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Comparative Analysis on the Performances of Monocrystalline and Polycrystalline Photovoltaic Cell (Pvc)

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ABSTRACT

The increasing demand for renewable energy has driven significant interest in solar photovoltaic (PV) technologies, particularly monocrystalline and polycrystalline solar cells. This study presents a comparative analysis on the performance of monocrystalline and polycrystalline photovoltaic cells under the climatic conditions of Sokoto, Nigeria. The research involved experimental measurements of voltage, current, and temperature over a daily solar exposure period, using natural sunlight. Key parameters such as room temperature, ambient temperature, PV module temperature, voltage output, and current output were recorded at hourly intervals. Results indicate that the performance of both PV technologies is significantly influenced by solar irradiance and temperature. Monocrystalline cells exhibited higher efficiency and stable voltage output, while polycrystalline cells were more cost-effective but showed slightly lower electrical performance. The highest power output occurred during late morning and early afternoon, corresponding with peak solar irradiance, whereas elevated module temperatures slightly reduced voltage output, highlighting the effect of thermal losses. The study also demonstrated that natural sunlight provides higher energy conversion. These findings confirm the suitability of monocrystalline PV cells for high-sunlight regions like Sokoto, with proper temperature management strategies recommended to optimize performance. It also provides valuable insights for solar energy system designers, engineers, and policymakers, supporting the selection of appropriate photovoltaic technologies to maximize energy yield, improve system efficiency, and promote sustainable solar energy adoption in hot and arid climates.

Keywords: Photovoltaic cells, monocrystalline, polycrystalline, solar energy, efficiency.

1.0 INTRODUCTION

The efficiency and performance of monocrystalline and polycrystalline PVCs are significantly influenced by environmental factors such as temperature, humidity, and solar irradiance. In Sokoto, high temperatures and intense sunlight can reduce the electrical output of PV modules, impacting system performance and economic viability. Despite the widespread use of both monocrystalline and polycrystalline modules in Nigeria, there is limited empirical data comparing their performance under local climatic conditions (Oladipo et al 2022).

The increasing demand for renewable energy sources has led to significant growth in the solar energy sector, as countries seek sustainable alternatives to fossil fuels. Photovoltaic cells (PVCs) are a crucial component of solar energy systems, converting sunlight directly into electrical energy. Among the various types of PVCs, monocrystalline and polycrystalline cells are the most widely used in Nigeria due to their availability and cost–performance balance. These two types of cells differ in efficiency and Performance because of their silicon structure and manufacturing processes; monocrystalline cells are made from single-crystal silicon wafers, whereas polycrystalline cells are made from multiple silicon crystals, which can slightly reduce energy conversion efficiency (Zhang, and Zhao, 2023).

This research aims to conduct a comparative analysis on the workability of monocrystalline and polycrystalline PVCs in Sokoto, Nigeria. The study will investigate the efficiency, voltage, and current output of both types of cells under varying temperature conditions, to determine which technology is more suitable for the local climate.

Nigeria has substantial solar energy potential due to its geographical location within the equatorial Sunbelt. Average solar radiation in Sokoto is approximately 5.5 kWh/m^2/day, making the region ideal for photovoltaic energy generation (Ibrahim, et al 2022). The Nigerian government has set an ambitious target of generating 13,000 MW of solar energy by 2030, aiming to diversify the national energy mix and reduce reliance on fossil fuels.

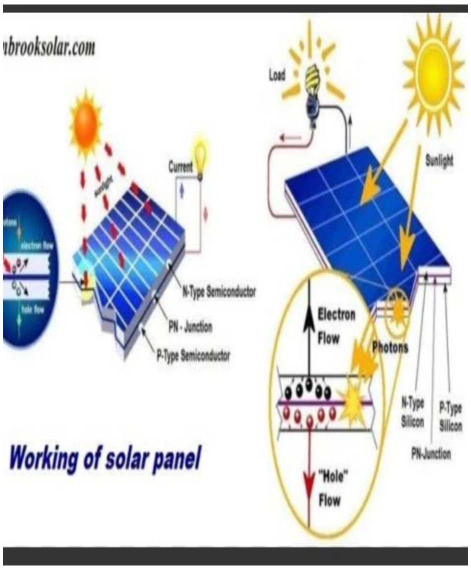
However, the performance of solar panels is affected by environmental factors, including temperature, humidity, and irradiance. High ambient temperatures, common in Sokoto, reduce PV efficiency by decreasing open-circuit voltage and overall electrical output. The conversion efficiency of PV modules generally declines by about 0.3–0.5% per degree Celsius above standard test conditions (Li, Chen, and Wang, 2024).

