

Assessment of Photovoltaic System Potential Across Different Climatic Zones of Nigeria

Njoku M.C., Mbagwu B.O., Odofor P.E., Emmanuel G.C., Igboanugo F.C. and Uche-Ben G.

Department of Mechanical Engineering, Federal Polytechnic Nekede, P.M.B. 1036 Owerri, Imo-State, Nigeria

Corresponding author: M.C. Njoku: Department of Mechanical Engineering, Federal Polytechnic Nekede, P.M.B. 1036 Owerri, Imo-State, Nigeria, *e-mail:* mnjoku@fpno.edu.ng, *ORCID iD:* <https://orcid.org/0000-0003-4983-4535>

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ABSTRACT: Accurate characterization of solar radiation distribution is essential for the optimization of photovoltaic (PV) system design and deployment in regions with diverse climatic conditions. This study investigates the spatial and seasonal variability of global solar radiation across three major climatic zones in Nigeria, defined as Zone I (9.04 – 13.01°N), Zone II (6.33 – 9.90°N), and Zone III (4.03 – 7.79°N). Monthly average solar radiation data were analyzed to quantify solar energy availability and identify regional suitability for PV applications. Results indicate a pronounced latitudinal gradient, with Zone I exhibiting the highest annual average solar radiation (5.56 – 6.14 kWh/m²/day) and a monthly range of 4.67 – 6.69 kWh/m²/day, reflecting the clear-sky conditions typical of the semi-arid north. Zone II displays moderate irradiance levels, with an annual average of 5.23 kWh/m²/day and a monthly range of 4.08 – 6.03 kWh/m²/day, characteristic of its transitional climatic nature. Zone III, influenced by high humidity and persistent cloud cover, records the lowest values, with annual monthly averages of 4.20 – 4.81 kWh/m²/day and a range of 3.18 – 5.27 kWh/m²/day. Despite these regional differences, all zones maintain sufficient irradiance to support year-round PV electricity generation. The findings highlight Nigeria's substantial solar energy potential and emphasize the importance of region-specific PV system optimization to enhance energy access.

Keywords: Climatic zones, Nigeria, Photovoltaic systems, Renewable energy, Solar radiation

1.0 Introduction

The socio-economic development of any nation is fundamentally driven by the availability of adequate, reliable, sustainable, and cost-effective energy. An increase and sustained level of national energy consumption typically manifests in enhanced industrial output, improved transportation systems, adequate housing, increased food production, and strengthened healthcare and human services [1]. Access to adequate and reliable energy supply is not common in many countries around the world. Nigeria exemplifies this challenge: although it is the largest economy and a major energy resource hub in Africa, and ranks as the world's ninth-largest crude oil exporter, access to sufficient and dependable electricity within the country remains limited [2, 3].

Nigeria is richly endowed with a wide range of energy resources such as coal, oil, gas, hydro-power, and biomass yet the country continues to struggle with inadequate electricity supply. Despite significant investments and various government-led reform initiatives, systemic corruption in the power industry has remained a major impediment to achieving reliable power

delivery. According to the 2025 third-quarter report, twenty-eight grid-connected and operational power plants consisting of five hydro-power stations, two steam plants, nineteen open-cycle gas turbines, and two combined-cycle gas turbines produced a total of 5,430.3 MW to serve Nigeria's population of over 190 million people that is growing at a rate of 2.5 % annually [4, 5]. This situation has resulted in a substantial proportion of the population lacking access to grid electricity, while grid-connected regions continue to experience frequent and prolonged outages as a result of obsolete power plant equipment and distribution system [6].

According to another report [7], electricity supply from the national grid in most parts of Nigeria is limited to approximately 4–5 hours per day, with complete outages lasting 2–3 consecutive days per week frequently observed in many areas. The continued inadequacy of grid-supplied electricity to meet the demands of Nigeria's expanding population has had significant economic repercussions, particularly hindering growth in rural and sub-rural regions [8]. This shortfall has further driven substantial youth migration from rural communities to urban areas in pursuit of improved livelihood prospects [9]. Furthermore, the unreliable electricity supply in Nigeria has forced about 26 % of households and 30 % of micro, small and medium enterprises to depend on generator sets with its estimated capacity to be eight times more than the capacity connected to the national grid, which significantly contributes air pollution linked to about 1,500 deaths annually [10].

In a recent development, the Aso Rock Presidential Villa in Abuja announced its decision to disconnect from the national electricity grid and operate solely on a dedicated PV system. This shift was necessitated by persistent and prolonged power interruptions that undermine the reliability of grid-supplied electricity in Nigeria [11–14]. Persistent instability in Nigeria's national electricity grid has also compelled both public and private sectors to start exploring alternative energy pathways. This development has prompted numerous federal institutions and private households to increasingly adopt decentralized renewable energy systems particularly PV technologies as a means of sustaining critical operations and ensuring uninterrupted power supply. The growing shift toward distributed generation is further driven by the need to reduce dependence on unreliable grid electricity, rising operational costs associated with generator sets, the growing availability of modular renewable technologies, minimize economic losses associated with prolonged outages, and improve overall energy resilience. The aim of this study is to analyse the characteristics of solar radiation across Nigeria in order to evaluate the nation's potential for PV electricity generation. The paper further seeks to formulate evidence-based recommendations for the effective deployment, optimization, and long-term management of PV systems within the Nigerian energy landscape.

