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MULTICRITERIA DECISION METHOD FOR RENEWABLE ENERGY PRODUCTION: SITING SOLAR, WIND AND SHP PLANTS IN ZIMBABWE

A DISSERTATION SUBMITTED TO THE UNIVERSITY OF CAPE TOWN IN FULFILMENT OF A MASTER OF SCIENCE DEGREE IN ENGINEERING (GEOMATICS)

BY

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Abstract

Energy plays an enormous role in economic growth, progress, and development. The energy development in Zimbabwe has not been coincident with the rising demand of energy, placing a large strain on existing resources. Most of the energy is powered by coal-fired stations that now require major upgrades. The low-capacity problem has resulted in frequent production stops and power cuts that affect economic performance of industries and services. These power shortages have led to the formulation of the National Renewable Energy Policy (NREP), which stipulates that by 2030, Zimbabwe needs to be driven by clean and sustainable energy sources. In this regard, the government has devoted itself to achieving the Sustainable Development Goals (SDGs).

The aim of the study was to identify suitable locations for renewable energy production plants in Zimbabwe. The first step in the process was to define suitability criteria for siting wind, solar and small hydro power plants. Vector and raster data sets corresponding to the criteria were gathered and a geodatabase was constructed. The process of identifying suitable areas involved the transformation of criteria values, generation of criteria-based maps, standardization, and ultimately locating the suitable energy plant sites using Multi Criteria Decision Method (MCDM). The method used to identify suitable regions for renewable energy in Zimbabwe were compared to the existing renewable resources in Zimbabwe and validated using models created for South Africa.

The study demonstrates that Zimbabwe has enormous potential for wind, solar, and SHP resources, all of which have the potential to alleviate the country's severe energy shortages. Hwange Rural, which has a land area of 26 974 km2, is the best place for solar power plants. The Beitbridge Rural District, which has a land area of 12 719 km2, is the best place for small-scale utility wind power turbines. Small hydropower plants would thrive in the Gwayi and Shangani Rivers.

Additionally, a thorough comprehension of the technical aspects of each renewable energy source is required. The availability of solar resources, PV module efficiency, spacing factor, and accessible land area are some examples of the information that must be gathered in order to derive the technical potential for the creation of solar PV systems. Addressing obstacles to the widespread adoption of renewable energy technologies in the country can be accomplished through the establishment of policies and regulatory frameworks.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
AICD	Africa Infrastructure County Diagnostics
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
AHP	Analytical Hierarchy Process
DBMS	Database Management System
DC	Direct Current
DRDLR	Department of Rural Development & Land Reform
DEM	Digital Elevation Model
CSP	Concentrated Solar Power
CSV	Comma Separated Variable
ERDDAP	Environmental Research Division Data Access Program
ESKOM	Electricity Supply Commission
ESRI	Environmental Systems Research Institute
DHI	Diffuse Horizontal Irradiation

DNI	Direct Normal Irradiance
GDP	Gross Domestic Product
GFS	Global Forecast System
GRASS	Geographic Resources Analysis Support System
GHI	Global Horizontal Irradiance
GIS	Geographic Information Systems
HAWT	Horizontal Axis Wind Turbine
HCB	Hidro Electrica de Cahora
HTF	Heat Transfer Field
ICT	Information Communication Technology
IDW	Inverse Distance Weighting
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity
NGI	National Geo-spatial Information
LFR	Linear Fresnel Reflector

M/S	Meter Per Second
MCDA	Multi-Criteria Decision Analysis
QGIS	Quantum Geographic Information System
MCDM	Multi-Criteria Decision Making
RS	Remote Sensing
SAGA	System for Automated Geoscientific Analyses
MEPD	Ministry of Energy and Power Development
MTOE	Million Tons of Oil Equivalent
USGS	United States Geological Survey
MZWP	Matabeleland Zambezi Water Project
NEP	National Energy Policy
NREL	National Renewable Energy Laboratory
NREP	National Renewable Energy Policy
PV	Photovoltaic
RCMRD	Regional Centre of Mapping of Resources for Development

SDG	Sustainable Development Goals
MTOE	Million Tons of Oil Equivalent
SRTM	Shuttle Radar Topographic Mission
TWH/YR	Terawatt-Hours
UNESCO	United Nations Educational Scientific and Cultural Organization
VAWT	Vertical Axis Wind Turbine
VNR	Voluntary National Review
WFP	World Food Programme
WSM	Weighted Sum Model
ZERA	Zimbabwe Electricity Regulatory Authority
ZESA	Zimbabwe Electricity Supply Authority
ZPC	Zimbabwe Power Company

1 INTRODUCTION

1.1 BACKGROUND OF STUDY

Energy plays a crucial role in economic growth, progress, and development. It contributes to poverty eradication as well as the security of any nation (Makonese, 2016). Humanity's need for energy has increased over the years. It is portrayed that the use of energy is strongly connected to almost every imaginable aspect of development (Wolde-Rufael, 2005).

Energy development has not been coincident with the rising demand in developing regions such as Zimbabwe, placing a large strain on existing resources (Makonese, 2016). The energy supply for Zimbabwe is a mixture of coal, hydroelectricity, and a small percentage of other renewable energy sources such as wind and solar. The diagram below shows the capacity utilisation of different energy resources for Zimbabwe in 2020 (IRENA, 2022).

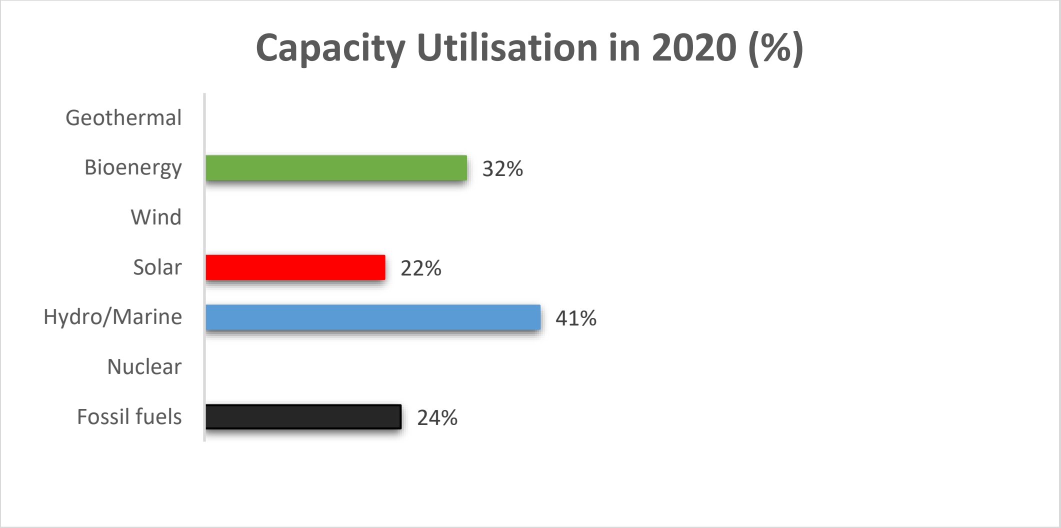


FIGURE 1-1 ENERGY UTILISATION OF ENERGY RESOURCES IN ZIMBABWE IN 2020 ADAPTED FROM (IRENA, 2022).

The major power plants are owned by a state enterprise, Zimbabwe Electricity Supply Authority(ZESA) Holdings through the Zimbabwe Power Company(ZPC) (Murombo, 2019). Access to electricity in rural areas is less than in urban areas due to the high-priced costs of extending national electricity grids (Makonese, 2016). The Ministry of Energy and Power Development(MEPD) is in charge of overseeing policy formation, performance, monitoring and regulation of the energy sector in Zimbabwe (Baruya and Kessels, 2013).

The National Energy Policy (NEP) was launched by the government in 2012 with plans and actions to extend electricity transmission and generation capacity. A capacity expansion of 800MW was to be generated at the Batoka Gorge hydro-electric power station and 300MW at the Kariba South hydro-electric power station. Power generation licenses are issued by the Zimbabwe Electricity Regulatory Authority(ZERA) (NREP, 2019)

It is said that ZESA Holdings has failed to produce enough electricity to meet the increased demand (Makonese,2016). The energy demand is because of urbanisation and insufficient investment in modern forms of energy. According to Hill (2019), power rationing has now become an imperative at Kariba hydropower station, which is a shared and major hydropower generation plant between Zambia and Zimbabwe. Coal-fired stations in Zimbabwe require major upgrades as they either face frequent production stops or are not producing at all (Makonese, 2016). Energy imports from neighbouring countries are not sufficient to overcome the low-capacity problem, resulting in power cuts that affect economic performance of industries and services (Murombo, 2019).

Zimbabwe has a renewable energy potential ranging from solar, wind, geothermal, hydropower to biomass and biofuels (Murombo, 2019). Zimbabwe's energy sector proposes to increase its power generation through renewable sources like wind, solar, geothermal and biomass (Ndhlovu, 2019). The crippling power shortages have also led to Zimbabwe formulating the NREP under the overall framework laid out by the National Energy Policy (NEP) of 2012, which recognises that by 2030 the economy needs to be driven by clean and sustainable energy sources (Madya, 2019). The aim of the policy is to remove barriers to the deployment of renewable energy sources as well as reduce government bureaucratic delays in project approvals NREP, 2019.

In many nations, there has been a lot of research done on the potential of solar photovoltaics because the cost of making electricity with this technology has dropped recently (Samu and Fahrioglu, 2017). The global weighted average levelised cost of electricity(LCOE) of new utility-scale solar PV projects fell by 13%, year-on-year, to USD 0.048/kWh in 2021(IRENA, 2022). Solar energy is already the least expensive method of producing new electricity. In comparison to 2006's 1.5 GW, global installations reached 115 GW in 2020. Solar generation is now appealing solely on the basis of price, despite the fact that government subsidies and environmental goals played a part in the growth of solar to this scale(Mackenzie, 2021). As a result, Zimbabwe is an even better location for solar power plants. The capital of Zimbabwe, Harare, has a relatively high solar energy potential. It receives an average of 5.72 kWh/m2/day from the sun. Since there is a plan to extend the grid, an integrated solar PV system that can be connected to the utility grid would be ideal (Chahuruva and Dei, 2017). The way in which renewable energy contributes to SDG 7 is yet another compelling reason to carry out research into locating suitable renewable energy. The UN SDG-Fund has approved Zimbabwe's 45 million dollar program to encourage investments in renewable energy to accelerate progress toward the SDGs (UNESCO, 2022).

A study of Zimbabwe's wind potential found that at a hub height of 80 meters, it might be possible to generate electricity. As a result, prototypes of wind turbines with ratings of 4 kW and 1 kW were made, tested well, and installed in Rusape (Samu, Fahrioglu and Ozansoy, 2019). The fact that a study was done on the suitability of wind power in Zimbabwe gives even more reason to find the optimal sites to harness the energy.

Undeveloped hydropower capacity ranges from approximately 47% in Europe and North America to 92% in Africa, indicating significant opportunities for hydropower development worldwide, with the greatest growth potential in Asia, Latin America, and Africa (Kumar *et al.*, 2011). Hydropower projects span a wide range of scales, it is more useful to evaluate them based on their economic or sustainability performance, which would provide indicators that are more realistic. Hydropower has a technical potential of 14576 TWh/yr and worldwide an installed capacity of 3721 GW, which is roughly four times the current capacity which is 1360 GW(International Hydropower Association, 2022).

Progress toward all the other SDGs and global climate protection targets can be sparked by decisive action on sustainable energy. Reaching the goals of SDG 7 is critical to the future of the world's quality of life(Villavicencio Calzadilla and Mauger, 2018). The quality of people's daily lives and the survival of future generations will be greatly impacted by the swift transition to a clean energy future for all. Clean cooking supplies are still unavailable to approximately 2.6 billion people. Even though global investments in renewable energy capacity increased by 2% to US$ 303.5 billion in 2020, the share of all renewables in total final energy consumption is only expected to rise to around 21.5% by 2030, from 17.1% in 2018 (Division for Sustainable Development Goals, 2021). Energy justice considerations must be taken into account when developing and implementing renewable energy policies and developments in order to achieve SDG Goal 7 without excluding anyone (Villavicencio Calzadilla and Mauger, 2018).

Public participation in the planning of renewable energy sources is becoming increasingly recognized (Ozorhon, Batmaz and Caglayan, 2018) . Therefore, in order to provide a transparent and solid evidence-base for the successful implementation of renewable energy strategies, it is necessary for planners, technical experts, stakeholders, and the general public to collaborate and communicate with one another (Molnarova *et al.*, 2012). Over the past few decades, a number of tools based on Geographic Information Systems (GIS) and MCDM have been developed in an effort to support accountable decision-making and facilitate the integration of stakeholder perspectives (Carver, 2019).

In decision-making issues, MCDM is a method for evaluating multiple competing criteria (Wiecek *et al.*, 2008). In MCDM, there are several ways to weigh criteria. AHP, analytic network process (ANP), fuzzy measures, Entropy, Swara, Dematel, Standard deviation, and others are some of these methods (Khajavi Pour, Shahraki and Hosseinzadeh Saljooghi, 2021). The methods' calculations is based on criteria and sub-criteria using topological, structural, and ecological data. In GIS, topological, structural, and ecological data can be displayed as layers. The final suitable and unsuitable locations can be determined by overlapping these layers, criteria, and restrictions. After that, a number of factors can be considered to determine a suitable area (Pamučar *et al.*, 2017).

1.2 AREA OF STUDY

Zimbabwe is a landlocked country in southern Africa, lying between latitudes 15° & 23° south and longitude 25° & 34° east with a population of approximately 14 million (United Nations, 2019). Most of the country is comprised of a central plateau extending from the southwest northwards with heights between 1 000 and 1 600 meters above sea level (Makonese, 2016). The highest mountain peak (Inyangani) is at 2 592 meters (Lister and Phil, 1987). The country's high average elevation and topography have a significant impact on temperature and precipitation. The dry season typically lasts from mid-May to mid-August, with daytime temperatures ranging from 20°C to 29°C (Zambuko, n.d). The hot season lasts from mid-August to mid-November, with daytime temperatures ranging from 26°C to 36°C (Nhekairo and Gumbie, 2013). The main rainy season lasts from mid-November to mid-March, with, at times, four to five dry spells in that period (Zambuko, n.d) . The rainy season occurs during the austral summer and typically lasts from November to March. This is followed by a "post-rainy season" from March to May. Between October/November and March, the summer months bring most of the country's precipitation (Bailey, Heinrich and Kruczkiewicz, n.d). Monsoon winds from the Indian Ocean bring high-intensity rainfall to the country during this time, particularly to the exposed eastern region. In the shadow of the eastern highlands, the high elevation plateau in the west, known as the Highveld, experiences cooler temperatures and is shielded from rain, resulting in a climate that is closer to semi-arid (Mungwena, 2002). This semi-arid zone reaches the southern part of the country, where there is a small area in the south-east that is almost desert-like (Mungwena, 2002).

Zimbabwe's land area is of approximately 390 750 km^2 and the country shares its borders with Mozambique, Botswana, Zambia, and South Africa (Nhekairo and Gumbie, 2013). Forests and rangeland make up 69% of the landmass, with forests and woodlands accounting for 42%, protected parks and other conserved sites for 13%, and rangeland grassland for 14% (Nhekairo and Gumbie, 2013). The country has a tropical climate and high humidity, with the southern regions known for their warmth and aridity while the eastern high regions experience cool temperatures and the most elevated precipitation in the country (Baruya and Kessels, 2013). Zimbabwe's climate is suitable for solar energy, with annual solar irradiance ranging from 1857 to 2257 kWh per square meter (van Kuijk, 2012). There are between 6.7 and 8.9 hours of sunshine each day on average in Zimbabwe. The west of the country experiences the most sunshine, with an average of 8.9 hours of sunshine per day. As little as 6.7 hours of sunlight per day are available to the elevated east (Climate Watch, 2020).

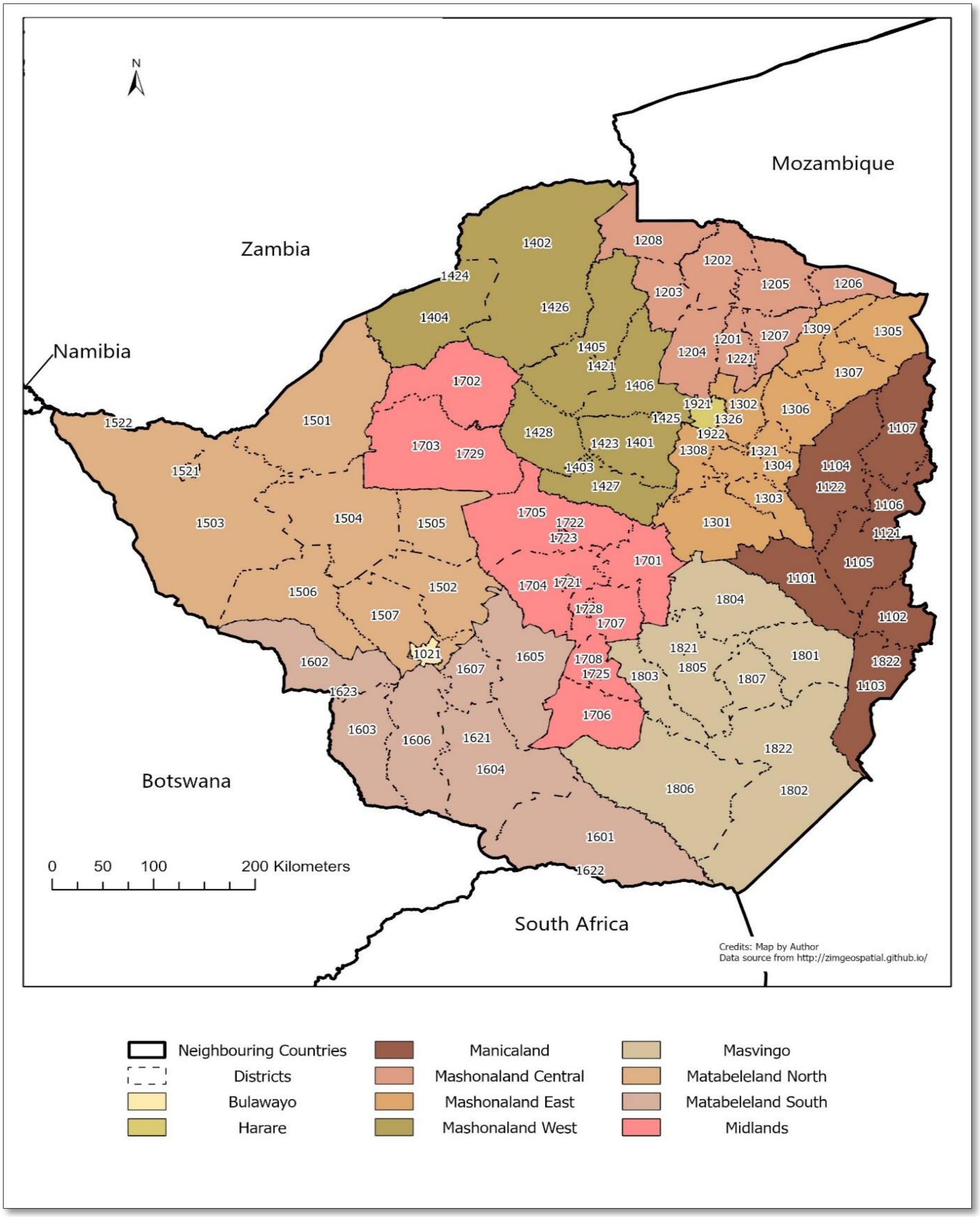
The Zambezi River, the Pungwe River, the Buzi River, the Save River, and the Limpopo River are Zimbabwe's five major rivers (Monda, 2016). Zimbabwe has 16 tributaries and 27 major rivers

(Monda, 2016). There are two main sources of hydroelectric power already operational in the Zambezi River: the Cahora Bassa Dam in Mozambique and the Kariba Dam in Zambia and Zimbabwe (Siccardi, n.d). The Zambezi River is Africa's fourth-longest river, its longest east-flowing river, and the largest African river that enters the Indian Ocean. The stream starts in Zambia and goes through eastern Angola, along Namibia's north-eastern boundary and Botswana's northern line, then, at that point, through Zambia and Zimbabwe to Mozambique, where it crosses the country to the Indian Ocean(Monda, 2016).

The Limpopo River is frequently mentioned as one of Zimbabwe's longest rivers which starts in South Africa and mostly goes east through Mozambique to the Indian Ocean (Monda, 2016). The drainage basin of the river is 415 000 square kilometers in size and measures approximately 1 750 kilometers. The Save River, located in southern Africa, runs from Zimbabwe to Mozambique and is 640 kilometers long. The river flows south and then east from the Zimbabwean highveld to its intersection with the Odzi River, which is approximately 80 kilometers south of Harare (Mberego, 2021).

