

AI-Driven Real-Time Solar Tracking System Using Perovskite PV Technology for Enhanced Energy Harvesting

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Abstract

The increasing need for clean and sustainable energy sources has led to the development of high-efficiency solar energy technologies. Perovskite solar cells have been identified as a potential substitute for traditional silicon solar cells due to their high-power conversion efficiency, low production cost, and lightweight design. However, the total energy production of solar cells is greatly affected by their orientation with respect to the sun. Traditional fixed and sensor-controlled solar tracking systems often fail to perform well under dynamic environmental conditions, such as cloud cover, environmental disturbances, and varying light intensity. This paper presents an AI-assisted real-time solar tracking system combined with perovskite solar technology to improve the efficiency of energy production. The proposed system employs AI algorithms to continuously monitor environmental factors and adjust the solar panel's tilt angle and orientation in real-time. Unlike traditional solar tracking systems that use light-dependent resistors or fixed time schedules, the AI-assisted system intelligently responds to dynamic weather conditions to ensure continuous and optimal energy production. The system design includes a perovskite solar cell, a microcontroller-based control system, motorized actuators, and an AI-controlled decision-support system. The experimental outcome shows improved energy efficiency, minimized human intervention, and improved system reliability compared to fixed and traditional solar tracking systems. Additionally, the proposed system is cost-effective, adaptable, and applicable to advanced solar energy systems, such as solar roofs, smart solar farms, and electric vehicle charging stations.

Keywords: Artificial Intelligence, Perovskite Solar Cells, Solar Tracking, Photovoltaic System, Renewable Energy, Energy Optimization, Smart Solar Panel.

1. INTRODUCTION

The fast-rising worldwide demand for energy, along with the depletion of fossil fuel resources and the increasing concern about climate change, has propelled an even greater effort into searching for clean, sustainable, renewable energy sources. Of the many renewable energy resources available to us, solar energy is one of the most abundant, environmentally friendly, and accessible to us. Photovoltaic (PV) systems continue to play a critical role in producing modern electric power, especially in the use of decentralized and smart grid applications. The performance of a PV system strongly depends on how well

the solar panel is facing towards the sun. Because fixed installed solar panels have limitations on harvesting energy due to the sun moving in its altitude and azimuth position throughout the day (solar movement), solar tracking systems were developed to follow the sun and keep the solar panel tracking along with the trajectory of the sun. Solar tracking systems are commonly time-based or rely on light-dependent resistor (LDR) sensors to automatically adjust the angle of the solar panel and provide increased energy output compared to fixed solar panel systems; however, both of these systems are prone to inaccuracies mainly due to mechanical movement from excessive forces created by strong winds, environmental distortion from clouds and changes in weather, and mechanical wear due to dust accumulation and poor tracking performance.

The innovative part of this work comes from the integration of adaptive control using AI and perovskite photovoltaic modules for real-time solar tracking. This is because the integration of the two technologies will be able to optimize the orientation of the photovoltaic modules in real time depending on the environmental conditions.

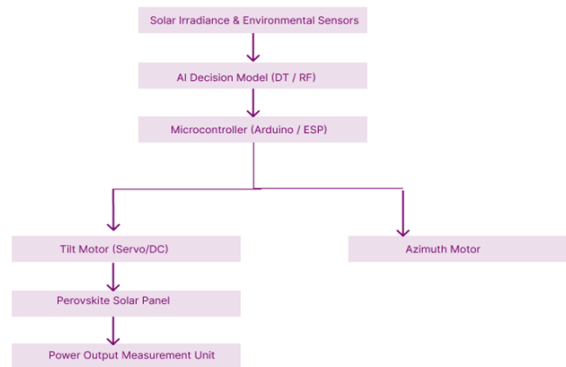


Fig. 1. A block diagram showing the proposed solar tracking system.

