



EVALUATION OF THE INFLUENCE OF METEOROLOGICAL INFORMATION ON PROCUREMENT EFFICIENCY AND PERFORMANCE OF SOLAR ENERGY PROJECTS IN NIGERIA

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Abstract

Nigeria, endowed with abundant solar radiation averaging 5.54 kWh/m²/day, faces a paradoxical energy crisis characterized by persistent grid unreliability and limited electricity access affecting approximately 90 million citizens. While solar photovoltaic (PV) technology presents a viable pathway toward sustainable electrification, project success hinges critically on the quality and utilization of meteorological information throughout the procurement lifecycle. This study examines the influence of meteorological data on procurement efficiency and project performance in Nigeria's solar energy sector. Through a systematic review of recent empirical studies, techno-economic assessments, and meteorological modeling approaches, the analysis reveals that accurate weather information fundamentally shapes system design optimization, technology selection, financial modeling, and operational planning. The study identifies significant challenges including dysfunctional meteorological stations, limited ground-based radiation measurements, and insufficient integration of climate variability considerations into procurement frameworks. Drawing on evidence from PVSyst simulations, HOMER Pro analyses, and machine learning forecasting models across Nigeria's diverse climatic zones, this study demonstrates that meteorological-informed procurement can enhance performance ratios by 12–15%, reduce levelized cost of energy to competitive levels, and improve investment returns. The findings underscore the imperative for developing robust meteorological infrastructure, adopting weather-aware optimization frameworks, and integrating climate risk assessment into solar energy procurement policies to accelerate Nigeria's energy transition.

Keywords: Meteorological information, solar energy procurement, photovoltaic performance, Nigeria, weather variability, renewable energy planning

1. INTRODUCTION

The global energy landscape is transitioning from fossil fuels toward sustainable, low-carbon alternatives (Ademola & AlKassem, 2025), a shift particularly critical for sub-Saharan Africa where energy access deficits, environmental degradation, and economic volatility intensify the urgency of cleaner energy adoption (Maduabuchi et al., 2023). Solar photovoltaics (PV) has emerged as a promising solution due to its scalability, declining costs, and minimal environmental impact (Ademola & AlKassem, 2025). Nigeria, Africa's most populous nation with over 200 million inhabitants, is endowed with substantial solar irradiation averaging 5.54 kWh/m²/day and annual incident solar energy estimated at 1831.06 kWh (Elenga et al., 2025; Agbo et al., 2021). Sunshine duration varies from 3.5 hours in the south to 9 hours in the north (Abdullahi et al., 2017). Despite this abundant resource, Nigeria's power sector faces a significant demand-supply gap: current demand is estimated at 17,520 MW while peak production capability hovers at approximately

5,300 MW, leaving roughly 90 million citizens without grid electricity access (Elenga et al., 2025). Of these, 73 million reside in remote areas where grid extension is unsustainable, while 17 million live in urban zones experiencing frequent blackouts (Federal Ministry of Power, 2016). This situation has profound socioeconomic consequences, as households and businesses increasingly resort to expensive diesel generators, undermining economic productivity (Ademola & AlKassem, 2025).

Solar PV technology has gained substantial traction, with studies demonstrating technical feasibility and economic competitiveness across Nigeria. Optimal grid-connected systems achieve performance ratios between 77% and 78% and levelized cost of energy (LCOE) ranging from \$0.068/kWh to \$0.079/kWh—substantially lower than the grid-only cost of \$0.724/kWh (Elenga et al., 2025; Ademola & AlKassem, 2025).

