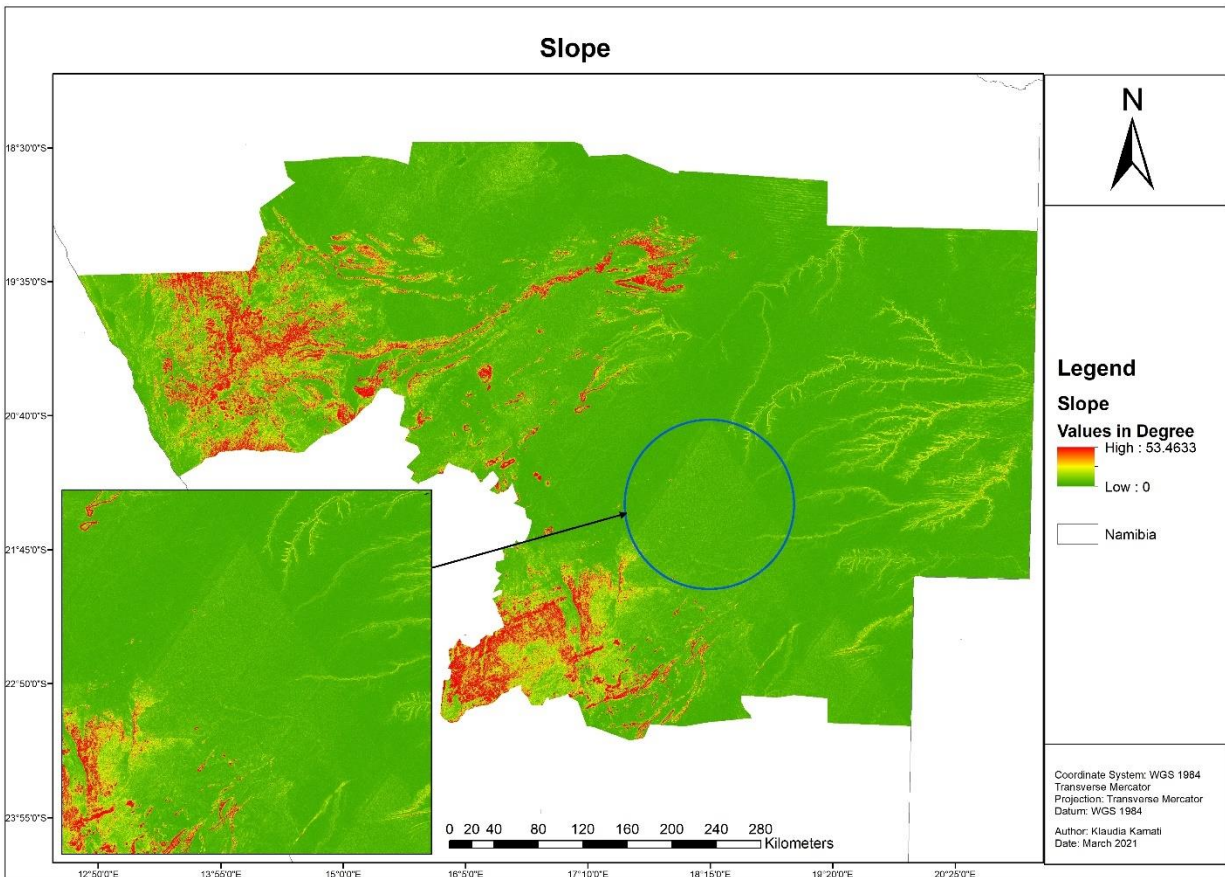


Figure 23: Slope

### Reclassified Slope

Table 7: Reclassified slope

Categories (° of slope)	Score	Suitability Ranking
0 – 1.7	4	Highly Suitable
1.7 – 2.8	3	Moderately Suitable
2.8 – 5.7	2	Barely Suitable
>5.7	1	Unsuitable

The reclassify tool has been used to classify the slope of CENORED supply area into four classes shown in Table 7. In this case when a range of 0 to 1.7 equals 4 and a range of 1.7 to 2.8 equals 3, the value 1.7 is assigned to the value 4 and value greater than 1.7 is assigned to the value 3 as output raster values. Figure 24 shows the reclassified slope which was obtained by applying the approach used in previous studies.

Most studies presented slope categories (thresholds) in percentage. According to Uyan (2013) and Uyan (2017), it has been found that slopes below 3% are the highly appropriate and ideal for locating solar PV sites. As the slope value rises, the investment's cost gradually increases (Kocabaldir & Yucel, 2020). This study used the same slope classes as in the above-mentioned studies, however slope thresholds were converted to degree of slope, because slope is commonly measured in units of degrees (Esri, 2016) . The output slope raster was also generated as degrees of slope. The conversion from percentage of slope to degree of is slope done using the following formula:

$$\text{Degree of slope} = \tan^{-1} \left( \frac{\text{rise}}{\text{run}} \right), \text{ where } \left( \frac{\text{rise}}{\text{run}} \right) = \frac{\text{Percent of slope}}{100} . \quad 4$$

Areas with a slope below 1.7° were investigated for the best solar PV energy plant site selection. Regions with land incline higher than >5.7° were assessed as unacceptable in the study. The steepest slopes are indicated in grey colour on the output raster slope and mostly found on the west and south-southwest of the study area.

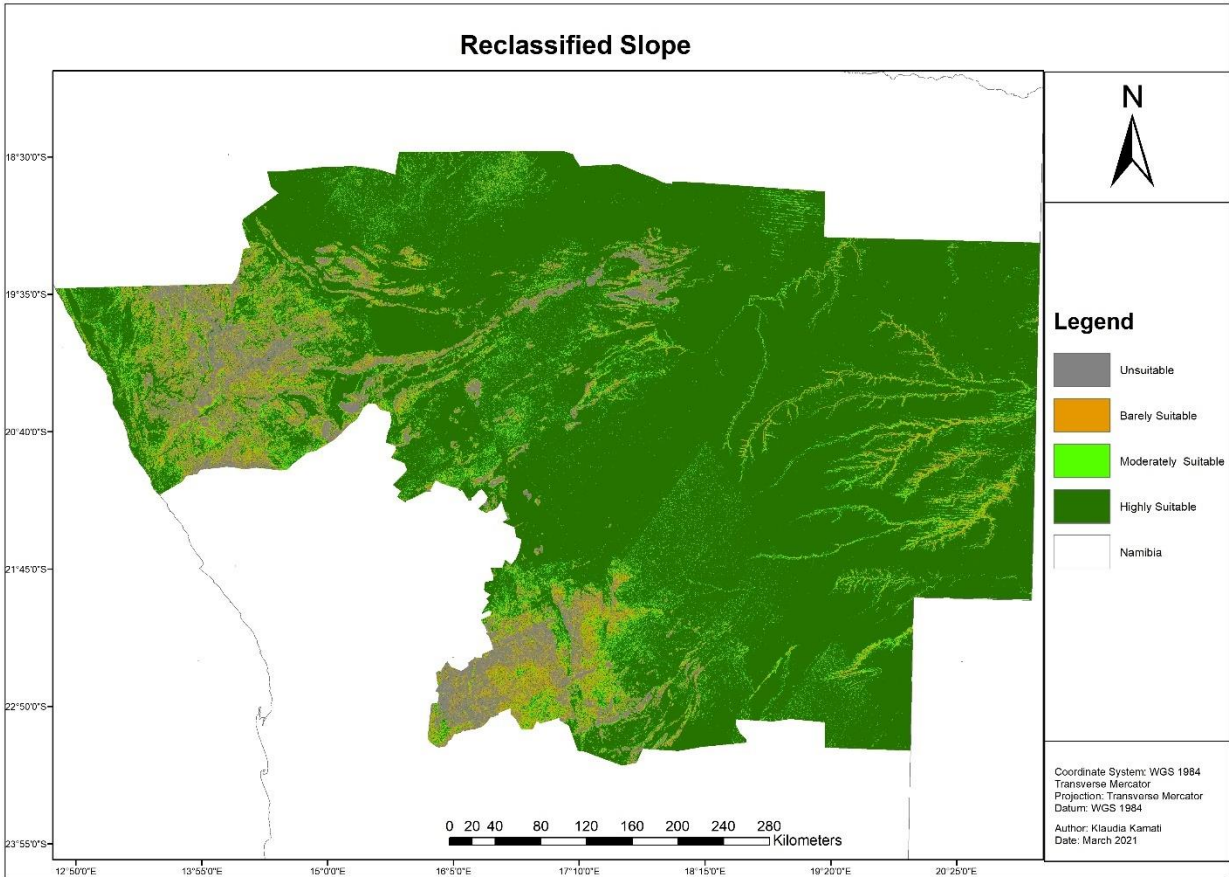


Figure 24: Reclassified slope

### 5.1.3 Aspect

An aspect determines slope orientation, which is measured in degrees ( $0^{\circ}$  to  $359.9^{\circ}$ ) clockwise from north. Aspect is crucial since it determines a specific area's solar potential. Aspect determines how solar-efficient an area is due to its ability to reflect sunlight. It has been observed that in the southern hemisphere, the slopes facing north receive the most solar radiation, whereas slopes facing south receive the least solar radiation (Khanna, 2021; Doorga, et al., 2019; Wiguna, et al., 2016). Therefore, because Namibia is geographically located in the southern hemisphere, surfaces facing the geographic north were prioritised. Throughout the year, these surfaces are much more exposed to the sun's irradiation than those facing south. The direction (N, NW, NE, E, S, SE, W, SW) and flat areas with the most solar exposure were given the highest weighting as suggested by Doorga, Rughooputh, and Boojhawon (2018). The aspect raster was calculated from the DEM using aspect tool in ArcMap shown in Figure 25.

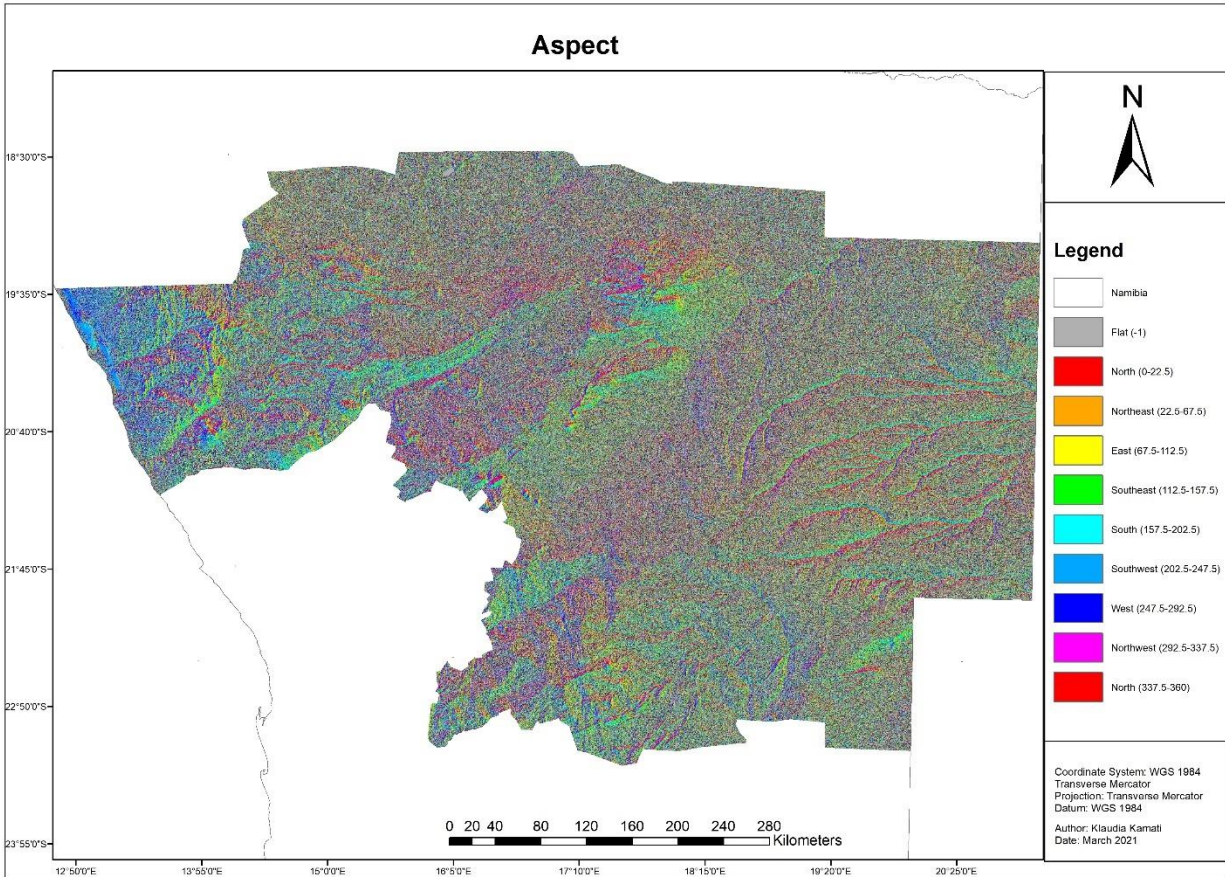


Figure 25: Aspect

### Reclassified Aspect

A value between -1 and 360 is assigned to each cell in the grid in the CENORED's aspect raster. A flat surface has an aspect value of -1 and therefore is defined as a high-suitability area. The aspect raster layer was reclassified into four categories based on their suitability ranking as illustrated in Figure 26. Table 8 depicts the reclassified values along with the suitability ranking. For the present study, a north-facing slope was given a score of 4 (highly suitable) because it is an ideal orientation for Solar PV sites, as it receives the most solar radiation. A good example is displayed on the inset map in Figure 27, which shows the high eligible areas in dark green colour. Therefore, these sites will have a higher power output, whereas south-facing slope was given a score of 1 (unsuitable). Figure 27 shows the Aspect map of CENORED after performing the reclassification based on Table 8 below.