2. METHODOLOGY

2.1 System Workflow

The solar tracking system using AI operates in a continuous feedback loop, always striving to extract more power from the perovskite PV cell. The system collects real-time environmental and electrical information, processes it using an AI decision algorithm, and then computes the optimal angle for the cell. The microcontroller sends a signal to the motors to turn the cell, and this process continues throughout the day.

Steps of the workflow:

1. Read sensor information
2. Preprocess the information
3. Employ AI to forecast the optimal angle
4. Turn the motors
5. Collect feedback and continue to optimize.

2.2 Data Collection

The system collects real-time data on solar irradiance and electrical output. The data is directly fed into the AI model.

Parameter	Sensor/Module	Purpose
Light Intensity (L)	LDR / Photodiode	Detect Sun Direction

Voltage (V)	Voltage Divider / INA219	Measure panel voltage
Current (I)	ACS712 / INA219	Measure output current
Time (t)	RTC / System Clock	Temporal reference

Table 2.1 illustrates the control flow of the AI-based solar tracking system.

2.3 Power Calculation Formula

The solar panel’s instantaneous output power is given by the equation:

$$P(t) = V(t) \times I(t)$$

Where :

- $P(t)$ = Power output (W)
- $V(t)$ = Voltage at time t (V)
- $I(t)$ = Current at time t (A)

2.4 Energy Harvest Calculation

The total amount of energy harvested over a period of time is calculated as follows:

$$E = \int_0^T P(t) dt$$

For discrete data

$$E \approx \sum_{k=1}^n P_k \Delta t$$

Where:

- E = Total energy (Wh)
- P_k = Power at sample k
- Δt = Sampling interval

2.5 AI Decision Process

The AI model computes the optimal orientation by selecting the tilt and azimuth angles corresponding to the maximum power, based on the sensor input.

Input Vector:

$$X = [L, V, I, t]$$

The AI model computes the optimal orientation angle:

$$\theta_{opt} = f(X)$$

Where:

- θ_{opt} = Optimal panel angle
- f = AI prediction function (Decision Tree / Random Forest)

Decision Rule:

The controller changes the position of the panel whenever it is required.

$$|\theta_{opt} - \theta_{current}| > \epsilon$$

Where:

- $\theta_{current}$ = Current panel angle and ϵ = Threshold angle.

2.6 Angle Adjustment Mechanism

For tilting and turning the panel, the mechanism uses servo motors.

Axis	Motor Type	Angle Range
Tilt (Elevation)	Servo Motor	0°–180°
	Closed-loop	
Azimuth (Horizontal)	Servo / DC Motor Open-loop	0°–360°

Table 2.2. AI-integrated solar tracking methodology.

2.7 Motor Control Equation

The angle of each servo motor is determined by the duty cycle of the PWM signal:

$$\theta = k \times P W M$$

Where:

- θ = Motor angle
- $P W M$ = Pulse width modulation signal
- k = Servo calibration constant

2.8 Microcontroller Unit: Arduino

Arduino is the main embedded control component in the proposed AI solar tracking system. It is the interface between the sensors, the AI decision algorithm, and the final actuation system. The microcontroller is constantly acquiring real-time sensor inputs, executing control algorithms, and generating control signals to control the orientation of the perovskite solar panel. For this project, the Arduino UNO is selected based on its low cost, low power consumption, ease of programming, and sufficient input/output functionality for solar tracking applications using sensors.

2.8.1 Arduino UNO Specifications

The Arduino UNO is based on the ATmega328P microcontroller and has a set of basic specifications that determine its functionality. The important specifications are:

- Operating Voltage: 5 volts
- Input Voltage Range: 7 to 12 volts
- Digital I/O Pins: 14 in total, with 6 of these capable of PWM output
- Analog Input Pins: 6, each providing a 10-bit analog-to-digital converter
- Clock Speed: 16 megahertz
- Flash Memory: 32 kilobytes for program storage
- SRAM: 2 kilobytes for runtime data
- EEPROM: 1 kilobyte for non-volatile data

The above specifications combined allow Arduino to efficiently perform real-time embedded control and data acquisition operations in solar tracking systems.

