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Understanding Climate Variability in Northeastern Nigeria for Effective Photovoltaic Planning

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Abstract

Information on spatial and temporal variation in climatic pattern is of prime importance for understanding the climate dynamics and prerequisite for preparation of strategies for photovoltaic system effective performance and efficiency. And for potential future planning as Nigeria is adopting PV. In this study, variability trend of four climate variables solar irradiance, temperature, wind speed and relative humidity from six states of the Northeastern Nigeria (Adamawa, Bauchi, Borno, Gombe, Taraba and Yobe) were analyzed using simple linear regression model from 1983 to 2022. The data were collected from the archive of Nigerian Meteorological Agency (NIMET). The study found that the climate is undergoing significant changes, characterized by generally rising temperatures with approximate annual increase 0.046^{O}C in Adamawa, 0.028 ^{O}C in Borno and 0.061 ^{O}C in Taraba, declining solar irradiance in the wetter climate states with trend line equation Y=-0.0217X in Taraba and rising solar irradiance in the drier climate states (Borno and Yobe) with trend line equation Y=0.02226X in Yobe, decreasing wind speeds in Borno, Gombe and Yobe, while stable wind speed in the remaining states. And reducing humidity generally except in Borno and Yobe where rising humidity observed. These trends were not uniform but exhibit a strong spatial signature across the six states, necessitating a localized rather than a one-size-fits-all approach to renewable energy policy and project development.

Key words: Climate Variability, Solar Irradiance, Temperature, Wind Speed, Relative Humidity.

Introduction

Nigeria's increasing demand for reliable energy solutions has led to a growing interest in solar photovoltaic (PV) systems. The northeastern region of Nigeria possesses significant renewable energy potential, particularly in solar resources. Studies indicate that the region could generate up to 367,702.10 MW of electricity using photovoltaic solar technology (Richard Balthi, 2021). Solar energy offers a promising alternative to the unreliable national grid, providing a clean and abundant power source, especially in areas with limited grid access (K. Bello et al., 2024). The region's solar potential is further validated by research using RETScreen Expert software, which demonstrates the techno-economic and environmental sustainability of grid-connected solar PV systems in the area (A. B. Owolabi et al., 2019). Additionally, other renewable sources such as wind, hydroelectric, and biomass show potential in various states across the region (Ahmadu Alhassan et al., 2023). To fully capitalize on these resources, supportive policies, infrastructure investments, and public awareness campaigns are necessary to attract investors and promote widespread adoption of renewable energy technologies (K. Bello et al., 2024).

Despite this potential, PV systems are heavily influenced by climate variability, which can impact their performance and efficiency. Understanding the variability of climate variables such as solar irradiance, temperature, relative humidity, and wind speed is crucial for effective PV planning and operation. Photovoltaic (PV) systems are significantly influenced by climate variability, impacting their performance and efficiency. High temperatures, humidity, dust accumulation, and coastal proximity can reduce PV system efficiency in tropical climates (Tofa Haruna et al., 2024). Weather conditions, particularly solar irradiance and temperature fluctuations, affect power output and conversion efficiency (T. Atyia & Mohib A. Qasim, 2023). Climate change is expected to have long-term impacts on PV system reliability, with effects varying over time due to aging (Altamimi & Jayaweera, 2021). Factors such as thermal stress, degradation, and internal faults contribute to climate-associated failures in PV systems (Altamimi & Jayaweera, 2021). Studies incorporating probabilistic climate change projections suggest that PV systems are increasingly vulnerable to climatic conditions in the long run, potentially affecting power grid reliability (Altamimi et al., 2017). These findings highlight the need for proactive design and maintenance strategies to mitigate climate change impacts on PV systems (Altamimi & Jayaweera, 2021).

Climate variability significantly impacts photovoltaic (PV) system performance and reliability. PV power generation is vulnerable to changes in temperature, irradiance, and shading, which affect operating voltages and power outputs (Altamimi et al., 2017). Long-term reliability assessments considering climate change effects on hierarchical levels of PV systems show decreased performance over time, with inconsistent impacts when aging is considered (Altamimi & Jayaweera, 2021). However, a European study suggests that climate change is unlikely to severely threaten the PV sector, with projected

alterations in PV supply ranging from -14% to +2% by the end of the century (Jerez et al., 2015). Climate-based degradation rates significantly influence PV inverter reliability, with estimated lifetimes varying across different climate zones. Considering these degradation rates in reliability assessments is crucial for predicting device failures and ensuring PV inverter longevity, especially in areas with high solar irradiation and extreme temperatures (Alavi et al., 2024).

In Northeastern Nigeria, where climate conditions are characterized by high temperatures and variable rainfall patterns, altering incoming solar irradiance through increase cloud cover, understanding these dynamics is essential for optimizing PV system design and performance. Yet there is a lack of comprehensive studies examining these patterns in the region. This study aims to bridge this knowledge gap by analyzing the variability of key climate variables, including solar irradiance, temperature, relative humidity, and wind speed. This article aims to analyze the variability of key climate elements affecting PV systems in Northeastern Nigeria. By examining the patterns and trends of solar irradiance, temperature, relative humidity and wind speed.

