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Research Article

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Special Issue
A Themed Issue in Honour of Professor Onukwuli Okechukwu Dominic (FAS).

This special issue is dedicated to Professor Onukwuli Okechukwu Dominic (FAS), marking his retirement and celebrating a remarkable career. His legacy of exemplary scholarship, mentorship, and commitment to advancing knowledge is commemorated in this collection of works.

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Analysis of the performance of rooftop mounted PV panels against horizontal panels and inclined panels

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Abstract
This study presents an experimental investigation of the performance of roof-top mounted photovoltaic (PV) panels compared to horizontal panels and panels inclined at the angle of the latitude. The aim is to provide technical recommendations for the optimal installation angle of PV panels, which is easy to implement in the absence of a tracking system. The materials utilized in this study include twelve 100W PV panels and twenty-four digital ammeters and voltmeters. Hourly measurements of the current and voltage from the PV panels placed in the following settings – rooftop (4), inclined (4), and horizontal (4) – were recorded over one year. Results obtained showed that the orientation of the PV panel plays a crucial role due to the rotation of the Earth. Inclined panels achieved the highest performance with superior current, voltage, and power outputs throughout the day. An 8-degree inclination angle (corresponding to the latitude) optimizes sunlight exposure while rooftop panels performed well but are affected by shading in the early morning and late afternoon, resulting in slightly lower performance compared to inclined panels. The key recommendations are that panels inclined at an 8-degree angle (matching the angle of latitude) provide the best performance, maximizing sunlight exposure and power output, and for rooftop installations, it is crucial to account for shading during sunrise and sunset, as positioning panels to minimize shading can significantly enhance overall performance.

Keywords: Solar, panels, inclined, horizontal, rooftop

1. Introduction

The global demand for renewable energy sources has surged in recent years, driven by the need to mitigate climate change, reduce greenhouse gas emissions, and achieve energy security. Among the various renewable energy technologies, photovoltaic (PV) systems have emerged as a prominent solution for harnessing solar energy. PV systems convert sunlight directly into electricity, offering a clean and sustainable energy source. The efficiency and performance of PV panels are influenced by several factors, including their orientation, tilt angle, and mounting configuration.

Rooftop-mounted PV panels have gained popularity due to their ability to utilize existing structures, such as residential and commercial buildings, without requiring additional land. This configuration not only maximizes the use of available space but also reduces installation costs and minimizes environmental impact. However, the performance of rooftop-mounted PV panels can vary significantly based on their orientation and tilt angle. Horizontal PV panels, which are installed parallel to the ground, are often used in large-scale solar farms and flat-roof installations. While this configuration simplifies installation and maintenance, it may not always provide optimal energy generation due to suboptimal exposure to sunlight, especially in regions with varying solar angles throughout the year. On the other hand, PV panels inclined at the angle of the latitude are designed to maximize solar energy capture by aligning the panels with the sun's path. This configuration aims to achieve the highest possible energy yield by optimizing the angle of incidence of sunlight on the PV panels. The angle of inclination is typically set equal to the latitude of the installation site, ensuring that the panels receive maximum sunlight throughout the year.

The performance of photovoltaic (PV) panels is influenced by various factors, including their orientation, tilt angle, and mounting configuration. Numerous studies have been conducted to evaluate the performance of different panel configurations. Studies have shown that rooftop-mounted PV panels can effectively harness solar energy, but their performance is influenced by factors such as shading, roof orientation, and tilt angle (Peng & Yang, 2016; Tarigan, 2018; Patankar et al., 2017; Sharma et al., 2018; Smith et al., 2018; Lee et al., 2017; Gupta et al., 2017; Kumar et al., 2018; Wang et al., 2019; Patel et al., 2019). Horizontal PV panels, installed parallel to the ground, are commonly used in large-scale solar farms and flat-roof installations. This configuration simplifies installation and maintenance but may not always provide optimal energy generation due to suboptimal exposure to sunlight. Research has shown that horizontal PV panels can be more efficient at capturing diffuse solar radiation, especially in regions with high levels of diffuse sunlight. However, their performance is significantly influenced by environmental factors such as temperature and humidity (Nassa et al, 2022; Booker, 2018). PV panels inclined at the angle of the latitude are designed to maximize solar energy capture by aligning the panels with the sun's path. This configuration aims to achieve the highest possible energy yield by optimizing the angle of incidence of sunlight on the PV panels. Studies have demonstrated that the optimal tilt angle for PV panels varies based on geographical location, season, and application. Research has also shown that adjusting the tilt angle on a monthly or seasonal basis can further enhance energy generation (Sumita et al., 2024; Mohammed & Alibaba, 2021; Amajama, 2017; Ukoima et al., 2024a; Ukoima et al., 2023; Ukoima et al., 2024b; Ukoima et al., 2024c).

