

DESIGN AND DEVELOPMENT OF A MICROCONTROLLER-BASED SOLAR TRACKING SYSTEM

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ABSTRACT

*Solar energy is one of the most promising and rapidly growing sources of renewable energy due to its abundance and environmental benefits. However, one of the main challenges with solar energy systems is their reliance on the angle of sunlight, which varies throughout the day. Fixed, stationary solar panels are limited by their inability to adjust their position relative to the sun's changing path, leading to suboptimal power generation, particularly during early morning and late afternoon hours when the sun is at a low angle. This study was carried out to design and construct a microcontroller-based sun tracking system and investigate the performance of a microcontroller-based one-axis solar tracking system compared to a stationary solar panel. The experiment was conducted by measuring the power output of both panels at one-hour interval and analysing the effectiveness of the tracking system in optimizing solar energy capture. The results showed that the microcontroller-based solar tracking system consistently outperformed the stationary panel system, with improvements ranging from 5.8% in the early morning to 71.2% in the late afternoon. An average peak power output of **43.67 W** was observed at midday (12:00), compared to the stationary panel's **39.28 W**, indicating an **11.2%** increment. Statistical analysis using a paired *t*-test confirmed the significance of these differences ($p < 0.05$). These findings have practical implications for solar energy applications in regions with fluctuating sunlight angles, suggesting that solar trackers can enhance energy yields and provide more consistent power output.*

Keywords: Solar, Micro-Controller, Tracker and PV

1 INTRODUCTION

The increasing global focus on environmental sustainability and energy security has intensified the search for alternative energy sources. Traditional fossil fuels, which have long powered the world's economies, are now recognized as finite resources with significant environmental drawbacks, including the emission of greenhouse gases that contribute to climate change. As a result, renewable energy sources, particularly solar energy, have gained prominence due to their potential to provide clean, sustainable, and inexhaustible power. Solar energy, being one of the most abundant and readily available renewable resources, offers a promising solution to the world's growing energy needs [1]. The efficiency of solar power systems remains a critical challenge in the transition to renewable energy. Fixed solar panels, which are the most common form of solar energy harvesting system, often fail to capture the full potential of the sun's energy due to their static orientation. As the sun moves across the sky throughout the day and changes its angle during different seasons, fixed panels are unable to maintain the optimal angle needed to maximize energy absorption. This misalignment results in significant energy losses, reducing the overall effectiveness of solar power systems and increasing the cost per unit of electricity generated. While solar tracking systems have been developed to address this issue, their widespread adoption has been hindered by several factors. Traditional tracking systems

