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Enhancing the Efficiency of a Solar Panel using a Developed Prototype Smart Photovoltaic Module Single-axis Solar Tracker

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Abstract: *There is a global compelling need to adopt a clean renewable energy in order to reduce carbon emissions driving climate change. Photovoltaic cells (PV) provide a solution, however they will be more economically viable if their efficiency are improved and their total cost optimized. Enhancing the performance efficiency of solar modules to overcome the limitations of geographical locations and climatic conditions in achieving full sun has led to the development of solar trackers. These solar trackers need to be energy efficient, low cost, easy to install, reliable in tracking the sun to be attractive. This paper discusses the development of an efficient, low cost, prototype single-axis solar tracker. The energy consumption of the developed solar tracker is minimized through the implemented components circuitry. Light dependent resistors are deployed as navigation sensors to control the horizontal movement of the PV solar panel. Trajectory calculations aided the solar tracker axis control. The obtained validation results show an average enhanced photovoltaic cell efficiency of 20.2% compared to a stationary photovoltaic panel of the same configurations. The commercialization of the developed prototype solar tracker will make the device available and affordable to users of solar modules especially in low income countries of Sub-Saharan Africa.*

Keywords: *Photovoltaic module, Photovoltaic cell efficiency, Navigation sensor, Solar tracker, Solar cell panel*

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1.0 Introduction

The urgent need to reduce carbon emissions that contribute to climate change has created a strong global shift toward cleaner and renewable sources of energy. Among these, solar power is emerging as one of the leading alternatives because it is sustainable, pollution-free, and relatively easy to install (Hammoumi et al., 2025). Solar panels are devices designed to capture sunlight and convert it into electrical energy, and their adoption has grown rapidly across the world over the past few decades. Typically, solar panels are installed in fixed positions and tilted to maximize sunlight capture. However, fixed installations have limitations: since the Earth is in constant motion and the sun's position changes with the seasons, solar panels in fixed orientations cannot always receive the maximum available sunlight (Algarín et al., 2017). The generating capacity of a solar panel depends on the amount of sunlight incident on it, which determines the number of photons available for conversion. As a result, increasing power output often requires installing additional panels (Babaei et al., 2023). This not only demands more land coverage but also increases costs. Even with more panels, fixed systems remain unable to track the sun's daily movement. To overcome this challenge, solar trackers were developed to boost efficiency by continuously adjusting panel orientation to follow the sun (Krishna et al., 2024).

A solar tracker is a mechanical control device that aligns solar panels toward the sun so that maximum sunlight continuously falls on them, thereby increasing the number of incident photons (Yao et al., 2014). By tracking the sun's path, energy production is significantly enhanced. Solar trackers are broadly categorized into Active Solar Trackers and Passive Solar Trackers. Active trackers employ motors and sensors to adjust the inclination angles of the panels (Barrios-Sánchez & Tlapanco-Ríos, 2025). The most common type is the Single-Axis Solar Tracker, which rotates horizontally to follow the east–west movement of the sun. A more advanced version is the Dual-Axis Solar Tracker, which moves panels both horizontally and vertically, thus enabling two-dimensional tracking (De-Souza et al., 2020). While dual-axis trackers capture more sunlight, especially in equatorial regions with high sun-angle variation, they are more complex and expensive. In contrast, passive solar trackers operate without motors or sensors. Instead, they rely on natural forces such as gravity or thermal expansion to adjust panel angles (Mohd et al., 2023). Though less expensive and simpler to construct, they are also less precise. Examples include tilted rack systems, where panels are installed at fixed angles, and seasonal adjustment systems, where manual repositioning is done according to seasonal changes (Prasann et al., 2025; Clifford & Eastwood, 2004).

Studies show that solar trackers can improve solar panel efficiency by between 15% and 67.65%, depending on the type of tracker and location (Muthukumar et al., 2023). Single-axis trackers are widely used in regions close to the equator, while dual-axis trackers are preferred in regions with greater sun-angle variation. Global research shows that contributions to single-axis tracker development are highest in Asia (49.2%), followed by Europe (23%), the Americas (11.9%), and Africa (15.1%). With navigation sensors, single-axis trackers can achieve efficiency gains of up to 57.4%, while dual-axis trackers may achieve up to 67.65% (Barker et al., 2013; Boukdir & Omari, 2022; Varshney et al., 2023).

Despite these benefits, the widespread adoption of solar trackers is limited by *their* high costs and complex mechanisms. Trackers also require frequent maintenance because of the wear and tear of moving parts, and some of the harvested energy must be diverted to power the tracking system itself, reducing net output (Arslan et al., 2024). Consequently, many users still prefer fixed solar panel systems despite their lower efficiency (Alexandru & Pozna, 2010). In addition, weather variations such as clouds and rainfall further reduce tracker performance. Conventional tracking systems often depend on pre-set algorithms that are unable to adapt effectively to rapidly changing environmental conditions, resulting in reduced efficiency (Helwa et al., 2000).