Table 8: Reclassified Aspect

Direction and Degrees	Scores	Suitability Ranking
East South-East (90-112.5) South (157.5 - 202.5) Southeast (112.5 - 157.5) Southwest (202.5 - 247.5) West-Southwest (247.5 - 270)	1	Unsuitable
West-Northwest (270 - 292.5) Northwest (292.5 - 337.5) East North-East (67.5 – 90)	2	Barely Suitable
Northwest (292.5 - 337.5) Northeast 9 (22.5 – 67.5)	3	Moderately Suitable
Flat (-1) North (337.5 - 0; 0 – 22.5)	4	Highly Suitable

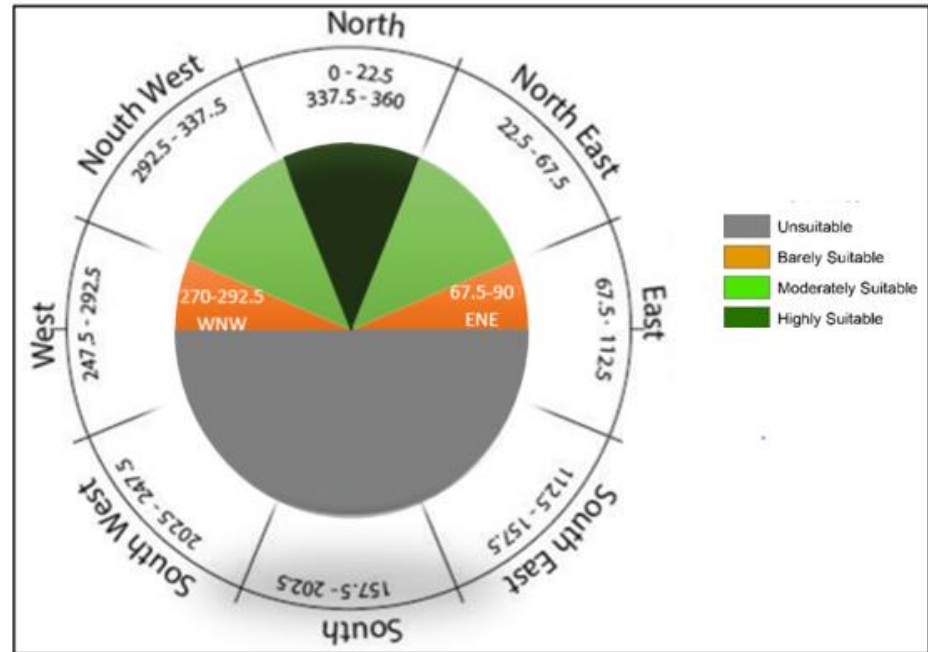


Figure 26: Suitable directions for PV power plant

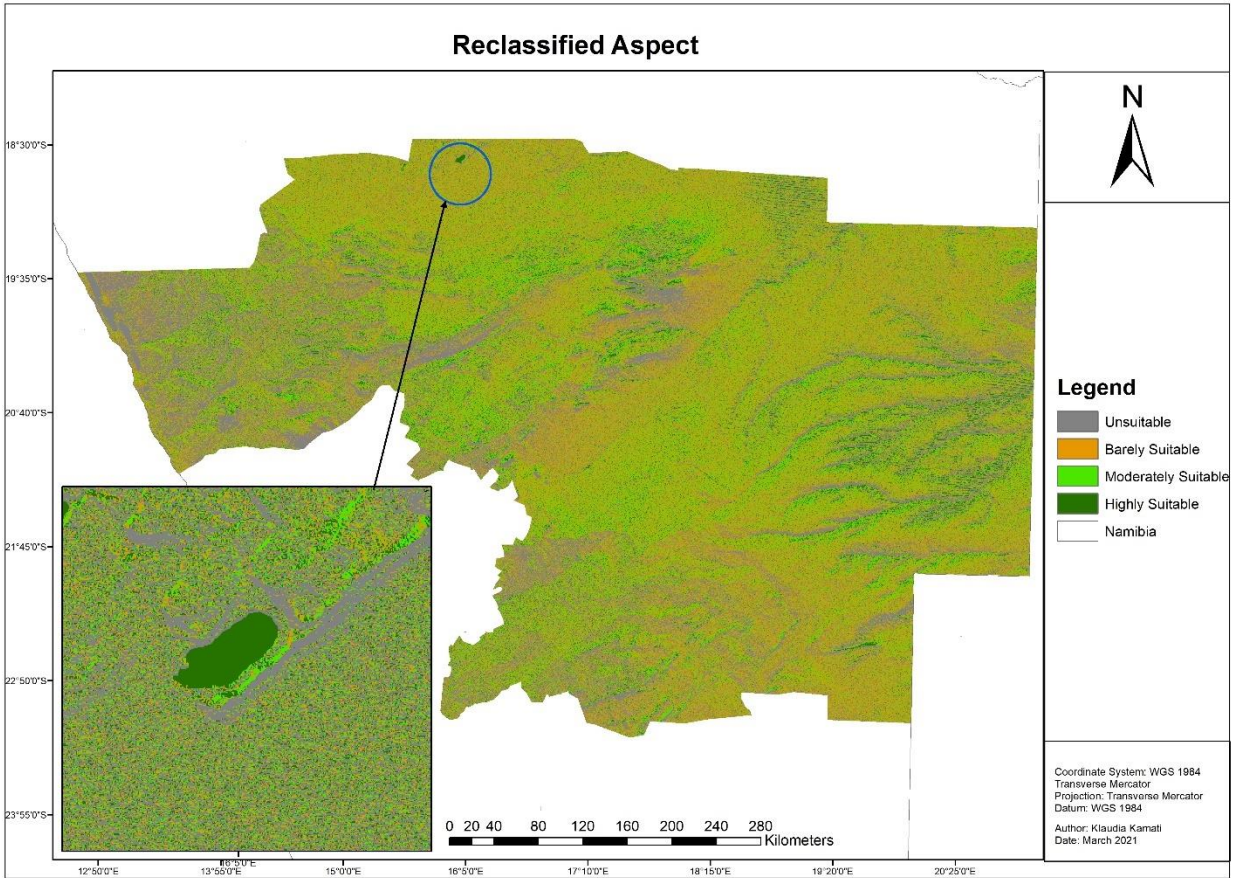


Figure 27: Reclassified Aspect

#### 5.1.4 Average Solar Irradiation

Solar PV panels require at least 1300 kWh/m<sup>2</sup>/y global solar irradiation (GHI) which is equivalent to 3.5 kWh/m<sup>2</sup>/ day for cost-effective operation (Kiatreungwattana & Michaud, 2013). The amount of solar radiation that a site receives heavily influences its suitability for solar PV installation, therefore, solar irradiance and energy production are positively correlated (Hassan & Anjali, 2017; Koc, et al., 2019; Turk, et al., 2021; Akkas, et al., 2017). For investors, it is preferable to build a solar PV energy plant in the area with a high potential for solar irradiance (Koc, et al., 2019). Al Garni and Awasthi (2017) also stated that there is some potential for utility-sized solar panels to be installed in location where GHI is high during the year. The inconsistency and variability of GHI, on the other hand, is one of the challenges in installing solar PV energy plants. GHI data was obtained at Global Solar Atlas on-line resource at 9.0 arc-sec (nominally 250 m) spatial resolution, which represents yearly time average for the period of 1994-2018 in kWh/m<sup>2</sup> in raster Geo-TIFF format as shown in Figure 28.

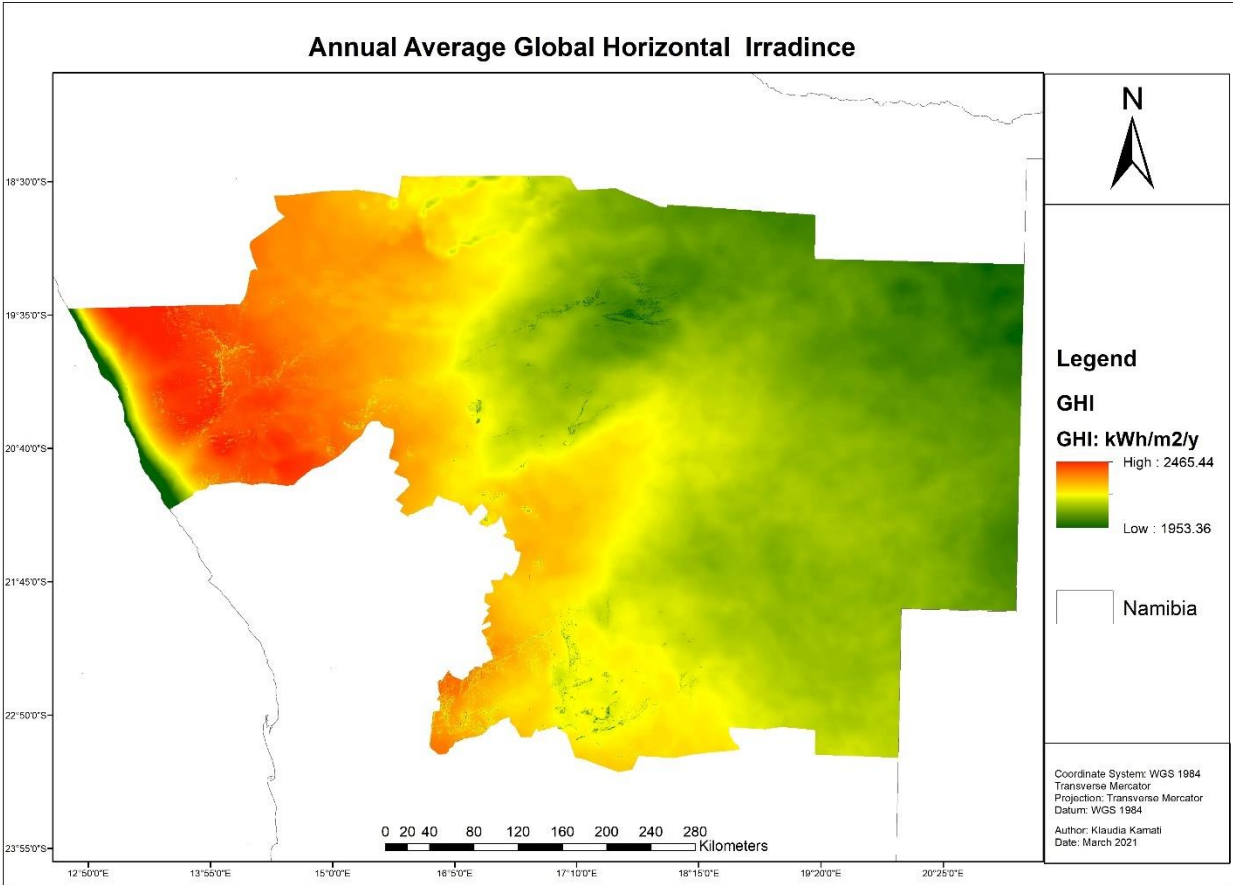


Figure 28: Average global horizontal irradiance

### Reclassified GHI

Reclassify tool has been carried out to classify GHI into three classes for their suitability. Regions with GHI below 1300 kWh / m<sup>2</sup>/y have been considered as unsuitable from this study in line with previous study findings (Ali, et al., 2019; Anwarzai & Nagaska, 2017). Figure 29 shows a minimum of 1953.36 kWh / m<sup>2</sup>/y and a maximum of 2465.44 kWh / m<sup>2</sup>/y GHI, hence in terms of the Global Horizontal irradiance solar requirement all areas are considered as suitable. The reclassified values are shown in the Table below, with their suitability ranking.