The following are additional rivers where small hydropower plants could be located: The Pungwe River which is 400 kilometers long. It rises below Mount Nyangani in Zimbabwe's Eastern Highlands and flows through Mozambique's Manica and Sofala provinces before entering the Urema Valley, the Great Rift Valley's southernmost region, where it forms the park's southern boundary (Monda, 2016). The Thuli River, formerly known as the Tuli River, is a significant tributary of Zimbabwe's Shashe River. It flows southward along the rift valley and, after rising close to Matopo Mission in Matobo District, it empties into the Shashe River near the hamlet of Thuli (Monda, 2016). The Thuli is a seasonal river with Mtshabezi, Mtshelele, Sengezane, and Mwewe Waterways as its feeders. Umzingwane River is a significant left-bank tributary of the Limpopo River in Zimbabwe. It starts close to Post Usher in Matobo Area, south of Bulawayo, and streams into the Limpopo Waterway close to Beitbridge, downstream of the Shashe Waterway's mouth and upstream of the Bubye Stream's mouth (Mberego, 2021). The river is an ephemeral river that only flows during rainy seasons (November through March). Its highest flow is between December and February unless dam construction has affected it. Major tributaries of the Mzingwane River include the Insiza, Inyankuni, Ncema, Umchabezi(not to be confused with Mtshabezi), and Mtetengwe Rivers.

Zimbabwe is currently divided into 10 administrative provinces, two of which are cities with provincial status (Marume, 2015) . In this study, the analysis focuses on the district level, which is the third level of administrative boundaries. District-level boundaries are used to break down suitable parts of the country into smaller pieces that can be easily analysed rather than provincial-level boundaries to identify the region where renewable energy is located. Because only a small amount of data is processed as opposed to a large amount, processing the data set for the regions is made simpler. Figure 1-2 page 10 shows the 59 districts in Zimbabwe labelled using codes. The codes are used instead of the original names for easy reference and aesthetic purposes on the maps. The largest district in Zimbabwe is Hwange (1503) with an estimated land area of 29 688 km^2 and the smallest district is Chitungwiza (1922) with an estimated land area of 63 km^2.



Credits: Map by Author
Data source from http://zimgeospatial.github.io/

FIGURE 1-2 ADMINISTRATIVE BOUNDARIES OF ZIMBABWE AND ITS NEIGHBOURING COUNTRIES.

1.3 RESEARCH PROBLEM

The rate of energy expansion in Zimbabwe does not match the increasing demand, introducing a large strain in its existing energy resources (Makonese, 2016). There have been no major developments in the country’s generation sector since the commissioning of the Hwange Coal Plant in 1988. According to the NREP (2019) the power generation capacity is about 1 400 MW against a demand of about 1 700 MW. The country is importing 50 MW power from Hidro electrica de Cahora Bassa (HCB), Mozambique and 300 MW power from Electricity Supply Commission(ESKOM), South Africa (NREP, 2019). The country still relies heavily on coal to generate grid electricity for both the industrial and household areas (Mbohwa, 2002). Although Zimbabwe’s level of industrial development is quite low by global standards, air pollution from the coal plant emissions still poses severe human health risks. Zimbabwe's per capita fossil carbon dioxide emissions are estimated to be 0.8, compared to 0.2 for Mozambique, 3.6 for Botswana, 1.7 for Namibia, 7.5 for South Africa, and 0.4 for Zambia (Climate Watch, 2020). A steady development of renewable energy resources is a crucial step toward overcoming the existing energy challenges in an environmentally friendly manner. These resources have a significant potential to provide solutions to the problem of long-term energy. For instance, the potential of solar photovoltaic (PV) power generation on a 100 km^2 area with 14 percent efficient PV panels, or 0.01 percent of the country's total land area can deliver energy comparable to 30 million tons of oil equivalent (MTOE) in Pakistan (Sheikh, 2009). Finding the suitable locations in Zimbabwe for wind, solar, and small hydropower plants will help determine how much energy these sites could contribute to the country's energy needs. The SDGs are primarily empowered by energy. As a result, it is necessary to investigate the relationship between the energy industry and SDG implementation (Simsek *et al.*, 2020).

1.4 AIM, OBJECTIVES AND RESEARCH QUESTIONS

The aim of the study is to identify suitable locations for renewable energy production plants in Zimbabwe using spatial analysis and data science. The study focuses on wind, solar and small hydropower plants as sources of renewable energy.

1.5 RESEARCH OBJECTIVES

1. To determine the minimum criteria for effective wind, solar and small hydropower energy production in Zimbabwe based on literature review.
2. To identify areas in Zimbabwe that meet the minimum criteria for efficient wind, solar and small hydropower.

1.6 RESEARCH QUESTIONS

Objective 1:

1.1 What are the minimum criteria for effective wind energy production?

1.2 What are the minimum criteria for effective solar energy production?

1.3 What are the minimum criteria for effective small hydropower energy production?

Objective 2:

2.1 What data are required to identify suitable locations?

2.2 What analytical processes should be followed to find the suitable locations?

1.7 RESEARCH PLAN AND DESIGN

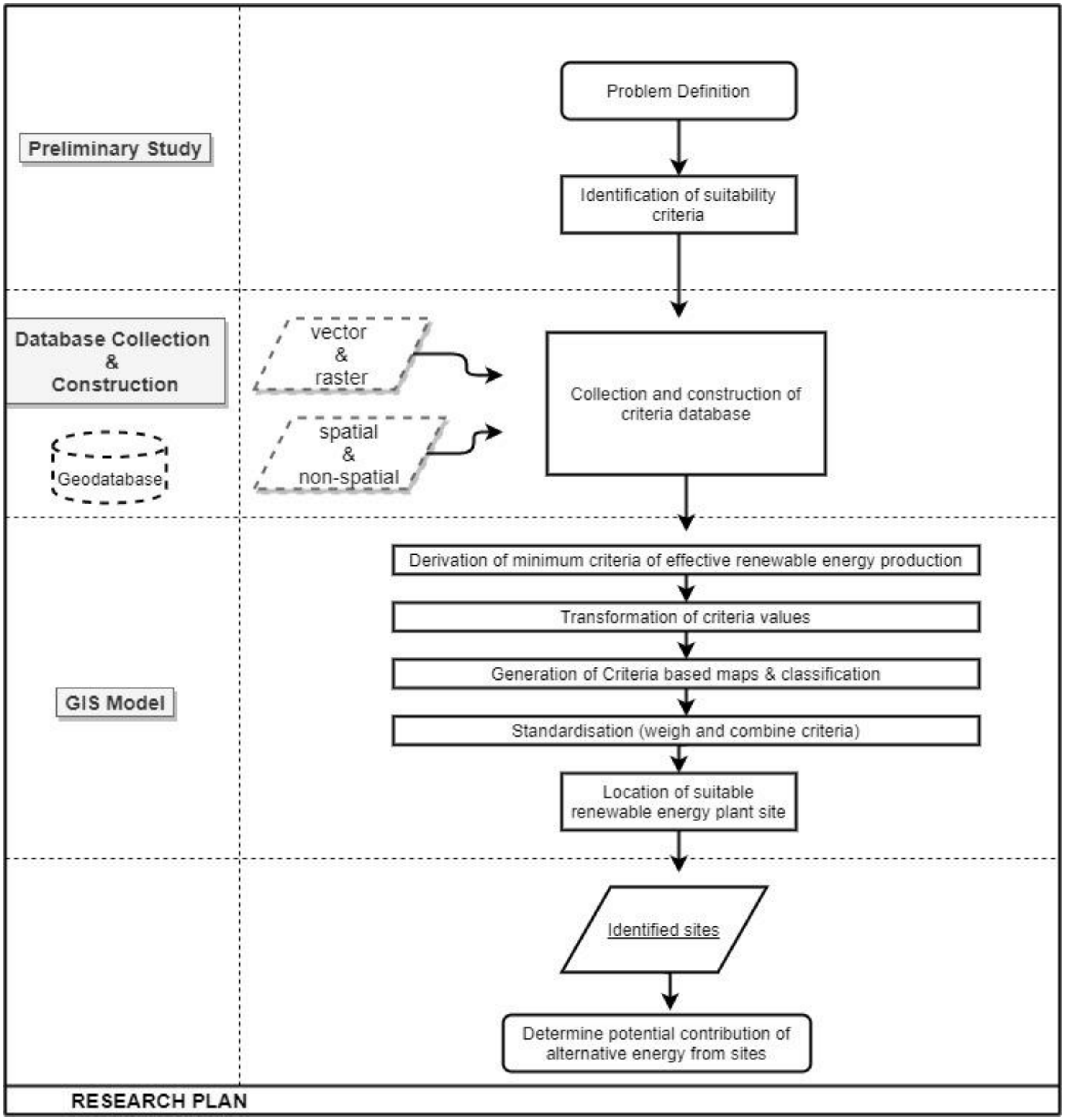


FIGURE 1-3 RENEWABLE ENERGY SITE IDENTIFICATION RESEARCH PLAN ADOPTED FROM **(PAMUČAR *ET AL.*, 2017)**.

Figure 1-3 page 14 shows an adopted research plan of the process of identifying suitable locations for renewable energy production plants in Zimbabwe (Pamučar *et al.*, 2017). The preliminary study of the framework involves problem definition and identifying the suitability criteria. This process produces a detailed and operational description of the difference between the existing situation and the desired situation. In this case, the existing situation is that the country relies heavily on the carbon intensive model and the desire to shift to renewable energy production. The goal is then to identify suitable renewable energy production plant sites based on minimum criteria.

Database collection and construction involve obtaining GIS data such as administrative boundaries, travel infrastructure, land cover, topography etc. Spatial analysis and data science enables the combination of information (e.g., slope, land cover, roads) with value-based information (e.g., expert judgement, surveys, and regulations) using regional scale resource data (Baseer *et al.*, 2017). It is also important to identify additional criteria that might impact the fiscal and technical feasibility of renewable energy production (Sunak *et al.*, 2015). If the collected data does not represent a particular criterion, it then must be derived from a base dataset. Transformation of the criteria values measured in different scales and weighing them relative to the other before combining them to create a suitability layer is a vital process. The suitability layer will reflect the characteristics of the location; hence integration of the subject and spatial requirements depict the renewable energy production plant sites (Pamučar *et al.*, 2017).

1.8 SUSTAINABLE DEVELOPMENT GOALS

The Zimbabwe Voluntary National Review (VNR) (2017) reveals that the government has devoted itself to achieving the SDGs, which are a universal call-to-action to end poverty, preserve the planet and ensure people enjoy peace and prosperity (NREP, 2019). This study focuses on goals related to the use of renewable energy sources, as described below.

Goal 1 of the SDGs seeks to end poverty in all its forms everywhere (Guterres, 2021). Energy is one of the key components of any sustainable development strategy, therefore, increase in production of energy through renewable sources can directly contribute to poverty alleviation (Li, Yang and Lam, 2013). The objective of goal 1 encourages productive decentralization, which will encourage entrepreneurship in poor areas. People in developing nations will continue to suffer from a lack of opportunity to advance in society if adequate energy services are not provided. Deprived of sufficient clean fuels for cooking, people will continue to be exposed to indoor air pollution that has huge impacts on health (Smith, 1993). The target is to ensure that all men and women have equal rights to economic resources and basic services. An indicator of this goal is the percentage of households that have access to basic services.

Goal 2 of the SDGs seeks to end hunger, achieve food security and improved nutrition as well as promote sustainable agriculture. Adequate access to energy makes it possible to grow and prepare food in sufficient quantity to avoid hunger and malnutrition (Struble and L. L. Aomari, 2003). Food, water and energy are inextricably linked where food production needs water, and energy is needed for water extraction, treatment and distribution (Hussey and Pittock, 2012).

Communities require pumped water not only for drinking but also for irrigation and livestock, hence the need for solar irrigation systems (Hussey and Pittock, 2012). The targets of this goal include ending hunger and making food accessible to all, especially in poor communities. This can be achieved by producing sufficient food all year round through doubling the agricultural productivity. Implementing resilient agricultural systems sustained by renewable energy can help improve productivity and sustainable agriculture (Struble and Laurie Lindsay Aomari, 2003).

Goal 3 of the SDGs strives to ensure healthy lives and promote well-being for all. Air and water pollution emitted by the use of fossil fuels is linked to breathing problems, neurological damage, cancer and a host of other health issues (Bagher *et al.*, 2016). Using clean energy enhances health and wellbeing by providing full solar electrification to hospitals and refrigerated vaccines and drugs. The target is to significantly reduce the death and illness statistics resulting from dangerous chemicals and polluted air. This can be measured by household related mortality and contamination of the surrounding air.

Goal 7 of the SDGs seeks to ensure access to affordable, reliable, sustainable, and modern energy for all (Guterres, 2021). Making energy access affordable means that most rural and urban households can be easily connected to the national grid electrical network without financial hindrances. Reliable energy is mandatory in order to function smoothly and develop equitably (Park, 2012). A well-established modern energy system can support as many sectors as possible ranging from businesses, medicine, education, agriculture, communications, and high technology. The indicator of an affordable, universal, and reliable energy service is the percentage of population with access to renewable energy as well as the percentage of population relying on it (Park, 2012). Additional targets involve an increase in the share of renewable energy in the global energy mix, together with doubling the global rate of improvement in energy efficiency. The energy intensity can be measured in terms of primary energy and gross domestic product (GDP) (International energy agency, n.d.).

Goal 11 of the SDGs plans to make cities and human settlements inclusive, safe, resilient, and sustainable. The underlying concept is the development of smart cities which are defined as cities in which Information Communication Technology (ICT) is merged with infrastructure, coordinated and integrated by new digital technologies (Batty *et al.*, 2012). Sufficient and sustainable energy is required to run and manage smart city services that include city administration, education, health, safety, real estate, transportation, and utilities. It entails a smart utility infrastructure which makes existing systems efficient and finds ways of producing and delivering public services (Washburn *et al.*, 2009). One of the targets is to enhance inclusive and sustainable urbanisation and ability for participatory, integrated, and sustainable rural and urban planning management. The pointer of this target is the ratio of land consumption to population increase.

Goal 13 of the SDGs is about taking urgent action to combat climate change and its impact. Changing our energy system and emphasising on the use of clean energy sources is the only way to slow the process of climate change, hence the step taken towards the use of renewable energy that produces little or no global warming emissions (Kuzemko *et al.*, 2016). One of the targets related to this goal is to integrate climate change measures into policies, strategies, and planning. The indicator will be the number of countries committed to identifying policies to improve their capacity to adapt to the adverse effects of climate change. These strategies need to promote climate resilience and develop low greenhouse gas emissions in a way that does not threaten food production.

1.9 SCOPE AND LIMITATIONS

The research aims to develop a raster-based suitability model that will show areas convenient to install wind, solar and small hydropower plants in Zimbabwe. The study does not include other renewable energy resources mentioned in page 1, because there was not enough spatial data to build suitability criteria for them. The building of the model consists of two key processes: identification of the suitability criteria, and construction of the GIS database (Pamučar *et al.*, 2017). Each of the fore-mentioned processes depends on the data required and the accuracy of the approaches. Since this research was carried out during the COVID-19 pandemic it was not possible to collect physical field data. However, secondary, free, and open-source data accessible online was used to carry out the analysis for the research project. The online sources are listed in Table **7**-**1** Data Sources page 114.

1.10 CONCLUSION

There is a need for renewable energy development in Zimbabwe. The NREP was formulated to foster the production of renewable energy power plants connected to the grid or off-grid. The energy resources that can be exploited in Zimbabwe are wind, solar and small hydropower.

Development of the renewable energy plants will support the SDGs and as a result, contribute to poverty alleviation, sustainable agriculture, healthy living, and access to affordable & reliable energy. The next chapter will review wind, solar and small hydropower energy resources and determine the minimum criteria for effective energy production.

The study has the potential to aid in the development of renewable energy in Zimbabwe, as well as assist the government with determining the country’s alternative renewable energy potential.

2 LITERATURE REVIEW

Chapter 2 discusses literature related to wind, solar, and small hydropower resources. The first part of the chapter reviews GIS site selection methods and minimum criteria used to identify suitable sites for wind, solar and small hydropower. The use of remote sensing satellite images as input to GIS is the primary focus of this chapter, as are GIS software, methods, and models. This chapter concludes by examining the integration of GIS with multi-criteria decision analysis techniques.

2.1 WIND POWER

Wind is the result of air in the atmosphere continuously moving with a velocity that is influenced by the local pressure gradient, rotation of the earth, and the irregularities of the surface of the earth (Ragheb, 2011). The kinetic energy of the air mass moving over the surface of the earth can be converted into electrical energy using wind turbines (Archer, 2013). Wind speed, turbulence and direction vary with height above the ground, in respect to the meteorological system or topography (Sunderland *et al.*, 2013). The amount of electricity that wind turbines can produce is related to the wind speed (Ottinger, 2019). Average annual wind speeds that are greater than four meters per second(m/s) are essential for small wind electric turbines whilst utility-scale wind power plants require minimum wind speeds of 6 m/s (Ottinger, 2019).

The average wind speed in Zimbabwe is approximated at 3,5 m/s at a standard height of 10 m above ground level (Makonese, 2016). Some areas that were found with fair average speed included: Bulawayo at 4,4 m/s, Chipinge and Gweru at 3,7 m/s and Harare at 3,4 m/s (Mungwena, 2002). According to Mungwena (2002), the wind power density in Zimbabwe is low and is mostly suitable for small wind electric turbines and water pumping.

There are two basic types of wind turbines. There is the horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) (Saad and Asmuin, 2014). The main rotor shaft and generator for the HAWT are arranged horizontally. The blades of the turbine move perpendicular to the wind, and the power is received through the whole rotation (Bussel and Mertens 2005). The HAWT is known to have good stability as well as high reliability and efficiency. Its drawbacks are the high maintenance costs, complex fabrication & installation, and its high noise levels (Eriksson, Bernhoff and Leijon, 2008). Unlike HAWT, VAWT captures wind from any directions. The VAWT main shaft and generator are arranged vertically allowing the generator to be located at the bottom of the tower (Rishmany *et al.*, no date); hence the installation, construction and maintenance of these turbines becomes easier. There are no adjustments that have to be made, the noise levels are low and it operates at low wind speeds (Eriksson, Bernhoff and Leijon, 2008).

Wind energy projects have the potential to provide communities with several real benefits. These include provision of a relatively safe and affordable source of energy, which contributes to the fight against climate change (Baban and Parry, 2001). Despite the high initial costs, low running – where there is also no input of fuel (Wang and Wang, 2015) and maintenance costs, in the long run, translate to wind turbines being a producer of inexpensive energy. Individuals, groups or communities can fund their own wind turbines. A turbine can sometimes be paid for as part of a larger commercial wind farm development, easing the burden of planning, and building costs (Molnarova *et al.*, 2012). Communities can also generate revenue from wind generation projects, and the revenue can be put toward school budgets, homeowner tax relief, and local infrastructure projects in communities that develop it (Ackermann, 2012).

Wind energy has its downsides. The inability to produce energy on a consistent basis is perhaps the most significant drawback of wind energy, as energy is only generated when there is wind blowing against the turbines (Beig and Muyeen, 2015). The speed of wind also affects the amount of energy turbines produce. As a result, wind energy is not ideal for use as a source of base load energy. Birds, bats, and other flying creatures have slim chances of surviving when taking a direct hit from a rotating wind turbine blade (Wang and Wang, 2015). Some people who live near wind turbines complain about the noise. The generator inside the turbine makes a mechanical hum, and the blades make a "whooshing" sound (Rashid, 2015). Wind turbines are a prominent part of any landscape sound as they move through the air because they need to be built high in order to capture enough wind (Dallas, 2014).

Figure **2**-**1** page 24, illustrates how wind energy may be harnessed and converted to electrical energy. The wind blows over the blades of the wind turbine, exerting a turning force (Archer, 2013). The wind turbine is responsible for converting wind energy into rotational (mechanical) energy. This is a result of the blades turning a shaft inside the nacelle which is housed in the gearbox (Ragheb, 2011). The gear system and coupling step up the rotation speed and transmit it to the generator, which then converts the rotational energy into electrical energy (Ragheb, 2011). The controller senses and monitors the wind direction, wind speed, generator output and temperature, and initiates suitable control signals for action (Saifullah, Karim and Karim, 2016).

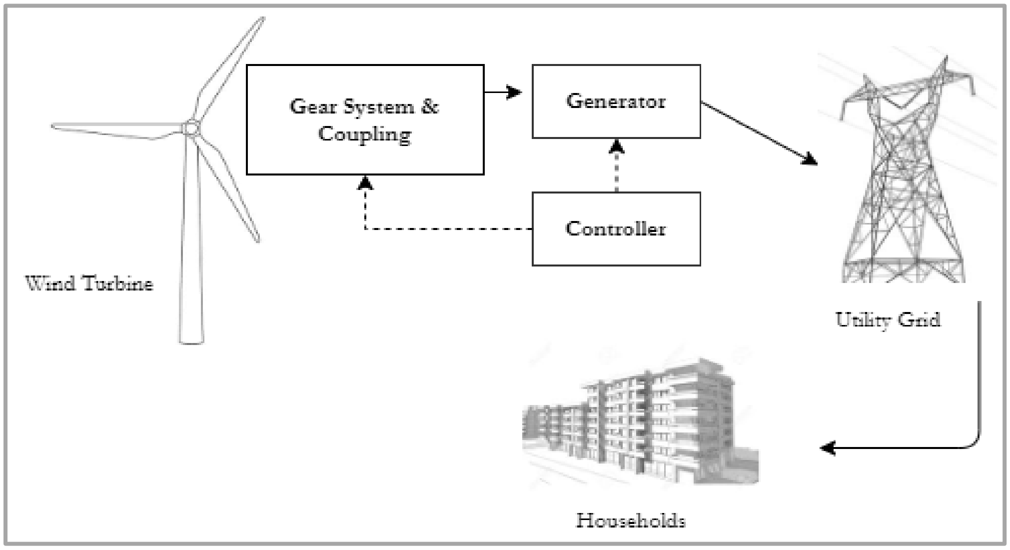


FIGURE 2-1 FLOW DIAGRAM OF WIND POWER ENERGY SYSTEM (SAIFULLAH, KARIM AND KARIM, 2016).