However, successful deployment depends fundamentally on the quality and utilization of meteorological information such as temperature, rainfall, wind, humidity, pressure, throughout the project lifecycle. Meteorological data influence virtually every aspect of solar project performance: solar irradiance determines energy yield; temperature affects module efficiency; wind speeds influence cooling and structural loading; humidity impacts soiling losses; and cloud cover introduces variability that must be managed through storage and grid integration strategies (Maduabuchi et al., 2023; Sigauke, 2025). The challenge facing renewable energy systems in Nigeria, as identified by Maduabuchi et al. (2023), is "the lack of appropriate, affordable, and available

meteorological stations that can accurately provide present and future trends in weather data and solar PV performance." This data deficit such as historical weather data on solar radiation creates significant barriers for investors and project developers who require reliable information for informed procurement decisions. This study therefore examines the influence of meteorological information (temperature, rainfall, humidity, wind, solar radiation) on procurement efficiency and performance of solar energy projects in Nigeria, with the specific objectives of: (i) assessing the current state of meteorological data infrastructure and its implications for solar energy planning; (ii) evaluating how meteorological information influences procurement efficiency across system design, technology selection, financial modeling, and supply chain planning; (iii) analyzing the relationship between meteorological conditions and solar project performance; and (iv) identifying strategies for enhancing meteorological data utilization in solar energy procurement.

2. MATERIALS AND METHODS

2.1 Study Design and Approach

This study employed a systematic review and synthesis design to examine the influence of meteorological information on procurement efficiency and performance of solar energy projects in Nigeria. A mixed-methods approach was adopted, combining qualitative synthesis of empirical literature with quantitative meta-analysis of reported performance metrics. The systematic review methodology followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

2.2 Search Strategy and Data Sources

A comprehensive literature search was conducted across multiple electronic databases including Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. The search covered publications from January 2015 to December 2025 to capture recent developments in solar energy procurement and meteorological applications in Nigeria. The search strategy combined keywords and Boolean operators: ("meteorological information" OR "weather data" OR "solar irradiance" OR "climate data") AND ("solar energy" OR "photovoltaic" OR "PV system") AND ("procurement" OR "project performance" OR "techno-economic") AND ("Nigeria" OR "West Africa").

2.3 Eligibility Criteria

Inclusion criteria: (i) peer-reviewed empirical studies, techno-economic assessments, and modeling studies; (ii) studies conducted in Nigeria or with direct relevance to Nigerian climatic conditions; (iii) studies reporting quantitative performance metrics (performance ratio, LCOE, energy yield, efficiency); (iv) studies examining meteorological parameters in relation to solar PV performance or procurement; (v) publications in English language.

Exclusion criteria: (i) studies focused exclusively on non-PV solar technologies (e.g., concentrated solar power); (ii) studies without quantitative performance data; (iii) conference abstracts, editorials, and non-peer-reviewed articles; (iv) studies conducted outside Nigeria without relevance to Nigerian conditions.

2.4 Data Extraction and Quality Assessment

Data were systematically extracted from eligible studies on photovoltaic (PV) systems in Nigeria using a standardized data-extraction

form. The extraction focused on meteorological parameters, including solar irradiance, ambient temperature, wind speed, relative humidity, and soiling; PV system specifications, including installed capacity, technology type, and configuration; performance and economic indicators, including performance ratio, levelized cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR), and energy yield; and findings related to procurement and investment decision-making. The literature search and data extraction were conducted using relevant electronic databases and scholarly search platforms, with the specific sources determined by the review's search strategy. Methodological quality was assessed using a modified version of the Newcastle–Ottawa Scale, adapted for cross-sectional and modelling studies. Studies were evaluated against predefined quality criteria and assigned scores ranging from 0 to 9, with higher scores indicating better methodological quality.

2.5 Meteorological Data Sources

Meteorological data used in the reviewed studies were obtained from four principal categories of sources. First, ground-based observations were obtained from Nigerian Meteorological Agency (NiMet) stations. The temporal coverage of these observations varied by station, meteorological parameter, and study; therefore, the exact observation periods were determined from the individual studies rather than assigned a single national coverage period. Second, satellite-derived datasets included NASA's Surface Meteorology and Solar Energy (NASA-SSE) and Climate Monitoring Satellite Application Facility (CM SAF) products. The NASA-SSE Release 5.1 dataset covered July 1983 to June 1993, whereas the

CM SAF Surface Radiation Data Set–Heliosat, Edition 3 (SARAH-3), provides a climate data record for January 1983 to December 2020, with operational extensions available beyond this period.

Third, Typical Meteorological Year (TMY) datasets were generated using the Sandia method, which selects representative meteorological months from a longer historical record to construct a synthetic 12-month reference year. Consequently, the underlying data coverage depends on the source dataset and the period specified in each study; the resulting TMY represents one typical year rather than a continuous historical record.