2.0 Material

Nigeria is situated along the western coast of Africa, extending between latitudes 3°15'N and 13°30'N and longitudes 2°59'E and 15°00'E [15]. The country is bordered by the Republic of Niger to the north, the Republic of Chad and the Republic of Cameroon to the east, the Republic of Benin to the west, and the Bight of Biafra to the south. Nigeria is commonly delineated into

Northern and Southern regions. Between these two broad regions lies the Middle Belt, a transitional zone characterized by its arid influence of the Sahara Desert in the north and the coastal influence of the Bight of Biafra in the south.

The average global solar radiation intensity data covering a period of forty-one (41) year (1984 - 2025) were obtained for forty-seven (47) locations from the National Aeronautics and Space Administration (NASA) database. The NASA solar data-set is derived from satellite-based observations, from which surface insolation values are estimated [16]. The selected locations consist of major urban centers across Nigeria, thereby ensuring that the derived solar radiation data are representative and can be reasonably extrapolated to adjacent communities.

3.0 Methodology

3.1 Estimation of Solar Radiation

In regions lacking direct measurements of solar radiation, it is common to estimate solar irradiance using empirical correlations based on locally observed meteorological parameters, such as sunshine duration, ambient temperature, relative humidity, or cloud cover [17–19]. Among these approaches, sunshine-based models particularly the Angström–Prescott model and its variants remain widely adopted due to their favorable balance of accuracy and practical applicability [20, 21]. To estimate the global solar radiation incident on a horizontal surface from recorded hours of bright sunshine, the Angström–Page model is frequently employed. This model assumes a linear relationship between the ratio of measured solar radiation to extraterrestrial solar radiation and the ratio of actual sunshine duration to the maximum possible sunshine duration. Mathematically, the Angström–Page model is expressed as [22]

$$\frac{\bar{H}}{\bar{H}_o} = a + b \frac{\bar{n}}{\bar{N}} \quad (1)$$

Where \bar{H} is the monthly global solar radiation on horizontal surface ($\text{MJm}^{-2}\text{day}^{-1}$), \bar{H}_o is the monthly extraterrestrial radiation for the study location ($\text{MJm}^{-2}\text{day}^{-1}$), \bar{n} is the monthly hours of bright sunshine, \bar{N} is the monthly maximum possible hours of bright sunshine and a and b are empirical constants to be determined.

The monthly extraterrestrial radiation for the study location is given as [23]

$$\bar{H}_o = \frac{24 \times 3600 G_{sc}}{\pi} \left(+0.033 \cos \frac{360n}{365} \right) \times \left(\cos \phi \cos \delta \sin \omega_s + \frac{\pi \omega_s}{180} \sin \phi \sin \delta \right) \quad (2)$$

Where G_{sc} is the solar constant given as 1367 W/m^2 [24], n is the day of the year, ϕ is latitude of study location, δ is the solar declination and ω_s is the sunset hour angle.

The declination (δ) and sunset hour angle (ω_s) can be calculated from the following equations [23]

$$\delta = 23.45 \sin \left[\frac{360}{365} (284 + n) \right] \quad (3)$$

$$\omega_s = \cos^{-1} (-\tan \phi \tan \delta) \quad (4)$$

The monthly maximum possible hours of bright sunshine is given as [23]

$$\bar{N} = \frac{2}{15} \cos^{-1}(-\tan\phi \tan\delta) \quad (5)$$

In this study, the monthly average global solar radiation intensity data for the forty-seven (47) study locations accessed from NASA [25] is presented in Table 1.

Table 1: global solar radiation data for the study locations from 1984 - 2025 (kWh/m²/day)

