

Design and Implementation of a Cost-Effective Hybrid Solar Energy System with LDR-Based Dual-Axis Sun Tracking for Enhanced Power Generation

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Abstract

The growing demand for clean and sustainable energy has increased the adoption of solar photovoltaic (PV) systems. However, conventional fixed PV panels are unable to capture maximum solar radiation throughout the day due to the sun's continuous movement, resulting in reduced energy efficiency. This paper presents the design and implementation of a cost-effective hybrid solar energy system integrated with an LDR-based dual-axis sun tracking mechanism. The proposed system combines monofacial and bifacial solar panels to harvest both direct and reflected solar irradiance, thereby enhancing overall energy generation. A dual-axis tracking system using four Light Dependent Resistor (LDR) sensors detects the direction of maximum sunlight, while two servo motors adjust the panel orientation along horizontal and vertical axes. An Arduino Uno microcontroller is used to process sensor inputs and execute the tracking algorithm efficiently. Additionally, a voltage sensing unit with an I2C LCD module provides real-time monitoring of output voltage and tracking direction. The proposed system improves energy harvesting efficiency, reduces manual intervention, and offers a low-cost, eco-friendly solution suitable for residential, agricultural, and remote area applications.

1. Introduction

The continuous increase in population, industrial growth, and technological development has led to a significant rise in global energy demand. At the same time, heavy dependence on conventional fossil fuels such as coal, petroleum, and natural gas has caused serious environmental concerns, including global warming, greenhouse gas emissions, and air pollution. These challenges have accelerated the shift toward renewable and sustainable energy sources. Among them, solar energy stands out as a reliable and abundant resource due to its wide availability, environmentally friendly nature, and minimal maintenance requirements [13].

Photovoltaic (PV) technology enables the direct conversion of sunlight into electrical energy using semiconductor materials. In recent years, PV systems have been widely adopted across residential, commercial, industrial, and agricultural sectors, as well as in remote areas lacking grid connectivity. However, conventional fixed PV systems operate with limited efficiency because they remain stationary while the sun continuously changes position throughout the day. This mismatch between panel orientation and solar position reduces the amount of captured solar radiation and leads to lower power generation [15].

To enhance energy capture, solar tracking systems have been developed to dynamically align PV panels with the sun's position. These systems can be classified into single-axis and dual-axis trackers. Dual-axis tracking systems are more effective as they allow movement along both horizontal and vertical directions, ensuring optimal alignment with solar radiation at all times. As a result, they significantly improve energy output compared to fixed and single-axis systems [1], [12], [14].

Recent advancements have focused on developing cost-effective tracking systems using simple sensors and microcontrollers. Light Dependent Resistors (LDRs) are widely used to detect variations in light

intensity, enabling real-time tracking of the sun. Microcontrollers such as Arduino Uno provide an efficient and flexible platform for processing sensor data and controlling actuators [10]. Servo motors are commonly used in such systems due to their precision, low power consumption, and ease of implementation, allowing accurate positioning of solar panels [11].

In this work, a dual-axis tracking mechanism is implemented using two servo motors, where one controls horizontal movement and the other controls vertical adjustment. Four LDR sensors are strategically placed to measure light intensity from different directions. Based on these inputs, the Arduino controller continuously adjusts the panel orientation toward the direction of maximum sunlight, thereby maximising energy harvesting.

To further enhance system performance, a hybrid photovoltaic configuration is introduced by combining monofacial and bifacial solar panels. While monofacial panels capture direct sunlight from the front surface, bifacial panels can also utilise reflected light from the rear side. This hybrid arrangement improves overall energy generation, particularly under varying environmental conditions, and enhances system efficiency [8], [9].

Additionally, a voltage sensing module is incorporated to monitor the electrical output of the system in real time. The measured voltage values and tracking status are displayed on an I2C-based LCD, allowing users to easily observe system performance. This feature improves system transparency and facilitates performance evaluation without requiring additional monitoring devices.

The proposed system is designed with simplicity, reliability, and cost-effectiveness in mind by utilising readily available components such as Arduino Uno, LDR sensors, servo motors, and display modules. It reduces manual intervention, minimises energy loss, and improves overall efficiency, making it suitable for applications in residential areas, agriculture, smart farming, street lighting, and remote off-grid locations.

Although significant research has been conducted on solar tracking and PV optimisation, most existing systems address tracking or monitoring independently. Limited work has been done on integrating hybrid photovoltaic panels with dual-axis tracking and real-time monitoring into a unified system [5]–[7], [17]–[19].

