Site Selection for Solar Power Stations in Parts of Kaduna State, Nigeria

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Abstract

Nigeria has an energy shortfall of 5,398 MW for over 200 million people in 2025. Its solar potential is high, especially in Kaduna State with 2,100–2,300 kWh/m² annually. This study assessed photovoltaic farm suitability across 7,986 km² in parts of Kaduna State. It used Geographic Information Systems and the Analytic Hierarchy Process. Eight criteria were weighted, including GHI at 34% and slope at 22%. Results showed 41.1% of the area, or 3,285.42 km², is highly suitable. These areas lie mainly in the northern part of Igabi LGA. GHI ranges from 1,915 to 2,130 kWh/m². Slopes are below 7% across 79% of the area. Bare or vegetated land covers 60.8%. All areas exceed 1,100 kWh/m²/year. Northern regions offer the best energy yield and cost benefits. Stakeholders should focus on these zones. Transmission lines are within 6,000 m of 19.5% of the area. Roads are within 5,000 m of 50%. Developers should use this infrastructure. Rural areas off the grid suit standalone microgrids. This method supports SDG 7 and works for Nigeria's solar-rich areas.

Keywords: AHP, Energy Accessibility, GIS, Solar Energy, MCDA & Site Suitability

Introduction

Energy accessibility is fundamental to industrialization and an improved standard of living (Demircioğlu & Eşİyok, 2022). Through adequate electricity, developed countries have achieved great economic height while developing nations aspire to grow their economy (Alemzero *et al.*, 2021). Fossil fuels dominate energy production, but their environmental toll air pollution, climate change, and resource depletion drive the need for renewables like solar, which Nigeria possesses in abundance with an average insolation of 2,300 kWh/m² annually (Sambo & Doyle, 1986; IRENA, 2023). Kaduna State, in Northern Nigeria, stands out with high solar potential, intensified by land-use shifts from urbanization and deforestation, yet its solar development lags due to insufficient planning (Aremu, 2020).

Compared to South Africa's electricity generation capacity of 42,000 MW for a population of 60 million, Nigeria's generation capacity of 5,398 MW in 2025 for a population exceeding 200 million highlights the urgency of tapping into its abundant solar resources (International Trade Administration, 2024; Federal Ministry of Power, 2025). However, large-scale PV projects risk failure without optimal siting (Goenka, 2020). In Kaduna and other parts of Nigeria, despite abundant sunshine and government interest in renewables, previous studies neglect integrated assessments of critical factors like terrain slope, grid proximity, and land use, leading to suboptimal site selections and investor hesitancy (Chiemelu *et al.*, 2021; Adebimpe & Usman, 2022; Abdullahi *et al.*, 2024 Isma'il *et al.*, 2016). This gap in site-specific analysis poses a significant challenge.

This study addresses this void by employing Geographic Information Systems (GIS) and Multi-Criteria Decision-Making (MCDM) to evaluate site suitability in Kaduna Metropolis comprising Kaduna North, Kaduna South and parts of Chikun and Igabi Local Government Areas. Using satellite imagery; 1984–2019 climate averages and infrastructure shapefiles, analyzed via the Analytical Hierarchy Process (AHP), the study maps optimal solar farm sites in the study area. Aligned with Sustainable Development Goal (SDG) 7 for affordable, clean energy, this study offers stakeholders a robust tool to maximize energy yield and socio-economic benefits, setting a precedent for renewable energy planning in Nigeria's sun-rich regions.

Conceptual Framework

Geographic Information Systems (GIS) form the foundation of spatial analysis in this study, integrating hardware, software, and data to capture, manage, and analyze location-based information (Ali, 2020). GIS enables the harmonization of diverse datasets such as satellite-derived solar radiation, digital elevation models, and infrastructure shapefiles into a unified platform for site suitability assessment. Its relational database management system organizes data into accessible layers, linking geographic features (e.g., points, lines, polygons) with attributes like slope or land use. Beyond mapping, GIS facilitates advanced spatial queries and visualizations, critical for identifying optimal solar farm locations in Kaduna State by revealing spatial relationships among environmental and infrastructural factors (Longley, 2005).

Land-Use Suitability Analysis

Land-use suitability analysis evaluates geographic areas based on specific criteria to determine their appropriateness for a given purpose, here solar power stations (Malczewski, 2004). Historically, this relied on manual overlays, but modern GIS-based approaches, pioneered by McHarg (1969), use digital layers to assess factors like solar irradiance, terrain slope, and land cover. In this study, it distinguishes between site inquiry (identifying potential areas) and site choice (ranking predefined sites), focusing on the former to map suitability across Kaduna Metropolis, Igabi, and Chikun LGAs. The process ranks areas by suitability, prioritizing high solar potential and minimal environmental constraints, providing a systematic basis for energy planning (Lehman, 2011).

Solar Photovoltaic (PV) Technology

Solar photovoltaic (PV) technology, the focus of this study, converts sunlight into electricity via the photovoltaic effect, where photons striking a semiconductor generate voltage (Goetzberger *et al.*, 2002). In Nigeria, with an annual solar potential of 2,300 kWh/m², PV offers a viable solution for Kaduna State's energy needs, leveraging abundant sunshine and requiring minimal maintenance, though site selection is key to maximizing efficiency (Sambo & Doyle, 1986).