Monocrystalline PVCs typically offer higher efficiency compared to polycrystalline modules due to their uniform crystalline structure, whereas polycrystalline cells are generally more cost-effective but slightly less efficient. Understanding how these modules perform under Sokoto's specific climatic conditions is essential for optimizing system design, maximizing energy yield, and ensuring reliable electricity supply (Zhang, and Zhao, 2023).

Photovoltaic (PV) cells are semiconductor devices that convert solar energy directly into electrical energy through the photovoltaic effect. When sunlight strikes the surface of a PV cell, photons with sufficient energy excite electrons within the semiconductor material, creating electron–hole pairs. An internal electric field formed at the p–n junction drives these charge carriers in opposite directions, generating direct current (DC) electricity (Messenger and Ventre, 2010). PV cells are the fundamental building blocks of solar modules and arrays used in residential, commercial, and utility-scale power generation systems.

Silicon is the most widely used material for photovoltaic cells due to its abundance, non-toxicity, and suitable electrical properties. Silicon-based PV cells are generally categorized into crystalline silicon cells which include monocrystalline and polycrystalline cells and thin-film cells, such as amorphous silicon, cadmium telluride, and copper indium gallium selenide (Kalogirou, 2014). Among these, crystalline silicon cells dominate the global market because of their higher efficiency, long service life, and well-established manufacturing processes (Green *et al.,* 2022).

The performance of photovoltaic cells is commonly evaluated using parameters such as open-circuit voltage, short-circuit current, fill factor, and conversion efficiency. These parameters are influenced by both material properties and environmental conditions, including solar irradiance and operating temperature (Skoplaki and Palyvos, 2009). Continuous advancements in PV technology aim to improve efficiency, reduce production costs, and enhance durability, making photovoltaic systems an increasingly attractive solution for sustainable energy generation worldwide (IEA, 2023).



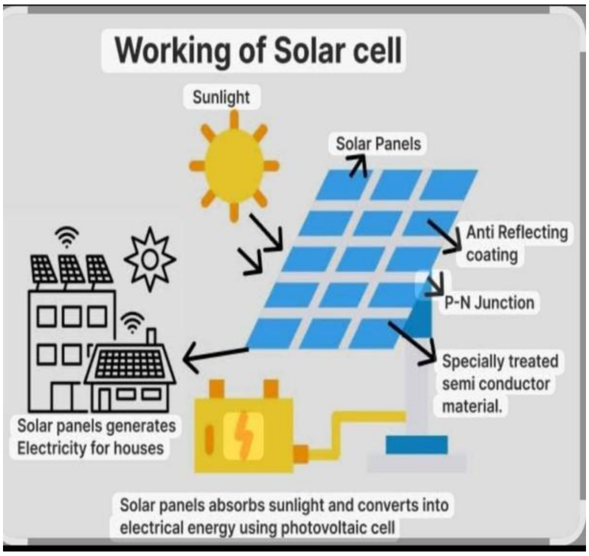


Fig 1: working of solar cell

A solar panel is an electrical device consisting of multiple photovoltaic (PV) cells arranged in a protective frame, designed to absorb solar radiation and convert it into usable electrical energy. The conversion process occurs through the photovoltaic effect, in which semiconductor materials commonly silicon generates electric current when exposed to light energy.

Solar panels function by allowing photons from sunlight to strike the surface of the PV cells, exciting electrons within the semiconductor material and causing them to flow, thereby producing direct current (DC) electricity. This electricity can be used immediately, stored in batteries, or converted into alternating current (AC) using an inverter for domestic and industrial applications.

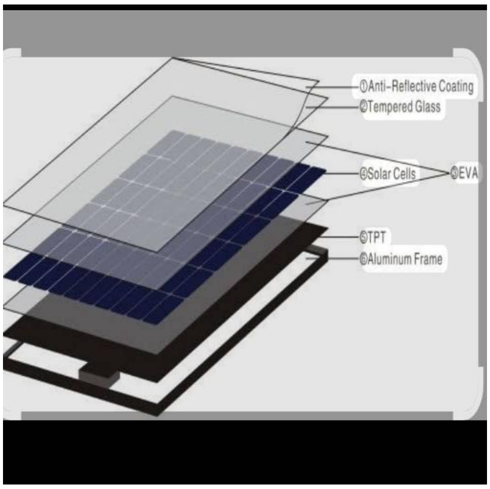
In addition to natural sunlight, solar panels can respond to artificial light sources, although with lower efficiency compared to natural solar irradiance. Solar panels are widely used in power generation systems due to their renewability, environmental friendliness, low operating cost, and sustainability, making them a key component in modern energy systems and sustainable building design.