Therefore, there is a need to develop an affordable, efficient, and adaptable solar tracking system using simple and locally sourced materials. The aim of this research is to design and build a single-axis tracker that automatically adjusts the inclination of a solar panel to maximize sunlight capture and improve power output. Specifically, the study seeks to reduce overall energy consumption by deploying fewer electronic components, thereby lowering the size, cost, and power requirements of the tracking device. This research covers the design and testing of a low-cost horizontal single-axis solar tracker, a performance comparison with a fixed panel, and validation of efficiency under identical weather conditions. The findings are expected to contribute to advancing research in solar power development and to provide a cost-effective solution that could encourage greater adoption of renewable energy technologies, particularly in resource-limited regions.

2.0 Materials and Methods

This section describes the development and validation of the smart photovoltaic module single-axis solar tracker. The developed device is at the prototype stage.

2.1 The System Architecture and Components

The solar tracker system controls the positioning of the solar panel to maintain alignment with the trajectory of the sun according to Wang and Lu (2021). The operation of the smart photovoltaic module single-axis solar tracker is presented in the block diagram in Fig. 1. The solar panel supplies power to the batteries through the solar charge controller. The batteries supply electric power to the microcontroller. The microcontroller controls the actuator using data received from the light-dependent resistors (LDRs) and the real-time clock (RTC) module. When sunlight intensity increases, the electric resistance of the LDRs decreases. The microcontroller evaluates this data and determines the magnitude of the transmitted current. Based on the input parameters, the stepper motor is triggered to move, causing the angle of inclination of the solar tracker to increase.

The stepper motor driver has been programmed to make a fixed angular rotation depending on the signal from the microcontroller.

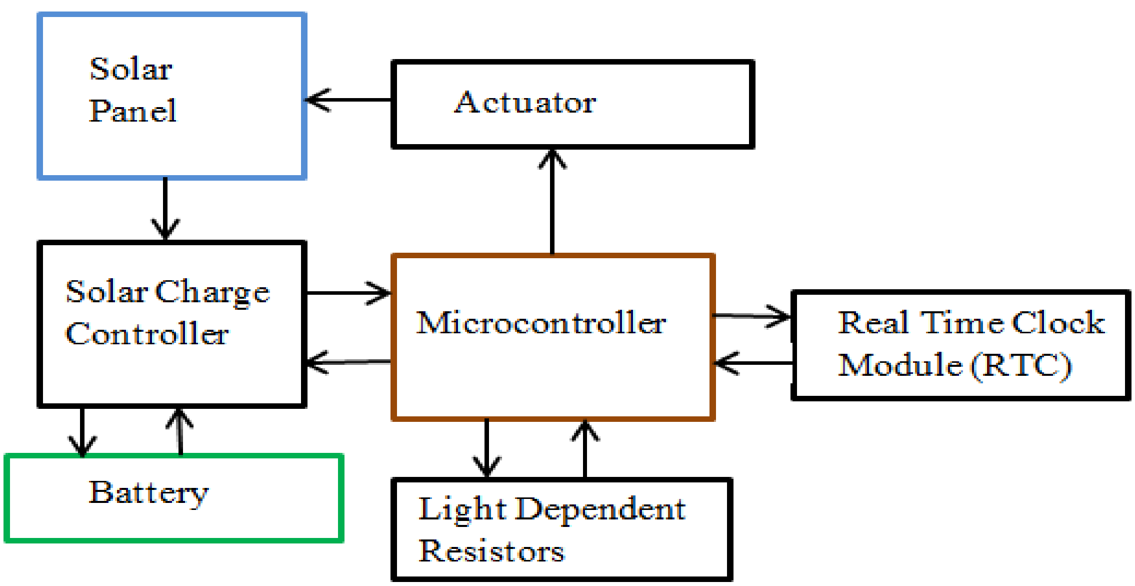

Fig. 1: Block Diagram of the Smart Photovoltaic Module Single-Axis Solar Tracker]

The RTC module sends a signal to the microcontroller once it is night, prompting the microcontroller to hibernate in order to conserve electric power. An activation notification signal is delivered to the microcontroller in the morning to switch from hibernation mode to active mode. The LDRs are then activated for operation. The stepper motor angle of inclination is reset, returning the solar panel to the starting position. The cycle continues during the daily operation of the solar tracker.

The circuit diagram of the smart photovoltaic module single-axis tracker is shown in Fig. 2. The connections of the stepper motor and the driver to the solar panel and the circuitry for the microcontroller are presented. The LDRs act as light sensors, whose resistance depends on the ambient light intensity. The developed prototype of the solar tracker is described in Fig. 3. The wooden structure provides support for the solar panel and secures the microcontroller and other components.