Fourth, reanalysis datasets included the European Centre for Medium-Range Weather Forecasts' ERA5 and NASA's Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). ERA5 covers January 1940 to the present, while MERRA-2 provides data from 1980 to the present, with the available endpoint depending on the product and data-access date. Data quality was assessed in relation to the temporal completeness and coverage of the records, spatial resolution, consistency of meteorological variables, and validation against ground-based observations where such comparisons were reported. For each study, the actual years of data used were distinguished from the overall temporal coverage of the source dataset to ensure accurate interpretation of the evidence.

2.6 Simulation and Modeling Framework

The synthesized studies employed various simulation tools and modeling approaches. PVSyst (version 7.x) was used for technical performance simulation, incorporating meteorological inputs for system sizing, orientation optimization, and performance ratio calculation. HOMER Pro was utilized for techno-economic optimization, integrating meteorological data with cost parameters to determine optimal system configurations. Machine learning approaches included Random Forest, artificial neural networks, and regression models for solar irradiance forecasting and gap-filling. The weather-aware optimization framework incorporated large-scale climate oscillations (MJO, ENSO) using 45 years of climatological data.

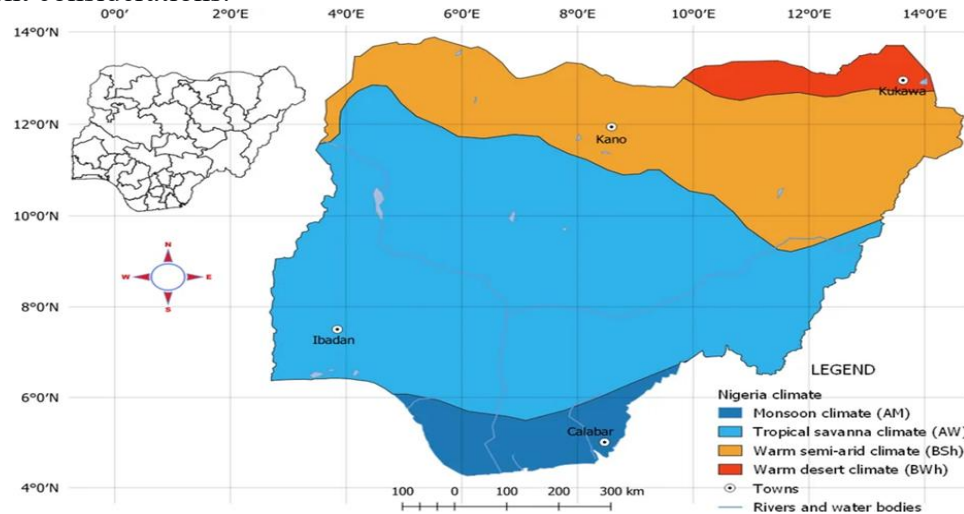
2.7 Performance Metrics and Analysis

Standard performance metrics were extracted and analyzed: Performance Ratio (PR) calculated as the ratio of actual to theoretical energy output; Levelized Cost of Energy (LCOE) computed as the ratio of total lifecycle costs to total energy generation; Net Present Value (NPV) and Internal Rate of Return (IRR) for economic feasibility; and Capacity Utilization Factor (CUF) for system efficiency assessment. Meta-analysis was conducted using random-effects models where sufficient homogeneity existed, with heterogeneity assessed using I^2 statistics. Sensitivity analysis examined the impact of meteorological parameter variations on performance outcomes.

2.8 Geographic and Climatic Zoning

Analysis was stratified by Nigeria's six geopolitical zones and four climatic zones: warm desert, warm semi-arid, tropical savanna, and monsoon climate. This stratification enabled comparison of meteorological influences across Nigeria's diverse climatic

conditions and identification of region-specific procurement considerations.



Map of Nigeria showing climatic zones and exact locations of stations

2.9 Ethical Considerations

This study involved secondary analysis of published literature and publicly available meteorological data. No primary data collection involving human participants was conducted. Ethical approval was therefore not required. All sources were properly cited and acknowledged.

