Strategic Siting of Photovoltaic Systems in Botswana

Amogelang Moemba[1], Marília Braga[2], Amanda M. F. Gomes[2], Daniel O. Dos Santos[2] and Ricardo Rüther[2]

[1] *Botswana Institute of Technology Research and Innovation, Gaborone (Botswana)*

[2] *Universidade Federal de Santa Catarina, Fotovoltaica/UFSC Laboratory, Florianópolis (Brazil)*

Abstract

Botswana is a landlocked country facing significant power supply challenges, characterized by frequent power interruptions and the need for load management strategies to stabilize the national grid. Coal-fired plants and imported energy from neighboring countries dominate electricity generation. The expansion of renewable energy (RE) generation through solar photovoltaic systems offers a promising pathway to diversify the energy mix. This study proposes a novel model for identifying strategic sites suitable for deploying large-scale photovoltaic (PV) systems using geographical information system (GIS) based spatial analysis and Analytical Hierarchy Process (AHP) to evaluate and weight multiple spatial criteria. The research will help decision-makers develop informed RE policies and development frameworks together with providing support and guidance towards Botswana's RE transition. The analysis integrates environmental, social, and economic factors when determining ideal locations for the PV systems. PV systems offer a low-cost, modular and rapid-deployment solution for Botswana's energy expansion. The results of the study show the top 10 suitable sites for PV deployment in Botswana, demonstrating their potential to contribute significantly to the country's RE targets. The final suitability map shows all the different sites.

*Keywords: Photovoltaic, Strategic sites, Botswana, Site Suitability, G*eographical information system (GIS)*, Analytical Hierarchy Process (AHP), Renewable energy*

1. Introduction

In Botswana despite exceptionally high solar irradiance levels, the energy sector is facing challenges, such as power shortages caused by increased energy demand, overreliance on coal power plants, and outdated national grid infrastructure. The overreliance on carbon intensive and imported power exposes the national energy sector to inefficiency and vulnerability. The global energy transition to renewable energy (RE) resources and the country's signatory status to the Paris Agreement have triggered the introduction of new policies and energy plans. In response to the energy sector's challenges, Botswana has developed the Integrated Resource Plan (IRP), a 20-year development plan 2020-2040 that models the country's electricity system development (Integrated Resource Plan for Electricity for Botswana, 2020).The IRP features a diverse matrix for new energy sources, including coal, which contradicts the country's plans to reduce carbon emissions. Despite that, the IRP shows that RE contributions to electricity generation are expected to increase. According to the IRP, solar PV installed capacity in Botswana is expected to reach 600 MW by 2040, accompanied by 140 MWh of Battery Energy Storage Systems (BESS) (Integrated Resource Plan for Electricity for Botswana, 2020). The Botswana Intended Nationally Determined Contributions (INDC) goal is to achieve an overall national greenhouse gases (GHG) emissions by 15% by 2030, with the energy sector targeted to achieve this reduction in emissions. Achieving this targets requires more than resource availability; it demands strategic and suitable sitting of PV plants which are economically viable and maximize energy yield. The use of Geographical Information Systems (GIS) combined with Multi-Criteria Decision-Making (MCDM) methods, such as the Analytical Hierarchy Process (AHP) is globally employed for resource allocation including identifying suitable sites for utility-scale RE projects. These methods integrate technical, environmental, economic criteria to develop suitability maps. Solar PV, as the lowest-cost energy generation technology currently available, is a suitable RE option for the energy transition and the most appropriate alternative to address most of the issues in Botswana's energy mix. Solar energy is highly recommended for semi-arid and arid regions (Koc et al., 2019). Identifying suitable sites for PV deployment maximizes benefits for society, government, and the public (Shriki et al., 2023). Thereby, this study applies a

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GIS-AHP site suitability methodology to identify and rank ten strategic sites for utility-scale PV projects deployment in Botswana. The identified suitable sites will provide a technical and planning foundation to support investment decisions, policy implementation, and future research on PV+BESS deployment strategies to enhance grid reliability and reduce carbon emissions in Botswana.

2. Literature Review

2.1. GIS and Multicriteria decision making

Identifying a suitable location for installing a PV power plant is a complex process due to the many conflicting factors involved (Sward et al., 2021). Studies for determining solar potential in different countries integrate various environmental, technical, and economic restrictions that make a certain location not suitable for PV plant installation. The Multi Criteria Decision Making (MCDM) is about making decisions when there are multiple criteria to be considered to choose between alternatives. The MCDM is used for resource allocation decisions and conflict resolution. A GIS is a software tool used in geographic data analysis. GIS has a range of applications, including techno-economic feasibility assessment, mineral prospecting, solar radiation level, and PV power potential studies (Cook & Pétursson, 2025). GIS allows for the visualization of the spatial analysis of all criteria used in this study. A GIS and MCDM methodology has been proven to be a useful tool to address decision issues in the energy sector, including site selection of a large-scale PV power plant (Bohra & Anvari-Moghaddam, 2022).