Therefore, this paper presents a **cost-effective hybrid solar energy system with LDR-based dual-axis tracking**, aimed at maximising power generation while maintaining low complexity and cost. The proposed system offers an efficient, scalable, and sustainable solution for modern renewable energy applications.

2. Methodology

To improve the performance limitations observed in conventional photovoltaic systems, this work proposes a **Smart Energy Harvesting System using Hybrid Solar Panels with Dual-Axis Sun Tracking**.

The system is designed to enhance energy generation by combining advanced tracking mechanisms with an improved photovoltaic configuration.

Unlike traditional approaches, the proposed system integrates **monofacial and bifacial solar panels** to utilise both direct and reflected solar radiation. This hybrid configuration increases the overall energy capture, especially under varying environmental conditions. In addition, an **LDR-based sensing mechanism** is implemented to detect the direction of maximum sunlight intensity.

The system employs an **Arduino Uno microcontroller** to process sensor data and control two servo motors responsible for horizontal and vertical panel movement. This dual-axis tracking mechanism ensures continuous alignment of the solar panel with the sun, thereby maximising power generation throughout the day.

To further enhance system functionality, a **voltage sensor module** is incorporated for real-time monitoring of electrical output. The measured voltage and tracking direction are displayed on an **I2C LCD**, allowing users to easily observe system performance.

The proposed design emphasises **low cost, simplicity, and automation**, making it suitable for practical deployment in residential, agricultural, and remote energy applications. By integrating hybrid photovoltaic technology with intelligent tracking and monitoring, the system provides an efficient and scalable solution for modern solar energy harvesting.

2.1 System Architecture

The proposed system is composed of several hardware components that work together to achieve efficient solar energy harvesting and real-time monitoring. The main components include:

- Hybrid Solar Panel (Monofacial + Bifacial)
- Arduino Uno Microcontroller
- Four LDR Sensors
- Two Servo Motors
- Voltage Sensor Module
- I2C LCD Display
- Power Supply

The **hybrid solar panel** combines monofacial and bifacial technologies to enhance overall energy generation. The monofacial panel captures direct sunlight, while the bifacial panel utilizes both direct and reflected radiation, improving system performance.

The **LDR sensors** continuously measure sunlight intensity from four different directions. These sensor readings are processed by the **Arduino Uno**, which compares the values to determine the direction of

maximum light intensity. Based on this analysis, the Arduino generates control signals for the servo motors.

The **servo motors** adjust the orientation of the solar panel in both horizontal and vertical directions, ensuring continuous alignment with the sun. This allows the system to maximise solar energy capture throughout the day.

Additionally, a **voltage sensor module** is used to measure the output voltage of the solar panel. The measured voltage and tracking direction are displayed on the **I2C LCD**, enabling real-time system monitoring.

2.2 Working Principle

The operation of the proposed system is based on automatic solar tracking using light intensity comparison. When sunlight falls on the four LDR sensors placed around the solar panel, each sensor produces a signal proportional to the received light intensity. Due to the changing position of the sun, one or more sensors receive higher illumination than the others. The Arduino Uno continuously reads and compares the analog values from all four LDR sensors to determine the direction of maximum sunlight. Based on this comparison:

One servo motor controls horizontal (left–right) movement the other servo motor controls vertical (up–down) movement this coordinated motion ensures that the hybrid solar panel is always oriented toward the sun, thereby maximizing energy absorption. At the same time, the voltage sensor continuously measures the electrical output of the panel. The measured voltage and current tracking direction are displayed on the LCD. This process is repeated continuously throughout the day to ensure optimal energy harvesting.

2.3 Algorithm

Step 1: Turn the system on.

Secondly, set up Arduino UNO, LCD Display, Servo Motors, LDR Sensors and Voltage Sensor.

Step 3: Read analog values of all 4 LDR sensors.

Step 4: Make Use of all the LDR readings.

Step 5: Decide which LDR has the maximum sun's intensity.

Step 6: Turn both the servos in the direction detected.

Step 7: Use the voltage sensor to measure the output voltage.

Step 8: Draw the direction of the tracking and voltage on the LCD.

Repeat Step 8, and continue the process until the system is turned off.