2.10 Limitations

Several limitations should be noted. First, reliance on published studies introduces potential publication bias. Second, variations in simulation tools, assumptions, and boundary conditions across studies may affect comparability. Third, limited ground-based meteorological data in Nigeria means many studies rely on satellite-derived data with inherent uncertainties. Fourth, the rapidly evolving nature of solar technology and meteorological modeling means some findings may become outdated. These limitations were addressed through sensitivity analyses and cautious interpretation of synthesized findings.

3. Meteorological Data Infrastructure and Solar Energy Planning in Nigeria

3.1 Current State of Meteorological Data Availability

Nigeria's meteorological data infrastructure presents significant challenges for solar energy planning. According to the Nigerian Meteorological Agency (NIMET), approximately 50 weather stations measure climatic parameters including temperature, sunshine hours, rainfall, atmospheric pressure, and relative humidity, but only about 18 stations measure solar radiation directly, creating substantial gaps in ground-based irradiance data coverage (Oyedepo et al., 2023). This limitation is particularly problematic given Nigeria's diverse climatic zones, which range from warm desert conditions in the far north to tropical savanna and monsoon climates in the central and southern regions (Oyedepo et al., 2023). The northern regions are characterized by high global radiation levels (21–25 MJ/m²/day), low relative humidity (as low as 15%), and constant wind speeds up to 4 m/s, while the southern regions experience high relative humidity (up to 80%), mediocre

radiation values, and moderate wind speeds of approximately 2.9 m/s (Kilanko et al., 2023). The inadequacy of ground-based measurement infrastructure has led researchers and practitioners to rely heavily on satellite-derived data sources, such as the NASA-SSE database. While satellite-based datasets provide comprehensive spatial coverage, they may not fully capture local microclimatic variations that significantly affect PV system performance (Ademola & AlKassem, 2025). This data gap creates uncertainty in project planning and procurement, as developers must make critical decisions based on modeled rather than measured meteorological conditions.

3.2 Seasonal and Climatic Variability

Nigeria experiences two distinct seasons—the rainy (wet) and dry seasons—with varying lengths from north to south (Kilanko et al., 2023). The rainy season, lasting from March to October in the south and June to September in the north, is characterized by high cloud cover, increased atmospheric attenuation, and reduced solar irradiance. The dry season, including the Harmattan period from November to February, features reduced cloud cover and higher irradiance, but also dust-laden air that can significantly reduce PV performance through soiling (Onu & Makinde, 2026). Research has demonstrated significant performance variations across seasons: peak system efficiency occurs during dry months due to higher irradiance, while the Harmattan season demonstrates reduced output caused by dust-laden air, and the rainy season experiences moderate performance under lower irradiance but cooler operating temperatures (Onu & Makinde, 2026). These seasonal interactions have important procurement implications, as system designers must account for the lowest

expected irradiance levels during the rainy season to ensure adequate power generation, requiring oversizing of PV arrays that affects procurement decisions regarding module quantities, inverter sizing, and battery storage capacity.

3.3 Implications for Solar Energy Project Planning

The limitations of existing meteorological data infrastructure have profound implications for solar energy project planning and procurement. Maduabuchi et al. (2023) observe that "there has been no detailed report showing the potential of clean power generation systems due to the dysfunctional meteorological stations in the country." This information gap creates significant barriers to investment, as developers and financiers require reliable data to assess feasibility, optimize design, and quantify financial returns. The lack of comprehensive meteorological data also complicates technology selection, as different PV technologies exhibit varying responses to climatic conditions. Comparative analyses have shown that amorphous silicon (a-Si), monocrystalline silicon (mc-Si), and polycrystalline silicon (pc-Si) PV technologies demonstrate different performance characteristics across Nigeria's climatic zones (Dioha et al., 2018). Furthermore, the absence of long-term, high-quality meteorological data hinders the development of robust performance models and validation of simulation tools, creating a vicious cycle where limited data leads to uncertain planning, which discourages investment, limiting the deployment of systems that could generate the performance data needed to improve planning.

