



MULTI AXIS SOLAR TRACKING SYSTEM

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ABSTRACT—

Solar photovoltaic output depends on the angle at which solar radiation strikes the panel surface. A fixed solar panel cannot continuously maintain an optimum orientation throughout the day, which can reduce the available energy conversion under changing solar positions. This paper presents an Arduino UNO-based dual-axis solar tracking system designed to automatically adjust the orientation of a photovoltaic panel in both horizontal and vertical directions. Four light-dependent resistors (LDRs) are used to detect the relative intensity of incident sunlight, and the Arduino UNO processes the sensor values to control geared motors through an L298N motor driver. The system incorporates a 12 V solar panel, charge controller, 12 V 7 Ah battery, 12 V-to-5 V buck converter, voltage and current sensing, and a 16×2 PC LCD for local monitoring of electrical parameters. A PCA9685 PWM servo driver with a servo motor is additionally considered for an optional automated panel-cover mechanism. The proposed system integrates solar tracking, energy storage, electrical parameter monitoring, and actuator control into a single embedded platform. The developed prototype can be evaluated using panel voltage, current, output power, and tracking response under different solar conditions.

Keywords—Arduino UNO, dual-axis solar tracking, LDR, photovoltaic system, solar energy, L298N, PCA9685, solar panel monitoring.

INTRODUCTION

Solar photovoltaic (PV) technology is an important approach for converting solar radiation into electrical energy. The electrical output of a PV panel is influenced by factors such as solar irradiance, temperature, and the angle of incidence of sunlight on the panel surface [1], [2]. Since the apparent position of the Sun changes continuously during the day, a fixed panel cannot maintain the same favorable orientation throughout the entire operating period.

Solar tracking systems address this limitation by changing the orientation of the PV panel according to the detected solar position. Tracking can be implemented using different sensing and control techniques, including light sensors, astronomical calculations, and closed-loop control methods [3], [4]. Among these approaches, LDR-based tracking provides a relatively simple method for detecting differences in illumination and generating control signals for electromechanical positioning.

A single-axis tracking generally provides movement along one rotational direction, whereas a dual-axis tracking provides two degrees of angular adjustment. The latter can accommodate changes in both the horizontal and vertical orientation of the panel and is therefore suitable for applications requiring continuous solar alignment [5], [6]. However, the practical implementation of a dual-axis system requires coordinated sensing, motor control, power management, and mechanical positioning.

This work presents a dual-axis solar tracking system based on an Arduino UNO microcontroller. Four LDR sensors are arranged to detect differences in sunlight intensity around the panel. The Arduino processes these sensor readings and controls geared motors through an L298N motor driver to adjust the horizontal and vertical positions. The system also incorporates a 12 V battery and charge controller for energy storage, a buck converter for low-voltage electronics, and voltage and current sensing for monitoring the electrical output. A 16×2 PC LCD provides local display of system parameters. An optional servo-operated panel cover using a PCA9685 PWM driver is also considered as an additional protection mechanism.

Necessity

The orientation of a PV panel affects the amount of solar radiation received by its active surface. Consequently, maintaining a suitable orientation during changing solar conditions is an important consideration in solar-energy harvesting systems [1], [2]. Manual adjustment is unsuitable for continuous operation because it requires regular human intervention.

An automated dual-axis mechanism can continuously respond to changes in illumination without requiring manual positioning. The use of multiple LDR sensors enables the controller to determine the direction of higher light intensity and generate corresponding motor-control actions. Integration of electrical sensing further allows the system to observe voltage, current, and output power during operation.

Objectives

The main objective of the proposed work is to develop an Arduino UNO-based dual-axis solar tracking system that automatically adjusts the horizontal and vertical orientation of a photovoltaic panel according to the detected sunlight direction. The system uses four LDR sensors for light-intensity comparison and geared motors for panel positioning, while voltage and current sensors are used to monitor the electrical output. A 12 V battery and charge controller provide energy storage, and a 16×2 I²C LCD enables local monitoring of system parameters. An optional PCA9685-based servo mechanism is also considered for automated panel-cover operation.

Organization of the Paper

The remainder of this paper is organized as follows. Section II presents the literature survey and comparison of existing solar-tracking approaches. Section III describes the proposed system architecture, hardware components, and power and signal flow. Section IV discusses the hardware implementation and software control. Section V presents the tracking algorithm and experimental methodology. Section VI discusses the measured results and system performance. Finally, Section VII presents the conclusion and future scope.