2.2. Botswana and international context of PV site suitability analysis studies

The combination of GIS and MCDM is a preferred method due to the complementary nature of the two techniques (Bohra & Anvari-Moghaddam, 2022). Several GIS and MCDM techniques used in literature are: Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), analytical network processing (ANP), Boolean overlay operation (BOO), ideal point method (IPM), preference ranking organization method for enrichment evaluation (PROMETHEE), order weight average (OWA), weighted linear combination (WLC), concordance analysis (CA), and the AHP (Richards et al., 2025). The AHP is the most widely used MCDM method (Papathanasiou & Ploskas, 2018) due to its simplicity and ability to apply it to qualitative and quantitative data (Rekik & El Alimi, 2024). In (Ohunakin & Saracoglu, 2018) the AHP is used in combination with other techniques like Consistency-Driven Pairwise Comparisons (CDPC), Decision Expert for Education (DEXi), Elimination and Choice Translating Reality (ELECTRE) for location selection of huge concentrated PV power plants in Nigeria. In Botswana no study has been made on the suitability analysis of PV plant installations hence the relevance of this study for the optimal siting of PV locations and better utilization of the solar resource. The methodology developed in this study informs decision makers and other stakeholders of the various contributing factors to consider in the development of PV projects. The study by (Häckner et al., 2024) used a GIS-based evaluation method for the suitability and implantation prospects for solar PV energy in Africa, and Botswana was included. Table 1 shows studies that GIS and AHP were used for site selection of PV projects, with the criteria used in each study. Amongst the studies of the MCDM-AHP methodology the major difference is the various criteria used to conduct the study. The unique nature of countries and regions in having different constraints on the development of PV projects necessitates the different criteria and having country specific studies.

3. Methodology

The flowchart presented in Figure 1 describes the methodology used in this study. The main objective of this research is to develop a model for the strategic siting of PV power plants using a GIS-based AHP Multi-Criteria Decision-Making approach. The developed model will then be used to identify suitable sites for installing tracking-mounted PV power plants in Botswana. Maps showing the power generation potential of the suitable sites will be provided, along with detailed techno-economic analysis, including each site's global horizontal irradiance, optimal tilt angle, temperature, elevation, and potential energy generation.

3.1. Study Area

Botswana is located between latitudes 17° and 27° S and longitudes 20° and 30° E, characterized by a semi-arid to arid climate. Botswana is a landlocked country in Southern Africa, as showed in Figure 2(a), with a total area of about 581,730 km^2 with 80 percent vast areas of land covered by the Kalahari Desert (Salih & Tedla, 1999).

Botswana has a high solar PV generation potential with a Direct Normal Irradiation (DNI) of about 3000 kWh/m^2/year, among the highest globally. The estimated solar PV power generation potential is in the range 1753-1972 kWh/kWp (*Solar Resource Maps of Botswana*, 2021) as shown in Figure 2(b). This makes the country a suitable candidate for utility-scale PV development. Figure 2(b) indicates the different PV power generation potential zones. The electricity demand in the country is met by 48% of local generation dominated by coal fired plants and importing 52% of power from the neighboring South Africa and the regional Southern African Power Pool (SAPP). Botswana's current installed capacity is 890 MW, but not all of the installed capacity is available (National Energy Use Survey, 2023). Due to the unreliable electricity imports and under performance of the Morupule B Coal Power Plant, the country is failing to meet its energy demand. Despite the country's abundance of solar resources, the energy sector is facing challenges, such as power shortages caused by increased energy demand, overreliance on coal power plants, and old national grid infrastructure. Technical problems at the country's biggest Morupule B Coal Power Plant have also exacerbated the power challenges. Botswana is faced with challenges of energy access and security. Peak demands far exceed the current available power from the installed capacity in countries.

Table 1: Summary of literature with GIS and AHP Application for PV site selection

Region	Study Title	Criteria used	Reference
Mauritius	Multi-criteria GIS-based modelling technique for identifying potential solar farm sites: A case study in Mauritius	Global solar radiation, Sunshine duration, Air temperature, Relative humidity, Elevation, Slope, Aspect, Proximity to roads and national grid,	(Doorga et al., 2019)
Saudi Arabia	Optimal solar plant site identification using GIS and remote sensing: framework and case study	Roads, powerlines, slopes, protected areas, distance from residential areas, solar irradiance	(Alhammad et al., 2022)
Brazil	Multi-criteria decision-making model for assessment of large photovoltaic farms in Brazil	Solar Irradiation, Slope, Substation Distance, Distance from Main Roads, Distance from residential Areas, Land Use, Agrological Capacity	(Rediske et al., 2020)
Turkey	A novel method for the site selection of large-scale PV farms by using AHP and GIS: A case study in Izmir, Türkiye	Solar radiation rate, Land use, slope, land cost, restricted areas, distance to road, Distance to transmission line	(Demir et al., 2023a)
Kuwait	GIS-based suitability analysis for siting solar power plants in Kuwait	GHI, Sunshine Duration, Temperature, Relative Humidity, Slope, Aspect, Distance to roads, Distance to power line, Distance to human settlements, Availability of derelict land	(Hassaan et al., 2021)
Nigeria	Integrating GIS and AHP for Photovoltaic Farm Site Selection: A Case Study of Ikorodu, Nigeria	Solar Irradiation, Average Air Temperature, Slope, Aspect, Proximity to Transmission Lines, Proximity to Major Roads, Proximity to Urban Areas, Elevation	(Onuoha et al., 2025)
Turkey	Multi-criteria decision-making in the location selection for a solar PV power plant using AHP	solar radiation, Climate conditions, clear days per year, Distance to bird migration locations, Safety, Distance from existing transmission line, Topographical properties	(Ozdemir & Sahin, 2018)
Cyprus	Optimal site selection for sitting a solar park using multi-criteria decision analysis and geographical information systems	Elevation, slope, Viewshed from primary roads, Land value, Distance from road network, Distance from electricity grid, Solar radiation	(Georgiou & Skarlatos, 2016)
Chile	Optimization of photovoltaic solar power plant locations in northern Chile	Slope, Orientation, Global irradiation, Temperature, Highway access	(Suuronen et al., 2017)