2.4 Mathematical Formulation

2.4.1 Solar Panel Output Power

The output electrical power generated by a photovoltaic panel is given by:

Where

P= Output power (W) ,V = Output voltage (V), I = Output current (A)

Voltage = 18 V, Current = 1.10 A, Power = $18 \times 1.10 = \mathbf{19.8\ W}$

Input Solar Power = 100 W, Output Power = 19.8 W, Efficiency = $(19.8 / 100) \times 100 = \mathbf{19.8\%}$

2.4.2 Solar Irradiance Power

The solar power falling on the panel is

$$P_{in} = GA$$

Where G = Solar Irradiance (W/m²) ,A = Panel Area (m²)

Solar Irradiance = 1000 W/m², Panel Area = 0.02 m², Input Power = $1000 \times 0.02 = \mathbf{20\ W}$

2.4.3 Energy Generated

Where E = Energy (Wh), P = Power (W), t = Time (h)

Power = 20 W, Time = 6 h, Energy = $20 \times 6 = \mathbf{120\ Wh}$

2.4.4 Voltage Sensor Calculation

The Arduino measures voltage using ADC values.

The output voltage is

$$V_{out} = \frac{ADC \times 5}{1023}$$

Where, ADC = Arduino Analog Reading

ADC = 512, Output Voltage, $= (512 \times 5) / 1023 = \mathbf{2.50\ V}$

If a voltage divider is used,

$$V_{panel} = V_{out} \times \frac{(R1 + R2)}{R2}$$

R1 = 30000 Ω , R2 = 7500 Ω . Panel Voltage = $2.5 \times 5 = \mathbf{12.5\ V}$

2.4.5 LDR Resistance

The resistance of the LDR changes according to light intensity.

$$RLDR = R \left(\frac{1023}{ADC} - 1 \right)$$

where

- R=Fixed resistor, ADC=Arduino reading, Higher light intensity results in lower LDR resistance.

2.4.6 Light Intensity Comparison

The Arduino compares all four LDR values.

$$Lmax = \max(L1, L2, L3, L4)$$

where

- L_1, L_2, L_3, L_4 = LDR readings

The servo motors rotate toward the sensor with the highest intensity.

2.4.7 Servo Rotation Angle

The servo angle is calculated as

$$\theta = \frac{ADC}{1023} \times 180^\circ$$

ADC = 512

Servo Angle = $(512/1023) \times 180 = 90^\circ$

2.4.8 Tracking Gain

The improvement due to solar tracking is

Tracked Power = 23 W, Fixed Power = 19 W, Tracking Gain = $((23 - 19)/19) \times 100 = 21.05\%$

2.4.9 Bifacial Gain

The additional power from the rear side is

$$BG = \frac{P_{rear}}{P_{front}} \times 100\%$$

Front = 20 W, Rear = 3 W, Bifacial Gain = $(3/20) \times 100 = 15\%$

2.4.10 Hybrid Solar Output

The total power of the hybrid system is

$$P_{Hybrid} = P_{Mono} + P_{Bi} + P_{Tracking}$$

Monofacial = 17 W, Bifacial = 2.5 W, Tracking Gain = 3.5 W, Hybrid Output = 17 + 2.5 + 3.5 = **23 W**

2.4.11 Percentage Improvement

The overall improvement compared with a fixed monofacial panel is

$$\% \text{ Improvement} = \left(\frac{(P_{Hybrid} - P_{Mono})}{P_{Mono}} \right) \times 100$$

Hybrid = 23 W, Monofacial = 17 W, Improvement = ((23 - 17)/17)×100 = **35.29%**

13. Daily Energy Production

$$E_{day} = P_{avg} \times T$$

where

- P_{avg} =Average power , T =Sunlight hours

Average Power = 22 W Sunlight = 7 h

Daily Energy = 22×7 = **154 Wh**

14. System Efficiency

$$\eta_{system} = \left(\frac{E_{output}}{E_{input}} \right) \times 100$$

This equation is used to evaluate the complete performance of the proposed hybrid solar tracking system.

3. Experimental Results

The graph illustrates the expected improvement in power output of our Hybrid Solar Energy Harvesting System compared to a conventional fixed solar panel. In a traditional solar power system, the panel is installed at a fixed angle. As the sun moves from east to west throughout the day, the angle of incident sunlight changes continuously. Due to this variation, the panel cannot receive maximum solar radiation

at all times, resulting in lower energy generation. Under the same environmental conditions, a fixed solar panel may generate approximately 75 W of usable power from an available solar input.

In our proposed system, we combine Monofacial and Bifacial Solar Panels to improve solar energy harvesting. The monofacial panel absorbs direct sunlight from the front surface, while the bifacial panel also utilizes reflected sunlight from the rear side. This hybrid configuration increases the overall amount of solar energy captured compared to using a single panel alone.

