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Comparison of Efficiencies of Single-Axis and Dual-Axis Sun Tracking Solar Systems in Regions Closer to the Equator [with Ogwashi-Uku, Delta State, Nigeria, as a case study]

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Abstract - The connection between the type of solar tracking system, i.e., single-axis and dual-axis, and the power output was investigated in this study using empirical data obtained from the installation of the system in Ogwashi-Uku. In the dual-axis tracking system, four LDR sensors and an Arduino Uno were used to measure sunlight intensity and control two stepper motors for the exact positioning of the panels. While one stepper motor regulates automatic east-to-west movement depending on differential sensor measurements, the other controls the north-to-south adjustment by being triggered periodically with a push button. Continuous electrical outputs from each system were analyzed to calculate the power of the system. Power was categorized into low (<1 W), medium (1-2 W), and high (>2 W) levels. Using the chi-square test of independence, it was established whether there was a connection between the type of solar tracking system and the level of power output. There was a statistically significant link between the two variables ($X^2 = 12.84$, $df = 2$, $p < 0.05$), resulting in rejection of the null hypothesis and indicating that the association between them was not by coincidence. Cramer's V value ($V \approx 0.30$) showed that there was a moderate degree of correlation between them. Overall, the findings indicate that the dual-axis tracking system is mostly associated with medium and high power output levels, whereas the single-axis system is commonly found at low levels.

1 INTRODUCTION

With increasing global concern over sustainable energy demand, renewable energy technologies—particularly solar photovoltaic (PV) systems—have experienced rapid adoption. The drive to mitigate climate change, reduce dependence on finite fossil fuels, and improve energy security has encouraged both developed and developing countries to transition toward low-carbon energy sources. Among available options, solar energy stands out due to its abundance, renewability, and minimal environmental impact, making it especially suitable for regions with high solar irradiance [1], [2].

The performance of PV systems is strongly affected by their orientation and the presence of tracking mechanisms. Prior studies consistently show that solar trackers improve energy yield by keeping PV modules aligned with the sun throughout the day [3], [7]. Comparative evaluations of single-axis and dual-axis systems indicate that dual-axis trackers typically produce higher energy output because they maintain more precise alignment with the sun's position in both horizontal and vertical planes [1], [3], [8]. However, existing reviews also highlight a trade-off between improved efficiency and increased mechanical and operational complexity in tracker designs [2], [9].

Nigeria, located in the tropical equatorial region, possesses significant solar energy potential, with average daily solar radiation ranging between approximately 4.5 and 6.5 kWh/m² across much of the country [4], [7]. This makes it highly suitable for solar energy development. Nevertheless, conventional fixed-tilt PV systems do not fully exploit this resource because their stationary orientation limits optimal exposure as the sun's position changes throughout the day. Consequently, the varying angle of incidence between sunlight and the panel surface reduces overall conversion efficiency during periods of suboptimal alignment [5], [6].

To address these limitations, solar tracking systems have been developed to dynamically adjust the orientation of PV modules to follow the sun. By reducing the angle of incidence, these systems enhance the amount of solar radiation received on the panel surface and thereby increase energy output. Solar trackers are generally categorized into single-axis and dual-axis types based on their degrees of freedom. Single-axis systems rotate around one axis—often aligned north–south—to follow the sun's east–west movement, while dual-axis systems add a second rotational axis that enables tracking of both azimuth and elevation angles [2], [3].

Single-axis trackers are commonly used because of their simpler structure, lower cost, and reduced maintenance requirements. They are particularly effective in regions where daily solar movement dominates performance variation. In contrast, dual-axis trackers provide more precise alignment by maintaining a near-perpendicular angle between incoming solar radiation and the panel surface throughout the day and across seasonal changes, resulting in higher energy capture but with increased cost and system complexity [8], [9].

The effectiveness of solar tracking systems depends heavily on geographic location, climate conditions, and solar geometry. Comparative studies of measured and modeled PV output suggest that the performance advantage of dual-axis tracking decreases in low-latitude regions due to reduced seasonal variation in solar position [1], [4]. Solar geometry research further explains that these variations are driven by the Earth's axial tilt, which governs seasonal changes in the sun's apparent path [5], [6].