Locations	Lat. (°N)	Long. (°E)	Elev. (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
Abakaliki	6.33	8.12	88.44	5.47	5.49	5.33	5.24	5.10	4.69	4.24	4.08	4.46	4.91	5.32	5.34	4.97
Abeokuta	7.15	3.37	80.92	4.97	4.97	5.08	5.15	5.04	4.56	3.92	3.69	4.17	4.78	5.13	4.93	4.70
Abuja	9.08	7.4	406.97	5.55	5.68	5.90	5.87	5.61	5.11	4.60	4.26	4.94	5.46	5.84	5.49	5.36
Ado-Ekiti	7.62	5.24	379.21	5.11	5.07	5.13	5.16	5.10	4.62	4.16	3.94	4.33	4.83	5.21	5.03	4.81
Akure	7.26	5.21	379.21	5.10	5.06	5.10	5.13	5.07	4.60	4.14	3.93	4.30	4.80	5.21	5.03	4.79
Asaba	6.21	6.7	103.94	4.99	4.90	4.89	4.92	4.81	4.40	4.01	3.93	4.21	4.60	5.01	4.96	4.63
Awka	6.23	7.09	103.94	5.19	5.15	5.10	5.09	4.95	4.55	4.13	4.02	4.34	4.74	5.16	5.13	4.79
Bauchi	10.31	9.83	518.79	5.74	5.96	6.26	6.29	6.09	5.86	5.53	5.23	5.70	5.98	6.03	5.74	5.86
Benin-City	6.34	5.61	93.92	4.93	4.79	4.76	4.81	4.74	4.29	3.76	3.74	4.04	4.51	4.97	4.90	4.52
Bida	9.08	6.01	126.59	5.30	5.50	5.78	5.84	5.67	5.12	4.58	4.26	4.88	5.44	5.70	5.32	5.28
Birnin Kebbi	12.44	4.2	241.96	5.40	5.75	6.08	6.34	6.27	6.12	5.73	5.36	5.83	6.03	5.70	5.47	5.84
Calabar	4.98	8.35	39.48	5.08	5.01	4.57	4.61	4.47	3.87	3.33	3.18	3.60	4.01	4.44	4.94	4.26
Damaturu	11.75	11.97	402.61	5.87	6.20	6.52	6.56	6.31	5.98	5.68	5.42	5.89	6.08	5.99	5.78	6.02
Duste	11.75	9.34	465.94	5.56	5.93	6.26	6.43	6.27	5.88	5.74	5.46	5.95	6.00	5.82	5.60	5.91
Enugu	6.46	7.55	151.33	5.19	5.15	5.10	5.09	4.95	4.55	4.13	4.02	4.34	4.74	5.16	5.13	4.79
Gombe	10.28	11.18	381.62	5.82	6.08	6.35	6.35	6.22	5.86	5.44	5.09	5.57	5.98	6.01	5.80	5.88
Gusau	12.17	6.68	529.87	5.44	5.76	6.17	6.43	6.29	6.16	5.83	5.39	5.91	6.02	5.71	5.43	5.88
Ibadan	7.38	3.95	188.89	4.97	4.97	5.08	5.15	5.04	4.56	3.92	3.69	4.17	4.78	5.13	4.93	4.70
Ijebu-Ode	6.83	3.92	90.82	4.93	4.93	5.00	5.05	4.78	4.11	3.92	4.17	4.26	4.72	5.08	4.94	4.66
Ikeja	6.61	3.36	25.49	4.93	4.93	5.00	5.05	4.78	4.11	3.92	4.17	4.26	4.72	5.08	4.94	4.66
Ikom	5.97	8.73	116.85	5.27	5.27	4.98	4.91	4.67	4.21	3.71	3.55	4.07	4.45	4.90	5.08	4.59
Ilorin	8.48	4.55	344.93	5.28	5.37	5.63	5.63	5.45	4.97	4.36	4.09	4.54	5.09	5.48	5.22	5.09
Jalingo	8.9	11.38	251.79	5.87	6.03	6.02	5.84	5.65	5.20	4.65	4.41	4.92	5.54	5.98	5.77	5.49
Jos	9.9	8.86	980.85	5.61	5.78	5.93	5.81	5.47	5.06	4.63	4.31	4.88	5.45	5.95	5.63	5.37
Kaduna	10.52	7.42	623.54	5.70	5.89	6.19	6.32	6.06	5.58	5.08	4.67	5.34	5.79	5.94	5.65	5.68
Kano	12.01	8.6	442.08	5.53	5.90	6.32	6.62	6.50	6.22	5.99	5.67	6.09	6.10	5.82	5.53	6.02
Katsina	12.97	7.63	474.54	5.44	5.73	6.22	6.51	6.35	6.14	5.90	5.47	6.00	6.00	5.68	5.45	5.91
Lafia	8.51	8.52	167.21	5.67	5.75	5.74	5.63	5.43	5.02	4.67	4.37	4.79	5.34	5.82	5.61	5.32
Lokoja	7.81	6.74	167.21	5.16	5.14	5.25	5.27	5.19	4.76	4.39	4.19	4.49	4.94	5.31	5.11	4.93
Maidugri	11.84	13.16	318.25	5.99	6.35	6.63	6.56	6.31	5.91	5.49	5.22	5.76	6.06	6.04	5.79	6.01
Makurdi	7.74	5.54	373.17	5.10	5.06	5.10	5.13	5.07	4.60	4.14	3.93	4.30	4.80	5.21	5.03	4.79
Mbaise	5.54	7.29	92.75	5.07	5.07	4.92	4.97	4.76	4.31	3.87	3.85	4.17	4.53	4.90	4.95	4.61
Minna	9.58	6.54	149.83	5.30	5.50	5.78	5.84	5.67	5.12	4.58	4.26	4.88	5.44	5.70	5.32	5.28
Nguru	12.88	10.46	345.61	5.72	6.09	6.48	6.69	6.61	6.27	6.07	5.81	6.19	6.19	5.97	5.66	6.14
Onitsha	6.14	6.8	103.94	4.99	4.90	4.89	4.92	4.81	4.40	4.01	3.93	4.21	4.60	5.01	4.96	4.63
Oshogbo	7.79	4.55	337.39	4.93	4.96	5.07	5.07	4.97	4.49	3.85	3.64	4.12	4.67	5.12	4.91	4.65
Owerri	5.47	7.02	62.54	5.07	5.07	4.92	4.97	4.76	4.31	3.87	3.85	4.17	4.53	4.90	4.95	4.61
Port-Harcourt	4.34	7.05	6.8	4.85	4.85	4.48	4.59	4.33	3.65	3.32	3.45	3.67	4.04	4.40	4.76	4.20
Potiskum	11.7	11.09	411.77	5.87	6.20	6.52	6.56	6.31	5.98	5.68	5.42	5.89	6.08	5.99	5.78	6.02
Sokoto	13.01	5.25	276.18	5.58	6.07	6.41	6.58	6.38	6.18	5.95	5.66	6.10	6.10	5.79	5.50	6.02
Umuahia	5.53	7.5	92.75	5.07	5.07	4.92	4.97	4.76	4.31	3.87	3.85	4.17	4.53	4.90	4.95	4.61
Uyo	5.04	7.92	39.48	5.07	5.07	4.92	4.97	4.76	4.31	3.87	3.85	4.17	4.53	4.90	4.95	4.61
Warri	5.55	5.57	9.6	4.86	4.73	4.70	4.82	4.57	3.98	3.46	3.69	3.83	4.35	4.84	4.81	4.38

