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SUITABILITY ANALYSIS OF SOLAR PHOTOVOLTAIC FARM LOCATIONS USING GIS: A CASE STUDY OF NAKURU COUNTY, KENYA

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Abstract

Renewable energy sources play a crucial role in reducing global reliance on fossil fuels. Advancements in technology has enabled harnessing of renewable energy from solar, wind, and ocean tides to be viable. Solar energy, in particular, has gained significant global recognition as a renewable energy alternative. This study integrates Multi-Criteria Evaluation (MCE) and Geographic Information Systems (GIS) to assess Solar Photovoltaic Farms (SPVFs) suitability in Nakuru County, Kenya.

The study considered seven criteria including; slope, solar radiation, aspect, land use land cover, proximity to roads, power transmission lines, and settlements. These were evaluated using the Analytical Hierarchy Process (AHP) to generate weights for each decision criterion. The weights were used to overlay independent criteria maps that were formed as a result of the reclassification of each criterion from which a composite rated map was developed. Similarly, a composite restriction map was created by leveraging on constraint criteria including; protected ecosystems, water bodies, settlement areas, slope over 20%, proximity to roads, proximity to the transmission line, and land use land cover.

Results obtained from overlaying the composite rated and restricted maps reveal Nakuru County's general suitability for SPVFs, except for Kuresoi North and Kuresoi South divisions which exhibit low solar radiation. Extremely-suitable areas accounted for 3.00% (224.14 km^2), very-suitable areas 34.05% (2541.45 km^2), moderately-suitable areas 7.76% (579.55 km^2), marginally-suitable areas 1.47% (109.77 km^2) while least-suitable areas covered 0.02% (1.39 km^2).

The study provides valuable data and information for government agencies and investors to identify potential Photovoltaic (PV) system sites. Furthermore, the government is encouraged to establish a favorable framework for solar PV exploration and provide incentives to the private sector to facilitate the establishment of SPVFs.

Keywords: suitability analysis, renewable energy, photovoltaic, multi-criteria evaluation, GIS, analytical hierarchy process

ANALIZA PRZYDATNOŚCI LOKALIZACJI FARM FOTOWOLTAICZNYCH Z WYKORZYSTANIEM GIS: STUDIUM PRZYPADKU HRABSTWA NAKURU, KENIA

Abstrakt

Odnawialne źródła energii odgrywają kluczową rolę w zmniejszeniu globalnego zapotrzebowania na paliwa kopalne. Postęp technologiczny umożliwił czerpanie odnawialnej energii ze słońca, wiatru i pływów oceanicznych. W szczególności energia słoneczna zyskała uznanie w skali globalnej jako odnawialna alternatywa energetyczna. Niniejsze badania integrują ocenę wielokryterialną *(Multi-Criteria Evaluation* – MCE) i systemy informacji geograficznej (*Geographic Information Systems* – GIS) dla oceny możliwości utrzymania fotowoltaicznych farm słonecznych (*Solar Photovoltaic Farms* – SPVF) w hrabstwie Nakuru, Kenia.

Badania brały pod uwagę siedem kryteriów: nachylenie, nasłonecznienie, kierunek ekspozycji, użytkowanie i pokrycie gruntu, bliskość dróg, linie wysokiego napięcia oraz obecność osiedli ludzkich. Były one oceniane przy użyciu metody hierarchicznej analizy problemów (*Analytical Hierarchy Process* – AHP), tak aby dla każdego kryterium decyzyjnego wygenerować wagi. Wagi zostały użyte by wypełnić mapy niezależnymi kryteriami, utworzonymi w wyniku ponownej klasyfikacji każdego kryterium, z których utworzono złożoną mapę z uwzględnieniem rang. Podobnie utworzono złożoną mapę ograniczeń, poprzez wykorzystanie kryteriów ograniczających takich jak: ekosystemy chronione, zbiorniki wodne, osiedla ludzkie, nachylenie terenu powyżej 20%, bliskość dróg, bliskość linii przekaźnikowych, użytkowanie i pokrycie gruntu.