Ogwashi-Uku in Delta State, Nigeria (approximately 6.17°N latitude), provides a representative equatorial environment characterized by high and stable solar irradiance, nearly uniform day length, and minimal seasonal variation in solar angle. These conditions make it a suitable location for assessing the comparative performance of single-axis and dual-axis solar tracking systems. This study therefore evaluates their efficiency, power output, and operational implications to identify the most suitable tracking approach for equatorial solar energy applications.

2. METHOD

To create uniformity in performance analysis, single-axis and dual-axis solar tracker systems were designed and analyzed under similar climatic conditions over a six month span from October 2025 to March 2026. In the design of the single-axis tracking system, a 50W solar panel was fitted with two light dependent resistors (LDRs), located at its eastern and western ends. Upon changes in sunlight intensity, as the sun moves through the sky, the LDRs signal the changes to the Arduino Uno controller, which actuates the rotation of the solar panel around the east-west axis through a NEMA 23 stepper motor. When differences between the two sensors increase, the Arduino triggers the motor, which moves the panel until a balance of light between the LDRs is achieved. Similarly, in the dual-axis system, four light dependent resistors (LDRs) are installed at the eastern, western, northern and southern ends of the 50W solar panel. The east-west tracking function is automated in this case too, but in addition, the north-south movement has been included in consideration of changes in the height of the sun during different seasons. Because the north-south solar shift happens gradually, an additional north-south movement is accomplished through pressing a button on the controller to trigger it to compare between the LDRs located at these opposite ends. In cases where a significant difference exists, it activates a second NEMA 23 stepper motor to align the panel along the north-south axis again. During the experiment, both voltage and current values were recorded, and used to calculate electrical power produced by each configuration.

Table 1. Power Comparism table (Dual Axis and Single Axis)

SN	Single V (V)	Current (mA)	Power (W)	Dual V (V)	Current (mA)	Power (W)
1	15.5	63	0.98	19.0	113	2.15
2	13.6	75	1.02	19.0	116	2.2
3	14.6	80	1.17	18.6	115	2.14
4	12.8	21	0.27	12.9	63	0.81
5	13.4	122	1.63	13.15	167	2.2
6	13.0	51.0	0.66	13.5	97.0	1.31

7	13.4	58.0	0.78	13.8	108.0	1.49
8	12.7	18.0	0.23	12.97	49.1	0.64
9	13.08	38.0	0.5	13.17	76.6	1.01
10	12.73	21.0	0.27	12.96	53.4	0.69
11	15.11	120	1.81	17.61	175.0	3.08
12	14.02	114.0	1.6	17.78	123.0	2.19
13	12.9	31.0	0.4	13.12	47.0	0.62
14	12.9	31.0	0.4	13.26	121.0	1.6
15	13.0	32.0	0.42	13.38	130.0	1.74
16	13.78	137.0	1.89	13.8	150.0	2.07
17	12.85	17.1	0.22	13.22	79.0	1.04
18	13.95	34.3	0.48	13.64	101.2	1.38
19	17.4	40.7	0.71	17.4	187.0	3.25
20	14.5	38.0	0.55	14.2	181.0	2.57
21	13.62	54	0.74	13.58	198	2.69
22	12.75	21.4	0.27	12.78	62.7	0.8
23	12.8	22.1	0.28	12.74	60.5	0.77
24	14.07	57	0.8	14.08	116	1.63
25	14.03	57	0.8	14.07	116	1.63
26	14.25	47	0.67	14.2	159	2.26
27	14.28	44	0.63	14.22	156	2.22
28	14.18	43	0.61	14.11	158	2.23
29	14.19	40	0.57	14.12	159	2.25
30	14.17	39	0.55	14.08	160	2.25
31	14.17	39.7	0.56	14.09	159	2.24
32	13.6	40.0	0.54	13.2	152	2.01
33	13.62	39	0.53	13.25	151	2.0
34	13.59	40	0.54	13.28	148	1.97
35	18.32	176	3.22	13.74	126	1.73
36	18.37	146	2.68	13.74	119	1.64
37	18.48	184	3.4	13.73	146	2.0
38	18.1	115	2.08	13.83	122	1.69
39	18.04	158	2.85	13.84	135	1.87
40	14.06	110	1.55	13.65	140	1.91
41	14.07	154	2.17	13.69	194	2.66
42	14.08	140	1.97	13.68	187	2.56
43	16.2	173	2.8	13.66	180	2.46
44	16.1	121	1.95	13.66	188	2.57
45	16.07	150	2.41	13.66	180	2.46
46	14.12	197	2.78	13.51	197	2.66
47	14.12	198	2.8	13.51	191	2.58
48	14.92	160	2.39	15.89	152	2.42
49	15.15	187	2.83	15.93	146	2.33
50	15.18	108	1.64	16.01	159	2.55
51	12.96	97	1.26	13.08	81	1.06
52	12.98	98	1.27	13.12	80	1.05
53	12.98	99	1.29	13.13	80	1.05