Multi-Criteria Decision-Making (MCDM) and Analytic Hierarchy Process (AHP)

Multi-Criteria Decision-Making (MCDM) addresses complex decisions involving multiple objectives and criteria~~,~~ such as balancing solar radiation with infrastructure proximity (Kumar *et al.*, 2017). Within MCDM, the Analytic Hierarchy Process (AHP)~~,~~ developed by Saaty (1980)~~,~~ structures this study's site selection by assigning weights to criteria through pairwise comparisons on a 1–9 scale. For example, higher weights may prioritize solar irradiance over slope, reflecting their relative importance. AHP then computes scores for each site, integrating these weights into a final suitability ranking, with consistency checks ensuring reliability (Barlina, 2017). This study employs AHP within GIS to produce a weighted overlay, offering a rigorous, reproducible method to identify optimal solar farm sites in Kaduna State.

GIS, MCDM, and AHP in Solar Farm Site Selection

Geographic Information Systems help map data for solar site selection. Multi-Criteria Decision-Making and the Analytic Hierarchy Process rank factors for suitability. These tools combine spatial and decision data effectively. Ruiz *et al*. (2020) used GIS and AHP in West Kalimantan, Indonesia. They studied solar radiation, land use, and infrastructure proximity. Their study covered 146,807 km². Only 0.03–0.07% was highly suitable, equaling 46.60–108.58 km². This area could generate 2,034–4,785 MW. Their work showed GIS-AHP balances resources and constraints well. Georgiou & Skarlatos (2016) assessed solar parks in Limassol, Cyprus. They used GIS and MCDM. They found 3% of the region highly suitable. Sensitivity analysis raised suitability to 83% with different weights. This flexibility aids investors in decision-making.

In Africa, Elboshy *et al*. (2022) studied PV farm suitability in Egypt. They used GIS and AHP methods. They included location, environmental, and climatic factors. Their work produced a suitability index. This index helps plan renewable energy projects. Doorga *et al*. (2019) evaluated solar sites in Mauritius. They applied GIS and AHP techniques. They identified northern plains as optimal locations. They weighted radiation, slope, and infrastructure proximity. Their high-resolution maps lowered planning costs. Asare-Addo (2022) assessed solar potential in Ghana. They examined PV and CSP options. They found 85% of land suitable. Their study estimated PV capacity at 68,622 TWh/year. They used GIS and AHP to support decarbonization.

In Nigeria, Chiemelu *et al*. (2021) evaluated solar potential in Eastern Nigeria. They used GIS-based MCDA. They identified 0.67% of the region as suitable. This area covers 59,000 ha. They considered radiation, slope, and land cover. Adebimpe & Usman (2022) studied Ewekoro LGA. They used GIS and AHP methods. They classified 15% of the area as highly suitable. Vegetation held the highest weight at 63.1%. Raji (2017) modeled PV suitability in Northwest Nigeria. They found 22.8% of the region highly suitable. Solar radiation had a weight of 0.3049. Their study focused near Kaduna. Opeyemi *et al*. (2022) analyzed PV suitability in Abuja. They used GIS and AHP tools. They identified 6% of the FCT as highly suitable. This equals over 45,000 ha. They included nine criteria like irradiance and elevation. Abdullahi *et al*. (2024) studied Kaduna Metropolis. They combined AHP and GIS methods. They identified five optimal PV sites. Their outputs ranged from 1,453.08 to 1,459.37 kWh/m²/year.

While GIS, MCDM, and AHP methods have been widely applied in solar site selection globally and within Nigeria, Kaduna Metropolis remains underexplored despite its high solar potential and proximity to a major energy demand hub. Studies like Raji (2017) broadly assessed Northwest Nigeria without focusing on Kaduna's urban and peri-urban zones, while others such as Adebimpe & Usman (2022) and Chiemelu *et al.* (2021) addressed different regions, leaving Kaduna's unique solar resources, infrastructure, and population density overlooked. Abdullahi *et al.* (2024) identified five optimal PV sites in Kaduna Metropolis but prioritized economic and technical factors without integrating infrastructural and land-use dynamics with energy demands. This study fills these gaps by leveraging GIS and AHP to provide a comprehensive suitability analysis for large-scale PV plants near Kaduna Metropolis, ensuring solutions tailored to optimize energy development in proximity to demand hubs.

Materials and methods

Description of Study Area

Kaduna Metropolis is located in Kaduna State, Nigeria, between latitude 10º 23' 00" and 10º 40' 00" N and longitude 7º 21' 26" and 7º 32' 00" E. The elevation ranges from 590 to 650 metres above sea level. This study covers Kaduna North, Kaduna South, and parts of Igabi and Chikun Local Government Areas, with boundaries adjoining Giwa to the north, Kachia to the south, Birnin Gwari to the west, and Kajuru to the east as shown in Figure 1.