Wyniki otrzymane z utworzenia złożonych map ocen i ograniczeń wskazują na to, że hrabstwo Nakuru zasadniczo nadaje się do wykorzystania SPVF, z wyjątkiem obszarów Północnego Kuresoi i Południowego Kuresoi, które wykazują niskie natężenie promieniowania słonecznego. Obszary wyjątkowo odpowiednie dla energii słonecznej stanowią 3.00% (224.14 km^2), bardzo odpowiednie stanowią 34.05% (2541.45 km^2), umiarkowanie odpowiednie – 7.76% (579.55 km^2), mało odpowiednie – 1.47% (109.77 km^2), a najmniej odpowiednie pokrywają 0.02% (1.39 km^2).

Badania dostarczają wartościowych danych i informacji dla agencji rządowych i inwestorów, którzy chcieliby wskazać miejsca możliwej instalacji systemów fotowoltaicznych (PV). Ponadto zachęca się rząd do utworzenia odpowiedniego ramowego planu badań nad PV i wprowadzenie ułatwień dla sektora prywatnego, aby umożliwić zakładanie SPVFs.

Słowa kluczowe: analiza trwałości i opłacalności, energia odnawialna, fotowoltaika, ocena wielokryterialna, GIS, metoda analizy hierarchicznej.

1. INTRODUCTION

Kenya's installed electricity capacity stood at 2,990 Megawatts (MW) in 2021. This generation energy mix comprised hydro at 838 MW, geothermal at 863 MW, 2% from biogas cogeneration, wind at 437 MW and solar at 173 MW. It is expected that generation will reach 5,000 MW by the year 2030, with the bulk of this coming from geothermal, natural gas (imports), wind, and solar [1, 2].

Geographic Information System (GIS) refers to a system of software, hardware, and procedures that aid the modeling, representation, analysis, management, manipulation, and visualization of geo-referenced data to solve complex problems concerning resource management and planning [3–5]. On the other hand, Multi-Criteria Decision-Making (MCDM) refers to a renowned decision support system where various factors affecting a single goal are solved. The system offers an appropriate option by comparing and evaluating the characteristic properties of the alternatives [6].

MCDM offers various management options to be evaluated in a clear method that is mathematically involving and straightforward to stakeholders [7]. MCDM provides a mathematical framework that involves stakeholders' and decision-makers' values *cum* technical know-how. This aids in the selection of the best alternative for the problem in question and gives room for a more evidence-based and data-driven rational resolution to be executed.

Ukwishaka *et al.*, [8] employed GIS as a spatial analysis tool blended with a Multi-Criteria Evaluation (MCE) model to determine potential Solar PhotoVoltaic Farm (SPVF) locations in Rwanda. In this case study, datasets for carrying out suitability analysis of SPVFs locations were chosen regarding certain decision criteria that was obtained from scientific studies and literature review. The decision criteria were classified into three: territorial limitations, exclusionary zones and productivity factors. The constraint criteria were the land use land cover maps obtained from remotely sensed data. The criteria weights through Analytical Hierarchy Process (AHP) method were applied to the decision criteria and then standardized. The weighted decision criteria were then reclassified and consolidated to generate the final suitability map [8].

The fact that the equator passes through Kenya results in the country experiencing relatively high temperatures throughout the year with little variation between seasons. The country has a diverse and varied landscape with numerous highlands and mountain ranges. Like most other countries in the tropics, Kenya boasts of reliable solar radiation at an average of 4.5 $kWh \cdot m^{-2} \cdot d^{-1}$. About ten percentage (10.1%) of Kenya's total land receives 6.0–6.5 $kWh \cdot m^{-2} \cdot d^{-1}$, 26.5% of the land receives between 5.5 and 6 $kWh/m^2/d$, while 34% of the land receives between 5 and 5.5 $kWh \cdot m^{-2} \cdot d^{-1}$ [9]. It is apparent that if solar energy was properly utilized, it would constitute a major and stable source for renewable energy that would ensure energy stability in the country, while at the same time conserving the environment.