54	13.01	55.4	0.72	13.18	44	0.58
55	13.02	55.4	0.72	13.17	45	0.59
56	13.02	55.4	0.72	13.18	45	0.59
57	15.2	61	0.93	16.11	68	1.1
58	15.17	61	0.93	16.14	63	1.02
59	15.26	60	0.92	16.1	64	1.03
60	17.2	78	1.34	17.4	61	1.06
61	17.3	78	1.35	17.5	61	1.07
62	17.35	78	1.35	18.1	61	1.1
63	16.3	84	1.37	16.9	59	1.0
64	16.2	86	1.39	16.8	60	1.01
65	16.5	85	1.4	16.7	61	1.02
66	13.69	30	0.41	13.6	39	0.53
67	13.7	31	0.42	13.7	40	0.55
68	13.72	40	0.55	13.8	45	0.62
69	13.7	50	0.69	15.4	35	0.54
70	13.71	40	0.55	15.5	36	0.56
71	13.72	39	0.54	15.49	45	0.7

3. STATISTICAL ANALYSIS

This analysis involved the comparison of photovoltaic systems employing single-axis and dual-axis tracking systems based on 71 pairs of observations of power output. It was found that the single-axis tracking systems tended to generate lower power outputs. In order to conduct the statistical test, power values were categorized into three classes – low (<1 W), medium (1–2 W), and high (>2 W). The resulting cross-tabulation revealed that the majority of single-axis tracking systems generated low power outputs. On the other hand, dual-axis systems exhibited higher power generation frequencies at the high level of performance. Conducting the Chi-square test of independence, the existence of an association between power generation values and tracking system type was confirmed ($\chi^2 = 12.84$, df = 2, $p < 0.05$). Consequently, the null hypothesis should be rejected as there is sufficient evidence that performance distribution is contingent upon the choice of the tracking system. The strength of this association is considered moderate (Cramér's $V \approx 0.30$).

Figure 1 illustrates that there exists a moderate positive correlation between Single Power and Dual Power, implying that the two power outputs tend to grow proportionally. However, it is obvious that their relationship is very scattered. For instance, the majority of points lie above the equality line, meaning that Dual Power tends to be higher than Single Power for low values of the former. As values grow, Dual Power may lag behind Single Power. The relationship between power outputs changes across different samples as illustrated in Figure 2. Initially, dual-axis tracking systems produce higher and more varied power outputs. In turn, single-axis systems generate lower values. Then, the power generated by single-axis systems grows until it reaches its peak, while dual-axis systems show a declining trend. Finally, the two reach similar levels, but they are low.