Types of solar cell

Monocrystalline cell

Polycrystalline cell

Thin-Film Solar Panels



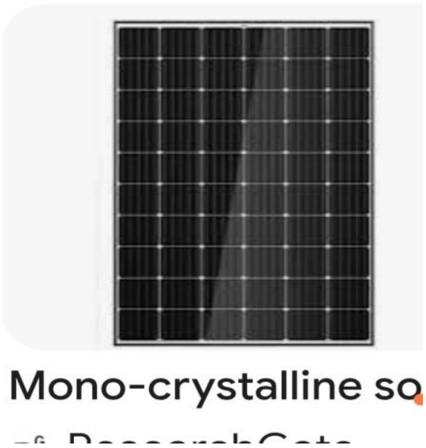


Fig 2: Monocrystalline

Monocrystalline PVCs are made from single-crystal silicon wafers. They are known for their high efficiency, long lifespan, and durability. Their production method results in a highly ordered crystal lattice with minimal structural defects, which enhances charge carrier mobility and reduces recombination losses within the cell (Kalogirou, 2014). Due to this uniform crystal structure, monocrystalline PV cells generally exhibit higher electrical performance compared to other silicon-based PV technologies.

Green (2022) reported that monocrystalline PV cells possess high conversion efficiency. As a result, monocrystalline modules are capable of producing more power per unit area, making them particularly suitable for installations where space is limited, such as rooftop systems, these cells are also characterized by their dark, uniform appearance and rounded cell edges, which arise from the cylindrical shape of the original silicon ingot.

Polycrystalline Photovoltaic Cells

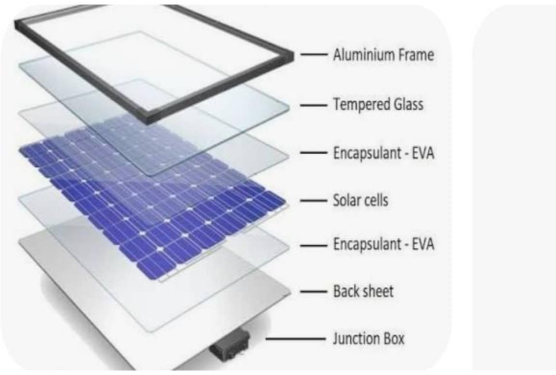


Fig 3: Polycrystalline

Polycrystalline PVCs are made from multi-crystal silicon wafers. They are less expensive than monocrystalline cells and are widely used in solar energy systems. They are produced by melting raw silicon and allowing it to cool and solidify in a mold, resulting in wafers composed of multiple silicon crystals with varying orientations. This manufacturing process is simpler and less energy-intensive than that used for monocrystalline cells, leading to lower production costs and reduced material waste (Kalogirou, 2014). The presence of multiple crystal grains gives polycrystalline cells their characteristic bluish, non-uniform appearance.

Due to the existence of grain boundaries within the silicon structure, polycrystalline photovoltaic cells generally exhibit lower conversion efficiency compared to monocrystalline cells. Grain boundaries act as recombination sites for charge carriers, reducing electron mobility and overall electrical performance (Messenger & Ventre, 2010). As a result, polycrystalline modules typically require a larger surface area to generate the same amount of electrical power as monocrystalline modules (Yong et al., 2024).

Despite their lower efficiency, polycrystalline PV cells remain widely used because of their cost-effectiveness and acceptable performance, particularly in large-scale solar installations where space availability is not a major constraint. Advances in cell design and manufacturing techniques have led to gradual improvements in the efficiency and reliability of polycrystalline modules, making them a viable option for many photovoltaic applications (Green et al., 2022).