Solar energy possesses several key benefits including: it is environmentally friendly since it does not produce any greenhouse gas emissions or other air pollutants and therefore helps to combat climate change; it is versatile and cost-effective since solar panels or photovoltaic cells have a long lifespan and it therefore provides a reliable source of energy for decades [10]. Solar energy systems are known to be one of the least polluting energy sources; however, they might also have direct or indirect negative implications. For instance, competition with other land use categories like agricultural [11].

Conceptually, solar energy is produced by nuclear reactions occurring in the sun's mass. This energy reaches the earth's surface in electromagnetic radiation form [12]. It is a renewable, sustainable, and clean energy since it does not produce greenhouse gases or air pollutants during operation. Solar power is captured and turned into two types of energy: Concentrated solar power (CSP) systems, which is one of these types, use mirrors in hundredfold to centralize sun radiation to 400°C –1000°C to produce heat or electricity. Furthermore, CSP can operate as a technology of solar energy through heat storage or by combining it with power plants utilizing fossil fuels, for instance, oil and natural gas to provide energy when there is no sunlight [13].

Photovoltaic (PV) electricity is the other solar energy application that directly converts sunlight into electricity. PV systems come in a variety of technologies and configurations – microcrystalline silicon, polycrystalline silicon (or multi-crystalline), copper-indium-gallium diselenide (CIGS) monocrystalline silicon solar cells, and cadmium telluride solar cells which are currently available on the market. The choice of solar PV technology does not affect the suitability assessment. However, the amount of electricity generated depends on the type of PV system. For instance, single crystalline produce more electricity compared to polycrystalline PV. This contributes to the panel's efficiency with the former having 15%–20% compared to the latter with 13%–16%.

The two main demerits of single crystalline PV are high cost due to the costly production process and reduced efficiency as the temperature drops to approximately 25 °C. Polycrystalline solar cells are advantageous due to lower price compared to single-crystalline [14]. These systems can offer clean energy for a variety of users. They are used to generate energy in commercial buildings, housing developments, private residences, public buildings, and offices worldwide [13].

Renewable energy is related to sustainable development through its effect on economic productivity and human development [15]. Renewable energy sources offer opportunities for energy access and security, social and economic development, mitigating climate change, and reducing health and environmental impacts [15]. Figure 1 shows the opportunities for renewable energy sources for sustainable development.

According to the Nakuru County Integrated Development Plan (CIDP) [10], 46% of Nakuru County residents use firewood, 40% of them use charcoal, 8% use paraffin and 5% employ Liquefied Petroleum Gas (LPG) as shown in Table 1. Thirty six percent (36%) of residents use lanterns as their major lighting source, a further 34% use electricity, 25% use tin lamps, and 1% employ fuel wood as shown in Table 2.

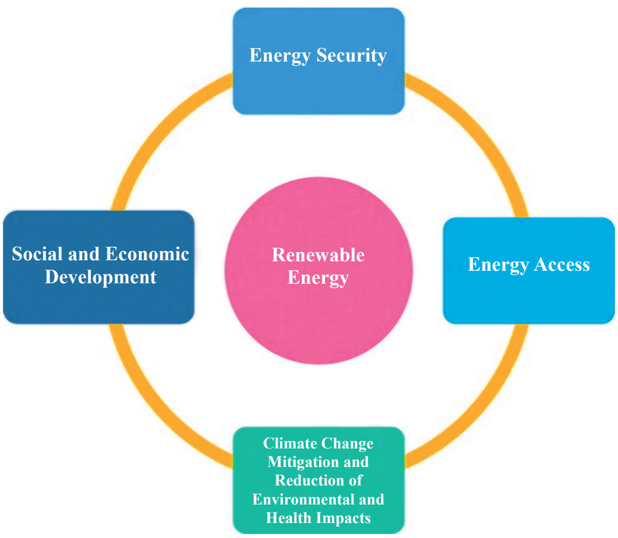

Fig. 1. Opportunities for renewable energy sources
Ryc. 1. Szanse dla energii odnawialnej

The energy supply in Kenya, though rapidly expanding, has not been sufficient to meet the growing demand that can be traced back to the rapid economic growth,

