

Geographic Impact Assessment on the Performance and Cost Efficiency of Solar Photovoltaic (PV) Systems Across Nigerian Climatic Zones

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Abstract: This study investigates the geographic impact on the performance and cost efficiency of solar photovoltaic (PV) systems across Nigeria's diverse climatic zones- arid, semi-arid, tropical rainforest, and mangrove. Using solar irradiance data, temperature profiles, and economic variables, the research analyzes how location influences energy output, and levelized cost of electricity (LCOE). Results reveal significant regional disparities: northern zones exhibit higher solar irradiance and system efficiency, while southern zones face reduced performance due to cloud cover and humidity. However, initial capital costs remain relatively uniform nationwide, making northern installations more cost-effective. The findings underscore the importance of location-specific planning for PV deployment to optimize energy yield and economic return. Finally, strategic recommendations for developers, policymakers, and investors are made in consideration of the technical and climatic conditions across the geographical regions in Nigeria, view of achieving higher efficiency and sustainability in solar PV installations.

Keywords: Photovoltaic; Irradiance; Solar System; Humidity; Geographic Regions; Peak-Sun-Hour (PSH).

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I. INTRODUCTION

Solar energy adoption in Nigeria has been studied with attention to its motivations, barriers, and regional trends. Urban residents are driven to adopt photovoltaic (PV)

systems largely by unreliable grid power, high fuel costs (especially for generators), energy cost savings and awareness of environmental issues (Abdullahi et. al. 2021). High upfront capital costs, limited access to finance, and weak regulatory frameworks are consistently cited as major

constraints. Technical challenges—such as poor maintenance, lack of local manufacturing and equipment quality-and socio-cultural issues like low public awareness also impede adoption. Studies focusing on rural and remote communities note that despite strong solar potential, adoption remains low due to affordability, lack of infrastructure, and low institutional support (Meita et. al. 2025). Empirical work in northeastern Nigeria illustrates that adoption was negligible until roughly the 2000s, followed by rapid growth but still far short of potential without policy interventions. Importance of geographic and climatic considerations. The primary objective of this study is to examine and propose ICT-based solutions to address the challenges associated with carbon credit verification for solar PV projects in Nigeria. Solar PV system performance is claimed to depend heavily on irradiance, temperature, and humidity, and therefore Nigeria's diverse climatic conditions lead to significant variations in efficiency and cost across regions (Yakubu et al., 2022). The specific objectives are:

- To identify and analyze the key barriers to accurate and reliable carbon credit verification in the Nigerian solar PV sector.
- To evaluate the current verification mechanisms and their limitations in ensuring transparency, traceability, and scalability.
- To explore the role of Information and Communication Technologies (ICTs) such as blockchain, IoT, and digital monitoring in improving verification processes.
- To propose a framework for integrating ICT tools into the Measurement, Reporting, and Verification (MRV) system for carbon credits in solar PV projects.

- To provide policy recommendations for stakeholders to adopt ICT-driven verification solutions at scale.

Regarding limitations, this study seeks to investigate the geographical landscape of Nigeria, with key focus on regions actively deploying solar PV systems, including rural, peri-urban, and urban areas; This will be carried out with respect to their respective technological, thematic and stakeholder-support potentials.

II. LITERATURE REVIEW

➤ Preamble

Our solar system comprises of the Sun, eight planets, five officially named dwarf planets (<https://science.nasa.gov/solar-system/>), hundreds of moons, and thousands of comets and asteroids. The solar system is located in the Milky Way (a barred spiral galaxy with two minor arms, and two major arms). It is in a small, partial arm of the Milky Way called the Orion Spur, or Orion Arm, between the Perseus and Sagittarius arms. The solar system orbits the center of the galaxy at about 828,000 kph (515,000 mph.), thereby taking about 230 million years to complete one orbit around the galactic center. Figure 1 shows a schematic drawing of the solar system. From the Figure, the sun has a diameter of 1,390,000km transmitting an irradiance of 1367W/m^2 through the extra-terrestrial region (between the Sun and the atmosphere). On the terrestrial region (between the atmosphere and the earth), an irradiance of 1000W/m^2 is received on the earth surface. The Sun is over 109times the earth with a temperature of 27 million°F (15 million°C), and a distance of 149,800,000km to the centre of the earth.

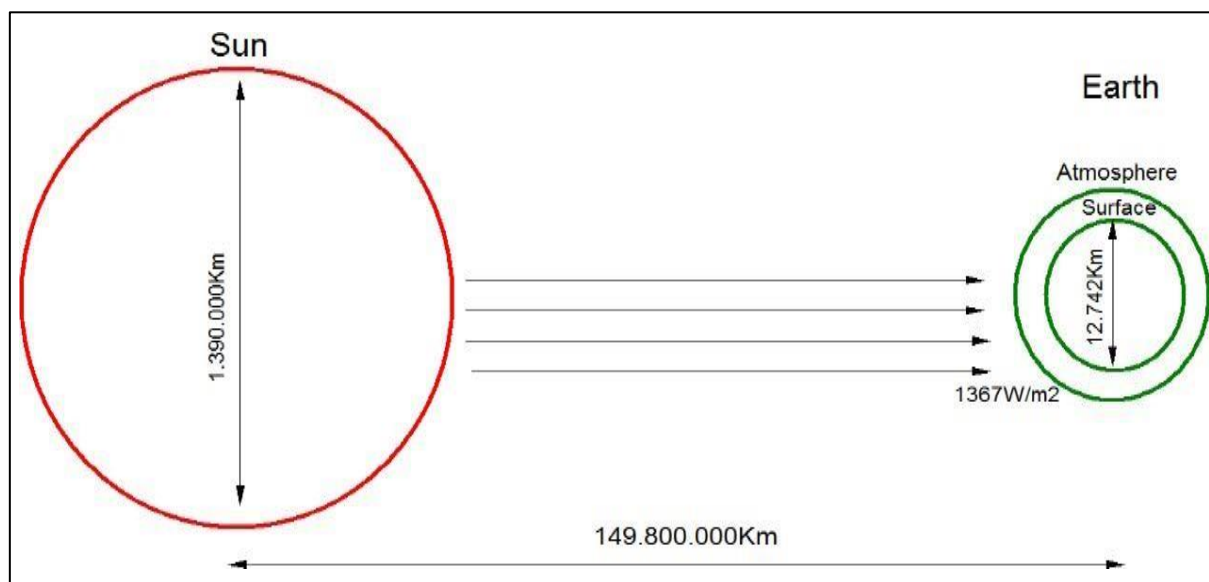


Fig 1 Solar Radiation
(Source: NAPTIN (<https://naptin.gov.ng/>))