Table 9: Reclassified average GHI

Categories (kWh / m <sup>2</sup> /y)	Scores	Suitability Ranking
1 953.36 – 2 153.5	2	Barely Suitable
2 153.5 – 2 263	3	Moderately Suitable
2 263 – 2 465.44	4	Highly Suitable

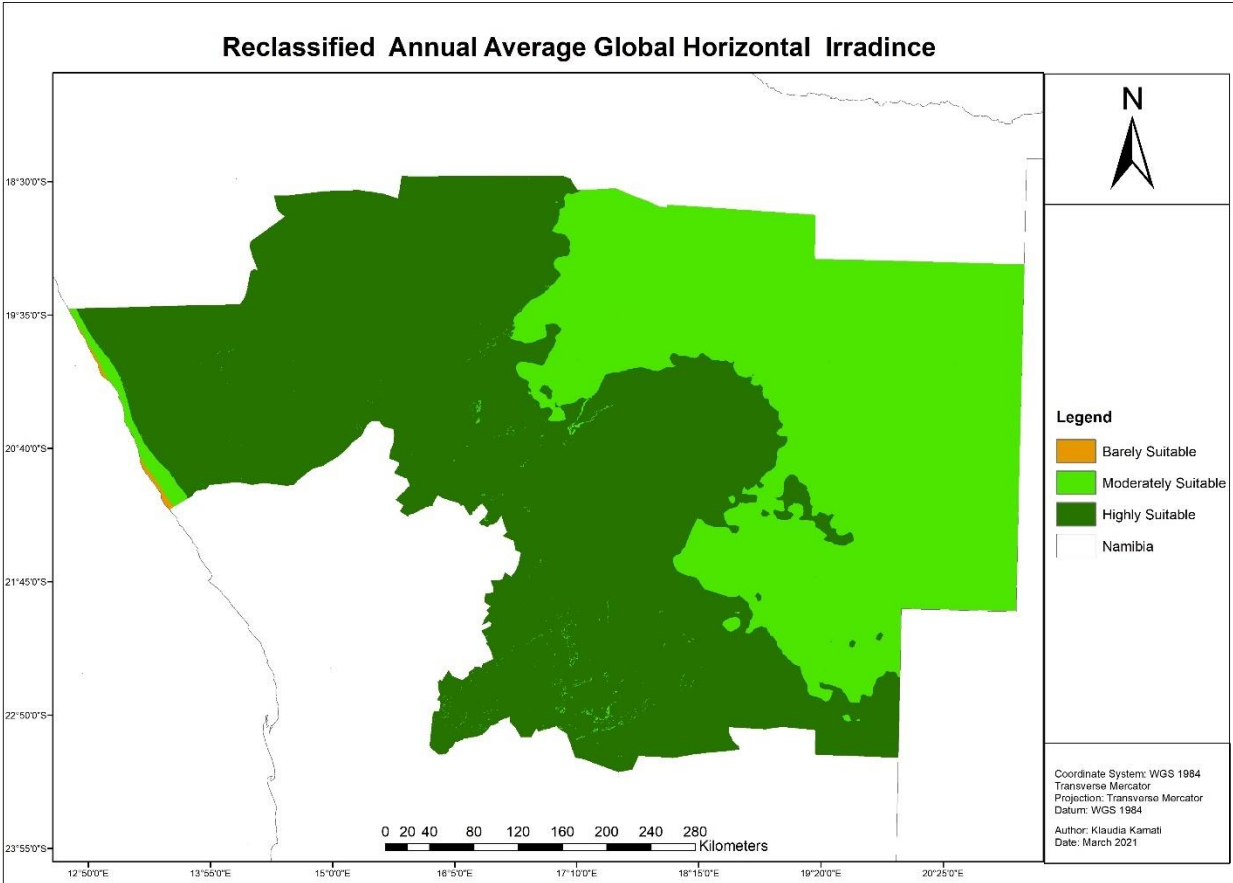


Figure 29: Reclassified Global Horizontal Irradiance

### 5.1.5 Average Air Temperature

Since the efficiency of solar PV systems are influenced by air temperature, it is also included in the list of evaluation criteria. Annual average air temperature dataset at 2 m height was obtained from Global Solar Atlas on-line resource at 30 arc-sec spatial resolution, which represents yearly time average for the period of 1994-2018, in degree Celsius and raster Geo-TIFF format. Raster dataset was clipped to the research area. As illustrated in Figure 30, the greatest yearly average air temperature is 24.1°C.

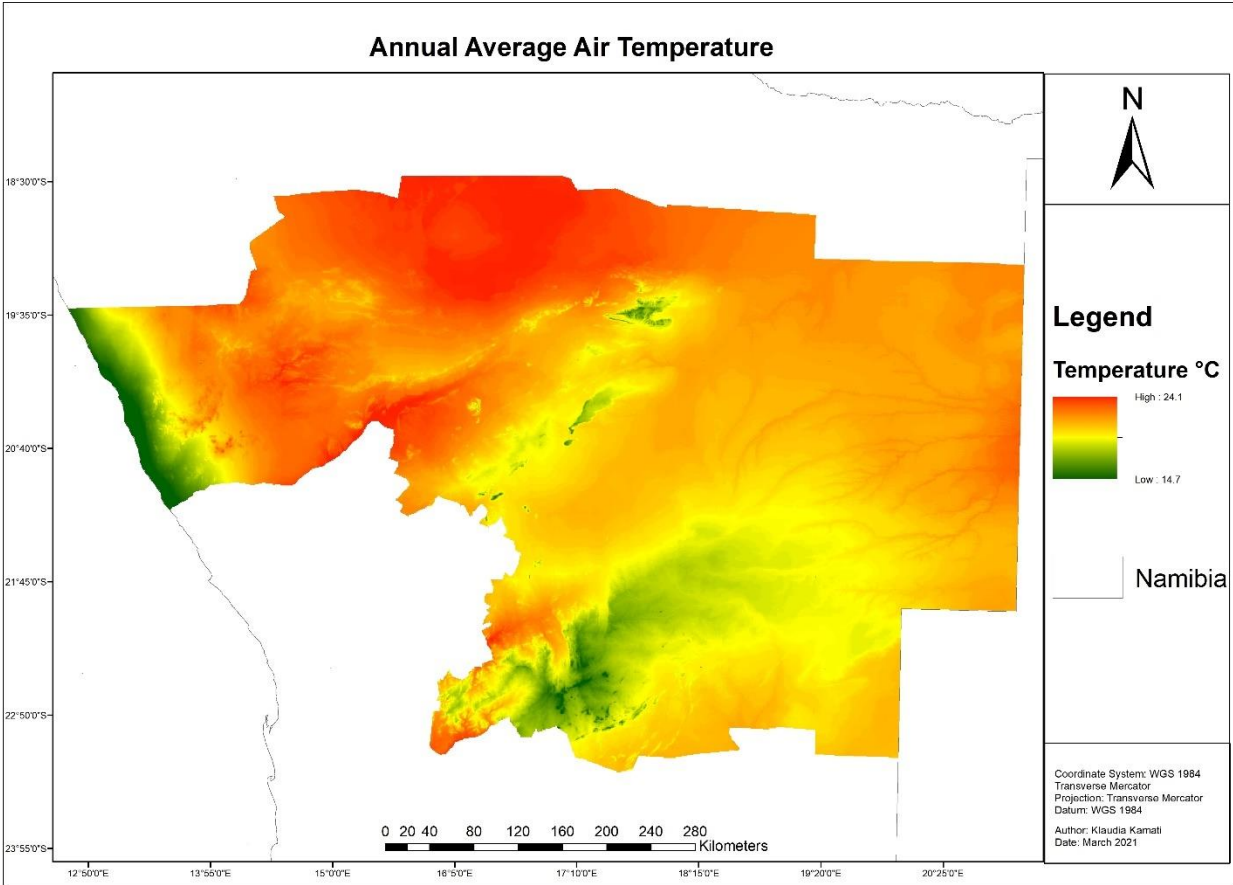


Figure 30: Yearly average of air temperature

### Reclassified Annual Average Temperature

Reclassify tool in ArcMap was then used to classify the temperature using Table 10, in alignment with the literature. The optimal air temperature of solar PV cell ranges between 15°C – 40°C. When the cell's temperature is 25 °C, the PV system produces at maximum efficiency (Popovici, et al., 2015; Habib, et al., 2020; Ramachandra, et al., 2011; Amelia, et al., 2016). However solar PV cells produce more power during the cold temperature on sunny days and can outperform values obtained during the standard testing at 25°C (Valda Energy, 2020). Therefore, in this study areas less than 18 °C were considered as highly suitable as shown in Figure 31: Reclassified annual average air temperature. This is because the panels work by utilising the sunlight, not the heat of the sun.

Table 10: Reclassified average air temperature

Classes	Scores	Suitability Ranking
14.7 – 20	4	Highly Suitable
20 – 22	3	Moderately Suitable

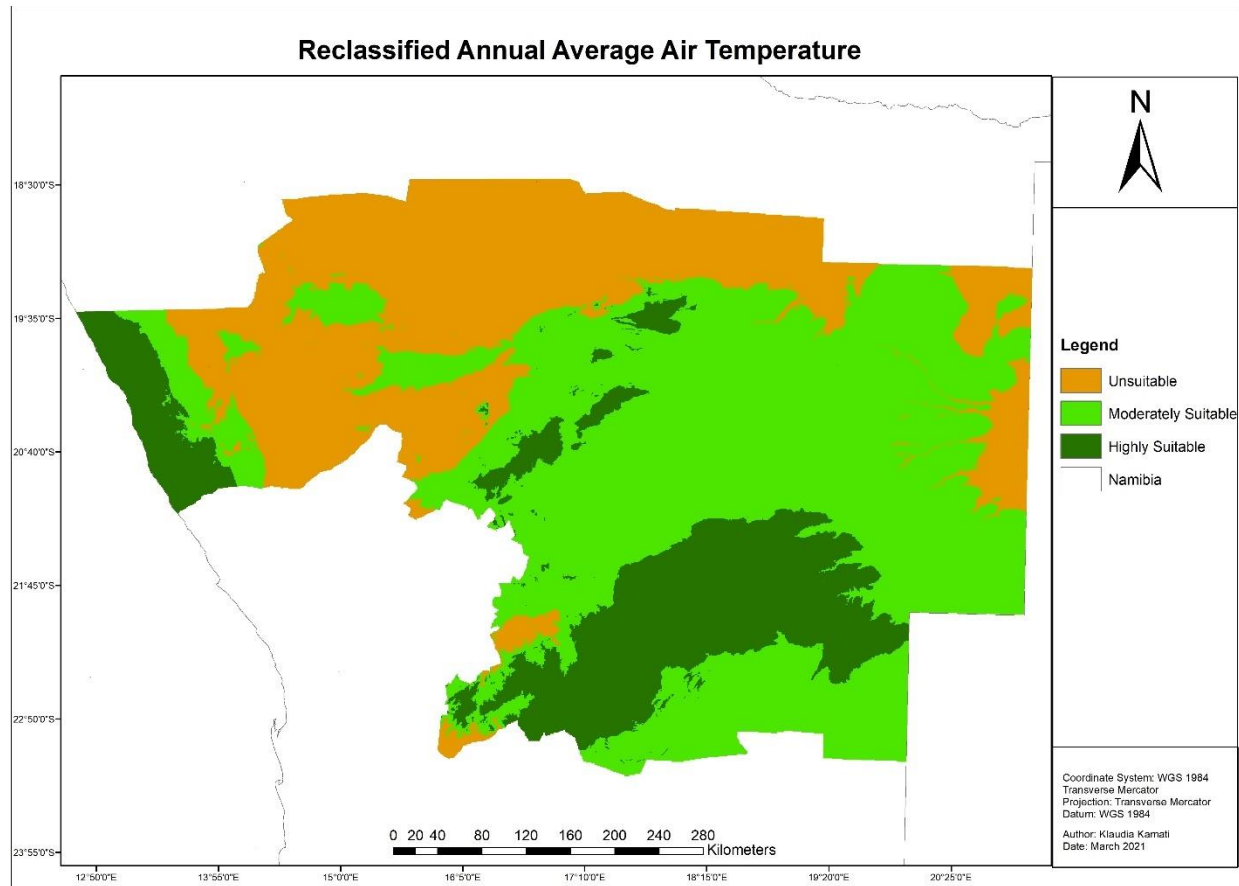


Figure 31: Reclassified annual average air temperature

### 5.1.6 Proximity to Roads

Roads are yet another important criterion to be considered while selecting potential locations for construction. The proximity of Solar PV energy facilities to transport routes is regarded as an economic aspect (Shorabeh, et al., 2019; Moradi, et al., 2020; Sadeghi & Karimi, 2017). The distance from the possible solar PV and wind power plant sites to roads should be minimised to lower the costs. Roads are needed for access to the site, transportation of material and regular monitoring and maintenance of the RESs energy plants. In most of the studies, the areas nearer to roads are more appropriate for solar and wind power plants installation (Shorabeh, et al., 2019) because a shorter distance reduces the additional expenses associated with the construction of new transportation infrastructure. However, it has been suggested that the site should be outside of the buffer zone from the road network. According to Uyan (2013) and Sadeghi and Karimi (2017), solar panels are best located more than 100 meters from roadways to minimise the amount of non-natural dust that may be exposed to the PV modules, to allow for possible future road

expansion through the addition of carriageways and lanes on the road. ArcMap’s buffer tool was used to generate a buffer zone of 0 to 100m from the roads. In present study this buffer zone has been designated as unsuitable area in comparison with similar studies (Uyan, 2013; Sadeghi & Karimi, 2017). ArcMap's Euclidean distance tool was then used to compute the distance between each raster cell and the nearest roads. As a result, the Euclidean distance road network raster was categorised into four classes based on suitability ranking shown on Table 11, in which highly suitable site is located 100 to 5 000 m away from the road. Areas more than 20 000m away from the roads were considered as barely suitable as shown in Figure 32: Classified roads.