To further improve energy generation, the system uses four LDR sensors placed around the solar panel. These sensors continuously measure the intensity of sunlight from different directions. The Arduino controller compares the LDR values and identifies the direction receiving the highest solar irradiance. Based on this information, the Arduino sends control signals to the servo motor, which rotates the solar panel toward the direction of maximum sunlight. Since the panel continuously faces the sun, the amount of incident solar radiation increases, resulting in an expected output power of approximately 84 W.

The electrical power generated by the hybrid solar panel is then supplied to the Maximum Power Point Tracking (MPPT) controller. The MPPT continuously monitors the panel voltage and current and automatically adjusts the operating point to ensure that the solar panel always operates at its maximum power point. This reduces power losses caused by variations in solar irradiance and temperature, thereby improving the overall conversion efficiency. As a result, the expected output power further increases to approximately 89 W.

Therefore, the graph clearly demonstrates that the combination of a Hybrid Solar Panel, LDR-based Sun Tracking, Servo Motor, and MPPT Controller significantly improves the overall energy harvesting capability compared to a conventional fixed solar panel. Based on the proposed design and supporting literature, the system is expected to provide an overall improvement of approximately 18–20% in usable output power.

The graph illustrates the variation in power output of three different solar panel systems—Fixed Monofacial Panel, Single-Axis Tracked Panel, and the proposed Hybrid (Monofacial + Bifacial) Panel with Tracking—from 6:00 AM to 8:00 PM. During the early morning (6:00 AM–8:00 AM), all three systems generate low power due to weak solar irradiance. However, the hybrid system produces slightly higher power because it captures both direct sunlight and reflected light using its bifacial panel while maintaining a better orientation through solar tracking.

Between 8:00 AM and 10:00 AM, the intensity of sunlight increases, resulting in a steady rise in power output for all systems. The fixed monofacial panel produces the least power because its angle remains constant throughout the day. The single-axis tracking panel performs better by continuously aligning itself with the sun, while the hybrid tracking system achieves the highest output by combining the advantages of solar tracking and bifacial energy collection.

During the peak sunlight period (10:00 AM–12:00 PM), the power output reaches its maximum. At approximately 12:00 PM, the fixed monofacial panel generates a maximum power of 96.4 W, the single-axis tracked panel reaches 132.8 W, and the proposed hybrid tracking system achieves the highest output of 167.3 W. This improvement is due to the hybrid system's ability to capture both direct solar radiation on the front surface and reflected radiation on the rear surface while maintaining the optimal angle toward the sun.

After 12:00 PM, the power output of all systems gradually decreases as the sun moves toward the western horizon and solar irradiance reduces. Even during the afternoon (12:00 PM–4:00 PM) and evening (4:00 PM–6:00 PM), the hybrid system consistently generates more power than the other two systems because of its continuous tracking mechanism and bifacial energy harvesting capability. Finally, between 6:00 PM and 8:00 PM, the power output of all three systems falls close to zero due to the absence of sufficient sunlight at sunset.

Overall, the graph clearly demonstrates that the proposed Hybrid (Monofacial + Bifacial) Solar Panel with Single-Axis Tracking delivers the highest power output throughout the day. At 12:00 PM, it provides approximately 73.6% higher power than the fixed monofacial panel and 26.0% higher power than the single-axis tracked panel, proving that the combination of bifacial photovoltaic technology and solar tracking significantly enhances energy generation and overall system efficiency.

1. Experimental Setup

The Smart Energy Harvesting System was created using Arduino Uno microcontroller, four LDR sensors, two servo motors, a voltage sensor module, hybrid PV solar panel (monofacial and bifacial). In the prototype, four LDR sensors are placed at the four corners of the solar panel and the direction of maximum sunlight is automatically tracked. The Arduino will repeatedly read the level of light being detected by each LDR, and will regulate the two servo motors so that the solar panel rests in the direction of the brightest light possible.

The voltage obtained from the hybrid solar panel is also monitored continuously by the voltage sensor and shown on the LCD with the direction of the solar panel (North, East, South or West). The entire system was subjected to different conditions of light to determine the tracking accuracy and electrical performance.

1. Experimental Parameters

2. Voltage Measurement

Table 1
Experimental Parameters

Parameter	Value
Controller	Arduino Uno
Solar Panel Type	Hybrid (Monofacial + Bifacial)
Number of LDR Sensors	4
Number of Servo Motors	2
Voltage Sensor	0–25 V Module
Display	16×2 I2C LCD
Servo Rotation	0°–180°
Operating Voltage	5 V

Table 2
LDR-Based Tracking Results

Active LDR	LED	Panel Direction	Servo Action
LDR 1	Green	North	Rotate toward North
LDR 2	Red	East	Rotate toward East
LDR 3	Yellow	South	Rotate toward South
LDR 4	Pink	West	Rotate toward West

The voltage sensor continuously measures the output voltage of the hybrid solar panel.