2.1.1 SITE SELECTION METHODS

The site suitability analysis is affected by social, environmental, economic and technical factors (Inglert, 2018). These factors are dependent on the physical topography, infrastructure in place, vicinity, location, and land use constraints and regulations (Brewer *et al.*, 2015). The site selection criteria can be established based on the literature which meets the terms and guidelines implemented nationally and internationally, place like Germany, India and United States of America (Ramachandra and Shruthi, 2007; Van Haaren and Fthenakis, 2011; Sunak *et al.*, 2015). Wind power siting based on MCDM has been implemented using different aggregation methods in several studies (Baban and Parry, 2001b; Bennui *et al.*, 2007; Tegou, Polatidis and Haralambopoulos, 2009; Al-Yahyai *et al.*, 2012; Noorollahi, Yousefi and Mohammadi, 2016).

Noorollahi et al (2016) constructed a decision support system for siting wind turbines in Western Turkey using GIS. Environmental factors were identified through literature review, government laws and regulations. Thereafter, the processing of these factors was carried out using GIS producing spatial data layers for the site selection analysis. Tegou et al. (2009) on the other hand developed an integrated framework for the selection of optimal sites for wind farm installation in an electricity autonomous island in Greece. The framework can be integrated with any GIS package with overlay capabilities. A set of environmental, technical, economic, and social criteria were used to appraise the study area to convey the most economically viable, environmentally friendly, technically feasible and socially acceptable sites.

Bennui et al. (2007) applied GIS integrated with MCDM for siting of a large wind farm in Thailand. The criteria for siting the wind farm were based on wind energy development guidelines and the government regulations of Thailand. Geo-processing tools including image, spatial and 3D analysts were used to perform the site suitability analysis. Al-Yahyai et al., (2012) used the new aggregation operator extension AHP-OWA combination for wind farmland suitability in Oman. The aggregation function was used to generate the scores for different criteria. The approach also included the preparation of physical, socio-economic, technical, and environmental data which was followed by processing in GIS. Baban and Parry (2001) generated siting procedures founded on a review of relevant literature and outcomes from a questionnaire following the rules governed countrywide. The questionnaire, shared to the public and private sectors, was used to define the minimum criteria, policies, and factors necessary to identify suitable location of wind farms in the UK.

2.1.2 MINIMUM CRITERIA FOR SITING WIND POWER PLANTS

The most important criterion to consider when siting a wind power plant is the promise of wind (Ackermann, 2005). The parameter that captures wind power potential at a site is the average wind speed (Baseer *et al.*, 2017). Wind turbines are usually laid out in single or multiple rows depending on the size and shape of the landscape (Janke, 2010). The rows are constructed perpendicular to the prevailing wind direction. Acquiring sufficient data on wind power speed and wind power density of the area results in the identification of optimum locations (Solangi *et al.*, 2018). Climate conditions also play a critical role where the performance of a wind turbine relies on the weather conditions at the site (Pryor and Barthelmie, 2010). The additional factor to consider is that wind speed must be consistent throughout the year. The average interpolated wind speed criterion is given the highest weighting in several reviewed studies (Janke, 2010b; Sliz-Szkliniarz and Vogt, 2011; Van Haaren and Fthenakis, 2011; Baseer *et al.*, 2017).

a) Proximity to power grid

Transmission lines between wind power plants and the electricity transmission network must be short in order to cut down on the construction cost related to cabling and reduce electricity losses (Baseer *et al.*, 2017). Hence, it is advised that wind power plants must be sited close to the electricity grid even though some studies have neglected this criterion in their analysis (Hansen, 2005; Aydin, Kentel and Duzgun, 2010; Latinopoulos and Kechagia, 2015).

b) Proximity to roads

The cost of constructing and maintaining wind power plants can be reduced by ensuring that the proposed wind power site is close to the road network. A considerable number of farm site selection projects consider the areas furthest from the roads less suitable than those closer (Tegou, Polatidis and Haralambopoulos, 2009; Sliz-Szkliniarz and Vogt, 2011; Gorsevski *et al.*, 2012; Latinopoulos and Kechagia, 2015). To ensure electrical safety and minimize visual disturbance, a safe distance of 500 meters must be allowed. As a result, areas that are less than 500 meters and more than 10,000 meters from roads are deemed unsuitable, while other areas are suitable. A buffer zone layer of 500 meters will be created and included in the wind suitability model (Ayodele *et al.*, 2018).

c) Proximity to settlements

Wind turbines located close to settlements can cause problems that are related to noise pollution and visual pollution (Van Haaren and Fthenakis, 2011). The noise emanates from the rotating blades, whilst visual pollution relates to the aesthetics of the landscape. Environmental, social and economic factors have to be considered when siting wind power plants (Wang and Wang, 2015). In Germany, strict regulations regarding the maximum sound pressure are implemented in urban areas in order to tackle the noise pollution (Sunak *et al.*, 2015). It is suggested that buffer distances to reduce visual impacts to suitable levels be defined. The buffer distances are clearly defined in most studies, however, these distances vary from one researcher to another (Baban and Parry, 2001b; Hansen, 2005; Sliz-Szkliniarz and Vogt, 2011; Latinopoulos and Kechagia, 2015).

d) Proximity to natural habitat, wildlife, and fish

Installation of wind power plants can have adverse environmental impacts such as the potential reduction, fragmentation, or degradation of natural habitat, with associated adverse effects on wildlife (Van Haaren and Fthenakis, 2011). Pre-emptive placement of wind turbines away from high wildlife population areas can reduce the ecological impacts (Van Haaren and Fthenakis, 2011). Tactical location of wind turbines outside imperative breeding grounds (near water bodies) and high wildlife population areas can ease the environmental impact (Miller, 2008).

e) Proximity to airports

Wind turbines have an interference with signals of aviation radars, hence it is important that they are placed away from airports (Hansen, 2005; Aydin, Kentel and Duzgun, 2010; Baseer *et al.*, 2017). The turbines also interfere with electromagnetic waves in such a way that they reflect or scatter the waves, thus interfering with telecommunications (Tegou, Polatidis and Haralambopoulos, 2010).

f) Slope

Steep slopes hinder access to wind power plant sites, and can potentially increase construction related costs (Tegou, Polatidis and Haralambopoulos, 2010). Slope has a high impact on establishing the optimum location for wind power plants. Literature shows that the allowable slope threshold ranges from 10% (Baban and Parry, 2001) to 30% (Tegou, Polatidis and Haralambopoulos, 2009). The threshold slope value of 10% is said to be the acceptable benchmark by most researchers, hence regions having higher slope values should be excluded from the surface analysis and regions having lower slopes being graded progressively (Noorollahi, Yousefi and Mohammadi, 2016).

g) Elevation

Elevation is another factor that affects siting of wind power plants. This is because wind tends to blow faster and constantly at higher elevation (Sunderland *et al.*, 2013). Over the mountains, the winds are stronger due to accelerated flow over the upwind mountainous slopes. The retardations caused by terrain features on hilly places influences siting of wind turbines (Hyvärinen, 2018). This is supported by wind conditions observed during field measurements in wind tunnel experiments (Lange *et al.*, 2016)

h) Land cover

Some land cover types are preferred to others. A study by the National Renewable Energy Laboratory (NREL) evaluated how large scale wind farms impact the land, indicating that wind farms situated within the same land use portrayed the same layout configurations (Heimiller and

Haymes, 2001). It was observed that wind farms sited on cropland, pasture and shrub took up less space than those sited on grassland and forestland. Installation configurations used in grassland were not the same in forested areas where clearing of vegetation is mandatory (Janke, 2010).

2.2 SOLAR POWER

Energy harnessed from the sun using concentrated solar power (CSP), solar thermal systems and photovoltaic (PV) technologies is referred to as solar irradiation (Ziuku *et al.*, 2014). The well-regarded technology worldwide is the CSP technology system that makes use of lenses or mirrors, and tracking systems to focus a large portion of the sun's radiation into a small beam (Balghouthi *et al.*, 2016). The concentrated heat is utilised as the heat source for a conventional power plant. CSP is a technology that has the capacity of generating utility-scale electricity, offering firm capacity and dispatchable power on demand by incorporating thermal energy storage (Mendelsohn, Lowder and Canavan, 2012).

CSP plants are projected to yield a global electricity contribution of 7% by the year 2030 and 25% by the year 2050 (Izquierdo *et al.*, 2010). Suitable locations for CSP plants around the world are identified by using the global distribution of direct normal irradiance (DNI) (Brown *et al.*, 2016). Land areas with large solar irradiation are well suited for setting up a large number of solar energy harvesting systems (Trieb *et al.*, 2009). Commercially viable CSP plants are being established based on a DNI of at least 2 000 – 2 800 kWh/m^2/yr. The viability of a DNI value > 1 800 kWh/m^2/yr has also been the subject of debate. Ziuku et al. (2014) discovered that, with a land area of 250

000 km^2, CSP has the capacity to generate 71 GW of electricity in Zimbabwe. It was observed that the country has numerous solar thermal applications in the domestic and industrial sectors (Batidzirai *et al.*, 2009).

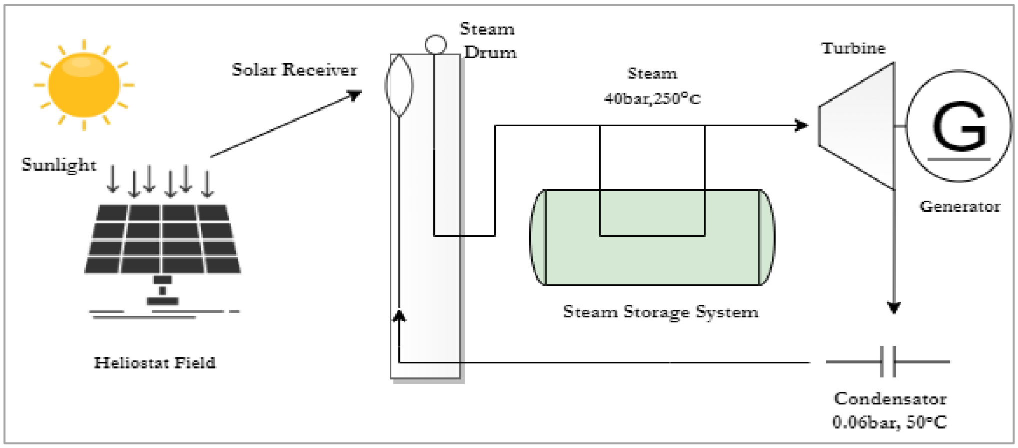


FIGURE 2-2 SCHEMATICS OF A CSP PLANT (PAVLOVIĆ *ET AL.*, 2012).

Figure 2-2 shows how solar irradiation is captured and converted into electricity using CSP technology. There are four types of CSP generation plants, which are:

a) Solar tower method, known as the central receiver system: it attains high temperatures due to the high concentration ratios obtained using different configurations (Silva-Pérez, 2017).

b) The parabolic dish solar concentrator, which has two axis solar tracking systems that concentrate the solar radiations to the thermal receiver positioned on the focal point of the dish collector. The dishes exploit only DNI and have two axis tracking mechanism to ensure a proper focus throughout the day (Orosz and Dickes, 2017).

c) The parabolic trough collector is the most appreciated technology of all CSP concepts. It is a linear concentrating system consisting of elongated, parabolic shaped mirrors and a receiver cylinder placed along the focal axis of the parabola (Orosz and Dickes, 2017). DNI is focused onto the receiver cylinder, where solar energy is absorbed by the heat transfer field (HTF).

d) The Linear Fresnel reflector (LFR) system concentrates solar beam radiation into a receiver tube mounted at the focal point of the Fresnel mirror (Poullikkas, Hadjipaschalis and Kourtis, 2013). Long rows of slightly curved mirrors move separately on one axis to reflect the sun's rays onto the stationary receiver. The major mechanisms of the LFR power generation consist of the linear reflective mirror, receiver tube and transmission system (Wei *et al.*, 2010).

Solar capture and conversion can also be done by photovoltaic (PV) technology (Lewis and Nocera, 2006). A solar cell, also referred to as a photovoltaic cell, is an electrical appliance that transforms the solar radiation directly into electricity by the photovoltaic effect (Bagher *et al.*, 2016). Storing electricity can be obtained by means of batteries (Ibrahim, Ilinca and Perron, 2007). Another storage method would be to store the electrical energy mechanically, where the energy could be utilised to drive turbines that pump water uphill in hybrid renewable energy systems (Schainker, 2004).

There are two categories of PV applications; stand alone and grid connected systems (Gow and Manning, 2000). Standalone systems are used in remote areas that do not have access to main utility grids. This system consists of a module, batteries, charge controller and an inverter to convert DC current from PV modules to AC current, appropriate for home appliances. **Figure 2-3 Overview of a solar PV power plant (Pavlović *et al.*, 2012)** page 35 shows an overview of a solar PV power plant in grid connected systems, where PVs are directly fused to the local electricity grid network (Pavlović *et al.*, 2012). The electricity produced throughout the day can be used instantly or sold to an electricity supply company (Fahrenbruch and Bube, 2012).

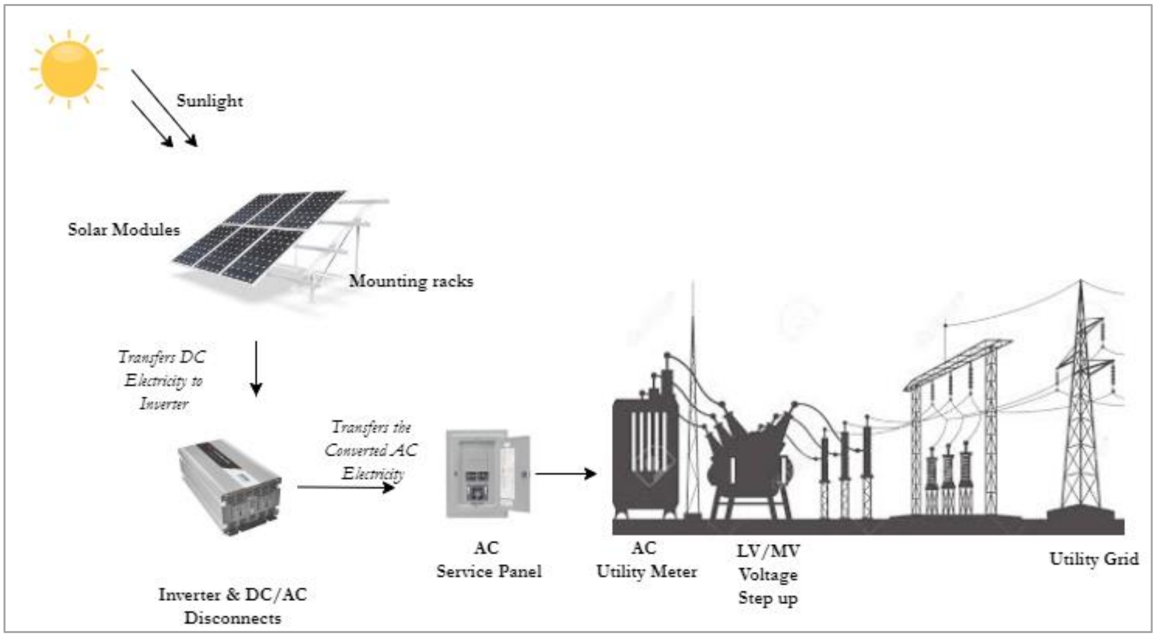


FIGURE 2-3 OVERVIEW OF A SOLAR PV POWER PLANT (PAVLOVIĆ *ET AL.*, 2012)

2.2.1 SITE SELECTION METHODS

Site suitability maps of utility scale solar installation can be influenced by physical and social constraints (Brewer *et al.*, 2015). Integrated frameworks that use mathematical optimisation and simulation have been used to best determine the size and location of solar farms (Noorollahi, Yousefi and Mohammadi, 2016). The Electre-tri method is a technique that has worked well with GIS systems in defining location, orography, climatology and environmental factors that influence the siting of solar power plants (Sánchez-Lozano *et al.*, 2013).

Noorollahi et al., (2016) identified suitable locations for solar energy in Iran using GIS and MCDM. The criteria were influenced by Iran's political divisions, where the land suitability index of each district was determined. Another research was based on a three phase approach, where land use criteria was merged with the solar resource data, and after identifying electricity transmission network constraints, the impact of slope on solar farm installation was investigated (Palmer, Gottschalg and Betts, 2019). The method of generating layers associated with defined constraints by GIS is very common (Qiu *et al.*, 2014). The technique includes identifying the evaluation criteria, determining the weight of evaluation criteria and finally overlaying layers to produce a land suitability map of regions for solar exploitation (Qiu *et al.*, 2014).

Most projects include slope and elevation as basic topographical factors affecting the siting of solar power plants (Bennui *et al.*, 2007; Janke, 2010b; Latinopoulos and Kechagia, 2015). It was suggested that large scale solar power plants be established on flat terrain (Anwarzai and Nagasaka, 2017). Charabi and Gastli,(2011) excluded locations with slope greater than 5%, while

Uyan,(2013) omitted areas with slope higher than 3%, and Noorollahi et al.(2016) excluded lands with slopes greater than 11%. Land use assessments are required before establishing solar energy projects (Jangid et al. 2016; Uyan, 2013). The most common and recommended form of land cover is barren land (Jangid *et al.*, 2016). Shorter vegetation is also preferred over taller vegetation to avoid obstruction of incoming solar irradiation (Janke, 2010). A number of authors consider the proximity to the power grid as an important factor, but, to the knowledge of the researcher, no research has studied whether grid lines have the capacity to fit-in extra distributed generation (Palmer, Gottschalg and Betts, 2019).

The determination of weight for evaluation criteria is often determined by managers, stakeholders, and interest groups (Ramachandra and Shruthi, 2007; Boroushaki and Malczewski, 2008; Hassaan, Hassan and Al-Dashti, 2020).

2.2.2 MINIMUM CRITERIA FOR SITING SOLAR POWER PLANTS

Energy generation system for solar power plants is determined by several spatial variables. For example, the electricity generated from solar PV systems is correlated with solar irradiation (Al Garni and Awasthi, 2017). Land topography can also influence solar irradiation distribution across the globe.

The most important factor for establishment of a solar power plant is the solar irradiation. It may be generally represented as Global Horizontal irradiance(GHI), which is the sum of direct normal irradiance(DNI), diffuse horizontal irradiation(DHI) and ground reflected irradiation (Yang *et al.*, 2013). There are many factors that contribute to high and efficient yielding of solar energy by an arrangement of photovoltaic planes (Ahmad, Murtaza and Sher, 2019). Regions having high insolation capacity influence the placement of solar power plants. The concentration of radiation determines the magnitude of electrical output from the system (Janke, 2010).

There are negative impacts that come with installing solar power plants near settlements. For example, it may alter the landscape in practical and aesthetic ways, including loss of local habitats and wildlife. Therefore, solar power plants must be sited away from residential areas (Uyan, 2013).

a) Aspect

The direction solar panels face plays a key role in determining the exposure to the received solar radiation (Kacira *et al.*, 2004). According to research in the southern hemisphere, solar panels must be oriented toward geographic north in order to maximize solar energy harvesting (Doorga, Rughooputh and Boojhawon, 2019).

b) Elevation

The height of the region from sea level is inversely relative to the viscosity of the atmosphere which influences the characteristics of solar potential (Doorga, Rughooputh and Boojhawon, 2019). The entry of long and short wave energy is influenced by the thickness and the compounds to the atmosphere (Noorollahi, Yousefi and Mohammadi, 2016). Atmospheric thickness is high at low elevations, hence elevated areas experience greater solar radiation potential than lower regions (Noorollahi *et al.*, 2016).

c Proximity to roads

Distance to roads is an important consideration when siting solar power plants. In a study conducted by Janke (2010), roads were included in the GIS data, and a 1500 m-resolution distance grid was created. Locations that were closer to existing roads were thought to be better suited for construction and maintenance. Proximity to roads was considered as one of the factors that influences the decision problem in a research (Sánchez-Lozano *et al.*, 2013)

2.3 SMALL HYDROPOWER ENERGY

Hydroelectric power is a result of a conversion of energy from flowing water into electricity (Demirbas, 2005). Makonese (2016) states that hydropower plants can be categorised into three sizes: micro (<100kW), small (100kW- 30 MW), or large (>30MW). Furthermore, hydropower potential of Zimbabwe has been approximated at 18 500 GWh per year (Makonese, 2016). The major source of hydropower in the country is the Zambezi River, which has an estimated total capacity of 7 200 MW. Apart from the Kariba hydropower plant, other small hydro plants are currently connected to the national grid. These include 750 kW Rusito Scheme in the Chimanimani area, Pungwe and Nyamhingura system in the Honde Valley, Aberfoyle (35 kW), Claremont (250 kW), Kwenda (75 kW), Mutsikira (3 kW), Nyafaru (20 kW), Sithole-Chikate (30 kW) and Svinurai (10 kW) (Mbohwa, 2002).