Solar panels or modules absorb incident photons and convert them to electrical signals following the process of electron excitation, generation of electron–hole pairs, charge separation, and current flow. The material structure is usually monocrystalline or polycrystalline silicon. The monocrystalline module is made from a single, continuous crystal, while polycrystalline consists of multiple crystals melted together. Monocrystalline silicon solar modules demonstrate slightly higher efficiency than polycrystalline modules, although they are more expensive due to higher production costs. Emerging solar cell technologies use materials with tunable crystal structures such as perovskites, according to Chin et al. (2011).

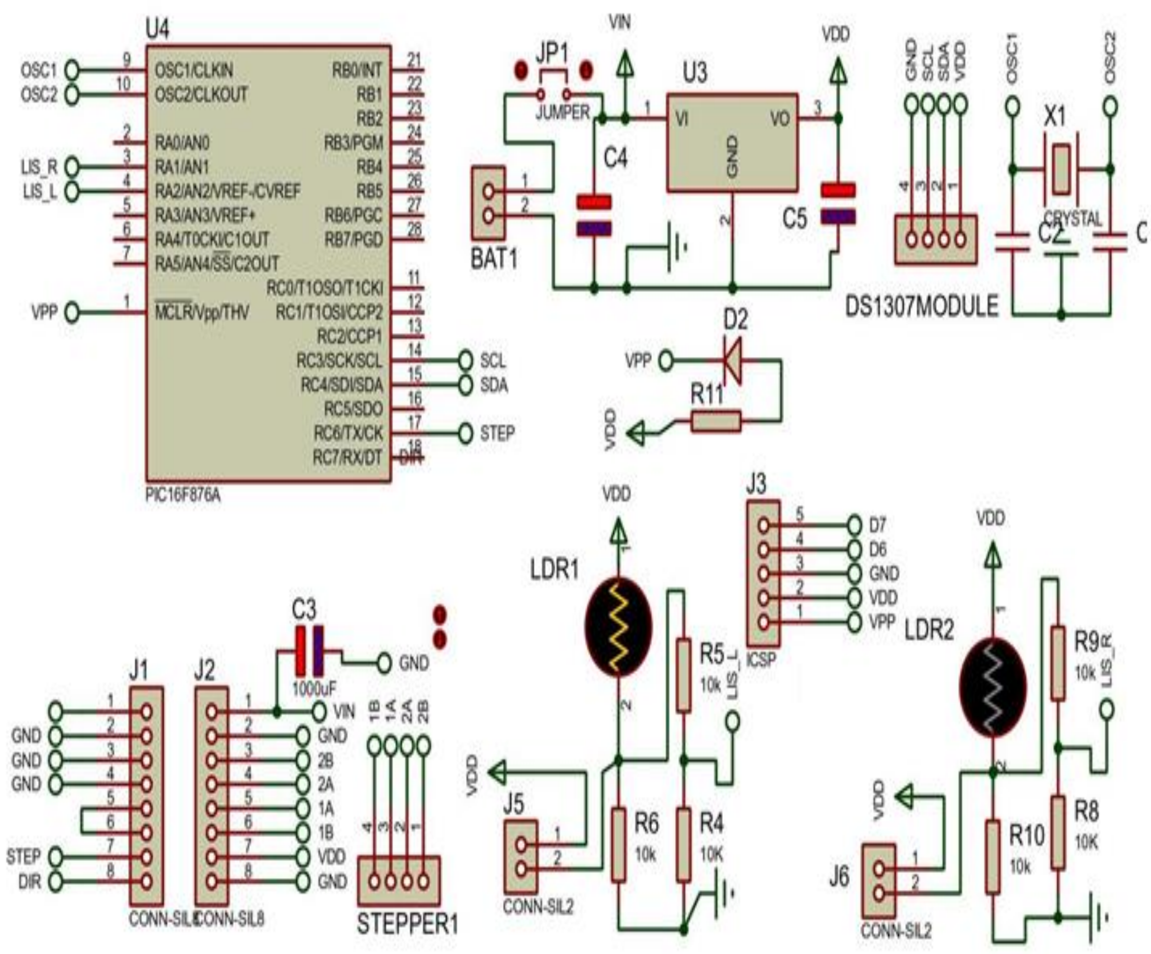

Fig. 2: Circuit Diagram of the Smart Photovoltaic Module Single-Axis Solar Tracker]