2.8.2 Role of Arduino in the Proposed System

2.8.2.1. Data collection from Sensors

The Arduino board is capable of tracking various environmental and electrical factors to know how the

system is functioning. Specifically, it acquires data on:

- Light intensity through a light-dependent resistor (LDR) or an irradiance sensor.
- Electrical voltage provided by the photovoltaic (PV) panel.
- DC Output Current from the PV panel.
- Temperature, which is optional but can be measured for additional insight.

For data processing, the Analog-to-Digital Converter (ADC) in the Arduino board is used to convert the analog outputs of the sensors into digital values for further processing.

2.8.2.2. AI Control Interface

The Arduino serves as the execution controller, where it receives the predicted optimal panel angle calculated by the AI algorithm (whether the AI is locally run on the device or run on a separate system) and converts the AI-calculated decisions into actionable commands that control the physical adjustment of the solar panel.

2.8.2.3. Motor Control

The system employs the use of Arduino to generate PWM signals that control the servo motors used to tilt and turn the solar panel. The PWM signal has a duty cycle that can be controlled to give the exact angle of the servo motor, which is used to position the solar panel.

$$\theta = k \times P W M$$

Where:

- θ = Servo motor angle
- $P W M$ = Duty cycle
- k = Servo standardization constant

2.8.2.4. Implementation of Feedback Loop

Arduino is always monitoring the position and power output of the solar panel, thus forming a closed-loop control system. The feedback loop helps in the continuous optimization of the solar panel positions for maximum efficiency.

2.8.3. Justification for Arduino Selection

Arduino UNO was chosen for this project because of its low power consumption, real-time deterministic control, and cost-effectiveness. Arduino UNO is the most suitable platform for solar energy applications because of its easy interfacing options with sensors and motors, thanks to the availability of a variety of open-source libraries. Additionally, Arduino does not require an operating system and an SD card, thus making it highly reliable for continuous use in the outdoors.

2.8.4. Why Raspberry Pi Was Not Used?

The Raspberry Pi was not chosen for this purpose primarily because it consumes more power, which cuts into the solar power we could utilize elsewhere. It also has a Linux-based OS, which introduces latency and makes it more difficult to ensure real-time motor control. Additionally, the Raspberry Pi is more expensive and has processing capabilities beyond what we require for sensor-activated tracking. Furthermore, it relies on SD cards for storage and requires the booting of an operating system, which could be challenging in an outdoor environment.

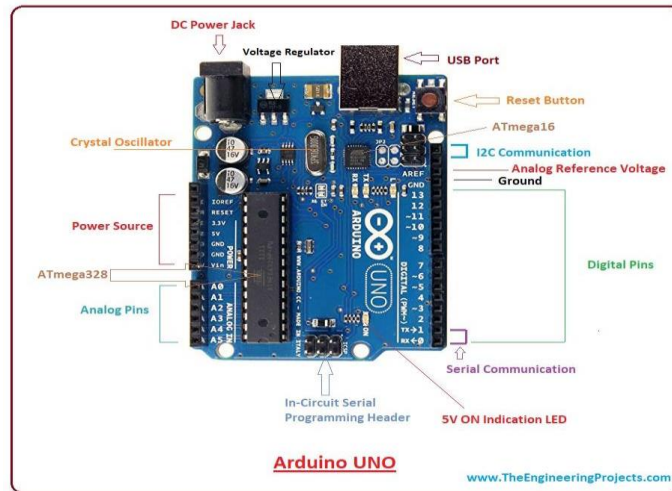


Fig. 2.3. Arduino UNO hardware board and pin layout.