There are three types of conventional hydropower plants, namely, pumped storage, diversion and impound (Mohamed, 2021). The impoundment hydropower plant is the most common large hydropower system, where water from the reservoir flows through a turbine, and activates a generator to produce electricity (Pérez-Díaz *et al.*, 2015). The diversion system, which is also known as "run-of-river", diverts a portion of a river through a penstock in order to use the natural descent of the river bed to produce hydropower (Anderson *et al.*, 2015). The water flow channelled to the turbines is regulated by gates, valves and turbines (Jha, 2010). Pumped storage hydropower is another type of hydropower which stores energy by pumping water from a reservoir at a lower elevation to a reservoir at a higher elevation (Botterud, Levin and Koritarov, 2014). When energy is in demand, the water in the upper reservoir is released back to the lower reservoir, thereby turning the turbine to produce electricity (Dujardin *et al.*, 2017).

Figure 2-4 page 39 shows how energy is produced in a run-of-river hydro-power system. The electrical energy is produced when water diverted from a flowing water body hits a turbine that converts the potential energy of water into mechanical energy of rotation (Paish, 2002). The contact between the water and runner blades results in a torque applied to the runner. The runner is attached to the driving shaft so as to drive an electric generator (Lajqi, Lajqi and Hamidi, 2016). The amount of energy produced depends on the flow of water and elevation of the inlet (Nasir, 2013). The plant consists of water intake, pen stock, and hydro-turbine, together with a control system and power house (Paish, 2002). According to (Punys *et al.*, 2011): the trash rack removes the silt from diverted water to minimize erosion; the fore-bay provides storage capacity for meeting immediate water demand; the penstock is a water transmission system to transport water to the turbine; the powerhouse building is a simple assembly casing the generating units and control arrangement; and the tailrace is a flow discharging conduit of open channel that transports the water out of the turbine to the river. Hydropower turbines are classified by their mode of operation and can either be impulse or reaction turbines (Paish, 2002)

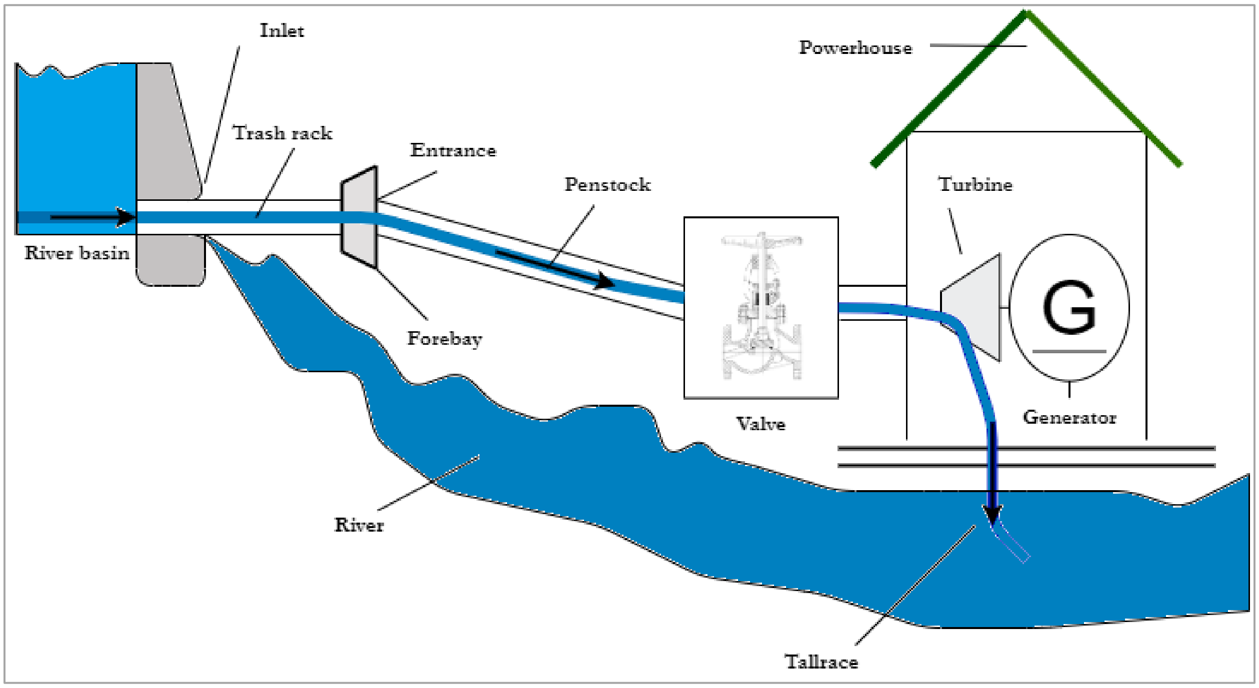


FIGURE 2-4 SCHEMATIC DIAGRAM OF SMALL HYDRO PLANT (BERISHA, HOXHA AND MEHA, 2017).

2.3.1 SITE SELECTION METHODS

The storage of water in a reservoir, through the use of dams or impoundments, is referred to as conventional hydropower. To generate electricity, the reservoir's released water flows through a turbine. This section discusses this kind of method for producing electricity. Small hydropower site selection is carried out with the aid of GIS technology (Rojanamon, Chaisomphob and

Bureekul, 2009). Conventional hydropower is the process of storing water in a reservoir using dams or impoundments; The water released from the reservoir flows through a turbine to generate electricity. This method of producing electricity is the subject of discussion in this section. GIS technology is used to select small hydropower sites.

A number of concepts for extraction of terrain characteristics such as slope, waterhead, and drainage network from DEM's are made possible using GIS geo-processing tools (Reed, 2003; Paz and Collischonn, 2007). Palla et al. (2016) used the integrated GIS method to calculate run-of-river hydropower potential of a single turbine. Remote sensing data was used to extract and map water resources and vegetation coverage to explore potential locations for small hydropower projects in India (Dudhani, Sinha and Inamdar, 2006). Kadellis (2007) considered the technical and economic factors to investigate existing and proposed small hydropower plants in Greece. Other small hydropower site selection projects did not include hydrologic and economic analysis (Belmonte *et al.*, 2009; Rojanamon, Chaisomphob and Bureekul, 2009; Larentis *et al.*, 2010; Goyal, Singh and Meena, 2015)

Ramachandra and Shruthi (2007) developed a GIS application that could assess small hydropower resources by acquiring existing distribution and capacity data of small hydropower plants in India. Belmonte et al.(2009) mapped the potential of small hydropower using GIS to calculate the annual mean flow and topographic drop of the channel. Digital Elevation Model (DEM) was used to outline the stream network and to establish the mean slope, elevation, area and length of the channel of a given catchment (Palla *et al.*, 2016). Criteria for siting small hydropower potential zones within a catchment were established and weighted by Goyal, Singh and Meena (2015). The water flow of river channel and establishing proper flow in the river depends upon the amount of precipitation received over the catchment area (Goyal, Singh and Meena, 2015)

2.3.2 MINIMUM CRITERIA FOR SITING SMALL HYDROPOWER POWER PLANTS

a) Precipitation

It is crucial to have a constant stream flow when planning to install SHP plant using the run-of-river method which directly uses stream flow (Kuriqi *et al.*, 2019). Hence, it is important to consider the precipitation levels associated with the different areas suitable to site the plant. Runoff data is derived from precipitation data, with consideration of losses such as evaporation and/or infiltration.

b) Proximity to rivers

Location of rivers is an important criterion in siting SHP plants. Modelling of SHP suitable sites critically depends on availability of adequate information on the river channel, catchment area, river runoff and other attributes (Kuriqi *et al.*, 2019).

c) Elevation

Elevation data plays a role in deriving other topographic factors, such as, natural head, which are required to site SHP plants (Yi, Lee and Shim, 2010). The data allows delimitation of the catchment area and determine its theoretical hydrographic network.

The criteria for siting solar power plants relating to proximity to power grid, major roads, proximity to settlements and land cover is similar to that outlined, in this study, for wind power and SHP. Refer to Section 2.1.2 page 26.

2.4 MULTI-CRITERIA DECISION ANALYSIS (MCDA) & GIS

Multicriteria decision analysis is a method that involves evaluation of multiple conflicting criteria in decision making (Linkov *et al.*, 2004). It allows the decision maker to generate qualitative valuations for determining (1) the performance of each alternative with respect to each criterion (2) relative significance of the criterion with respect to the overall objective of the problem (Deng, 1999). MCDA in a raster data model permits more clearance among variables where the model selection can lead to diverse optimal solutions (Eastman, 1999).

MCDA has different approaches. The following methods are widely used in conjunction with GIS: Analytical Hierarchy Process (AHP) and Weighted Sum Model.

2.4.1 ANALYTICAL HIERARCHY PROCESS(AHP)

The AHP method established by wind and Saaty is broken down to stages, as illustrated in page 43 (Wind and saaty, 1980).

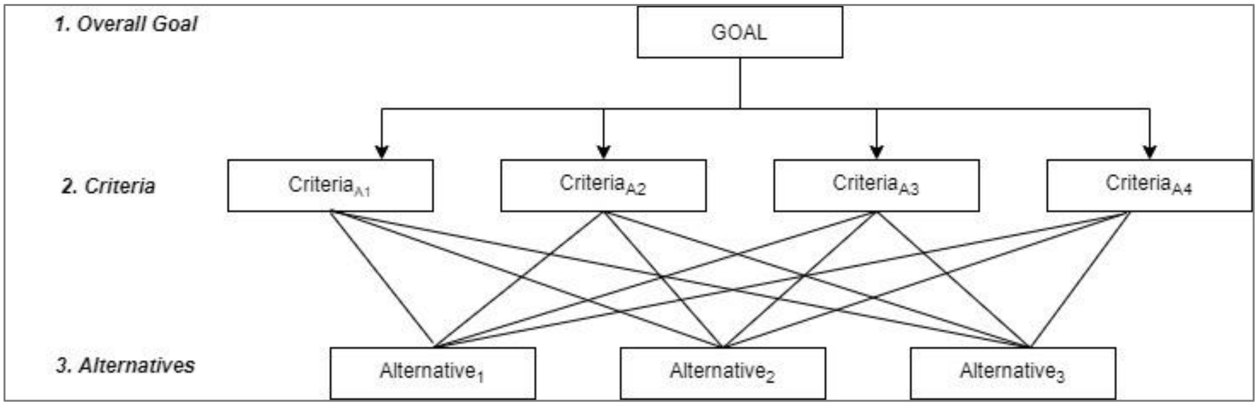


FIGURE 2-5 DIAGRAM DEPICTING HIERARCHY OF THE AHP METHOD(WIND AND SAATY, 1980).

The first stage involves structuring the decision problem into a hierarchy. Composing this hierarchical structure provides an overall view of the dynamic relationships and helps assess whether the elements in each level are comparable (Wind and Saaty, 1980). At the top level of the hierarchy is the overall goal of the problem. The next level has the criteria showing the various possibilities from which the alternatives can be considered. The lower level is composed of decision alternatives, which are the various choices that one can make.

The second stage involves the calculation of priorities of each criterion, with respect to goal and priority of each alternative with respect to one ideal criterion. The rating of the priority is carried out by assigning a weight between 1 (equal importance) and 9 (extreme importance) to the more important criteria, where the reciprocal of this value is assigned to the other criterion in the pair.

The third stage involves carrying out a consistency check of the pairwise comparison matrix which is generated using pairwise comparison method with a 1-9 fundamental scale (Saaty, 1980). For pairing within each criterion, the most suited option is given a score again, on a scale between 1 (equally good) and 9 (better), whilst the other option in the pairing is given a rating equal to the reciprocal value.

In the last stage, a set of priorities is summarised to make the final decision. The alternative that has the highest priority with respect to the goal is the final decision choice. The option scores are joined with the criterion weights to produce a final score for each option. Table **2**-**1** Pairwise comparison scale for AHP (Saaty 1980) shows the scale for pairwise comparison in AHP (Saaty and Vargas, 2012).

TABLE 2-1 PAIRWISE COMPARISON SCALE FOR AHP (SAATY 1980).

Degree of importance	**Definition**	**Explanation**
1	Equal importance	Two candidates contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one candidate over another
5	Strong importance	Experience and judgement strongly favour one candidate over another
7	Very strong importance	One candidate is favoured very strongly over another
9	Extreme importance	The evidence favouring one candidate over another is the highest possible order of affirmation
Degrees of 2,4,6,8 can be used to express intermediate values. **Degrees of 1.1, 1.2 ,1.3, etc. can be used for alternatives that are very close in importance**		

The AHP compared to other multicriteria methods is flexible and provides the ability to check for inconsistencies. The data input in the pairwise comparison form is found to be straight forward and convenient. By breaking down the overall objective into constituent parts and building the hierarchical structure, the importance of each element becomes very clear (Alkaradaghi *et al.*, 2021).

Despite the popularity of this method, various researchers have expressed concern over several issues in the methodology. Ranking irregularities can occur when variants are used. AHP can be considered as a complete aggregation method of the additive type, where the compensation between good scores on some criteria and bad scores on the other criteria can occur, leading to a loss of information by such aggregation (Ossadnik, Schinke and Kaspar, 2016).

2.4.2 WEIGHTED SUM MODEL (WSM)

Geographic Information system (GIS) is a system encompassing computer hardware, software and data that enables manipulation, analysis, visualisation, and dissemination of spatial and non-spatial data (Herring, 1991). Inverse Distance Weighting (IDW) interpolation technique produces estimates that are based on values at nearby locations weighted only by distance from the interpolation location (Achilleos, 2011). IDW assumes that things that are close to another are more alike than those further apart (Tobler, 2004). To predict a value for an unknown location, IDW uses the measured values surrounding the prediction location. The values measured close to the prediction location have more influence on the predicted value than those furthest. Weighted sum model (WSM) also known as weighted linear combination is a MCDA method that evaluates several alternatives with respect to a number of decision criteria (Kamano, 2018). This method is embedded in ARCGIS Pro as a geo-processing tool having the ability to weight and combine multiple inputs to create an integrated analysis. This tool is applicable only when all data is expressed in the same unit or scale.

WSM can be ranked for alternatives(A_1,A_2,….A_m) by n criteria(C_1,C_2…C_n) shown in **Table 2-2 Ranking of the WSM method** page 42.

TABLE 2-2 RANKING OF THE WSM METHOD (UNIWERSYTET W BIAŁYMSTOKU AND ROSZKOWSKA, 2013).

		Criteria		**WSM Score**
	C_1	C_2	. . .	C_n
Weighting	w_1	w_2	. . .	w_n
A_1	a_{11}	a_{12}	. . .	a_{1n}
A_2	a_{21}	a_{22}	. . .	
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
A_m	a_{m1}	a_{m2}	. . .	a_{mn}

Table 2-2 shows the degree in which alternative(A_1, A_2,….A_m) satisfies criterion C_j,(j=1,…,n) and is denoted by a_{ij}. All the elements of the decision matrix have to be converted to the same unit

or scale(the interval [0, 1] is the basic interval). Suppose w_j denotes the relative weight of the importance of the criterion C_j and a_{ij} is the performance value of alternative A_i when evaluated in terms of criterion C_j. The overall importance of alternative A_i is defined as:

$$A_i = \sum_{j=1}^{n} w_j\, a_{ij},\ for\ i = 1,2,3,\ldots.,m.$$

The overall score, $A_1^{\text{WSM-score}} = (a_{11} \text{ x } w_1) + (a_{12} \text{ x } w_2) + \ldots + (a_{1n} \text{ x } w_n)$.

In GIS, multiple raster inputs representing multiple factors can be easily combined, thereby incorporating their weights or relative importance. The weighted sum tool does not rescale the reclassified values back to an evaluated scale, hence the analysis maintains its resolution. The values of continuous rasters are grouped into categories based on suitability. It works by multiplying the designated field value for each raster by the specified weight. It then sums all the input rasters together to create an output raster.

2.5 CONCLUSION

The minimum criteria for siting suitable wind, solar and small hydropower plants, pursuant to objective 1 page 10, were established from supporting literature. The simple data structures are said to make the construction of a GIS raster data model simpler, quicker, and more effective. It is possible to construct a raster suitability surface that identifies the areas in Zimbabwe that are suitable for wind, solar, and small hydropower plants by integrating the AHP and the weighted sum method.

3 Methodology

Chapter 3 describes the methods used to build a suitability model for siting of renewable energy power plants in Zimbabwe. It describes the processes followed to build the ideal index model within a GIS database. It further explains the ways of obtaining the scores and weights within the criteria, as well as building a suitability raster surface that contains the exclusion and rated areas within the boundaries of the country.

3.1 TYPE OF STUDY

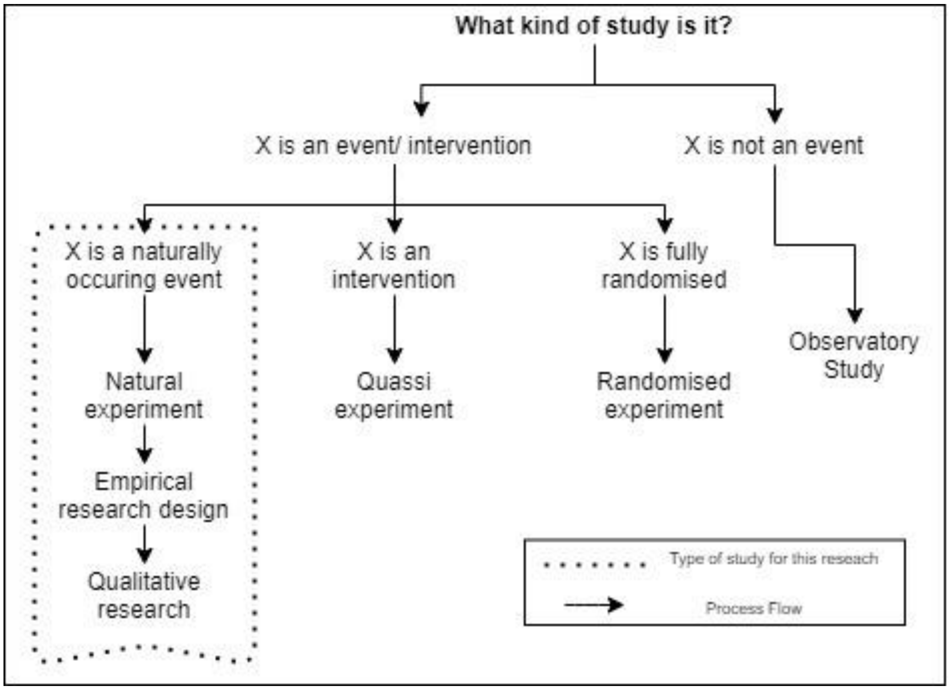


FIGURE 3-1 RESEARCH DESIGN FRAMEWORK (DE VOCHT *ET AL.*, 2021).

Figure 3-1 Research design framework (de Vocht *et al.*, 2021) demonstrates the type of study used in this research. The aim was to test and observe how GIS can be used to identify suitable locations for renewable energy plants using the integration of AHP and WSM. A GIS raster model was created to generate a suitability index / suitability map that highlighted the optimal sites for the renewable energy plants. Due to the comprehensive data required to build the GIS model, a scientific method was applied to the geographic data using the following steps:

1. Observing the phenomena and creating question-based observations. Maps and other methods of geo-visualization provided means of observing the data, making it possible to quickly recognize patterns and ways in which the data could be analysed.
2. Selecting and using existing case studies and theories on site selection methods used to identify renewable energy power plants.
3. Acquiring and manipulating data required to perform the spatial analysis.
4. Performing the experiment and recording results (natural experiment as illustrated in **Figure 3-1**) page 48.

Figure **3-2** gives a general concept of the analytical process that was followed to identify suitable sites for solar, wind, and small-hydropower plants in Zimbabwe.