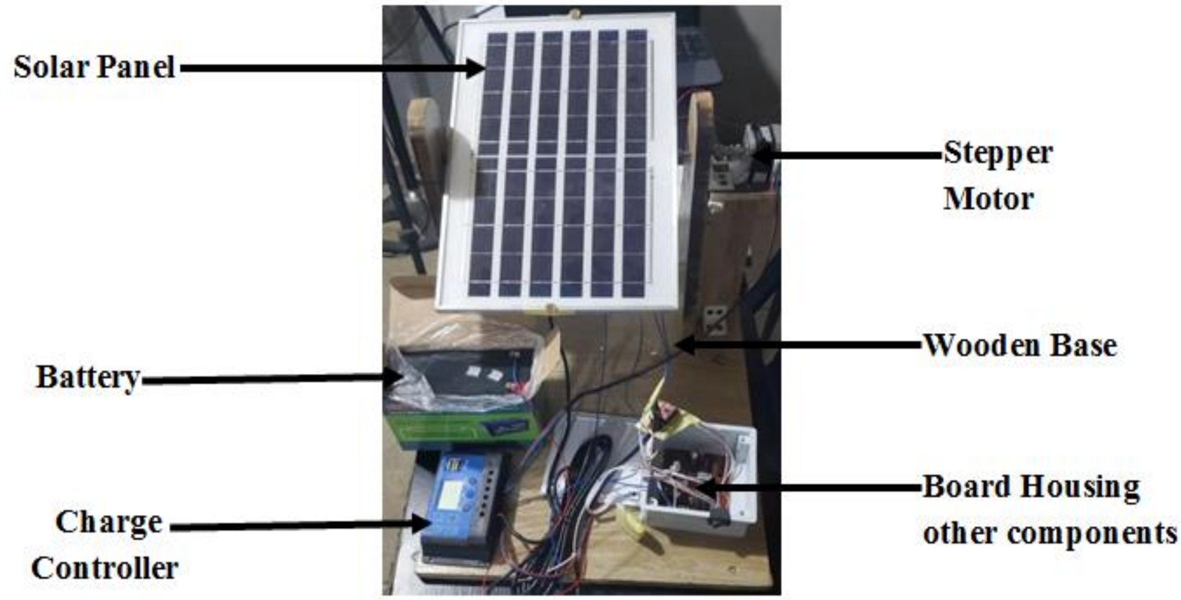

Fig. 3: Prototype of the Smart Photovoltaic Module Single-Axis Solar Tracker]

2.2 The Solar Panel

A 12-volt, 15-watt monocrystalline silicon solar module with dimensions of 37.1 cm × 36.1 cm and thickness of 1.8 cm was mounted on the prototype solar tracker. The connection of the solar panel in the device is shown in Fig. 3.

2.3 The Solar Charge Controller

The charge controller is a smart manager for the energy produced by the solar panel. Its main function is to regulate the amount of electricity flowing from the panel to the battery during charging. It ensures that the battery is charged properly with the ideal current and protects it from overcharging, which could damage the battery.

The solar charge controller model used was W88-B**,** with rated voltage: 12V/24V, rated current: 20 A, and maximum PV voltage of 50V.

2.4 The Battery

The battery is the storage unit for the energy generated by the solar panels. It stores electricity produced during the day so that it can be used when the sun is not shining, such as at night or on cloudy days. The battery acts as a backup power source**,** providing a steady supply of energy even when the panels are not producing electricity.

A 12-volt, 7.5 ampere-hour lead-acid battery, shown in Fig. 3, was used in the development of the prototype solar tracker.

2.5 Actuator

The solar panel requires a machine that produces torque so its orientation can continuously align with the direction of the sun. Actuators are like the muscles of the solar tracking system, enabling the inclination angle of the solar panel to change toward the sun's direction. The actuator physically moves the solar panel based on instructions from the microcontroller. They ensure that the panels are always facing the sun. Actuators can be motors or other mechanical devices with the strength and precision to move the panels smoothly, as shown by Rizman et al. (2018).

In this prototype, a stepper motor of 12V (model: 17HS3401), shown in Fig. 3, was used due to its high torque, which keeps the solar panel stable when it does not need to move. The stepper motor required a driver to initiate movement, and an A4988 stepper motor driver was deployed in this solar tracker.

2.6 Microcontroller

The PIC16F876A microcontroller was implemented in the development of the solar tracker, as shown in Fig. 2. The microcontroller serves as the ***brain*** of the solar tracking system. It is programmed to control and manage the system by receiving information from the light sensors and making decisions about how to move the solar panels. The RTC provides time-of-day information, which also forms part of the logic in determining when the device should hibernate at night to conserve energy, according to Bawa and Patil (2013).

2.7 Light-Dependent Resistors (LDRs)

These are special sensors that detect sunlight intensity based on variations in their resistance. The resistance of an LDR decreases as light intensity increases. They are positioned at different places on the solar panel to measure sunlight from multiple angles. The microcontroller interprets the information received from the LDRs to determine the sun's position and trigger panel movement through the stepper motor.