➤ Overview of Nigerian Climatic Zones

Ugbehe et. al., 2025a claims Nigeria's climate is diverse and is often classified into zones based on rainfall, humidity, vegetation temperature and altitude. One commonly used scheme divides the country into three major climatic zones;

the Guinea Coast (southern), Savannah (central), and Sahel (northern) zones. The Guinea Coast (approx. 4-8°N) is sub-humid, with high rainfall (approx. 1,575-2,533 mm annually), lush vegetation, and more uniform temperature. The Savannah zone (approx. 8-11°N) transitions between the

humid south and drier north, with rainfall declining to about 897-1,535 mm and more distinct dry seasons. The Sahel zone (approx. 11-14°N) is semi-arid, with a unimodal rainy season (July-September) and lower annual rainfall (approx. 434-969 mm). A more recent bioclimatic approach, useful for architectural, energy, and comfort studies, categorizes Nigeria into five climatic regions: hot-dry, temperate-dry, hot-humid, temperate-humid, and temperate-dry with cool climate. These categories better account for both moisture and temperature extremes, as well as altitude effects (particularly in highlands), than simpler north-south dichotomies. (Ghanim et. al. 2023). These classifications are critical for solar PV deployment planning, since solar irradiance, panel degradation due to heat, dust, and maintenance costs differ markedly across these zones.

The far northern parts experience the highest solar irradiance (Ugbehe et. al., 2025b). Global Horizontal Irradiance (GHI) values are as high as 5.5–6.0 kWh/m²/day during dry months. Temperatures can reach maxima of approx. 40-44 °C in peak dry season, though average values

are typically approx. 30-31 °C. Humidity is low (relative humidity declining northwards), often approx. <70% in dry season and rising during rainy seasons. Sunshine duration is very high, often above 3,300 hours/year in far north. This region exhibits intermediate irradiance (4.5-5.5 kWh/m²/day), with average annual temperatures of approx. 27-28 °C and more moderate daily maxima. Relative humidity is higher than in north, cloud cover more pronounced, especially in rainy season, reducing solar gain at times. Southern Nigeria, particularly coastal and rainforest zones, has the lowest GHI among the regions (approx. 3.7-5.0 kWh/m²/day) due to frequent cloud cover, high humidity (often >80-90%), and more diffuse solar radiation (Adediji et. al. 2021). Temperatures are somewhat moderated by maritime influence—daily highs often around 30-32 °C, lower night minima. These climatic gradients are critical for solar PV planning: northern regions offer higher potential, though challenges of heat, dust, and wide temperature swings must be managed; southern regions need design that copes with cloud cover, high moisture, and more diffuse insolation. Figure 2 highlights solar resource maps of Africa.

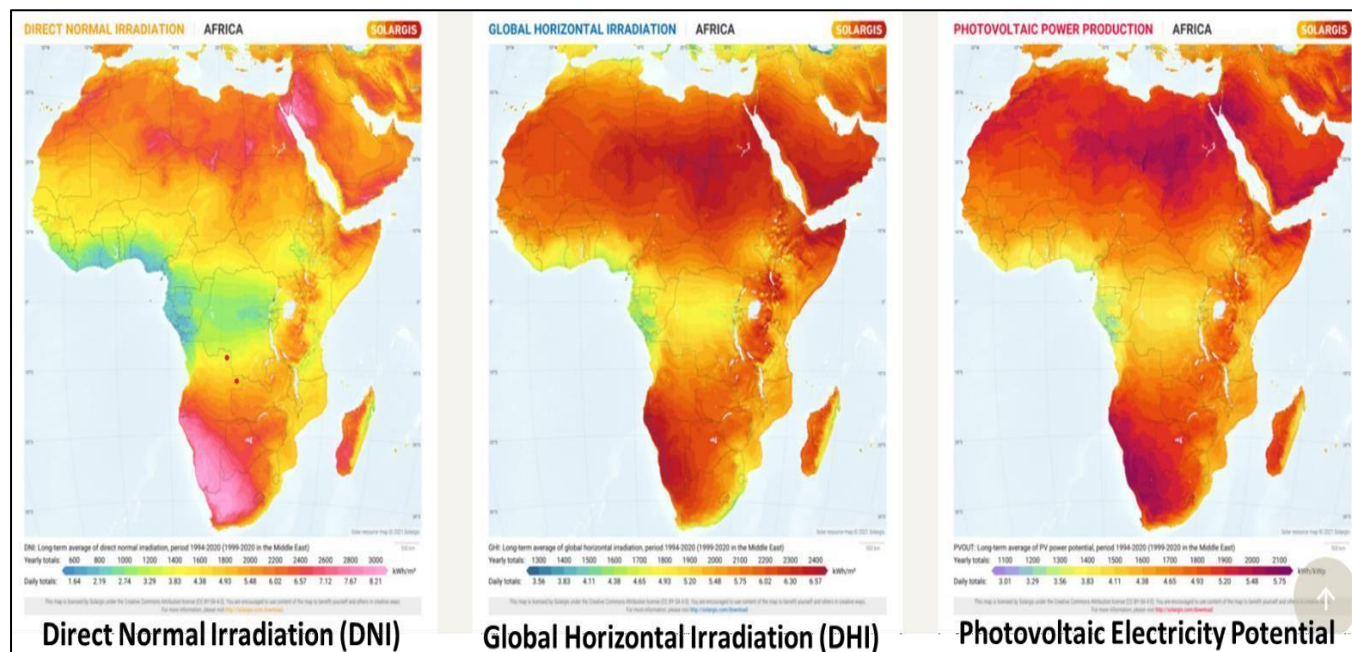


Fig 2 Solar Resource Maps of Africa

(Source: SolarGIS (<https://solargis.com/resources/free-maps-and-gis-data?locality=africa>))

Nigeria experiences distinct seasonal variations and weather patterns driven primarily by the movement of the Inter-Tropical Convergence Zone (ITCZ) and the dominance of two main air masses: the dry, dusty harmattan winds from the northeast and the moist southwest monsoon winds from the Atlantic Ocean. The country has two main seasons: the rainy season and the dry season, which vary by region. In the southern coastal zones, the rainy season lasts from March to November, with a short dry spell in August, known as the “August Break.” Rainfall is heavy (up to 2,500 mm/year), and relative humidity often exceeds 80%. (Okhakhu, 2016). In the northern regions, the rainy season is shorter, typically from June to September, with annual rainfall between 500–1000 mm. The dry season here includes the harmattan (November to February), characterized by low humidity, hazy skies, and

cooler nights. Temperature also varies seasonally, ranging from 25°C to 35°C, but can exceed 40°C in the arid north during peak dry months. (Schwanghart and Schutt, 2008). These seasonal patterns significantly influence solar irradiance, energy demand, and PV system performance, necessitating regional adaptation strategies for optimal solar deployment.