typically involve complex mechanical structures and advanced electronics, which are both expensive to manufacture and maintain. These costs can be prohibitive, especially in developing regions where financial resources are limited. Furthermore, the complexity of these systems can pose challenges in terms of installation, operation, and maintenance, particularly in areas with limited technical expertise. Researchers are trying to make power system more and more efficiently by incorporating tracking system. Solar tracking systems are designed to orient solar panels or photovoltaic arrays to follow the apparent motion of the sun throughout the day [2]. This dynamic orientation allows solar panels to capture sunlight more effectively, significantly increasing energy generation compared to fixed solar installations. Solar tracking systems can be categorized into two main types: single-axis and dual-axis tracking systems. Single-axis systems track the sun's apparent motion on one axis, typically east-west, while dual-axis systems track it on both east-west and north-south axes [3, 4]. These systems offer various advantages, such as a higher energy yield and a more even energy production curve throughout the day, making them an attractive choice for renewable energy generation [5]. Tracking systems collect the sun's energy with maximum efficiency when the optical axis is aligned with incident solar radiation. This tracking movement is achieved by coupling linear actuators to the mechanism such that the panel maintains its face always perpendicular to the sun to generate maximum energy. This is achieved by using a programmed microcontroller to deliver stepped pulses in periodical time intervals for 12 hours for linear actuators to rotate the mounted panel in one direction and return to the start point for the next day light as desired [6]. Advancements in microcontroller technology present a potential solution to these challenges. Microcontrollers are small, low-cost, and highly versatile electronic devices that can be programmed to perform specific tasks. When integrated into a solar tracking system, microcontrollers can provide precise control over the movement of solar panels, allowing them to continuously follow the sun's path with minimal energy consumption and operational costs. By leveraging microcontroller-based technology, it is possible to design a solar tracking system that is not only efficient but also affordable and accessible, making it a viable option for a wide range of applications, from residential to industrial-scale solar installations. There is a pressing need for a solution that can enhance the efficiency of solar power systems without imposing significant financial or technical burdens. This research aims to bridge this gap by designing and constructing a microcontroller-based solar tracking system that is both cost-effective and easy to implement. The system will utilize the capabilities of microcontrollers to precisely control the movement of solar panels, ensuring that they remain aligned with the sun's position at all times. By maximizing the energy absorbed by the panels, the system is expected to significantly improve the overall efficiency of solar power installations. This research aimed to design and construct a microcontroller-based sun tracking system. The research is multifaceted and extends to various aspects of Nigeria's energy landscape and broader socio-economic development. Research on microcontroller-based solar tracking systems holds the potential to substantially enhance energy efficiency in Nigeria. Given the country's intermittent power supply and energy access challenges, the development of a system that can accurately track the sun's movement and optimize energy capture is of paramount importance. This increased efficiency translates to a more reliable source of electricity, which can benefit households, businesses, and industries alike. Secondly, the study contributes to improved energy accessibility, particularly in rural and underserved areas. A PV system is a technology that converts sunlight directly into electricity using semiconductor materials that exhibit the photovoltaic effect. When light strikes these materials, typically silicon, it excites electrons, causing them to flow and generate an electric current. This current can then be harnessed for various applications, from powering small devices to supplying electricity to homes and businesses [7]. PV systems are highly scalable, ranging from small rooftop installations for individual homes to large solar farms that generate electricity on an industrial scale. Their ability to generate clean and renewable energy without emitting greenhouse gases makes them a key component in the global transition to sustainable energy sources. Solar PV accounted for 4.5% of total global electricity generation, and it remains the third largest renewable electricity technology behind hydropower and wind. The global power generation from solar PV increased has reached 270 TWh in 2022, up by 26% on 2021 [8]. Primarily, the sun emits about 7,000 times more energy than what is required for human consumption. This means that an enormous amount of energy is still untapped from the sun [9]. Traditionally, solar energy is exploited in Nigeria through open drying purposes. Studies have demonstrated that this energy is abundant in Nigeria, most especially in the north as evident in Nigeria's solar resource map (Figure 1) and can be harvested as solar photovoltaic or solar thermal [10].

A substantial use of this resource for electrical power generation can help meet the nation's climate action target as specified in the Nationally Determined Contributions (NDCs) [11]. The exploitation of solar energy via solar PV can considerably minimize greenhouse gas emissions and further boost the per capita electricity consumption in the country [12].