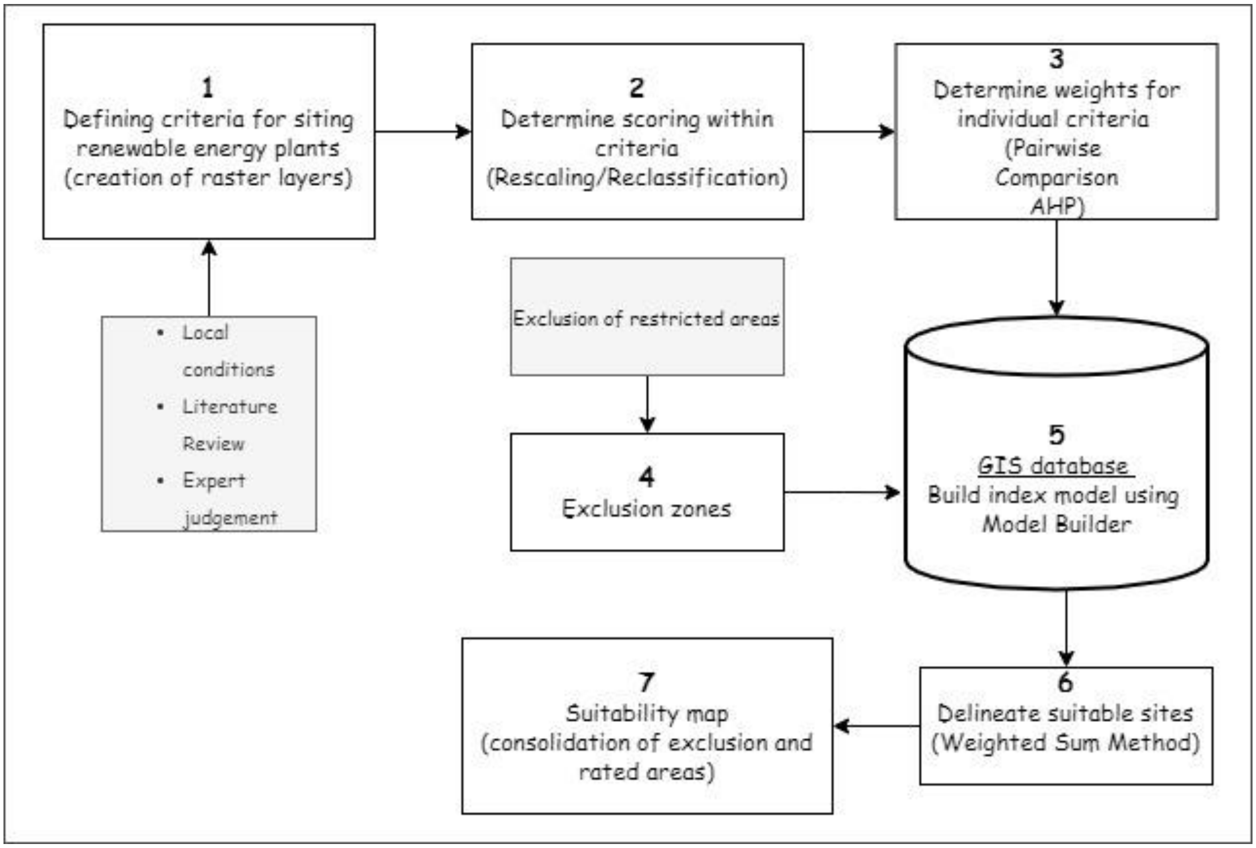


FIGURE 3-2 METHODOLOGICAL FRAMEWORK OF SITING WIND, SOLAR & SHP PLANTS ADOPTED FROM (BASEER *ET AL.*, 2017).

3.2 MINIMUM SUITABILITY CRITERIA FOR WIND, SOLAR, AND SHP POWER PLANTS

The first objective was to determine the minimum criteria for effective wind, solar, and small hydropower production as mentioned in Section 1.5. The data for the criteria was sourced from online portals as secondary data and converted into appropriate formats that could be manipulated in ArcGIS Pro. The criteria maps were represented on a 6-point scale ranging from extremely suitable to unsuitable.

3.2.1 WIND DATA

Wind data for Zimbabwe was extracted from weather forecast data generated by GOES-R satellite imagery. It was downloaded from ERDDAP servers[1], under the global forecast system (GFS) atmospheric model. A data query form was generated, and thegraph type was set to vector (in order to generate vector shape file in grid format). Vector X was set to ugrd10m, and Vector Y was set to vgrd10m,(where ugrd10m is eastward wind velocity at 10 m above the ground and vgrd10m is the northward wind velocity at 10 m above the ground). The area of interest was selected from the map and the data was exported as a CSV (comma separated variable file). Values for wind direction and wind speed were generated from the data in a spreadsheet. To calculate these variables, the arctangent(atan2) was applied with the arguments U & V as shown below.

EQUATION 3-1

$$\boldsymbol{Wind\,direction} = \boldsymbol{Atan2}(\boldsymbol{vgrd10m}, \boldsymbol{ugrd10m})$$

EQUATION 3-2

$$\boldsymbol{Wind\,speed} = \sqrt{\boldsymbol{ugrd10m^2} + \boldsymbol{vgrd10m^2}}$$

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[1] https://pae-paha.pacioos.hawaii.edu/erddap/griddap/ncep_global.graph

The CSV file was exported to a geo-database table in ArcGIS Pro and visualized as a point grid layer. The point grid layer was converted to raster format using the inverse distance weighting interpolation (IDW).

3.2.2 PRECIPITATION DATA

Precipitation data of Zimbabwe was downloaded from WorldClim[2] which is a database of high spatial resolution global weather and climate data. The variable of interest is the average minimum precipitation (mm) between 2010 - 2018 at a spatial resolution of 2.5 arc minutes.

3.2.3 SOLAR DATA

Solar data for Zimbabwe was sourced from the Global Solar Atlas[3], which is published by the World Bank Group and prepared by Solargis. The solar resource map provides estimated solar energy available for power generation and other applications. The parameter used for energy yield calculation for CSP and PV technologies in the study was the DNI. The DNI [kWh/m^2] data and other parameters are given as raster in two formats: GeoTIFF and AAIGRID. The DNI denotes the long-term average of yearly/daily sum of direct normal irradiation at a nominal spatial resolution of 250 m.

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[2] https://www.worldclim.org/data/worldclim21.html

[3] https://globalsolaratlas.info/download/zimbabwe

3.2.4 MAJOR ROADS

The primary road network of Zimbabwe was attained from Open Street Map[4] data made by World Food Programme (WFP). The dataset consists of highway, primary, secondary, and tertiary road networks. The primary roads, renamed as major roads in this study, included other attributes such as road width, condition, and surface type.

Figure **3**-**3** page 54 shows the first set of criteria including wind, precipitation, solar and major roads data of Zimbabwe. The extremely suitable wind speeds for small-scale utility generation are found in Matabeleland South province, and the highly suitable wind speeds are located along the central plateau extending from Bulawayo, Midlands, to Mashonaland East. The Mashonaland West, Manicaland, and Masvingo are sited as unsuitable for wind power production. The precipitation data shows that the northern part of the country receives more precipitation than the rest of the country, making that area most suitable for establishing a run of river SHP plant. The solar data shows high solar irradiation in the Matabeleland North, Matabeleland South, Bulawayo as well as the Midlands provinces. The road network data is densely populated in Harare, Bulawayo and Masvingo province.

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[4] https://geonode.wfp.org/layers/geonode:zwe_trs_roads_osm

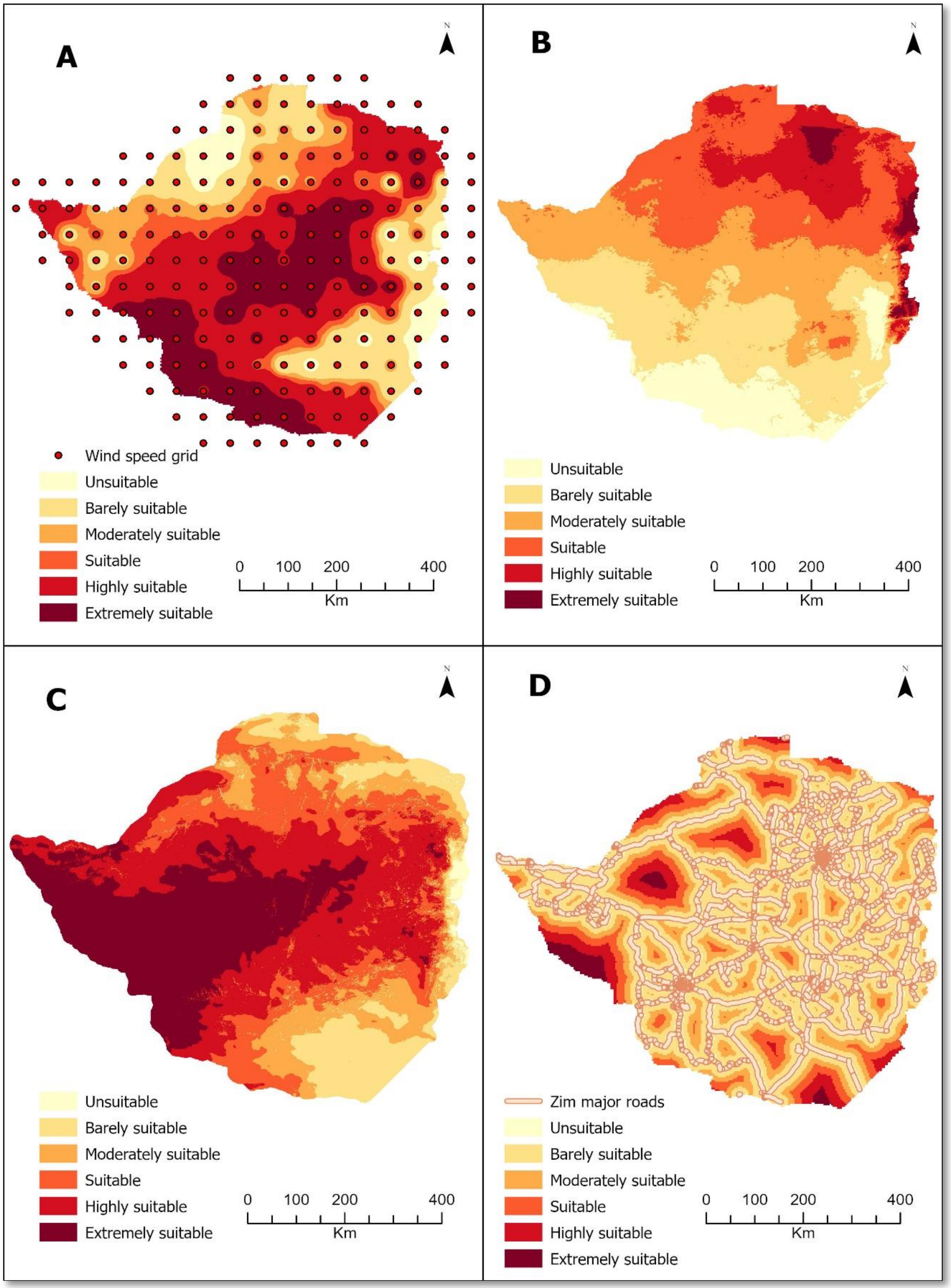

FIGURE 3-3 WIND(A), PRECIPITATION(B), SOLAR(C) & MAJOR ROADS(D) CRITERIA MAPS.

3.2.5 AIRPORTS

The airports data was obtained from OurAiports.com[5] community website. Zimbabwe has 3 international airports namely: Joshua Mqabuko Nkomo Airport located in Bulawayo, Robert Gabriel Mugabe Airport located in Harare and the Victoria Falls Airport located in Victoria Falls. The country also has 11 unscheduled and 2 military airports that are currently operational.

3.2.6 POWER GRID

The Zimbabwe Electricity Transmission Network data was obtained from the AICD[6] study led by the World Bank. The network represents medium and high voltage transmission lines, and consists of the following attribute data: transmission line capacity in kilovolts, name of the locality where it starts and where it ends, and status of link (existing, planned, proposed, under study). Existing and future transmission lines range from 66 kV to 400 kV. The cross-border interconnectors are also shown including lines to Botswana, Mozambique, South Africa, and Zambia.

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[5] https://ourairports.com/data/

[6] https://datacatalog.worldbank.org/search/dataset/0039590

3.2.7 SETTLEMENTS

The settlements data was derived from the population census data that was taken from Zimbabwe data portal[7] supported by the World Bank. The settlement data shows that urban population densities are high and are positively correlated with electricity network density.

3.2.8 WATER-BODIES

The waterbodies data was obtained from the Regional Centre of Mapping Resources for Development[8](RCMRD). The main waterbodies, including Lake Kariba and Victoria Falls, are located along the western border of the country with Zambia. The key river systems of Zimbabwe include the Zambezi, Limpopo, Runde and Save along with their several tributaries.

Figure 3-4 page 58 displays the airports, power grid, settlements, and water-bodies criteria maps. The airports data shows that the country has several unscheduled airports and aerodromes referred to in Section 3.2.5, with three international airports located in Bulawayo, Harare, and the Matabeleland North province. These airports and aerodromes are distributed throughout the country with a great number of them located in the Matabeleland North province as well as the Mashonaland East province. The national power grid data shows a distribution stretching from Matabeleland North, Matabeleland South, Midlands, Mashonaland West, Mashonaland Central to some parts in Manicaland and Masvingo. A large portion of Masvingo and Manicaland is not

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[7] https://data.humdata.org/dataset/zimbabwe-settlements

[8] http://geoportal.rcmrd.org/layers/servir%3Azimbabwe_rivers

covered by utility grid network. The settlements data shows a concentration of people in the urban areas around Harare and Bulawayo. Further away from the major cities, the population is evenly distributed. Matabeleland North is the province with the least cluster of population. The water-bodies data shows a dense network of rivers and tributaries distributed throughout the country.

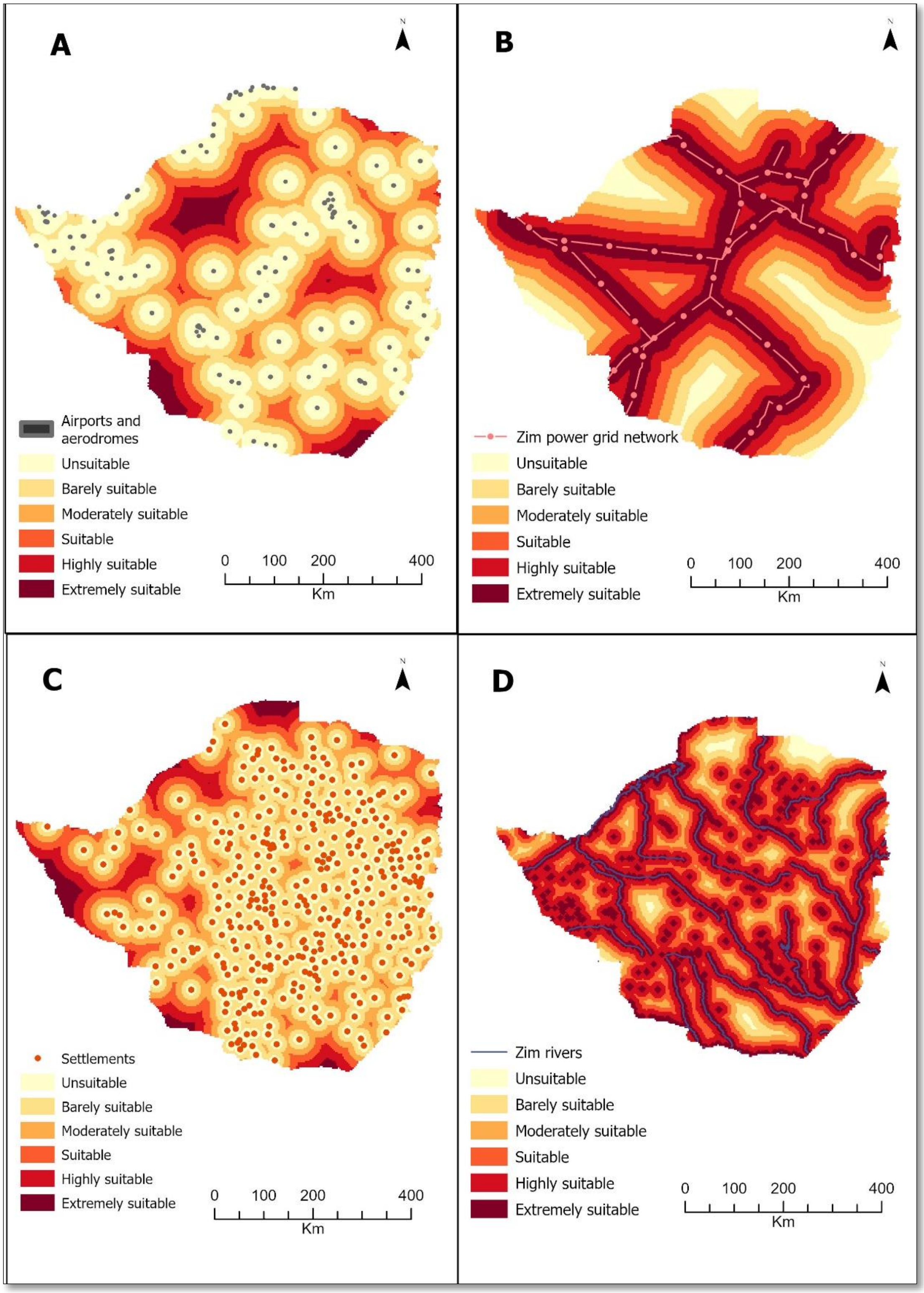

FIGURE 3-4 AIRPORTS(A), POWER GRID(B), SETTLEMENTS(C), AND WATER BODIES(D) CRITERIA MAPS.

3.2.9 ELEVATION

The elevation data was derived from the shuttle radar topography mission[9](SRTM) which is a satellite radar system used to acquire topographic data. The data characterises 30 m images of Zimbabwe created through mosaicking tiles and clipping to the extent of the country. The data was used to derive two other raster criteria maps, that is, slope and aspect.

3.2.10 LAND COVER

Land cover data was obtained from RCMRD[10] geo-portal as a raster with 30 m spatial resolution. The raster surface was categorized according to suitability for development. The most suitable places contained short vegetation, such as shrubs, grassland, and bare areas, which would not obstruct wind or affect solar insolation. The areas that were less suitable contained sparse vegetation, and aquatic vegetation, which would make it difficult to develop the renewable energy plants due to their environmental significance. Places that were not suitable contained trees, cropland, built-up areas, and open water that would make it impossible to develop due to their inaccessibility, or present development.

Figure **3**-**5** page 61 shows the elevation, land cover, slope, and aspect criteria maps. The elevation data shows that the central part of the country has high elevation because of the central plateau. Masvingo has the most extremely suitable land due to its flatness including parts of Mashonaland

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[9] https://opendata.rcmrd.org/datasets/zimbabwe-srtm-dem-30-metres/explore

[10] http://geoportal.rcmrd.org/layers/servir%3Azimbabwe_sentinel2_lulc2016

West and Matabeleland North. The most suitable land cover type chosen for siting of renewable energy plants were shrubs, grassland, sparse vegetation, and bare areas. The land cover data shows that most of the country is covered by shrubs and grassland although, due to map scale, it was not possible to visualise the sparse vegetation and the bare areas. The slope data shows that steep slopes are found in part of Matabeleland North and along the Mashonaland West, Mashonaland Central and Manicaland provinces. Literature suggests that the mounting of solar panels in Zimbabwe should face North to get the maximum sunshine hours.

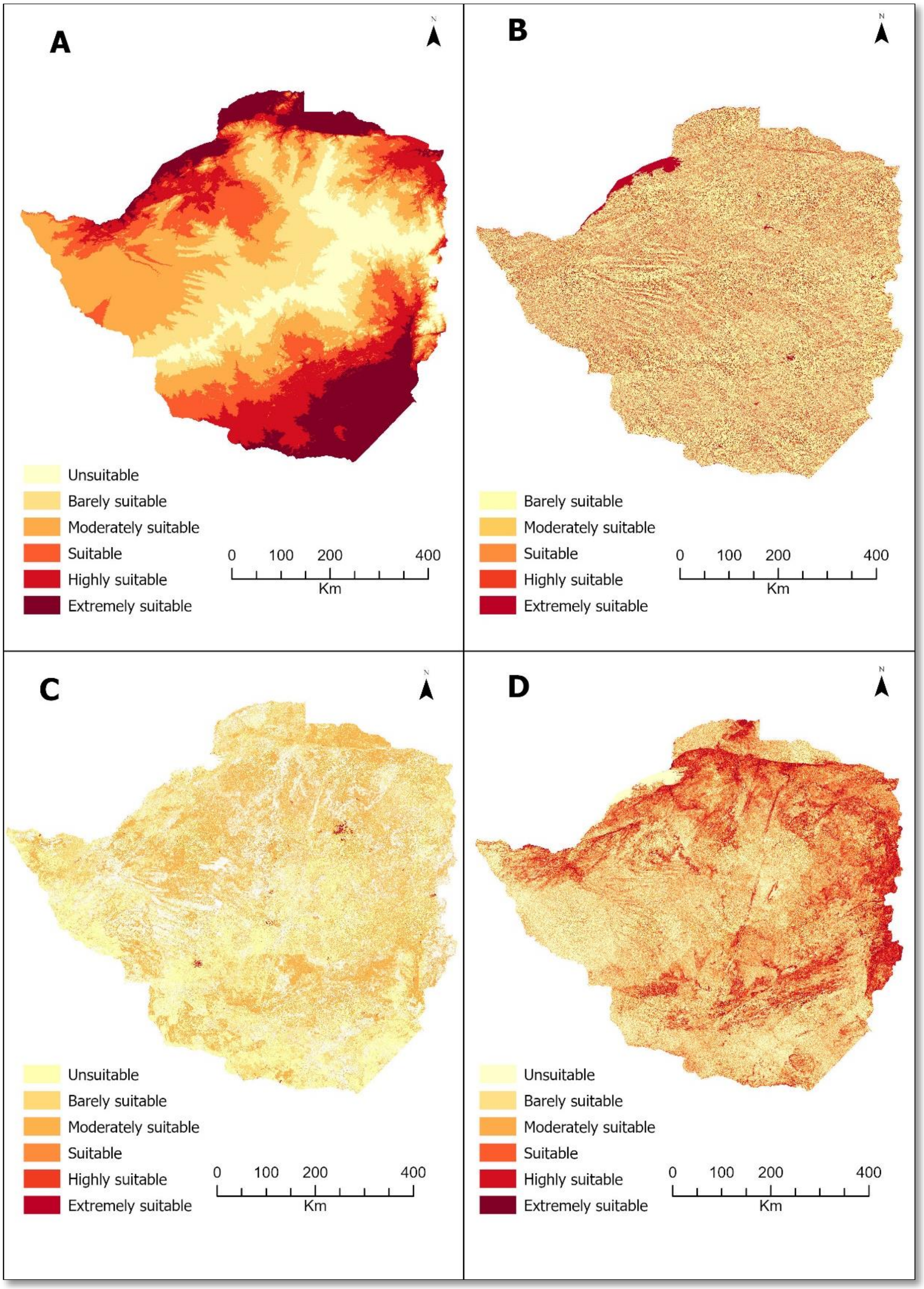


Figure 3-5 Elevation(A), Aspect(B) Land Cover(C) & Slope(D) Criteria maps.