These studies focused on evaluating the performance of these configurations individually. However, there is a lack of comprehensive studies that compare the performance of all three configurations combined. This research aims to fill this gap by conducting an experimental investigation to compare the energy output, efficiency, and overall performance of rooftop-mounted PV panels, horizontal PV panels, and PV panels inclined at the angle of the latitude. By analyzing these different configurations together, this study seeks to provide valuable insights into the optimal design and installation practices for PV systems, ultimately supporting the development of more efficient and effective solar energy solutions.

2. Study location

The study area is named Okorobo-Ile in Andoni Local Government Area of Rivers State, Nigeria. It is located at 4.47°N and 7.58°E. The site solar data was obtained from NASA solar energy radiation database as shown in figure 1. The village has an average solar irradiation of 4.27 kWh/m^2/d. This shows good potential for generating electricity from the sun.

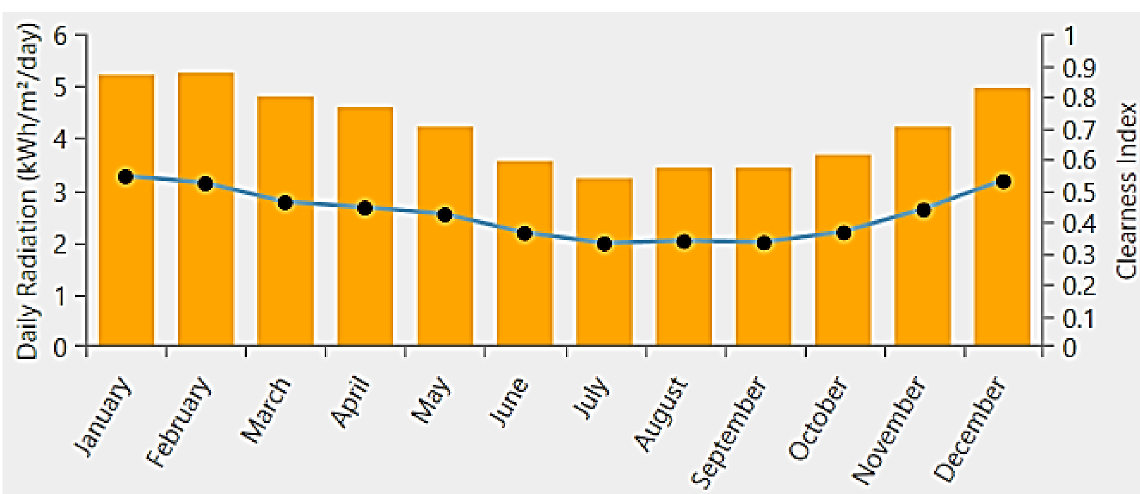

Figure 1: Solar radiation profile with clearness index from NASA

3. Materials and methods

3.1 Materials

3.1.1 PV Panels

The setup consisted of five solar panels inclined at different angles including the optimal angle obtained from PVGIS. Polycrystalline PV modules are used. The electrical power output of a solar PV panel is given as:

$$P = cf\left(\frac{g_t}{g_{t,stc}}\right)\left[1 + \gamma\left(t_c - t_{c,stc}\right)\right] \quad (1)$$

c= rated capacity of the PV panel, f= PV panel derating factor, g_t= instantaneous radiation on the PV panel (kW m^{-2}), $g_{t,stc}$= radiation on the PV panel at standard test condition (stc) (1 kW m^{-2}), γ= temperature coefficient of power (%/°C), t_c= instantaneous cell temperature (°C), $t_{c,stc}$= cell temperature at stc (°C). The electrical characteristics of the pv panel is given in table 1 while the temperature coefficients is given in table 2