4. Influence of Meteorological Information on Procurement Efficiency

4.1 System Design Optimization

Meteorological information is foundational to the design optimization of solar PV systems. Accurate data on solar irradiance, temperature, wind speed, and other climatic parameters enable determination of appropriate system sizing, component selection, and configuration. The design of a PV system involves determining optimal array size, orientation, tilt angle, inverter capacity, and battery storage requirements, all of which depend on site-specific meteorological conditions. Ademola and AlKassem (2025) demonstrated the critical role of meteorological data in system design through a techno-economic assessment of a 500 kWp grid-connected PV system for Ibadan, Nigeria. Using PVSyst with NASA-SSE data, they determined an optimal array configuration comprising 1,350 crystalline silicon PV modules arranged in 75 strings with 18 modules in series, mounted at a fixed tilt angle of 11° and oriented due south (Ademola & AlKassem, 2025). The authors highlighted the importance of understanding monthly variation in solar irradiation and ambient temperature for system sizing and performance simulations, noting that "these climatic factors directly influence PV system performance, as high irradiation enhances potential energy yield while elevated temperatures contribute to module efficiency losses" (Ademola & AlKassem, 2025). Elenga et al. (2025), optimizing hybrid renewable energy systems for Nigerian residential buildings, similarly emphasized meteorological information importance, finding that "the system's techno-economic performance is strongly affected by environmental factors such as weather conditions." Using HOMER Pro, they found the optimal solution integrated 4 kW PV with

battery storage and grid connection, producing the lowest net present cost of \$8,712 and LCOE of \$0.068/kWh (Elenga et al., 2025).

4.2 Technology Selection

Meteorological conditions significantly influence the performance of different PV technologies, making climate-specific technology selection a critical procurement consideration. Dioha et al. (2018) conducted a comparative performance analysis of pc-Si, mc-Si, and a-Si PV technologies across Nigeria's six geopolitical zones using PVSyst, finding that a-Si and pc-Si PV plants exhibited the highest and lowest energy yield, performance ratio, and capacity utilization factor respectively, while mc-Si plants demonstrated maximum overall system efficiency and annual energy density in all selected cities (Dioha et al., 2018). Oyedepo et al. (2023) conducted an extensive analysis across four climatic zones (warm desert, warm semi-arid, tropical savanna, and monsoon climate), revealing that performance ratio was high in monsoon and tropical savanna climates due to cool-moist air and low temperature, while the least performance ratio was observed in warm desert and warm semi-arid climates due to dusty wind and high temperature (Oyedepo et al., 2023). These climate-specific performance variations have important procurement implications: project developers must select PV technologies optimized for specific meteorological conditions, considering temperature coefficients, spectral response, and soiling susceptibility. The substantial performance differences across technologies and climates—with performance ratios ranging from 0.82 to 0.89—underscore the economic significance of climate-informed technology selection (Oyedepo et al., 2023).

4.3 Financial Modeling and Risk Assessment

Meteorological information is essential for accurate financial modeling and risk assessment in solar energy projects. Economic viability depends on projected energy generation, which depends on site-specific solar resource conditions. Variations in irradiance, temperature, and other meteorological parameters directly affect energy yield and project revenues. Economic evaluation typically employs metrics including LCOE, Net Present Value (NPV), Internal Rate of Return (IRR), and payback period. Oyedepo et al. (2023) found the average LCOE across Nigeria's climatic zones is \$0.21/kWh, lower than the \$0.25/kWh grid tariff. Average NPV and IRR were \$31,164 and 22% respectively, making projects economically feasible, with payback periods ranging from 3.7 to 5.2 years (Oyedepo et al., 2023). However, projection accuracy depends on meteorological data quality: uncertainty in solar resource assessment translates directly into uncertainty in energy yield projections and financial returns. Understanding variability and potential extreme events enables project developers to incorporate appropriate risk mitigation measures. Knowledge of dust storm frequency during Harmattan can inform decisions regarding soiling mitigation strategies.

4.4 Supply Chain and Logistics Planning

Meteorological information also influences procurement through its impact on supply chain and logistics. In Nigeria, where transportation infrastructure is often inadequate, weather conditions significantly affect transportation and installation of PV components. Heavy rainfall during the wet season can render access roads impassable, delaying equipment delivery and installation.