3.3 DETERMINING THE CRITERIA AND SCORING FOR SITING RENEWABLE ENERGY PLANTS

The criteria used for building the suitability map, along with the method of scoring, were derived from literature as described in Chapter 2.

Table **3-1**, **Table 3-2**,and Table **3**-**3**, below, show the criteria chosen for the suitability analysis of wind, solar and SHP power plants. The overall method of scoring was adopted from Bennui et al.(2007), where the score for each criterion depends on its importance and suitability. The suitability scores are classified in a 6-point scale where 0= unsuitable/exclusion, 1= barely suitable, 2= moderately suitable, 3= suitable, 4= highly suitable, 5= extremely suitable.

TABLE 3-1 RANGING SCORES FOR WIND POWER CRITERIA (BENNUI *ET AL.*, 2007).

Criteria	**Suitability Score**						
	Exclusion zone / unsuitable (0)	*Barely suitable(1)*	*Moderately suitable(2)*	*Suitable (3)*	*Highly suitable (4)*	*Extremely suitable(5)*	*References*
Mean wind speed(m/s)	>25.0	<4.0	4.0 – 6.00	6.0 – 8.0	8.0 – 10.0	10.0 – 25.0	(Ottinger, 2019)
Proximity to a power grid(km)	<0.2	>1.0	0.8- 1.0	0.7 – 0.8	0.5 – 0.6	0.2 – 0.4	(Sliz-Szkliniarz and Vogt, 2011)
Proximity to major roads(km)	<0.5	>2.5	2.0 – 2.5	1.5 – 2.0	1.0 – 1.5	0.5 – 1.0	(Bennui *et al.*, 2007)
Proximity to settlements (km)	<1.0	1 .0 – 2.0	2.0 – 3.0	3.0 – 4.0	4.0 – 5.0	>5.0	(Bennui *et al.*, 2007)

Proximity to water bodies(km)	<0.4	0.4 – 0.6	0.6 – 0.8	0.8 – 1.0	1.0 – 1.2	>1.2	(Baban and Parry, 2001)
Proximity to airports(km)	<3.0	3.0 – 6.0	6.0 – 9.0	9.0 – 12.0	12.0 - 15.0	>15.0	(Bennui *et al.*, 2007)
Slope of terrain(%)	>30.0	>25.0	20.0 – 25.0	15.0 – 20.0	10.0 – 15.0	<10.0	(Latinopoulos and Kechagia, 2015)
Land cover	Open water	Aquatic vegetation	Sparse vegetation	Grassland	Shrubs	Bare areas	(Janke, 2010)

Table 3-2 Ranging Scores for solar power criteria (Bennui *et al.*, 2007).

Criteria	**Suitability Score**						
	Exclusion zone/ unsuitable(0)	*Barely suitable(1)*	*Moderately suitable(2)*	*Suitable (3)*	*Highly suitable(4)*	*Extremely suitable(5)*	*References*
Solar irradiation(KW/m^2)		<2050	2050 - 2100	2100 - 2150	2150 - 2200	>2200	(Aly, Jensen and Pedersen, 2017)
Proximity to a power grid(km)	<0.2	>1.0	0.8- 1.0	0.6 – 0.8	0.4 – 0.6	0.2 – 0.4	(Sliz-Szkliniarz and Vogt, 2011)
Proximity to major roads(km)	<0.5	>2.5	2.0 – 2.5	1.5 – 2.0	1.0 – 1.5	0.5 – 1.0	(Bennui *et al.*, 2007)
Proximity to settlements (km)	<1.0	1 .0 – 2.0	2.0 – 3.0	3.0 – 4.0	4.0 – 5.0	>5.0	(Bennui *et al.*, 2007)
Proximity to water bodies(km)	<0.4	0.4 – 0.6	0.6 – 0.8	0.8 – 1.0	1.0 – 1.2	>1.2	(Baban and Parry, 2001)

Aspect(degrees)		67.5 – 292.5(not facing north)	10.0 – 22.5	22.5 – 67.5	292.5 – 337.5	337.5 - 360, 0- 10.0	(Noorollahi, Yousefi and Mohammadi, 2016)
Elevation(m)	<40	40.0 – 80.0	80.0 – 120.0	120.0 – 150.0	150.0 – 200.0	> 200	(Bennui et al., 2007
Land cover	Open water	Aquatic vegetation	Sparse vegetation	Grassland	Shrubs	Bare areas	(Janke, 2010)

TABLE 3-3 RANGING SCORES FOR SMALL HYDROPOWER CRITERIA (BENNUI *ET AL.*, 2007).

Criteria	**Suitability Score**						
	Exclusion zone/ unsuitable(0)	*Barely suitable(1)*	*Moderately suitable(2)*	*Suitable (3)*	*Highly suitable(4)*	*Extremely suitable(5)*	*References*
Precipitation(mm/yr)		<300	300 – 450	450 – 600	600 - 750	>750	(Unganai, 1996)
Proximity to a power grid(km)	<0.2	>1.0	0.8- 1.0	0.6 – 0.8	0.4 – 0.6	0.2 – 0.4	(Sliz-Szkliniarz and Vogt, 2011)
Proximity to major roads(km)	<0.5	>2.5	2.0 – 2.5	1.5 – 2.0	1.0 – 1.5	0.5 – 1.0	(Bennui *et al.*, 2007)
Proximity to settlements(km)	<0.2	>1.0	0.8 – 1.0	0.8 – 0.6	0.6 – 0.4	0.4 – 0.2	(Rojanamon, Chaisomphob and Bureekul, 2009)
Proximity to rivers(km)		>1.0	1.0 – 0.8	0.8 – 0.6	0.6 – 0.4	<0.4	(Rojanamon, Chaisomphob and Bureekul, 2009)

Elevation(m)	<40	40.0 – 80.0	80.0 – 120.0	120.0 – 150.0	150.0 – 200.0	> 200	(Bennui et al., 2007

The Euclidean distance, spatial interpolation (IDW), and map algebra functions were used to produce the criteria maps for wind, power, and small hydro power plants. To standardize the input raster data layers, reclassification was employed. The maps were reclassified into six classes (with 6 corresponding to extremely suitable, and 1 to barely suitable). The following map algebra equation was used to reclassify the layers: **EQUATION 3-3** is used to rescale the criteria when close proximity is required and **EQUATION 3-4** is applied when close proximity is not required.

EQUATION 3-3

$$v_{is} = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

EQUATION 3-4

$$v_{is} = 1 - \left(\frac{X_i - X_{min}}{X_{max} - X_{min}}\right)$$

Where, v_{is} is the standardized value of the i^{th} pixel for the s^{th} criterion; X_i is the value of the i^{th} pixel for the s^{th} criterion; X_{max} and X_{min} are the maximum and minimum value of the s^{th} criterion.

3.4 EXCLUSION ZONES

The exclusion of infeasible sites involved identifying criteria with constraints related to the siting of the renewable energy power plants. The map layers chosen were converted from vector to raster data models using the Boolean operator AND where 0 = unsuitable site, 1 = suitable site. The constraint criteria maps were then fed into the database to be combined with the evaluation criteria maps which were reclassified on a continuous index scale.

3.5 DETERMINE WEIGHTS USING GIS & MCDA

The AHP was used to assign different weights on the criteria through applying pairwise comparisons. This method was chosen over other ranking methods discussed in Section 2.4.1 because it could be easily integrated with GIS, where the designated field value of each input raster in the WSM model was multiplied by the specified weight.

The first step was to create an (n x n) pairwise comparison matrix, where two criteria were evaluated at a time in terms of their relative importance. A 9-point scale was used to express individual preferences or judgments, creating a reciprocal ratio matrix. If criterion A was just as important as criterion B, the pair received an index of 1. If A was much more important than B, the index of 9 was allocated. For a less important relationship, the factors 1/2 to 1/9 were assigned respectively. If A was much less important than B, the rating was 1/9. The values were completed row by row into a cross-matrix, such that the diagonal of the matrix contained only values of 1. The right upper half of the matrix was completed until each criterion had compared to every other one. If A to B was rated with the relative importance of n, B to A was rated with 1/n. The lower half of the matrix was then filled with the matching fractions. TABLE 3-4 below shows the n x n pairwise comparison matrix that was computed to determine the weights for each wind power criterion. The index values in the matrix were adopted from literature review.

TABLE 3-4 PAIRWISE COMPARISON TABLE FOR THE WIND POWER CRITERIA.

	Mean Wind Speed	Proximity to power grid	Proximity to major roads	Proximity to settlements	Proximity to water bodies	Proximity to airports	Slope of terrain	Elevation	Land Cover	**Weight**
Mean Wind Speed	1	5	7	5	1/7	9	4	3	5	**0.2463**
Proximity to power grid	1/5	1	3	1/3	2	2	5	6	6	**0.1396**
Proximity to major roads	1/7	1/3	1	1	1/5	4	3	7	5	**0.0909**
Proximity to settlements	1/5	3	1	1	1	4	5	5	4	**0.1341**
Proximity to water bodies	7	1/2	5	1	1	5	5	3	7	**0.2187**
Proximity to airports	1/9	1/2	1/4	1/4	1/5	1	7	8	8	**0.0914**
Slope of terrain	1/4	1/5	1/3	1/5	1/5	1/7	1	2	1	**0.0297**
Elevation	1/3	1/6	1/7	1/5	1/3	1/8	1/2	1	1/3	**0.0221**
Land Cover	1/5	1/6	1/5	1/4	1/7	1/8	1	3	1	**0.0272**

Let F1 =Mean Wind Speed, *F2*=Proximity to power grid, *F3*=Proximity to major roads, *F4*=Proximity to settlements, *F5*=Proximity to water bodies, *F6*=Proximity to airports, *F7*=Slope of terrain, *F8*=Elevation, *F9*=Land Cover.

a) Calculation of weights was carried out on the solar and SHP pairwise comparison table and the weights of criteria are shown in Table 3-4, Table 3-5, & Table 3-6.

Table 3-5 Pairwise comparison table for the Solar power criteria.

	Solar irradiation	Proximity to power grid	Proximity to major roads	Proximity to settlements	Proximity to water bodies	Aspect	Elevation	Land Cover	**Weight**
Solar irradiation	1	7	6	9	9	5	2	2	**0.2847**
Proximity to power grid	1/7	1	3	8	2	1/7	4	5	**0.1429**
Proximity to major roads	1/6	1/3	1	7	6	8	2	2	**0.1364**
Proximity to settlements	1/9	1/8	1/7	1	3	5	1/5	1/3	**0.0513**
Proximity to water bodies	1/9	1/2	1/6	1/3	1	6	1/4	1/6	**0.0482**
Aspect	1/5	7	1/8	1/5	1/6	1	8	6	**0.1618**
Elevation	1/2	1/4	1/2	5	4	1/8	1	5	**0.1017**
Land Cover	1/2	1/5	1/2	3	6	1/6	1/5	1	**0.0732**

Table 3-6 Pairwise comparison table for the small hydropower criteria.

	Precipitation	Proximity to power grid	Proximity to major roads	Proximity to settlements	Proximity to rivers	Elevation	**Weight**
Precipitation	1	9	7	2	1/6	1/5	**0.228**
Proximity to power grid	1/9	1	5	8	9	8	**0.284**
Proximity to major roads	1/7	1/5	1	3	7	1/7	**0.1**
Proximity to settlements	1/2	1/8	1/3	1	1/8	1/6	**0.021**
Proximity to rivers	6	1/9	1/7	8	1	5	**0.195**
Elevation	5	1/8	7	6	1/5	1	**0.174**

3.6 BUILDING AN INDEX MODEL

The building of the GIS model was performed using Model Builder which is a visual language in ArcGIS Pro that allows one to build new tools that model the geo-processing workflow. Geo-processing tools were chained together in a sequence, feeding the output of one tool as the input of another. The processing tools and data elements were visually represented as diagrams, showing the existing input data variables in blue, derived / output data variable in green and the built-in tools in yellow performing specific operations on the data as shown on Figure **3**-**6**. The data variables are the model elements that contain the descriptive information about the data including the field information, spatial reference, and path. The arrows represent the connection between the data variables and the tools.

FIGURE 3-6 ILLUSTRATION OF A WIND INDEX MODEL CONSTRUCTED USING MODEL BUILDER.

FIGURE 3-7 ILLUSTRATION OF A SOLAR INDEX MODEL CONSTRUCTED USING MODEL BUILDER.

FIGURE 3-8 ILLUSTRATION OF A SHP INDEX MODEL CONSTRUCTED USING MODEL BUILDER.

3.7 WEIGHTED SUM OVERLAY

The weighted overlay tool was used to produce the final suitability surface (map). This approach was chosen because it provided the ability to evaluate (weigh) and combine the inputs at once, creating an integrated multi-criteria analysis. The criteria were easily combined incorporating the weights generated by the AHP pairwise matrix. The cell values of each standardized (reclassified) raster were multiplied by the raster's weight.

3.8 VALIDATION OF THE GIS MODEL

Data used for spatial analysis is affected by uncertainty, which can be an error due to variation in the database or analytical model, therefore, validation of a model is required (Graham *et al.*, 2008). Validation of the renewable energy suitability model can be done by choosing a different region where wind, solar or small hydro power plants already exist and establish whether the suitable areas identified by the model match the location of the existing power plants. The region selected for model validation was South Africa because it is a neighbouring country to Zimbabwe and shares some similar geographic and climatic features. Most land use, including agricultural land, arable land, permanent crops, forests, etc., is somewhat the same (CIA factbook, 2022). Another advantage of using South Africa is the availability of spatial data, which makes it easier to build a criteria database.

4 RESULTS AND ANALYSIS

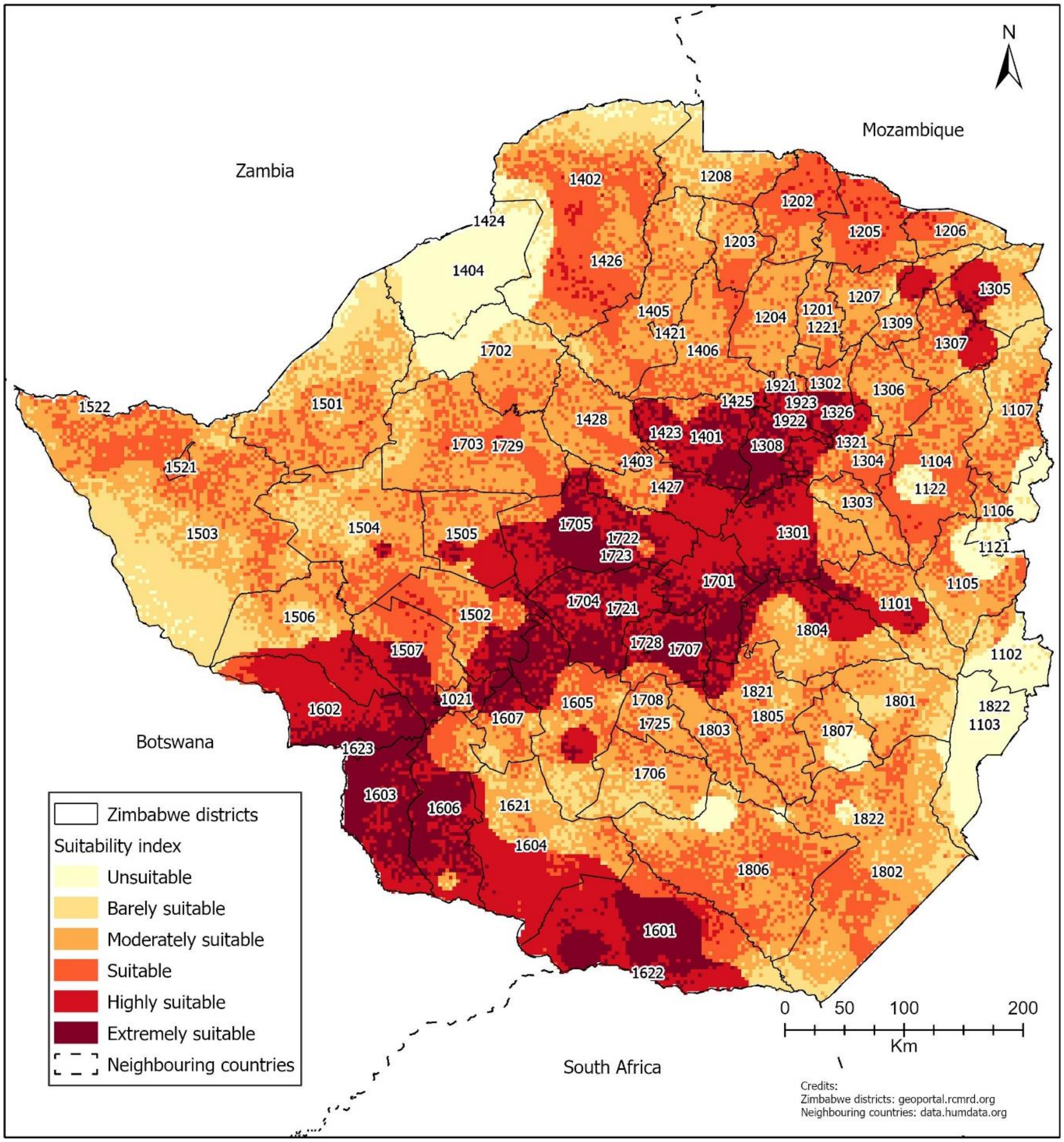
This chapter presents detailed analysis conducted in this study, centred on the methodology reviewed in chapter 3. The chapter is broken down into sections presenting the model output of the three renewable resources identified in this study, that is, wind, solar and small hydropower. The chapter further displays the suitability maps generated for each energy resource and provides a calculated theoretical potential contribution of the alternative sites. GIS model validation is performed using the same criteria but on a different dataset. In addition, existing renewable resources are checked against the generated suitability map to determine if a connection exists. The criteria maps created were weighted using the AHP method and a workflow created by the model builder in ArcGIS Pro was used to connect the criteria and perform a weighted overlay analysis. The overlay analysis resulted in suitability maps for wind, solar and SHP power plants.

4.1 SUITABLE AREAS IDENTIFIED FOR WIND POWER

Figure 4-1 page 76 shows the generated wind power suitability map of Zimbabwe. The extremely suitable sites with average wind speeds greater than 10 m/s, within 400 m of the power grid and major roads, 5 km away from settlements, 1.2 km away from water bodies, 15 km away from airports and with slopes less than 10% were found in the following provinces: Matabeleland South, Midlands, and Mashonaland East. Areas with wind speeds less than 4 m/s, 1 km away from the power grid, 2.5 km away from major roads, 1.0-2.0 km from settlements, 0.4 - 0.6 km from water bodies, within 3 to 6 km from airports, and on slopes greater than 25% were found in Mashonaland West and Manicaland province. Extremely suitable and highly suitable sites were considered as potential sites for wind power production.

The identified suitable locations are consistent with findings of the Worldwide Sustainable power Organization, who, through the Africa Clean Energy Passage Program, produced maps depicting suitable regions in the provinces of Matabeleland South, Midlands, and Mashonaland Central by utilizing the wind thresholds of 200 W/m2, 250 W/m2, and 300 W/m2 to identify wind resource options in central Zimbabwe (Wu *et al.*, 2015). They found that in Matabeleland South province, districts like Bulima, Mangwe, Matobo, and Umguza were found to be extremely suitable; in Mashonaland province, districts like Muzarabani, Mount Darwin, Shamva, and Mbire housed highly suitable locations. These locations are consistent with the findings of this study.

In another study, Ruwa, which is in Mashonaland East, was sighted as a high potential location (Samu, Fahrioglu and Ozansoy, 2019). This, like in the case of a study that was carried out in the Mangwe district of Zimbabwe's Matabeleland South province, where wind speeds were estimated using online weather datasets (Gunda *et al.*, 2021), and the results showed that a 2.5kW wind turbine establishment in Mangwe can create more than 3MWh of energy per annum at hub heights above 40m, which is sufficient to supply capacity to a Zimbabwean provincial town (Gunda *et al.*, 2021), are all locations that are within the areas identified by this study.