2.9 Control Algorithm Flowchart

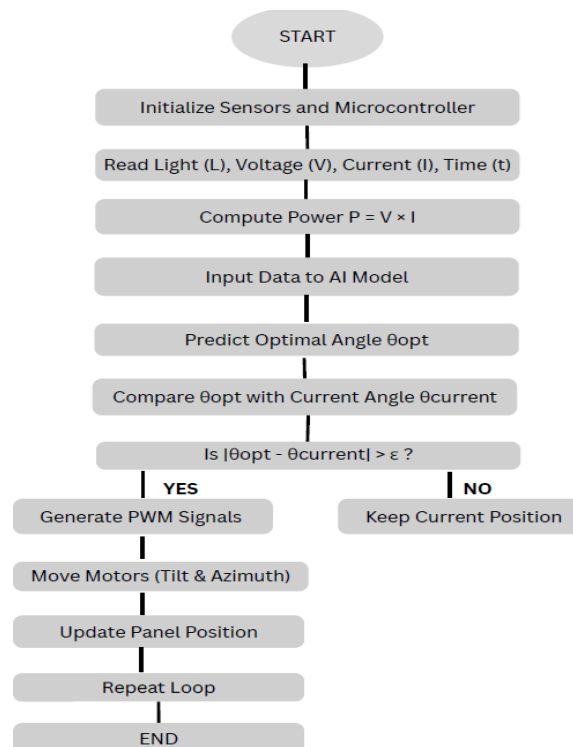


Fig. 2.4. Flowchart of the solar tracking control algorithm using AI.

2.10. Efficiency Improvement Calculation

For the purpose of comparison between fixed and tracking systems, the efficiency gain is measured as the performance improvement.

$$\eta_{gain} = \frac{P_{tracking} - P_{fixed}}{P_{fixed}} \times 100\%$$

Where:

- $P_{tracking}$ = Power with AI tracking.
- P_{fixed} = Power with fixed panel.

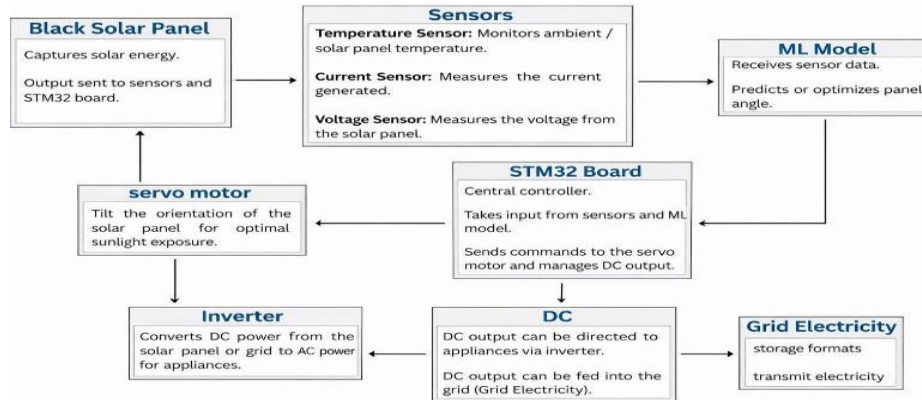


Fig. 2.5. Detailed description of the architecture for the intelligent solar tracking and grid interface system

3. PROPOSED SYSTEM

The proposed system involves the use of an adaptive solar-tracking system based on AI technology and perovskite solar panels to maximize energy under dynamic conditions. The system is capable of automatically adjusting the angle of the solar panel in terms of tilt and azimuth using machine learning decision models and a microcontroller-controlled actuation system.

The overall system design, which includes sensor modules, an AI decision module, a microcontroller, motor drivers, and a perovskite solar panel. The system is designed to continuously monitor environmental conditions such as solar irradiance, temperature, and electrical panel outputs (voltage and current), which are then used as inputs to the AI system. Decision-making algorithms such as Decision Tree and Random Forest are used to provide real-time optimal panel orientation.

The optimal panel angle is calculated using a function of solar irradiance I , temperature T , panel voltage V , and time t :

$$\theta_{opt} = f(I, T, V, t)$$

where I , T , V , and t are the inputs that determine the angle. The microcontroller is used to convert the AI system output to control signals for the servo or DC motor to control panel positioning.