The global energy transition to RE resources and the Botswana's signatory status to the Paris Agreement (Government of Botswana, 2024) have triggered the introduction of new policies and energy plans. In response to the energy sector's challenges, Botswana has developed the IRP, a 20-year development plan (2020-2040) that models the country's energy system and identify RE resources and generation technologies that optimally meet energy needs (Integrated Resource Plan for Electricity for Botswana, 2020).

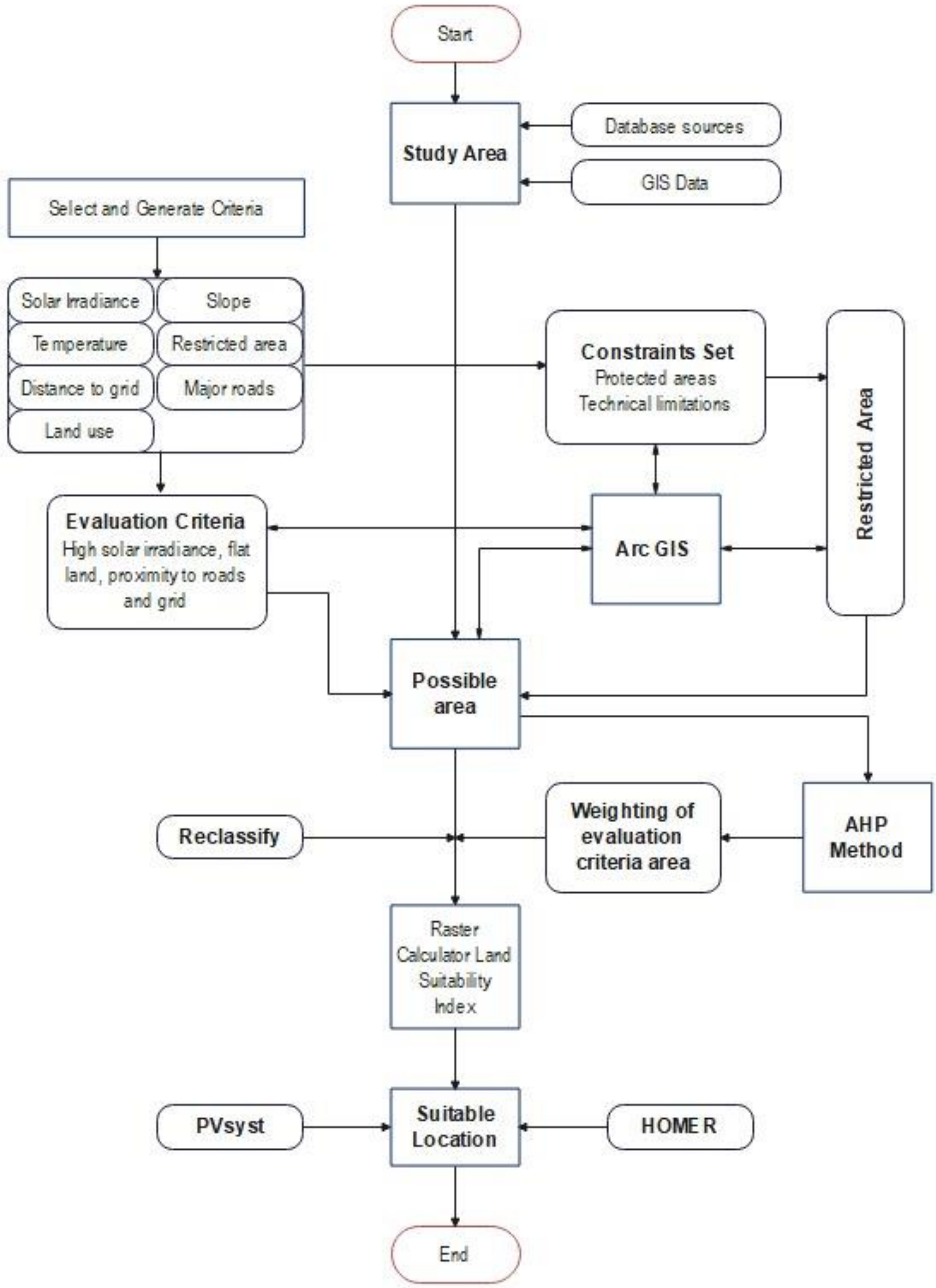
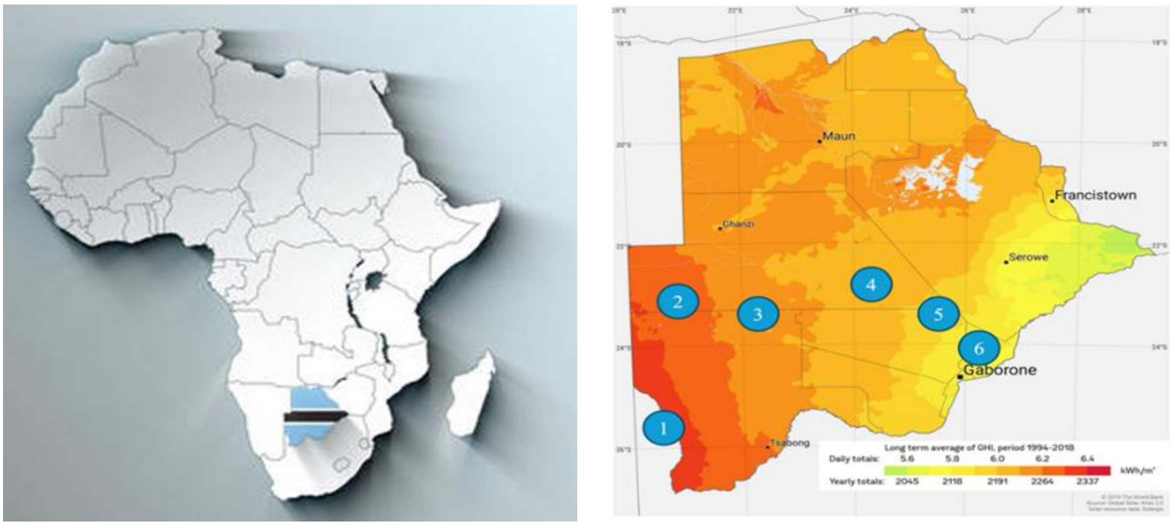