STUDY AREA

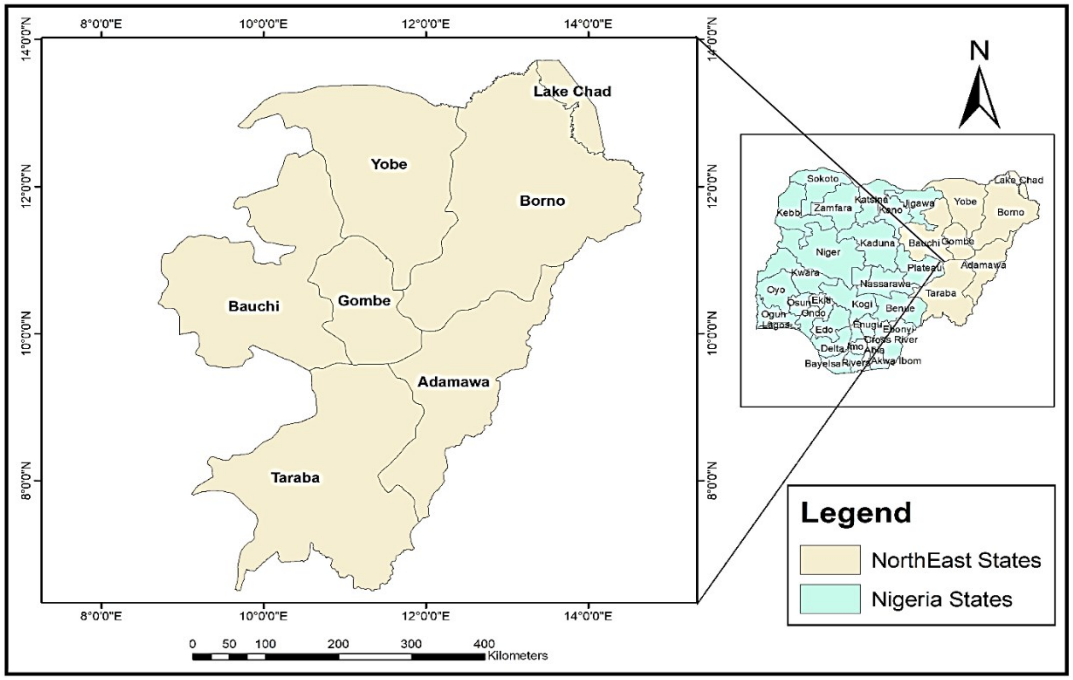


Figure 1: The Study Area.

The North-Eastern Nigeria, often hyphenated to the North-East, is one of the six geopolitical zones of Nigeria, representing both a geographic and political region of the country's northeast. It comprises of six states: Adamawa, Bauchi, Borno, Gombe, Taraba, and Yobe. The region is located approximately between **Latitude** 7°30′00″N and 14°00′00″N and

Longitude 9°30′00″E and 15°00′00″E. The region is geographically diverse, with a range of landscapes from the Sahel savannah in the far north to the tropical rainforests in the south, and several large rivers flowing through it, including the Benue, Gongola, and Yobe Rivers. It is bordered by several states and countries. To the west, it is bordered by the North-West region of Nigeria. To the south, it is bordered by the North-Central region and the East region of Nigeria. Internationally, North-Eastern Nigeria shares land borders with Niger Republic to the north, Chad Republic to the northeast, and the Republic of Cameroon to the east.

The region is characterized by its Sudan-Sahelian climate, has historically experienced distinct wet and dry seasons. The wet season, typically spanning May to September, brought annual rainfall ranging from 600 to 1000 mm, while the dry season, from October to April, was marked by arid conditions and the prevalence of the Harmattan winds (Oladipo, 2021). Temperatures in the region averaged between 26°C and 28°C, with relatively stable seasonal patterns that supported traditional agricultural practices and livestock rearing. In recent decades, however, the region has witnessed significant climatic changes. Rainfall patterns have become increasingly erratic, with annual precipitation declining to 400-800 mm in some areas (Mohammed et al., 2023). This reduction in rainfall has been accompanied by prolonged dry spells and more frequent extreme weather events, such as intense rainfall episodes and heatwaves. Additionally, average temperatures have risen by approximately 0.8°C since the 1960s, exacerbating the challenges faced by the region's predominantly agrarian communities (Abubakar and Ibrahim, 2024). Looking ahead, climate models project further changes in the region's climate. By 2050, temperatures are expected to rise by 1.5°C to 2.5°C, with a 20-30% reduction in annual rainfall. These changes are likely to result in shorter growing seasons, increased frequency of extreme weather events, and heightened vulnerability to climate-related disasters (Hassan et al., 2023).

The impacts of these climatic changes on Northeastern Nigeria are profound, particularly in the areas of agriculture, economy, and infrastructure. Agriculture, the backbone of the region's economy, has been severely affected by declining rainfall and rising temperatures. Crop yields have decreased by 30-40%, and traditional farming calendars have been disrupted, leading to increased crop failures and reduced livestock productivity (Yakubu, 2024). These challenges have, in turn, contributed to food insecurity and rising food prices, further straining the region's economy. Economically, the decline in agricultural productivity has led to a 25% reduction in the sector's contribution to the region's GDP (World Bank, 2023). Many farming communities have been forced to migrate in search of better opportunities, leading to demographic shifts and increased pressure on urban centers. The rising cost of agricultural insurance and the need for climate-resilient farming practices have further burdened the region's already fragile economy. Infrastructure in Northeastern Nigeria has also been significantly impacted by climate change. Extreme rainfall events have damaged roads, bridges, and urban drainage systems, while prolonged dry spells have stressed water infrastructure. The need for climate-resilient construction and increased maintenance costs has placed additional strain on the region's limited resources (Ibrahim et al., 2024).