LITERATURE SURVEY

Solar tracking has been investigated as a method for improving the utilization of available solar radiation by dynamically adjusting the orientation of photovoltaic modules. Existing systems differ in their sensing method, number of tracking axes, actuator mechanism, and control strategy. LDR-based systems are particularly common in low-cost prototypes because the sensors can provide a simple indication of the direction of maximum illumination [7], [8].

Single-axis tracking systems generally rotate the panel along one axis and offer a comparatively simple mechanical structure. Dual-axis systems provide movement in two directions and can compensate for changes in both the horizontal and vertical position of the Sun [9], [10]. Studies comparing fixed and tracking configurations have reported improvements in the electrical energy obtained from photovoltaic systems, although the actual improvement depends on geographical location, weather conditions, tracking accuracy, mechanical losses, and system configuration [11], [12]. Microcontrollers have also been widely used to implement automatic tracking because they can acquire multiple sensor signals and generate control commands for motors or actuators. LDR-based differential sensing is commonly implemented by comparing illumination levels from sensors positioned around the panel and moving the actuator toward the higher-intensity direction [13], [14].

Recent research has additionally focused on integrating tracking with monitoring and control functions. Measurement of photovoltaic voltage and current allows instantaneous electrical power to be determined and provides a basis for evaluating tracking performance [15]. Battery storage and charge-control circuits can further support standalone operation by storing generated energy and supplying the controller and associated electronics when required [16].

The proposed work combines these concepts into a compact embedded system using four LDR sensors, an Arduino UNO, geared motors, an L298N motor driver, electrical parameter sensing, battery storage, and an LCD interface. An optional servo-controlled panel cover is also incorporated as a supplementary protection mechanism.

Table I - comparison of selected solar tracking approaches

Reference	Tracking Type	Sensing/Control Method	Actuator	Main Focus
[7]	Single-axis	LDR-based	DC motor	Automatic solar alignment
[8]	Dual-axis	LDR sensors	Motorized mechanism	Two-direction tracking
[9]	Single-axis	Sensor-based control	DC motor	PV output improvement
[10]	Dual-axis	Light sensing	Motor/actuator	Solar-position tracking
[11]	Dual-axis	Microcontroller-based	Motors	Tracking performance
[12]	Dual-axis	Sensor feedback	Motors	Fixed vs. tracking comparison
[13]	Dual-axis	LDR differential sensing	Geared motors	Low-cost implementation
[14]	Dual-axis	Embedded controller	DC motors	Automated positioning
[15]	—	Voltage/current sensing	—	PV performance monitoring

[16]	—	Charge-control system	—	Battery-supported PV operation
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2.1 Research Gap

The reviewed systems demonstrate that automatic tracking can improve photovoltaic energy utilization, but practical implementations must balance tracking performance, hardware complexity, actuator power consumption, and system cost. Some systems concentrate primarily on panel positioning, while electrical monitoring and energy-storage functions are treated separately [11], [15].

Therefore, the proposed system focuses on integrating dual-axis LDR-based tracking with electrical parameter monitoring and battery-supported operation using a common Arduino UNO control platform. The addition of an optional automated panel-cover mechanism provides an additional functional feature that can be investigated in future experimental evaluation.

PROPOSED SYSTEM

System Overview

The proposed system is a multi-axis solar tracking and protection system developed to improve photovoltaic energy utilization while providing an automated mechanism for protecting the solar panel under unfavorable environmental conditions. An Arduino UNO is used as the main controller. Four LDR sensors are positioned around the solar panel to detect variations in sunlight intensity, and their readings are processed to control the panel-positioning motors. The tracking mechanism provides horizontal and vertical movement according to the difference in illumination detected by the LDR sensors.

In addition to solar tracking, the system incorporates a motor-operated solar-panel cover. The cover is controlled based on signals from water and vibration sensors. When water is detected or abnormal vibration is sensed, the Arduino activates the cover motor to protect the panel. The system also includes voltage and current monitoring, a 16×2 PC LCD, a buzzer, a 12 V charge controller, a 12 V 7 Ah battery, and a 12 V-to-5 V buck converter.

System Architecture

The proposed architecture consists of sensing, control, actuation, monitoring, and power-management units. The sensing unit includes four LDR sensors for sunlight detection, a voltage sensor, a current sensor, a water sensor, and a vibration sensor. The Arduino UNO receives these signals and generates appropriate control commands.

The LDR readings are used for horizontal and vertical positioning of the solar panel through the L298N motor driver and geared motors. A separate geared motor operates the solar-panel cover when a water or vibration event is detected. The PCA9685

servo driver and servo motor shown in the original design can be retained as an optional actuator interface for the cover mechanism.