Table 1. Data Sources
Tabela 1. Źródła danych

Data	Format	Source	Product
Administtrative Boundaries	Vector	Kenya 6IS Data World Resources Institute	Area of Study
Digital Elevation Model (30 m Resolution)	Raster	US Geological Surveys	Slope and Aspect maps
Road Network	Vector	Kenya Roads Board	Road Eudidean map
Water Bodies	Vector	Diva GIS	River and Lake maps
Protected Areas	Vector	World database on Protected areas	Protected Area map
Transmission Lines	Vector	KETRACO	Transmission Lines Eudidean map
Land Use/Iand Cover	Raster (Geotiff) Resolution 20 m	European Space Agency (ESA) Climate Change Initiative Land Cover Team	Land Use/Land Cover and Bullt Up Areas map

Table 2. Value score per criterion
Tabela 2. Wartość przyznawana poszczególnym kryteriom

Value	Solar radiation (kWh/m^2, year)	Slope (%)	Aspect	Roads (m)	Transmiss Ion lines (m)	Settlements (m)	Land cover/ land use
0		> 20		0–200	0–200	0–500	Built-up areas, open water, vegetation aquatic/flooded
1	1866–1969	16–20	North, Fiat	> 5000	> 10 000	> 5000	Tree cover
2	1969–2021	12–16	North East, North West	3200–5000	6000–10 000	3000–5000	Cropland & Grasslands
3	2021–2062	8–12	East, West	2200–3200	4000–6000	2000–3000	Shrubs
4	2062–2100	4–8	South East, South West	1200–2200	2000–4000	1000–2000	Sparse vegetation
5	> 2100	0–4	South	200–1200	200–2000	500–1000	Bare ground

urbanization, and industrialization that the country has gone through. This has broadened the demand-supply gap in the energy sector. Coupled with periodic shortage of hydro electric energy, which is the main energy supply source, the energy deficiency has led to recurrent power crises in the country [16]. The situation is further exacerbated by the environmental impact of climate change [17, 18].

Furthermore, the state of affairs in the energy sector has led to a rise in the country's reliance on imported fuel. The year 2017 saw 79 million kWh of energy, out of the total production of 9 billion kWh, being imported [19]. The limited energy supply *vis-a-vis* energy demand necessitates the development of renewable energy sources. Solar energy is becoming increasingly popular since solar photovoltaics and other equipment are relatively inexpensive. In many countries, solar energy is already cost-competitive compared to fossil fuels and is expected to become even more affordable over time (Figure 2, 3).

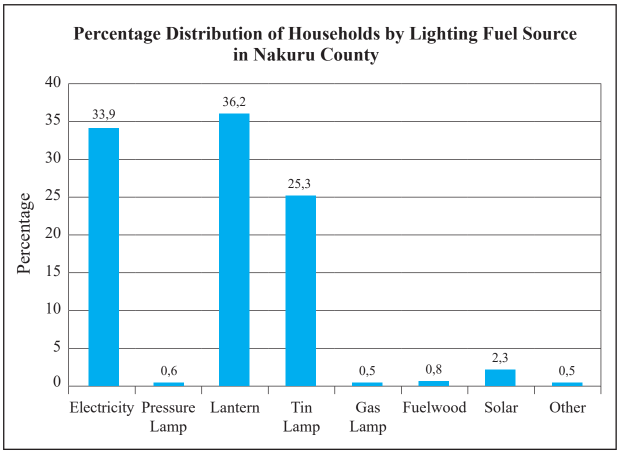

Fig 2. Percentage Distribution of Households by Source of Lighting Fuel in Nakuru County

Fig. 2. Rozkład procentowy gospodarstw według użycia źródeł energii przeznaczonej do oświetlania w hrabstwie Nakuru