➤ Solar PV System Fundamentals

Solar PV systems have been extensively studied for their role in renewable energy generation. Early foundational research established the PV effect as the basis for electricity generation using semiconductor materials (Abdelrahman et. al. 2025). The advancement of PV technology has brought about massive improvement in conversion efficiencies from

below 10% to over 25% in laboratory cells, while commercial modules typically achieving 15–20% efficiency. According to Edgar (2025), the performance of PV system not only depends on panel efficiency but also on system design factors such as tilt angle, orientation, irradiance, and temperature effects. According to Edgar's study, the classification into grid-tied, off-grid, and hybrid systems is widely recognized, with each configuration addressing specific application needs and energy access challenges. Edgar's study also stresses the importance of energy yield (actual energy produced per installed capacity with respect to the rated power), as it

accounts for environmental and operational conditions. Rajendran et. al. (2025) focused on optimizing PV performance through smart inverters and energy storage integration to enhance reliability and grid stability, while Yakubu et al. (2022) compared in-plane solar irradiance received by mono-facial and bi-facial PV modules across various climatic regions. Experimental fallouts of Yakubu et al.'s investigation show bi-facial modules consistently outperform mono-facial ones due to better adaptation to location-specific irradiance and climatic conditions across Nigeria. Figure 3 shows the solar resource map of Nigeria.

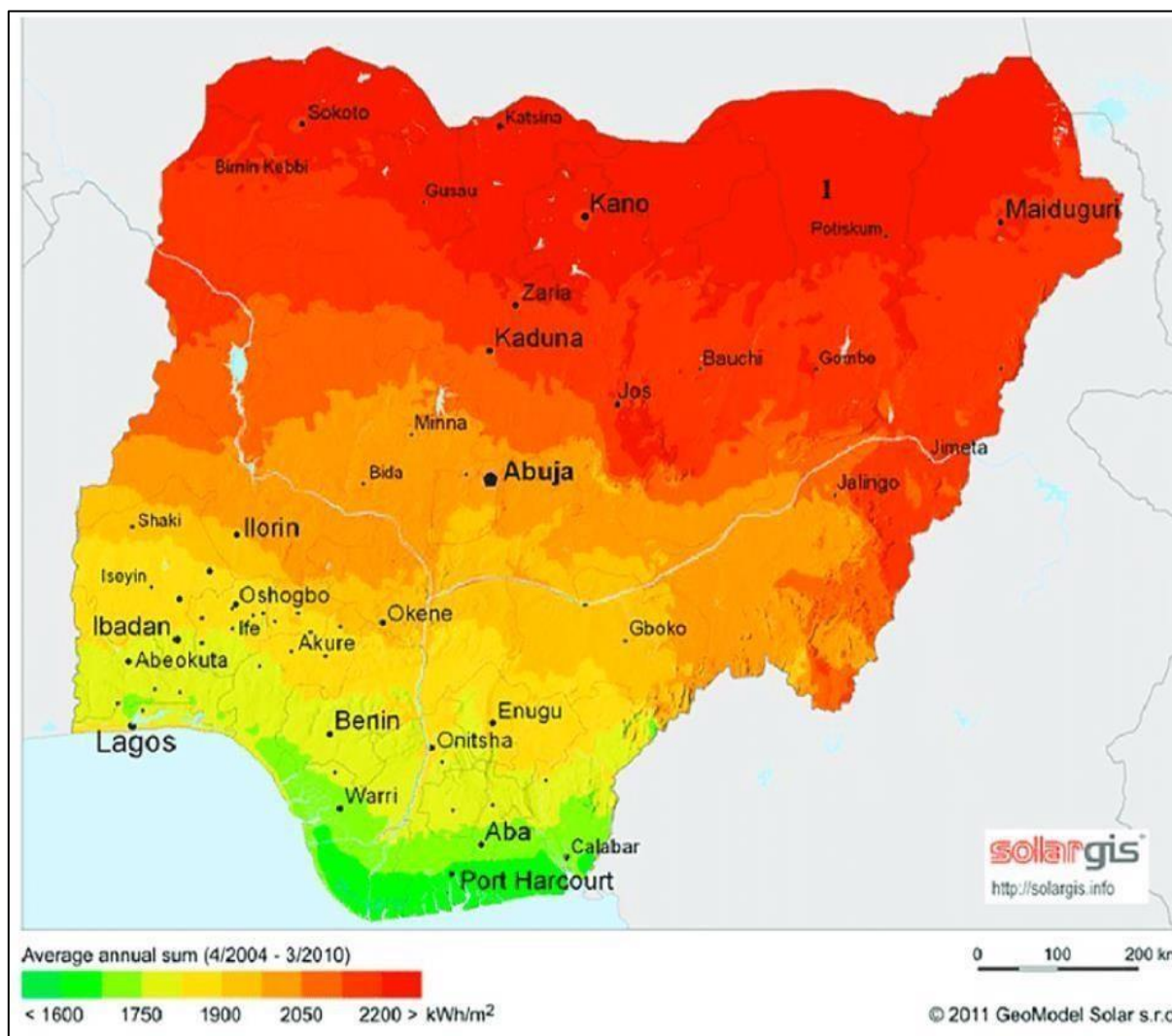


Fig 3 Solar Resource Map of Nigeria

(Source: SolarGIS (<https://solargis.com/resources/free-maps-and-gis-data?locality=africa>); Abdulhameed et. al., 2019)

Solar PV operation is founded based on the PV effect, as foremost observed by Becquerel in 1839 and extensively developed in semiconductor physics (Green, 1982). When sunlight composed of photons strikes a PV cell, it excites electrons in the semiconductor material (typically silicon), creating electron-hole pairs that generate electric current (Rajendran et. al., 2025). The core of a PV cell is a p-n junction that separates charges, enabling the flow of direct current (DC) electricity. PV cells are said in Abubakar et. al. (2022) to be connected in series to form a module and in series and/ or parallel to form arrays to get desired voltage

and current levels. According to Abubakar et. al.'s literature, there are key factors which affects the performance of PV module, these includes solar irradiance, temperature, and orientation angle, which impacts the cell's efficiency and power output. Advances in material science, such as multi-junction and thin-film cells, aim to enhance conversion efficiency and reduce costs. Understanding these principles is crucial for optimizing system design and deployment across diverse geographic and climatic conditions.

PV systems are broadly categorized into grid-tied, off-grid, and hybrid systems, each serving different energy needs. Grid-tied systems connect directly to the electricity grid, enabling energy export and import, thus reducing costs and enhancing reliability (Chand et. al., 2019). Off-grid systems operate independently, relying on batteries for energy storage, commonly used in remote areas without grid access, while hybrid systems combine both, integrating batteries and grid connectivity to balance reliability, cost, and energy availability (Khan et. al. 2025). In Khan et. al.'s literature, he highlighted that the choice of system depends on area, load requirements, and economic factors, with hybrid systems gaining attention for flexibility and resilience. Figure 4 highlights the solar resources and Peak Sun Hours (PSH) in Nigeria.