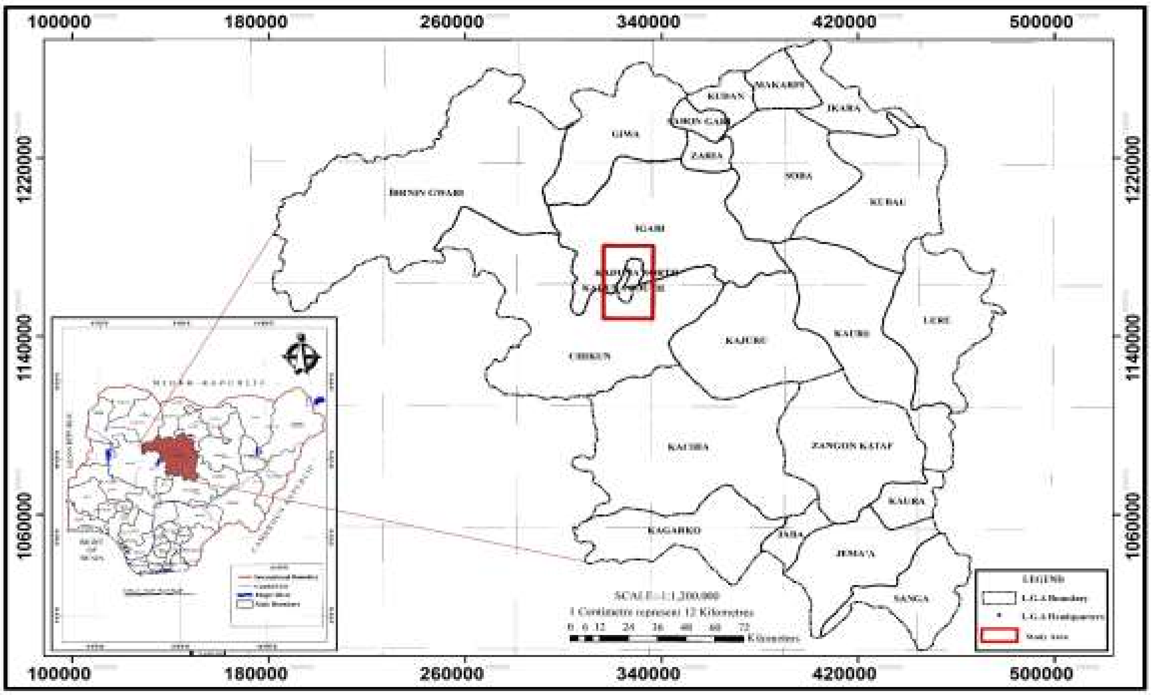

Figure 1: Kaduna Metropolis in Kaduna State, Nigeria

Source: Kaduna Polytechnic Library (2023)

In 2024, Kaduna Metropolis received an average annual rainfall of 1200mm to 1800mm with 90 to 115 rain days, according to the Nigerian Meteorological Agency (NiMet, 2025). The dry season occurs from November to April with an annual mean maximum temperature of 30 to 34ºC, and the wet season lasts from May to October. The hot season occurs from March to May with an annual mean maximum temperature of 30 to 34ºC, and the wet season lasts from May to October. Solar radiation averaged 239-289 W/m²/day in 2024, peaking at 347 W/m²/day between January and March, equivalent to an annual Global Horizontal Irradiance of 2100-2300 kWh/m² (NiMet, 2025). Sunshine hour has the month of May recording a peak of 336 hours (Nomadseason, 2025). Insolation values range from 4.92 kWh/m²/day in August to 7.00 kWh/m²/day in March (Isma'il *et al.*, 2016). Kaduna Metropolis has a population of over 1.8 million people (National Population Commission projected population, n.d.), making it a major energy demand center with many transmission lines and roads connecting to Igabi and Chikun. Land use includes built-up areas in Kaduna North and South, and agricultural and open lands in Igabi and Chikun.

Methodology

This study utilized secondary data to assess site suitability for photovoltaic (PV) solar farms in Kaduna Metropolis, Nigeria, covering Kaduna North, Kaduna South, and parts of Igabi and Chikun LGAs. Data included administrative boundaries, Landsat 8 imagery (30 m, 2022, earthexplorer.usgs.gov), Global Horizontal Irradiance (GHI) and air temperature (1984–2019, globalsolaratlas.info), a Digital Elevation Model (DEM, 12.5 m, search.asf.alaska.edu), and shapefiles of roads (openstreetmap.org), transmission lines (data.nigeriase4all.gov.ng), and settlements (diva-gis.org) (Table 1).