The vegetation in North-East Nigeria is primarily characterized by the Sahel savanna and the Sudan savanna (Abaje et al., 2020). The Sahel savanna, found in the northern parts of the region, is a semi-arid transitional zone between the Sahara Desert and the more fertile southern regions (Buba et al., 2023). This area features sparse vegetation, dominated by drought-resistant grasses, shrubs, and scattered trees (Ojoye et al., 2021). In contrast, the Sudan savanna, located further south, consists of tropical grasslands with denser vegetation, including taller grasses and a wider variety of trees and shrubs (Akinsanola et al., 2022). These vegetation zones are dynamic and have been shifting due to climate change and human activities, such as deforestation and overgrazing (Odjugo, 2021). Notably, desertification remains a critical environmental challenge, with the Sahara Desert expanding southward into the Sahel (Buba et al., 2023). The aridity gradient in the region varies significantly, with the northern Sahelian areas experiencing higher aridity, prolonged dry seasons, and minimal rainfall (Abaje et al., 2020). This creates semi-desert conditions with limited vegetation cover. In contrast, the southern Sudan savanna receives more rainfall and has a shorter dry season, supporting denser and more diverse plant species (Akinsanola et al., 2022).

The region contains several ecologically and economically significant wetland regions. The Hadejia-Nguru wetlands, located in Yobe State, form a vast floodplain in the Sudano-Sahelian zone, a transitional belt between the Sudanian Savanna (south) and the Sahel (north) (Mohammed et al., 2023). These wetlands, including Nguru Lake, support biodiversity, agriculture, and fisheries but face threats from declining rainfall, population pressure, and upstream dam construction (Dami et al., 2021). The most critical wetland in the region is Lake Chad, a freshwater lake shared by Nigeria, Niger, Chad, and Cameroon. Historically, Lake Chad covered 28,000 km² in the 19th century, but climate change and excessive water extraction have reduced it to less than 10% of its 1960s size (UNEP, 2022). The lake's basin spans 1 million km², fed mainly by the Chari River (south) and the seasonal Komadugu-Yobe River (northwest) (Okonkwo et al., 2020). As a lifeline for over 30 million people, its drastic shrinkage has triggered food insecurity, migration, and conflicts (Bila & Ajibola, 2023).

Material and Method

The observed climate data for this study were sourced from the Nigerian Meteorological Agency (NiMet) archive. For model-based climate projections, the study used Simple Linear Regression Model to project the required data. Additionally, survey data collected through questionnaires were utilized to achieve the second objective of the study. The data used was annual Solar Irradiance, Temperature, Wind speed and Relative Humidity data of 40 years spanning from 1983 to 2022.

Method of Data Analysis

The study employed a Linear Regression Analysis Model to analyzed the trends and pattern of Solar Irradiance, Temperature, Wind Speed and Relative Humidity between 1983 and 2022 for each station in the study area. Below is the detailed of the method

To analyze the relationship between the independent variable (time) and dependent variable (climate variable), a linear trendline was fitted to the dataset using Microsoft Excel's regression tool. The trendline generates a simple linear regression (SLR) model of the form:

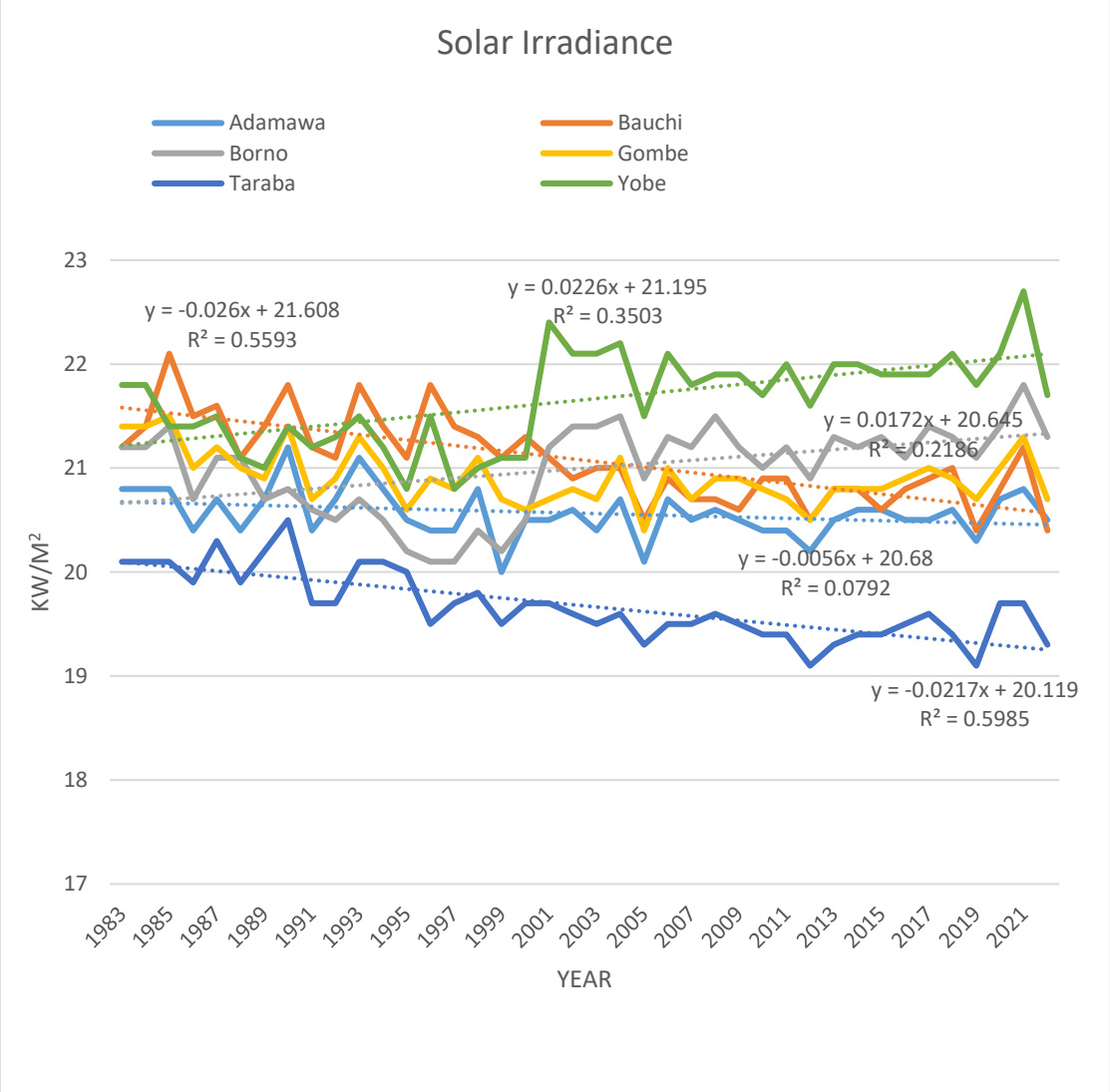
$$Y = \beta + \beta x + \varepsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where:

Y = Dependent variable (predicted outcome), β= Y-intercept (constant term), β1 = Slope coefficient (rate of change in Y per unit change in X), X= Independent variable (predictor), ε = Residual error (difference between observed and predicted Y).

Results

Solar Irradiance



Source: Research Analysis 2025

Figure 2: Solar Irradiance Variability pattern over Northeastern States

The solar radiation trends in Adamawa State from 1983 to 2022 reveals critical insights into the variability and long-term patterns of solar energy potential in this region as shown in figure 2 above, Adamawa is represented in blue line. The trendline equation, Y=−0.056X+20.68, indicates a slight declining trend of 0.056KW/M2/year over the four-decade period, with an R-square value of 0.0792. This low R-square value suggests that only 7.92% of the variability in solar radiation is explained by the linear trend. The maximum insolation was recorded in 1990 at 21.2 kWh/m²/day, while the minimum value occurred in 1999 at 20.0 kWh/m²/day. Similarly, the solar radiation trends in Bauchi from 1983 to 2022 presents a nuanced understanding of solar energy dynamics. Bauchi is represented in Red line on figure 2. The trendline equation, Y = -0.026X + 21.608, reveals a gradual decline of 2% annually in solar radiation over the four-decade period, with a relatively strong R-square value of 0.5593. This indicates that approximately 56% of the variability in solar radiation can be explained by the linear trend, suggesting a more consistent pattern compared to other states in the region. The maximum insolation was recorded in 1985 at 22.1 kWh/m²/day, while the minimum occurred in 2019 at 20.4 kWh/m²/day. The declining trend is more pronounced in Bauchi than in Adamawa but shows less interannual variability than Yobe.

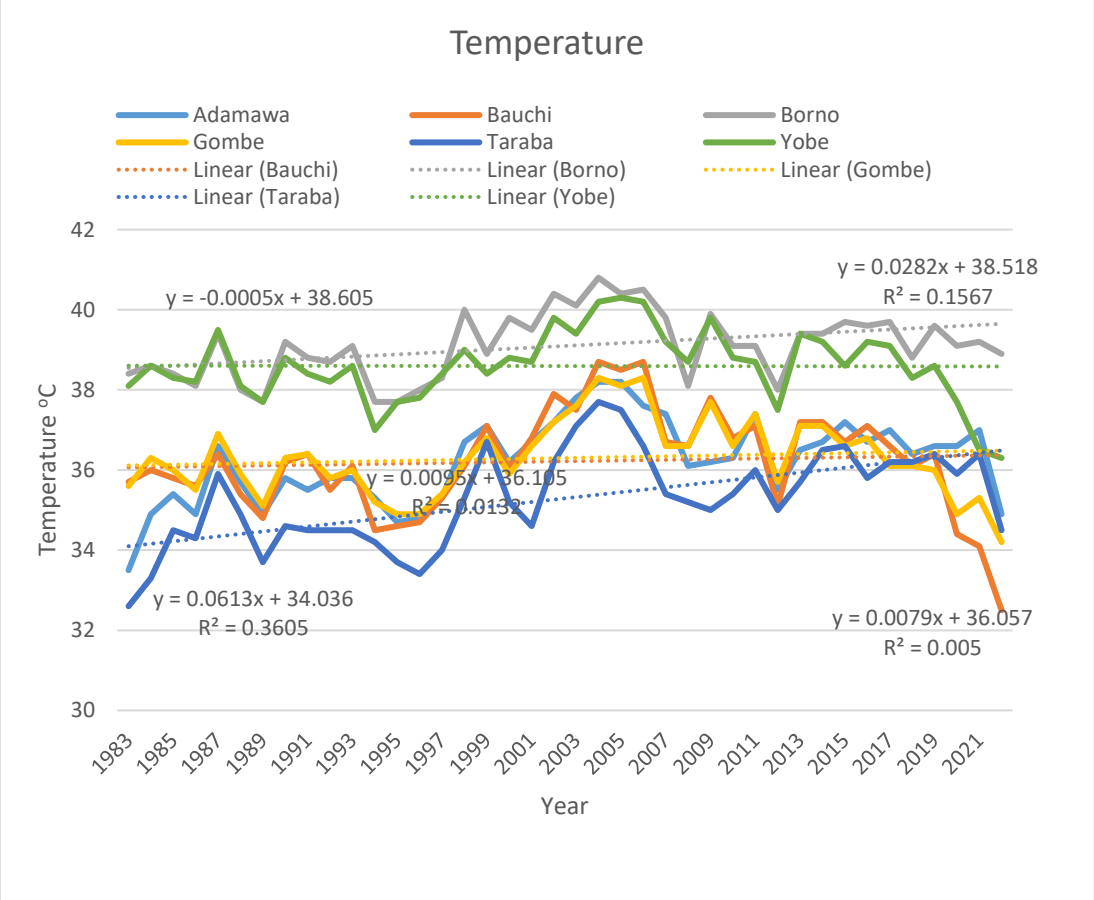
Figure 2, ash color line displayed the solar variability Borno. The solar radiation trends in Borno State from 1983 to 2022 presents a complex picture of solar energy dynamics in Nigeria's extreme northeastern region. The trendline equation, Y = 0.0172X + 20.645, indicates a slight upward trend of 1.7% in solar radiation over the study period, though with a relatively weak R-square value of 0.2186. This suggests that only about 22% of the variability in solar radiation is explained by the linear trend, pointing to significant influence from other climatic and environmental factors. The maximum insolation was recorded in 2021 at 21.8 kWh/m²/day, while minimum values occurred in 1995 with 20.2 kWh/m²/day and 1996 with 20.1 kWh/m²/day. The modest positive trend in solar radiation in Borno contrasts with the declines observed in Adamawa and Bauchi, but aligns somewhat with upward trajectory in Yobe.