Figure 1: Method flowchart for the research Source: Adapted from (Gouareh et al., 2021).

The IRP features a diverse matrix for new energy sources, including coal, which contradicts the country's plans to reduce carbon emissions. Botswana's economy is dominated by mining, with the diamond and coal mining having the largest share(Bank of Botswana Annual Report, 2023). Botswana has an estimated coal deposits of 28.2 billion tons. Despite that, the IRP shows that RE contributions to electricity generation are expected to increase. According to the IRP, PV installed capacity in Botswana is expected to reach 600 MW by 2040, accompanied by 140 MWh of BESS. The Botswana INDC goal is to achieve an overall emissions reduction of 15% by 2030, with the energy sector targeted to achieve this reduction in emissions by installing PV plants which due to PV been the most cost-effective energy generation technology currently available on the market (IRENA, 2024b). The installation of the PV systems can be undertaken at the largest power plants (Kácsor et al., 2025) or distributed generation (DG) (Adefarati & Bansal, 2016) sites on the ground, on roofs, or integrated into buildings (Atmaja, 2013).The PV installation process is rapid, and the system can be modular, thus making PV a suitable RE option for the energy transition. Additionally, PV is the most appropriate alternative to address most of the issues in Botswana's energy mix. In recent years there has been an increase in PV installations in Botswana e.g. the 60MW Mmadinare Solar plant and several roof top installations totaling about 50MW (Botswana Energy regulatory Authority, 2025); however, there is no or little information on which sites in the country to perform the installations, cost of systems, adequate sizes and the grid performance is also unknown (Kassem et al., 2023). The RE development, particularly solar PV, has been recognized as crucial for addressing the country's growing energy demand and enhancing energy security (Maswabi et al., 2021). The coal-powered plant currently provides baseload power. PV integration will help stabilize the country's power supply issues and future projects can integrate BESS to help with the intermittent PV energy and store energy during periods of low PV generation, which often coincides with peak energy demand. The BESS will be important for balancing power output and consumption (Tasneem et al., 2025). Botswana's utilization of its abundant solar energy is very low (IRENA, 2024a).

To represent the diversity of geographic and environmental conditions in the whole country, ten key locations were selected across the six zones in Figure 2(b). The map also indicates the different zones, from zone (1) with the highest potential, up to Zone (6), with the least potential. Analysis of different sites within each zone was conducted to select the most suitable site. The selection is based on the different criteria as discussed below. The selection of locations was made with due consideration for the relevant geographical and statistical data of each site, including population, total area, demographic density, national context relevance, and climatic data. The selected locations are Gaborone, Francistown, Maun, Bokspits, Tsabong, Jwaneng, Nata, Letlhakane, Serowe, and Selebi-Phikwe.



(a) (b)

Figure 2: Botswana characteristics: (a) location and (b) PV power potential Botswana map (adapted from Solar Resource Maps of Botswana, 2021).