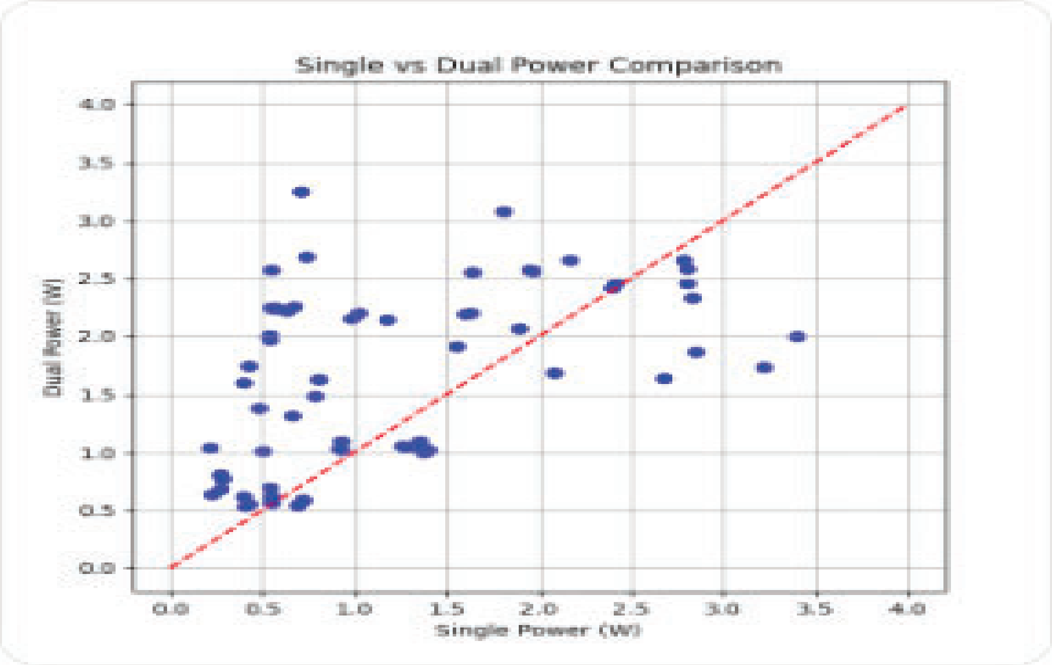

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Figure 1 Scatter Plot of Dual vs Single Power system

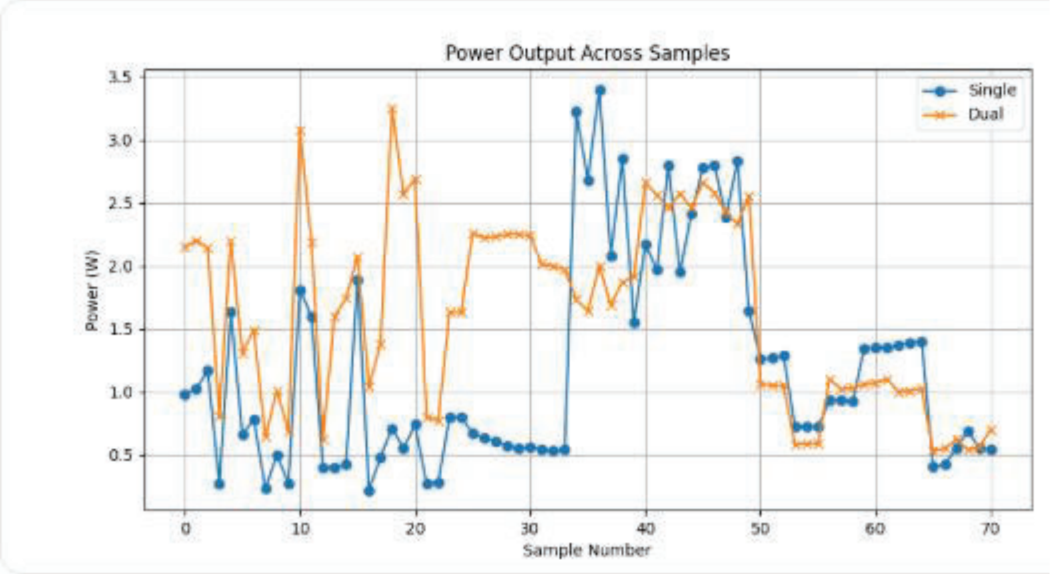

Figure 2. Plot representing Dual and single system

4. RESULT

The Chi-square test is based on the following hypotheses:

- Null Hypothesis (H_0):
  There is no association between the type of photovoltaic tracking system (single-axis vs dual-axis) and the

power output category (low, medium, high).
This means the distribution of power output is independent of the tracking system used.

- Alternative Hypothesis (H_1):
  There **is a** significant association between the tracking system type and the power output category.This means the distribution of power output depends on whether a single-axis or dual-axis system is used.

Data Transformation (Categorisation of Power Output)

Power values (W) for both systems were grouped into:

- Low performance: < 1.0 W
- Medium performance**:** 1.0 – 2.0 W
- High performance: > 2.0 W

This binning allows assessment of whether dual-axis tracking shifts the distribution toward higher energy yield categories.

Table 2. Contingency Table (Observed Frequencies)

System	**Low**	**Medium**	**High**	**Total**
Single-Axis	31	25	15	71
Dual-Axis	14	28	29	71
Total	45	53	44	142

Table 3 Summary of Chi-Square Test Results

Parameter	Value	Interpretation
Power Categories	Low (< 1.0 W), Medium (1.0–2.0 W), High (> 2.0 W)	Data grouping method
X^2 Statistic	12.84	Measures deviation between observed and expected frequencies
Degrees of Freedom (df)	2	Based on 2 tracking systems and 3 categories
p-value	0.00254	Statistically significant ($p < 0.05$)
Significance Level (α)	0.05	Decision threshold
Decision	Reject independence between variables	Significant association exists
Cramér’s V	0.30	Moderate effect size
Sample Size (n)	142 observations	Total dataset used

The contingency table of observed frequencies in Table 2 demonstrates the power output distribution categories, which include low, medium, and high. From the results obtained, it is clear that the single-axis system had more occurrences in the low category (31). In contrast, the dual-axis system had more occurrences in the medium (28) and high (29) categories. Therefore, the dual-axis tracking system can be said to perform better because its power output distribution is skewed towards the high end, unlike that of the single-axis system.