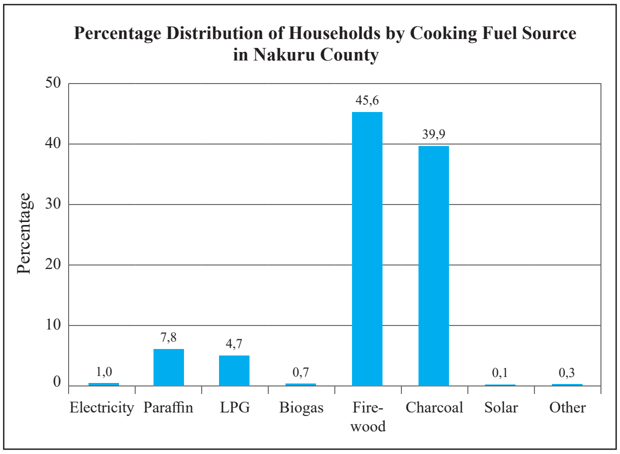

Fig. 3. Percentage Distribution of Households by Source of Cooking Fuel in Nakuru County

Fig. 3. Rozkład procentowy gospodarstw wg użycia źródeł energii używanej do przyrządzania posiłków w hrabstwie Nakuru

This study aims to bridge the energy supply gap by identifying suitable sites for the establishment of Solar Photovoltaic Farms (SPVFs) to enable solar energy production. However, there is a challenge in locating the best sites for setting up SPVF to obtain maximum solar energy and this is where GIS comes in. By integrating GIS and MCDM, decision-makers can make more informed and data-driven decisions that take into account the complex spatial relationships between different criteria in the suitability analysis of SPVF locations. The main objective of the study was to identify the best location for siting Solar Photovoltaic Farms (SPVFs) in Nakuru County, Kenya.

2. DATA AND METHODS

Nakuru County is situated within the Great Rift Valley and neighbors Baringo and Laikipia counties to the north, Kericho and Bomet counties to the west, Narok to the southwest, Kajiado and Kiambu counties to the south, and Nyandarua to the east. The county is situated between Longitudes 35° 28′ and 35° 36′ East and Latitudes 0°13′ and 1° 10′ South accounting for an area of 7,495.1 km² [10] as shown in Figure 4 while Figure 3 highlights the approach employed in the study. Nakuru County was selected for the study since its located near the equator and generally receives continuous sunlight throughout the year.

Decision criteria refer to the measurable logical factors used to make decisions within the problem scope. These were drawn from various expert opinions and scientific publications. They were divided into different components: climatic (solar radiation), environmen-

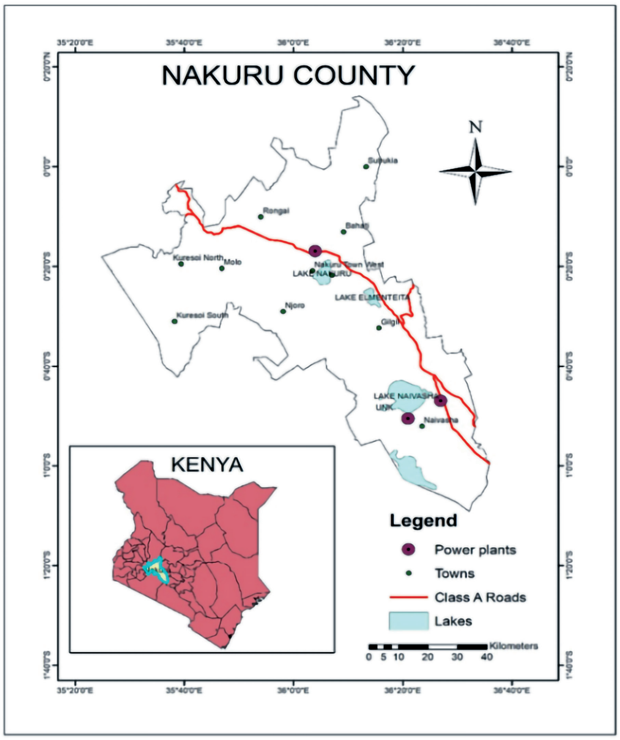

Fig. 4. Study Area

Ryc. 4. Obszar badań

tal (land cover), economic factors (distance from roads, high voltage transmission lines, built-up areas), and topographical (slope and aspect). Decision criteria used in the study comprised of both constraints and factors. The decision constraints enabled sites that are unsuitable for SPVF setup to be identified. Unsuitable sites were assigned 0 whilst suitable sites were assigned 1.

