[1] Oshomah B. Abdulai
[2]Evbogbai M. J. Edeki
[3]Amhenrior E. Henry

The Influence of Tilt and Orientation on Photovoltaic System Voltage Output in Auchi, Edo North, Nigeria.

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Abstract: - This study examines how tilt angle and cardinal orientation (North, South, East, and West) affect the voltage output of solar panels throughout the day in Auchi, Edo North, Nigeria. The experimental setup consisted of an iron stand measuring 1.2 m in height, supporting four 20 W solar panels, each connected to a 75 Ah battery through an individual 12 V charge controller. Voltage readings were taken simultaneously from the four panels at a single tilt angle per day, ranging from 1° to 30° in increments of 5°, at 30-minute intervals between 17 July and 16 August 2023.The results show that tilt angle and orientation play a significant role in performance. At lower tilt angles (0°–9°), all orientations delivered closely matched and stable voltage values during peak hours (09:00–16:00). Increasing the tilt angle to around 10° improved voltage production during early morning and late afternoon, thereby widening the effective generation period and boosting total daily energy output. The south-facing panel at 10° recorded the highest peak voltage (22.9 V), exceeding its nominal open-circuit voltage and indicating local irradiance above the standard 1000 W/m² [10] or [13] (irradiance–voltage behavior). A modest decline in peak voltage was noted at tilt angles after 10 degree tilt. Overall, despite all panels following the typical daily voltage profile-rising after sunrise, reaching maximum output around midday, and falling toward sunset, the analysis highlights that optimal energy capture depends on an appropriate combination of tilt angle, orientation, and local irradiance conditions. These findings offer valuable guidance for PV system design in similarly hot and sunny environments.

Keywords: Photovoltaic (PV) systems, orientation, optimal performance, tilt angle, energy yield, and solar irradiance.

I. INTRODUCTION *(HEADING 1)*

Photovoltaic (PV) systems are increasingly vital for sustainable energy generation, particularly in regions with abundant solar resources. The performance of these systems is heavily dependent on two critical factors: the tilt angle and the orientation (azimuth) of the solar panels [1],[2]. These parameters dictate the amount of solar irradiance intercepted by the panel surface throughout the day, directly influencing the output voltage, current, and power. In regions near the equator, where the sun's path is high in the sky for most of the year, the optimal tilt and orientation can differ significantly from those in higher latitudes [3],[4].

This study aims to experimentally analyze the effects of various tilt angles (1° to 30°) and cardinal orientations (North, South, East, West) on the voltage output of a PV system in Auchi, Edo State, Nigeria. The research uses both a physical experimental setup and a MATLAB/Simulink model to plot the voltage–time characteristics. The primary goal is to identify the optimal tilt angle and orientation that maximizes voltage output and extends the daily productive period, thereby providing valuable data for local PV system designers and installers [3],[5].

The photovoltaic (PV) performance is strongly influenced by module orientation, tilt angle, and environmental conditions. Studies across sub-Saharan and tropical regions confirm that south-facing modules with tilts approximating the local latitude yield the highest annual output, with slight seasonal adjustments improving summer or winter generation [1]–[5]. Experimental assessments further demonstrate that deviations from optimal tilt or azimuth reduce energy yield by 5–15%, reinforcing the importance of location-specific optimization [3], [4], [6], [7].

Dynamic modeling research highlights that rapid irradiance and temperature fluctuations cause transient voltage drops and instability, emphasizing the need for accurate time-dependent models and enhanced MPPT algorithms [8]–[10]. Temperature-related studies show that rising module temperatures significantly lower voltage and efficiency, making thermal behavior a critical factor in predicting PV performance [11],[16]. Meanwhile, satellite-derived solar radiation databases and validated analytical frameworks offer reliable tools for resource assessment and system design across diverse climates [14]. The Voltage - Time characteristic curves revealed that the terminal voltage of the solar panels varies with time of the day, as earlier presented by [12], [13], [15], [17], [19].

The tilt angle increases slightly above the geographical site location for maximum yield of voltage during the rainy season and slightly below during the dry season as presented by [18], [19].

[1] *Oshomah Abdulai Edo State University
[2] Evbogbai M.J.Edeki Edo State University
[3] Amhenrior E. Henry Edo State University

Overall, existing literature converges on three themes: (i) optimal orientation and tilt are foundational to maximizing PV output; (ii) real-world environmental dynamics require robust, transient-capable performance models; and (iii) accurate solar resource estimation and thermal analysis are essential for reliable PV system sizing and operation. These insights provide a strong basis for the present research and guide the methodological framework applied in this study.