Table 1: PV panel electrical characteristic

Electrical characteristic	Value
Maximum Power (Pmax)	100W
Voltage at Pmax (Vmp)	18V
Current at Pmax (Imp)	5.56A
Open Circuit Voltage (Voc)	22V
Short Circuit Current (Isc)	6.11A
Module Efficiency	15.5%

Table 2: PV panel temperature coefficients

Temperature coefficient	Value
Pmax	-0.45%/°C
Voc	0.35%/°C
Isc	
+0.05%/°C	

3.1.2 Digital Ammeter and Voltmeter

This is used to measure the current and voltage generated from the solar panels.

3.2 Methodology

1. **Site Selection**: The experiment was conducted at a specific site, with latitude and longitude accurately determined using GPS technology. The geographic location is critical for aligning panel angles with the sun's trajectory and ensuring optimal exposure to sunlight.

2. **Panel Setup:**
   i. **Rooftop Panels**: Four panels were installed on the rooftop, one on each side (north, south, east, west), reflecting real-world rooftop orientations. This setup aims to simulate typical residential or commercial rooftop installations, accounting for shading effects throughout the day (Figure 2).
   ii. **Inclined Panels:** Four panels were placed on the ground, each inclined at the site's latitude angle and facing the same orientation as the rooftop panels. This configuration represents the optimal tilt for maximizing solar energy capture, as supported by existing studies.
   iii. **Horizontal Panels:** Four panels were positioned horizontally on the ground (tilt angle = 0°) to measure their effectiveness in capturing diffuse sunlight.
3. **Instrumentation:** Digital voltmeters, ammeters and data loggers were used to measure and record current and voltage outputs at hourly intervals between 06:00 and 18:00, ensuring a comprehensive dataset.
4. **Data Analysis:** The collected data were statistically analyzed to compare the energy generation of different panel configurations. Standard deviation, variance, and percentage differences were calculated to evaluate performance consistency and identify significant trends.

The energy generated by the solar panels, denoted as E_p, is expressed in equation (2) as:

$$Ep = Power\ obtained\ (IV)\ x\ duration\ of\ sunshine\ x\ number\ of\ (s) \quad (2)$$

Figure 2: Aerial view of roof top

4. Results

4.1 Results of average values for the year

4.1.1: Average data values

Table 3: Average PV panel data general performance characteristics

Time (Hour)	Rooftop Current (A)	Rooftop Voltage (V)	Rooftop Power (W)	Inclined Current (A)	Inclined Voltage (V)	Inclined Power (W)	Horizontal Current (A)	Horizontal Voltage (V)	Horizontal Power (W)
06:00	0.2	12.5	2.5	0.3	12.7	3.81	0.1	12.3	1.23
07:00	0.5	13.0	6.5	0.6	13.2	7.92	0.4	12.8	5.12
08:00	1.0	13.5	13.5	1.2	13.7	16.44	0.8	13.3	10.64
09:00	1.5	14.0	21.0	1.7	14.2	24.14	1.2	13.8	16.56
10:00	2.0	14.5	29.0	2.2	14.7	32.34	1.6	14.3	22.88
11:00	2.5	15.0	37.5	2.7	15.2	41.04	2.0	14.8	29.6
12:00	3.0	15.5	46.5	3.2	15.7	50.24	2.4	15.3	36.72
13:00	3.5	16.0	56.0	3.7	16.2	59.94	2.8	15.8	44.24
14:00	3.0	15.5	46.5	3.2	15.7	50.24	2.4	15.3	36.72
15:00	2.5	15.0	37.5	2.7	15.2	41.04	2.0	14.8	29.6
16:00	2.0	14.5	29.0	2.2	14.7	32.34	1.6	14.3	22.88
17:00	1.5	14.0	21.0	1.7	14.2	24.14	1.2	13.8	16.56
18:00	1.0	13.5	13.5	1.2	13.7	16.44	0.8	13.3	10.64