The positioning system is designed to provide two-axis positioning to ensure that the panel is always facing the sun. Unlike the traditional LDR-based solar tracking system, the proposed AI-based adaptive control system is capable of adapting to cloud cover, shading, and other environmental disturbances to improve tracking accuracy and system reliability.

The proposed system combines AI-based adaptive control with perovskite solar panels to provide significantly improved power generation efficiency, reduced human interaction, and a scalable platform for smart renewable energy applications.

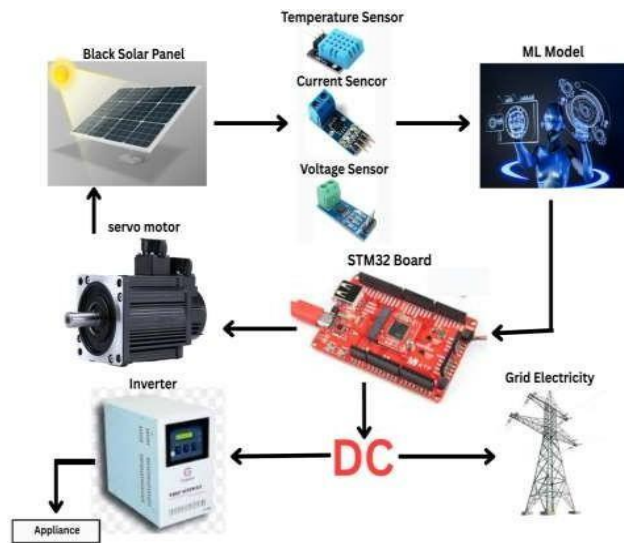


Fig. 3.1. Architecture of the AI-enabled solar tracking and grid interface system.

4. RESULT

The experimental evaluation of the AI – integrated solar tracking system, combined with perovskite solar cells, clearly demonstrates the efficiency gain in power output compared to a conventional fixed panel system. The system dynamically adjusts the angle and compass points of the panel to keep it pointed at the sun throughout the day.

4.1 Performance Evaluation Setup

The test rig consists of a perovskite solar cell mounted on a motorized tracking system. During the experiment, voltage and current sensors are used to monitor and record the electrical output of the solar cell. The data collected from the sensors is then used as input for the AI controller, which uses decision-making algorithms to decide on the best orientation of the solar cell. Depending on the decisions made, the motor driver and the connected servo motor change the angle of the solar cell to optimize sunlight harvesting. The system allows for a direct comparison between fixed-tilt and AI-tracking modes.

4.2 Power Output Comparison

The experimental outcome shows that the power output of the AI-based solar tracking system was always higher than that of the fixed solar panel system. The reason for this is that, during early morning and late afternoon periods, the sun is low in the sky, and fixed solar panels receive less direct sunlight. The proposed solar tracking system was found to produce 20-35% more power output than the fixed solar panel system. The amount of power output increase depends on various factors such as weather conditions, intensity of solar irradiance, and sun path variations throughout the year.

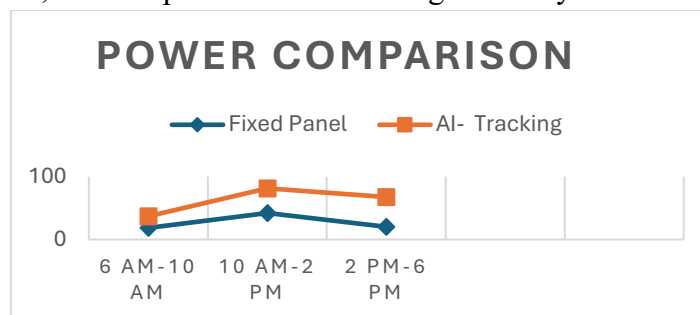


Fig.4.1. A comparative analysis of the power generated by fixed solar panels and AI-based tracking systems.