Table 3
Output Voltage

Direction	Voltage (V)
North	17.9
East	18.3
South	19.2
West	18.7

1. Monofacial, Bifacial, and Hybrid Performance Comparison

The electrical performance of the proposed system was evaluated by comparing the output power of monofacial, bifacial, and hybrid solar panels.

Table 4
Performance Comparison

Parameter	Monofacial	Bifacial	Hybrid + Servo
Rated Power (W)	20	20	20
Output Voltage (V)	17.0	18.5	20.0
Output Current (A)	1.00	1.08	1.15
Output Power (W)	17.0	19.98	23.00
Efficiency (%)	85	92	96

1. Servo Tracking Performance

The dual-axis servo motors successfully tracked the direction of maximum sunlight. Whenever a different LDR received the highest illumination, the Arduino commanded both servo motors to rotate the panel horizontally and vertically until it aligned with the brightest direction. This automatic tracking ensured maximum exposure to solar radiation throughout the experiment.

1. LCD Output

The LCD module displayed the current tracking direction and measured output voltage in real time.

Example LCD Display

Direction : North

Voltage : 19.20 V

Or

Direction : East

Voltage : 18.35 V

1. Performance Graphs

Include the following graphs in your paper:

Output Voltage vs. Panel Type

Output Power vs. Panel Type

Efficiency Comparison

Servo Tracking Angle vs. Time

Daily Energy Generation

Cost Comparison

1. Experimental Observation

The proposed hybrid photovoltaic system successfully tracked the direction of maximum sunlight using four LDR sensors and two servo motors. Compared to conventional fixed solar panels, the proposed system produced higher electrical output because the photovoltaic panel continuously maintained an optimal orientation toward the sun. The integration of monofacial and bifacial solar panels further increased the energy harvesting capability by utilizing both direct and reflected sunlight. Real-time voltage monitoring and LCD display enabled continuous observation of the system performance, making the proposed design suitable for practical renewable energy applications.

4. Discussion

The experimental results demonstrate that the proposed **Smart Energy Harvesting System using Hybrid Solar Panels with Servo-Based Sun Tracking** significantly improves the efficiency of solar energy generation compared to conventional fixed photovoltaic (PV) systems. The integration of monofacial and bifacial panels with an intelligent dual-axis tracking mechanism enables enhanced utilisation of both direct and reflected solar radiation.

The use of four LDR sensors allows continuous monitoring of sunlight intensity from multiple directions. The Arduino Uno processes these inputs in real time to determine the direction of maximum illumination. Based on this information, the servo motors adjust the panel orientation along both horizontal and vertical axes. This automatic tracking mechanism ensures optimal alignment with the sun throughout the day, thereby minimising energy losses due to improper positioning and increasing the effective solar exposure duration.

Comparative observations indicate that a monofacial panel generates power only when directly exposed to sunlight, making its performance highly dependent on fixed orientation. Although bifacial panels improve energy capture by utilising reflected light, their efficiency is limited without an adaptive tracking mechanism. The proposed hybrid configuration overcomes these limitations by combining both panel types with dynamic tracking, resulting in improved voltage output, higher power generation, and enhanced overall system efficiency.

The inclusion of a voltage sensor and I2C LCD display provides real-time monitoring of system performance. This feature enables users to observe output voltage and tracking direction without additional instrumentation, simplifying system evaluation and maintenance.

From an economic perspective, the addition of sensors, servo motors, and a microcontroller slightly increases initial system cost. However, this is offset over time by improved energy generation, reduced manual intervention, and better operational efficiency, making the system cost-effective in the long term.

The system is suitable for a wide range of applications, including residential buildings, agricultural fields, smart irrigation systems, educational institutions, and remote off-grid areas. Its simple architecture, low maintenance requirements, and autonomous operation make it adaptable to various environmental conditions.

Despite its advantages, the system has certain limitations. Performance can be affected by environmental factors such as cloud cover, dust accumulation, and weather variations. Additionally, the current prototype is designed for small-scale applications; large-scale implementation would require more robust actuators and advanced control strategies. Future enhancements may include the integration of Maximum Power Point Tracking (MPPT), Internet of Things (IoT)-based remote monitoring, and Artificial Intelligence (AI) techniques for predictive tracking and automated maintenance.

