

Geographical Evaluation of Solar Energy Potential in Niger State, Nigeria: A Geospatial and Multi-Criteria Decision Analysis

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Abstract

This study presents a geospatial evaluation of solar energy potential across the twenty-five Local Government Areas (LGAs) of Niger State, Nigeria. Twenty years (2002-2022) of ground-measured solar radiation data from the Nigerian Meteorological Agency (NIMET) and satellite-derived data from NASA's Surface meteorology and Solar Energy (SSE) database were standardised to kWh/m²/day and combined with topographic parameters like slope, aspect, and elevation derived from a Digital Elevation Model (DEM). kriging was used to interpolate solar radiation at locations without ground stations, and the Analytic Hierarchy Process (AHP) was applied to weight and integrate the four criteria (solar radiation 0.40, slope 0.25, aspect 0.20, elevation 0.15; consistency ratio = 0.08) into a composite solar potential map. Results show that 52.76% of Niger State falls within the High or Very High potential classes, concentrated around Chanchaga, Bosso and Shiroro, while only 0.13% is classed as Very Low. Comparison of the two data sources revealed a systematic underestimation by satellite data relative to ground measurements, with discrepancies of 1.49-1.59 kWh/m²/day, largest at Rijau. The findings support prioritising high-potential LGAs for utility-scale solar development and recommend localised calibration of satellite-derived radiation products for solar resource assessment in similar data-sparse regions of the Sahel.

Keywords: Solar Energy Potential, Geospatial Analysis, Kriging Interpolation, Analytic Hierarchy Process, Niger State, SatelliteGround Data Comparison

1. Introduction

Solar energy is the most abundant renewable resource available at the Earth's surface, yet its contribution to Nigeria's energy mix remains marginal relative to the country's endowment. Nigeria receives an annual average daily solar radiation of about 5.25 kWh/m²/day, ranging from roughly 3.5 kWh/m²/day at the coast to 9.0 kWh/m²/day in the far north, positioning the northern states in particular as promising sites for solar development. Despite this potential, reliable spatial information on solar radiation remains scarce because ground-based measuring instruments are costly and unevenly distributed, while satellite-derived products, though spatially continuous, are known to generalise local atmospheric and terrain effects. Niger State, the largest state in Nigeria by land area (approximately 76,363 km²), exemplifies this data gap: dense ground-station coverage exists only at a handful of locations, leaving most of its twenty-five LGAs without direct measurement. Reliable spatially explicit estimates of solar radiation are therefore essential both for identifying technically suitable sites for solar installations and for evaluating the accuracy

of the satellite products often used in their place. This study addresses that gap with three objectives: (i) to predict solar radiation in LGAs lacking ground stations using spatial interpolation; (ii) to identify optimum solar energy potential sites in Niger State and (iii) to compare ground-measured and satellite-derived solar radiation data to quantify and explain any systematic differences between the two sources [1-3].

2. Materials and Methods

2.1 Study Area and Data Sources

Niger State lies in Nigeria's North-Central geopolitical zone, roughly between latitude 8°20'-10°30'N and longitude 3°30'-7°20'E, bordered by Kebbi and Zamfara to the north, Kaduna to the north-east, Kogi to the south-east, Kwara to the south, the Federal Capital Territory to the east, and the Republic of Benin to the west. The state experiences a tropical continental climate with distinct wet and dry seasons and a harmattan period from November to February. Two datasets covering 2002-2022 were used. Ground-measured solar radiation, recorded in MJ/m²/day by solarimeters at NIMET stations

in Minna and Bida, was converted to kWh/m²/day using the International Energy Agency's standard energy conversion factor for consistency with the satellite product. Satellite-derived solar radiation was obtained from NASA's Surface meteorology and Solar Energy (SSE) archive. Elevation data were sourced from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model.

2.2 Spatial Interpolation of Solar Radiation

Ordinary kriging, a geostatistical interpolation method that accounts for spatial autocorrelation, was used to predict solar radiation at LGAs without ground stations. Observed values from the Minna and Bida stations were standardised to a common Universal Transverse Mercator (UTM) reference system, after which an exploratory spatial analysis assessed stationarity and underlying trends. An experimental semi-variogram was computed and fitted with a theoretical model to characterise the spatial dependence structure, and kriging weights were solved to produce unbiased, minimum-variance predictions at unsampled locations. Cross-validation, achieved by alternately withholding each station's observations, was used to assess prediction accuracy. The general kriging estimator takes the weighted-

sum form of Dancy [4]:

$$\hat{Z}(s_0) = \sum \lambda_i Z(s_i), i = 1 \dots N$$

where $Z(s_i)$ is the measured value at the i -th location, λ_i is the corresponding kriging weight, s_0 is the prediction location, and N is the number of measured values. Interpolation and mapping were implemented in ArcGIS 10.3 using its Geostatistical Analyst extension.

2.3 Site Suitability Analysis via the Analytic Hierarchy Process

Optimum solar energy sites were identified by integrating four criteria -- solar radiation, elevation, slope and aspect -- within a GIS-based Analytic Hierarchy Process (AHP). The study area was georeferenced to the WGS 1984 coordinate system, and a DEM was interpolated in ArcGIS from field-recorded elevation points and SRTM data. Slope and aspect rasters were derived from the DEM using the Spatial Analyst and Surface Analysis tools respectively. Pairwise comparisons among the four criteria, following AHP methodology, produced the relative weights in Table 1, with an acceptable consistency ratio (CR = 0.08 < 0.1) [5-11].