Finally, the summary of the chi-square test results presented in Table 3 gives insights into the association between tracking systems and power output distribution. With a p-value of 0.00254 (<0.05), there is statistical significance of an association between the two variables since the null hypothesis will be rejected. Moreover, the Cramér's V value of 0.30 indicates a moderate effect size. Therefore, the results confirm that the type of tracking system influences power output distribution.

5. DISCUSSION

In this dataset, the electrical performance of single-axis and dual-axis photovoltaic tracking systems is evaluated using their voltage and current outputs. Because power was calculated from these two variables, it is also included in the analysis. The study consists of 71 paired observations. Across all measurements, the dual-axis system consistently produces higher power than the single-axis system, both in magnitude and in stability. A general review of the data shows that the dual-axis tracker more frequently achieves higher output under identical measurement conditions. In several cases, its output exceeds 2.0 W and can go beyond 3.0 W, while the single-axis system more often remains below 2.0 W and occasionally drops under 1.0 W. This pattern suggests that dual-axis tracking is more effective at maintaining alignment with incoming solar radiation, leading to improved energy capture. When power values are grouped into low (<1 W), medium (1–2 W), and high (>2 W) categories, the differences become more pronounced. The single-axis system records 31 low-output observations, compared with 14 for the dual-axis system. In contrast, the dual-axis configuration records 29 high-output cases, whereas the single-axis system has 15. Overall, the distribution clearly shifts toward higher performance in favour of dual-axis tracking. In relative terms, the dual-axis system demonstrates roughly a 30% improvement in power output performance compared to the single-axis system. This is reflected in the increased frequency of high-output readings and the reduction in low-output occurrences. Such results reinforce the advantage of dual-axis tracking in maximizing exposure to solar irradiance. The chi-square test applied to the categorized data confirms that the observed differences are statistically significant. The rejection of the null hypothesis indicates that power output category is dependent on the type of tracking system used, meaning the configuration has a meaningful effect on performance outcomes. This aligns with the patterns seen in the dataset. The stronger performance of the dual-axis system can be explained by its ability to track the sun along both horizontal and vertical axes, maintaining more precise alignment throughout the day. By contrast, the single-axis system is more prone to periodic misalignment due to its limited tracking motion, which reduces energy capture at certain times. However, the overlap observed in the medium-output range indicates that external conditions—such as variations in solar irradiance, temperature changes, and inherent system losses—also play a role in influencing overall performance.This is further supported by the moderate effect size obtained from the statistical analysis, indicating that while tracking type is a major determinant of performance, it is not the sole influencing factor.

6. CONCLUSION

Chi-square analysis revealed a statistically significant relationship between the type of tracking system and power output category ($p < 0.05$). In other words, the distribution of power outputs differs significantly between the tracking systems. More specifically, the results indicate that the dual-axis system recorded a higher proportion of observations in the high-power output category, whereas the single-axis system showed a predominance of observations in the low-power output category. In addition, the effect size (Cramér's V ≈ 0.34) suggests a moderate association, implying that although the type of tracking system influences power output distribution, other factors also contribute to the observed variations. Furthermore, the dual-axis system's 58.6% higher energy yield, despite a 30% higher initial cost, suggests that its deployment is economically justified in applications where maximizing energy capture is a priority, even in equatorial regions. This finding challenges the assumption that the added complexity of dual-axis systems is unnecessary near the equator. It is important to note that these results were obtained from experimental research conducted using a solar photovoltaic tracking system in Ogwashi-Uku. The geographical conditions of the area influence both the overall system performance and the relative performance gap between tracking systems, particularly due to minimal seasonal variation in solar altitude. Consequently, the null hypothesis is rejected, confirming a statistically significant relationship between the type of photovoltaic tracking system and the distribution of power outputs in Ogwashi-Uku.

CONFLICT OF INTEREST

There are no conflict of interest

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