Table 11: Reclassification distance of roads values

Classes	Scores	Suitability Ranking
0 – 100	1	Unsuitable
100 – 5 000	4	Highly Suitable
5 000-20 000	3	Moderately Suitable
>20 000	2	Barely Suitable

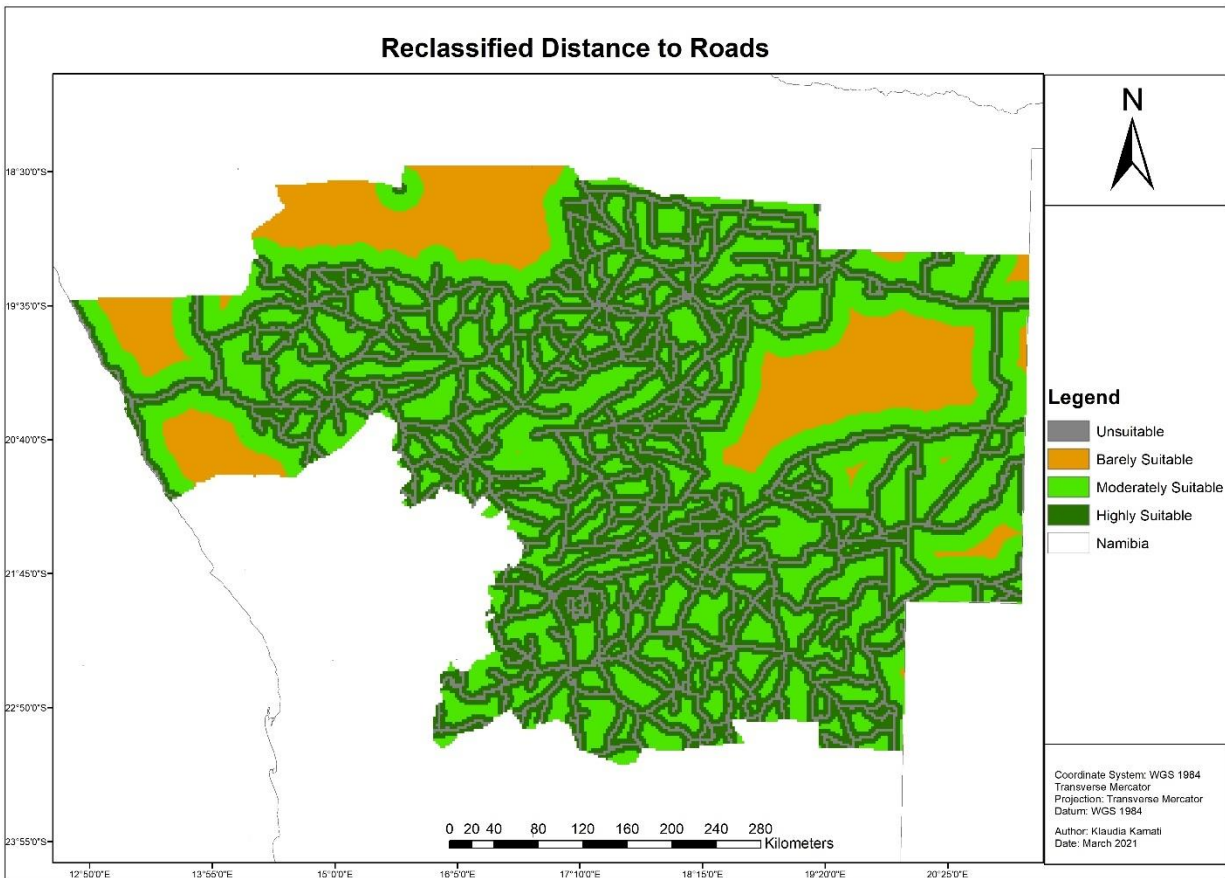


Figure 32: Classified roads

### 5.1.7 Proximity to Power lines

Transmission lines transmit energy generated by power plants to power stations, and the distribution is carried out from there to the end users. The distance between the proposed sites and transmission grid depends on the area's topography and distribution network. The distance to the nearby electrical network grid is another important factor (Rediske, et al., 2018; Zoghi, et al., 2017; Sadeghi & Karimi, 2017; Colak, et al., 2020; Hassan & Anjali, 2017; Sadeghi & Karimi, 2017). The solar plant must be at least a few meters away from the edge of the power line servitude clearance, which ranges from 22 and 80 meters depending on the voltage level of the power line. The safe distance between the electrical line and any other system should also be observed for safety operating purposes (Republic of Namibia, 2011). Therefore, in present study, areas less than 200 m from the power lines have been considered as unsuitable considering the electricity regulations. Areas above 20 km away from electrical lines have been observed as barely suitable for development of solar PV as shown in Figure 33. These would help to avoid voltage dropping, decrease energy loss caused by the long distance of transmission energy and less infrastructure costs such as construction of a new power line. The spatial data for power lines were obtained from CENORED database. Euclidean distance tool in ArcMap was used and then reclassified the distance into four classes according to their suitability ranking as shown in Table 12 (Colak, et al., 2020; Dawod & Mosaad, 2016).

Table 12: Reclassification distance of Power lines values:

Classes	Scores	Suitability Ranking
0 – 200	4	Unsuitable
200 – 10 000	3	Highly Suitable
10 000 – 20 000	2	Moderately Suitable
>20 000	1	Barely Suitable

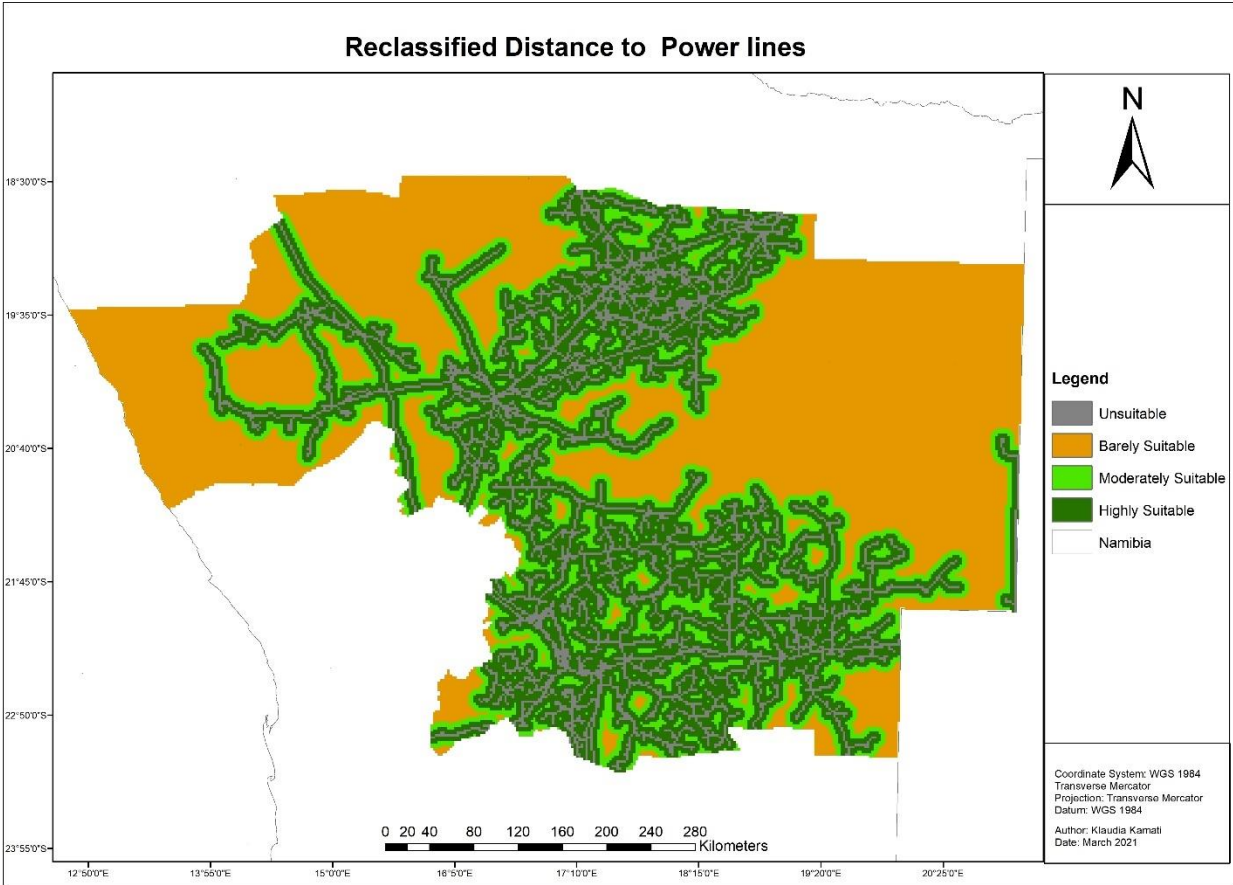


Figure 33: Power lines

### 5.1.8 Analytical Hierarchy Process

In this study, average solar irradiation (C1), and annual average air temperature (C2), are considered as the most important criteria, because these two criteria determine the output energy capacity of PV power plant shown in Figure 34 and Table 13. Secondly, the slope and land aspects criteria are listed in descending order of importance because they determine how much irradiance the solar panels received. Lastly, the distance to power lines, roads follow in importance, as they influence the construction transmission cost and infrastructure. The pairwise comparison matrix was generated based on the literature criteria comparison (Ayodele, et al., 2018; Moradi, et al., 2020; Xu, et al., 2020). In Table 13 a higher weight indicates that the criterion has a greater influence on the location of the solar PV power plant. In the present study, the degree of consistency is acceptable (0.0146856).

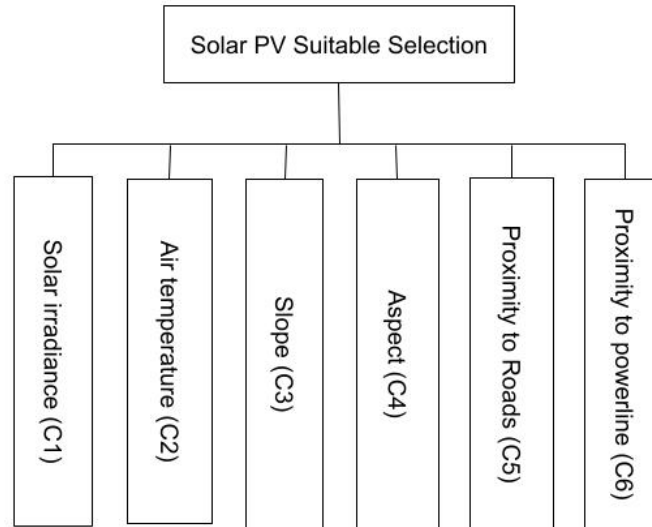


Figure 34: Decision criteria considered in PV site selection

Table 13: The adopted decision criteria are evaluated in a matrix.

Criteria	C1	C2	C3	C4	C5	C6	Weighted
C1	1	2	3	4	5	9	0.39212634
C2	½	1	2	2	4	5	0.22480719
C3	1/3	½	1	1	3	5	0.14288893
C4	¼	½	1	1	3	7	0.14899323
C5	1/5	½	1/3	1/3	1	1	0.05296965
C6	1/9	½	1/5	1/7	1	1	0.03821466
					$\lambda_{max}$		6.091785
					CI		0.018357
					CR		0.0146856

### 5.1.9 Weighted Overlay Tool

To combine raster layers in a single analysis, each cell for criterion was reclassified into a common preference scale from 1 to 4, where 4 is most favourable. Weighing scores for each criterion is derived from AHP, by directly comparing the importance of one criterion to another criterion. The AHP, on the other hand, is a useful tool for tackling complex issues with many objectives that may have interactions and correlations. As a result, combining the GIS and AHP approaches creates a framework for comprehensively exploring complex challenges while also providing fast feedback to decision-makers. Finally, to obtain the final map in Figure 36 the vectorisation tool was used to remove ‘salt and pepper’ pattern in Figure 35. The results are all valid but for practical reason it is not viable to consider small, isolated sites and larger more homogenous regions are preferred. Hence the small ‘salt and pepper’ areas are reduced. There is also the factor that the resolution of the input data does not support fine scale analysis. Hence the very small regions which may pass the criteria test perhaps have less confidence than the larger more homogeneous regions.

The goal is to reach a specified level of aggregation to identify the most viable regions for solar PV installation. Not so much that the details are lost, but not so little that the results are difficult to interpret.

Figure 36 depicts the spatial distribution of potential sites for solar energy plant installation within the CENORED supply area. Highly suitable areas are mostly found in the southwest and southern regions, with a few scattered spots in the north-west of the study area. The areas of moderate suitability are located in the north and southeast parts of the study area. Whereas unsuitable areas can be found all over the study area. Lastly, the restricted areas predominate the northwest and west regions of the study area, with some scattered in the middle section of the study area. The restricted areas represent constraint areas where this type of project cannot be established at all

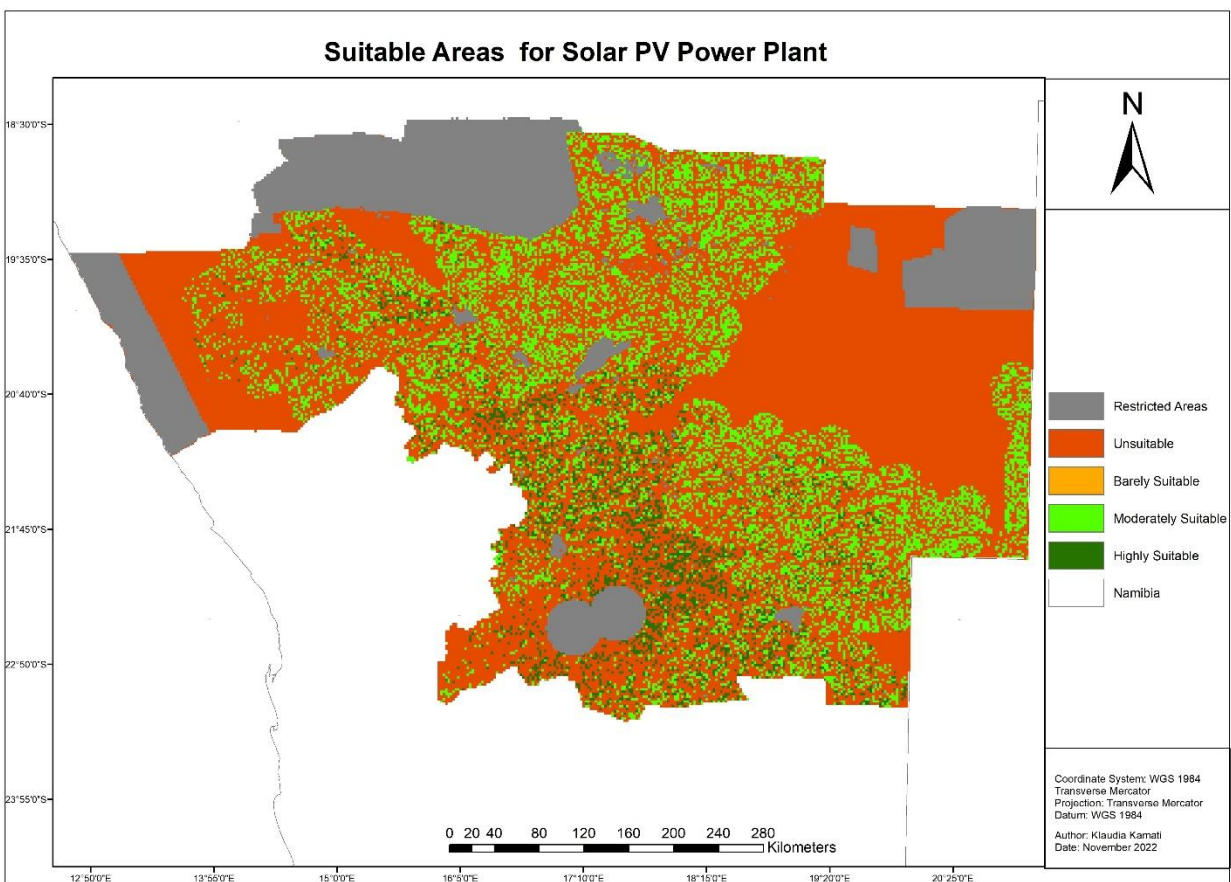


Figure 35: Suitable areas for solar PV energy plant before reducing salt and pepper