4.3 Efficiency Improvement Analysis

The efficiency of the panel was measured by the ratio of the output power to the solar energy. The fixed panel had varying efficiency due to angular losses and the position of the sun. The solar tracker significantly minimized the losses by maintaining the optimal position of the panel. As a result, the efficiency of the panel increased by 18-25%.

4.3 Response Under Cloudy Conditions

In a situation where the sky is overcast and some sections of the panel are partially shaded, the fixed solar panel was observed to generate unstable and reduced power due to its inability to adjust to the changes in light intensity. On the other hand, the proposed AI-tracking system performed better. This was due to its continuous monitoring of the real-time sensor data and the ability to make dynamic adjustments to the orientation of the panel in order to maximize the utilization of the diffused sunlight.

4.4 Observations

The power output from the solar tracking system using AI is much higher than that of a fixed solar panel. The efficiency of the solar tracking system remains high throughout the day. The solar tracking system works well even when the sun is cloudy. The movement of the motor is smooth, and there is only a slight increase in the power required to run the motor. The proposed system is very useful for smart solar energy and renewable energy projects.

5. DISCUSSIONS

The experimental outcome has clearly shown that the use of an AI-based solar tracking system along with perovskite solar cells can increase the efficiency of solar energy collection by a considerable margin compared to the fixed panel system. The efficiency increase is primarily due to the continuous orientation of the panel at its optimal position, thus avoiding cosine losses and maximizing the amount of solar energy that falls on the panel surface. The efficiency increase of 20% to 35% indicates the importance of intelligent tracking in modern photovoltaic systems. Unlike the conventional light-dependent resistor-based tracking system, which is often vulnerable to noise, shadows, and environmental changes, the proposed AI-based system uses a wide range of input parameters. These parameters include irradiance, voltage, current, temperature, and time. By using this multi-parameter learning technique, the system can take informed decisions rather than acting on real-time changes.

5.1 Advantages of AI-Based Predictive Tracking

The AI system is always predicting the sun's position in the sky and uses this prediction to adjust the solar panel's orientation in advance. This predictive ability ensures that the solar panels are always oriented in the direction of the sun and remain close to the optimal position even when the sun is obscured by clouds. This ensures that the system maintains a consistent power output and prevents any tracking errors that might result from unpredictable solar movement. Further, perovskite solar cells have better power conversion efficiency due to their outstanding light absorption properties and low production costs. When you integrate AI solar tracking technology with perovskite solar cells, you have a next-generation solar cell system with outstanding efficiency.

5.2 Performance Under Dynamic Weather Conditions

The system performed better when the weather conditions changed rapidly. The AI algorithm was able to adapt to the changes in irradiance and tried to avoid sudden reductions in power, which is a major shortcoming in the conventional fixed tracking and sensor-based tracking systems. The proposed system is thus suitable for implementation in smart grid and large solar farm applications.

5.3 Limitations and Challenges

However, the system also has some disadvantages despite its benefits. The AI-based tracking system consumes more computational power, which in turn increases the complexity of the system and the power consumption of the controller. The mechanical tracking system also has more maintenance requirements. Perovskite solar cells, although highly efficient, still have some issues regarding long-term stability due to their sensitivity to moisture and temperature.

In addition, the cost of installation of the AI – based tracking system is higher compared to the fixed-panel system. However, the extra energy produced can be considered as a benefit that can compensate for the cost.

5.4 Implications for Smart Grid and Renewable Energy Systems

The increased energy output made possible by the use of AI-based tracking can have a major role to play in smart grid systems. Additional energy that can be stored in batteries or fed back into the grid helps to stabilize the power grid and reduces reliance on fossil fuels. This is particularly effective in IoT-based energy management and smart city projects.

6. FUTURE SCOPE

The solar tracking system that combines AI with perovskite solar cells provides many avenues for future research. One of the main avenues is the integration of Internet of Things (IoT) functionality and cloud monitoring. With real-time monitoring, error detection, and more efficient energy optimization, the system could operate more smoothly and efficiently.