<i>Yelwa</i>	10.84	4.75	257.74	5.47	5.73	5.92	6.08	6.02	5.62	5.10	4.74	5.23	5.68	5.76	5.44	5.56
<i>Yenegoa</i>	4.93	6.28	17.26	4.85	4.84	4.52	4.67	4.35	3.68	3.39	3.69	3.75	4.18	4.51	4.84	4.27
<i>Yola</i>	9.04	12.5	344.13	5.94	6.19	6.37	6.27	6.00	5.66	5.18	4.88	5.35	5.88	6.07	5.83	5.80
<i>Zaria</i>	11.13	7.73	646.9	5.52	5.82	6.19	6.38	6.21	5.84	5.55	5.17	5.75	5.92	5.77	5.54	5.80
			<i>Ave</i>	5.33	5.44	5.54	5.60	5.43	5.00	4.58	4.40	4.81	5.19	5.41	5.27	5.16
			<i>Max</i>	5.99	6.35	6.63	6.69	6.61	6.27	6.07	5.81	6.19	6.19	6.07	5.83	6.14
			<i>Min</i>	4.85	4.73	4.48	4.59	4.33	3.65	3.32	3.18	3.60	4.01	4.40	4.76	4.20

4.0 Discussion

Solar radiation intensity represents the fundamental energy input for PV electricity generation. The total incident irradiance comprises of direct beam radiation, diffuse radiation, and ground-reflected radiation that governs the quantity of power that PV modules is capable to produce. Through the photovoltaic effect, semiconductor materials within the modules convert this radiant energy into electrical energy, with conversion efficiency strongly dependent on irradiance magnitude, spectral composition, module operating temperature, angle of incidence, and environmental conditions such as dust loading and partial shading [26 - 28]. Therefore, precise characterization of solar radiation intensity is essential for performance modelling, optimal system sizing, and the overall reliability of PV system design and operation.

Table 1 shows that the average monthly maximum global solar radiation across Nigeria ranges from 5.81 - 6.69 kWh/m²/day, while the corresponding minimum average monthly values vary between 3.19 to 4.85 kWh/m²/day. Based on these observations, the overall average monthly global solar radiation for the country can be characterized as lying within the interval of 3.19 – 6.69 kWh/m²/day. While the average annual minimum and maximum solar radiation intensity is estimated as 4.20 and 6.14 kWh/m²/day, respectively. This range underscores the substantial solar resource availability nationwide, reinforcing the suitability of Nigeria’s climatic conditions for photovoltaic energy harvesting throughout the year.

Seasonal variation in solar resource availability across Nigeria is strongly influenced by shifts in atmospheric conditions between the dry and rainy seasons. April records the highest mean monthly global solar radiation, averaging approximately 6.64 kWh/m²/day, largely due to clearer skies and reduced aerosol moisture prior to the onset of the main rainy season. In contrast, August typically exhibits the lowest solar radiation level, around 3.18 kWh/m²/day, coinciding with peak monsoonal activity when increased cloud cover, high humidity, and elevated particulate matter significantly reduce incident irradiance across Nigeria . This pronounced seasonal asymmetry has important implications for photovoltaic system sizing, energy yield assessments, and overall renewable-energy planning, particularly in regions with high electrification deficits. Understanding these temporal fluctuations is therefore essential for optimizing solar energy utilization and ensuring year-round system reliability in Nigeria’s diverse climatic zones [29 - 31].

The magnitude of solar radiation intensity observed across Nigerian cities underscores the strong potential for electricity generation using PV modules, which are conventionally rated at a standard test condition (STC) irradiance of 1000 W/m². Although actual field conditions may vary due to atmospheric and environmental factors. Given that the measured global solar

radiation values across the country fall well within the range suitable for effective PV module operation, the available resource is sufficient to drive optimal module performance for both residential, small scale business, farms etc.

Climatically, Nigeria is characterized by two principal seasons: the dry season and the rainy season [32]. The dry season, which typically spans from November to April, is predominantly influenced by the north-east trade winds originating from the Sahara Desert. These winds are cold, dry, and often heavily laden with dust particles, producing hazy atmospheric conditions that can significantly reduce solar transmittance due to increased aerosol concentration. In contrast, the rainy season extends from May to October and is marked by substantial spatial and temporal variability in rainfall intensity and cloud cover across the country’s climatic zones. The high humidity and frequent cloud formation during this period contribute to greater atmospheric attenuation of solar radiation.