2.8 Real-Time Clock Module (RTC)

The RTC module is a small electronic device designed to keep time very accurately. It has an internal clock that continues ticking even when the power is turned off. Thus, even if the solar tracking system is shut down or there is a power outage, the RTC module will still maintain the correct time when the system is reactivated. It helps the solar tracking system determine the exact time of day. This function ensures that tracking stops at night, preventing unnecessary battery drainage. The solar panel hibernates at night and automatically activates during the day.

2.9 Cost Analysis for the Developed Prototype

The cost of the developed prototype smart solar tracker is presented in Table 1. The choice of the circuit design with optimal electronic components reduced the cost and power consumption of the prototype.

Table 1: Cost of Developing the Prototype Smart Photovoltaic Module Single-Axis Solar Tracker

Component Description	Quantity	Cost (NGN)
(12V, 15W) Solar PV Panel	1	12,000
(12V, 7.5Ah/20Hr) Battery	1	14,500
(12V, 20A) Charge Controller	1	7,000
PIC 16F876A Microcontroller	1	16,000
17HS3401 Stepper Motor	1	10,500
A4988 Driver (for stepper motor)	1	2,140
Light-Dependent Resistors	2	600
PCB, resistors and transistors	–	2,500
Wooden Panel Support	1	15,000
DS1307 RTC Module	1	1,540
Total Cost		**81,780**

3.0 Results and Discussion

3.1 Experimental setup

The developed prototype solar tracker was coupled to a solar panel with dimensions 37.1 × 36.1 cm and a thickness of 1.8 cm. Another fixed solar panel of the same dimensions was mounted without the tracker for comparison. The two experimental setups consisted of one panel with the solar tracker and another panel fixed in place. Both solar panels were exposed to the same ambient weather conditions and placed on top of a table outdoors. They were positioned in such a manner that no shading occurred during the experiment.

The experiment was conducted between 11:00 and 16:00 GMT, with both solar panels initially set at a tilt angle of 15° from the horizontal axis, facing the sun at the start time. A data logger was used to measure the generated voltage and power from both panels. The experiment was carried out only under clear sky conditions, without rainfall. Voltage and power measurements were logged starting from 13:00 GMT, when the tracker began to adjust its orientation. Both setups were closely monitored to ensure that no obstruction interfered with solar exposure. The average recorded values are presented in Table 2.

Table 2: Comparison of average voltage and power logged for the fixed solar panel and the solar panel with tracker using Fluke 1732 and 1734 Three Phase Power Measurement Data Logger

Date Time (GMT+01:00)	Average Voltage (Fixed Panel) [V]	Average Voltage (Solar Tracker) [V]	Average Power (Fixed Panel) [W]	Average Power (Solar Tracker) [W]
12/08/2024 13:00–13:59	8.16705	8.21587	13.34179	13.50010
12/08/2024 14:00–14:59	8.15061	8.62181	13.28794	14.86890
12/08/2024 15:00–15:59	6.96260	8.64356	9.71163	14.94223

The total power and voltage generated by the fixed solar panel compared to the tracker-assisted panel are presented in Table 3. These values were used to evaluate the efficiency of the developed smart solar tracker. A graphical comparison of their total output is shown in Fig. 4.

Table 3: Total voltage and power produced by the fixed solar panel compared to the solar panel with a tracker

	Fixed Solar Panel	Solar Tracker	Difference
Total Voltage Generated (V)	1602.77	1760.09	157.32
Total Power Generated (W)	2429.43	2921.18	491.75
Total Energy (kJ)	31,048	37,333	6,285

The energy conversion efficiency (ECE) of the single-axis solar tracker relative to the fixed panel was calculated using the following equations

$$ECE\ (\%) = \frac{\text{Energy output of solar tracker} - \text{Energy output of fixed panel}}{Energy\ output\ of\ fixed\ panel} \times \frac{100}{1}$$

$$ECE\ (\%) = \frac{(37333\text{kJ} - 31048\text{kJ})}{E31048kJ} \times \frac{100}{1} = 20.20\%$$

3.2 Experimental Observations and Discussion

It was observed that the voltage and power produced by both the fixed solar panel and the tracker-assisted panel remained nearly identical during the first 1 hour and 48 minutes. As the tilt angle of the prototype tracker gradually increased, its output voltage and power also began to rise.

The maximum solar irradiance recorded by the tracker occurred between 14:03 and 16:09 GMT. During this period, the tracker consistently generated higher voltage, whereas the fixed solar panel exhibited fluctuations and a general decline in voltage. These fluctuations were attributed to the rotation of the Earth on its axis, which alters the angle of solar incidence. While the fixed panel could not adjust to these changes, the tracker automatically reoriented itself to maintain optimal exposure, thereby validating its functionality as an intelligent system. This outcome is further supported by the graphical results in Fig. 4.