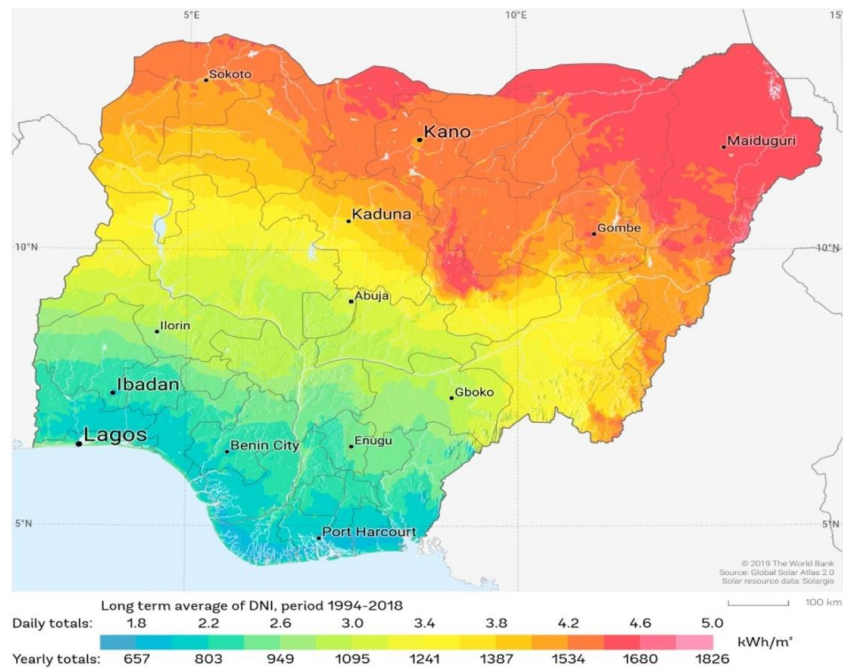


Figure 1. Nigeria solar map based on Direct Normal Irradiance

Nigeria having a land area of 923,768 km² and normal solar radiation estimated at 229.1667W/m², it only requires about 36 days of steady sunshine to obtain an equivalent energy reserve of total fossil fuels in the country which comprises of natural gas, crude oil, tar sand, and coal [11]. It was thereafter proposed that solar-to-electricity potential of about 181 TWh/y with only 1% of suitable direct normal irradiance areas is possible in seven of the states in the north. This suggests that a PV of 671-1790 MW and 84 MW capacities are desirable for the mini-grids and SHSs, respectively. Presently, Nigeria electrical power production through solar PV has been estimated as 15 MW of dispersed solar PV. This low utilization of solar energy for the purpose of electricity generation in the country has been attributed to lack of skilled technical personnel in Nigeria and life span of battery; lack of access to the huge capital cost and credit to consumers; and as well as insufficient awareness about solar and resistance of the masses to adapt to new technology (socio-cultural behaviour) [13]. Notwithstanding, capital cost is going down and more PV system installations are presently going on in Nigeria, namely a 100 MW solar power project is under discussion by the Azura Independent Power Plant (IPP) in Katsina State, another 200 MW Ashama solar project in Delta State and many more small, medium as well as large scale PV projects in the country.

1.1 Overview of the Solar Tracking Systems: Types and Components

The two main solar tracking system types that depend on the movement degree of freedom are single axis solar tracking system and dual axis solar tracking system. Several sun tracking systems are evaluated and showed to keep the solar panels, solar concentrators, or other solar applications as the recent studies of single axis tracking[14], dual axis tracking[15], single and dual axis tracking with respect to the tracking systems types[16]. A single axis solar tracking system is a technique to track the sun from one side to another using a single pivot point to rotate. This system has main three types: horizontal, vertical, and tilted single axis tracking system. The axis of rotation is horizontal with respect to the ground at the horizontal single axis tracking system, where the face of the system collector or module is oriented parallel to the axis of rotation, and this type usually used in tropical regions. The axis of rotation is vertical with respect to the ground at the vertical single axis tracking system, where the face of the system collector or module is oriented at an angle with respect to the axis of rotation, and this type usually used in high latitudes locations. The axis of rotation is between horizontal and

vertical axes at the tilted single axis tracking system, where the face of the system collector or module is oriented parallel to the axis of rotation.

1.2 Solar Tracker Drive Types

The solar tracker drive systems are classified into five types based on their tracking technologies: active tracking, passive tracking, semi-passive tracking, manual tracking, and chronological tracking. The five main types of tracker drivers have plenty of advantages, disadvantages, features, components used, and even in the operating principles. The active solar tracker drive system is considered as the most widely used and investigated among the scholars compared to the other four types. Studying this type is particularly considered for enhancing the performance and accuracy of solar tracking dealing with mainly control circuits and signals from sensors to measure the amount of light. Likewise, the chronological tracking type which uses control system but with different operating principle; it depends on the chronological data collected to define the accurate tracking position, which is more energy-efficient since there is no loss of energy due to calibration. On the other hand, for passive, semi-passive and manual tracker devices, the aims of studying these types is mainly directed to the simplicity and lower the movements, in other words, the components used resulting in lower cost and easy to deal with in terms of operation[17].The advent of microcontroller-based solar tracking systems represents a paradigm shift in the field of renewable energy. These systems are designed to dynamically orient solar panels to follow the apparent movement of the sun across the sky throughout the day. The key component enabling this dynamic tracking is a microcontroller, a small programmable device that serves as the brain of the system [18]. While various types of microcontrollers can be employed, popular choices include Arduino and Raspberry Pi due to their flexibility, affordability, and rich ecosystems of software and hardware components. Microcontrollers are at the heart of these systems, responsible for receiving and processing data from various sensors and controlling the movement of the solar panels or arrays. This process involves continuous tracking and adjustment to ensure the solar panels are optimally aligned with the sun's position. The microcontroller calculates the sun's azimuth and elevation angles based on the date, time, and geographical coordinates of the installation site. This data informs the movement of the solar panels, ensuring that they consistently face the sun throughout the day. One of the key advantages of using microcontroller-based systems is their adaptability to different geographical locations and solar panel types. Solar tracking systems require precise and responsive control, and microcontrollers offer the flexibility to fine-tune the control algorithms based on specific parameters. This adaptability is vital in a country as diverse as Nigeria, where solar radiation, weather conditions, and geographical coordinates can vary significantly [19]. Various research teams have investigated the performance of trackers in different regions, including Europe [20], Jordan [21], Egypt and Germany [22], Malaysia [23], Ghana [24], and Nigeria [11], and many others. These studies employed a mix of experimental, analytical, and simulation methods to evaluate tracking system performance.