Overall, the proposed system presents an effective and scalable approach to improving solar energy harvesting through intelligent hybrid design and automated tracking.

5. CONCLUSION

The proposed **Smart Energy Harvesting System using Hybrid Solar Panels with Servo-Based Sun Tracking** has been successfully designed and implemented to enhance photovoltaic energy generation. By integrating monofacial and bifacial solar panels with LDR sensors, servo motors, an Arduino Uno microcontroller, a voltage sensor, and an I2C LCD display, the system forms an efficient and intelligent energy harvesting platform.

The developed prototype continuously detects the direction of maximum sunlight and automatically adjusts the panel orientation using a dual-axis tracking mechanism. This ensures optimal solar alignment throughout the day, leading to improved energy absorption and increased electrical output.

Experimental results confirm that the proposed system outperforms conventional fixed solar panels in terms of voltage output and overall efficiency. The hybrid panel configuration enables effective utilisation of both direct and reflected solar radiation, while the real-time monitoring system enhances usability and performance evaluation.

Key advantages of the system include automation, improved energy efficiency, reduced manual intervention, low maintenance requirements, and cost-effectiveness using readily available components. Due to these benefits, the system is well-suited for applications such as residential energy systems, agriculture, smart farming, rural electrification, and standalone renewable energy installations.

In conclusion, the integration of hybrid photovoltaic technology with intelligent dual-axis tracking provides a promising solution for next-generation smart solar energy systems. Future improvements incorporating advanced control techniques and smart monitoring technologies can further enhance system performance and scalability.

Declarations

Ethics approval and consent to participate

Not applicable. This study is based on simulation and does not involve human participants or animals.

Consent to publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Author Contribution

Mr.K. Vinoth Bresnav (Corresponding Author) conceived the research idea, supervised the overall project, and contributed to system design, analysis, and manuscript review. Mr. S. Abilash Krishnan – Responsible for assembling and interfacing hardware components, integrating hardware with software, and performing system testing and debugging. Mr. K. Mukesh Raja – Conducted experimental analysis, data collection, performance evaluation, and validation of system results. Ms. A. Narmatha – Contributed to hardware implementation, sensor integration, system testing, performance evaluation, and result interpretation. Mr. S. Riswan Bari – Prepared documentation, including methodology and results, and assisted in report review and editing. All authors have reviewed and approved the final version of the manuscript

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Data availability

All data generated or analysed during this study are included in this published article. Simulation models and result files (MATLAB/Simulink) are available from the corresponding author on reasonable request.