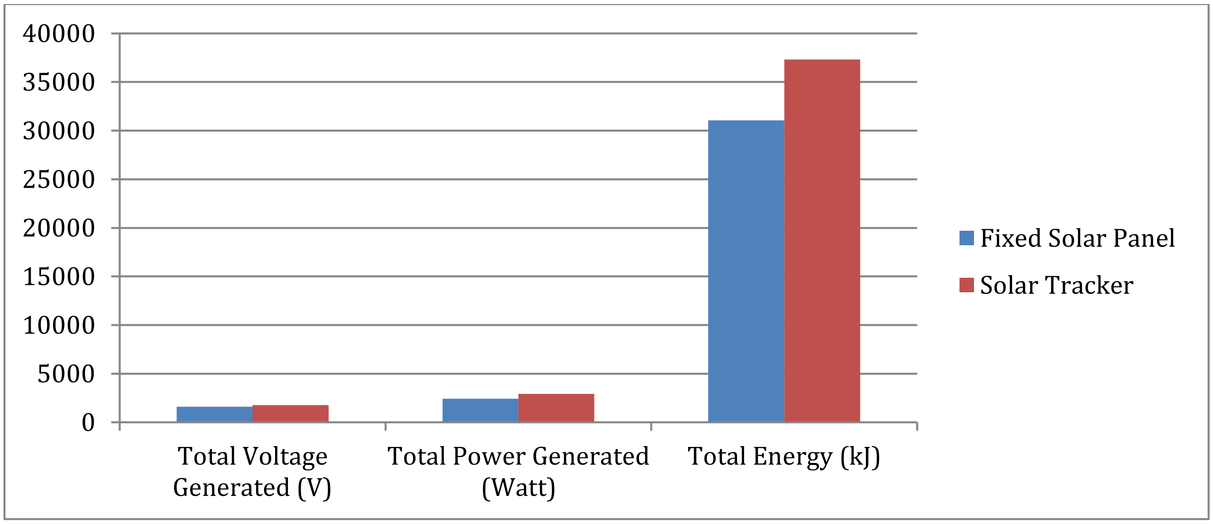

Fig. 4. Total output produced by the fixed solar panel compared with the output from the solar panel connected to a solar tracker

The energy conversion efficiency of the prototype single-axis tracker was found to be 20.2% higher than that of the fixed panel. This increase in efficiency is justified, since the power output of the tracker consistently exceeded that of the stationary module.

3.3 Novelty of the Developed Prototype Smart Photovoltaic Single-Axis Solar Tracker

The novelty of the developed prototype lies in the use of fewer electronic components, which reduced both the cost and the power consumption of the device. The total fabrication cost was approximately ₦81,780.00 (Eighty-one thousand, seven hundred and eighty Naira).

In contrast, many existing variants of solar trackers employ complex circuitry in an attempt to achieve perfect automation of solar panel alignment. Such complexity increases power consumption, drains the battery, and reduces overall efficiency. Furthermore, some designs integrate artificial intelligence features that make them costly and difficult to install, often requiring expert handling (Afarulrazi et al., 2011).

The simplicity and cost-effectiveness of this prototype make it suitable for deployment in smart cities, hospitals, and industrial facilities where stable power supply is essential.

3.4 Limitations of the Research

The scope of this study does not include the fabrication of the electronic components or the manufacturing of the materials used in building the prototype. The tracker was deliberately designed with a single-axis horizontal movement to minimize cost and optimize power consumption. While this approach sacrifices the higher light-harvesting capability of more advanced robotic trackers, it achieves greater efficiency through minimal power usage. Also, the prototype does not provide remote monitoring features such as Wi-Fi or wireless connectivity, which could be incorporated in future improvements.

3.5 Contributions to Knowledge

This work demonstrates the feasibility of designing a cost-effective, single-axis solar tracking system using low-cost and optimally selected electronic components. The developed tracker significantly improves solar energy conversion efficiency compared to conventional fixed photovoltaic systems.

By addressing the limitations of unstable or fluctuating solar radiation, this system ensures better utilization of solar energy capacity. Its affordability and operational efficiency make it especially attractive for low-income countries in Sub-Saharan Africa, where the demand for cost-efficient renewable energy solutions is high.

3.6 Application to Industry

The developed solar tracker is affordable, reliable, easy to install, serviceable, and highly efficient in converting incident photons into electricity. Stable electricity supply is critical across industries, and this device can serve as a catalyst for increasing solar-based electricity production. The efficiency gains from using this tracker are expected to encourage broader adoption of solar technology and accelerate the transition from fossil-fuel generators to cleaner, renewable solar energy.