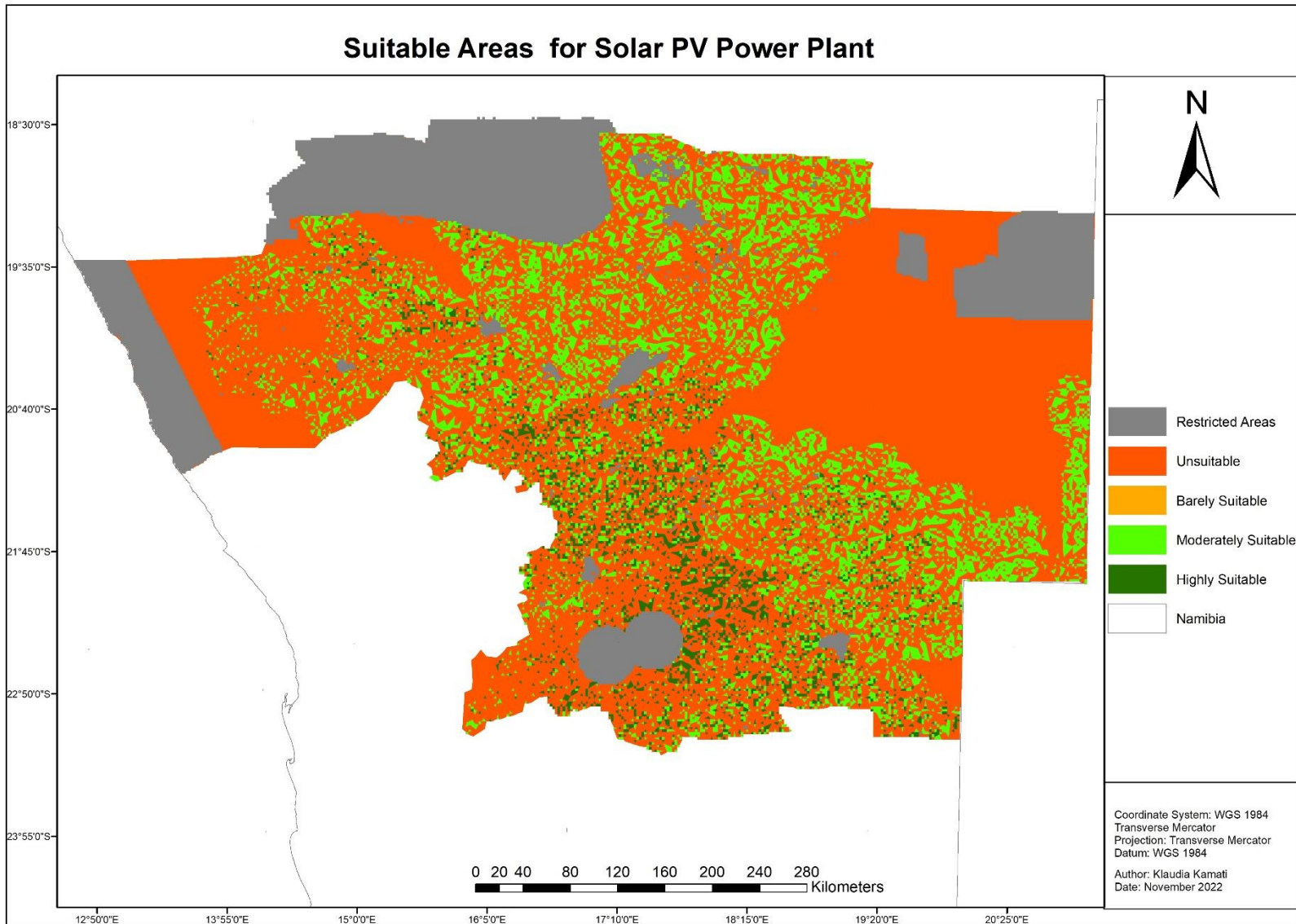


Figure 36: Final solar PV power plant Suitability

Additionally, the results clearly indicate that this study closely aligns and is relatively equivalent to other previous research in establishing the suitable and most cost-effective locations for solar PV energy plants. For example, the study published by the World Bank on global PV power potential by country, provides a comprehensive and harmonised analysis of solar resources and the potential for installing PV power plants at a utility-scale (World Bank Group, 2019). The outcome of their study, Potential Photovoltaic Electricity Production (PVOUT), presented in Figure 37 was obtained from Global Solar Atlas in a raster Geo-TIFF format and was clipped to the study area to validate the findings attained in the current research. Although the PVOUT study used a different method (SolarGIS algorithm) where only two criteria (Solar irradiation and air temperature) were considered, there is a strong similarity between their results and the current study's results. The current study result was overlaid on top of World Bank result, both results show the correspondence in Figure 38. Figure 38 indicates that the highest favourable locations are in the south-west and west regions of the research area. Furthermore, the present study is more detailed because it considered and integrated most of the factors that can hinder the installations of solar PV power plant. In addition, these findings would provide critical information to CENORED, investors, researchers, politicians, students, and the public on preliminary sites selection for solar PV energy plant development.

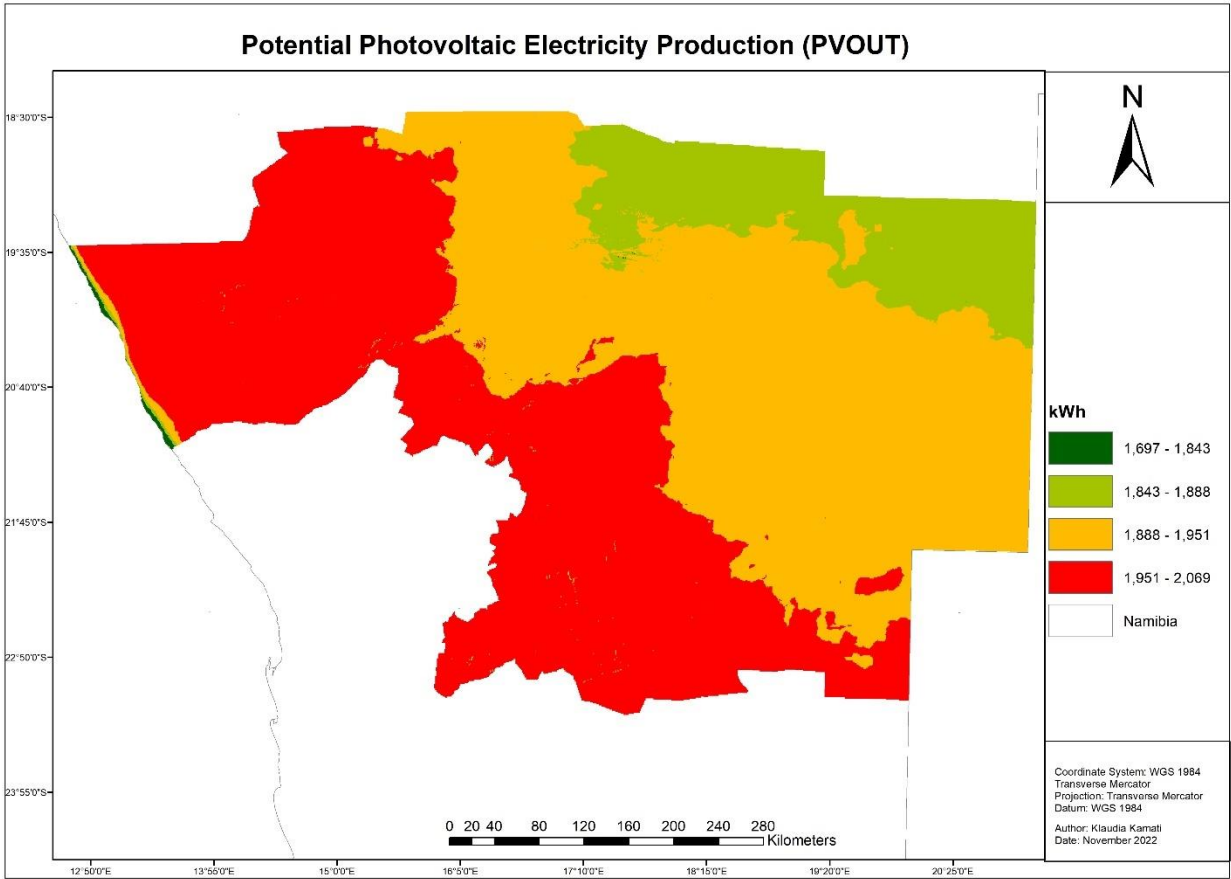


Figure 37: Potential PV electricity production

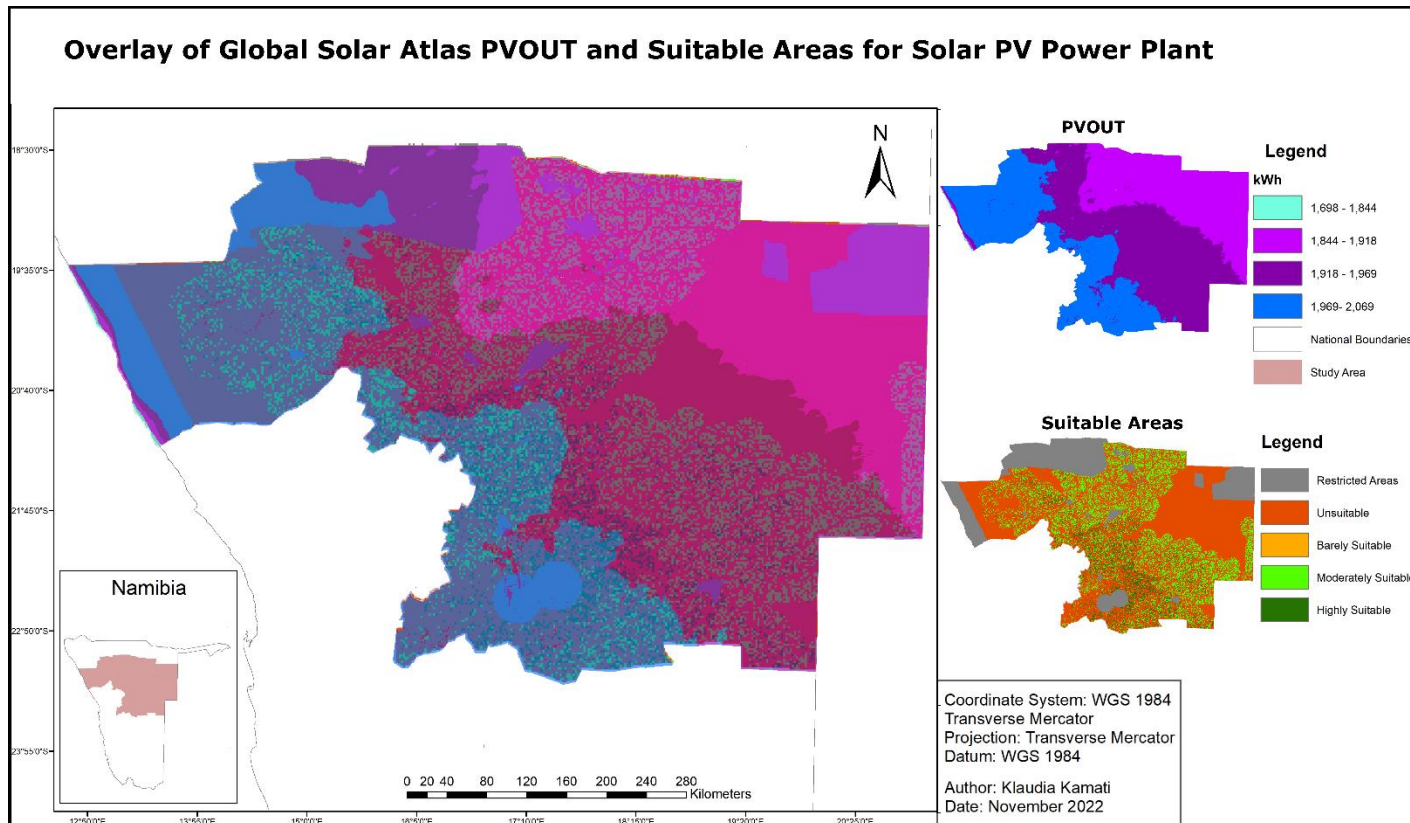


Figure 38: Comparison with similar study

## 5.2 Wind Farm Power Plant

As in the previous assessment on identifying potential locations for solar PV energy plants within the research region, site selection for wind energy plants also involves examination of a comprehensive set of factors in assessing the suitability of a particular area. Several criteria, including slope, wind speed, road, and power lines, were identified in the literature to be considered in the development of wind energy site selection. Similar factors were considered during the wind energy plant locations selection in this study. Table 14 shows how identified criteria were classified into two key groups: technical and economic.