The pattern of solar radiation in Gombe from 1983 to 2022 reveals a complex interplay of climatic factors influencing solar energy potential in this region. The solar irradiance pattern is shown in a yellow line on figure 2. The trend line equation, Y = -0.0094X + 21.105, indicates a very gradual decline of 0.9% annually in solar radiation over the four-decade period, though with a notably weak R-square value of 0.1791. The maximum insolation was recorded in 1985 at 21.5 kWh/m²/day, while the minimum occurred in 2005 at 20.4 kWh/m²/day, demonstrating a relatively narrow range of variation compared to some neighboring states. The pattern of solar radiation in Taraba reveals a distinct climatic profile that differs notably from other states in the northeastern region. Presented by a purple line on figure 2, the trend line equation, Y = -0.0217X + 20.119, demonstrates a clear declining trend of 2% yearly in solar radiation over the study period, with a relatively strong R-square value of 0.5958, this indicates that nearly 60% of the variability in solar radiation can be explained by the linear trend. This suggest a more consistent pattern of decline compared to neighboring states. The maximum insolation

was recorded in 1990 at 20.5 kWh/m²/day, while the minimum occurred in 2019 at 19.1 kWh/m²/day, representing a significant 1.4 kWh/m²/day difference between the two extremes. Taraba's solar radiation patterns show both similarities and contrasts with Adamawa trends. While both states exhibit declining solar radiation, Taraba's trend is more pronounced and better defined statistically, as evidenced by the higher R-square value.

The analysis of solar radiation trends in Yobe State from 1983 to 2022 reveals distinct patterns that contribute to our understanding of solar energy potential in northeastern region as revealed by figure 2 represented by a green line. The trendline equation, Y=0.0226X+21.195, indicates a gradual increase of 2% annually in solar radiation over the study period, with an R-square value of 0.3503. This moderate R-square value suggests that approximately 35% of the variability in solar radiation can be explained by the linear trend, highlighting the influence of both long-term climatic shifts and short-term atmospheric conditions. The maximum insolation was recorded in 2021 at 22.7 kWh/m²/day, while the minimum values occurred in 1995 and 1997 at 20.8 kWh/m²/day.