Credits:
Zimbabwe districts: geoportal.rcmrd.org
Neighbouring countries: data.humdata.org

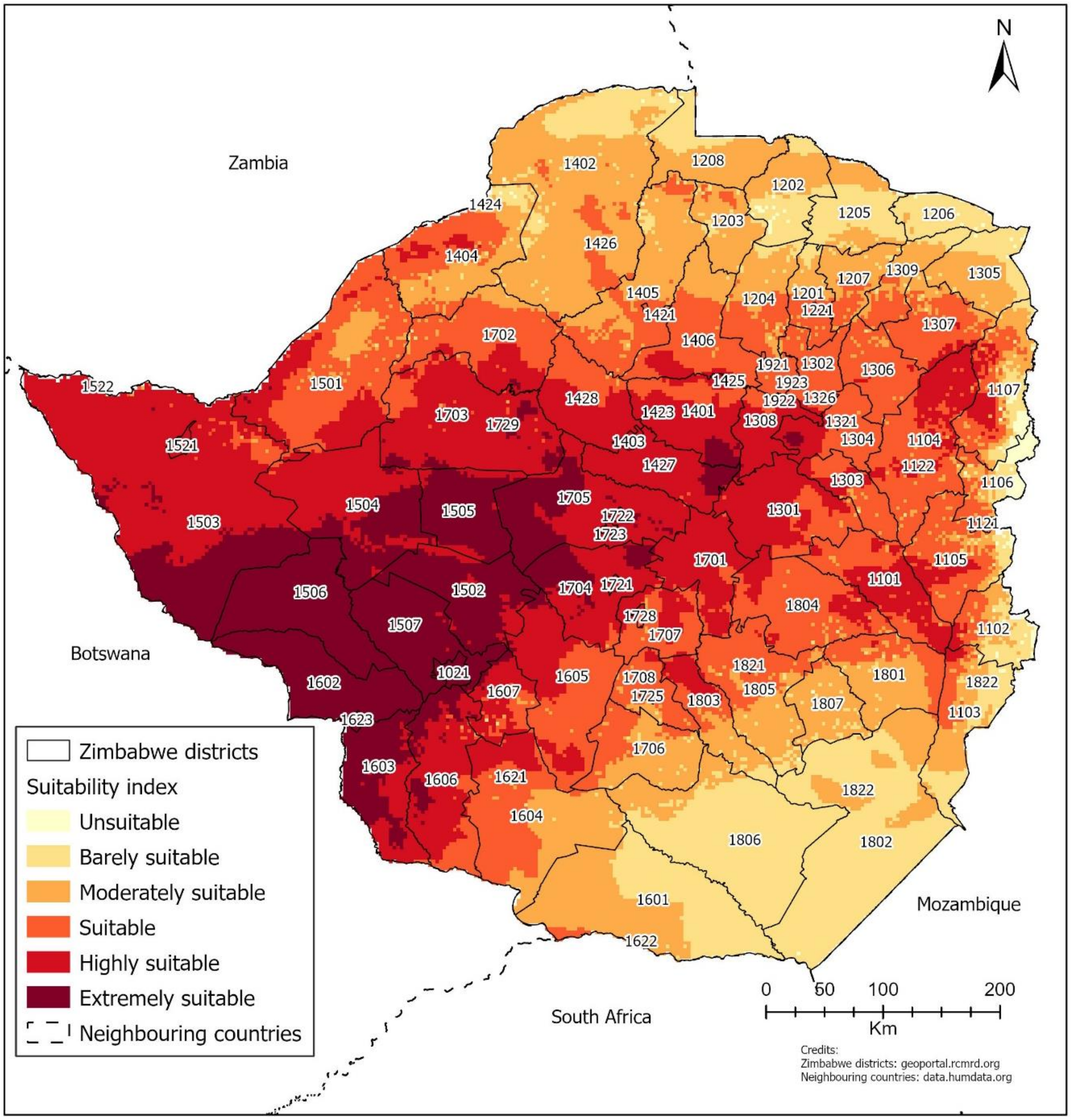
FIGURE 4-1 WIND POWER SITE SUITABILITY MAP GENERATED BY THE WEIGHTED OVERLAY METHOD.

4.2 SUITABLE AREAS IDENTIFIED FOR SOLAR POWER

Figure 4-2 page 79 shows the generated solar power suitability map of Zimbabwe. The extremely suitable areas with solar irradiation greater than 2 200 KW/m^2, within 400 m from the power grid and 500 m from major roads, 5.0 km away from settlements, 1.2 km away from water bodies and elevation greater than 200 m were in Matabeleland North, Bulawayo and part of Matabeleland South as well as the Midlands province. The unsuitable areas with solar irradiation less than 2 050 KW/m^2, 1 km away from the power grid, 2.5 km from major roads, within 2 km of the settlements and 600 m to water bodies and elevation that was less than 40 m were in Masvingo, Mashonaland West and parts of Mashonaland Central.

There is lack of information regarding Zimbabwe's planned or existing solar farms. However, research revealed that the Mashonaland East province of Zimbabwe will host the 50MW Rufaro Solar PV power project. It is anticipated that the farm, whose construction began in 2022, will begin commercial operations in 2023 (Carmen, 2022). Another 20 MW solar power plant is being installed in Seke, which is in Mashonaland east. (Takouleu, 2021). The aforementioned projects are located in the areas identified by this study as suitable regions for generation of solar power.

Additionally, power plants under construction including: the 5 MW Sunset Technologies Solar Park in Gwanda, which is located in the province of Matabeleland South; a 25 MW Chidobe-Mizpah projectin the Hwange District of Matebeleland North; a 5 MW Guruve Solar Park in Guruve district of Mashonaland Central province have all been approved as PV solar plants to begin commercial operation(Bellini, 2021). These solar power plants are located in the regions that have been identified by this study as highly to extremely suitable.



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Neighbouring countries: data.humdata.org

FIGURE 4-2 SOLAR POWER SITE SUITABILITY MAP GENERATED BY THE WEIGHTED OVERLAY METHOD.

4.3 SUITABLE AREAS IDENTIFIED FOR SMALL HYDRO POWER

Error! Reference source not found. Figure 4-3 page 81 shows the suitability map for small hydropower plants in Zimbabwe. The selected type of small hydropower is the run of river described in Section 2.3. The river network was used to identify which river catchment area would be suitable for the run of river SHP plants. Extremely suitable sites with average precipitation greater than 750 mm, 400 m to power grid, 500 m to major roads, 400 m from settlements, within 500 m of the river channel and an elevation greater than 200 m were found along the Gwayi, Shangani, Lukhosi, Hunyani, Nyagui and Odzi river channels. Areas with precipitation that was less than 300 mm, 1 km away from the power grid, 2.5 km away from major roads, 1 km away from settlements, 1 km away from rivers and elevation less than 40 m were identified along the Thuli, Mzingwane and Save river channels.

Studies reveal that there are a number of hydro power stations either already setup or in the pipeline, in areas that this study has identified as suitable locations for hydro power. In Manicaland province, the 1.6 MW Kupinga hydropower station opened in 2017 (Poindexter,2017). Gairezi, which is in the Nyanga district traveling north from the Eastern Highlands before joining the Mazowe and Zambezi Rivers—along with the Ruenda River and has an estimated 30 MW of potential capacity (Global data, 2018).

The Matabeleland Zambezi Water Project (MZWP) a 245km project from Gwayi- Shangani Dam to Bulawayo, an area sited by the model as suitable for small hydropower production, is being undertaken in the Matabeleland North province of Zimbabwe.. (Chikandiwa, 2022).

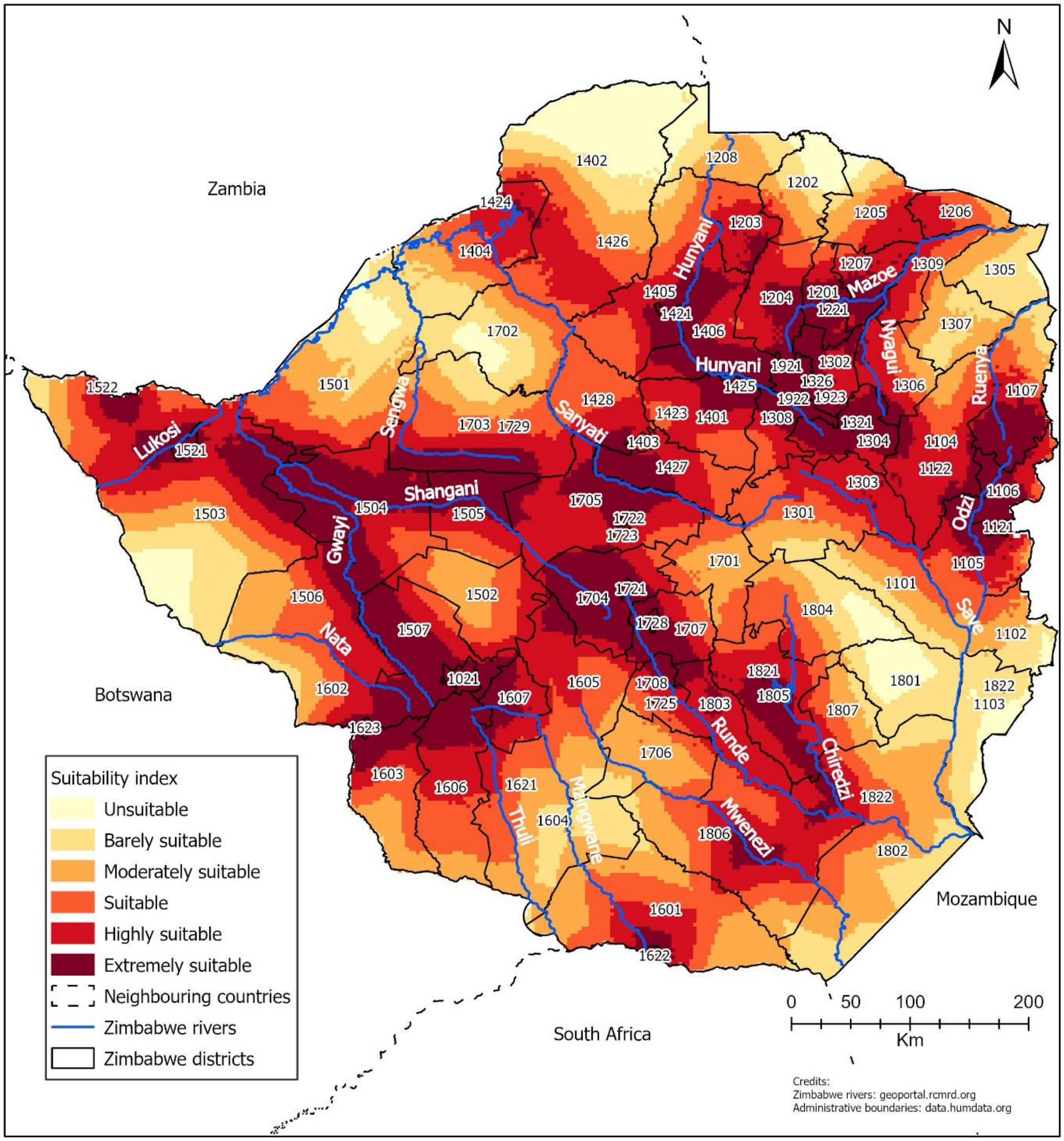

FIGURE 4-3 SHP SITE SUITABILITY MAP GENERATED BY THE WEIGHTED OVERLAY METHOD.

4.4 VALIDATION

The same criteria and methodology used to identify suitable regions in Zimbabwe were implemented in South Africa to validate the GIS suitability model. If the suitability map generated for South Africa matches with existing renewable energy resources, the model can therefore be regarded as valid. Hence, the suitability maps generated for Zimbabwe can be relied upon. The reasons for choosing South Africa are mentioned in Section 3.8.

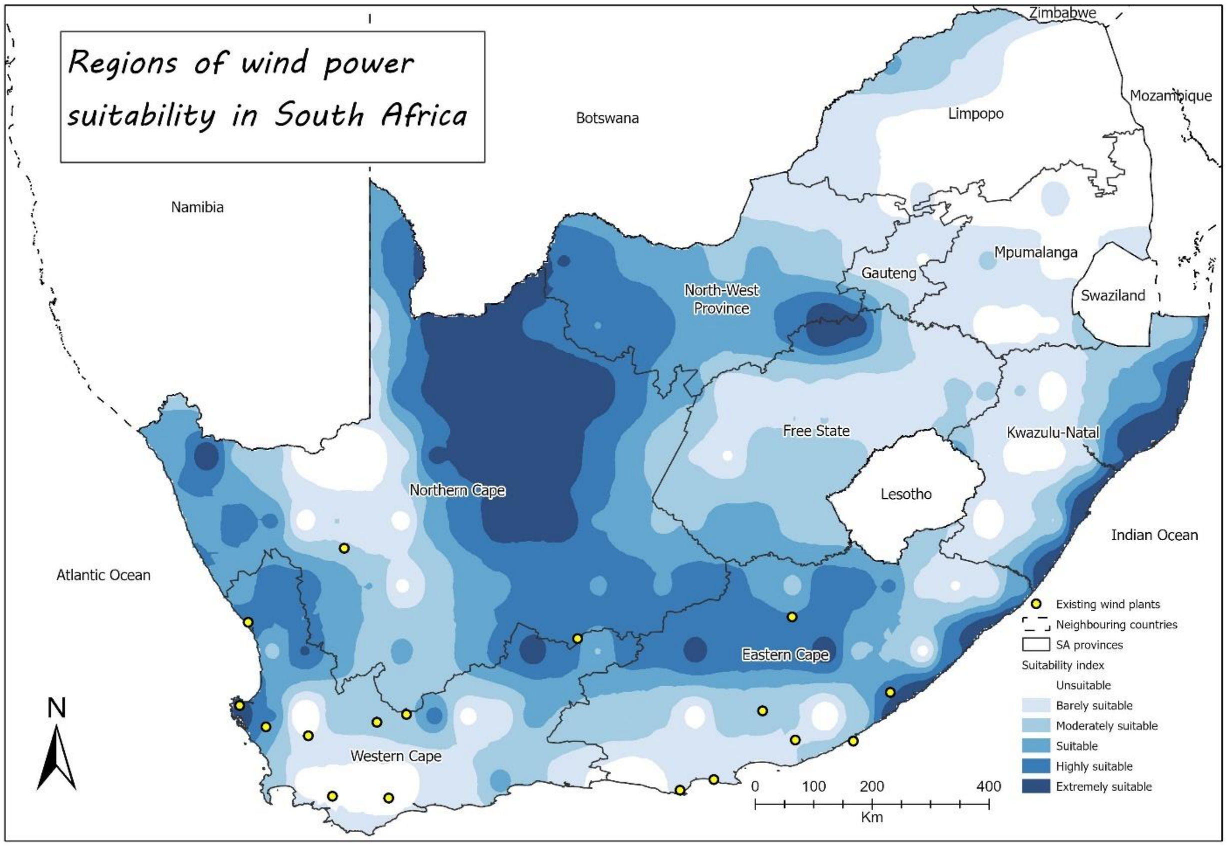

FIGURE 4-4 WIND POWER SITE SUITABILITY MAP GENERATED BY THE WEIGHTED OVERLAY METHOD.

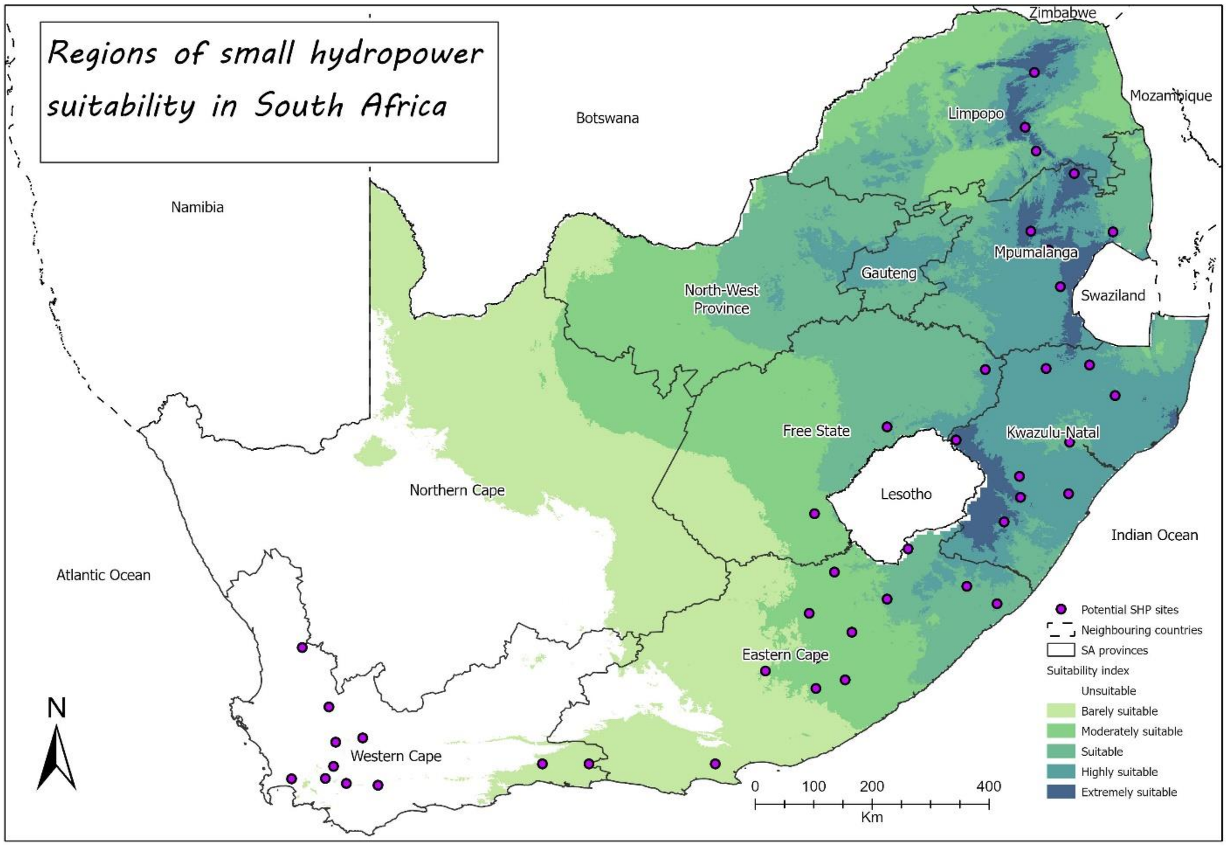

FIGURE 4-5 SMALL HYDRO SITE SUITABILITY MAP GENERATED BY THE WEIGHTED OVERLAY METHOD.

Figure 4-4 page 82, Figure 4-5 and Figure 4-6 page 84, show maps generated from the suitability analysis depicting suitable regions for wind, solar and SHP in South Africa. The maps were generated from the utility scale renewable energy generation sites of South Africa shown in Figure **7**-**1** in the Appendix section. The map shows a distribution of solar, wind, gas, hydropower, and bioenergy across the 9 provinces of South Africa, which are the Western Cape, Northern Cape, Eastern Cape, Free State, KwaZulu Natal, Mpumalanga, Limpopo, Gauteng, and Northwest. These provinces are used to described where most of the resources are in South Africa.

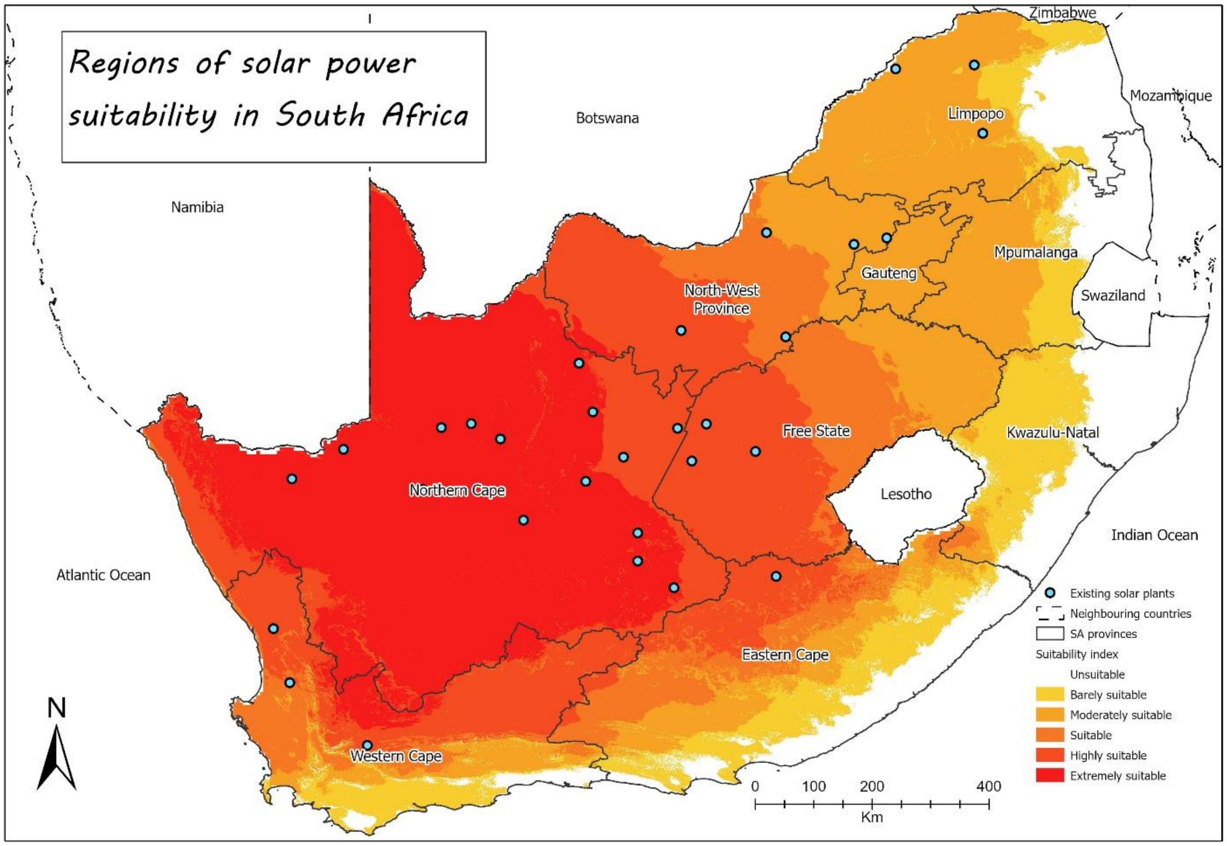

FIGURE 4-6 SOLAR POWER SITE SUITABILITY MAP GENERATED BY THE WEIGHTED OVERLAY METHOD.