Decision factors, on the other hand, were allowed the degree of suitability for solar farm locations considering the respective attributes. Different criteria weights were assigned to the decision factors and this was after forming the AHP pairwise matrix and normalizing it to obtain the calculated criteria weights. The varied levels of importance among the decision factors, for pairwise matrix creation, were obtained from literature review of various expert opinions and scientific publications (Figure 5). From the decision criteria relevant data sets were identified and sourced as shown in Table 1.

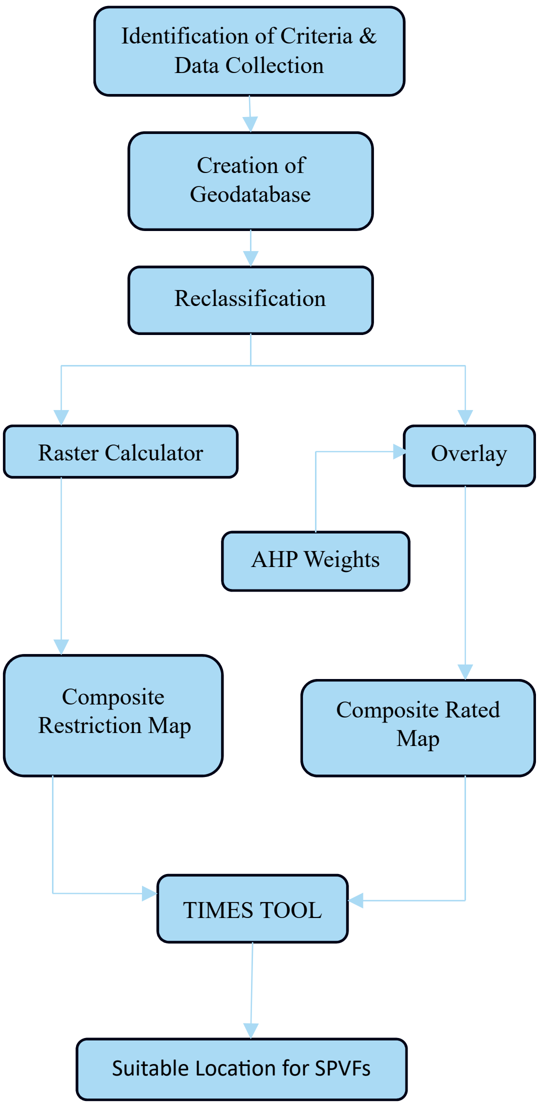

Fig. 5. Methodology Flowchart
Ryc. 5. Schemat blokowy przedstawiający metodologię

In preparation for data analysis, all raw data was projected to WGS_1984_UTM_Zone_37S. Clipping of data was performed to both the vector and raster data sets using the area of extent (Nakuru County). A geodatabase was then created. The data was then resampled according to the decision criteria to accuracy 30m resolution. Data processing was done using the geo-processing tools in Arc Map 10.6.

Reclassification to individual factor maps was done according to Table 2. A score value of 0 means that the site is unfeasible, a score value of 1 indicates the site is least suitable, a score value of 2 indicates the site is marginally suitable, a score of 3 means the area is moderately suitable, a score value of 4 denotes that the site is very suitable and a score of 5 means the area is extremely suitable.

3. RESULTS AND DISCUSSION

Restricted areas constituted approximately 53.69% and this was mainly due to protected areas (they constitute 29.19%), as in these areas, SPVFs cannot be constructed. Almost half of the county was suitable for SPVF setup (46.31%) as the county receives high solar radiation levels while the land slope is mostly under 20% as shown in Figure 6.

The Sub-counties of Gilgil, Rongai, and Naivasha are the most suitable and cost-effective counties as they are served by power transmission lines and have good road network distribution (Figure 6). Subukia sub-county power transmission line is not well distributed as it serves the lower region. This is not cost-effective as the central and northern regions would have to construct a power line so that power generated from these sides reaches the National Grid.