3.2. Identification of Decision Criteria

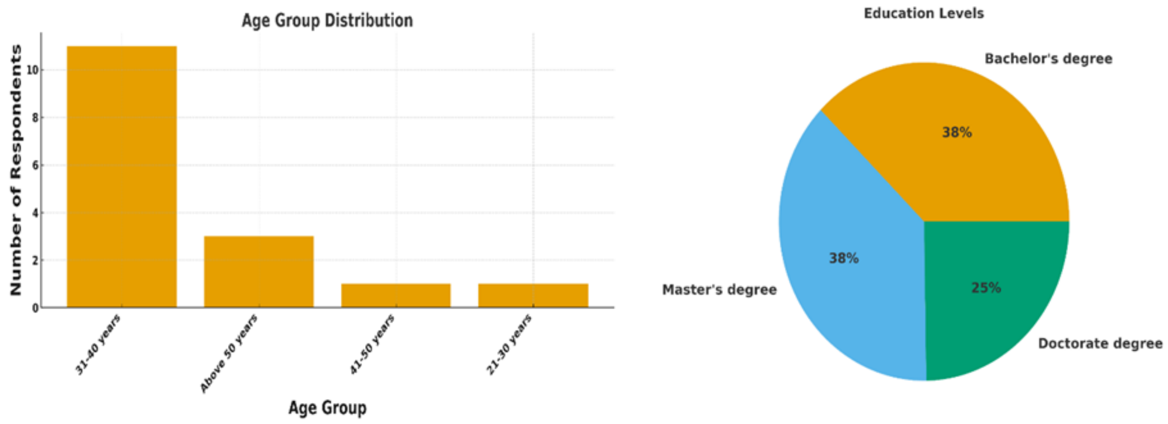
The geographic, environmental, social, technical, and economic factors are analyzed when determining ideal locations for the PV systems in this study. The selection of a suitable site is location based and highly dependent on local factors in that area (Ruiz et al., 2020). According to the literature review and the study objectives, twelve decision criteria are proposed: solar irradiance, land slope, average air temperature, distance from protected areas, distance to transmission lines, distance to main roads, distance to railroads and stations, distance from residential areas, elevation, land use, public interest and policy support, and the environmental risks. The twelve criteria can be grouped into three categories: technical, environmental, and economic. Technical criteria are solar irradiance, temperature, slope, and elevation. Environmental criteria are distance from protected areas, land use, and environmental risks. The economic criteria are distance to transmission lines, distance to main roads, distance to railroads and stations, distance from residential areas, public interest, and policy support. Certain possible areas will not be selected due to technical, environmental and economic limitations. Protected areas like mining and national parks cannot be selected even when they meet the set criteria constraints. There are restricted areas where PV plant installation will not be permitted like military areas and historic locations. The technical limitation constraints can be due to areas with higher slopes or inaccessible areas. The Arg GIS software is used for location mapping of all the locations and for visual representation of possible areas. The criterion for selecting possible areas is further discussed below.

- *Solar irradiance:* the amount of solar irradiance in an area highly influences solar power generation. Priority in site selection is given to areas with relatively high levels of solar irradiance and more sunshine hours.
- *Temperature:* the temperature is an important factor because different solar modules have different temperature coefficients. Generally, high temperatures may cause heat, which affects the performance of PV modules.
- *Slope:* the slope of an area affects the type of construction material to be used e.g. the mounting structures. Sites with steep slopes must be avoided and preference be given to flat sites. Access to areas with high slopes might also be a challenge.
- *Restricted areas:* areas like national parks and monuments will not be possible to install PV plants on. Built up areas like urban areas might also be restricted due to future developments and high cost of acquiring land.
- *Distance to grid:* the distance to the grid determines the cost of connecting the PV plant to the grid. Closeness to the grid or transmission lines reduces the cost and power losses that could be incurred.
- *Distance to major roads:* proximity to major roads is important for transportation of construction materials to site. Access to roads will help with fast response time during emergencies and for maintenance.
- *Land use:* the land use information gives the activities going on in the selected site. Some sites might be used for other purposes that are more important than the solar PV plant.

3.3. Analytical Hierarchy Process

The AHP is widely used in MCDM planning and resource allocation (Saaty, 1987). The AHP is used to compare the decision criteria in a pairwise process that obtains a favorability scale in a set of alternatives, the comparisons are made by decision makers who must have knowledge and experience of the problem area (Vargas, 1990). In this study the AHP method is used to give the importance of ranking of each of the selected twelve criteria against each other. A questionnaire is designed for experts and decision makers to compare the decision criteria and give the level of preference of each criteria for siting of PV plants in Botswana. The AHP assigns weights for the different criteria. A comparison scale of values from 1 to 9 is used to represent the importance of one criteria to another (Saaty, 1987). The scale is from intensity of weight 1 with equal importance when two criteria contribute equally to an object to the highest intensity of weight 9 with absolute importance where the evidence favoring one criteria over another is of the highest possible order of affirmation. Figure 3(a) below shows the age group distribution of participants and Figure 3(b) shows the education level for the survey participants. The response from the decision makers is analyzed to create a comparison matrix. The comparison matrix is an expert's opinion of the level of importance of each criteria against the other. The importance of a criteria against itself is one. Following the collection of survey feedback the matrix is then normalized according to the total weight of each criteria. The last stage of the AHP is to calculate the consistency ratio, CR (Demir et al., 2023a). If the result of CR is equal or less than 0.10, the pairwise comparison results are acceptable, otherwise they should be revised (Aly et al., 2017).