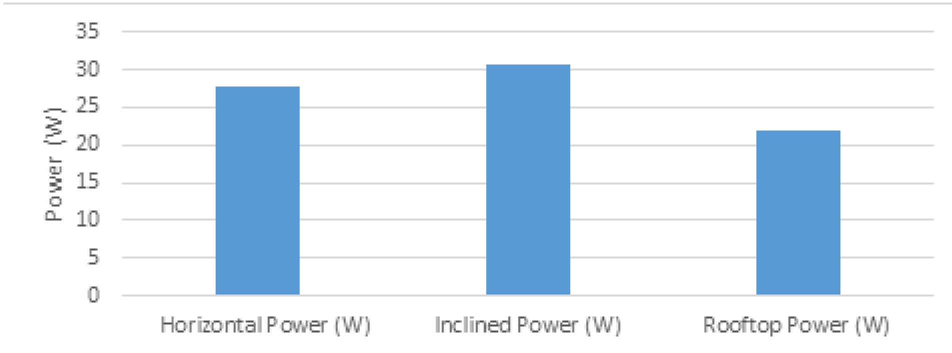

Figure 3: Average power from average data

4.1.2: Result from roof – top (RT) mounted PV panels

Table 4: Roof-top (RT) data

Time (Hour)	RT A (A)	RT A (V)	RT A (W)	RT B (A)	RT B (V)	RT B (W)	RT C (A)	RT C (V)	RT C (W)	RT D (A)	RT D (V)	RT D (W)
06:00	0.1	12.5	1.25	0.1	12.5	1.25	0.2	12.5	2.5	0.2	12.5	2.5
07:00	0.3	13.0	3.9	0.3	13.0	3.9	0.4	13.0	5.2	0.4	13.0	5.2
08:00	0.8	13.5	10.8	0.8	13.5	10.8	1.0	13.5	13.5	1.0	13.5	13.5
09:00	1.2	14.0	16.8	1.2	14.0	16.8	1.5	14.0	21.0	1.5	14.0	21.0
10:00	1.6	14.5	23.2	1.6	14.5	23.2	2.0	14.5	29.0	2.0	14.5	29.0
11:00	2.0	15.0	30.0	2.0	15.0	30.0	2.5	15.0	37.5	2.5	15.0	37.5
12:00	2.4	15.5	37.2	2.4	15.5	37.2	3.0	15.5	46.5	3.0	15.5	46.5
13:00	2.8	16.0	44.8	2.8	16.0	44.8	3.5	16.0	56.0	3.5	16.0	56.0
14:00	2.4	15.5	37.2	2.4	15.5	37.2	3.0	15.5	46.5	3.0	15.5	46.5
15:00	2.0	15.0	30.0	2.0	15.0	30.0	2.5	15.0	37.5	2.5	15.0	37.5
16:00	1.6	14.5	23.2	1.6	14.5	23.2	2.0	14.5	29.0	2.0	14.5	29.0
17:00	1.2	14.0	16.8	1.2	14.0	16.8	1.5	14.0	21.0	1.5	14.0	21.0
18:00	0.8	13.5	10.8	0.8	13.5	10.8	1.0	13.5	13.5	1.0	13.5	13.5