The final suitability map (Figure 7) shows that 46.31% (3456.30 km^2) of the total land in Nakuru County is suitable for SPVFs. Out of this suitability, 96.78% (3345.14 km^2) of the feasible areas ranged from moderately suitable to extremely suitable, and 80.02% (2765.59 km^2) of the feasible sites were very suitable and extremely suitable areas. Least and marginally suitable areas account for 3.22% (111.16 km^2) of the total

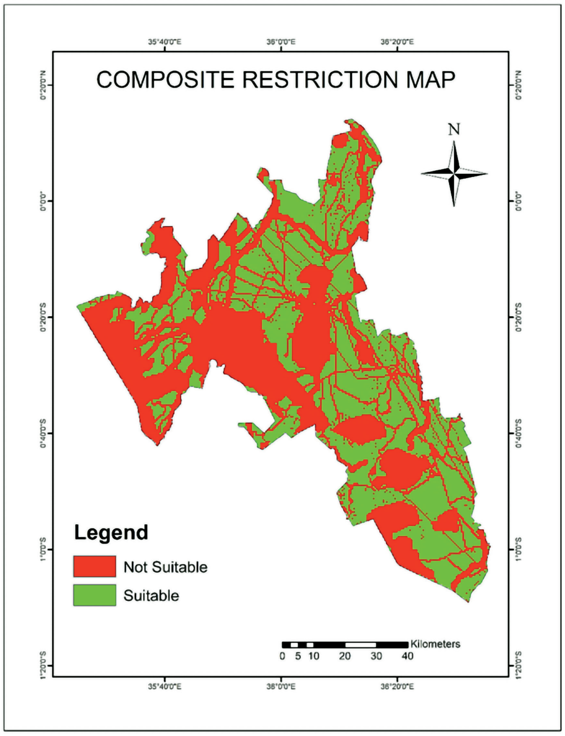

Fig. 6. Composite Restriction Map for Nakuru County
Ryc. 6. Złożona mapa ograniczeń dla hrabstwa Nakuru

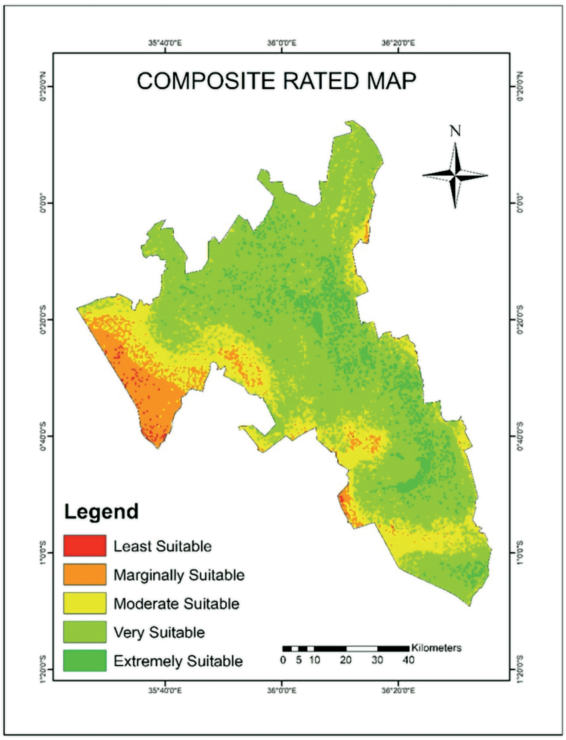

Fig. 7. Composite Rated Map of Nakuru County
Ryc. 7. Złożona mapa rankingowa dla hrabstwa Nakuru