The consistency index (CI) is calculated from λ_{max} , the large eigenvalue of the pairwise comparison matrix and the number of decision criteria used (n). The random consistency index (RI) for the twelve different criteria in this study is n = 12 and RI= 1.48. The last AHP stage is the weighting of each criteria as a matrix. The results of the survey are shown in Table 2. The matrix is used in raster calculation using the Arc GIS toolbox. The raster calculation toolbox creates and executes map algebra on the original GIS data. In the final step the maps obtained are the suitable locations for PV plant installation.



(a) (b)

Figure 3: Respondents analysis: (a) education level and (b) age group.

Table 2: Criteria used for ranking.

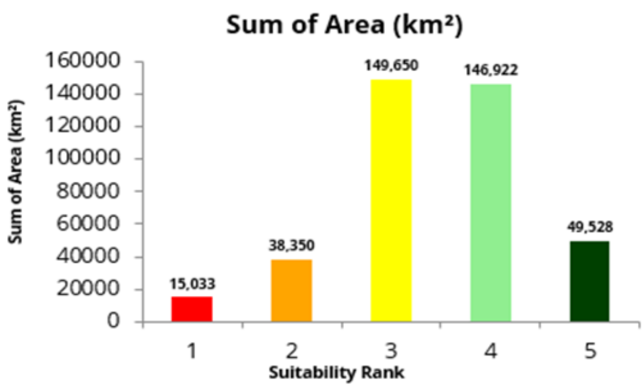
Rank	Criteria	Weight
1	Environmental risks	22%
2	Public interest and policy support	13%
3	Solar irradiance	11%
4	Distance to transmission lines	11%
5	Distance from protected areas	10%
6	Land Use/Land Cover	10%
7	Distance from residential/built-up areas	6%
8	Distance to main roads	4%
9	Elevation	4%
10	Average air temperature	4%
11	Land slope	3%
12	Distance to railroads and stations	3%

3.4. Software selection

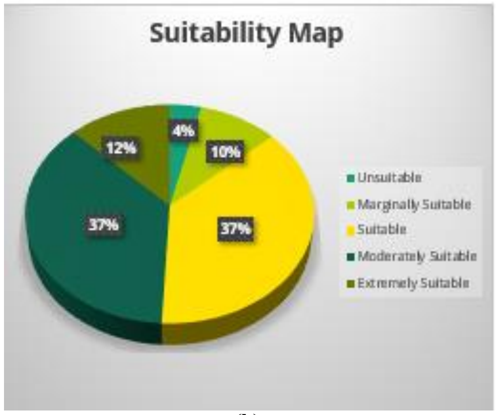
The GIS tool ArcGIS Pro developed by Esri, is used for spatial analysis and geospatial data management. ArcGIS is suitable for use in this study for its advanced spatial modeling functionality of raster analysis, digital elevation models, and Euclidean distance analysis. The integration of ArcGIS with AHP is done using the weighted sum model (Aly et al., 2017), where the criteria weights from AHP are superimposed on the raster maps collected from different sources. ArcGIS tools are used to develop suitability maps based on each criteria. A sensitivity analysis is performed by assigning equal weights to all decision criteria. This validates the proposed methodology by defining how sensitive the method is to change in criteria.

4. Results and Discussions

The result of this study shows the total area that is available for PV plant installations in Botswana, having taken into consideration the twelve criteria with their different weights from the AHP survey. The AHP survey shows that the environmental risks criteria are the most important factor for the respondents. This criteria involves the risks posed to the installed PV system like flooding and earthquakes. The area is further ranked as unsuitable, marginally suitable, suitable, moderately suitable, and extremely suitable. Figure 4(a) shows the total area per ranking, and Figure 4(b) shows the percentage share for each rank. The maps in Figures 5 and 6 show the different normalized raster for the different criteria. The individual criteria maps show the different suitability levels in the country. The annual solar irradiation map shows the suitability levels highest in the west and lowest in the eastern part of the country, this is contradictory to the suitability levels of the distance to the grid criteria. This conflicting results are to be expected because individual criteria use different indicators with different levels across the country. To avoid this contradiction, multiple criteria were used, and the maps of each criteria were then overlayed in ArcGIS using the AHP weights to produce the final Suitability map in Figure 7. The final composite suitability map considers each criteria map according to its weight and ranking. The extremely suitable sites cover 49528 km^2 or 12% of the available study area and the unsuitable area is 15033 km^2 or 4%. The result could encourage the government and investors to show the PV potential that the country has. There are two PV plants already existing in the country, one PV plant in Jwaneng is in the moderately suitable zone according to the methodology developed and the other, a 50 MW plant is in the unsuitable zone.