High temperatures and humidity affect storage and handling of sensitive electronic components. Effective procurement planning must account for these weather-related logistics challenges, including scheduling delivery during favorable weather windows, specifying appropriate packaging and storage requirements, and incorporating contingencies for weather-related delays. These considerations are particularly important for large-scale projects requiring transportation of significant equipment quantities over extended periods.

5. Meteorological Conditions and Solar Project Performance

5.1 Solar Irradiance and Energy Yield

Solar irradiance is the most fundamental meteorological parameter affecting PV system performance. Nigeria's solar resource is substantial, with average daily irradiation ranging from 4.5 to 5.5 kWh/m²/day in the south to over 6 kWh/m²/day in the north (Ademola & AlKassem, 2025; Kilanko et al., 2023). Research has established clear relationships between irradiance levels and energy yield. Ademola and AlKassem (2025) projected annual energy yield of 714,188 kWh for a 500 kWp system in Ibadan, with performance ratio ranging from 77% to 78% over the 25-year lifespan. Machine learning approaches have been increasingly applied to forecast solar irradiance in Nigeria. Sigauke (2025) developed a two-stage forecasting approach for Ibadan predicting clear-sky irradiance using weather variables, then forecasting actual irradiance by integrating predicted clear-sky irradiance with weather variables and cloud type. Random Forest models demonstrated the best performance, with nRMSE values of 0.19 for Global

Horizontal Irradiance (Sigauke, 2025). Seasonal variation significantly affects irradiance and energy yield: Sigauke (2025) found dry season forecasts achieved nRMSE values of 0.12 for GHI, while wet season forecasts achieved 0.27, underscoring the importance of accounting for seasonal patterns in project planning and operation.

5.2 Temperature Effects on PV Performance

Temperature is a critical meteorological factor affecting PV system performance. PV module efficiency decreases with increasing temperature, with crystalline silicon modules typically decreasing by 0.35% to 0.5% per degree Celsius above 25°C. Nigeria's tropical climate results in relatively high ambient temperatures throughout the year, ranging from 24°C to 34°C (Ademola & AlKassem, 2025). These elevated temperatures can significantly reduce PV module efficiency and energy yield. Ademola and AlKassem (2025) note that while high irradiation enhances potential energy yield, elevated temperatures contribute to efficiency losses, creating a trade-off that must be carefully balanced. The relationship between temperature and PV performance is particularly important in northern Nigeria, where high temperatures coincide with high irradiance. Oyedepo et al. (2023) found PV performance was relatively low in warm desert and warm semi-arid climates due in part to high temperatures. In contrast, monsoon and tropical savanna climates experience lower temperatures due to cool-moist air, contributing to higher performance ratios despite lower irradiance. Understanding temperature effects is essential for procurement decisions: specifications for PV modules and inverters must account for expected temperature extremes, module temperature coefficients

become important selection criteria particularly in hotter regions, and cooling strategies such as mounting configurations promoting airflow may also be specified.

5.3 Soiling and Atmospheric Attenuation

Soiling accumulation of dust, dirt, and particulates on PV module surfaces—is a significant performance factor in Nigeria, particularly during the Harmattan season. Onu and Makinde (2026) observed reduced voltage and current output "caused by dust-laden air and decreased transmittance," significantly reducing PV system performance during the dry season. Soiling loss magnitude depends on local dust concentrations, precipitation patterns, and module tilt angles. Regions in the path of Saharan dust plumes experience more severe soiling. Oyedepo et al. (2023) note that warm desert and warm semi-arid regions experience "dusty wind from the Sahara desert," contributing to reduced performance ratios. Atmospheric attenuation—reduction of solar radiation due to scattering and absorption by atmospheric constituents—also affects PV performance. High aerosol concentrations during Harmattan increase diffuse radiation and reduce direct normal irradiance, affecting systems optimized for direct radiation. Procurement decisions must account for soiling and atmospheric attenuation: module selection should consider soiling resistance, cleaning strategies must be planned based on expected soiling rates, and performance guarantees should account for site-specific soiling conditions. Soiling losses of 5–15% are common in dust-prone regions, and optimal cleaning frequency depends on soiling rates requiring ongoing monitoring.