Thin-Film Solar Panels

Fig 4: Thin-Film

Thin-film solar panels are a type of photovoltaic panel produced by depositing one or more extremely thin layers of photovoltaic material onto a substrate such as glass, plastic, or metal. Unlike crystalline silicon panels, thin-film panels use much less semiconductor material, making them lightweight, flexible, and adaptable to various surfaces. They convert sunlight into electrical energy through the photovoltaic effect but generally operate at lower efficiency and have a shorter operational lifespan compared to monocrystalline and polycrystalline solar panels.

Factors Affecting the Performance of Photovoltaic Cells

The performance of photovoltaic (PV) cells is influenced by a combination of environmental, material, and operational factors. These factors determine the amount of electrical energy generated under real operating conditions and often cause deviations from rated performance values obtained under standard test conditions (STC). Understanding these factors is essential for accurate performance evaluation, system design, and long-term reliability of PV installations.

Solar Irradiance: the most significant factor affecting the output of photovoltaic cells. It represents the amount of solar energy incident on the surface of the PV cell per unit area. An increase in irradiance generally leads to a proportional increase in the generated current and power output of the PV cell (Skoplaki & Palyvos, 2009). However, variations in irradiance due to cloud cover, time of day, seasonal changes, and atmospheric conditions can cause fluctuations in PV system performance.

Temperature: has a pronounced effect on the electrical characteristics of photovoltaic cells. As the operating temperature of a PV cell increases, the open-circuit voltage decreases, leading to a reduction in overall conversion efficiency. This phenomenon is attributed to the intrinsic properties of semiconductor materials and is expressed using the temperature coefficient of the PV cell (Dubey, Sarvaiya, and Seshadri, 2013). High ambient temperatures, common in tropical regions, can therefore negatively impact PV system performance if adequate cooling and ventilation are not provided.

Humidity and Moisture: exposure significantly affect the long-term performance and durability of photovoltaic cells and modules. Moisture ingress can lead to corrosion of metallic contacts, degradation of encapsulation materials, and electrical insulation failure, ultimately reducing power output over time (Jordan and Kurtz, 2013). High humidity environments, especially in coastal and tropical regions, accelerate degradation mechanisms and may shorten the operational lifespan of PV systems.

Dust and Soiling: reduces the amount of sunlight reaching the cells, thereby decreasing power output. Soiling losses can be substantial in arid and dusty environments and may range from minor efficiency reductions to significant power losses if regular cleaning is not performed (Mani and Pillai, 2010).

Shading: Partial or complete shading of photovoltaic cells, even over a small portion of a module, can lead to a significant reduction in power output. Shading causes electrical mismatch within PV modules and arrays, potentially resulting in hot spots that can damage cells if not properly mitigated using bypass diodes (Messenger and Ventre, 2010).

Aging and Degradation: Over time, photovoltaic cells experience gradual performance degradation due to factors such as thermal cycling, ultraviolet radiation exposure, mechanical stress, and material fatigue. This degradation leads to a slow decline in power output, typically quantified as an annual degradation rate (Jordan and Kurtz, 2013). Although modern PV modules are designed for long service life, degradation remains an important consideration in performance assessment.

Tables 1: Comparison between Monocrystalline and Polycrystalline

Parameter	Monocrystalline PVCs	Polycrystalline PVCs
Efficiency	15–20%	12–15%
Lifespan	Up to 25 years	Up to 20 years
Cost	High	Lower
Durability	Durable	More durable

2.0 METHODOLOGY

The research work comparative experimental design to evaluate the performance of monocrystalline and polycrystalline PVCs was conducted at the Umaru Ali Shinkafi Polytechnic Sokoto, Nigeria.

2.1 Population

The population for this study consisted of some commercially available photovoltaic cells (PVCs) in Sokoto, Nigeria, including monocrystalline and polycrystalline types. These include residential, commercial, and laboratory-scale solar panels used for electricity generation within the region. The population encompasses various brands, capacities, and manufacturing specifications, reflecting the diversity of PVCs accessible in Sokoto.

Sample

A purposive sampling technique was employed to select two representative solar panels for the experiment:

Monocrystalline Solar Panel – selected for its high efficiency and common use in residential and commercial installations.

Polycrystalline Solar Panel – selected due to its lower cost and widespread availability in Sokoto.

Rationale for Sample Selection:

The study focuses on comparing the **performance characteristics** of monocrystalline and polycrystalline PVCs rather than assessing all available panels.

Using one panel of each type allows for controlled **experimental measurements** of voltage, current, power output, and efficiency under identical environmental conditions.

Sample Size Limitation:

Only two panels were used due to **resource and logistical constraints**, and findings may be indicative rather than fully generalizable.