Temperature



Source: Research Analysis 2025

Figure 3: Temperature Variability Pattern over Northeastern States

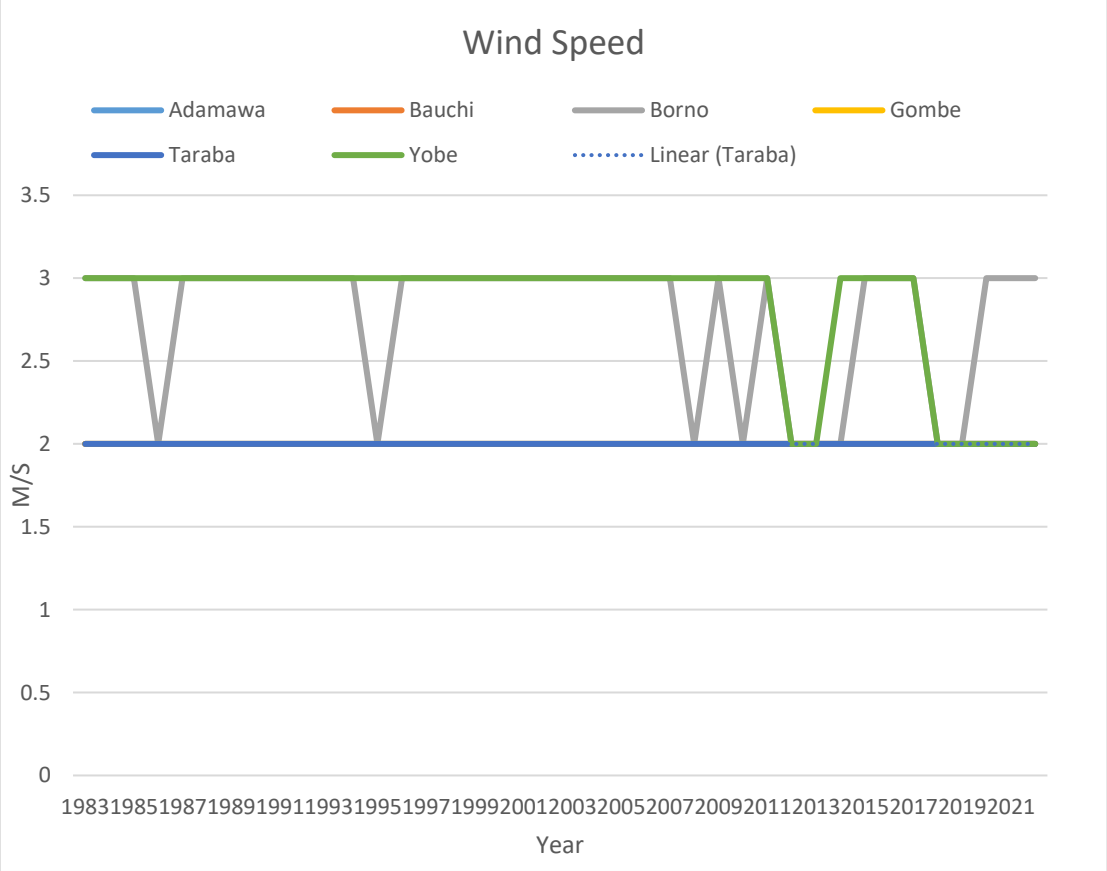
The temperature trends in Adamawa from 1983 to 2022 reveals important climatic patterns that align with broader regional observations while demonstrating unique local characteristics as shown in figure 3 represented by a blue line. The trendline equation, $Y = 0.0463X + 35.278$, indicates a gradual warming trend of 4% annually over the four-decade period, with temperatures increasing by approximately 0.046°C per year. However, the low R-square value of 0.02639 suggests that only about 2.6% of the temperature variability is explained by this linear trend, pointing to significant interannual fluctuations and the influence of other climatic factors. The maximum temperatures were recorded in 2004 and 2005 (38.2°C), while the minimum occurred in 1983 (33.5°C), representing a considerable 4.7°C range between extreme years. The extreme temperatures recorded in 2004-2005 coincide with documented periods of intense heat across West Africa, as noted in the IPCC's (2014) assessment of regional climate patterns. Figure 3 red line revealed the analysis of temperature trends in Bauchi State from 1983 to 2022 with a complex climatic pattern that warrants careful interpretation. The trendline equation, $Y = 0.00079X + 36.057$, indicates an extremely gradual warming trend of approximately 0.00079°C per year, which is substantially lower than the regional average reported in previous studies. The exceptionally low R-square value of 0.005 suggests that less than 1% of the temperature variability can be explained by this linear trend, pointing to remarkable stability in Bauchi's temperature regime compared to other northeastern states. The maximum temperatures were recorded consecutively in 2004, 2005, and 2006 (38.7°C), while the minimum occurred most recently in 2022 (35.5°C), demonstrating a 3.2°C range between extreme values.

The analysis of temperature trends in Borno State from 1983 to 2022 reveals a gradual but statistically significant increasing trend, as evidenced by the trendline equation $Y = 0.0282X + 38.518$ shown on figure 3 represented by an ash color line. While the R^2 value of 0.1567 indicates that only about 15.67% of the temperature variation is explained by this linear trend, the positive slope confirms an overall warming pattern over the 40-year period. The highest temperature was recorded in 2004 at 40.8°C, while the lowest temperatures occurred in 1989, 1994, and 1995 at 37.7°C, demonstrating both the long-term warming trend and considerable interannual variability. The findings show a comparable warming rate in Borno of approximately 0.028°C per year (or 0.28°C per decade), reinforcing the evidence of sustained climate change in the region. The relatively low R^2 value in this study suggests that while the overall trend is upward, other factors contribute significantly to temperature variability in Borno State. Temperature trends in Gombe from 1983 to 2022 shown on figure 3 represented by a yellow line reveals a climatic pattern that reflects both regional warming influences and local moderating factors. The trendline equation, $Y = 0.0095X + 36.105$, indicates a gradual warming trend of approximately 0.0095°C per year, equivalent to 0.095°C per decade. This warming rate is slightly lower than the 0.07°C per decade reported for Maiduguri in Hassan et al.'s (2017) study of northeastern Nigeria from 1949-2014. The R-square value of 0.0132 suggests that only about 1.3% of the temperature variability is explained by the linear trend, indicating substantial interannual fluctuations around the overall warming pattern. The

maximum temperatures were consistently recorded in 2004, 2005, and 2006 (38.3°C), while the minimum occurred most recently in 2022 (34.2°C), demonstrating a 4.1°C range between extreme values.

Temperature trends in Taraba from 1983 to 2022 reveals a statistically significant increasing trend, as evidenced by the trendline equation Y=0.0613X+34.036 and an R^2 value of 0.3605. This is shown in figure 3 indicated by purple line. This indicates a moderate positive correlation, suggesting that temperatures in Taraba have risen at an average rate of approximately 0.0613°C per year over the study period. The highest temperature was recorded in 2004 at 37.7°C, while the lowest occurred in 1983 at 32.6°C, demonstrating a clear upward trajectory in mean annual temperatures. Green line on figure 3 shows that the temperature trends in Yobe State from 1983 to 2022 reveals a slight decreasing trend, as indicated by the trendline equation Y=−0.0005X+38.605. This suggests a marginal decline in temperature over the 40 year period, although the trend is minimal. The highest temperatures were recorded in 2004, 2005, and 2006, reaching 40.3°C, while the lowest temperature occurred in 2022 at 36.3°C.