5.4 Weather Variability and Grid Integration

Weather variability presents significant challenges for solar project performance and grid integration. PV output varies with irradiance changes caused by cloud cover, atmospheric conditions, and seasonal cycles, affecting power quality, grid stability, and economic value. The weather-aware optimization framework developed by Nnachi and Abiodun (2026) highlights the importance of accounting for weather variability in renewable energy planning. The framework introduces a variability criterion for site selection, identifying optimal locations by evaluating generation variability under major climate oscillations, including the Madden-Julian Oscillation modulated by El Niño-Southern Oscillation (Nnachi & Abiodun, 2026). The research demonstrates that MJO and ENSO significantly affect solar radiation across Africa: El Niño enhances subsidence in MJO phases, while La Niña amplifies convection, affecting solar irradiance and cloud cover over Nigeria on intra-seasonal to interannual timescales. Nnachi and Abiodun (2026) emphasize "the necessity of accurately forecasting these regimes to enhance system resilience and inform long-term planning." Integration of weather variability considerations into procurement is essential for managing grid integration challenges: projects must maintain reliable operation under variable weather conditions, potentially requiring array oversizing or energy storage incorporation, and grid connection agreements must account for solar generation variability, including sudden output drops due to cloud cover.

6. Enhancing Meteorological Data Utilization for Solar Energy Procurement

6.1 Weather-Aware Optimization Frameworks

Development and adoption of weather-aware optimization frameworks represent a significant opportunity for improving solar energy procurement and project performance in Nigeria. The framework by Nnachi and Abiodun (2026) provides a model for integrating meteorological variability into renewable energy planning, identifying optimal locations by considering both resource potential and generation variability using 45 years of climatological data. The framework's novelty lies in explicit consideration of weather regimes—"large-scale recurring patterns in the atmospheric circulation, which can persist for periods from days to weeks" (Nnachi & Abiodun, 2026). By linking generation variability to underlying climate drivers, the framework offers a robust pathway for optimizing renewable energy expansion while enhancing system resilience. The framework also supports climate services in procurement decision-making: by incorporating meteorological forecasts and climate projections, developers can make more informed decisions regarding system design, technology selection, and risk mitigation. This is particularly important for long-term planning where climate change impacts on solar resource availability must be considered.

6.2 Machine Learning and Forecasting Approaches

Advanced machine learning approaches offer significant potential for improving meteorological data quality and utilization in Nigeria, complementing existing ground-based and satellite-derived datasets with higher-resolution predictions. Maduabuchi et al. (2023) developed a machine learning-inspired forecasting approach using 19 years of NASA data, building diverse regressive neural

networks to predict daily air temperature, relative humidity, atmospheric pressure, wind speed, and rainfall. Their model achieved low mean-squared error of 7×10^{-3} and high regression correlations of 96% during training, demonstrating feasibility of using machine learning to fill data gaps (Maduabuchi et al., 2023). Sigauke (2025) advanced this approach with a two-stage forecasting methodology for Ibadan predicting solar power output using meteorological variables and system specifications. The approach effectively captures cloud influence, the primary cause of irradiance variability. Machine learning applications provide procurement benefits: more accurate resource assessment in locations without ground-based measurements; improved energy yield forecasting reducing financial uncertainty; and season-specific performance predictions supporting optimized procurement decisions.

6.3 Typical Meteorological Year (TMY) Development

Development of Typical Meteorological Year (TMY) datasets represents another important approach for enhancing meteorological data utilization. TMY datasets provide representative annual meteorological profiles for system simulation, performance prediction, and financial modeling. Kilanko et al. (2023) generated TMY data for six locations representing Nigeria's geopolitical zones using the Sandia method. Analysis revealed seasonal variations in all locations, with the North desirable for solar-thermal systems due to high radiation (21–25 MJ/m²/day). The study also found high monthly temperature variations (~18°C), low relative humidity (15%), and constant wind speeds (4 m/s) in the first three months aid wind energy installation and

evaporative cooling application. Region-specific TMY datasets support procurement by providing standardized meteorological profiles enabling consistent comparison of potential project sites and technologies, while reducing uncertainty associated with incomplete or non-representative data. TMY datasets are particularly valuable for financial modeling and performance guarantee agreements.