2 METHODOLOGY

The materials used in this research work are shown in Table 1 and the specifications of the solar panels used in this research work are presented in Table 2.

Table 1. Materials used and their Descriptions

S/N	Materials	Description
1	Servo motor	This moves the solar panel module inthe desired direction.
2	Sector Limiter	This regulates the movement of thelinear actuators.
3	Solar Sensors	The sensors respond to the level of intensity of sunlight and provides a proportional resistance
4	Arduino Nano Microcontroller	The Arduino Nano essentially accepts requisite inputs, processes the input according to program logic and generates suitable output for the linear actuator
5.	Solar Panel	Generates electricity from ultra violetrays of the Sun
6.	Charge Controller	Provides optimum charging performance for the battery via the solar panels
7.	70Ah 12 V Battery	Provides storage and backup power forthe system

Table 2. Solar panel specification

Specification	Fixed mounting	Solar Tracker
Peak power (W)	50	50
Voltage (V)	17.3	17.3
Current (A)	2.89	2.89
Open circuit voltage (V)	20.7	20.7
Open circuit current (A)	3.12	3.12
Dimensions	695 × 510 × 70 mm	695 × 510 × 70 mm
Type	Mono-crystalline	Mono-crystalline

2.1 Circuit Design

The circuit design for the microcontroller-based solar tracking system designed according to ISO 9001 standard involves integrating various components to ensure seamless operation. The core of the circuit design centres around the Arduino Nano microcontroller, which processes input from the solar sensors and controls the linear actuator to adjust the solar panel's orientation. The circuit components are;

Solar Sensors: Two solar sensors are mounted at opposite ends of the solar panel (along the length and width axes). These sensors detect the intensity of sunlight and provide a varying resistance based on the amount of light they receive.

Arduino Nano Microcontroller: The Arduino Nano receives analogue signals from the solar sensors and processes these signals to determine which direction the panel should move to maximize exposure to sunlight. It then sends control signals to the linear actuator accordingly.

Linear Actuator: The linear actuator adjusts the position of the solar panel based on the commands it receives from the microcontroller. It moves the panel to the optimal angle for sunlight exposure.

Charge Controller: This component manages the charging of the battery from the solar panel, ensuring that the battery is charged efficiently without overcharging.

70Ah 12V Battery: The battery stores energy generated by the solar panel and provides backup power to the system, ensuring it operates even when sunlight is insufficient.

Power Supply: The power supply circuit provides necessary voltage levels to the Arduino Nano and other components, ensuring stable operation.

2.2 Circuit Diagram

The complete circuit diagram (Figure 2) illustrates the connections between the solar sensors, the Arduino Nano, the linear actuator, and the other components. The diagram outlines the power supply connections, signal pathways from the sensors to the microcontroller, and control lines from the microcontroller to the actuator.

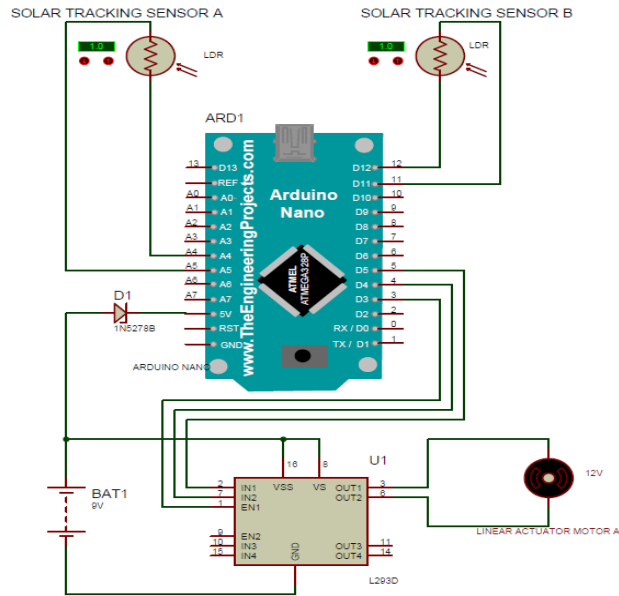


Figure 2. Complete circuit diagram

The designed solar tracker is based on the ability of the solar tracking sensors to respond proportionally to the intensity of light exposure. Since the resistance of the solar sensors changes with changes in light intensity, it essentially uses to monitor the amount of light exposure presence by forming a resistor voltage divider configuration with a resistor of a fixed value. To effectively leverage the functionality of the solar sensor, two different sensors are mounted at the end of the solar panels (across the length and width axis). By comparing the intensity of the sunlight on the two solar sensors the device is programmed to accurately align the panel to the direction of the highest intensity of sunlight. Figures 3 and 4 presents the full assembly and orthographic view presentations of the PV system experimental set up.