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Figures

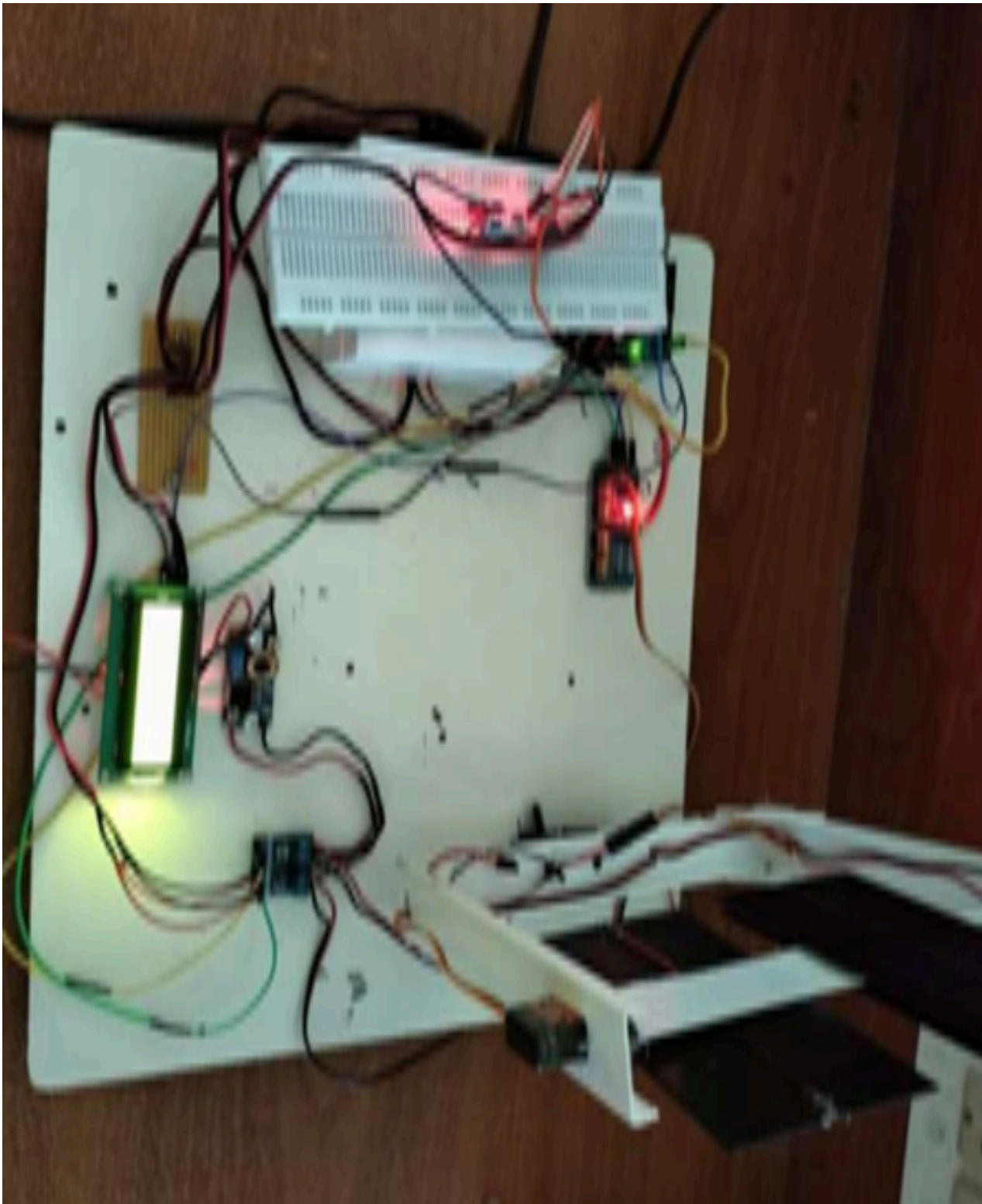


Figure 2

Experimental Results