Table 1: Summary Details and Sources of Required Data

S/N	Data	Source	Format	Details
1	Satellite Image	earthexplorer.usgs.gov	Raster	Landsat 8, 30 m, 2022, Path 189-053/052
2	GHI	globalsolaratlas.info	Raster	1984–2019 average, kWh/m²
3	Air Temperature	globalsolaratlas.info	Raster	1984–2019 average, ºC
4	DEM	search.asf.alaska.edu	Raster	12.5 m resolution
5	Transmission Lines	data.nigeriase4all.gov.ng	Shapefile	KAEDCO grid
6	Roads	openstreetmap.org	Shapefile	Major roads
7	Settlements	diva-gis.org	Shapefile	Major settlements
8	Boundary	Surveyor General, Nigeria	Shapefile	Administrative boundaries

Source: Researcher (2023)

The Analytical Hierarchy Process (AHP) within Multi-Criteria Decision-Making weighted eight criteria: GHI, air temperature, land use/land cover (LULC), elevation, slope, and distances to urban areas, transmission lines, and roads. Pairwise comparisons used a 1–9 scale (1 = equal, 9 = highest importance), forming a reciprocal matrix (Eij = 1/Eji). Weights were calculated as normalized geometric means. Consistency was checked with the Consistency Index (CI):

$$CI = \frac{\lambda_{max} - m}{m-1} \text{ ……………… …Equation 1}$$

where m = number of criteria, λmax = largest eigenvalue, and Consistency Ratio (CR):

:

$$CR = \frac{CI}{RI} \text{ ………………………Equation 2}$$

where RI = random index. CR < 0.1 ensured consistency; otherwise, comparisons were repeated. Criteria thresholds included GHI > 1,300 kWh/m²/year, temperature 15–40°C, slope < 5%, and distances > 500 m from urban areas, < 600 m from transmission lines, and < 500 m from roads (Kereush & Perovych, 2017).

Analysis was done using Microsoft Office 2020 and ArcGIS 10.8. Excel computed AHP weights and LULC accuracy; ArcGIS preprocessed data (mosaicking, subsetting), derived slope from DEM, and classified LULC from Landsat bands 5, 4, 3 using maximum likelihood, with accuracy assessed via an error matrix. Euclidean distance measured proximity to roads, transmission lines, and urban areas. Datasets were reclassified (1 = most suitable, 6 = least suitable) and combined via weighted overlay in ArcGIS, applying AHP weights to produce a suitability map.

Result of the Findings and Discussion

This study processed eight datasets using GIS and AHP across 7,986 km² in Kaduna Metropolis, Igabi, and Chikun LGAs to assess solar PV farm suitability.

Global Horizontal Irradiance (GHI)

GHI ranged from 1,915 to 2,130 kWh/m²/year, with the northern part of Igabi LGA at 2,095–2,130 kWh/m² (21.9%, 1,748.62 km²) scored 1, and southern areas at 1,915–1,951 kWh/m² (0.03%, 2.12 km²) scored 6. All GHI values for the study area exceeded 1,100 kWh/m²/year. This confirms the area's viability for PV farms, with the northern part of Igabi LGA offering maximum energy yield. This finding agrees with a study by Isma'il *et al*. (2016) which noted Kaduna's high solar potential. Figure 2a and 2b show GHI distribution and reclassification.

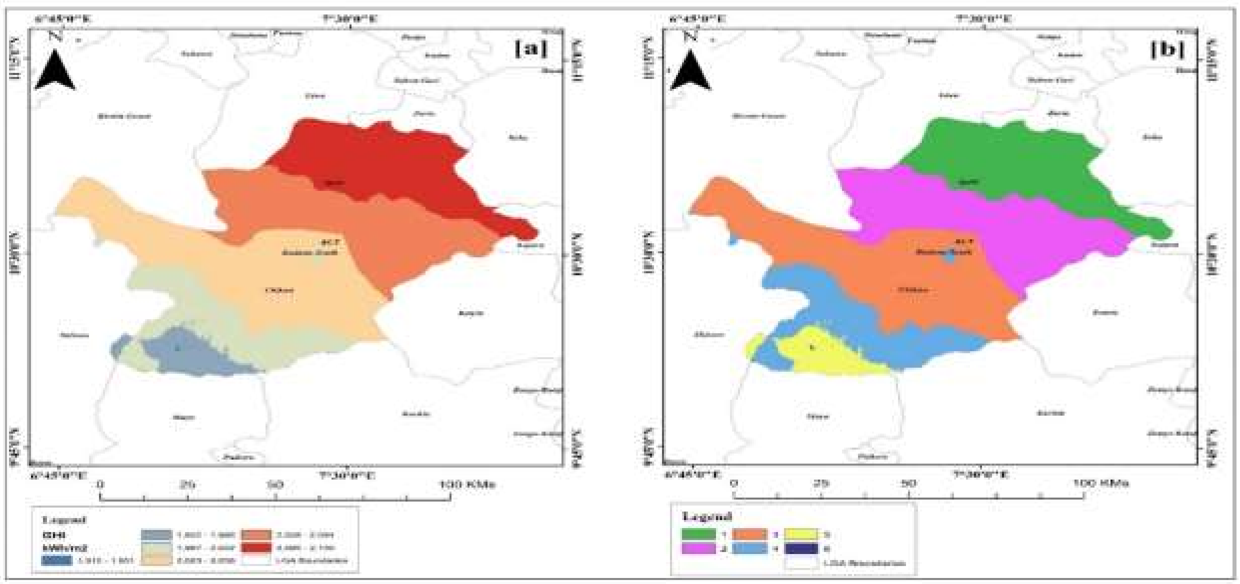

Figure 2a: Global Horizontal Irradiance of the Study Area
Figure 2b: Reclassified GHI (1 = 2,095–2,130 kWh/m², 6 = 1,915–1,951 kWh/m²)

Source: Author (2024)

Air Temperature

Air temperature ranged from 24.8 to 27.3°C, with 24.8–25.192°C (21.7%, 1,735.58 km²) scored 1, and 26.69–27.3°C (3.4%, 274.61 km²) scored 6; 62.5% was below 25.8°C. All values were under 40°C, ensuring PV efficiency. Cooler areas enhance performance, supporting widespread suitability. This finding is consistent with Doorga *et al*. (2019) whose study favored temperatures below 25°C.