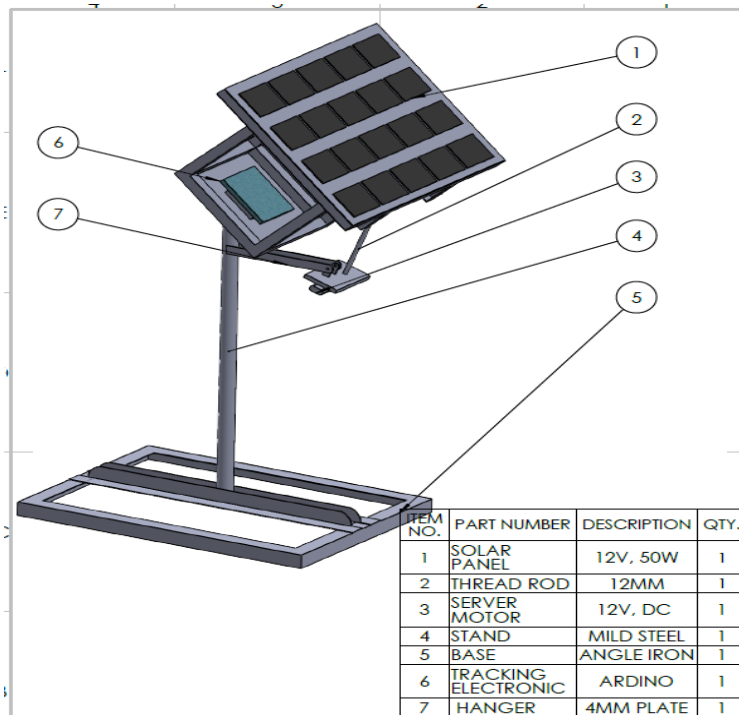


Figure 1. Design layout of the solar tracker

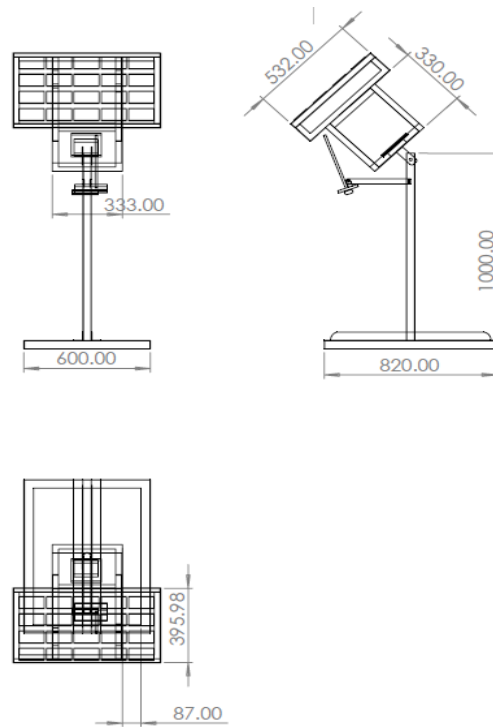


Figure 2. Exploded view of the solar tracker

2.3 Standard Followed in the Design

The design of the microcontroller-based solar tracking system was structured following industry-standard practices for photovoltaic (PV) systems and microcontroller integration. Key standards include:

Component Selection: Components like the Arduino Nano microcontroller, servo motors, solar sensors, and a charge controller were selected based on their proven reliability and efficiency in similar applications. These components comply with standard electrical and mechanical specifications, ensuring compatibility and optimal performance.

2.3.1 Design Methodology:

The design relied on precise engineering principles. For example:

Circuit Design: The circuit integrated sensors to detect sunlight intensity and actuators is controlled by the Arduino Nano to optimize panel alignment.

Programming Standards: The microcontroller was programmed with logical algorithms to adjust panel orientation in response to sensor inputs, ensuring accurate and energy-efficient operations.

Solar Sensor Configuration: The use of resistor voltage dividers for proportional resistance ensured consistent monitoring of light intensity, adhering to electrical engineering best practices.

Prototyping and Testing: The system was assembled and evaluated under real-world conditions at the University of Maiduguri. The seven-day testing period involved continuous data collection, ensuring the design met practical performance benchmarks. The tracker was designed according to IEC 62817 standard. The design adhered to global best practices for renewable energy systems, ensuring scalability and reliability in various environmental conditions.