Wind Speed



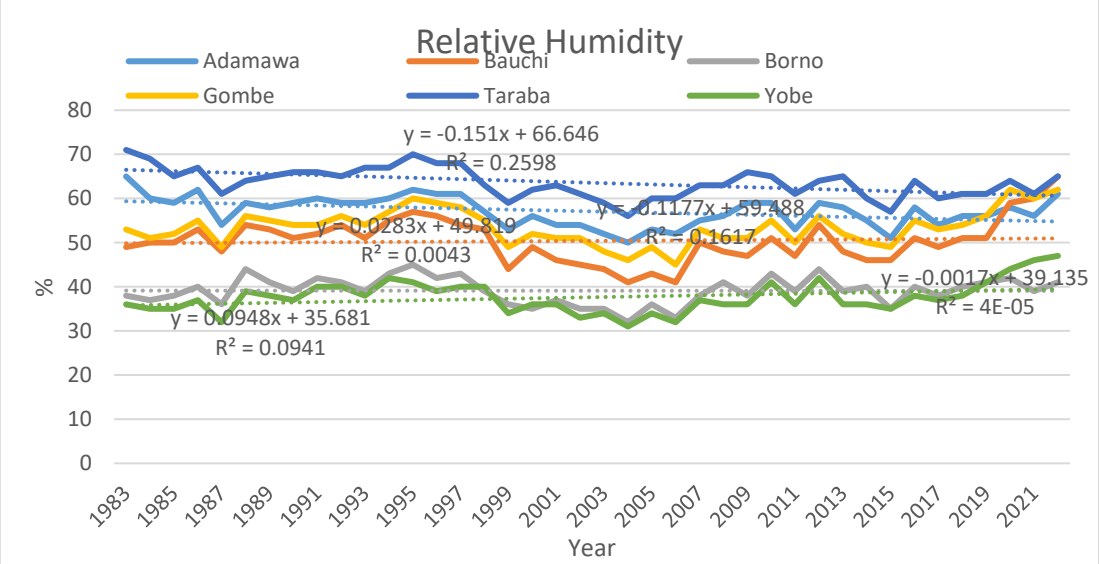
Source: Research Analysis 2025

Figure 4: Wind Speed Variability pattern over Northeastern States

Figure 4 displays the wind speed trends across the region. Adamawa shown in blue, Bauchi shown in red, Borno shown in ash color, Gombe shown in yellow, Taraba shown in purple, and Yobe displayed in green, from 1983 to 2022 reveals distinct spatial and temporal variations, consistent with the broader climatic patterns observed in northeastern Nigeria. The trendline equations and R^2 values indicate varying degrees of wind speed changes across the states, with Borno, Gombe, and Yobe exhibiting more pronounced trends compared to Adamawa, Bauchi, and Taraba. In Borno, the trendline equation $Y=-0.0098X+2.9769$ and R^2 value of 0.0741 suggest a slight decreasing trend in wind speed over the study period. The maximum wind speed of 3 m/s and minimum of 2 m/s. The low R^2 value indicates that other factors, such as interannual climatic variability and local topography, may also influence wind speed trends in Borno. Gombe, the trendline equation $Y=-0.0102X+2.7846$ and R^2 value of 0.057 similarly indicate a marginal decline in wind speed. The maximum and minimum wind speeds of 3 and 2 m/s, respectively. The low R^2 value suggests that Gombe's wind speed trends are less linear, possibly due to localized environmental changes, such as afforestation efforts or urban development. Yobe's trendline equation $Y=-0.0202X+3.2385$ and R^2 value of 0.3754 reveal a more significant decreasing trend compared to Borno and Gombe. The maximum wind speed of 3 m/s and minimum of 2 m/s.

In contrast, Adamawa, Bauchi, and Taraba states exhibited stable wind speeds, with trendline equations $Y=2$ and no significant variability. The spatial interpolation of wind speed trends across the study area reveals a north-south gradient, with higher wind speeds in the northern states (Borno, Gombe, Yobe) and lower speeds in the southern states (Adamawa, Bauchi, Taraba).

Relative Humidity



Source: Research Analysis 2025

Figure 5: Relative Humidity Variability Pattern

The trends of relative humidity (RH) across the region from 1983 to 2022 reveals significant spatial and temporal variations. The trendline equations and R^2 values indicate diverse RH behaviors across the states, with some showing increasing trends while others exhibit declines. Blue line on figure 5 shows that, in Adamawa, the trendline equation $Y=-0.1177X+59.488$ and R^2 value of 0.1617 suggest a gradual decline in RH over the study period. This decrease contrasts with the higher RH values recorded in the early years (e.g., 65% in 1983) compared to the lower values in recent years (e.g., 50% in 2004). The low R^2 value indicates considerable interannual variability. Bauchi displayed a slight increasing trend as shown in figure 5 with red line, $Y=0.0283X+49.819$, though the R^2 value of 0.0043 means minimal explanatory power, reflecting high variability. The maximum RH of 65% in 2022 and the minimum of 41% in 2004 and 2006 highlight the erratic nature of humidity in this region. On the Figure 5 indicated by ash color line displayed the RH pattern in Borno, the trend line $Y=0.0282X+38.518$ indicates a marginal increase in RH. The R^2 value of 0.1567 suggests modest predictability, while the recorded extremes (45% in 1995 and 32% in 2004). The yellow line on figure 5 revealed a positive trend in Gombe as $Y=0.0392X+52.646$. The R^2 value of 0.013 indicates high variability, with extremes ranging from 62% in 2022 to 45% in 2006. The Taraba relative humidity trend as shown in figure 5 presented in purple line displayed the most pronounced decline $Y=-0.151X+66.646$, $R^2 = 0.2598$, with RH dropping from 71% in 1983 to 56% in 2004. The stronger R^2 value suggests a more systematic decline. While the trend of relative humidity in Yobe revealed an increasing trend $Y=0.0948X+35.681$, $R^2 = 0.0941$ contrasts with its reputation as a dry region, with RH rising from 31% in 2004 to 47% in 2022. This could reflect localized irrigation or the expansion of water bodies, though the low R^2 value indicates significant variability. The findings echo Dammo et al. (2016), who noted Yobe's RH as the second-lowest after Borno, emphasizing the region's vulnerability to aridification.