Suitable analytical tools for solar PV design, simulation, and performance assessment of systems according to Mazumder et. al., (2025) include PVsyst, HOMER, and SolarGIS:

- PVsyst – A professional software used for PV system design, energy yield estimation, and loss analysis. It supports detailed modeling using meteorological and system-specific data. (PVsyst SA, 2020).
- HOMER (Hybrid Optimization of Multiple Energy Resources) – Useful for simulating hybrid systems (solar, diesel, battery) and evaluating cost-effectiveness in off-grid and mini-grid scenarios. (HOMER Energy, 2021).
- SolarGIS – A professional software that provides climate data for the study of Solar Energy systems in the form of full historical time-series and TMY.

These tools provide a great resource in system sizing, energy output simulation, financial analysis, and feasibility studies, it aids decision-making in project development across varying Nigerian geographical and climatic zones.

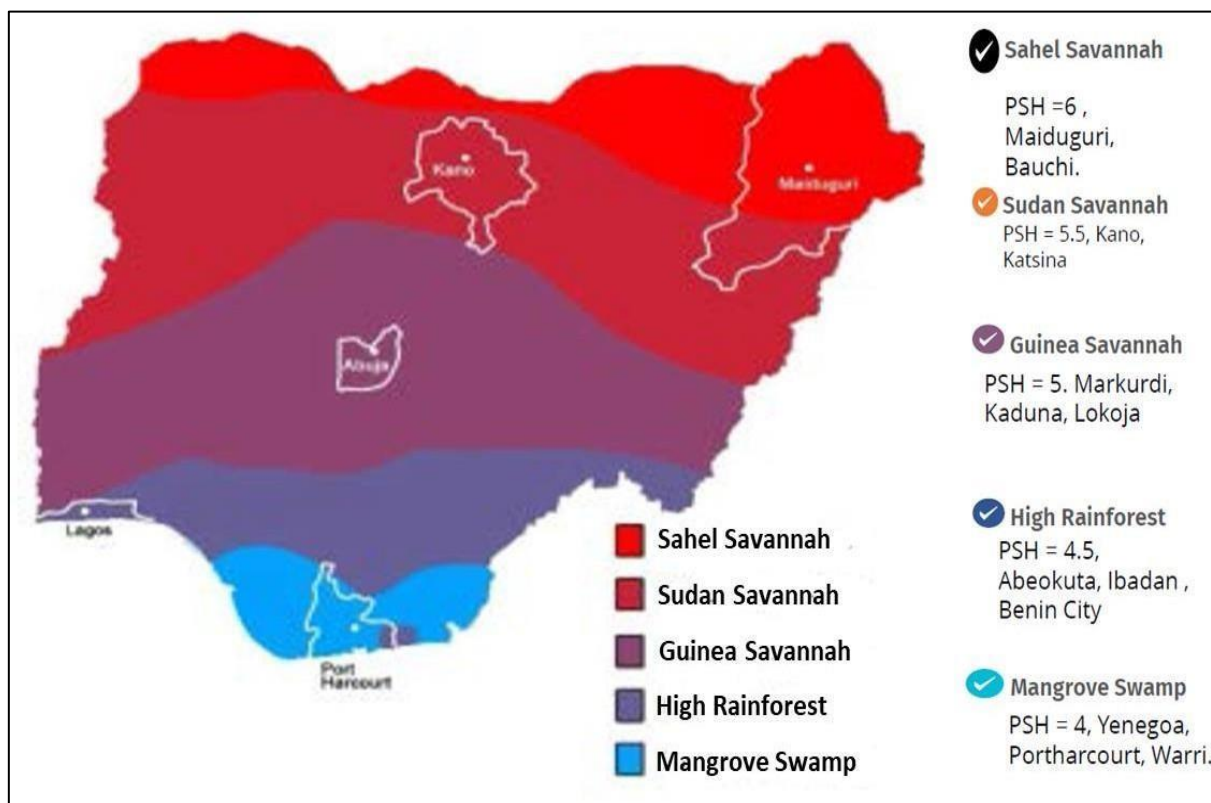


Fig 4 Solar Resources and Peak Sun Hours (PSH) in Nigeria
(Source: SolarGIS (<https://solargis.com/resources/free-maps-and-gis-data?locality=africa>))

III. METHODOLOGY FOR GEOGRAPHIC IMPACT ASSESSMENT

This study foremost carried out collection solar PV data across the climatic and geopolitical zones of Nigeria. Data collection remains critical in evaluating the performance and feasibility of solar PV systems. The procedure employed adopted satellite data using solar PV simulation tools including PVsyst, HOMER, and SolarGIS. Satellite data provides broad, long-term, and locationspecific solar radiation information. These tools according to Kim et. al.,

(2025) offer access to irradiance, temperature, and cloud cover data with global coverage. This method is especially useful in data-scarce regions (as with Nigeria), and for preliminary assessments. Onsite measurements involve using instruments like pyranometers, data loggers, and weather stations to collect highaccuracy, real- time data on solar irradiance, humidity, temperature and panel output, which are essential for site validation, system performance monitoring, and empirical research.

The PVsyst, HOMER, and SolarGIS simulation tools are deployed to integrate climatic, technical, and financial data to model PV system performance and economic viability of this study, just as in Mazumder et. al., (2025). These tools according to Mazumder et. al. use historical meteorological inputs and system specifications to identify patterns and

envisage outputs such as energy yield, system losses, and cost efficiency. Integrating all three methods ensures robust system design and performance analysis, particularly in geographically diverse and data-limited regions like Nigeria. As in Kumar (2020), the algorithm for the assessment of this study is presented in Figure 5.