4.0 Conclusion

The study developed and tested a prototype single-axis smart solar tracker using optimally selected low-cost electronic components. The experimental results showed that the solar tracker consistently produced higher voltage and power compared to a fixed solar panel of the same dimensions under identical weather conditions. The tracker achieved a total energy output of 37,333 kJ compared to 31,048 kJ from the fixed panel, resulting in a 20.2% improvement in energy conversion efficiency. The system demonstrated reliability in adjusting automatically to the movement of the sun, thereby reducing the fluctuations observed in the fixed solar panel and sustaining higher output during peak irradiance periods. The novelty of the tracker lies in its simplified design with fewer electronic components, which reduces cost and power consumption while maintaining performance.

In conclusion, the developed prototype single-axis solar tracker is cost-effective, efficient, and suitable for applications requiring stable energy supply. Its simplicity makes it more affordable and easier to maintain compared to existing complex variants that often require expert handling and higher costs. Although the system does not incorporate dual-axis tracking, wireless communication, or advanced robotics, it nonetheless achieves a significant efficiency gain while minimizing energy consumption. This makes it a practical solution for renewable energy deployment, particularly in low-income regions such as Sub-Saharan Africa.

Based on the findings, it is recommended that future work should focus on integrating wireless monitoring and remote control capabilities to enhance usability and system management. Further improvements could also include the design of a dual-axis version to maximize solar capture throughout the day. Scaling up the design for larger solar farms and industrial applications is strongly encouraged, as the device has the potential to serve as a catalyst for wider adoption of renewable solar power and to accelerate the transition from fossil-fuel-based energy systems to clean, sustainable alternatives.

5.0 References

Abas, M. A., Kadir, S. A., & Azim, A. K. (2010). Improved structure of solar tracker with microcontroller based control. *IEEE 2nd International Conference on Advances in Computing, Control and Telecommunication Technologies,* 55-59. doi: 10.1109/ACT.2010.28

Afarulrazi, A. B., Utomo, W. M., Liew, K. L., & Zarafi, M. (2011). Solar tracker robot using microcontroller. *IEEE International Conference on Business, Engineering and Industrial Applications*, 47-50. Doi: 10.1109/ICBEIA.2011.5994256.

Alexandru, C., & Pozna, C. (2010). Simulation of a dual-axis solar tracker for improving the performance of a photovoltaic panel.

Proceedings of the Institution of Mechanical Engineers, Journal of Power and Energy, 224, 6, pp. 797-811. https://doi.org/10.1243/09576509JPE871.

Algarín, C.R., Castro, A.O., & Naranjo, J.C. (2017). Dual-axis solar tracker for using in photovoltaic systems. *Int. J. Renew. Energy Resour.*, 7, 1, pp. 137-145, Doi: 10.20508/ijrer.v7i1.5147.g6973

Arslan, A.R., Talha, A., Khan, C.F., & Abdelrahman E.l.L. (2024). Pyramidal Sun Sensor: A Novel Sun Tracking System Solution for Single Axis Parabolic Trough Collector. *Autom. Control Comput. Sci.* 58, 6, pp. 722–734. https://doi.org/10.3103/S0146411624701189

Babaei, R., David S.K.T., & Rupp, C. (2023). Feasibility analysis of solar tracking technologies connected to renewable energy systems. In Turbulence & Energy Laboratory Annual Conference, pp. 125-156. *Cham: Springer Nature Switzerland*, https://doi.org/10.1007/978-3-031-47237-4_7

Barker, L., Neber, M., & Lee, H. (2013). Design of a low-profile two-axis solar tracker. *Solar Energy*, 97, pp. 569-576. http://dx.doi.org/10.1016/j.solener.2013.09.014

Barrios-Sánchez, J.M., & Tlapanco-Ríos, E.I. (2025). Dual-Axis Solar Tracking System for Enhanced Photovoltaic Efficiency in Tropical Climates. *Sustainability*. 17, 1117, https://doi.org/10.3390/su17031117

Bawa, D., & Patil, C.Y. (2013). Fuzzy control based solar tracker using Arduino Uno. *International Journal of Engineering and Innovative Technology*, 2, 12, pp. 179-187. https://www.ijeit.com/vol%202/Issue%2012/IJEIT1412201306_34.pdf

Boukdir, Y., & Omari, H.E. (2022). Novel high precision low-cost dual axis sun tracker based on three light sensors. *Heliyon*, 8, 12, e12412. DOI: 10.1016/j.heliyon.2022.e12412

Chin, C.S., Babu, A., & McBride, W. (2011). Design, modeling and testing of a standalone single axis active solar tracker using MATLAB/Simulink. *Renewable Energy*, 36, 11, pp. 3075-3090. https://doi.org/10.1016/j.renene.2011.03.026.