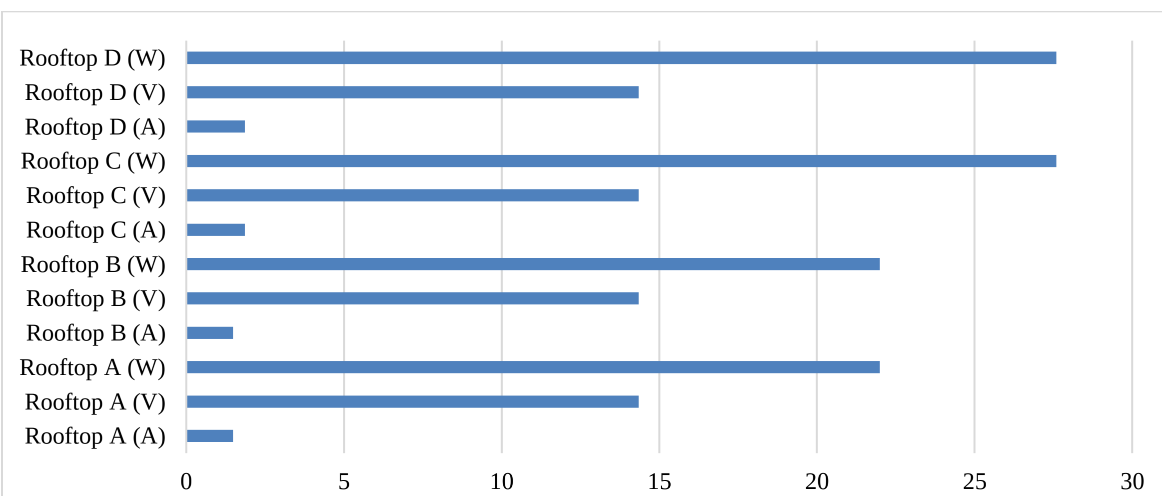

Figure 4: Roof top mounted PV panels comparison

4.1.3: Result from horizontal PV panels

Table 5: Data from horizontal pv panels

Time (Hour)	Horizontal A (A)	Horizontal A (V)	Horizontal A (W)	Horizontal B (A)	Horizontal B (V)	Horizontal B (W)	Horizontal C (A)	Horizontal C (V)	Horizontal C (W)	Horizontal D (A)	Horizontal D (V)	Horizontal D (W)
06:00	0.1	12.3	1.23	0.1	12.3	1.23	0.1	12.3	1.23	0.1	12.3	1.23
07:00	0.4	12.8	5.12	0.4	12.8	5.12	0.4	12.8	5.12	0.4	12.8	5.12
08:00	0.8	13.3	10.64	0.8	13.3	10.64	0.8	13.3	10.64	0.8	13.3	10.64
09:00	1.2	13.8	16.56	1.2	13.8	16.56	1.2	13.8	16.56	1.2	13.8	16.56
10:00	1.6	14.3	22.88	1.6	14.3	22.88	1.6	14.3	22.88	1.6	14.3	22.88
11:00	2.0	14.8	29.6	2.0	14.8	29.6	2.0	14.8	29.6	2.0	14.8	29.6
12:00	2.4	15.3	36.72	2.4	15.3	36.72	2.4	15.3	36.72	2.4	15.3	36.72
13:00	2.8	15.8	44.24	2.8	15.8	44.24	2.8	15.8	44.24	2.8	15.8	44.24
14:00	2.4	15.3	36.72	2.4	15.3	36.72	2.4	15.3	36.72	2.4	15.3	36.72