The electrical energy generated by the solar panel is supplied to the 12 V charge controller and stored in the 12 V, 7 Ah battery. The battery supplies the motor-driving circuit, while the buck converter provides a regulated 5 V supply for the Arduino and other low-voltage electronic circuits.

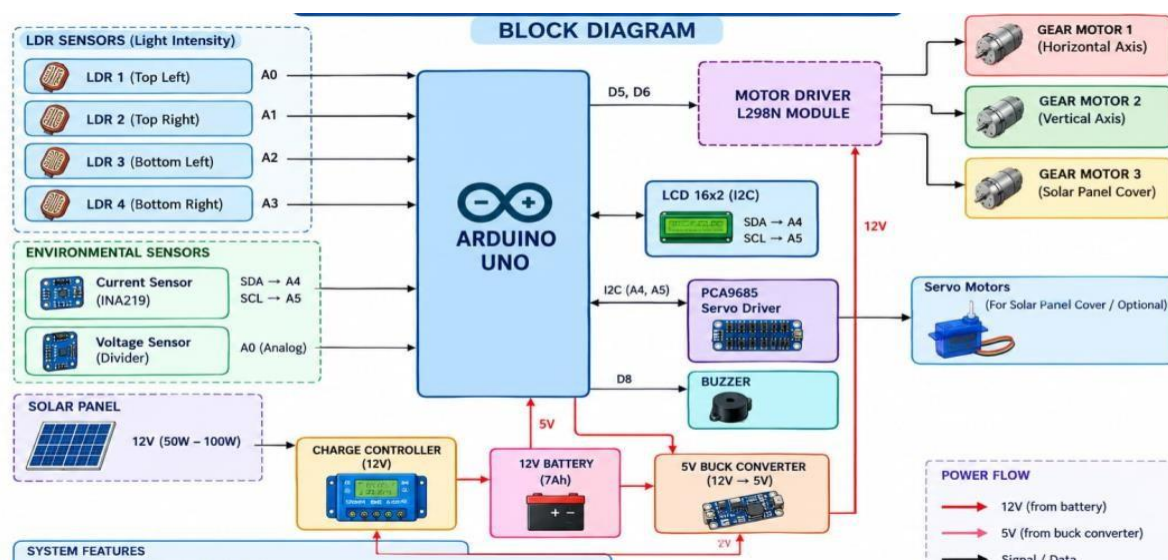


Fig. 1. Block diagram of the proposed multi-axis solar tracking and protection system.

3.1 Multi-Axis Tracking and Protection Mechanism The four LDR sensors are arranged as top-left, top-right, bottom-left, and bottom-right sensors. The Arduino compares their corresponding readings to determine the direction of greater illumination. The difference between the left and right sensor groups is used for horizontal positioning, while the difference between the top and bottom groups is used for vertical positioning. This approach is consistent with the sensing and error-calculation method described in the project methodology.

The tracking operation can be represented by:

$$E_H = (LDR_1 + LDR_3) - (LDR_2 + LDR_4) \quad E_V = (LDR_1 + LDR_2) - (LDR_3 + LDR_4)$$

where E_H represents the horizontal tracking error and E_V represents the vertical tracking error.

When either error exceeds a predefined threshold, the Arduino activates the corresponding motor through the L298N driver. If the error is within the specified threshold, the motor remains stationary to reduce unnecessary movement and power consumption.

Automated Solar-Panel Cover

The solar-panel cover is an additional protection mechanism rather than a conventional solar-tracking axis. Water and vibration sensors are used to detect environmental conditions that may require the panel to be covered.

When the water sensor detects rain or water exposure, the Arduino generates a control signal for the cover motor. Similarly, a significant vibration signal can indicate an external disturbance, after which the controller can activate the protective cover. The cover motor operates through the motor-control circuit, allowing the panel to be moved to the protected position.

The buzzer can also be activated to provide an audible indication when a protection event is detected.

Power Flow

The power system consists of the solar panel, charge controller, battery, buck converter, motor driver, and electronic control circuits. The solar panel supplies energy to the charge controller, which manages battery charging. The stored 12 V supply is used for the motor-driving section, while the buck converter reduces the voltage to 5 V for the Arduino and associated electronics.

Signal and Data Flow

The Arduino UNO acts as the central processing unit. The four LDR sensors provide sunlight-intensity information for panel positioning, while the voltage and current sensors provide electrical measurements for system monitoring. The water and vibration sensors provide environmental-event signals for controlling the protective cover.

The 16×2 I²C LCD displays relevant system parameters, while the buzzer provides an audible alert during selected system events. The PCA9685 communicates with the Arduino through the I²C interface and may be used to control the optional servo-based cover mechanism.