Clifford, M. J., & Eastwood, D. (2004). Design of a novel passive solar tracker. *Solar Energy*, 77, 3, pp. 269-280, 2004. https://doi.org/10.1016/j.solener.2004.06.009

De-Souza, L., F., Da-Silva, V.A., De-Alencar, N.I., Da-Silva, L.N..D., & Da-Silva, M.C. (2020). The efficacy of a dual-axis solar tracking device in tropical climate. *Res. Soc. Dev.* 2020, *9*, e96371102. DOI: https://doi.org/10.33448/rsd-v9i11.9637.

Gisi, M., Hase, F., Dohe, S., & Blumenstock, T. (2011). Camtracker: A new camera controlled high precision solar tracker system for FTIR-spectrometers. *Atmospheric Measurement Techniques*, 4, 1, pp. 47-54. https://doi.org/10.5194/amt-4-47-2011.

Hammoumi, A.E., Motahhir, S., Ghzizal, A.E., Chalh, A., & Derouich, A. (2025). A simple and low-cost active dual-axis solar tracker. *Energy Science & Engineering*, 6, 5, pp. 607-620, https://doi.org/10.1002/ese3.236

Helwa, N. H., Bahgat, A. B., El Shafee, A. M., & El Shenawy, E. T. (2000). Maximum collectable solar energy by different solar tracking systems. *Energy Sources*, 22, 1, pp. 23-34. Doi: 10.1080/00908310050014180

Jamroen, C., Komkum, P., Kohsri, S., Himananto, W., Panupintu, S., & Unkat, S. (2020). A low-cost dual-axis solar tracking system based on digital logic design: Design and implementation. *Sustainable Energy Technologies and Assessments. Elsevier*, 37, 100618. DOI: 10.1016/j.seta.2019.100618

Krishna, K., P., Upender, P.B., Mithu, S., Sishaj, P.S., & Venkateswarlu, G. (2024). *Energy Reports*, 12, pp. 3566-3583, https://doi.org/10.1016/j.egyr.2024.09.038.

Mohd, S. R. (2023). Dual-axis solar energy tracking and monitoring system with arduino as a microcontroller. *Sci. Res. J.*, 20 (2), pp. 131-145, Doi:10.24191/srj.v20i2.22365

Muthukumar, P., Manikandan, S., Muniraj, R., Jarin, T., & Sebi A. (2023). Energy efficient dual axis solar tracking system using IOT. *Elsevier BV*, 28, pp. 100825-100825.

Prasann, S., & Pooja, S. (2025). Hydraulic solar tracker: Solar energy enhancer with hydraulic tracking system. *AIP Conf. Proc.* 14 February 2025; 3162, 1, 020061. https://doi.org/10.1063/5.0241829

Rizman, Z. I., Ishak M. T., Hashim, F. R., Yassin, I. M., Zabidi, A., Zaman, F. K., Yeap, K. H., & Kamarudin, M. N. (2018). Design a simple solar tracker for hybrid power supply. *Journal of Fundamental and Applied Sciences*, 10, pp. 333-346. http://dx.doi.org/10.4314/jfas.v10i2s.26

Solar tracking systems: Advancements, challenges, and future directions. A review,

Varshney, G., Mittal, U., Kishore, M. P., & Saxena, U. (2023). Design, implementation and performance assessment of a low-cost dual-axis solar tracker. *Journal of Physics*, 2570, 1, pp. 012005-012005. DOI:10.1088/1742-6596/2570/1/012005

Wang, J.M., & Lu C.L. (2021). Design and Implementation of a Sun Tracker with a Dual-Axis Single Motor for an Optical Sensor-Based Photovoltaic System. *Sensors*. 13, 3, pp. 3157-3168, 20213. https://doi.org/10.3390/s130303157.

Yao, Y., Hu, Y., Gao, S., Yang, G., & Du, J. (2014). A multipurpose dual-axis solar tracker with two tracking strategies. *Renewable Energy*, 72, pp. 88-98, Doi: 10.1016/j.renene.2014.07.002

Declaration

Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data public

Ethical Considerations

This study was carried out under strict laboratory conditions, without the involvement of human or animal subjects. All procedures complied with institutional and international research guidelines. Glyphosate and mushroom substrates were handled responsibly, ensuring biosafety and minimizing environmental risks through safe disposal practices. The research team maintained integrity, transparency, and accountability throughout the study, ensuring results were obtained, analyzed, and reported ethically in line with accepted scientific and environmental protection standards.

Competing interest

The authors declared no conflict of interest. This work was sole collaboration among all the authors

Funding

There is no source of external funding

Authors Contributions

U.I. Oduah conceived, designed, supervised, and edited the study. E.A. Agbojule assembled the prototype, implemented circuitry, and collected data. P.C. Nwosu designed system architecture and validated experiments. C.G. Chukwuka analyzed data and prepared figures. D. Oluwole handled electronics and circuit design. I. Okungbowa tested the device and drafted discussion. All authors approved the final manuscript.