(a)

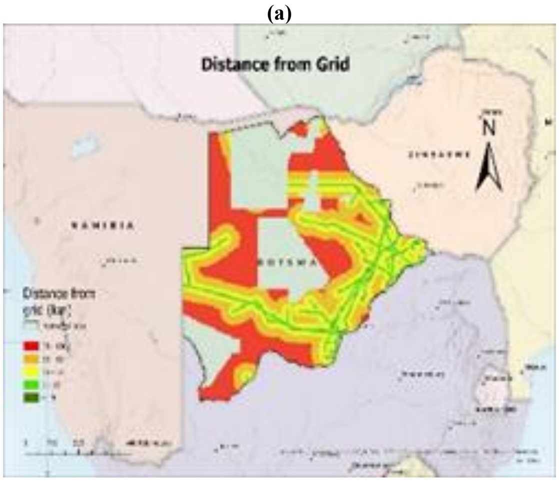


(b)

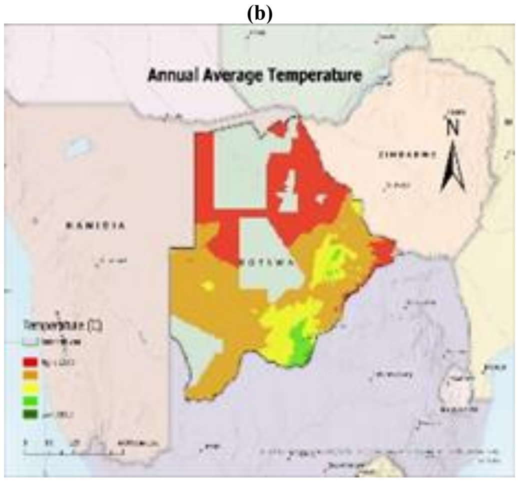
Figure 4: Area analysis: (a) sum of the area of suitable sites and (b) percentage area of each suitability ranking.

(a)

(b)

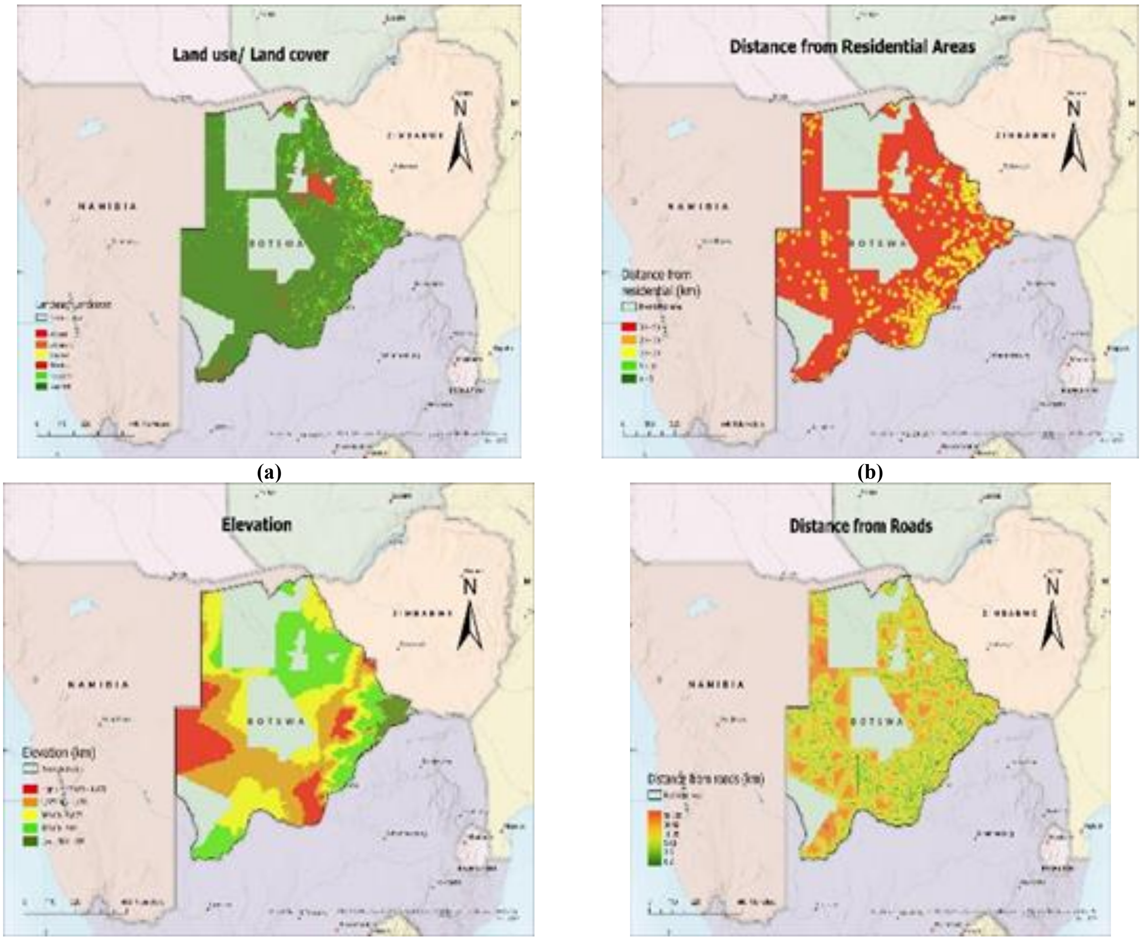


(c)



(d)

Figure 5: Individual criteria result maps: (a) restricted areas, (b) annual global solar irradiation, (c) distance from grid, and (d) annual average temperature.