These seasonal variations exert a direct influence on the quantity and quality of solar radiation received in different cities, thereby affecting the overall performance and energy yield of PV module systems. During the dry season, despite dust-related attenuation, clearer skies generally support higher irradiance levels, while the rainy season will lead to reduced PV output due to persistent cloudiness and diffuse radiation dominance. Understanding these climatic dynamics is essential for accurate PV system design, performance prediction, and long-term energy planning in Nigeria. Hence, following the methodology of Ref. [33] as cited in Ref. [34], the monthly average solar radiation across Nigeria has been categorized into three distinct climatic zones, as summarized in Table 2. This zonal classification provides a practical framework for evaluating the spatial distribution of solar energy potential across the country, accounting for regional variations in climatic and atmospheric conditions.

Table 2 annual monthly average global solar radiation zone

Zones	Annual average of global solar radiation (kWh/m ² /day)	Locations
Zone I	5.56 - 6.14	Bauchi, Birnin kebbi, Damaturu, Duste, Gombe, Gusau, Kaduna, Kano, Katsina, Maidugri, Nguru, Potiskum, Sokoto, Yelwa, Yola, Zaria
Zone II	4.93 - 5.43	Abakaliki, Abuja, Bida, Ilorin, Jalingo, Jos, Lafia, Lokoja, Minna
Zone III	4.20 - 4.81	Abeokuta, Ado-Ekiti, Akure, Asaba, Awka, Benin-City, Calabar, Enugu, Ibadan, Ijebu-Ode, Ikeja, Ikom, Makurdi, Mbaise, Onitsha, Oshogbo, Owerri, Port-Harcourt, Umuahi, Uyo, Yanegoa

Table 3 presents the locations within Zone I, situated in the northern region of Nigeria between latitudes 9.04°N - 13.01°N. This zone predominantly corresponds to the semi-arid and arid climatic belts of the country. The average annual solar radiation intensity in this region ranges from 5.56 - 6.14 kWh/m²/day, while the average monthly maximum and minimum values vary between 5.81 – 6.69 kWh/m²/day and 4.67 – 6.08 kWh/m²/day, respectively. Accordingly, the overall average monthly solar radiation intensity in Zone I can be classified within the range of 4.67 – 6.69 kWh/m²/day, reflecting a consistently high solar resource potential throughout the year. The substantial quantity of monthly solar radiation in this zone indicates a strong potential for electricity generation using PV module systems. April, with an average monthly solar

radiation of 6.69 kWh/m²/day, exhibits the highest irradiance level in the zone, whereas August records the lowest value at 4.67 kWh/m²/day.

Table 3: global solar radiation data for zone I from 1984 - 2025 (kWh/m²/day)

Locations	Lat. (°N)	Long. (°E)	Elev. (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave	
Bauchi	10.31	9.83	518.79	5.74	5.96	6.26	6.29	6.09	5.86	5.53	5.23	5.7	5.98	6.03	5.74	5.86	
Birinin Kebbi	12.44	4.2	241.96	5.4	5.75	6.08	6.34	6.27	6.12	5.73	5.36	5.83	6.03	5.7	5.47	5.84	
Damaturu	11.75	11.97	402.61	5.87	6.2	6.52	6.56	6.31	5.98	5.68	5.42	5.89	6.08	5.99	5.78	6.02	
Duste	11.75	9.34	465.94	5.56	5.93	6.26	6.43	6.27	5.88	5.74	5.46	5.95	6	5.82	5.6	5.91	
Gombe	10.28	11.18	381.62	5.82	6.08	6.35	6.35	6.22	5.86	5.44	5.09	5.57	5.98	6.01	5.8	5.88	
Gusau	12.17	6.68	529.87	5.44	5.76	6.17	6.43	6.29	6.16	5.83	5.39	5.91	6.02	5.71	5.43	5.88	
Kaduna	10.52	7.42	623.54	5.7	5.89	6.19	6.32	6.06	5.58	5.08	4.67	5.34	5.79	5.94	5.65	5.68	
Kano	12.01	8.6	442.08	5.53	5.9	6.32	6.62	6.5	6.22	5.99	5.67	6.09	6.1	5.82	5.53	6.02	
Katsina	12.97	7.63	474.54	5.44	5.73	6.22	6.51	6.35	6.14	5.9	5.47	6	6	5.68	5.45	5.91	
Maidugri	11.84	13.16	318.25	5.99	6.35	6.63	6.56	6.31	5.91	5.49	5.22	5.76	6.06	6.04	5.79	6.01	
Nguru	12.88	10.46	345.61	5.72	6.09	6.48	6.69	6.61	6.27	6.07	5.81	6.19	6.19	5.97	5.66	6.14	
Potiskum	11.7	11.09	411.77	5.87	6.2	6.52	6.56	6.31	5.98	5.68	5.42	5.89	6.08	5.99	5.78	6.02	
Sokoto	13.01	5.25	276.18	5.58	6.07	6.41	6.58	6.38	6.18	5.95	5.66	6.1	6.1	5.79	5.5	6.02	
Yelwa	10.84	4.75	257.74	5.47	5.73	5.92	6.08	6.02	5.62	5.1	4.74	5.23	5.68	5.76	5.44	5.56	
Yola	9.04	12.5	344.13	5.94	6.19	6.37	6.27	6	5.66	5.18	4.88	5.35	5.88	6.07	5.83	5.8	
Zaria	11.13	7.73	646.9	5.52	5.82	6.19	6.38	6.21	5.84	5.55	5.17	5.75	5.92	5.77	5.54	5.8	
				Ave	5.66	5.98	6.31	6.44	6.26	5.95	5.62	5.29	5.78	5.99	5.88	5.62	5.90
				Max	5.99	6.35	6.63	6.69	6.61	6.27	6.07	5.81	6.19	6.19	6.07	5.83	6.14
				Min	5.40	5.73	5.92	6.08	6.00	5.58	5.08	4.67	5.23	5.68	5.43	5.56	