II. METHODOLOGY

The physical experiment was conducted at Campus I of Auchi Polytechnic, located in Auchi, Edo State, Nigeria. Auchi is the administrative headquarters of Etsako West Local Government Area and also serves as the capital of the Edo North Senatorial District. Geographically, Auchi is situated at approximately latitude 7.0676° N and longitude 6.2636° E.

The experimental setup, illustrated in Figure 1, consists of four monocrystalline photovoltaic (PV) modules rated at 20 W each, four 12 V charge controllers, four 75 Ah batteries, four 4 mm² DC cables, one clamp meter, and 2.5 mm² connecting cables. The PV modules were mounted on an iron support structure positioned 1.2 m above ground level and installed in an open area to ensure unobstructed exposure to direct solar radiation.

The support structure served as a rigid mounting platform for the four PV panels. Each panel was securely attached and designed to allow rotational adjustment between 0° and 180° along the horizontal axis, enabling controlled variation of the panel orientation during measurement of solar radiation, temperature, voltage and current.

Figure 1: Experimental setup showing the PV modules, charge controllers, batteries, and measurement instruments installed at Auchi Polytechnic.

Voltage and time data were recorded from four solar panels positioned at various tilt angles, adjusted incrementally from 1° to 30°, and oriented in four cardinal directions: North, South, East, and West. Data were recorded at regular intervals of 30 minutes throughout the day (approximately 06:00 to 19:00) for each configuration. The study period spanned from July 17 to August 16, 2024. The collected data was then plotted as voltage versus time characteristics using MATLAB Simulink scripts, 2018a edition to facilitate detailed analysis of the performance of each configuration.

III. RESULTS AND DISCUSSION

A. Voltage–Time Characteristics at Zero Tilt Angle (1°)

Figure 2 shows the voltage–time characteristics obtained on Day 1 (17 July 2024) for solar panels mounted horizontally (1° tilt) and oriented toward the North, South, East, and West. The measurements span the period from approximately 06:00 to 18:00.

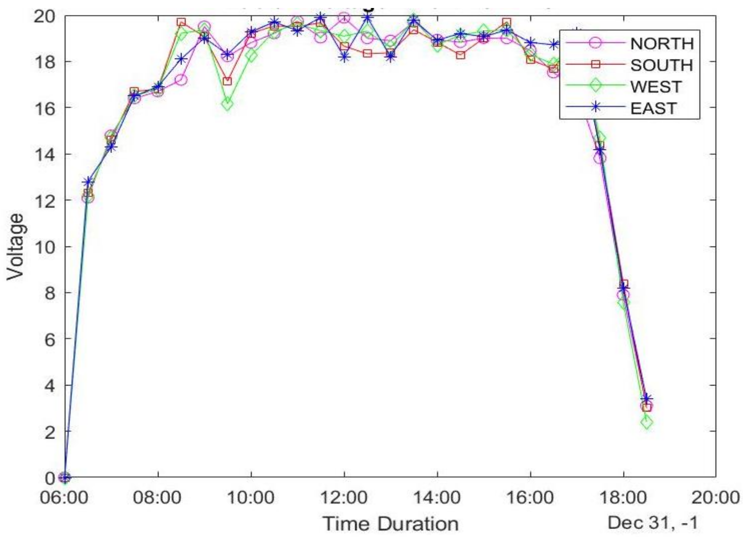

Figure 2: Voltage–Time characteristics of the solar panels at one degree (10)

All orientations exhibit a similar diurnal voltage profile. The output voltage is minimal at sunrise, increases rapidly between 07:00 and 09:00, remains nearly constant during midday, and declines sharply after 17:00. This behavior reflects the dependence of PV module voltage on incident irradiance and cell operating conditions under outdoor exposure [7]–[9].

At 10 tilt, orientation-dependent differences are negligible during peak solar hours due to the high solar altitude and dominance of diffuse radiation. Similar observations have been reported for near-equatorial regions, where horizontal or near-horizontal PV installations show limited azimuth sensitivity around solar noon [13], [17]. However, reduced voltage levels in the early morning and late evening indicate sub-optimal capture of low-angle solar radiation at this tilt [2], [10].

B. Voltage–Time Characteristics at Five Degrees (5°)

Figure 3 presents the voltage–time characteristics recorded on Day 2 (22 July 2024) when the tilt angle was increased to 5°. Measurements were taken from approximately 06:00 to 19:00 for panels facing the four cardinal directions.