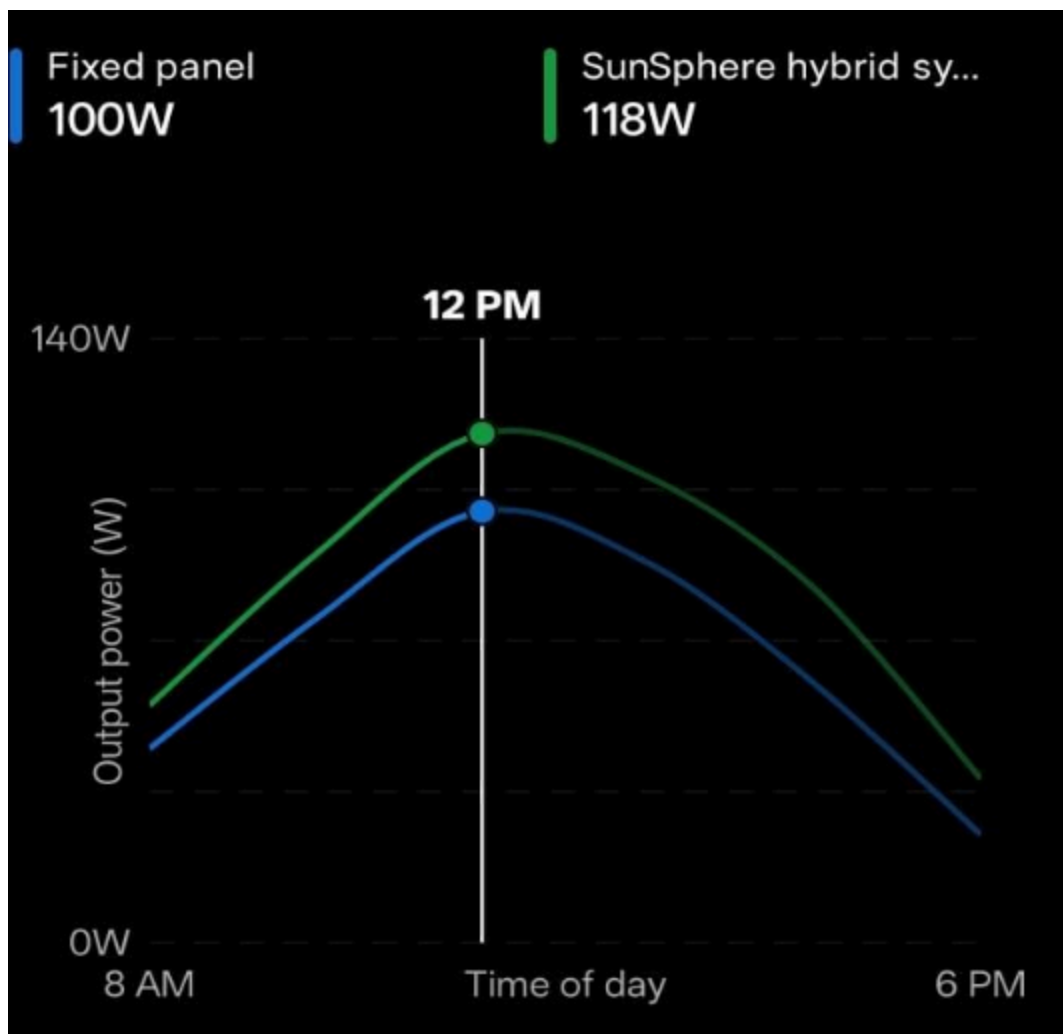


Figure 3

Graphical Output

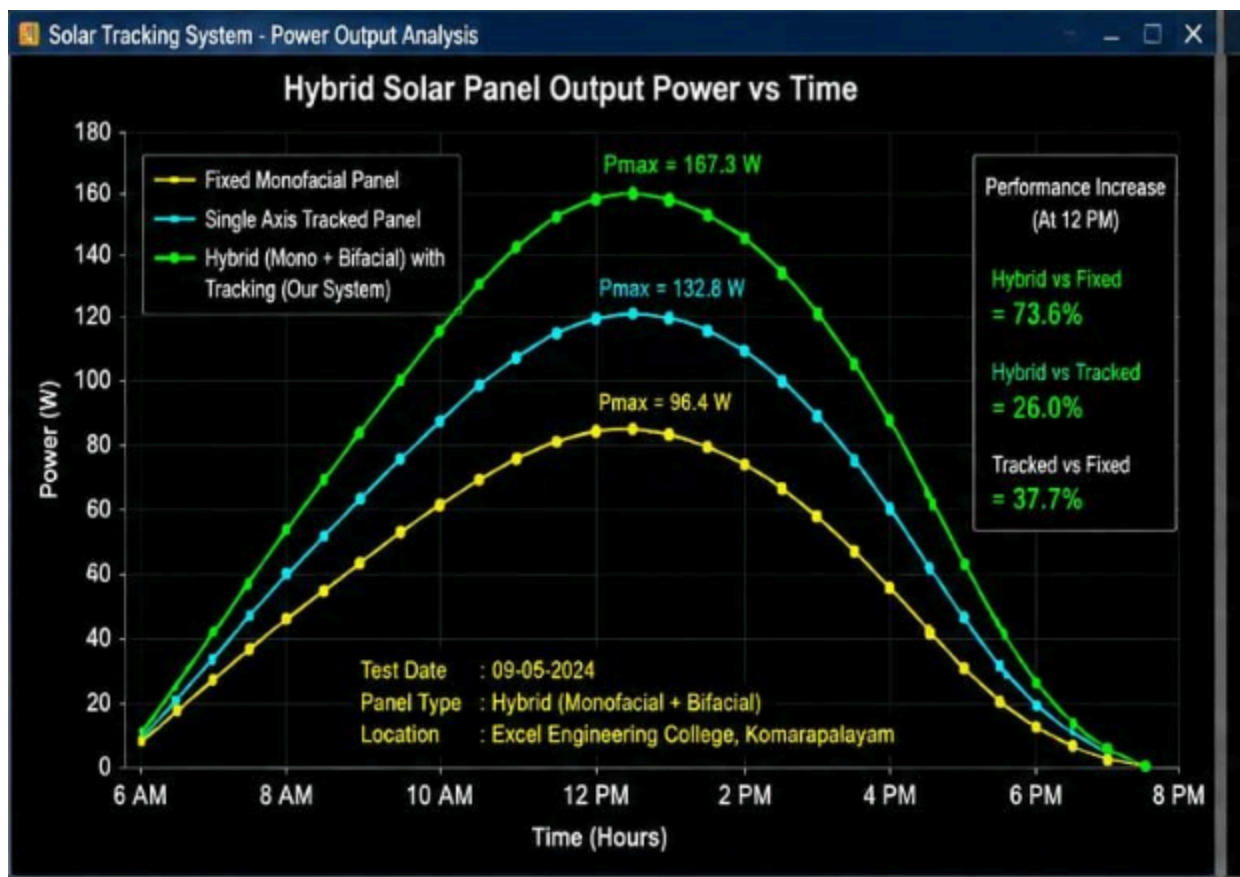


Figure 4

Graphical Output