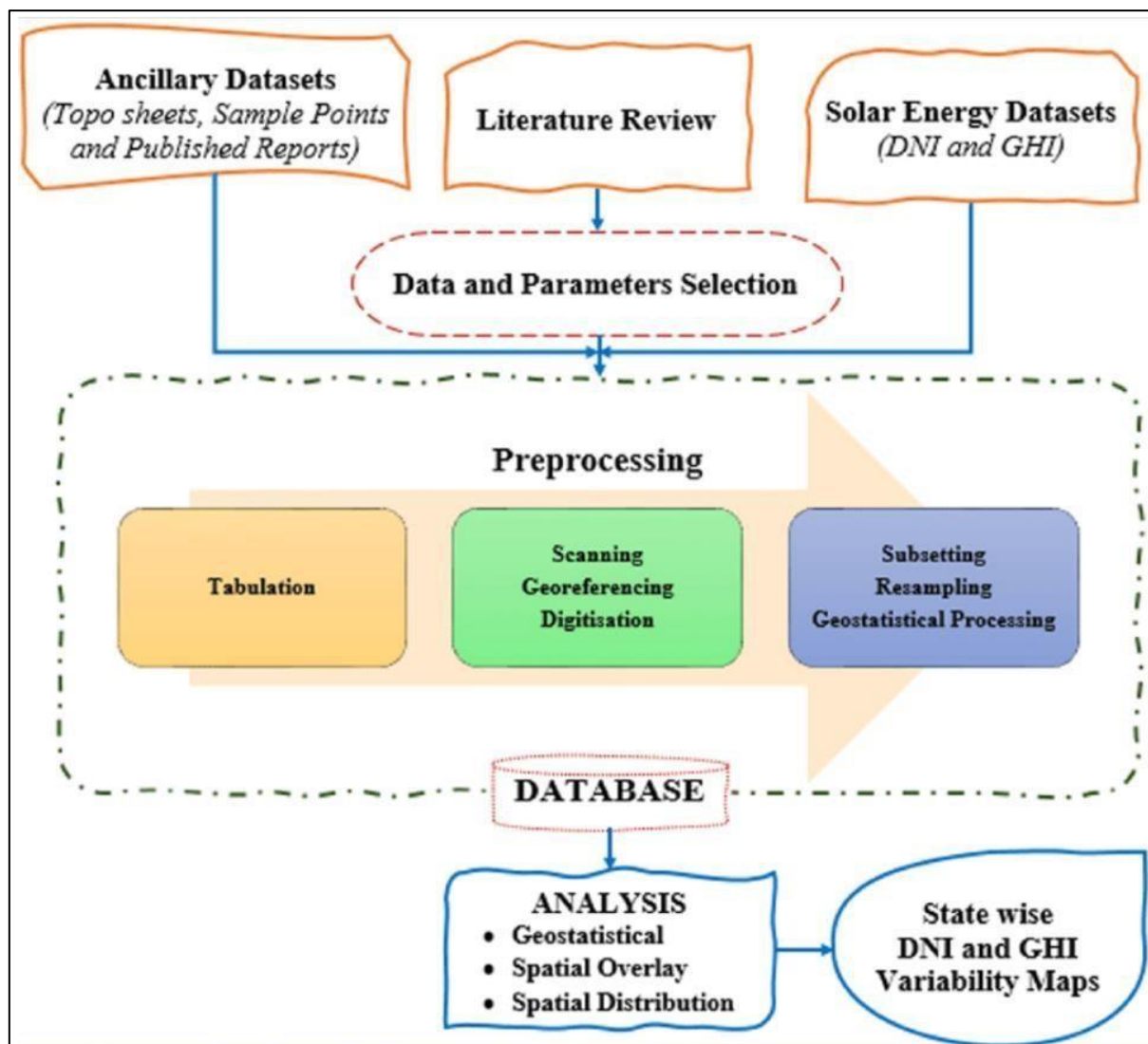


Fig 5 Algorithmic Design Analysis (Adapted from Kumar, 2020)

➤ *Levelised Cost of Energy (LCOE), and Return on Investment (ROI)*

The LCOE represents the average cost of generating 1 kWh of electricity over a solar PV system's lifetime, including capital, operation, and maintenance costs. LCOE is presented in Equation (1).

$$LCOE = \frac{\text{Total lifetime cost}}{\text{Total lifetime energy production}} \quad (1)$$

LCOE varies by region due to solar irradiance, system performance, and maintenance costs. The Northern Nigeria have lower LCOE of approximately \$0.05 to \$0.08/kWh due to the high solar output in these regions. On the other hand,

Southern Nigeria has a greater LCOE of approximately \$0.10 to \$0.15/kWh due to its relatively lower irradiance, and higher level of equipment degradation caused by humidity. A lower LCOE means better cost efficiency.

ROI refers to a popular profitability metric used in evaluating how well an investment has performed over time. It is expressed as a percentage, and is evaluated as the ratio of investment's net profit (or loss) to its initial cost or outlay. In this study, ROI measures the profitability of a solar investment over a time period. The expression for ROI is given in Equation (2).

$$ROI = \left(\frac{\text{Net gain of investment}}{\text{Total cost of investment}} \right) * 100 \quad (2)$$

A higher ROI is expected in zones with strong irradiance and low maintenance costs. ROI is affected by energy tariffs, system degradation, and policy incentives.

IV. RESULTS AND DISCUSSION

➤ Key Outcomes

The fallouts of the assessment of this study is shown in Tables 1 to 4. Table 1 shows the Solar PV system

performance across different zones in Nigeria; Table 2 highlights the breakdown of system output and efficiency per climatic zone; Table 3 shows the cost efficiency evaluation across zones; and Table 4 shows Solar PV performance across zones.

Table 1 Solar PV System Performance Across Different Zones in Nigeria

SN	Region	Geopolitical zone	GHI KWh/m ² /day	Mean Temp. (°C)	Humidity (%)	Characteristi	cs	Implication
1	^a Sahel and Sudan Savannah Zones	North-East and North-West	5.5 – 6.5	25°C - 44°C	Between 10% and 25% in dry season. Between 25% and 75% in wet season.	High potential, skies, humidity	solar clear low	Excellent for solar PV deployment, though high temperatures and dust may reduce panel efficiency
2	^b Guinea Savannah and Middle Belt	North-Central	4.5 – 5.5	27°C - 34°C	Averagely between 60 and 80%.	Moderate irradiance with a balance of sunny and cloudy days		Good solar resource with moderate climate-related degradation

3 ^cTropical South 3.5 – 4.5 17–24°C Averagely 60– Frequent cloud Lower solar Rainforest and 90% cover, high output; requires Coastal Zones humidity, and careful system rainfall design for efficiency

Table 2 Breakdown of System Output and Efficiency Per Climatic Zone

S/N	Region	Geopolitical zone	Solar Irradiance	System Output	Efficiency Factors	Net Efficiency
1	Sahel and Sudan Savannah	North	5.5 – 6.5	High energy yield per installed kWp (approx. 1,500–1,800 kWh/kWp/year)	High irradiance boosts output, but elevated temperatures (above 40°C) and dust accumulation can reduce panel efficiency by 10–20%.	Approx. 14–17% (real-world)
2	Guinea Savannah / Middle Belt	Central	4.5 – 5.5	Moderate yield (approx. 1,200–1,500 kWh/kWp/year)	Balanced sunlight and temperatures; less dust than north, moderate humidity.	Approx. 15–18%
3.	Rainforest and Coastal Zones	South	3.5 – 4.5	Lower yield (~1,000–1,200 kWh/kWp/year)	High humidity, cloud cover, and frequent rain reduce irradiance and increase inverter derating.	Approx. 13–16%

Table 3 Cost Efficiency Evaluation Across Zones

Zone	CAPEX	OPEX	Main Drivers
North (Sahel)	Low–Moderate	High	Dust, heat, cleaning, cooling
Middle Belt	Moderate	Low	Balanced climate, lower maintenance
South (Coastal)	High	Moderate–High	Moisture protection, corrosion, oversizing