2.4 Performance Evaluation

After the system has been tested and calibrated, a performance evaluation was conducted in the Centre for Entrepreneurship and Enterprise Development, University of Maiduguri, to assess the effectiveness of the solar tracking system in improving the energy output compared to a fixed solar panel system. The electricity generated by the solar panel when using the tracking system was measured

over a period and compared to the output from a fixed, non-tracking solar panel under the same conditions.

3 RESULTS AND DISCUSSION

The primary objective of the research was to design a microcontroller-based solar tracking system and compare its power output with a stationary solar panel under identical conditions. The testing was conducted over a period of seven days, from 07:00 to 17:00 daily. The stationary solar panel was positioned at a fixed inclination angle of 25°C, while the tracking system was designed to follow the sun's path throughout the day. Plate 1 depicts the designed and constructed microcontroller based solar tracker and the fixed mounted PV systems.



Plate 1. Assembled microcontroller based and the fixed mounted PV system

Table 3 presents the average power output from the panel with the tracking and that without the tracking system. Also Figure 5 presents the comparison of the power outputs from the two systems. The experiment recorded the power output of both the stationary solar panel and the solar panel with the tracker across 11-time intervals between 7:00 and 17:00. Both systems exhibited increasing power generation as the solar intensity increased throughout the morning, peaking around midday before gradually declining in the afternoon. However, the microcontroller based solar tracking system consistently outperformed the stationary panel, with the most pronounced differences occurring during the early morning and late afternoon periods, when the angle of incidence between the sunlight and the solar panels is more variable. As depicted in the Table 4 and Figure 7, at 7:00, the average power output of the stationary panel was 18.19 W, while the solar panel with the tracking system generated an average of 19.25 W (5.8% increase). By 12:00, the power output raised by an average of 11.2% in favour of the solar tracker. This trend continued in the afternoon hours, with the power output of the stationary panel decreasing faster than that of the panel with the tracker. By 17:00, the stationary panel's power output dropped to an average of 19.01 W, whereas the tracking system still generated an average of 32.54 W (average of 71.2% increase). These results clearly demonstrate that the solar tracker significantly improves energy yield, particularly during non-peak hours. For Morning Energy Gains, the solar tracker showed a 5.8% improvement in power output at 7:00 compared to the stationary panel. This aligns with the work of [19], who demonstrated how tracking systems improve energy capture during low-light conditions by aligning panels to the sun's early angles. The trend continued as sunlight intensity increased, with the tracker outperforming the stationary system by an average of 17.4% at 9:00. This highlights the effectiveness of dynamic tracking, supported by similar results from studies by [12]. During Midday Performance, the peak sunlight hours (10:00–14:00), the tracking system maintained a 9.5% to 11% performance advantage. This finding is consistent with [23], who reported that even during optimal sunlight conditions, tracking systems outperform stationary setups due to continuous alignment with the sun. However, at the afternoon energy capture, late afternoon improvements were dramatic,

with a 71.2% increase at 17:00. This result mirrors findings from [10], who emphasized that trackers significantly extend the power generation window during sunset hours.

Table 3. Average power output from the PV system with and without tracking system

Time of the day (hour)	Solar radiation (Wh/m ²)*	Temperature (°C)*	Power Output (W)	
			Without tracker	With tracker
7	85.25	26.30	18.19±2.67	19.25±2.35
8	217.75	27.80	20.45±3.41	23.76±4.07
9	580.875	29.68	24.03±3.37	28.20±1.25
10	664.75	31.13	28.61±1.89	31.33±0.97
11	680.25	32.08	34.26±2.84	39.29±3.36
12	778.25	32.70	39.28±3.91	43.67±3.88
13	754.25	32.91	39.47±3.41	43.44±3.56
14	663.5	33.13	36.75±2.13	40.74±2.40
15	393.375	31.58	30.64±1.02	38.79±2.85
16	251.625	30.28	22.79±1.08	35.49±2.23
17	92.625	28.94	19.01±1.10	32.54±3.49

Values are means of 8-day experimental analysis and their standard deviation.