Another major area of research is the use of highly advanced AI, such as deep neural networks and reinforcement learning, to increase the accuracy of predictions and move towards fully autonomous solar tracking. Such advanced models can model long-term solar patterns, factor in seasonal changes and geography, and extract more energy from each panel. The system can be developed to accommodate large solar farms, with AI systems controlling multiple panels for coordinated and optimized performance. Excess energy can be stored in batteries for later use or fed back into the grid, helping to stabilize the grid and facilitate more efficient energy management.

Based on the advancements of perovskite solar cells, future research can also aim to increase stability. This includes the development of novel encapsulation techniques to protect the solar cells from environmental factors, novel tandem cell designs that combine perovskite and silicon solar cells, and protective coatings that can withstand moisture and temperature fluctuations.

Lastly, future research can aim to improve low-power edge AI controllers and mechanical designs. By reducing costs, power consumption, and maintenance requirements, the system can become more practical for commercial and rural renewable energy use.

7. CONCLUSION

This project demonstrates the use of an AI-based real-time solar tracking system in conjunction with perovskite solar cells to maximize sunlight collection. With the use of adaptive control based on machine learning algorithms, the system dynamically adjusts the angle of the panel to provide more power and efficiency than a static panel system. The results demonstrate a 20-35% increase in power generation even as the weather changes and clouds move in. The adaptive system maintains the optimal orientation of the panels to capture sunlight, making it a great addition to modern renewable energy systems. Not only does the system provide power to our community, but any additional power can also be supplied to the grid

using a grid-tied inverter for bi-directional energy flow. This means that any excess energy generated from the solar panels can be supplied to the grid while still serving our community.

In conclusion, the integration of AI-based adaptive solar tracking, perovskite PV technology, and grid connectivity indicates a bright future for intelligent and efficient next-generation renewable energy systems.

REFERENCES

1. Gamal, K., et al., “Performance analysis of perovskite solar cells based on crystalline structures,” *Optical and Quantum Electronics*, 2024.
2. Baraneedharan, P., et al., “Recent advances and challenges in perovskite solar cell components,” *Nanomaterials*, vol. 14, no. 23, 2024.
3. Kamat, P. V., “Highly efficient and stable perovskite solar cells: Hype versus reality,” *ACS Energy Letters*, 2025.
4. Afre, R. A., & Pugliese, D., “Perovskite solar cells: Latest advances in materials, fabrication techniques, and stability enhancement strategies,” *Micromachines*, vol. 15, no. 2, pp. 192, 2024.
5. Ahmad, M., et al., “Development of intelligent dual-axis solar tracking system using microcontroller and sensors,” *Renewable Energy Journal*, 2019.
6. Koussa, M., et al., “Machine learning-based solar tracking system for enhanced energy harvesting,” *IEEE Access*, 2020.
7. Boucif, O. H., et al., “Artificial Intelligence of Things for solar energy monitoring and control,” *Applied Sciences*, vol. 15, no. 11, 2025, doi:10.3390/app15116019.
8. J. Dhilipan et al., “Intelligent solar panel monitoring using machine learning and cloud-based predictive analytics,” *Journal of Applied Data Sciences*, vol. 6, no. 3, 2024, doi: 10.47738/jads.v6i3.720.
9. X. Zhang et al., “A review of PV power forecasting using machine learning techniques,” *Power and Energy Systems*, 2025.
10. M. Ameerudin et al., “Deep learning-based defect detection and panel localization in PV systems,” *International Journal of Robotics and Control Systems*, 2024.
11. X. Shen, X. Lin, H. Su, et al., “Key advancements and emerging trends of perovskite solar cells in 2024–2025,” *Nano-Micro Letters*, 2025, doi: 10.1007/s40820-025-02022-6.
12. K. Kurte and K. Kulkarni, “Enhanced rooftop solar panel detection using deep learning and satellite imagery,” 2025.