Table 14: Factors for Wind turbine power plant installation

Factors	Criteria	Classes	Suitability	References
Technical	Slope (°)	0 – 2.9 2.9 – 5.7 5.7 – 8.5 >8.5	Highly suitable Moderately Suitable Barely Suitable Unsuitable	(Noorallahi , et al., 2016; Sadeghi & Karimi, 2017; Bennui, et al., 2007; Satkin, et al., 2014)
	Wind Speed (m/s)	0 – 5.6 5.6 – 6.9 6.9– 9.5 >9.5	Unsuitable Barely Suitable Moderately Suitable Highly Suitable	(Gorsevski, et al., 2013; Noorallahi , et al., 2016; Latinopoulos & Kechagia, 2015; Moradi, et al., 2020)
Economic	Distance from Roads (m)	0 – 100 100 - 5000 5000 - 20000 >20000	Barely Suitable Highly Suitable Moderately Suitable Unsuitable	(Noorallahi , et al., 2016; Shorabeh, et al., 2019; Moradi, et al., 2020; Mierswiak & Calka, 2017; Sadeghi & Karimi, 2017; Uyan, 2013)
	Distance from Power lines (m)	0 – 250 250 - 5000 5000 - 20000 >20000	Unsuitable Highly Suitable Moderately Suitable Unsuitable	

### 5.2.1 Slope of Terrain

For economic and transportation reasons mentioned in solar PV power plant site selections above, slope remains a crucial criterion. Some studies have not taken slope into account (Nguyen, 2007; Aydin, et al., 2010; Sliz-Szkliniarz & Vogt, 2011). Others, in contrast, paid more attention to the slope and regarded it as an AHP criterion (Noorallahi , et al., 2016; Moradi, et al., 2020; Hofer, et al., 2016; Xu, et al., 2020; Sadeghi & Karimi, 2017). The slope greater than 15% is restricted for wind turbine power plant development in many studies (Noorallahi , et al., 2016; Sadeghi & Karimi, 2017; Bennui, et al., 2007; Satkin, et al., 2014). In the present study, areas with slopes greater than 15% were considered not suitable as per literature. The slope dataset was derived from DEM of CENORED area. A slope map like the one generated in Figure 23 was used for wind turbine with different thresholds. In this study, the same slope thresholds as in above studies were used, however the threshold values were converted from percentage slope to degrees of slope, since slope is commonly expressed as a degree. Figure 39 shows the classified areas for the slope criterion. Areas with land inclination less than  $2.9^\circ$  were determined to be suitable for optimal wind turbine site selection, whereas areas with land inclination above  $8.5^\circ$  were disqualified from the study. The steepest slopes are indicated in grey colour in the output raster. Table 15 displays the reclassified classes as well as their suitability ranking.

Table 15: Slope of Reclassification

Classes ( $^\circ$ of slope)	Score	Suitability Ranking
0 – 2.9	4	Highly Suitable
2.9 – 5.7	3	Moderately Suitable
5.7 – 8.5	2	Barely Suitable
>8.5	1	Unsuitable

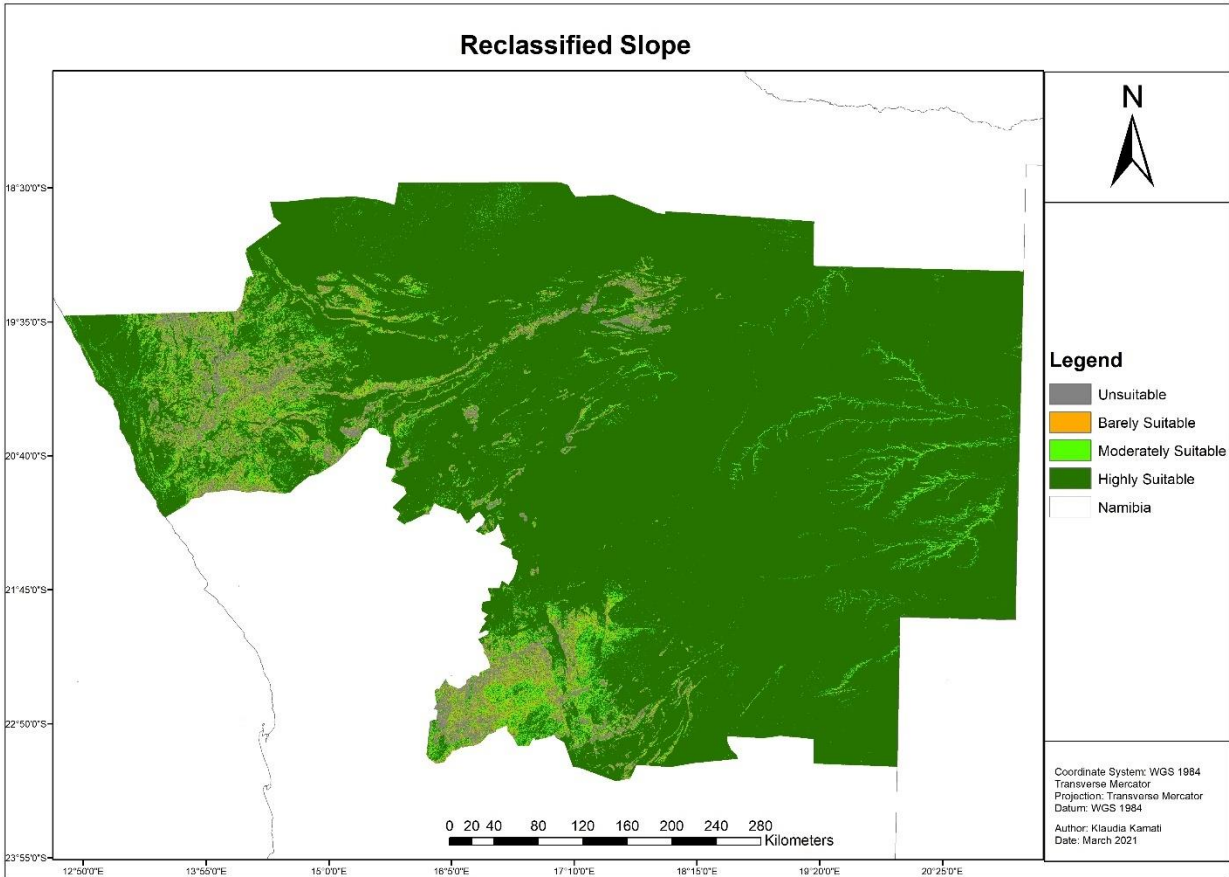


Figure 39: Reclassified slope

### 5.2.2 Average Wind Speed

For wind energy development, average wind speed is the most significant technical indicator, because average wind speed determines the best location for wind turbine installation (Gorsevski, et al., 2013). A high wind speed would indicate that wind resources are abundant and beneficial to increase power production (Xu, et al., 2020; Latinopoulos & Kechagia, 2015). Areas with high wind speed are classified as most suitable areas than areas with low wind speed. The wind speed dataset was acquired from Global Wind Atlas on-line resource and was captured at a height of 100 meters above the Earth’s surface. The dataset represents yearly time average of 2008-2017 in m/s in raster Geo-TIFF format as shown in Figure 40. The average height for the tower of a wind turbine is from 60m to 120m (Duval, 2021). Taller towers are preferable because winds are stronger at higher altitudes, resulting in more power produced per turbine installed (U.S Department of Energy, 2002).

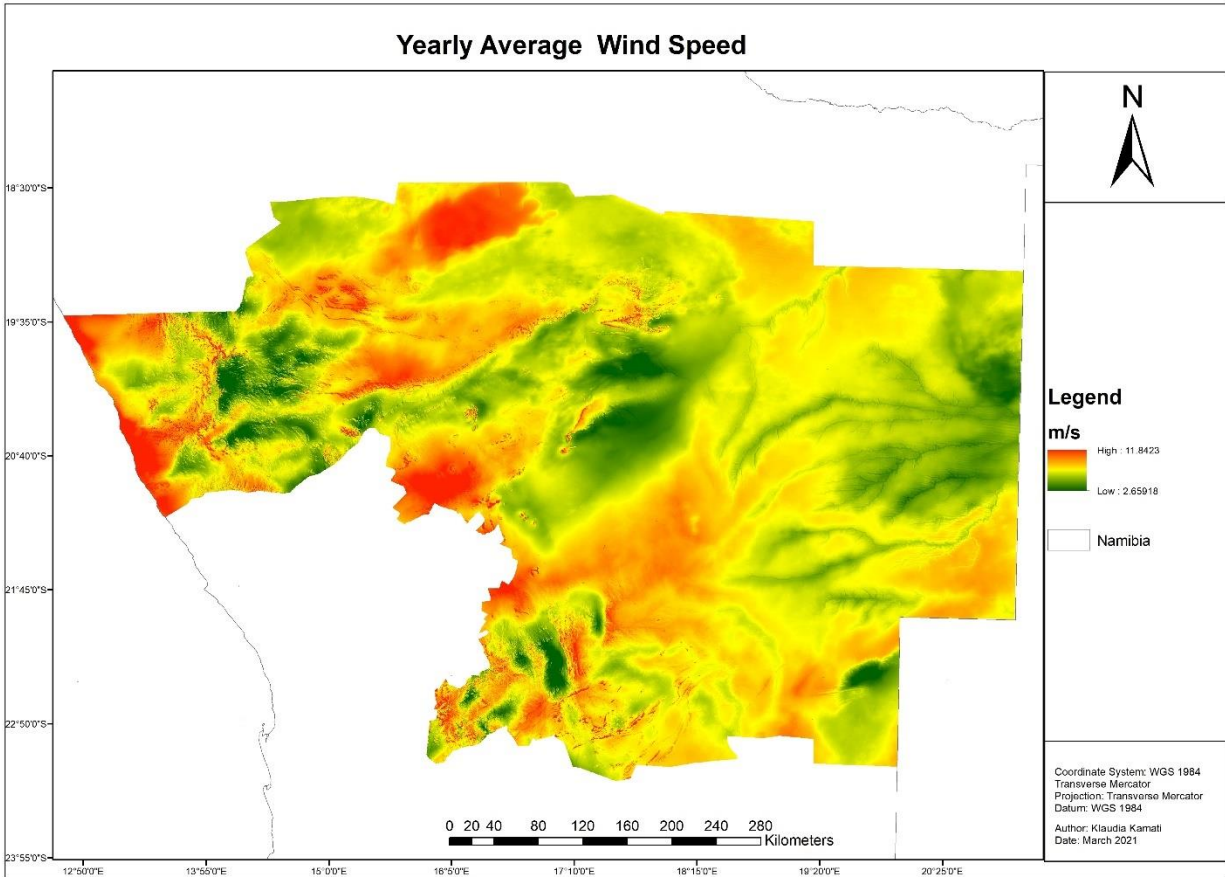


Figure 40: The average wind speed at 100 m altitude

### Reclassified Average Wind Speed

The wind speed data was classified into four classes of annual average wind speeds, ranging from unsuitable (1) to Highly suitable (4) based on literature (Gorsevski, et al., 2013; Noorallahi, et al., 2016; Latinopoulos & Kechagia, 2015; Moradi, et al., 2020; Al-Shabeeb, et al., 2016; Ayodele, et al., 2018). The classification is shown in Table 16 and Figure 41, areas represented in dark green colour are associated with strongest wind speed while areas in grey colour represent unfeasible locations for wind energy plant development. The wind speed, on the other hand, appears to be related to the slope of the terrain. Wind speeds are lower on steep slopes than in plane areas. This is verified by other researchers (Hofer, et al., 2016; Baban & Parry, 2001; Rodman & Meentemeyer, 2006). This correlation is particularly strong in the west part of the region, where steep slopes cause the region's lowest wind speed.