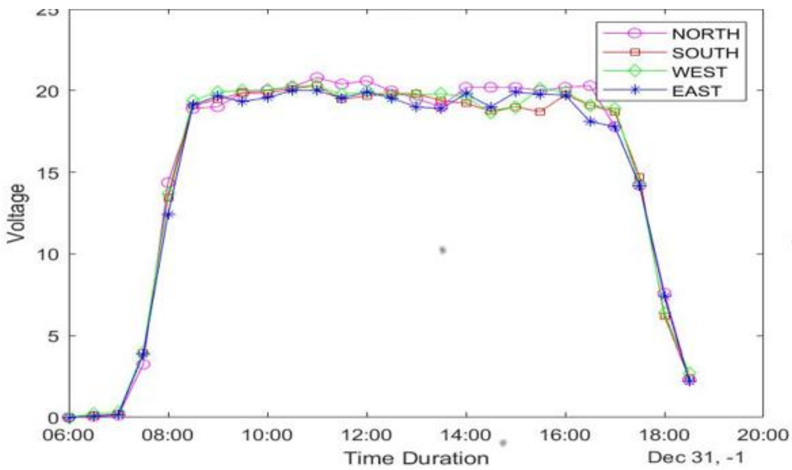

Figure 3 Voltage -Time characteristics of the solar panels at two degrees (2^0)

The voltage output rises sharply after sunrise and stabilizes within the range of 19–21 V during peak irradiance hours (08:00–17:00), followed by a rapid decline after sunset. Minimal variation among orientations is observed during midday, indicating that at low tilt angles, azimuth alignment has little influence on voltage performance in near-equatorial locations [5], [18].

This result agrees with previous studies showing that shallow tilt angles provide a wide acceptance angle for solar radiation, enabling consistent voltage output regardless of panel orientation during periods of high solar elevation [2], [13].

C. Voltage–Time Characteristics at Ten Degrees (10°)

Figure 4 shows the voltage-time response of the PV panels at a tilt angle of 10°, measured on Day 3 (27 July 2024). Compared with lower tilt angles, voltage generation begins earlier in the morning and extends slightly later into the evening.

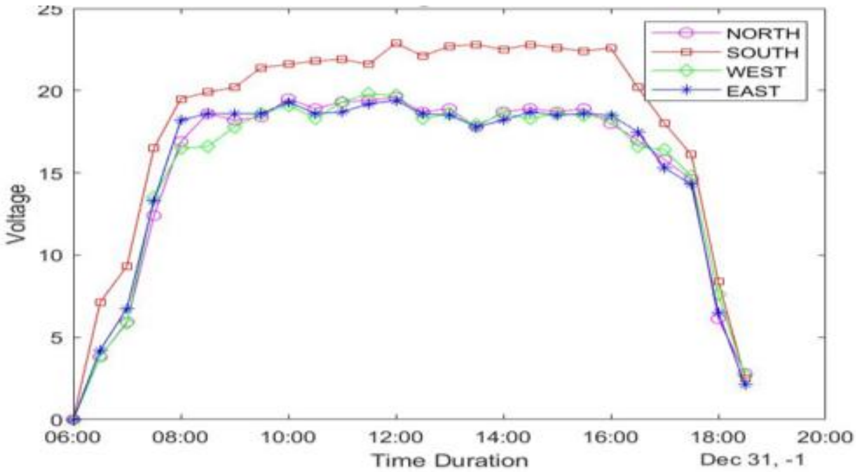

Figure 4: Voltage–Time characteristics of the solar panels at ten degrees (10^0)

Midday voltage remains stable between 20 and 21 V for all orientations, indicating limited azimuth sensitivity during peak hours. The improved morning and evening performance at this tilt is attributed to improved alignment between the panel surface and the sun's trajectory at low solar elevations [2], [3].

Experimental and modeling studies have shown that tilt angles in the range of 10°–15° in tropical regions can increase daily energy yield by approximately 6–10% compared to horizontal installations [2], [19]. East- and West-facing panels also exhibit marginal advantages during morning and evening periods, respectively, which may be beneficial for time-dependent load matching [3], [17].

D. Voltage–Time Characteristics at fifteen Degrees (15°)

Figure 5 illustrates the voltage–time characteristics obtained on Day 4 (1 August 2024) for panels inclined at 15°, covering the period from 06:00 to 20:00.