2.2 Data Collection Methods

In this study, primary data were collected through experimental measurements.

2.3 Experimental Measurements

The main focus of this study was the comparative performance of monocrystalline and polycrystalline photovoltaic cells (PVCs). Data were collected over a period of 14hours from 5:00 am to 7:00 pm at 60-minute intervals using the following instruments Monocrystalline and Polycrystalline photo voltaic cells, change controller, stop watch, GPS Map camera, dry cell 24volt

(3) Location, Sokoto State Polytechnic, Rugar Woro, Sokoto, Nigeria, 26°27′59″ N, 13°01′47″80, Long: 5°20′08″24 Tuesday, 16/12/2025 07:09 am – 7:00 pm

Solar charger controller (12/24 v: 59A For ragulentin controllen and measure of voltage, current and temperature) energy GPS ma pcamera (version 1. 8. 5 to measure location and real, Time

Pyranometer (Kipp & Zonen, Model CMP 11): To measure solar irradiance (W/m²).

Thermocouple (Type K): To measure ambient and panel temperature (°C).

Multimeter (Fluke, Model 289): To measure voltage (V) and current (A).

Data Logger (Campbell Scientific, Model CR1000): To record real-time readings automatically.

3.3 power

power = current × potent difference

P= I × V ………………. (i)

I=P/V ………………… (ii)

The efficiency of each solar panel was calculated using the following formula:

Efficiency (%) = (Power Output (W) / (Irradiance (W/m²) × Area (m²))) × 100

Where:

Current output = power output/voltage output
Power Output (W) = measured electrical output of the solar panel
Irradiance (W/m²) = solar irradiance incident on the panel surface
Area (m²) = surface area of the solar panel

3.0 Data Analysis techniques

The data were analyzed using statistical methods, including mean, standard deviation, and regression analysis. The efficiency of the solar panels was calculated using the following formula:

Efficiency (%) = $((I_{out} \times V_{out})/ (E \times A)) \times 100\%$

Where I_{out} = Output current, V_{out}= Output voltage, E= Solar irradiance=1000W/m^2 (under STC), A= panel Surface Area

Experimental Procedure

1. The solar panels were installed and connected to the data logger.

2. The pyranometer and thermocouple were installed and connected to the data logger.

3. The multimeter was used to measure the voltage and current output of the solar panels.

4. Data were collected at 60-minute intervals.

5. The experiment was conducted for 13hours.

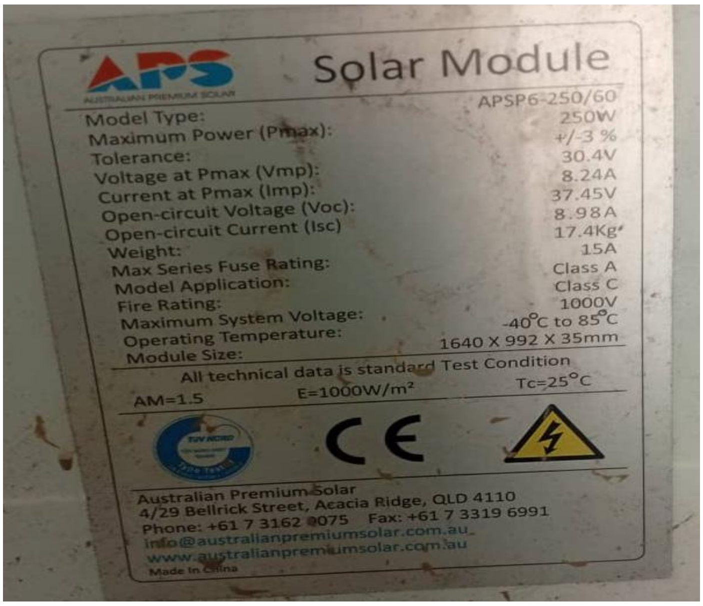


Figure 5: panel both monocrystalline and polycrystalline

4.0 Results

The data represent hourly observations of solar energy system performance parameters taken from morning to evening. The key variables include time, room temperature, photovoltaic (PV) module temperature, voltage output, and current output. These parameters are analyzed to understand the performance behavior of the solar panel under sokoto metropolitan environmental conditions.