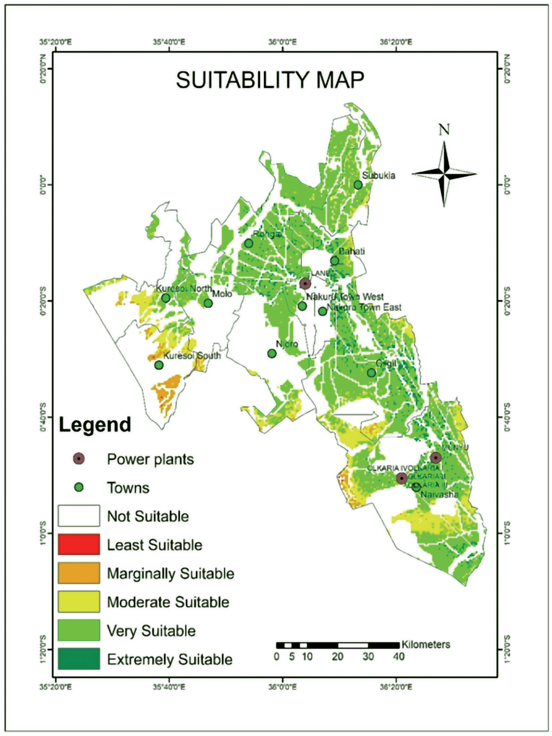

Fig. 8. Final Nakuru County SPVFs Suitability Map
Ryc. 8. Ostateczna mapa hrabstwa Nakuru pokazująca przydatność zastosowania SPVF, aby było zgodne z zasadami zrównoważonego rozwoju

feasible areas. Moderately suitable areas account for 16.77% of feasible areas, very suitable areas account for 73.53% of feasible areas and extremely suitable areas account for 6.48% of the total feasible areas.

Nakuru County is suitable for Solar Photovoltaic Farms since 44.82% (3345.14 km^2) of the total land accounts for moderate to extremely suitable regions as illustrated in Figure 8. For the best places to set up (very and extremely suitable regions), they account for 37.07% (2765.59 km^2) of the total land (Table 3).

The spatial resolution of the remotely sensed data employed in the study was deemed appropriate for the coarser scale at which this preliminary work was conducted. However, for demarcation of individual SPVFs, higher spatial resolution data such as Sentinel 2 would be required. The results of the study were validated using ground-truthing techniques. From this it was established that a 40 MW solar plant was already established within the study area. Additionally, several large flower exporting companies had also set up SPVFs to generate their own solar power.

Table 3. Approximate areas of priority levels to the total study area

Tabela 3. Przybliżone powierzchnie poszczególnych rejonów o różnym priorytecie na całym obszarze badań

Priority Areas	Approximate area of Priority area (km^2)	Approximate Percentage of the study area (%)
Least Suitable	1.39	0.02
Marginally Suitable	109.77	1.47
Moderate Suitable	579.55	7.76
Very Suitable	2541.45	34.05
Extremely Suitable	224.14	3.00
TOTAL	3456.30	46.31

Although the study did not consider the economic factor, this needs to be included for especially business enterprises and in view of the huge capital investments required in setting up commercially viable SPVFs. Such solar plants would be expected to generate at least a few MWs of solar power with surplus power uploaded to the national grid. From a socio-economic perspective it would also be prudent to better understand the perception of local communities to SPVF development and infer their potential resistance to possible land acquisition. This could be accompanied by programs aimed at creating awareness of the value and relevance of SPVF development to the local economy. Moreover, inclusive business strategies such as Public-Private Partnerships (PPP) that seek to mainstream participation of local communities would also need to be fostered.

4. CONCLUSIONS

The study showed that 46.31% of Nakuru County is suitable for solar generation with most of the County classified as mostly moderate (7.76%) and very suitable (34.05%) for the location of SPVFs. Most parts of the study area were found to be suitable except for the western region. This is due to a greater amount of solar irradiation, suitable slopes, aspect, and proximity to power, roads, and settlements. In contrast the western region receives little sunlight and does not have transmission lines.

For vast rural areas in sub-counties with relatively low household electricity access such as Kuresoi North (28.6%), Rongai (42,4%), Bahati (36.8%), and Kuresoi South (24.1%) use of solar power should be encouraged and supported to enhance electricity access. Furthermore, there is need to undertake Cost Benefit Analysis for mainstreaming SPVFs in order to evaluate the sustainability of the sites.

The GIS Model used in the study offers a case in point of GIS as a Decision Support System (DSS) in advancing Kenya's plan of action in terms of SPVFs. These sites if exploited could contribute towards addressing the nation's energy demand and supply issues as well as the shrinking energy gap between urban and rural populations.

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