The total average monthly solar radiation is estimated at 71.24 kWh/m²/day, with the dry and rainy seasons contributing 50.38% and 49.62%, respectively. This near-uniform distribution demonstrates that PV modules installed in Zone I are capable of generating electricity year-round, making the region highly suitable for both small- and large-scale solar energy projects. However, periodic cleaning of PV modules will be necessary, particularly during the dry season, to mitigate the effects of dust accumulation from the Sahara Desert, which can reduce module efficiency. Overall, Zone I represents one of the most promising areas in Nigeria for sustained and reliable photovoltaic energy harvesting.

Table 4: global solar radiation data for zone II from 1984 - 2025 (kWh/m²/day)

Locations	Lat. (°N)	Long. (°E)	Elev. (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
Abakaliki	6.33	8.12	88.44	5.47	5.49	5.33	5.24	5.1	4.69	4.24	4.08	4.46	4.91	5.32	5.34	4.97
Abuja	9.08	7.4	406.97	5.55	5.68	5.9	5.87	5.61	5.11	4.6	4.26	4.94	5.46	5.84	5.49	5.36
Bida	9.08	6.01	126.59	5.3	5.5	5.78	5.84	5.67	5.12	4.58	4.26	4.88	5.44	5.7	5.32	5.28
Ilorin	8.48	4.55	344.93	5.28	5.37	5.63	5.63	5.45	4.97	4.36	4.09	4.54	5.09	5.48	5.22	5.09
Jalingo	8.9	11.38	251.79	5.87	6.03	6.02	5.84	5.65	5.2	4.65	4.41	4.92	5.54	5.98	5.77	5.49
Jos	9.9	8.86	980.85	5.61	5.78	5.93	5.81	5.47	5.06	4.63	4.31	4.88	5.45	5.95	5.63	5.37
Lafia	8.51	8.52	167.21	5.67	5.75	5.74	5.63	5.43	5.02	4.67	4.37	4.79	5.34	5.82	5.61	5.32
Lokoja	7.81	6.74	167.21	5.16	5.14	5.25	5.27	5.19	4.76	4.39	4.19	4.49	4.94	5.31	5.11	4.93
Minna	9.58	6.54	149.83	5.3	5.5	5.78	5.84	5.67	5.12	4.58	4.26	4.88	5.44	5.7	5.32	5.28

	Ave	5.47	5.58	5.71	5.66	5.47	5.01	4.52	4.25	4.75	5.29	5.68	5.42	5.23
	Max	5.87	6.03	6.02	5.87	5.67	5.20	4.67	4.41	4.94	5.54	5.98	5.77	5.49
	Min	5.16	5.14	5.25	5.24	5.10	4.69	4.24	4.08	4.46	4.91	5.31	5.11	4.93

Table 4 presents the average monthly global solar radiation for locations within Zone II, situated along the latitudinal belt of 6.33 – 9.90°N. This zone occupies an intermediate position in Nigeria, approximately equidistant from the arid influence of the Sahara Desert to the north and the humid coastal influence of the Bight of Biafra to the south. Consequently, Zone II constitutes a transitional climatic belt characterized by moderate atmospheric moisture, variable cloud cover, and pronounced seasonal fluctuations in solar irradiance.

The average annual solar radiation in Zone II is estimated at 5.23 kWh/m²/day, within a range values of 4.93 - 5.49 kWh/m²/day. The total average monthly solar radiation is calculated at 62.81 kWh/m²/day, with the dry season contributing 52.77% and the rainy season 47.23% of the total value. In this zone, February records the highest average monthly solar radiation at 6.03 kWh/m²/day, while August exhibits the lowest value at 4.08 kWh/m²/day. The average monthly minimum and maximum solar radiation intensities range from 4.08–5.31 kWh/m²/day and 4.41 – 6.03 kWh/m²/day, respectively, resulting in an overall average monthly solar radiation interval of 4.08 – 6.03 kWh/m²/day.

The annual and monthly average solar radiation values in this zone generally falls below that of the Zone I but remains adequate for PV energy generation. These values indicate that Zone II possesses a moderately high and relatively consistent solar resource, suitable for the deployment of PV systems throughout the year. While the peak irradiance occurs predominantly during the dry season, the rainy season still provides sufficient solar energy to maintain reasonable PV system output, albeit at slightly reduced efficiency due to increased cloud cover and atmospheric moisture during the rainy periods. The relatively balanced contribution of both seasons ensures that PV modules installed in this transitional climatic belt can achieve sustained energy generation, making Zone II a viable region for both decentralized solar installations and larger-scale utility projects.