Table 2: results of performance of mono crystalline and poly crystalline PVC samples

S/N	Time Interval	Room Temp (°C)	Temp of Mono Crystalline PVC Cell (°C)	Temp of poly Crystalline PVC Cell (°C)	Voltage of Mono Crystalline PVC Cell (V)	Current of poly Crystalline PVC Cell I (A)	Voltage of Crystalline PVC Cell (V)	Current of Crystalline PVC Cell I (A)	Sun rise and Sun set
1.	6:53	20oc	22	20	22.10	11.360	28.80	8.920	6:52am
2.	7:53	24oc	24	24	34.20	7.350	35.20	7.140	
3.	8:53	28oc	31	28	34.30	7.350	34.90	7.350	
4.	9:53	25	38	40	33.60	7.570	34.20	7.350	
5.	10:53	24	43	45	33.50	7.570	34.10	7.350	
6.	11:53	24	37	46	33.40	7.570	33.70	7.570	
7.	12:53	25	36	49	32.80	7.810	33.20	7.570	
8.	1:53	24	48	39	32.70	7.810	33.50	7.570	
9.	2:53	27	39	38	32.50	7.810	33.30	7.570	

10.	3:53	32	50	39	32.70	7.810	33.10	7.570	
11.	4:53	28	42	36	32.80	7.810	33.30	7.570	
12.	5:53	29	35	32	30.90	8.330	30.10	8.330	6:22pm

(2) Arrangement of the Apparatus: of the Apparatus, was done by 6:00am the dura time of the research was 13 hours

(3) Location
Sokoto State Polytechnic
Rugar Woro, Sokoto, Nigeria
26°27′59″ N, 13°01′47″80
Long: 5°20′08″24

Tuesday, 16/12/2025

5.0 Discussion

5.1 Time Interval and Sun Rise/Sun Set

Measurements were taken at hourly intervals from 6:53 am to 5:53 pm, covering the effective solar exposure period for the day. The recorded sunrise time was 6:52 am, while sunset occurred at 6:22 pm. This period defines the operational window of the solar panels. The results show that solar panel performance followed a daily pattern, with low output in the early morning, peak output around midday, and gradual decline toward evening.

5.2 Room Temperature

Room temperature increased gradually from 20°C in the early morning to a maximum of about 32°C in the afternoon before decreasing slightly toward evening. This increase reflects the general warming of the environment as solar radiation intensified during the day. Although room temperature does not directly determine PV output, it gives an indication of the surrounding thermal conditions influencing the panel temperature.

The temperature of the monocrystalline photovoltaic cell increased steadily from morning to midday, reaching its highest values in the early afternoon. The monocrystalline cell temperature was consistently higher than the room temperature, showing that the panel absorbed solar radiation and converted part of it into heat. High operating temperature is known to affect PV performance by reducing voltage output. This trend agrees with photovoltaic theory, which states that crystalline silicon cells have a negative temperature coefficient.

Similarly, the temperature of the polycrystalline photovoltaic cell increased from morning to midday and decreased toward evening. In several instances, the polycrystalline cell recorded slightly higher temperatures than the monocrystalline cell. This may be due to differences in material structure and heat dissipation characteristics. Higher temperatures in polycrystalline cells can contribute to greater voltage losses compared to monocrystalline cells.

5.3 Voltage Output Characteristics

The voltage output of the monocrystalline PV cell showed relatively small variations throughout the day. Voltage increased slightly from morning to mid-morning as sunlight intensity increased but remained fairly stable during peak sunshine hours. At higher temperatures, slight reductions or stabilization of voltage were observed. This confirms that voltage is less dependent on solar irradiance and more affected by temperature. Despite high temperatures, the monocrystalline cell maintained stable voltage output, indicating better performance under hot conditions.

The polycrystalline PV cell also showed similar voltage trends, with gradual increase in the morning and slight reduction during periods of high temperature. However, the voltage output of the polycrystalline cell was generally slightly lower and less stable compared to the monocrystalline cell. This difference can be attributed to the multiple crystal structure of polycrystalline cells, which increases recombination losses and reduces electrical efficiency.

5.4 Current Output Characteristics

The current output of the monocrystalline PV cell increased significantly from morning to midday, corresponding directly with increasing solar irradiance. Low current values were recorded in the early morning due to low sunlight intensity. Peak current values occurred during late morning and early afternoon when solar radiation was strongest. This confirms that current output is directly proportional to solar irradiance.