Table 4 Solar PV Performance Across Zones

Region	Solar Irradiance (kWh/m ² /day)	System Performance	Maintenance Considerations	Economic Viability
Sokoto	5.86	High	Dust accumulation	Very High
Abuja	4.81	Moderate	Moderate dust levels	High
Lagos	3.5–4.5	Low	High humidity	Moderate
Enugu	6.25	High	Standard maintenance	High

➤ Discussion

Table 1 represents the performance of solar PV system across different zones in Nigeria. As shown in the table, solar irradiance levels across Nigeria vary by climatic zone, influencing solar PV performance. The Sahel and Sudan Savannah (northern region) receive the highest irradiance, ranging from 5.5 to 6.5 kWh/m²/day, due to clear skies and low humidity. The Guinea Savannah (Middle Belt) experiences moderate levels between 4.5 and 5.5 kWh/m²/day, with balanced sunlight and seasonal cloud cover. In contrast, the zones in southern regions which includes the Rainforest and Coastal zones, have the least value of irradiance, between 3.5 to 4.5 kWh/m²/day, due to frequent rainfall and high humidity. These variations are important for PV system design, as locations with higher irradiance give greater solar energy potential. (IRENA, 2016). Solar irradiance levels vary significantly across Nigeria's climatic zones due to differences in cloud cover, atmospheric dust, humidity, and latitude. The Global Horizontal Irradiance (GHI), which is a key metric for solar PV potential ranges from 3.5 to 6.5 kWh/m²/day across the country. Understanding these irradiance patterns is critical for optimal PV system sizing and technology choice across.

Also, system output and efficiency of solar PV systems vary significantly across Nigeria's climatic zones due to

differences in solar irradiance, temperature, dust levels, and humidity. Table 2 shows the breakdown of system output and efficiency per climatic zone. As highlighted in Table 2, environmental factors such as temperature, dust, and humidity significantly affect the performance and efficiency of solar PV systems, especially in diverse climatic regions like Nigeria. The system performance across geographical regions/ locations is shown in Figure 6. As per temperature, high ambient temperatures reduce the efficiency of PV cells. An increase of 1°C above 25°C (the Standard Test Condition (STC)), majority of silicon-based panels lose an efficiency of 0.4–0.5%.

In northern Nigeria, where temperatures can exceed 40°C, this can lead to 10–20% power loss if not properly mitigated (KlugmannRadziemska, 2003). Dust accumulation on PV modules (common in arid northern regions) blocks sunlight, reducing irradiance reaching the cells. Studies show dust can lower energy output by 10–40%, depending on exposure, tilt angle, and cleaning frequency (Nezamisavojbolaghi et. al. 2023). This effect is most severe during harmattan season. High humidity that is prevalent in southern Nigeria, breeds moisture ingress into PV modules, causing corrosion, delamination, and electrical leakage. It also increases cloud cover, reducing solar irradiance and daily energy yield (Hassan et.al., 2021).

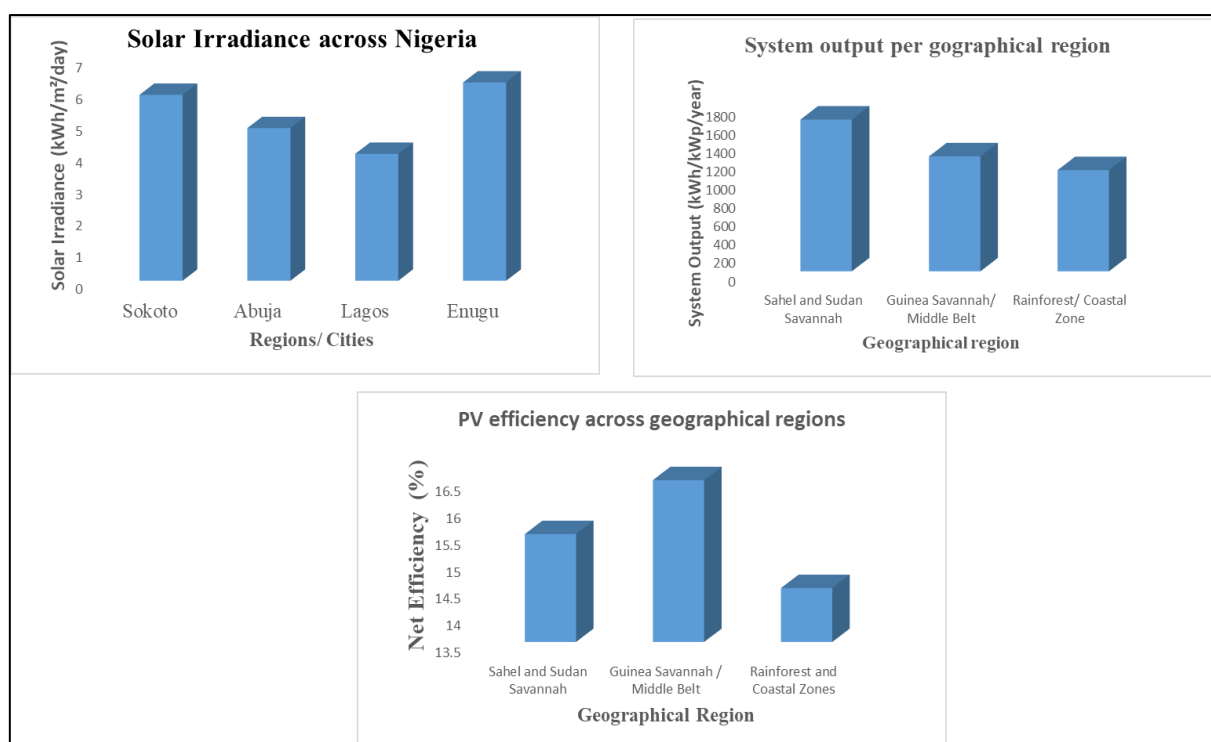


Fig 6 System Performance Across Geographical Regions/ Locations

Cost efficiency evaluation of solar PV systems involves comparing the total system cost (CAPEX + OPEX) against the energy output over the system's lifetime. Key metrics include Levelized Cost of Electricity (LCOE) and payback period. Regions with high solar irradiance and low maintenance costs, such as Nigeria's Middle Belt, typically offer better cost efficiency, while harsher environments (e.g., dusty or humid zones) increase operational costs and reduce financial returns. The capital (CAPEX) and operational (OPEX) costs of solar PV systems in Nigeria vary across climatic zones due to differences in environmental conditions, infrastructure availability, maintenance needs, and system degradation rates. In the Sahel and Sudan Savannah (Northern Nigeria), CAPEX is typically lower per watt due to high solar irradiance, which infers fewer panels needed for same output. OPEX is higher, due to frequent panel cleaning (dust) and temperature-related component degradation. Dust accumulation may require automated or regular manual cleaning, increasing cost of maintenance interventions. However, cooling or ventilation enhancements may be needed to offset high ambient temperatures. For the Guinea Savannah or Middle Belt (Central Nigeria), CAPEX is moderate. Good irradiance allows for efficient sizing without high environmental stress. OPEX is lower, with reduced dust and moderate temperature. Less frequent maintenance is required than in the northern region. Most cost effective zone when balancing output and system durability. In the rainforest and coastal zones (Southern Nigeria), CAPEX is higher basically due to larger system sizing (lower irradiance) and need for moisture-resistant equipment. OPEX is moderate to high due to inverter failures, corrosion risk, and less predictable output (from cloud cover). Frequent replacement of components like connectors and inverters is common in this zone. The summary is presented in Table 3.