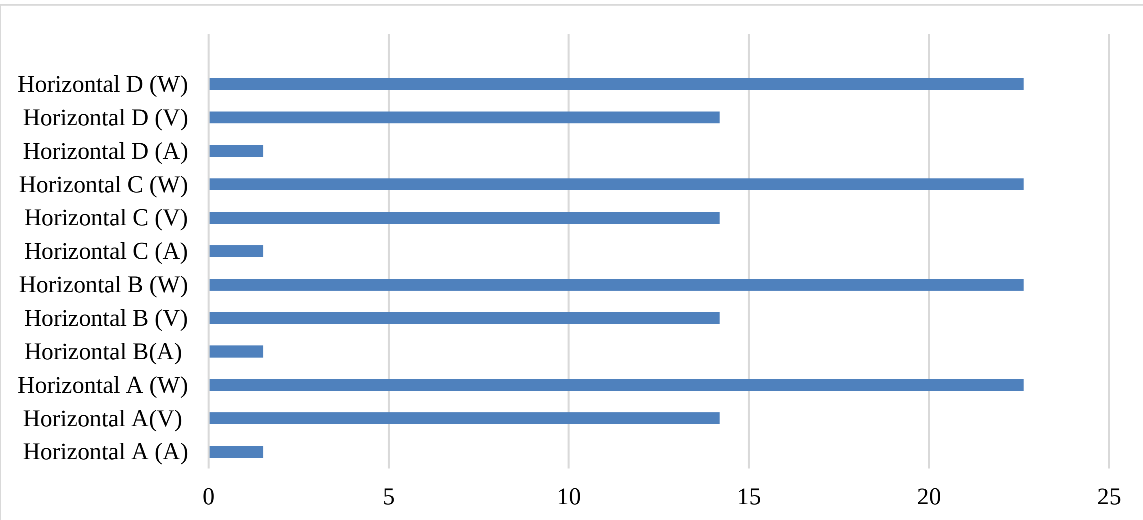

Figure 5: Horizontal panel comparison

4.1.4: Result from Inclined (IC) PV panels

Table 6: Data from inclined (IC) pv panels

Time (Hour)	IC A (A)	IC A (V)	IC A (W)	IC B (A)	IC B (V)	IC B (W)	IC C (A)	IC C (V)	IC C (W)	IC D (A)	IC D (V)	IC D (W)
06:00	0.3	12.7	3.81	0.3	12.7	3.81	0.3	12.7	3.81	0.3	12.7	3.81
07:00	0.6	13.2	7.92	0.6	13.2	7.92	0.6	13.2	7.92	0.6	13.2	7.92
08:00	1.2	13.7	16.44	1.2	13.7	16.44	1.2	13.7	16.44	1.2	13.7	16.44
09:00	1.7	14.2	24.14	1.7	14.2	24.14	1.7	14.2	24.14	1.7	14.2	24.14
10:00	2.2	14.7	32.34	2.2	14.7	32.34	2.2	14.7	32.34	2.2	14.7	32.34

11:00	2.7	15.2	41.04	2.7	15.2	41.04	2.7	15.2	41.04	2.7	15.2	41.04
12:00	3.2	15.7	50.24	3.2	15.7	50.24	3.2	15.7	50.24	3.2	15.7	50.24
13:00	3.7	16.2	59.94	3.7	16.2	59.94	3.7	16.2	59.94	3.7	16.2	59.94
14:00	3.2	15.7	50.24	3.2	15.7	50.24	3.2	15.7	50.24	3.2	15.7	50.24
15:00	2.7	15.2	41.04	2.7	15.2	41.04	2.7	15.2	41.04	2.7	15.2	41.04
16:00	2.2	14.7	32.34	2.2	14.7	32.34	2.2	14.7	32.34	2.2	14.7	32.34
17:00	1.7	14.2	24.14	1.7	14.2	24.14	1.7	14.2	24.14	1.7	14.2	24.14
18:00	1.2	13.7	16.44	1.2	13.7	16.44	1.2	13.7	16.44	1.2	13.7	16.44