The polycrystalline PV cell also showed increasing current output from morning to midday. However, the current values were generally slightly lower compared to those of the monocrystalline cell. This indicates that while both cells respond positively to increased irradiance, monocrystalline cells convert sunlight to electrical current more efficiently.

From the results, it is evident that both monocrystalline and polycrystalline photovoltaic cells are strongly influenced by temperature and solar irradiance. However, monocrystalline cells demonstrated better overall electrical performance.

Monocrystalline PV cells produced more stable voltage output even at higher temperatures, while polycrystalline cells showed slightly greater voltage reductions. This confirms that monocrystalline cells are more efficient and better suited for high-temperature environments like Sokoto.

In terms of current output, both cell types followed the same pattern of increasing current with increasing solar irradiance. However, monocrystalline cells consistently produced higher current values, especially during peak sunshine hours. This resulted in higher overall power output for monocrystalline panels.

Although high temperatures reduced voltage efficiency in both cell types, the increase in current during peak irradiance compensated for these losses, leading to maximum power generation during midday periods. This shows that high solar irradiance in Sokoto plays a major role in improving PV performance despite thermal losses.

The performance of both photovoltaic cells followed a typical daily pattern:

Morning: Low temperature, low voltage and current output

Midday: High temperature, stable voltage, maximum current output

Afternoon: Gradual reduction in temperature and electrical outputecific time each observation wasmorning to evening.eriment setup. **ature (°C)** – Outdoor environmental temperature around the PV panels.e temperature of the mono-crystalline solar panel.emperature of the poly-crystalline solar panel.

Results match standard photovoltaic behavior.

Mono-crystalline PV modules perform best under high sunlight but can experience slight voltage drops at high temperatures.

Current output is strongly dependent on solar irradiance, which explains peak energy generation at midday.

PV module temperatures were consistently higher than ambient and room temperatures due to solar heat absorption.

Proper temperature management through ventilation, spacing, or cooling strategies is important for maintaining efficiency in hot climates like Sokoto.

Overall, findings confirm that mono-crystalline PV panels are reliable for high-sunlight regions and emphasize the need for thermal control for optimal performance.

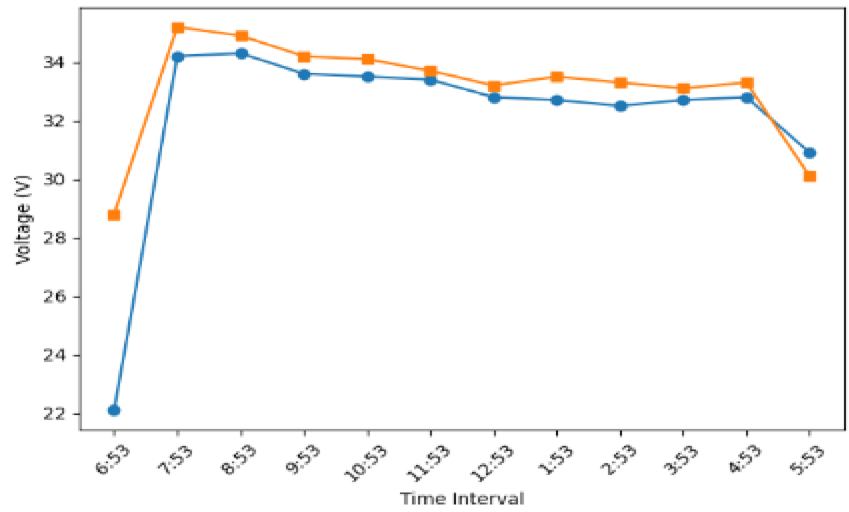


Fig 6: Voltage variation with time of mono crystalline

Key:

X-axis: Time Interval (Hours)

Y-axis: Voltage (V)