Criterion	Weight
Solar Radiation	0.40
Slope	0.25
Aspect	0.20
Elevation (DEM)	0.15

Solar radiation received the highest weight given its direct control over energy yield, followed by slope and aspect, which govern installation feasibility and panel orientation efficiency; elevation was weighted lowest as a secondary, indirect influence. The four weighted layers were combined by weighted overlay in ArcGIS to classify the state into five solar energy potential categories: Very Low, Low, Medium, High and Very High.

2.4 Comparison of Ground-Based and Satellite-Derived Data

For each LGA, mean solar radiation values were computed separately from the kriged ground-station data and the NASA SSE satellite data over the 2002-2022 period. The discrepancy between the two sources was calculated for every LGA to identify the direction, magnitude and spatial pattern of any systematic bias between ground and satellite estimates.

3. Results and Discussion

3.1 Predicted Solar Radiation Across LGAs

Kriging interpolation of the ground-station data produced a continuous solar radiation surface across all 25 LGAs, with mean values ranging from 4.300 kWh/m²/day in Bida to 4.400 kWh/m²/day in Chanchaga. Notably, the smaller-area LGAs of Chanchaga (65.25 km²) and Bosso (1,572.75 km²) recorded the highest radiation values, while larger, more spatially heterogeneous LGAs such as Borgu (10,473.75 km²) and

Mashegu (9,195.75 km²) recorded marginally lower means (4.345 and 4.343 kWh/m²/day respectively), reflecting greater internal variability and lower ground-station density in these areas. High-radiation LGAs -- Chanchaga, Bosso and Shiroro -- emerge as favourable candidates for solar development, while moderate-radiation LGAs such as Edati and Gbako may benefit from supplementary data collection to reduce prediction uncertainty.

3.2. Identifying the Optimum Solar Energy Potential Sites for Solar Energy in the Study Area

The DEM-derived slope layer showed that 94.16% of Niger State (67,944.56 km²) is gently sloping or flat and therefore classed as High Potential for installation, substantially lowering the anticipated engineering cost of solar deployment across most of the state. Aspect was more evenly distributed, with 33.15% High, 32.56% Moderate and 34.28% Low potential, indicating that a meaningful share of the terrain may require sun-tracking or reconfigured mounting to achieve optimal orientation. Solar radiation itself was the most discriminating criterion: only 32.90% of the area fell into the High class against 38.80% Low, underscoring that terrain suitability alone does not guarantee high energy yield and that radiation levels must anchor site prioritisation.

Integrating all four AHP-weighted criteria produced the composite classification summarised in Table 1.

Solar Energy Potential Class	Area (km ²)	Percentage (%)
Very Low	97.74	0.13
Low	7,721.54	10.52
Medium	26,839.69	36.58
High	28,481.74	38.82
Very High	10,223.71	13.94
Total	73,364.42	100.00

High and Very High potential zones together cover 52.76% of Niger State (approximately 38,705 km²), concentrated in Chanchaga, Bosso and Shiroro, and represent the strongest candidates for utility-scale solar development. Medium Potential areas (36.58%) remain viable but may require terrain adjustment or adaptive technologies such as sun-tracking mounts, while the negligible Very Low class (0.13%) should be excluded from solar planning altogether. These results are consistent with Adavuruku, who similarly reported substantial but spatially uneven solar potential across Niger State using geospatial techniques [1].

3.3 Comparison of Satellite and Ground-Based Radiation Data

Across all 25 LGAs, ground-station measurements consistently exceeded satellite-derived values (Table 3 presents representative LGAs; the full 25-LGA comparison is available in the underlying thesis). Satellite estimates ranged from 2.801 to 2.894 kWh/m²/day, compared with 4.300-4.400 kWh/m²/day from ground stations -- a systematic underestimation of 1.49 to 1.59 kWh/m²/day. The largest discrepancy occurred at Rijau and the smallest at Mokwa, but the direction of bias was uniform across the state.

LGA	Satellite (kWh/m ² /day)	Ground Station (kWh/m ² /day)	Discrepancy (kWh/m ² /day)
Chanchaga	2.806	4.400	1.594
Bosso	2.806	4.388	1.582
Shiroro	2.806	4.384	1.578
Rijau	2.894	4.353	1.459
Bida	2.801	4.300	1.499
Mokwa	2.801	4.326	1.525

This consistent underestimation is attributable to the coarse spatial and temporal resolution of satellite radiative-transfer models, which struggle to resolve local cloud cover, aerosol loading and microclimatic variation that ground stations capture directly. The results reinforce the case, made elsewhere in the literature, for integrating ground observations with satellite products rather than relying on either source alone, particularly in data-sparse regions of the Sahel where ground networks are thin [8,12,13].

4. Conclusion and Recommendations

Integrating twenty years of ground-measured and satellite-derived solar radiation data with topographic criteria through kriging interpolation and the Analytic Hierarchy Process provides a robust basis for solar energy planning in Niger State. Just over half of the state (52.76%) falls within High or Very High solar potential, concentrated in Chanchaga, Bosso and Shiroro, making these LGAs priority sites for large-scale solar development, while Medium Potential areas (36.58%) remain usable with terrain or technological adaptation. Satellite-derived radiation data was found to systematically underestimate ground-measured values by 1.49-1.59 kWh/m²/day, highlighting the necessity of localised calibration before satellite products are used for solar resource assessment in this region.

On this basis, it is recommended that: (i) High and Very High potential LGAs be prioritised for utility-scale solar investment; (ii) Medium Potential areas be developed with adaptive technologies such as sun-tracking systems; (iii) satellite-derived radiation products be locally calibrated against ground observations before use in solar planning; (iv) the ground-station network across Niger State be expanded to reduce interpolation uncertainty, particularly in large, sparsely monitored LGAs such as Borgu and Mashegu; and (v) future work incorporate atmospheric variables such as aerosol optical depth and cloud fraction to refine bias-correction of satellite estimates in similar Sahelian settings.

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