*Average hourly value of solar radiation and temperature was obtained from the Nigerian Meteorological Agency (NIMET)

The average current, average power and the resulting power output obtained for the stationary panel is presented in Figure 5 and that of the panel with tracker in Figure 6. As it can be observed from Figures 5 and 6, the voltage of the panel with a tracker consistently exceeds that of the stationary panel across all measurements, with differences ranging from 0.1V to 2.1V depending on the conditions. This indicates that the tracker enhances voltage by optimizing the angle of solar incidence. In contrast, the current values for both panels are nearly identical, varying only slightly by up to 0.03A in some cases. These results suggest that while the tracker primarily improves the voltage-and consequently the power output, it has a minimal effect on the current produced. The general trend of increased power output with the tracking system is consistent with the work of [12], which highlights the role of dynamic solar trackers in enhancing energy capture throughout the day.

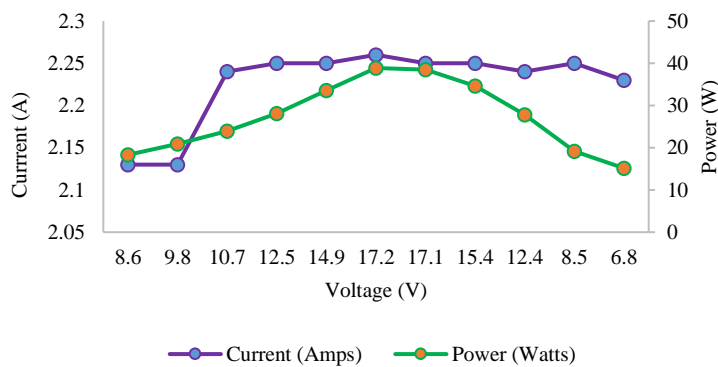


Figure 5. Average current, voltage and power characteristics for stationary panel

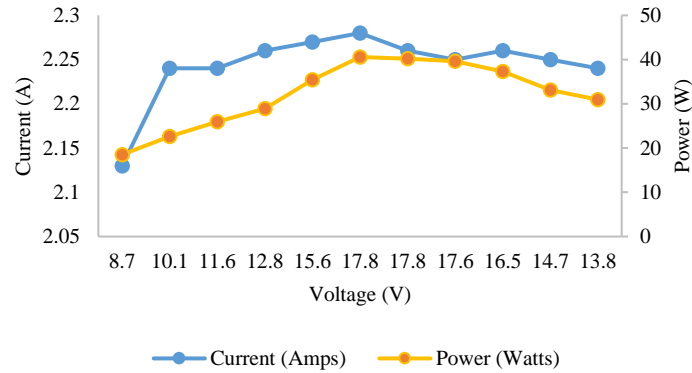


Figure 6. Average current, voltage and power characteristics for panel with tracker

The early morning hours present a critical period for solar energy generation, as the angle of the sun is low, and solar panels are not yet exposed to direct sunlight. During this time, solar panels without a tracking system are less efficient, as they cannot optimize their orientation relative to the position of the sun. In contrast, a solar tracking system adjusts the panel's position throughout the day, allowing it to capture more sunlight even when the angle of the sun is not optimal. From 7:00 to 9:00, the tracking system consistently produced higher power output than the stationary panel. At 7:00, the tracker yielded an average of **19.25 W**, an increment of **5.8%** compared to the stationary panel's average power output of **18.19 W**. The margin of difference expanded as the sun's intensity increased, with the tracker producing an average of **17.4%** improvement over the stationary panel's **24.03 W**. This early morning advantage can be attributed to the tracker's ability to align with the sun's position as it rises. Stationary panels, fixed in place, cannot compensate for the changing angle of sunlight, which is particularly low in the morning. This reduced angle causes a significant reduction in the amount of direct sunlight captured by the stationary panel. In contrast, the tracking system rotates the panel to face the sun directly, maximizing the amount of solar radiation hitting the panel's surface. These findings align with previous studies that have demonstrated the superior performance of solar tracking systems during early morning hours. For instance, the work of [26] showed that solar trackers improved morning energy capture by **15-20%** compared to stationary panels, consistent with the present study's results. During midday, when the sun is at or near its zenith, solar irradiance is at its peak, and both stationary and tracking systems generate their highest levels of power output. As expected, the performance gap between the two systems narrowed slightly during these peak hours, as the stationary panel benefits from the more direct sunlight without needing to adjust its position. At 10:00, the PV with tracking system produced an average of **31.33 W**, compared to the stationary panel's average power output of **28.61W**, representing an average **9.5%** increment. Similarly, at 14:00, the tracker generated an average increment of **11%** compared to the stationary panel's average output of **36.75W**. These results indicate that while the stationary panel benefits from the direct sunlight during midday, the tracking system's ability to adjust its orientation still provides an advantage, ensuring that it captures more sunlight than the fixed panel. These findings are in agreement with the findings of [5] which reported that solar trackers provided an average improvement of during midday, even when both the stationary and tracking panels received high levels of direct sunlight. At 16:00, the stationary panel generated an average power output of **22.79 W** while the solar tracker powered system generated an average of **35.49 W** indicating an average increment of **55.8%**. By 17:00, the power output of the stationary panel system decreased to an average of **19.01 W**, while the tracking system continued to produce an average of **32.54 W**, representing an average of **71.2%** improvement. This significant increase highlights the effectiveness of solar trackers in maintaining energy generation during low-light conditions, as they continue to optimize the panel's position relative to the sun. The superior performance of solar trackers during the late afternoon aligns with the findings of [27] which found that solar trackers could improve energy capture by up to **25-50%** in the late afternoon, as the sun's angle becomes less favourable for stationary panels.