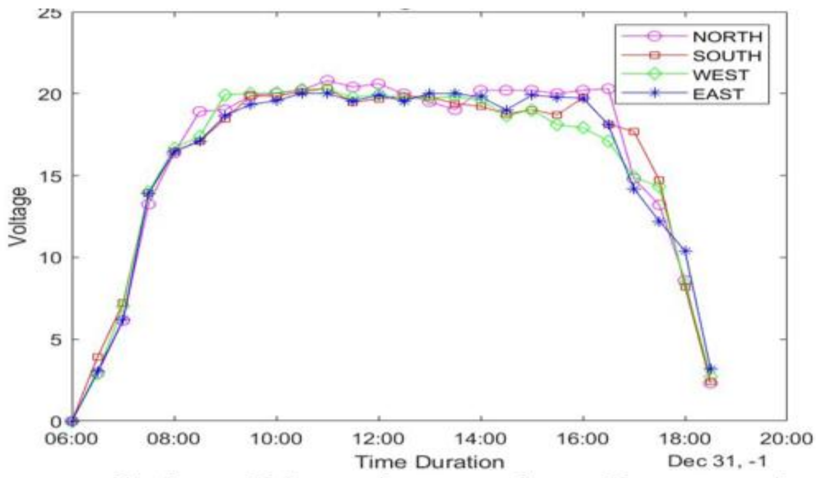

Figure 5: Voltage – Time characteristics of the solar panels at fifteen degrees (15^0)

All orientations reach peak voltages of approximately 20–21 V during midday. East- and North-facing panels attain peak voltage earlier in the morning, while South- and West-facing panels maintain higher voltages later in the afternoon. Despite these differences at the edges of the day, voltage levels during peak irradiance hours remain comparable across all orientations.

The extended high-voltage duration of the South-facing panel indicates superior daily performance, consistent with established findings that south-facing orientations maximize solar exposure in the Northern Hemisphere, including southern Nigeria [5], [18].

E. Voltage–Time Characteristics at Twenty Degrees (20°)

Figure 6 shows the voltage–time characteristics for panels inclined at 20°, recorded on Day 5 (6 August 2024).

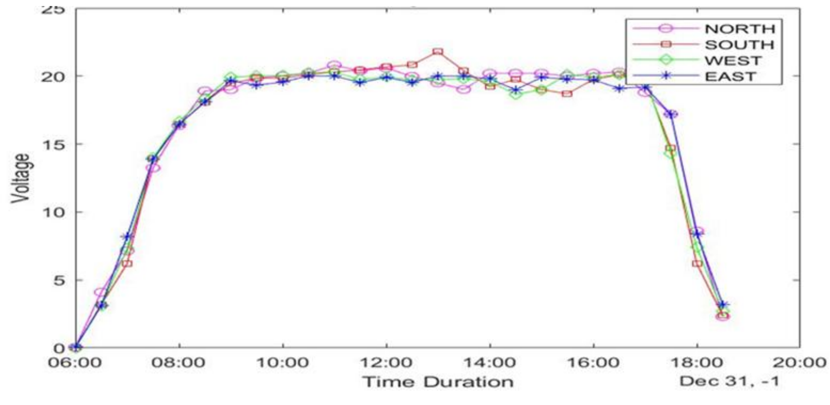

Figure 6: Voltage -Time characteristics of the solar panels at twenty degrees (20^0)

All orientations follow the expected sunrise-to-sunset trend, with peak voltages around 19–20 V.Orientation effects are most pronounced in the early morning and late afternoon. East-facing panels exhibit higher voltages shortly after sunrise, while South- and West-facing panels maintain slightly higher voltages later in the day. During midday, voltage differences are small. These results indicate that at moderate tilt angles, PV voltage output becomes less sensitive to azimuth orientation during periods of high irradiance. Similar behavior has been reported in tropical climates, where diffuse radiation dominates midday performance [6], [10], [13].

F. Voltage–Time Characteristics at Twenty-Five Degrees (25°)

Figure 7 presents the voltage–time characteristics recorded on Day 6,11th August for panels inclined at 25°. All orientations exhibit a consistent voltage rise after sunrise, a stable midday plateau, and a decline toward sunset, with peak voltages in the range of 20–21 V.