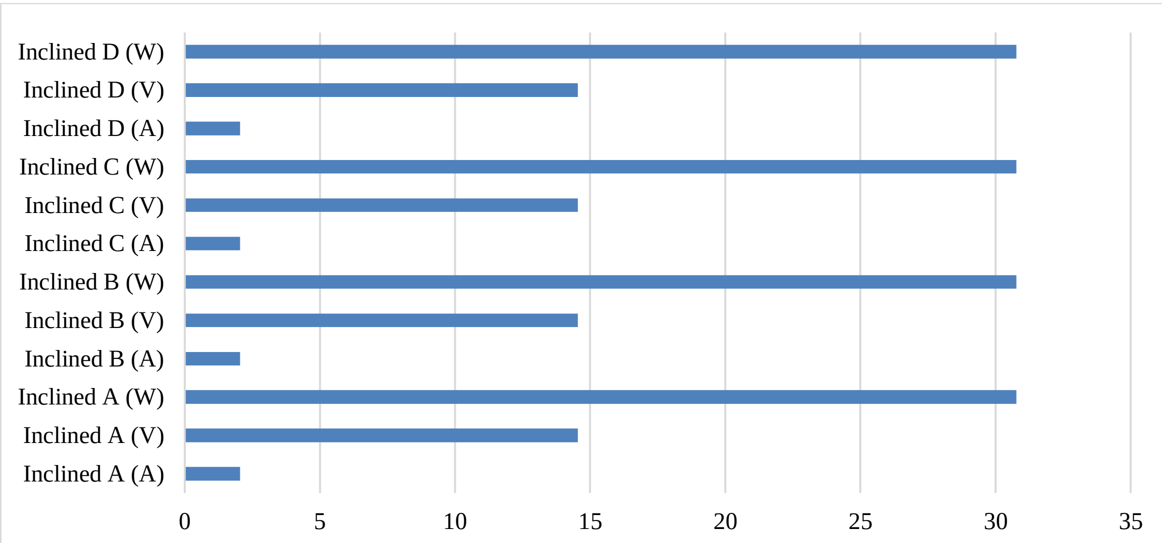

Figure 6: Inclined pv panel comparison

4.2: MONTHLY RESULTS

Table 7: Monthly average data values

Month	Rooftop Panels (kWh/day)	Horizontal Panels (kWh/day)	Inclined Panels (kWh/day)
January	0.75	0.70	0.80
February	0.83	0.77	0.88
March	0.90	0.84	0.96
April	0.98	0.91	1.04
May	0.90	0.84	0.96
June	0.83	0.77	0.88
July	0.75	0.70	0.80
August	0.75	0.70	0.80
September	0.83	0.77	0.88
October	0.90	0.84	0.96
November	0.98	0.91	1.04
December	0.83	0.77	0.88

Table 8: Statistical data

Statistic	Rooftop Panels (kWh/day)	Horizontal Panels (kWh/day)	Inclined Panels (kWh/day)
Mean	0.85	0.79	0.91
Standard Deviation	0.08	0.07	0.08
Variance	0.0064	0.0049	0.0064

5 Discussion

5.1 Average values for the year

Here, the average values from the four roof panels, the four horizontal panels and the four inclined panels were obtained. This approach simplifies the analysis by using the provided data as average values. It gives a general overview but misses the seasonal performance variations. Table 3 and figure 3 shows that overall, the inclined panels performs better than the horizontal and roof top panels

5.2: Comparative analysis of the data for the rooftop-mounted, horizontal, and inclined PV panels.

5.2.1 Rooftop Panels: Power output starts at 1.25 W at 06:00, peaks at 44.8 W at 13:00, and decreases to 10.8 W by 18:00. The power output is affected by shading in the early hours. This is shown in table 4 and figure 4

5.2.2 Horizontal Panels: Power output starts at 1.23 W at 06:00, peaks at 44.24 W at 13:00, and decreases to 10.64 W by 18:00. The power output is slightly lower than the inclined panels. This can be seen in table 5 and figure 5.

5.2.3 Inclined Panels: Power output starts at 3.81 W at 06:00, peaks at 59.94 W at 13:00, and decreases to 16.44 W by 18:00. The inclined panels consistently have the highest power output. This is shown in table 6 and figure 6.

5.3Monthly data

This approach provides a detailed analysis, accounting for seasonal changes. It helps in understanding how different times of the year affect the performance of the PV panels. The performance of roof - top panels varies due to shading effects. This is shown in table 7. The monthly average energy generated by three different configurations of photovoltaic (PV) panels: rooftop, horizontal, and inclined. As shown in table 8, he inclined panels consistently produced the highest average energy, followed by rooftop panels, with horizontal panels generating the least energy. Specifically, the mean energy generated by inclined panels was 0.91 kWh/day, compared to 0.85 kWh/day for rooftop panels and 0.79 kWh/day for horizontal panels.

5.4 Statistical Analysis

As shown in table 8, inclined panels have the highest average energy generation, followed by rooftop and horizontal panels. All configurations have similar variability, with horizontal panels showing slightly less variability. The variance effects the spread of energy generation values around the mean, with horizontal panels having the least spread.

The superior performance of inclined panels can be attributed to their optimal angle, which maximizes exposure to sunlight throughout the day. This configuration allows for better capture of solar radiation, especially during the peak sunlight hours. It also reduces reflection losses and ensures optimal capture of direct sunlight all day. Rooftop panels, while also effective, are subject to shading effects (particularly in the morning and late afternoon) and suboptimal angles depending on the roof's orientation and pitch. Additionally, rooftop panels are subject to heat build-up due to limited airflow, which can negatively impact their efficiency by increasing resistance in photovoltaic cells. Horizontal panels, on the other hand, are less efficient due to their flat positioning, which limits their ability to capture sunlight at lower angles during the morning and evening. While horizontal panels can capture diffuse solar radiation effectively in overcast conditions, their overall energy output is hindered by the lack of direct sunlight during significant parts of the day.