Table 16: Reclassification of average wind speed

Classes (m/s)	Score	Suitability Ranking
0 – 5.6	1	Unsuitable
5.6– 6.9	2	Barely Suitable
6.9 – 9.5	3	Moderately Suitable
>9.5	4	Highly Suitable

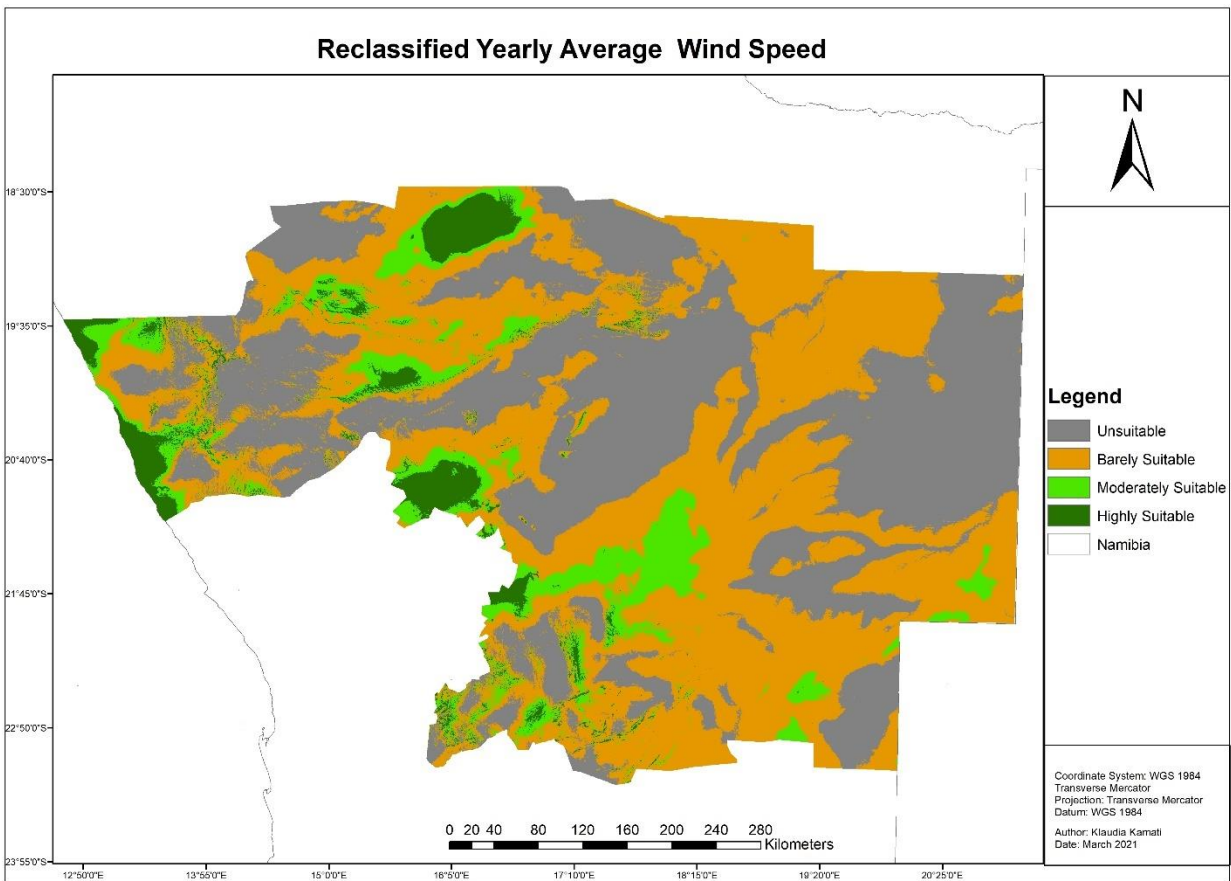


Figure 41: Reclassified annual average wind speed

### 5.2.3 Proximity to Power Lines

Installing a wind energy plant close to the existing electrical network is cost-effective. These would aid in avoiding voltage drops, reducing energy loss due to the long distance travelled by generated energy, and lowering infrastructure costs such as the construction of a new power line. If the wind farm's distance from an existing power line is not considered, the cost of constructing new power lines may exceed the cost of installing a wind farm itself (Moradi, et al., 2020). According to the North Rhine-Westphalia wind energy enactment, a minimum distance of one rotor diameter must be maintained between the rotor blade tip and

the overhead power line. The rotor blade diameter of the reference wind turbine is 101 m. As a result, areas closer than 100m to the electrical network are designated as restricted (Hofer, et al., 2016). However, wind development should be kept at least 250 m away from electrical grid, according to the literature (CNdV Africa Planning and Design, 2006; Noorallahi , et al., 2016; Sadeghi & Karimi, 2017). Euclidean distance tool in ArcMap was used and then reclassified the distance into four classes according to their suitability ranking as shown in Table 17. As shown in Figure 42, highly suitable areas are between 250 m to 5 000 m, and areas within 250 m are unsuitable and areas further than 20 000 m are barely suitable. A buffer zone of 250 m was created on both sides of power lines.

Table 17: Reclassified power lines

Classes (m)	Score	Suitability Ranking
0 – 250	1	Unsuitable
250 – 5000	4	Highly Suitable
5000 – 10000	3	Moderately Suitable
>20000	2	Barely Suitable

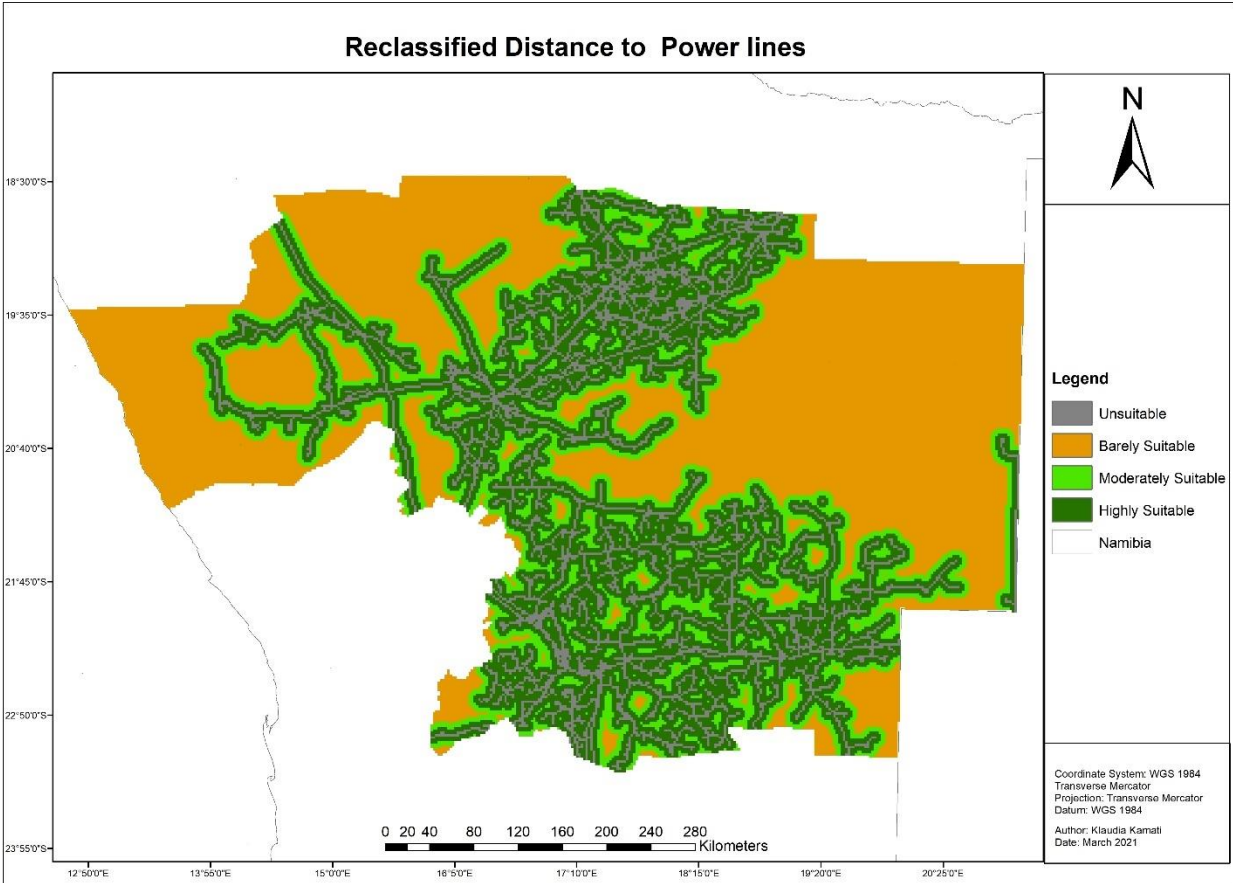


Figure 42: Reclassified power lines

### 5.2.4 Proximity to Roads

Access roads is a socioeconomic factor that might enhance project costs. If an adequate route is not available, transporting turbines can be complex and costly. Therefore, proximity to transport systems is a key aspect in the planning stage. Almost all studies conclude that areas closer to roads are better suited for establishing a wind turbine (Noorallahi , et al., 2016; Satkin, et al., 2014; Xu, et al., 2020; Latinopoulos & Kechagia, 2015; Sadeghi & Karimi, 2017; Moradi, et al., 2020). According to Noorallahi et al, (2016), Moradi, et al. (2020), and Sadeghi & Karimi (2017) a buffer distance of 500 m should be kept from roads. ArcMap’s buffer tool was used for this. ArcMap’s Euclidean distance tool was applied to calculate the distance and then reclassify the distance based on Table 18. Wind turbine construction is not permitted within a 500 m buffer radius from roads. Areas more than 20 000 m away from the roads were considered as barely suitable as shown in Figure 43.

Table 18: Reclassified Road

Classes (m)	Score	Suitability Ranking
0 – 500	1	Unsuitable
250 – 5000	4	Highly Suitable
5000 – 10000	3	Moderately Suitable
>20000	2	Barely Suitable

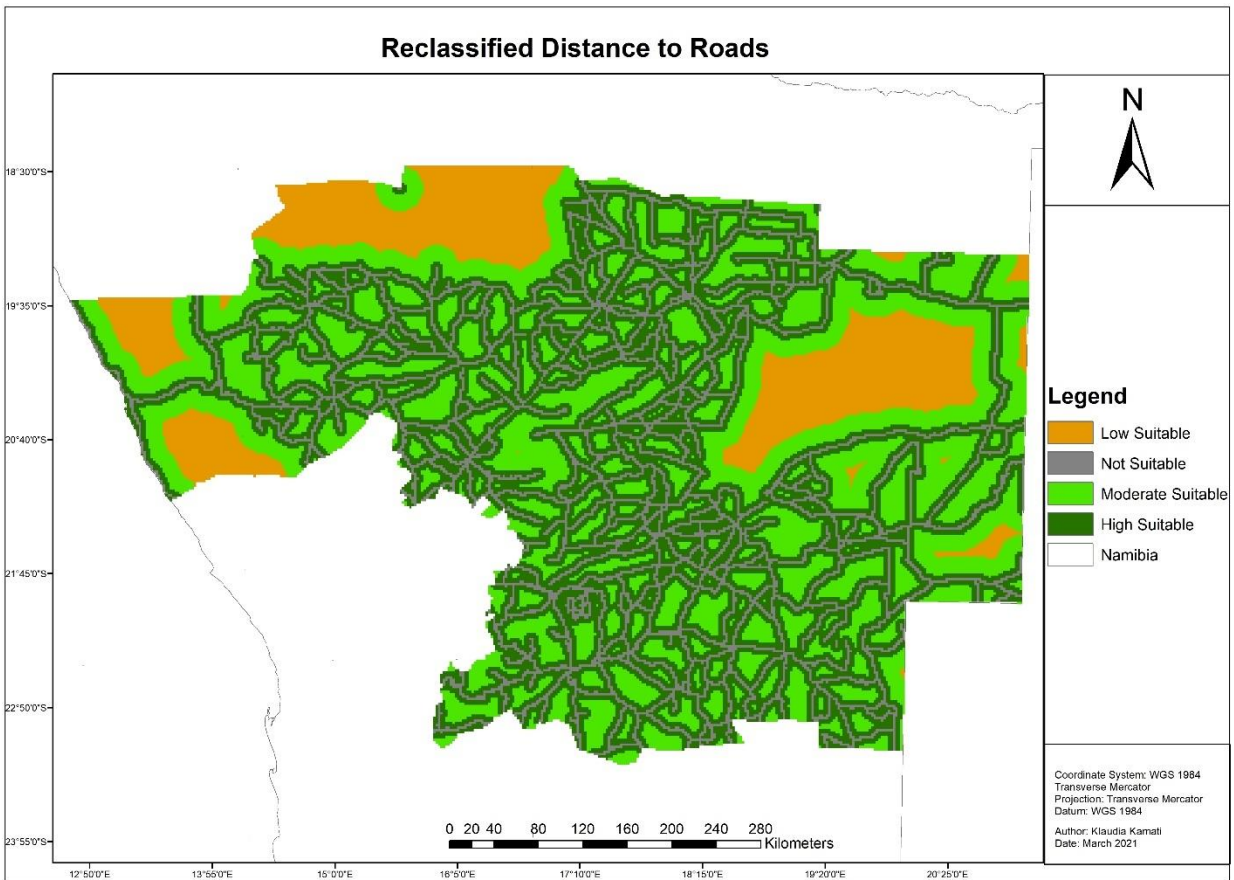


Figure 43: Classified Road network

### 5.2.5 Analytical Hierarchy Process

The experts' criteria comparison judgements obtained from Ayodele, et al. (2018) were used in AHP calculation. Same methods in Section 4.9, Chapter 4 was utilised to determine the weighted criteria's weights. The CR was also calculated to assess the level of consistency in pairwise comparison matrix shown in Table 19. Based on the output results of the AHP, wind speed (C1) is the most important evaluation criterion in wind turbine sites selection and thus has the greatest influence on suitability evaluation, as

shown in Figure 44 and Table 19. The weights obtained from AHP were entered into the Weighted overlay tool to determine the potential sites for wind energy development within CENORED supply area.

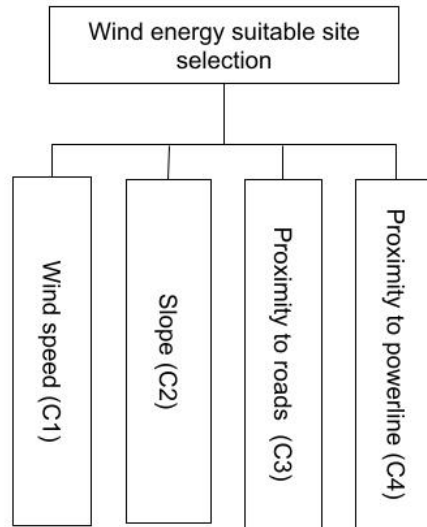


Figure 44: Considered decision criteria in wind energy sites selection

Table 19: The adopted decision criteria's comparison matrix.