Figure 3a and 3b show air temperature distribution and reclassification.

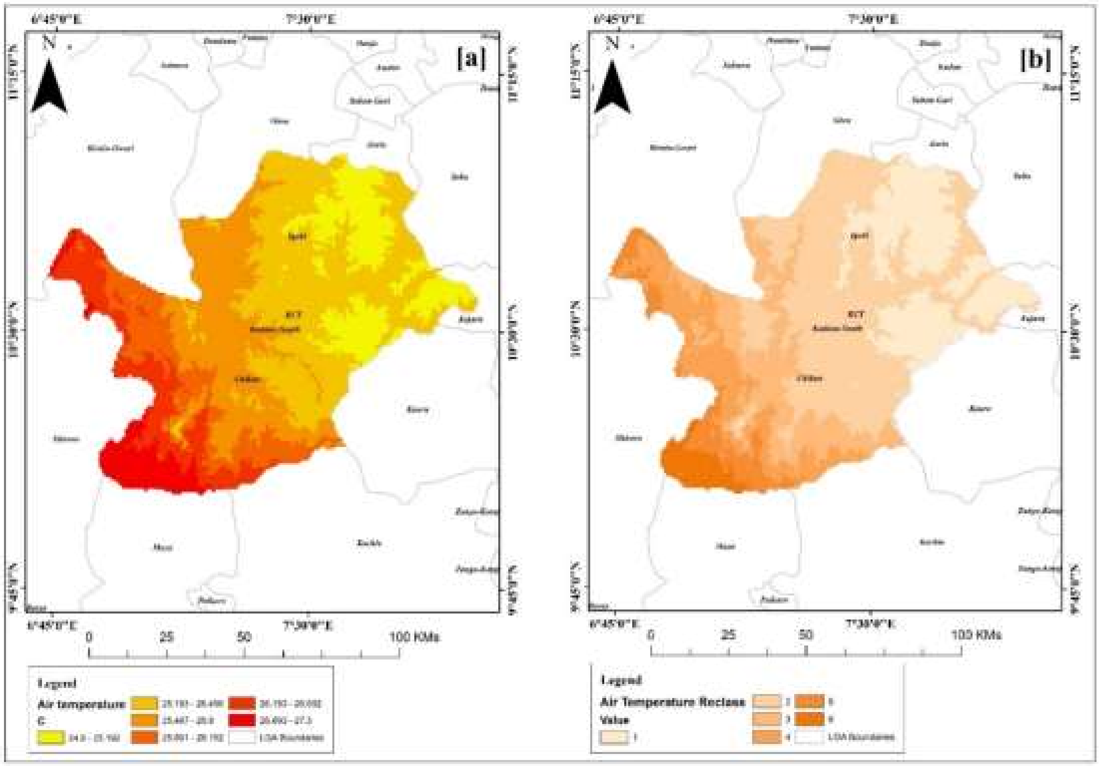

Figure 3a: Spatial Distribution of Air Temperature
Figure 3b: Reclassified Air Temperature (1 = 24.8–25.192°C, 6 = 26.69–27.3°C)
Source: Author (2024)

Elevation

Elevation ranged from 391 to 864 m, with 786–864 m (0.02%, 1.46 km²) scored 1, and 391–470 m (4.7%, 371.76 km²) scored 6; 57.8% (4,612.86 km²) was 629–706 m. Higher elevations boost radiation but raise costs. Most areas balance these factors. However, this contrasts with a study by Loquias *et al*. (2022) which preferred lower elevations for economic reasons.

Slope

Slope ranged from 0 to 69%, with 0–4% (34.5%, 2,750.90 km²) scored 1, and 49–69% (0.14%, 11.44 km²) scored 6; 79% was below 7%. Flat terrain reduces costs and shading, favoring most areas. This finding agrees with a study by Omoloso *et al* (2020) which prioritized flat lands for solar projects.

Figure 4a and 4b show slope distribution and reclassification.