Line orange 1: Voltage under Artificial Light

Line blue 2: Voltage under Natural Sunlight

Voltage variation with time of poly- crystalline

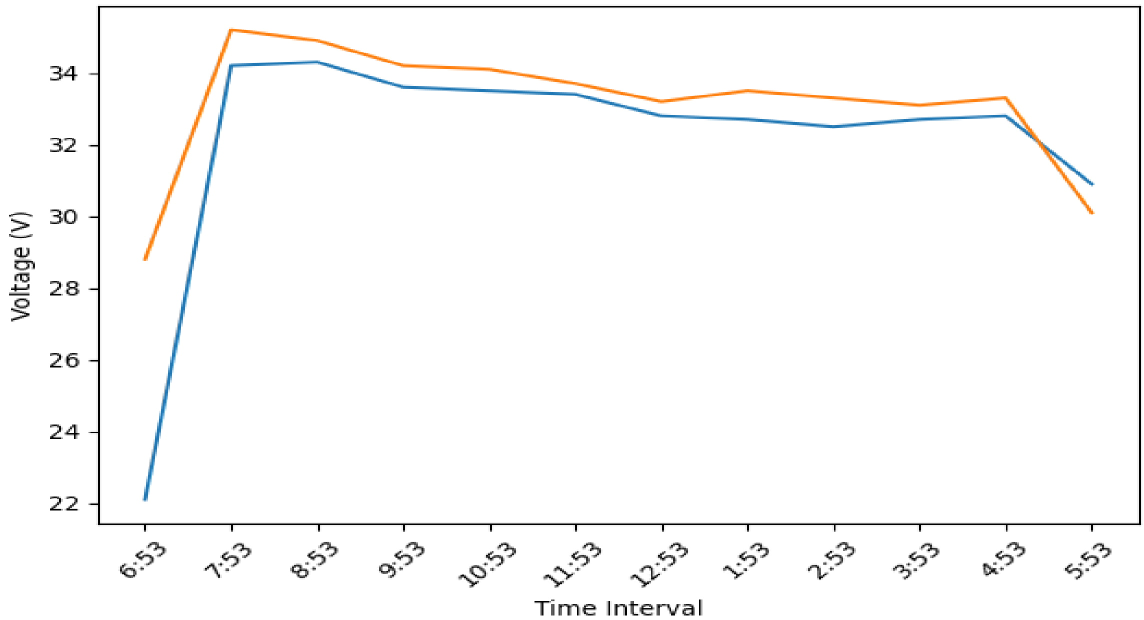


Figure 7: Voltage variation with time of poly crystalline

Key:

X-axis: Time Interval (Hours)

Y-axis: Voltage (V)

Line one blue: Voltage under Artificial Light

Line two orange: Voltage under Natural Sunlight

6.0 Conclusion

Based on the results and analysis presented in this study, the following conclusions can be drawn:

Solar panel performance is strongly influenced by time of day and solar irradiance. Electrical output was lowest in the early morning and late afternoon and highest during late morning and early afternoon when solar intensity was at its peak.

PV module temperature was consistently higher than ambient and room temperatures, confirming that solar panels absorb and retain heat during operation. This thermal buildup is typical in hot and semi-arid regions such as Sokoto.

Voltage output showed minimal variation throughout the day, indicating that voltage is less sensitive to changes in solar irradiance but is negatively affected by increased operating temperature.

Current output increased significantly with increasing solar irradiance, confirming that current is directly proportional to sunlight intensity and serves as a reliable indicator of solar availability.

Although high temperatures slightly reduced voltage efficiency, the increase in current during peak sunshine compensated for this effect, resulting in improved overall power generation during midday periods.

Natural sunlight produced higher voltage and current outputs compared to artificial light, confirming that natural solar irradiance is more effective for photovoltaic energy

7.0 Recommendations

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

Proper Installation and Ventilation: Solar panels should be installed with adequate spacing and ventilation to allow air circulation beneath the modules, which will help reduce operating temperature and improve efficiency.

Use of Cooling Techniques: Passive cooling methods, such as elevated mounting structures and reflective roofing materials, should be adoptedrin hot regions like Sokoto to minimize thermal losses.

Optimal Panel Orientation: Solar panels should be oriented and tilted correctly to maximize exposure to sunlight during peak irradiance hours, especially between late morning and early afternoon.

Regular Cleaning and Maintenance: Due to dust and soiling common in arid regions, regular cleaning of solar panels is recommended to maintain high energy output.

Preference for High-Efficiency Panels: In areas with limited installation space, high-efficiency monocrystalline panels are recommended due to their higher power output per unit area.

Policy and Awareness: Government agencies and stakeholders should promote awareness and provide technical guidelines on proper solar panel installation and maintenance to improve system performance and longevity.

Future studies should compare monocrystalline and polycrystalline panels simultaneously under identical conditions in Variaous location to provide a more detailed comparative analysis.

Long-term performance studies should be conducted to assess degradation rates over several years.

Further research can explore the impact of advanced cooling techniques on PV efficiency in hot climates.

Studies involving thin-film and emerging PV technologies are recommended for broader performance comparison.

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