Criteria	C1	C2	C3	C4	Weighted
C1	1	3	5	9	0.4974
C2	1/3	1	3	7	0.2449
C3	1/5	1/5	1	5	0.2081
C4	1/9	1/7	1/5	1	0.0378
				$\lambda_{max}$	5.2197
				CI	0.0549
				CR	0.0495

### 5.2.6 Weighted Overlay

The final suitable areas were defined, as shown in Figure 45, by overlaying the output of the restrictive and classification methods. In this Section, vectorisation is not necessary since the generated result does not contain salt and pepper. Most of the areas in the Southern region and northeast region of the CENORED supply area have been determined to be inconvenient for wind turbine installation. Lack of strong wind speed and steep terrain in the northeast and east regions, make the regions unfavourable for wind turbine installation. As a result, the northwest region is a good potential area for the construction of wind energy plant because it is characterised by highly suitable areas, which is beneficial to electricity production. This is because of their abundant wind resources, flat terrain, and short distance from power lines. As far as the researcher knows, no studies have ever been conducted on wind energy development within the study

area. Hence, there is no study that could be used as a comparison to the current study to verify the generated results, like what the researcher did for solar.

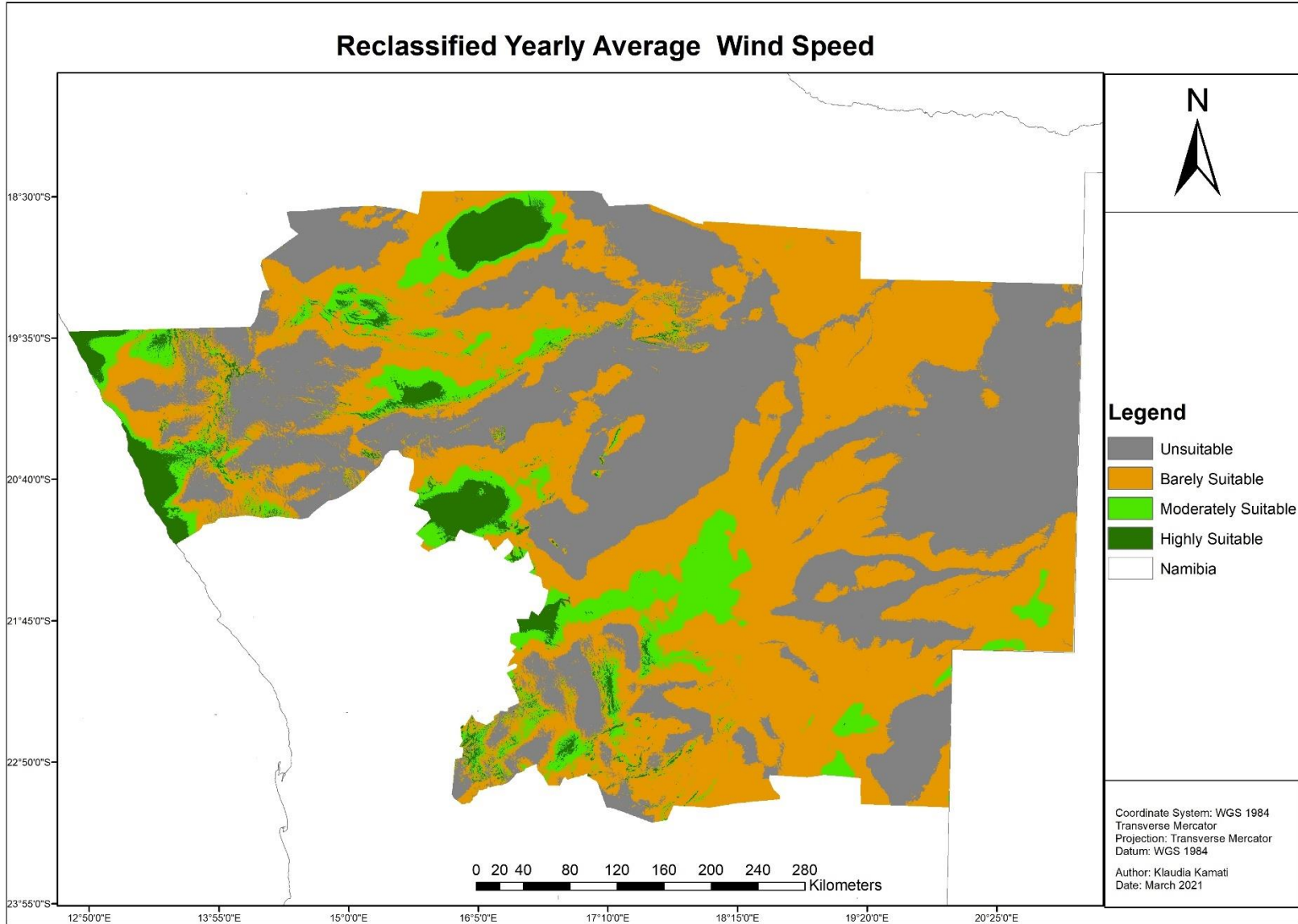


Figure 45 Final wind turbine power plant suitability areas

### **5.3 Chapter summary**

In summary, this Chapter has presented detailed information of all the analyses conducted in the present study as well as their outcomes. Based on the results obtained, some conclusions and recommendations can now be made, as presented in the following Chapter.

## **CHAPTER 6: CONCLUSION AND RECOMMENDATION**

This chapter gives the conclusion of the study after discussing and summarising the analyses performed and the results obtained in Chapter 6. This chapter also includes suggestions for prospective future research that might be conducted to enhance the current study.

### **6.1 Conclusion**

Conventional sources of energy are used to generate most of the world's energy. Alternative energy sources should be explored in light of the depletion of non-renewable energy sources and, more crucially, the environmental impact, which leads to global climate change. Solar and wind energy, among other RESs, have been regarded as a feasible alternative to conventional source of energy since they can contribute to the generation of power in a future that is sustainable, reliable, and low in carbon emissions. Therefore, solar PV and wind energy have emerged as critical clean energy sources on a worldwide scale.

Studies show that Namibia is experiencing electricity shortages and can result in socio-economic problems. The exorbitant electricity tariff in Namibia is causing power providers and distribution companies (like CENORED) to face a challenge as customers choose to go off-grid simply by using solar energy as an alternative. For CENORED to be sustainable and cost-effective, RESs is necessary to supplement its existing power generation capacity. As a result, renewable energy is in high demand. The development of RESs applying geospatial analysis can have a positive outcome in reducing the electricity tariffs and can have a major role in reducing environmental impacts.

Geospatial analysis helps to provide a deep understanding of sites as well as the criteria and considerations involved. The use of geospatial analysis enables wind and solar farms to be located more precisely. By using GIS technology and mapping techniques, policymakers and planning commissions can more easily select the prospective location for wind farm and solar PV projects. The time required to consider and select a specific site is a significant advantage of spatial analysis over existing methods. A site's geospatial dimensions enable development planning around restricted locations without the need to physically implement the plan on the field. For example, the researcher was able to determine a project's environmental impact, whether the construction of RES plant in the area would disrupt habitats or migratory patterns. All this information paints a clear picture of which areas would be ideal for implementing RESs and which would be a waste of resources.

Based on the information and results derived from this study, an effective solution has been found to the complex issue of planning for wind farm and solar PV power plant installations. The absence of this critical stage of assessment and evaluation may result in a considerable waste of resources as well as timewasting. This study's main aim is to locate potential sites for installing solar and wind energy plants within CENORED supply area. To accomplish the study's aim, the objectives established at the outset of the study were pursued. To achieve these objectives, GIS techniques and MCDM (AHP) methods were applied for solar PV and wind energy exploitation and site evaluation in central north region, Namibia. The AHP is used to determine the weights of criteria and evaluate their importance. GIS and the AHP methodology play a crucial role in the effective and quick evaluation of solar PV and wind energy plants site selection. As part of the computation process, topographical, economic, climatic, and environmental factors were considered.

As a result, the study question of which method of geospatial data analysis is appropriate for effectively identifying suitable sites for wind and solar PV energy plant installation is answered. Through this study's comprehensive approach and methodology, different factors influencing the selection of wind and solar PV energy plant locations have been identified. In this study, fourteen (14) criteria for determining the potential locations for solar PV and wind energy plants were identified based on the literature and legislative boundary constraints in Namibia. This helped to answer the question of what factors and criteria determine wind and solar PV power site's suitability.

The last objective pursued was to generate suitability of sites for solar PV and wind farm power plants. In selecting the suitable location for utility-scale solar PV and wind energy power plants, AHP method was applied to assess the importance of each decision criterion and was found to be effective in terms of incorporating multiple factors. The number of criteria is found to be adequate based on the nature of the study area and similar studies on the subject. However, it should be noted that these results vary depending on the region's peculiarities and the ratio of the number of factors. In this study, it was helpful to identify the constraint zone early in the site selection process to reduce the computational burden. Geographically, large exclusion areas are mostly located in the north, east, and west part of the study area near the coastal area. The objectives pursued, the method used, and the results obtained in this study answered all the study questions.

An integrated GIS and MCDM technique have been found to be an effective and powerful decision support tool for addressing problems relating to solar PV and wind plant siting. GIS cannot, therefore, be used as a stand-alone tool to locate potential locations for RESs installation. However, when combined with other methods the system becomes acceptable and powerful. All reclassified raster datasets that provide

information about air temperature, wind speed, solar radiation, slope, aspect, power lines, wind speed, and roads were aggregated. These raster datasets were combined based on their weighting from AHP. Resulting from this research, solar radiation, aspect, slope, and wind speed are the factors that are most influential in locating optimal locations for wind farm and solar PV power plants.

This study generated potential maps shown in Figure 36 and 45 that highlight the locations with the highest potential for solar PV and wind energy plants installation within CENORED supply areas. The locations with the greatest solar PV energy potential in the research area are in the south-west, north-west, and south-central regions. The size of the area, on the other hand, has a major impact on the amount of energy that can be gathered from it. Bigger area available will receive large amount of solar radiation. In contrast, the northwest region is highly potential for wind farm power plant development. Additionally, it is encouraging to see that combining wind and solar power together increases energy stability compared to just using wind or solar power alone. PV energy has the greatest potential in the northwest, southwest, and south-central regions of the research area.

These results can be used as a guide in the development of the solar and wind energy market, the conservation of energy for future demand, and the promotion of regional sustainable initiatives. Therefore, the results may be used to increase the percentage of energy generated by renewable energy in the CENORED supply area, allowing it to meet its renewable energy targets while also reducing its carbon footprint. The findings can be used by governments, commercial investors, and other stakeholders to determine prospective sites for solar and wind energy generating deployment in the CENORED section and These techniques can assist Namibia and other countries in achieving their renewable energy portfolio targets to establish a more sustainable energy future and achieve the 2030 development goals.

## **6.2 Recommendation and Future Work**

GIS-based site selection analysis combines geographical and non-spatial data to generate visually appealing information for decision makers. Using illustrative maps derived from GIS-based multi criteria analysis, decision makers can find very accurate solutions to challenges. In the present study, suitable areas for solar PV power plants and wind turbine power plants were identified, and the results were visually interpreted, demonstrating that the GIS method produces relatively accurate and practical results. CENORED currently has no wind turbine power plants. Although in Tsumkwe, CENORED commissioned a hybrid solar PV-diesel system with a 200kW peak installed capacity, one-megawatt of battery storage and three diesel generators integrated (Juwi AG, 2011)..

According to the researcher's best knowledge, no study was done using MCDM method on the selection of optimal sites for both wind and solar PV energy plant installation for the entire region. This is advantageous for the company because the results in the present study will help the company to develop solar PV and wind plants with minimal environmental impact. Therefore, the suitability maps can be applied as a guide to narrow the search scope of potential sites for solar and wind energy plants on a large-scale area. To be considered for a project, all sites must either complete a basic assessment or a full scoping and EIA, depending on the severity of the project's impacts on the site. Impacts are measured based on the significance of a specific project, which is based on its characteristics such as, scope, magnitude, duration, as well as probability that they occur in the future. The limitations of this study have already been discussed in the first chapter. Furthermore, prior to making any investment in development of solar PV or wind energy plants, the final decision-making process must incorporate survey work and possible on-site measurements. The mapping results must still be validated by field measurements of solar irradiance and wind speed, as well as observation of any ecological variables that may exist in any specific place, such as migratory bird paths.

In addition to the lack of bird migration datasets, additional investigation will be well worth conducting before making final decisions on wind turbine power plants site selection. Furthermore, considering average monthly maximum temperatures could also be an advantage when determining the site of solar power plants since it gets hotter on certain days during the summer season, the temperatures spike to the levels where they disrupt solar PV energy production. As a result of the limited maximum air temperature data in this study, the only available data was the average yearly air temperature. These dataset's availability as additional criteria may enhance sites selection outcomes even further.

Decisions making about the capacity of a power plant can be studied as part of future research. Wind turbines near airports should be built in collaboration with airports and air traffic control to examine each unique issue affecting aviation operations and discover strategies to minimise or mitigate them.

Lastly, I recommend that other MCDM methods, such as fuzzy-TOPSIS and fuzzy-ANP, should be used to validate the quality of solution obtained in the present study. Furthermore, the outcomes of those methodologies can be compared to the outcomes of the present study to better understand which method performs well under which conditions.

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