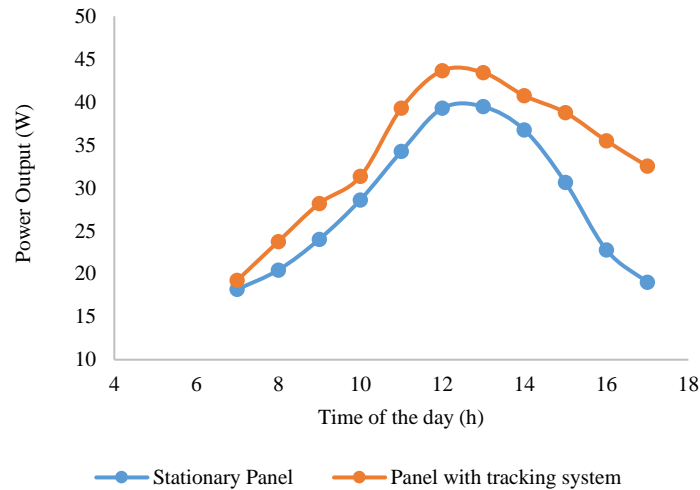


Figure 7. Power output comparison between stationary and PV with tracking system

To validate the statistical significance of the differences in power output between the stationary and tracking systems, a paired t-test was performed on the data collected across the 11-time intervals. The results indicate a statistically significant difference in power output between the two systems ($p < 0.05$), confirming that the solar tracking system provides a measurable improvement in energy generation throughout the day. Table 5 presents the summary of the statistical analysis of the results obtained. The lower standard deviations observed in the tracking system’s power output, particularly during the early morning and late afternoon periods, suggest that the tracking system provides not only more energy, but also more consistent energy generation compared to the stationary panel. The findings of this research is in agreement with the findings of [28, 29] which states that using solar trackers system increases the amount of solar energy received by the solar panels and improves the energy output of the heat/electricity which is generated by up to 20-30% compared to fixed panels.

Table 5. Summary of Pair-wise t-test result

Parameters	Without tracker	With tracker
Mean	28.498	34.227
Variance	59.648	58.723
Standard deviation	7.723	7.663
n		11
t		-4.939
Degree of Freedom		10
Critical value		2.228

The findings of this study have significant implications for the practical application of solar energy systems. In regions where sunlight angles change significantly throughout the day, such as areas closer to the equator or regions with variable solar angles due to mountainous terrain, solar trackers can provide a substantial improvement in energy yield. The ability to generate more power during the early morning and late afternoon hours is particularly relevant for locations with high energy demand during these times, such as residential areas or industrial zones that operate for extended periods each day. Statistical validation of paired t-test analysis ($p < 0.05$) confirmed the statistical significance of these energy gains, echoing previous validations in studies like [16] that used similar statistical approaches to demonstrate the impact of tracking systems on energy output. These findings are in line with what was reported by [30].

4 CONCLUSIONS

A microcontroller-based solar tracking system was designed and developed in this research. The system was designed and developed with components which include solar PV, solar sensors, Arduino Nano, and servo motors. The developed system was evaluated and found that the system

effectively enhanced solar energy generation. The tracker consistently outperformed stationary panels, with energy yield improvements ranging from 5.8% in the early morning to 71.2% in the late afternoon. Even during peak sunlight hours, the tracking system provided a notable 9.5% to 11% performance advantage. The system demonstrated seamless integration of its adaptability to varying sunlight angles makes it suitable for regions with significant solar intensity variations, such as Nigeria. The findings are particularly relevant for areas with fluctuating sunlight, where energy demand aligns with morning and evening periods. Solar trackers offer a practical solution for increasing energy yields in residential, industrial, and rural electrification projects.

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