Geographic factors such as climate, temperature, humidity, and dust levels significantly influence the maintenance requirements and lifespan of solar PV systems. In arid northern regions, high dust accumulation demands frequent cleaning to maintain efficiency, increasing operational costs and potentially causing abrasion that shortens panel life. Elevated temperatures accelerate material degradation, reducing inverter and panel lifespan. In humid southern zones, moisture ingress leads to corrosion, electrical faults, and delamination, necessitating robust weatherproofing and more frequent inspections. These conditions can shorten system lifespan by 5 to 10 years compared to drier zones. Middle Belt regions with moderate climate have relatively lower maintenance demands and longer system durability. Summarily, geographic conditions dictate maintenance frequency, component replacement rates, and overall system reliability, making location-specific strategies vital for maximizing PV system lifespan and performance.

Regarding the overall regional PV performance, a detailed analysis of selected solar photovoltaic (PV) installations across Nigeria's diverse climatic zones specifically in Sokoto, Abuja, Lagos, Enugu is conducted. Analytical fallouts reveal significant regional variations in performance, maintenance requirements, and economic

viability. From Table 4, Sokoto (northern Nigeria) has an approximate solar irradiance of 5.86 kWh/m²/day. This indicates high solar energy potential. When looking at system performance, hybrid PV/battery systems in Sokoto state are found to demonstrate up to 35 to 49% decrease in net present cost and an 80 to 92% decrease in greenhouse gas emissions likened to grid-only systems, while looking at maintenance interference, dust accumulation makes it necessary for regular cleaning and increased operational costs. Economic viability in the region offers the lowest cost of energy at \$0.0837/kWh, and an internal rate of return (ROR) of 17.7%, making it highly attractive for solar investments. Abuja (in Central Nigeria) has its estimated solar irradiance at 4.81 kWh/m²/day, reflecting a moderate solar potential. In Abuja, the System performance for hybrid systems is rated to reduce the cost of energy by 43 to 58%, and a 43–58% reduction in net present cost. For maintenance, the moderate dust levels and temperatures result in manageable maintenance needs. While economic viability is not as cost-effective as in Sokoto, Abuja presents a balanced environment for solar investments.

In Lagos (Southern Nigeria), solar irradiance is approximately 3.5 to 4.5 kWh/m²/day, indicating lower solar energy potential. Systems in Lagos experience reduced efficiency due to frequent cloud cover and humidity. High humidity accelerates equipment degradation, leading to increased maintenance and replacement costs. The higher operational costs and lower energy output result in a higher levelised cost of energy compared to the northern regions. In Eastern Nigeria (Enugu), solar irradiance is approximately 6.25 kWh/m²/day, which correlates to the highest among the selected regions, as per deep learning model predictions. High irradiance supports efficient energy production, making Enugu favorable for solar installations. Moderate humidity levels require standard maintenance practices for installations in the region. In terms of combination of high energy output and manageable maintenance costs positions, Enugu as an attractive location for solar investments. This analysis underscores the importance of considering regional climatic conditions when planning solar PV installations in Nigeria. Northern regions like Sokoto offer high solar potential and economic returns, albeit with increased maintenance due to dust. Central regions such as Abuja provide a balanced environment, while southern regions like Lagos face challenges due to lower irradiance and higher humidity, affecting system performance and maintenance.

Given the assessment outcomes. Table 5 suggests the region-tailored solar energy investment implications. It details the possible implications of investing in the respective regions.

Table 5 Region-Tailored Solar Investment Implications

Region / climatic zone	Solar PV investment implications
i. Northern Nigeria (Sahel and Sudan Savannah zones)	Provide generous subsidies or tax breaks for solar PV systems designed to withstand high heat and dust. Support local manufacturing capacity for rugged solar hardware to reduce import dependence and costs Establish off-grid mini-grid or hybrid solar-battery programs to serve rural, remote communities with weak grid access
iv.	Incentivize frequent maintenance / cleaning services to maintain high output
i. ii. Middle Belt (Guinea Savannah) iii. iv.	Promote grid-tied and hybrid PV systems through feed-in tariffs or net-metering to leverage moderate irradiance and grid availability Enact quality certification standards for components and installations to ensure reliability Provide low-interest finance and tax incentives that reflect moderate CAPEX and OPEX . Develop capacity building and technical training centred in these regions since they offer good compromise between performance and environmental stress
Southern Nigeria (Rainforest / Coastal zones) i. ii. iii.	Design solar PV systems with moisture/ humidity protection Support systems with higher battery storage or backup to compensate for lower irradiance. Use bundled incentives to offset higher CAPEX due to specialized hardware
iv.	Encourage community solar and rooftop solar policies in urban/coastal areas, combined with awareness programmes on solar benefits and maintenance under humid conditions.

These initiatives provided in Table 5 are to be backed by strong regulatory frameworks, data collection efforts, and regional planning, so each region's solar potential, climate stresses, cost structures are properly accounted for in policy design. Hassan (2026) acknowledged that broad “one-size-fits-all” incentives often fail to address unique geographic and environmental challenges in Nigeria's diverse zones.

➤ Incentives for region-specific solar adoption

Some region-specific incentive ideas to promote solar energy adoption in Nigeria, drawn from best practices and literature, which can guide tailored region-specific solar adoption are presented below, and in Table 6. Key incentives for adoption include:

- Import-Duty and VAT Exemptions for solar panels, batteries, and related equipment reduce capital costs substantially. ii. Tax Credits and Pioneer Status Incentives for companies investing in solar manufacturing or large installations.
- Low-Interest / Preferential Loans through institutions like the Central Bank of Nigeria (CBN), Bank of Industry, Rural Electrification Agency (REA), to reduce financing costs, especially in off-grid / rural zones.
- Capital Subsidies or grants for mini-grids, solar home systems, and rural electrification.