The standard deviation and variance values indicate that the energy generation for all configurations is relatively consistent, with horizontal panels showing slightly less variability (0.07) compared to rooftop (0.08) and inclined panels (0.08). This suggests that while horizontal panels generate less energy on average, their performance is more predictable and stable over time.

5.4.1 Performance comparison

1. Inclined vs. Rooftop: Inclined panels generated approximately 7.1% more energy than rooftop panels.
2. Inclined vs. Horizontal: Inclined panels generated approximately 15.2% more energy than horizontal panels.
3. Rooftop vs. Horizontal: Rooftop panels generated approximately 7.6% more energy than horizontal panels.

The percentage performance comparison reinforces the superior energy generation of inclined panels, attributed to their optimal tilt angle, which maximizes exposure to sunlight.

Table 9: Comparative performance of PV panel configurations: Insights from data and literature

Aspect	Our Findings	Existing Literature	Energy Efficiency	Environmental Suitability	Cost-Effectiveness	References
Inclined Panels	Superior performance due to optimal tilt; highest energy generation all year.	Optimal tilt angles reduce reflection losses and maximize sunlight capture.	Highest energy output across seasons.	Suitable for regions with high solar irradiance.	High installation cost, but long-term efficiency compensates.	Shaik et al. (2024)
Rooftop Panels	Affected by shading in mornings and afternoons; slightly lower efficiency.	Shading and heat buildup reduce performance; orientation matters.	Moderate energy efficiency; impacts from shading.	Suitable for urban environments and space-constrained areas.	Moderate cost; aesthetic considerations may increase expenses.	Fakhraian et al. (2021)
Horizontal Panels	Consistent but lowest energy output; effective for diffuse sunlight.	Flat positioning limits morning/evening capture; good for overcast conditions.	Lower energy efficiency; best for diffuse sunlight.	Suitable for overcast conditions or flat roof installations.	Low cost; ideal for simple installations.	Stephen et al. (2024)

Table 9 highlights the superior performance of inclined panels across all metrics, consistent with existing literature emphasizing the efficiency benefits of optimal tilt angles. Rooftop panels perform well but face limitations due to shading and heat buildup, in line with previous studies on panel orientation. Horizontal panels, while less competitive, are effective under specific conditions, such as diffuse sunlight or flat roofs. Cost-effectiveness varies, with inclined panels requiring higher upfront investment but offering superior long-term returns.

5.5 Implications

These findings have significant implications for the design and installation of PV systems in residential and commercial buildings. Inclined panels should be preferred for maximizing energy generation, especially in regions with high solar irradiance. Rooftop panels are also a viable option, particularly when space constraints or aesthetic considerations are important. However, horizontal panels may be less desirable unless specific conditions, such as flat roofs or limited installation options, necessitate their use. For policymakers and energy planners, these results underscore the importance of promoting optimal PV panel configurations to enhance the efficiency and effectiveness of solar energy systems. Incentives and guidelines for the installation of inclined panels could lead to substantial improvements in energy yield and overall system performance.

6. Conclusion and recommendations

In conclusion, we analysed the performance of rooftop mounted pv panels against horizontal panels and inclined panels. The findings offer valuable insights for designing and implementing efficient photovoltaic (PV) systems, contributing to the broader goal of sustainable and renewable energy development. In terms of performance, the inclined panels achieved the highest performance with superior current, voltage, and power outputs throughout the day. An 8-degree inclination angle optimizes sunlight exposure. The rooftop panels performed well but are affected by shading in the early morning and late afternoon, resulting in slightly lower performance compared to inclined panels. Horizontal panels perform well too but slightly below the performance of inclined panels.

6.1Key Recommendations:

1. **Optimal Installation Angle:** From a practical standpoint, it is recommended that installers tilt panels to align with the latitude angle of the installation location, as this has been found to optimize solar energy capture throughout the year. Horizontal panels, although less competitive, may still be suitable in scenarios requiring simplicity and cost-effectiveness, such as installations in regions with consistent diffuse sunlight or limited resources.
2. **Shading Considerations**: For rooftop installations, it is crucial to account for shading during sunrise and sunset. Positioning panels to minimize shading can significantly enhance overall performance.

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