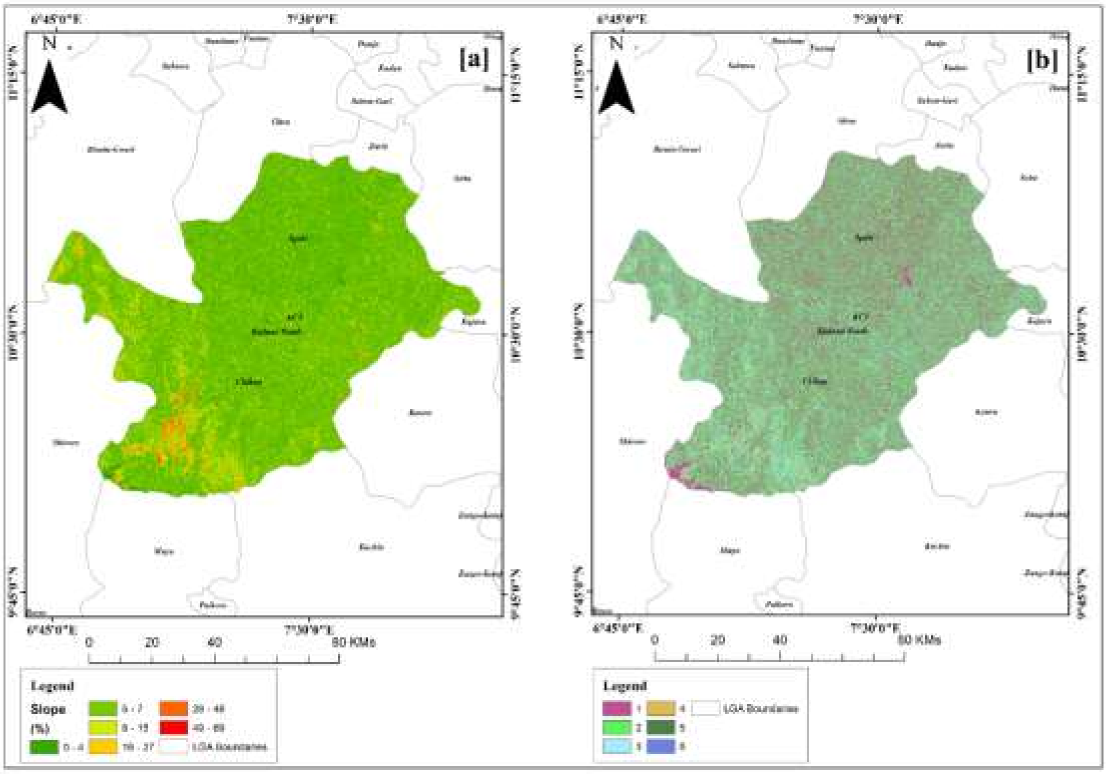

Figure 4a: Slope Distribution Across the Study Area
Figure 4b: Reclassified Slope (1 = 0–4%, 6 = 49–69%)
Source: Author (2024)

Land-Use/Land-Cover (LULC)

LULC showed bare surfaces (27.8%, 2,221.27 km²) scored 1, vegetation (33%, 2,632.19 km²) scored 2, and water bodies (0.7%, 56.24 km²) scored 6 (91% accuracy). Bare surfaces suit PV farms, minimizing environmental impact. This finding is consistent with Halder *et al*. (2022) whose study favored bare lands for solar development.

Figure 5a and 5b show LULC distribution and reclassification.

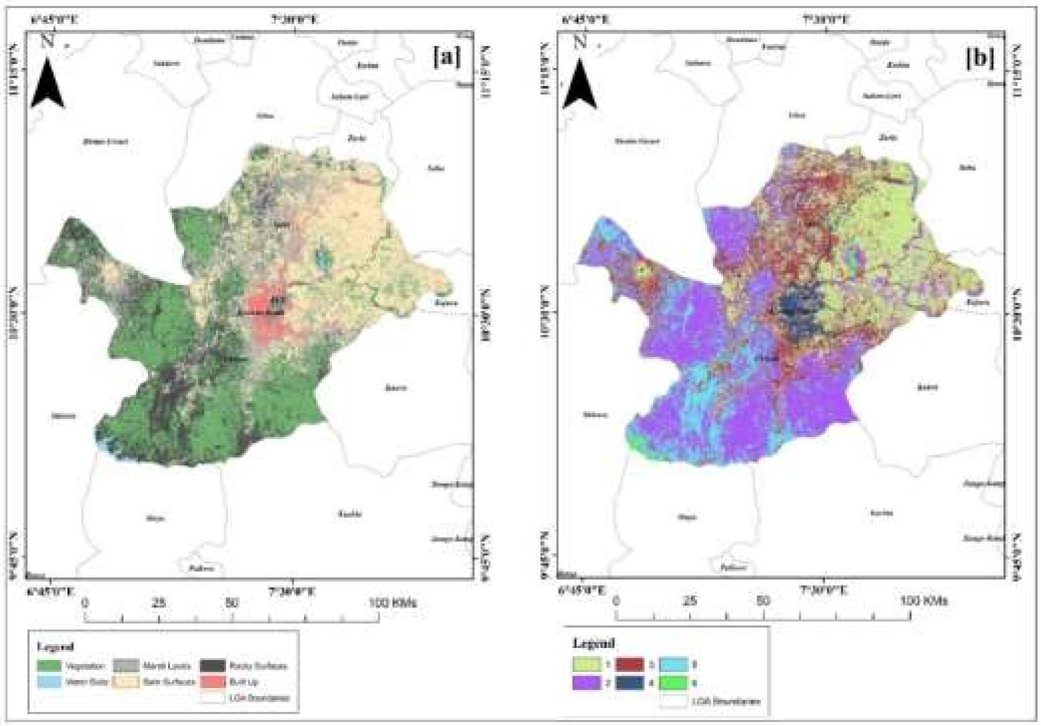

Figure 5a: Land-Use/Land-Cover Map of the Study Area
Figure 5b: Reclassified LULC (1 = Bare Surfaces, 6 = Water Bodies)

Distance from Transmission Lines

Proximity to transmission lines showed 0–600 m (2%, 161.08 km²) scored 1, and 50,052–60,063 m (1.5%, 121.86 km²) scored 6; 19.5% was within 6,000 m. Close proximity cuts losses and costs, benefiting the northern part of Igabi LGA. This finding agrees with a study by Okosun (2022) which highlighted Northern Nigeria's grid proximity advantage.