Table 5: global solar radiation data for zone III from 1984 - 2025 (kWh/m²/day)

Locations	Lat. (°N)	Long. (°E)	Elev. (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
Abeokuta	7.15	3.37	80.92	4.97	4.97	5.08	5.15	5.04	4.56	3.92	3.69	4.17	4.78	5.13	4.93	4.7
Ado-Ekiti	7.62	5.24	379.21	5.11	5.07	5.13	5.16	5.1	4.62	4.16	3.94	4.33	4.83	5.21	5.03	4.81
Akure	7.26	5.21	379.21	5.1	5.06	5.1	5.13	5.07	4.6	4.14	3.93	4.3	4.8	5.21	5.03	4.79
Asaba	6.21	6.7	103.94	4.99	4.9	4.89	4.92	4.81	4.4	4.01	3.93	4.21	4.6	5.01	4.96	4.63
Awka	6.23	7.09	103.94	5.19	5.15	5.1	5.09	4.95	4.55	4.13	4.02	4.34	4.74	5.16	5.13	4.79
Benin-City	6.34	5.61	93.92	4.93	4.79	4.76	4.81	4.74	4.29	3.76	3.74	4.04	4.51	4.97	4.9	4.52
Calabar	4.98	8.35	39.48	5.08	5.01	4.57	4.61	4.47	3.87	3.33	3.18	3.6	4.01	4.44	4.94	4.26
Enugu	6.46	7.55	151.33	5.19	5.15	5.1	5.09	4.95	4.55	4.13	4.02	4.34	4.74	5.16	5.13	4.79
Ibadan	7.38	3.95	188.89	4.97	4.97	5.08	5.15	5.04	4.56	3.92	3.69	4.17	4.78	5.13	4.93	4.7
Ijebu-Ode	6.83	3.92	90.82	4.93	4.93	5	5.05	4.78	4.11	3.92	4.17	4.26	4.72	5.08	4.94	4.66
Ikeja	6.61	3.36	25.49	4.93	4.93	5	5.05	4.78	4.11	3.92	4.17	4.26	4.72	5.08	4.94	4.66
Ikom	5.97	8.73	116.85	5.27	5.27	4.98	4.91	4.67	4.21	3.71	3.55	4.07	4.45	4.9	5.08	4.59
Makurdi	7.74	5.54	373.17	5.1	5.06	5.1	5.13	5.07	4.6	4.14	3.93	4.3	4.8	5.21	5.03	4.79
Mbaise	5.54	7.29	92.75	5.07	5.07	4.92	4.97	4.76	4.31	3.87	3.85	4.17	4.53	4.9	4.95	4.61

Onitsha	6.14	6.8	103.94	4.99	4.9	4.89	4.92	4.81	4.4	4.01	3.93	4.21	4.6	5.01	4.96	4.63
Oshogbo	7.79	4.55	337.39	4.93	4.96	5.07	5.07	4.97	4.49	3.85	3.64	4.12	4.67	5.12	4.91	4.65
Owerri	5.47	7.02	62.54	5.07	5.07	4.92	4.97	4.76	4.31	3.87	3.85	4.17	4.53	4.9	4.95	4.61
Port-Harcourt	4.34	7.05	6.8	4.85	4.85	4.48	4.59	4.33	3.65	3.32	3.45	3.67	4.04	4.4	4.76	4.2
Umuahia	5.53	7.5	92.75	5.07	5.07	4.92	4.97	4.76	4.31	3.87	3.85	4.17	4.53	4.9	4.95	4.61
Uyo	5.04	7.92	39.48	5.07	5.07	4.92	4.97	4.76	4.31	3.87	3.85	4.17	4.53	4.9	4.95	4.61
Warri	5.55	5.57	9.6	4.86	4.73	4.7	4.82	4.57	3.98	3.46	3.69	3.83	4.35	4.84	4.81	4.38
Yenegoa	4.93	6.28	17.26	4.85	4.84	4.52	4.67	4.35	3.68	3.39	3.69	3.75	4.18	4.51	4.84	4.27
			Ave	5.02	4.99	4.92	4.96	4.80	4.29	3.85	3.81	4.12	4.57	4.96	4.96	4.60
			Max	5.27	5.27	5.13	5.16	5.1	4.62	4.16	4.17	4.34	4.83	5.21	5.13	4.81
			Min	4.85	4.73	4.48	4.59	4.33	3.65	3.32	3.18	3.6	4.01	4.4	4.76	4.2

Table 5 shows the global solar radiation for locations within the latitudinal belt of 4.03 – 7.79°N in Nigeria. This zone corresponds to the southern part of the country, which is characterized by high annual rainfall, elevated humidity levels, and persistent cloud cover. These climatic conditions significantly enhance atmospheric attenuation of incoming solar radiation through increased scattering and absorption by clouds, aerosols, and water vapor. Consequently, the amount of solar energy reaching the Earth’s surface in this region is comparatively lower than that of the northern and central zones.

The average maximum and minimum monthly solar radiation levels in this zone range from 4.16 – 5.27 kWh/m²/day and 3.18 – 4.85 kWh/m²/day, respectively, resulting in an overall average monthly radiation interval of 3.18 – 5.27 kWh/m²/day. Annually, the total average monthly solar radiation for this zone is estimated at 55.25 kWh/m²/month, with the dry season contributing 53.25% and the rainy season accounting for 46.75% of the total. August records the lowest monthly solar radiation value at 3.18 kWh/m²/day, representing the least favorable month for solar energy harvesting. In contrast, January and February each exhibit the highest levels, with monthly averages of 5.27 kWh/m²/day. Overall, the average annual monthly solar radiation in this zone varies between 4.20 and 4.81 kWh/m²/day, with a mean value of 4.60 kWh/m²/day.