The locations of these power plants were digitised using ArcGIS Pro and stored as separate vector layers (points) representing the solar and wind power locations.

The results show that the existing RE power plants are located within the suitable regions produced by the validation model. Most of the wind power plants are in the Eastern Cape and a few in the Western Cape and one in the Northern Cape provinces. An example of an existing wind farm sited within the suitable region for wind power is the Kangas wind farm located in the Nama

Khoi Municipal area, in the Northern Cape, producing 140 MW. Another wind farm is the Jeffreys Bay located in the Eastern Cape producing 138 MW (Fullerton, 2019). Most solar power plants are in the Northern Cape, which is identified as the extremely suitable region for solar power potential. The Bokpoort CSP project is a case of an existing solar plant located in the Northern Cape producing 50 MW (Acwa power, 2016). Another big solar farm that is sited in the Northern Cape is the De Aar project. This project is a PV solar facility providing a maximum potential generating capacity of 175 MW (Labuschagne, 2022).

A feasibility study of hydrokinetic power was carried out and a map showing potential sites for the development of micro hydropower was produced (Balance,2000). Points from the SHP suitability map were digitised, and a SHP vector layer (points) was created. The points were overlayed with the SHP suitability map generated for South Africa. The results showed that the potential sites were in suitable regions identified by the validation model, and these spread-out in the Eastern Cape, Mpumalanga and KZN provinces. It has been concluded that the Eastern Cape and KZN are endowed with the potential for SHP development especially 10 MW hydropower plants (Barta and Grøn, no date).

5 CONCLUSION AND RECOMENDATIONS

The aim of the study was to identify suitable renewable energy regions within the boundaries of Zimbabwe using MCDM. GIS integrated with the AHP was used to build a raster-based suitability model. Criteria maps representing wind, solar, and small hydropower resources in Zimbabwe were created using data from online secondary resources. These maps demonstrated that objective one, which was to identify the minimum requirements for efficient wind, solar, and small hydropower energy production in Zimbabwe, based on a literature review, was met. The use of secondary data only resulted in a slight decrease in the precision of the derived criteria.

The suitability model workflow was created using model builder in ArcGIS Pro, producing weighted site suitability maps. These maps show locations in Zimbabwe that are suitable for wind, solar, and small hydropower plants. With a land area of 26 974 km2, Hwange Rural is the most suitable location for solar power plants. With a land area of 12 719 km2, the Beitbridge Rural District is the most suitable location for wind power plants. The Gwayi and Shangani Rivers are ideal locations for small hydropower plants. Successfully siting these locations therefore meets the requirements of objective 2, which was to find locations in Zimbabwe that meet the minimum requirements for efficient wind, solar, and small hydropower plants.

To test the model's validity, wind, solar, and SHP suitability maps were created for South Africa using the same approach. These maps' outcomes demonstrated that the model produced maps that were fairly accurate; This is backed up by the presence of renewable energy plants in the designated ideal locations.

The generated suitability maps can, therefore, feed into determining the potential contribution of the identified sites to the energy needs of country. The process involves creating exclusion criteria were all land areas that are infeasible for implementation are deducted from the suitable locations. An example of such land areas includes privately owned land, protected places, agricultural sites etc. This enables the calculation of the technical potential, which is the geographical potential reduced by the loss of the conversion of primary energy to secondary energy source.

Furthermore, there is need for extensive understanding of technical aspects of each renewable energy resources. For example, deriving technical potential for the development of solar PV systems, information required includes solar resource availability, PV module efficiency, spacing factor, and accessible land area. The calculation of the technical potential of wind power is complex since the resources differ considerably over the area of an entire country. Wind turbines for a particular identified region must be carefully considered, including the minimum spacing required.

In conclusion, the study shows that Zimbabwe has vast potential in wind, solar and SHP resources that could contribute to the alleviation of the high energy deficits. Zimbabwe has a lot of small hydropower resources that could be used. Most of these locations, which are along the Zambezi, necessitate international agreement with Zambia. In Zimbabwe, the average wind speed is between 2 and 4 meters per second(m/s), which isn't enough for big turbines but good for small scale turbines. In order to take advantage of the enormous potential of solar energy, several independent power producers in Zimbabwe are planning to connect to the national grid (Bellini, 2021). The development of renewable energy in Zimbabwe is hampered by a lack of available technology and expensive capital. A favourable policy environment and regulatory framework can be used to address obstacles to the widespread adoption of renewable energy technologies in the country.

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7 APPENDIX

TABLE 7-1 DATA SOURCES.

Criteria	Original data structure	Feature type	Source
Wind speed	Vector	10m	https://pae-paha.pacioos.hawaii.edu/erddap/griddap/ncep_global.graph
Rivers	Vector	Polyline	http://geoportal.rcmrd.org/layers/servir%3Azimbabwe_rivers
Airports	Vector	Polygon	https://ourairports.com/data/
Elevation	Raster	30m	https://opendata.rcmrd.org/datasets/zimbabwe-srtm-dem-30-metres
Land Cover	Raster	30m	http://geoportal.rcmrd.org/layers/servir%3Azimbabwe_sentinel2_lulc2016
Solar irradiation	Raster	250m	https://globalsolaratlas.info/download/zimbabwe
Precipitation mm/hr.	Rasters	2.5 arc minutes	https://biogeo.ucdavis.edu/data/worldclim/v2.1/base/wc2.1_30s_prec.zip
Major roads	Vector	Polyline	https://datacatalog.worldbank.org/dataset/zimbabwe-roads-0
Power grid	Vector	Polyline	https://datacatalog.worldbank.org/dataset/zimbabwe-electricity-transmission-network
Settlements	Vector	Points	https://data.humdata.org/dataset/zimbabwe-settlements

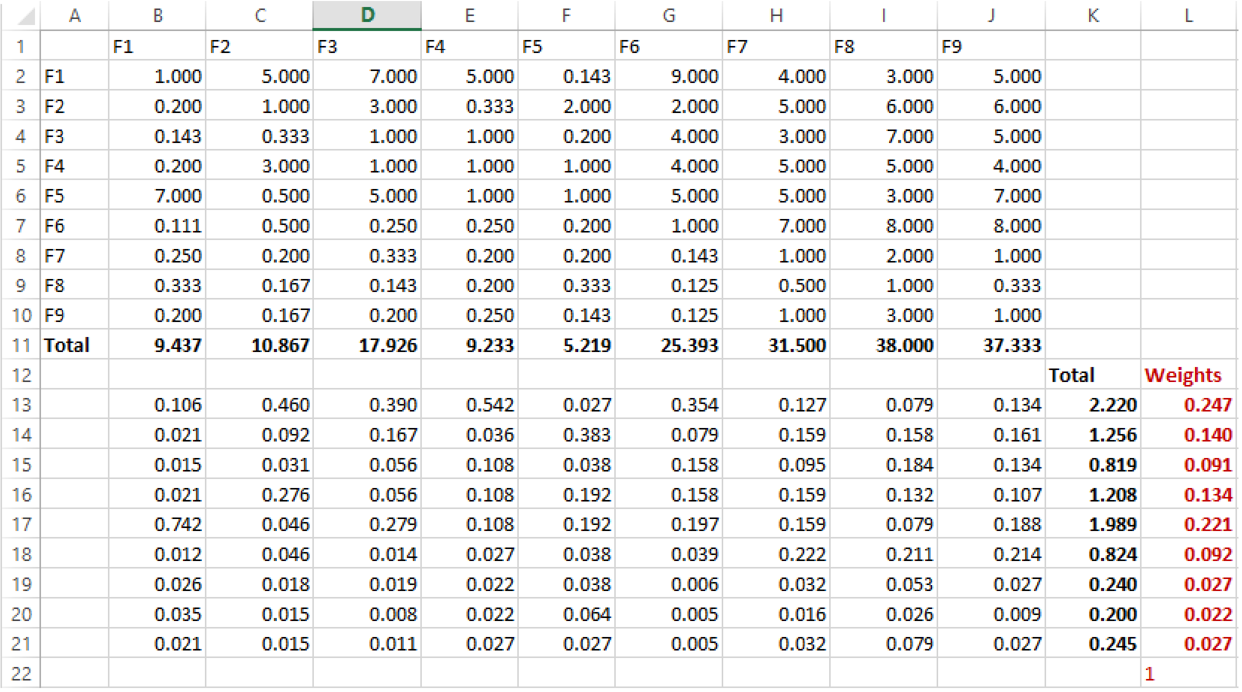
Table 7-2 Zimbabwe Districts.

District code	District	
1021	Bulawayo	
1101	Buhera	
1102	Chimanimani	
1103	Chipinge Rural	
1104	Makoni	
1105	Mutare Rural	
1106	Mutasa	
1107	Nyanga	
1121	Mutare Urban	
1122	Rusape	
1201	Bindura Rural	
1202	Centenary/ Muzarabani	
1203	Guruve	
1204	Mazowe	
1205	Mount Darwin	
1206	Rushinga	
1207	Shamva	
1208	Mbire	
1221	Bindura Urban	
1301	Chikomba	
1302	Goromonzi	
1303	Hwedza	
1304	Marondera	
1305	Mudzi	
1306	Murehwa	
1307	Mutoko	
1308	Seke	
1309	Uzumba Maramba Pfungwe	
1321	Marondera Urban	
1326	Ruwa Local Board	
1401	Chegutu Rural	
1402	Hurungwe	
1403	Kadoma Urban	
1404	Kariba Rural	
1405	Makonde	
1406	Zvimba	
1421	Chinhoyi	
1423	Chegutu Urban	
1424	Kariba Urban	
1425	Norton	
1426	Karoi	
1427	Mhondoro-Ngezi	
1428	Sanyati	
1501	Binga	
1502	Bubi	
1503	Hwange Rural	
1504	Lupane	
1505	Nkayi	
1506	Tsholotsho	
1507	Umguza	
1521	Hwange Urban	

1522	Victoria Falls	
1601	Beitbridge Rural	
1602	Bulilima	
1603	Mangwe	
1604	Gwanda Rural	
1605	Insiza	
1606	Matobo	
1607	Umzingwane	
1621	Gwanda Urban	
1622	Beitbridge Urban	
1623	Plumtree	
1701	Chirumhanzu	
1702	Gokwe North	
1703	Gokwe South	
1704	Gweru Rural	
1705	Kwekwe Rural	
1706	Mberengwa	
1707	Shurugwi Rural	
1708	Zvishavane	

1721	Gweru Urban	
1722	Kwekwe Urban	
1723	Redcliff	
1725	Zvishavane Urban	
1728	Shurugwi Urban	
1729	Gokwe South Urban	
1801	Bikita	
1802	Chiredzi Rural	
1803	Chivi	
1804	Gutu	
1805	Masvingo Rural	
1806	Mwenezi	
1807	Zaka	
1821	Masvingo Urban	
1822	Chiredzi Urban	
1822	Chipinge Urban	
1921	Harare	
1922	Chitungwiza	
1923	Epworth	

TABLE 7-3 CALCULATION OF WEIGHTS USING MICROSOFT EXCEL SPREADSHEET (EFFAT, 2014).



	A	B	C	D	E	F	G	H	I	J	K	L
1		F1	F2	F3	F4	F5	F6	F7	F8	F9		
2	F1	1.000	5.000	7.000	5.000	0.143	9.000	4.000	3.000	5.000		
3	F2	0.200	1.000	3.000	0.333	2.000	2.000	5.000	6.000	6.000		
4	F3	0.143	0.333	1.000	1.000	0.200	4.000	3.000	7.000	5.000		
5	F4	0.200	3.000	1.000	1.000	1.000	4.000	5.000	5.000	4.000		
6	F5	7.000	0.500	5.000	1.000	1.000	5.000	5.000	3.000	7.000		
7	F6	0.111	0.500	0.250	0.250	0.200	1.000	7.000	8.000	8.000		
8	F7	0.250	0.200	0.333	0.200	0.200	0.143	1.000	2.000	1.000		
9	F8	0.333	0.167	0.143	0.200	0.333	0.125	0.500	1.000	0.333		
10	F9	0.200	0.167	0.200	0.250	0.143	0.125	1.000	3.000	1.000		
11	**Total**	**9.437**	**10.867**	**17.926**	**9.233**	**5.219**	**25.393**	**31.500**	**38.000**	**37.333**		
12											**Total**	**Weights**
13		0.106	0.460	0.390	0.542	0.027	0.354	0.127	0.079	0.134	**2.220**	**0.247**
14		0.021	0.092	0.167	0.036	0.383	0.079	0.159	0.158	0.161	**1.256**	**0.140**
15		0.015	0.031	0.056	0.108	0.038	0.158	0.095	0.184	0.134	**0.819**	**0.091**
16		0.021	0.276	0.056	0.108	0.192	0.158	0.159	0.132	0.107	**1.208**	**0.134**
17		0.742	0.046	0.279	0.108	0.192	0.197	0.159	0.079	0.188	**1.989**	**0.221**
18		0.012	0.046	0.014	0.027	0.038	0.039	0.222	0.211	0.214	**0.824**	**0.092**
19		0.026	0.018	0.019	0.022	0.038	0.006	0.032	0.053	0.027	**0.240**	**0.027**
20		0.035	0.015	0.008	0.022	0.064	0.005	0.016	0.026	0.009	**0.200**	**0.022**
21		0.021	0.015	0.011	0.027	0.027	0.005	0.032	0.079	0.027	**0.245**	**0.027**
22												1

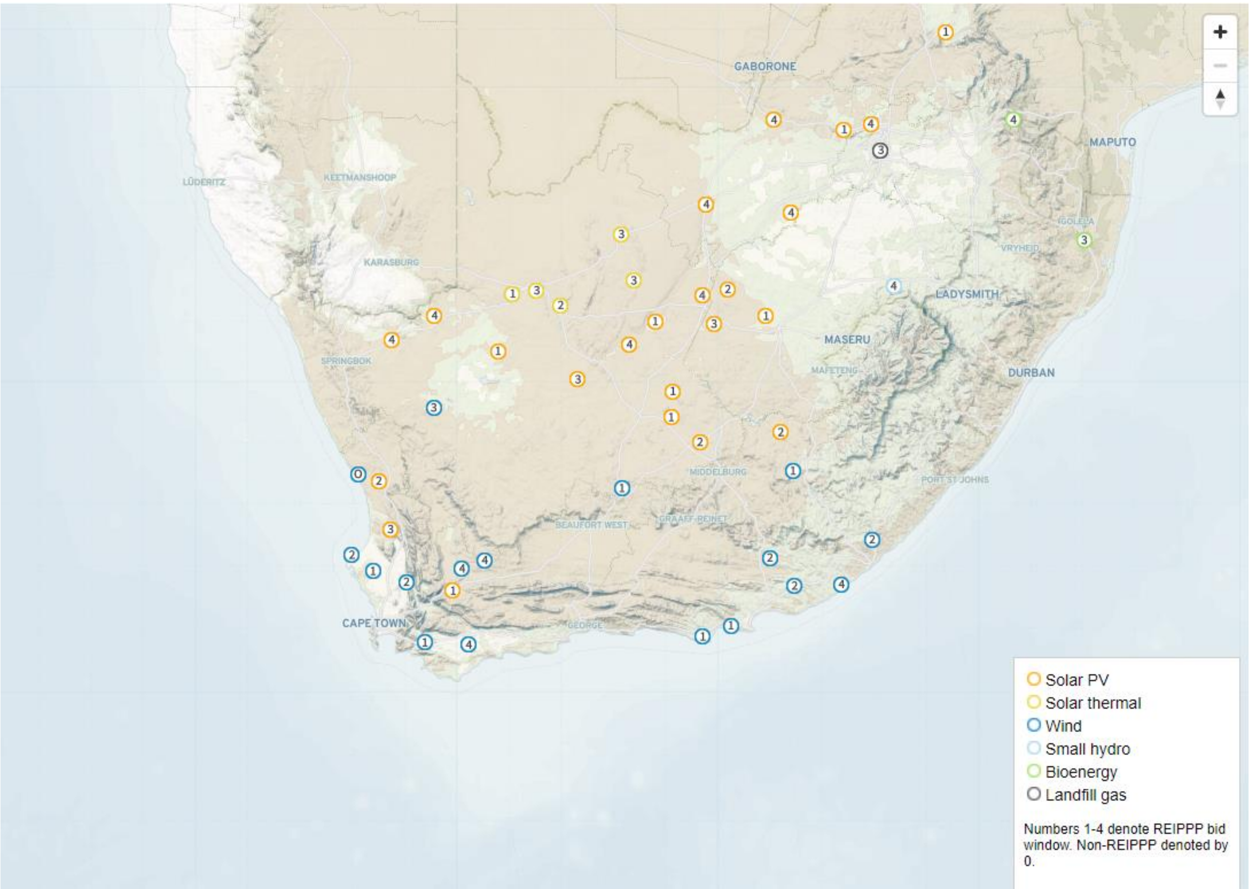


FIGURE 7-1 EXISTING RENEWABLE ENERGY POWER PLANTS IN SOUTH AFRICA.

HTTP://WWW.ENERGY.ORG.ZA/MAP-SOUTH-AFRICAN-GENERATION-PROJECTS

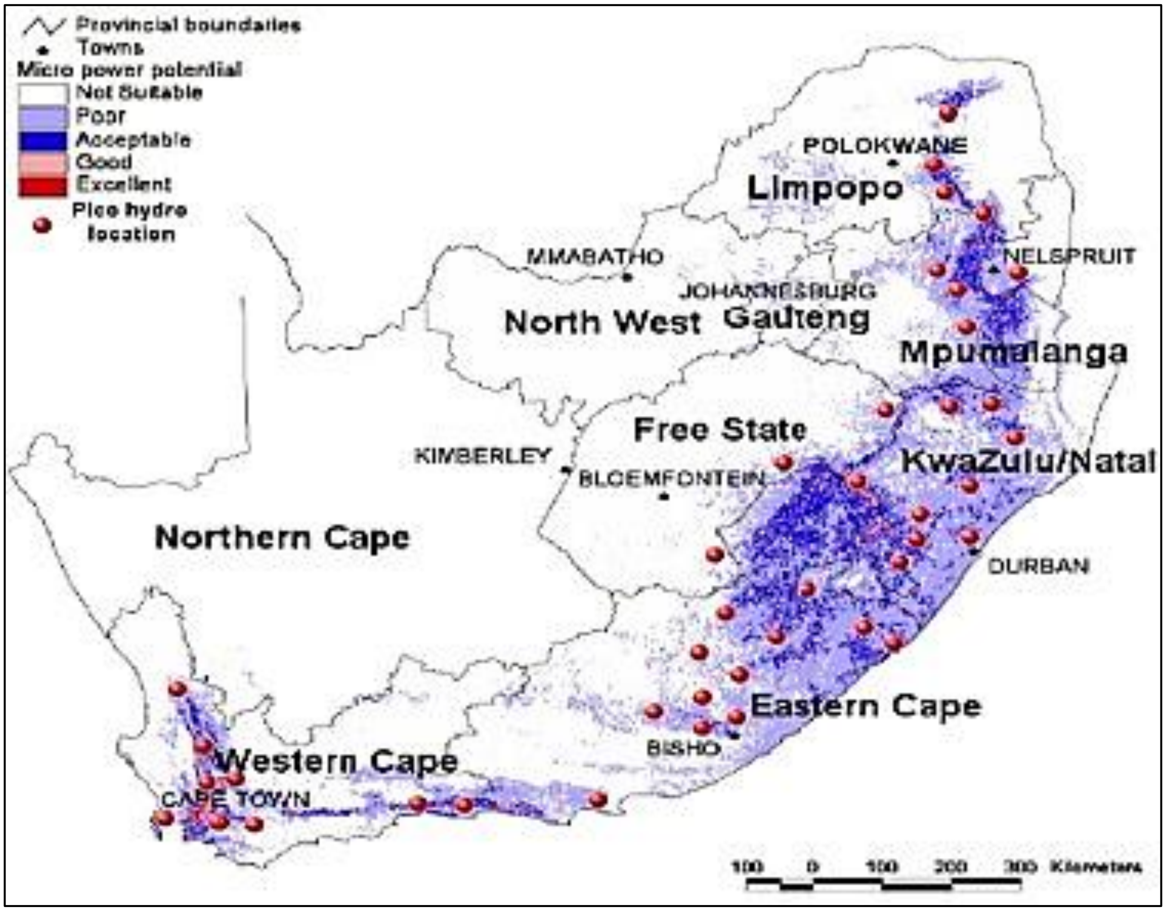


Figure 7-2 potential locations for small hydropower.

https://www.researchgate.net/profile/Herman-Vermaak-2/publication/266630234/figure/fig1/AS:295739465977860@1447521191410/Small-scale-hydropower-distribution-in-South-Africa.png