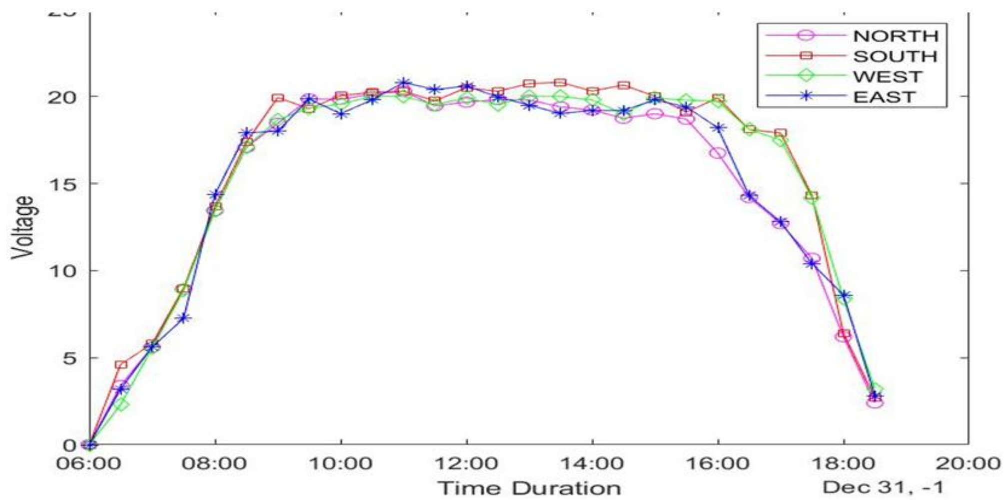

Figure 7: Voltage–Time characteristics of the solar panels at twenty five degrees (25^0)

At this tilt, voltage differences among orientations are negligible during most of the day, suggesting an expanded effective solar capture window. The increased tilt compensates for azimuth misalignment by improving incident angles over a wider range of solar positions [17], [18]. This finding supports the feasibility of flexible orientation for fixed PV installations in near-equatorial regions [1], [5].

G. Voltage–Time Characteristics at Thirty Degrees (30°)

Figure 8 shows the voltage–time response of the panels inclined at 30°, recorded on 16 August 2024. All orientations exhibit similar voltage profiles, with peak values around 19–20 V and a pronounced midday plateau.

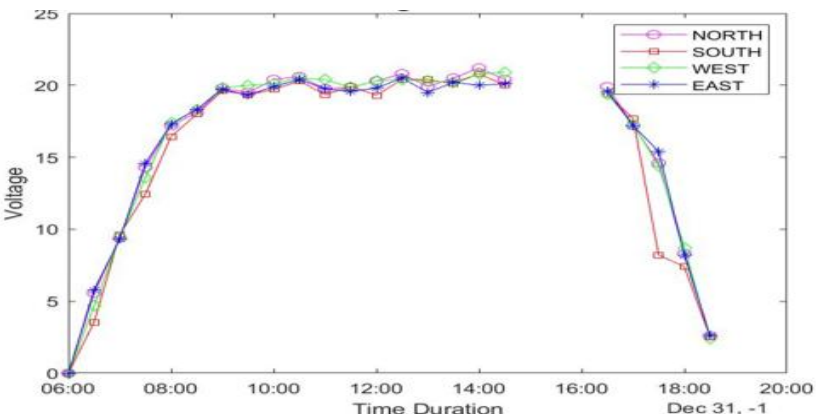

Figure 8: Voltage – Time characteristics of the solar panels at thirty degrees (30^0)

East-facing panels show a slightly faster voltage rise in the early morning; however, orientation-dependent differences become negligible by mid-morning and remain minimal throughout peak hours. At this tilt, diffuse solar radiation contributes significantly to voltage generation, reducing sensitivity to panel azimuth [8], [10], [12].

IV. CONCLUSION

The voltage- time analysis across multiple tilt angles demonstrates that PV voltage performance in Auchi, Edo North, is strongly influenced by tilt at low inclinations but becomes progressively less sensitive to orientation as tilt increases. Among the configurations studied, a south-facing panel inclined at 10° produced the highest voltage output, reaching a peak of 22.9 V at noon, and is therefore identified as the optimal configuration for the study location.

At tilt angles above 15°, voltage performance becomes increasingly influenced by environmental factors such as cloud cover and diffuse irradiance, occasionally reducing the dominance of the south-facing orientation. Overall, the results confirm that low-to-moderate tilt angles combined with a south-facing orientation maximize voltage output in near-equatorial regions, in agreement with previously reported experimental and analytical studies [2], [5], [17], [19].

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