6.4 Hybrid Simulation Frameworks

Hybrid simulation frameworks integrating technical and economic modeling with meteorological data provide comprehensive procurement support. Ademola and AlKassem (2025) developed a hybrid framework using PVSyst for technical performance analysis and HOMER Pro for economic optimization, with PVSyst outputs integrated as HOMER inputs. This hybrid approach provides advantages: integrated assessment of technical and economic performance supporting decisions balancing energy yield with cost; sensitivity analysis to understand how meteorological changes affect economics; and comprehensive platform for comparing system configurations, technologies, and procurement strategies. The framework also supports performance validation and benchmarking: by comparing simulation results with actual system performance, developers can refine modeling assumptions and improve prediction accuracy. This is particularly important in Nigeria where limited performance data creates uncertainty for new projects.

6.5 Policy and Institutional Recommendations

Effective integration of meteorological information into solar energy procurement requires supportive policy and institutional frameworks:

- i. **Strengthening Meteorological Infrastructure:** Establishment of additional ground-based solar radiation measurement stations across Nigeria's climatic zones should be a priority, with maintenance and calibration of existing stations essential. A target of at least one dedicated solar radiation monitoring station in each of six geopolitical zones would provide comprehensive coverage.
- ii. **Promoting Open Data Access:** Meteorological data should be made freely available to project developers and researchers. Publicly accessible databases and TMY datasets would reduce project development cost and uncertainty. Data sharing agreements between NIMET, research institutions, and private sector should be established.
- iii. **Developing Local Capacity:** Training programs in meteorological data analysis, system simulation, and solar project planning would enhance local capacity. University curricula should incorporate meteorological data analysis and solar resource assessment into engineering and energy programs.
- iv. **Integrating Climate Risk Assessment:** Procurement frameworks should incorporate climate risk assessment requirements ensuring projects withstand expected variability and long-term climate change impacts, including potential changes in solar resource availability, temperature extremes, and precipitation patterns.
- v. **Supporting Research and Innovation:** Funding for research on meteorological data collection, analysis, and application in solar energy should be enhanced, including support for machine learning approaches, forecasting methodologies, and climate modeling specific to Nigeria's conditions.
- vi. **Establishing Performance Standards:** Development of performance standards and guidelines for meteorological data collection, analysis, and application in solar energy would support consistent and reliable procurement practices.
- vii. **Creating a Solar Resource Atlas:** Development of a comprehensive Solar Resource Atlas for Nigeria would provide a central reference for project developers and policymakers, including spatial maps of solar radiation, temperature, and TMY datasets.

7. Conclusion

Meteorological variability across Nigeria's diverse climatic zones significantly affects PV system performance. Performance ratios range from 0.82 to 0.89 across climate zones, with highest performance in monsoon and tropical savanna climates and lowest in warm desert and warm semi-arid climates. Seasonal variability introduces additional performance variation that must be accounted for in system design and operation. Integration of meteorological information into procurement decision-making can substantially enhance project economics: optimized system design based on accurate meteorological data can achieve LCOE values of \$0.068/kWh to \$0.079/kWh, well below Nigeria's grid tariff. Appropriate technology selection further enhances performance, with different silicon-based PV technologies showing distinct advantages across climatic zones. Advanced

approaches including weather-aware optimization frameworks, machine learning forecasting, TMY development, and hybrid simulation offer significant potential for improving meteorological data utilization. These approaches can fill data gaps, improve prediction accuracy, and support integrated technical and economic assessment. The study recommends strengthening meteorological infrastructure, promoting open data access, developing local capacity, integrating climate risk assessment into procurement frameworks, supporting research and innovation, establishing performance standards, and creating a comprehensive Solar Resource Atlas for Nigeria. Implementation of these recommendations would significantly enhance the integration of meteorological information into solar energy procurement, accelerating Nigeria's transition to sustainable energy.

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