Discussion

The findings of this study reveal a complex and spatially heterogeneous pattern of climate variability across Northeastern Nigeria from 1983 to 2022. These trends have profound and direct implications for the planning, deployment, and long-term viability of solar photovoltaic (PV) systems in the region. While the overarching narrative of global climate change often suggests uniform warming, our state-level analysis uncovers critical nuances that must inform regional energy policy and technology selection.

The most significant finding for solar energy potential is the divergent trend in solar irradiance. The observed decline in Adamawa, Bauchi, Gombe, and Taraba states, particularly the statistically strong decrease in Taraba ($R^2 = 0.5958$), is concerning. This suggests a potential long-term reduction in the solar resource itself, possibly linked to increasing aerosol loading, dust pollution, or changing cloud cover patterns associated with the regional climatic shifts described in the study area. Conversely, the increasing irradiance in Borno and Yobe aligns with descriptions of intensified desertification and reduced cloudiness in the Sahelian zones

(Buba et al., 2023). While this appears positive for energy generation, it is likely a symptom of broader environmental degradation. Furthermore, higher insolation couples with rising temperatures to create a challenging environment for PV modules, whose efficiency declines with increased heat.

The pervasive warming trend across most states, most notably in Taraba (0.0613°C/year) and Adamawa (0.0463°C/year), directly threatens the technical performance of PV infrastructure. The core efficiency of silicon-based solar panels decreases by approximately 0.3% to 0.5% per degree Celsius rise in temperature above standard test conditions (Atyia & Qasim, 2023). The warming reported here, therefore, translates to a projected long-term degradation of power output, independent of panel aging. This thermal stress also accelerates the physical degradation of components, potentially leading to more frequent failures of modules, inverters, and connections, as noted in the review by Altamimi and Jayaweera (2021). The anomalous slight cooling in Yobe requires further investigation but may be related to localized meteorological phenomena or data artifacts.

The trends in wind speed and relative humidity present a dual challenge. The documented decrease in wind speed, especially in the northern states of Yobe, Borno, and Gombe, reduces the natural convective cooling of PV modules. This lack of airflow exacerbates the heat-induced losses in efficiency, creating a compound effect alongside the rising temperatures. Furthermore, the general decline in relative humidity, most severe in Taraba, has a significant operational implication: it increases the potential for dust accumulation (soiling). Low humidity allows dust particles to remain dry and loosely adhered to panel surfaces, drastically reducing the amount of light that reaches the cells. This effect is a dominant factor in PV yield loss in arid and semi-arid regions, as confirmed by Tofa Haruna et al. (2024). The marginal increases in humidity in some states, while potentially mitigating dust, could introduce risks of corrosion or organic growth.

Synthesizing these interconnected variables, it is clear that PV system designers can no longer rely on static historical averages. The climate is a dynamic system, and PV infrastructure must be designed for resilience. The increasing temperatures necessitate the selection of modules with a superior temperature coefficient. The prevalence of dust demands the integration of automated cleaning systems and a rigorous operational maintenance schedule. The reduced wind speed may even influence the structural design for cooling. These findings validate the concerns raised in the literature about climate vulnerability (Altamimi et al., 2017) and underscore that the techno-economic models for sustainability, like those used by Owolabi et al. (2019), must now incorporate these declining climate trends to avoid overestimating future energy yields and financial returns.

Conclusion and Recommendation

This study has successfully achieved its aim of analyzing the variability of key climate elements affecting PV systems in Northeastern Nigeria. The analysis of a 40-year dataset provides conclusive evidence that the climate is undergoing significant changes, characterized

by generally rising temperatures, declining solar irradiance in the southern states, decreasing wind speeds, and reducing humidity. These trends are not uniform but exhibit a strong spatial signature across the six states, necessitating a localized rather than a one-size-fits-all approach to renewable energy policy and project development.

The implications are clear: climate variability is a present and growing risk to the energy security promised by solar investment in the region. Proactive and adaptive strategies are essential to mitigate these impacts and ensure the long-term reliability and economic viability of PV power generation.

Based on the findings of this study, the following recommendations are made:

i. For Policy Makers: Energy policies and master plans must be updated to reflect these dynamic climate trends. Incentives should be created for the deployment of climate-resilient PV technologies, such as those with better temperature coefficients and integrated cleaning systems.

ii. For System Designers and Investors: Financial and engineering models for prospective PV projects must incorporate location-specific climate projections rather than relying solely on historical averages. Site selection should strongly consider the climatic findings of this study, prioritizing areas with more stable irradiance and lower thermal stress.

iii. For Future Research: This study should be extended by investigating the impact of these specific climatic trends on the actual performance and degradation rates of existing PV installations in the region. Furthermore, research should explore the efficacy of different mitigation technologies, such as active cooling systems and anti-soiling coatings, under the precise environmental conditions of Northeastern Nigeria.

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