Distance to Roads

Proximity to roads ranged from 0 to 24,214 m, with 0–1,000 m (19.6%, 1,568 km²) scored 1, and 20,001–24,214 m (1.2%, 98 km²) scored 6. Over 50% was within 5,000 m, easing access. This finding is consistent with Goshem & Hailu (2022) whose study prioritized near-road areas.

Distance to Urban Areas

Proximity to urban areas ranged from 0 to 24,214 m, with 20,176–24,214 m (highest priority) scored 1, and 0–4,035 m scored 6; over 80% was beyond 20,000 m. Distance avoids conflicts, supporting suitability. This finding agrees with a study by Ndiritu (2021) which emphasized remote siting.

AHP Weights

Table 2 shows AHP weights and pairwise comparisons.

Table 2: Pairwise Comparison of Criteria and Weights

Criterion	GHI	Air Temp	Slope	Elevation	LULC	Transm. Lines	Roads	Urban	Weight (%)
GHI	1	4	2	6	5	7	9	8	34
Air Temperature	0.25	1	0.5	4	3	5	7	6	16
Slope	0.5	2	1	5	4	6	8	7	22
Elevation	0.167	0.25	0.2	1	0.333	3	5	4	7
LULC	0.2	0.333	0.25	3	1	4	6	5	11
Transmission Lines	0.143	0.2	0.167	0.333	0.25	1	4	3	5
Roads	0.111	0.143	0.125	0.2	0.167	0.25	1	2	3
Urban Areas	0.125	0.167	0.143	0.25	0.2	0.333	0.5	1	2

CR = 0.07. Source: Author (2024)

GHI (34%) and slope (22%) led weights, with CR 0.07, prioritizing radiation and terrain. This finding agrees with a study by Raji (2017) which emphasized climatic factors, but contrasts with Omoloso *et al* (2020) whose study prioritized grid proximity.

Solar Site Suitability

After processing and reclassifying all the individual datasets, an overlay analysis was conducted to generate a comprehensive suitability map. This map integrates the influence of GHI, air temperature, elevation, slope, LULC, distance from transmission lines, distance from major roads, and distance from urban areas to identify the most promising areas for large-scale solar projects. The final suitability map categorizes areas into different suitability classes, ranging from highly suitable to unsuitable. Regions with high GHI, moderate air temperature, low slope, suitable LULC (bare surfaces), proximity to transmission lines and major roads, and sufficient distance from urban areas are classified as highly suitable. Conversely, areas with low GHI, extreme temperatures, steep slopes, unsuitable LULC (water bodies, dense vegetation), and remoteness from infrastructure are classified as unsuitable. The weighted overlay analysis combined all criteria into a suitability map, categorizing areas into high (41.13%), medium (49.45%), and low (9.42%) suitability levels. High suitability areas were predominantly located in the northern regions, with optimal GHI, gentle slopes, bare surfaces, and favorable proximity factors. This pattern aligns with the results of Elboshy *et al.* (2022), emphasizing the intersection of climatic and technical factors in solar development. The final suitability map is presented in Figure 6.