Despite these limitations, the region still receives sufficient solar radiation to support PV electricity generation, particularly during the dry season when cloud cover is reduced. However, PV system performance in this zone is more sensitive to seasonal variations, necessitating careful system sizing, performance forecasting, and consideration of local climatic factors such as prolonged rainfall and shading effects. Understanding the solar radiation profile of this southern belt is therefore essential for optimizing PV deployment strategies and ensuring reliable year-round power generation.

The analysis of solar radiation across the three defined zones: Zone I (far north), Zone II (central transitional belt), and Zone III (southern humid region) reveals clear spatial and seasonal gradients in solar energy availability driven by Nigeria’s climatic diversity. Overall, the three zones exhibit a decreasing gradient of solar radiation from north to south, reflecting the combined influence of latitude, atmospheric clarity, rainfall patterns, and cloud cover. Zone I stands out as the most favorable region for high-performance solar energy generation, followed by Zone II with moderate but reliable resources, and Zone III with the lowest yet still viable solar potential. These spatial patterns provide crucial insights for optimizing photovoltaic system

design, resource planning, and investment strategies in Nigeria's expanding renewable energy sector.

4.1 Recommendations

Based on the spatial and seasonal assessment of global solar radiation across the three climatic zones in Nigeria, the following recommendations are proposed to enhance PV system deployment, performance, and long-term sustainability:

I. Region-specific PV System Design:

PV installations should be tailored to the solar radiation characteristics of each zone. Higher capacity PV systems with optimized tilt angles are suitable for Zones I and II, while Zone III requires careful consideration of cloud cover, humidity, and potential shading effects.

II. Strengthening Solar Energy Policy and Investment:

Government agencies and policymakers should prioritize solar energy development in regions with the highest irradiance, particularly Zone I, to maximize energy yield and economic efficiency. Incentives such as tax credits, low-interest financing, and reduced import duties on PV components can accelerate adoption.

III. Regular Maintenance and Cleaning Protocols:

Zone I requires routine cleaning of PV panels to mitigate efficiency losses caused by dust accumulation from the Sahara Desert. Establishing community-based maintenance programs can help ensure optimal system performance, especially for rural installations.

IV. Promotion of Decentralized Renewable Energy Systems:

Given the consistent solar resource across the country, decentralized PV systems, including mini-grids and stand-alone systems, should be promoted to improve energy access in under-served and off-grid communities.

V. Seasonal Energy Management Strategies:

In Zones II and III, storage systems and hybrid configurations (e.g., solar–battery or solar–diesel hybrids) should be considered to compensate for seasonal reductions in irradiance during the rainy season.

VI. Capacity Building and Technical Training:

National programs aimed at training technicians, engineers, and local installers will help ensure high-quality system installation, reduce operational failures, and enhance long-term system reliability.

VII. Research and Development Support:

Further studies on module performance under Nigerian climatic conditions particularly effects of humidity, dust, and temperature should be supported to guide technology selection and improve system efficiency.

4.2 Policy Implications

The findings of this study carry significant implications for energy policy and planning in Nigeria. The clear spatial and seasonal variability of solar radiation underscores the need for region-specific renewable energy policies that optimize PV deployment based on local solar resource availability. Policymakers should prioritize investment in Zones I and II, where high and moderate solar irradiance can ensure maximum energy yield, while also designing supportive frameworks for Zone III to encourage reliable decentralized solar energy systems despite lower irradiance.

Incorporating these insights into national energy planning can accelerate the transition from reliance on an unstable national grid to sustainable and resilient energy systems, reducing electricity deficits and fostering rural electrification. Policies that promote financial incentives, such as subsidies, tax relief, and low-interest loans for solar installations, can stimulate private sector investment and community-level adoption. Furthermore, establishing regulatory standards for PV system design, maintenance, and performance monitoring can safeguard long-term efficiency and reliability, particularly in regions affected by dust accumulation or high humidity. Finally, integrating solar energy considerations into broader energy security and climate change strategies will not only enhance Nigeria's renewable energy portfolio but also contribute to achieving national and international sustainability targets. A coordinated approach involving government agencies, private investors, and local communities is essential to fully leverage the country's substantial solar potential.

5.0 Conclusion

The assessment of global solar radiation across climatic zones in Nigeria demonstrates a strong and geographically consistent solar resource capable of supporting widespread PV energy deployment. Zone I, located in the semi-arid northern region, exhibits the highest solar radiation levels, with minimal seasonal variation and favorable atmospheric conditions that enable sustained and efficient PV electricity generation throughout the year. Zone II presents moderate yet reliable solar irradiance, reflecting its transitional climatic characteristics; despite seasonal fluctuations, the solar resource in this zone remains sufficient for both residential and utility-scale PV applications. Zone III, situated in the humid southern region, records the lowest solar radiation values due to persistent cloud cover and high atmospheric moisture; however, even in this zone, annual averages remain above the threshold required for effective PV system performance.

Overall, the results confirm that Nigeria possesses substantial solar energy potential across all geographic zones, with each region offering viable opportunities for solar power development. The north-to-south gradient in solar irradiance highlights the need for region-specific system design, operation, and maintenance strategies, particularly considering dust accumulation in the north and cloud-related attenuation in the south. These findings provide a strong foundation for informed energy planning, guiding policymakers, investors, and system designers in optimizing

solar deployment strategies to enhance national energy security, reduce dependence on fossil fuels, and promote sustainable electrification across the country.

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