Table 6 Region-Tailored Incentives for Solar Adoption

Region	Incentives
Northern Nigeria (Sahel and Sudan Savannah)	Stronger off-grid subsidies and grants; cheaper financing for solar + storage; incentives for high dust/heavy heat resistant modules; reward maintenance services (cleaning, monitoring) via outcome-based grants.
Middle Belt	Feed-in tariffs / net-metering policies for grid-tied solar; incentives for hybrid systems; tax incentives for commercial installations; support for local installers.
Southern Coastal / Rainforest Zones	Incentives for moisture-protected equipment; grants or tax relief for dual / backup storage to cover rainy or overcast periods; higher import exemptions for corrosion-resistant materials; incentives for rooftop solar (urban) and community systems.

➤ Strategies for Optimizing System Design Based on Geographical Locations in Nigeria

Key strategies proposed for optimizing solar PV system design based on Nigeria's diverse geographic and climatic zones, backed by best practices from research and real-world projects are presented in this session. Ijagbemi et al., (2023) claimed that a latitude- sensitive design improves annual yield by up to 8–12%. In Sokoto (Northern zones), steeper tilt angles of approximately 15–25° is advised in order to maximise dry-season output and improve self-cleaning of panels (reduce dust accumulation), while in places such as Lagos and Port Harcourt (in the Southern zone), a lower tilt angles of approximately 5–10° is used due to more diffused

radiation and higher rainfall (less soiling). As per component selection based on environmental stressors, in high-temperature areas, it is recommended to use PV modules with low temperature coefficients (monocrystalline or PERC modules), and inverters with thermal management systems. For the humid/ rainforest zones, corrosion-resistant mounting frames (anodized aluminum or coated steel) with seal enclosures of IP65/ IP67 standards to protect from moisture are recommended. In dust-prone areas, anti-soiling coatings (or glass) and automated or scheduled cleaning systems is advised.

Optimisation for excess daytime production and feed-in (if grid-connected) or use lower panel count for the same output in high irradiance areas like Enugu and Sokoto, is advised for system sizing to match solar resource and load profiles; while for cloudy/ rainy zones like Port Harcourt, slightly oversized arrays or an increased battery storage capacity is required to maintain availability during periods of low irradiance. The use of hybrid systems in grid-unreliable or off-grid zones in central and northern states with poor grid access, hybrid systems (PV + battery + generator integration) provide better reliability. Smart controllers are to be included to optimize battery cycling and generator runtime.

Considering modular and scalable designs, it is best to allow for future expansion in regions where energy demand is expected to grow (rural electrification zones). This can be achieved with the use micro-inverters or string-level monitoring for better fault isolation and performance tracking. Design O&M schedules based on environmental loads suggest a weekly cleaning in dusty Sahel region, quarterly corrosion checks in humid zones, temperature monitoring and thermal imaging in high-heat areas. Table 7 shows the strategic PV system optimizing based on geographical locations in Nigeria.

Table 7 Strategic PV System Optimizing Based on Geographical Locations in Nigeria

Zone Key Stressors		Design Optimization
Sahel/ North	Dust, high temp	Steep tilt, anti-soiling panels, thermal-rated inverters
Savannah/ Middle Belt	Moderate climate	Hybrid systems, standard design, seasonal tilt
Coastal South	Humidity, rainfall	Corrosion-proof mounts, sealed systems, oversizing
Rainforest East	Cloud cover	Smart controls, batteries, tilt for rainy season

V. CONCLUSION

This study investigates the geographic impact on the cost-efficiency and performance of solar photovoltaic (PV) systems across Nigeria's diverse climatic zones. The investigative fallouts of this study highlight that solar irradiance, humidity, temperature, and dust levels vary significantly across regions affecting system output, efficiency, maintenance requirements, and economic viability. It further shows that geographic and climatic differences across Nigeria significantly affect solar PV system cost-efficiency and performance. Northern region, such as Sokoto, benefits from higher solar irradiance and lower LCOE, making them more viable for large-scale solar deployment. Southern zones face challenges from lower irradiance, humidity, and higher maintenance costs. However, temperature, dust, and environmental stressors were shown to impact system lifespan and output. Data limitations and inconsistent policy frameworks are clued to hindering optimized deployment. The study highlights the need for a region-specific system designs, incentives, and infrastructure support to enhance solar adoption and ensure long-term sustainability across Nigeria. In summary, this study expatiated how geographic and climatic differences across Nigeria affect the performance and cost- efficiency of solar PV systems. The main findings are:

- Solar irradiance varies widely by region.
- Environmental factors significantly impact performance:
- System output and efficiency reflect regional conditions.
- Cost efficiency differs by location.
- v. Policy and infrastructure gaps exist

These findings stressed the need for geographically tailored solar strategies in Nigeria to maximise energy access, system performance, and investment returns.

➤ Strategic Recommendations

While a geography-aware approach to solar PV deployment will significantly help in improving

performance, reduce costs, and support sustainable energy access across Nigeria, it is also required in addition to adopt the following recommendations in view of sustainability, and optimal PV system performance across various geographical zones in Nigeria:

- Adopt region-specific system designs.
- Develop localized incentives procedure.
- Enhance data collection.
- Promote local capacity building. v. Strengthen policy frameworks.

However, for the respective stakeholders in Nigeria, the following will also be recommended:

- *Developers:* It is recommended that developers design and size solar PV systems tailored to regional climatic conditions (such as corrosion-proof systems in the south, and dust-resistant panels in the north.), integrate hybrid solutions with battery storage in areas with relatively variable sunlight or weak grids, and prioritise regular maintenance intervention programs, especially in dusty and humid environments, to sustain lifespan and performance.
- *Policymakers:* It is also recommended that policymakers implement region-specific incentives such as subsidies, tax breaks, and import duty exemptions aligned with local potentials and challenges, strengthen regulatory frameworks to streamline project approvals while ensuring quality standards, and invest in meteorological infrastructure to enhance solar resource data availability and accuracy.
- *Investors:* Investors are recommended to focus investments on northern and middle-belt zones where solar yields and ROI are higher, support projects with proven maintenance and monitoring plans to mitigate impending environmental risks, and encourage partnerships with local manufacturers and service providers for cost reduction and sustainability improvement.

These targeted strategic recommendations will potentially enhance solar PV efficiency and scalability across Nigeria's diverse zones.

➤ *Credit Author Statement*

Prosper O. Ugbehe; Conceptualisation, Methodology, Data curation, writing the original draft, reviewing and editing; Idibie Emmanuel Emuesiri, Sunday Ogheneyehovwo, Etaredafe Aghogho Faith Olokpa Ewvorhovwo Favour, Ogbodogbo Oghenevwogaga Precious, Onyegbadue Ikenna Augustine, Precious Oscar-Daniels, and Ngbodi Anthonia Ozioma: Writing the original draft, reviewing and editing.

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No potential conflict of interest was reported by the author(s).

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The data that support the findings of this study are available in a public, open access repository.

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