(a) (b) (c) (d)

Figure 6: Individual criteria result maps: (a) land use, (b) distance from residential areas, (c) elevation, and (d) distance from roads.

5. Conclusion

There are many factors that decision makers consider when identifying PV plant sites. The model in this study used multiple criteria and the AHP survey to implement a GIS AHP based decision making approach. The results of this study will assist the decision makers to make informed decisions on the selection of locations of future PV plants in the country. It is critical to identify the right locations to install PV plants as it saves the project implementors time and money. The identification of suitable sites in the country will further assist the government with the implementation of the RE projects to help the country achieve its 2030 and 2040 targets. To improve the accuracy of the developed model and make it more reliable will require involving more stakeholders in the AHP survey and using updated datasets for the different criteria. Further techno-economic studies are needed to analyze each suitable site for the transition to RE. The extremely suitable areas identified are in the desert part of the country; further research is needed on the impact of the desert conditions on the PV plants installed. This is the first study in the country dealing with identification of suitable PV plant sites. The model will be an important tool for future RE projects in the country. It is concluded that this study is necessary and adds to the available resources to be used by decision makers in formulation of policy and implementing RE projects.

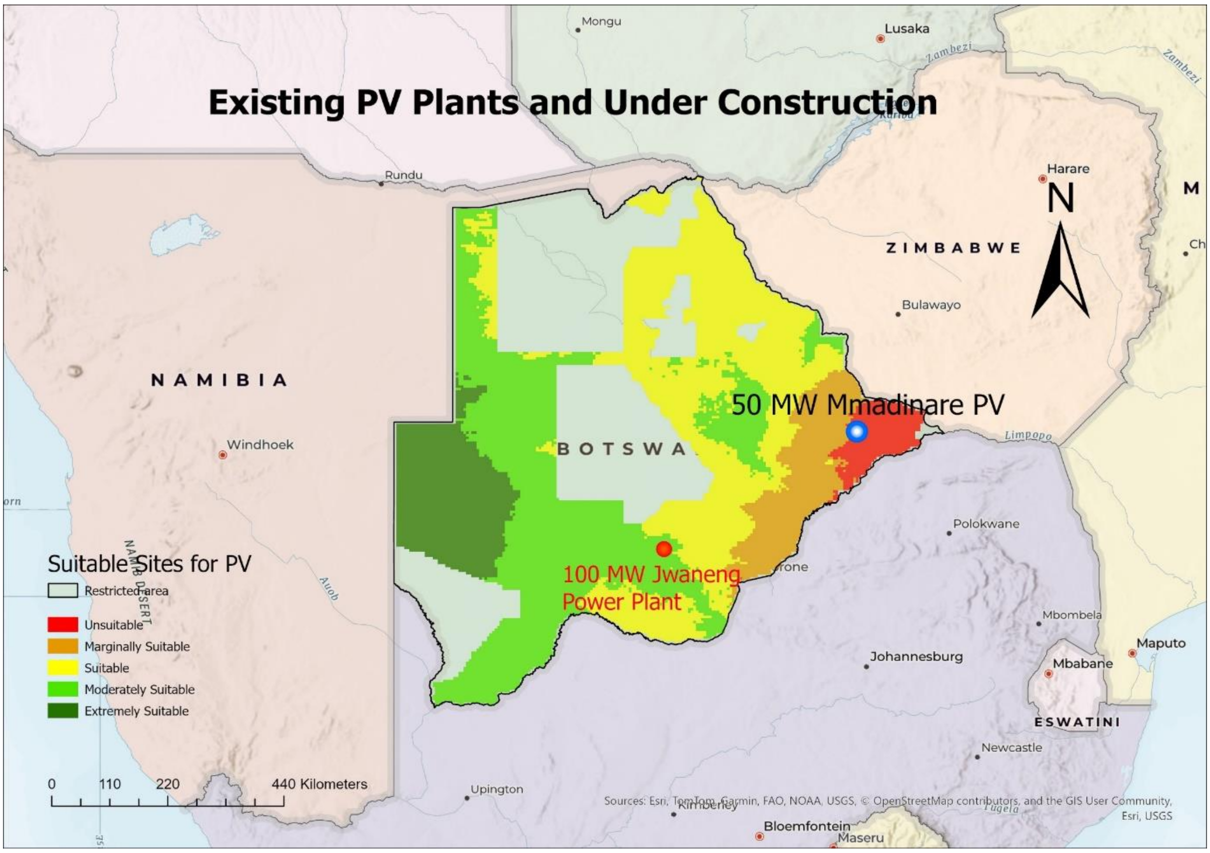


Figure 7: Resulting large scale PV suitability map developed in this study. The two existing PV plants are marked on the map.

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