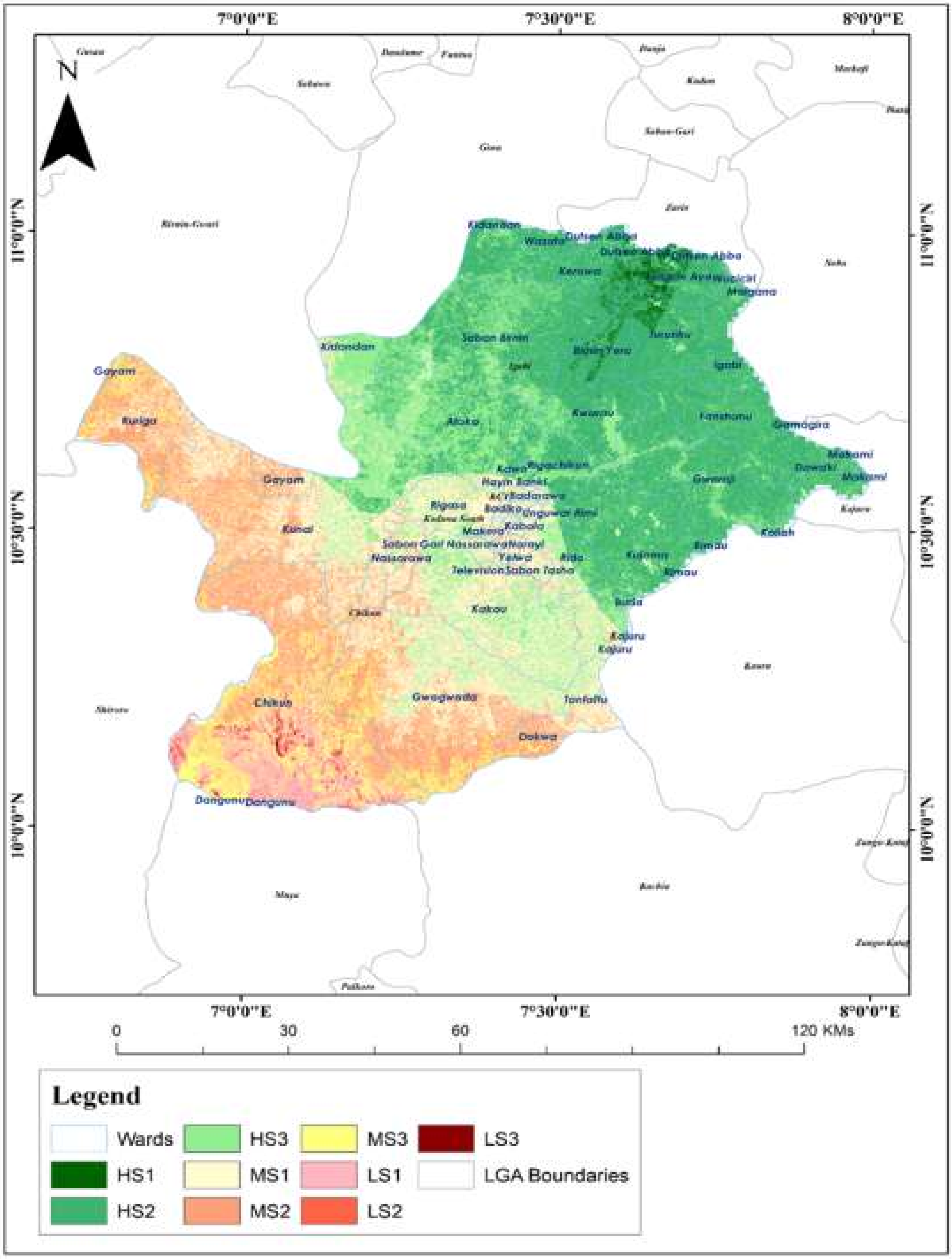

Figure 6: Solar Site Suitability (HS1–LS3)
Source: Author (2024)

Optimum Sites Identification

Table 3. Sample coordinates for optimum sites.

S/N	Northing	Easting	Suitability	LGA	Ward
	10.9402	7.6470	HS1	Igabi	Zangon Aya
	10.9327	7.6094	HS1	Igabi	Kerawa
	10.8847	7.6463	HS1	Igabi	Turunku
	10.8699	7.6431	HS1	Igabi	Turunku
	10.9081	7.6667	HS1	Igabi	Zangon Aya
	10.9659	7.6729	HS1	Igabi	Zangon Aya
	10.8504	7.7621	HS2	Igabi	Igabi
	10.6725	7.8064	HS2	Igabi	Fanshanu
	10.5615	7.7183	HS2	Igabi	Gwaraji
	10.5886	7.5903	HS3	Igabi	Rigachikun
	10.6141	7.7927	HS3	Igabi	Gwaraji
	10.4746	7.1539	MS1	Chikun	Kunai
	10.2279	7.4810	MS1	Chikun	Gwagwada
	10.1576	7.3123	MS2	Chikun	Gwagwada
	10.1128	7.0557	MS3	Chikun	Chikun

Source: Author (2024)

Conclusion

This study assessed solar PV potential in parts of Kaduna State. It covered 7,986 km². Results showed 41.1% of the area is highly suitable. This equals 3,285.42 km². The northern part of Igabi LGA stood out. GHI ranged from 1,915 to 2,130 kWh/m². Slopes were below 7% across 79% of the area. Bare surfaces covered 27.8%. All areas exceeded 1,100 kWh/m²/year. This confirms viability for PV farms. Transmission lines reached 19.5% within 6,000 m. Roads reached 50% within 5,000 m. The northern zones showed the highest potential.

Recommendations

From the findings of this study, the following recommendations are made:

i. Prioritize Northern Igabi LGA for PV Development: The northern part of Igabi LGA has high suitability. It covers 41.1% of the area, or 3,285.42 km². GHI reaches 2,095–2,130 kWh/m²/year. Slopes are below 7%. Stakeholders should focus here. This area offers the best energy yield and cost benefits.

ii. Leverage Existing Infrastructure: Transmission lines are within 6,000 m of 19.5% of the area. Roads are within 5,000 m of 50%. Developers should use these networks. This reduces connection costs and it will speed up project implementation.

iii. Develop Standalone Solar Microgrids in Rural Areas: Rural areas show high suitability but lack grid access. Standalone microgrids can provide power. This target underserved regions. It boosts energy independence. It supports sustainability goals.

iv. Conduct Grid Upgrade Studies: Current transmission lines cover only 19.5% within 6,000 m. More capacity may be needed. Further studies should assess grid upgrades. This ensures large-scale PV farms operate efficiently. It prevents energy bottlenecks.

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