Overall Operating Sequence

The system initially measures the four LDR values and determines the required panel orientation. The Arduino continuously compares the sensor values and drives the corresponding motors until the illumination difference falls within the selected tracking threshold. At the same time, voltage and current parameters are monitored and displayed on the LCD.

Independently, the water and vibration sensors are continuously monitored. When either sensor detects a predefined protection condition, the controller interrupts the normal cover state and activates the solar-panel cover mechanism. After the environmental condition is cleared, the cover can be returned to its normal position according to the programmed control logic.

Thus, the proposed system combines multi-axis solar positioning, electrical monitoring, and sensor-based solar-panel protection in one embedded control system.

HARDWARE IMPLEMENTATION

The hardware implementation of the proposed system consists of a microcontroller-based control unit, multi-axis solar panel positioning mechanism, environmental sensing units, motor/actuator drivers, and a protective solar panel covering mechanism. The system is designed to automatically control the orientation and protection of the solar panel according to the detected environmental conditions. The microcontroller acts as the central processing unit and receives signals from the water and vibration sensors. Based on the sensor conditions, it determines whether the solar panel should remain in its normal operating position or be moved to a protected position. A multi-axis mechanism is incorporated to provide flexible movement of the solar panel and improve its ability to respond to the required positioning conditions.

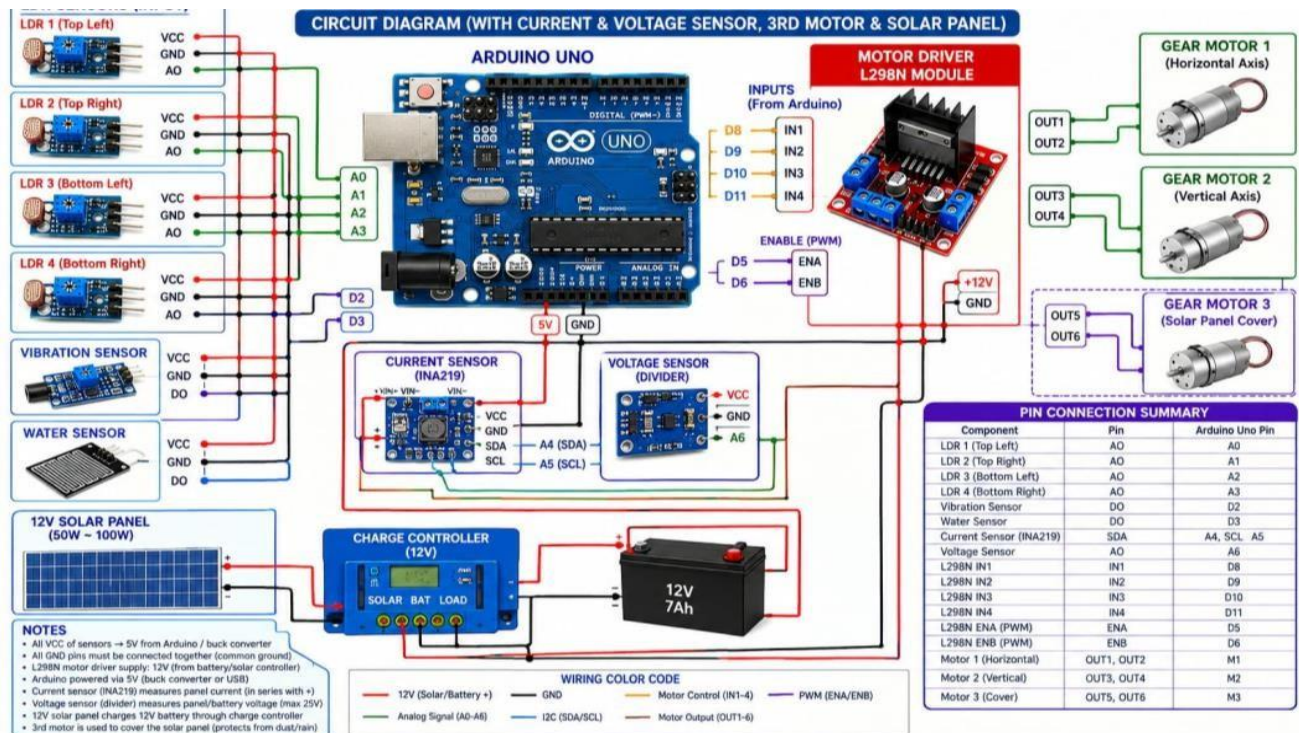


Fig. 4.2.1 Circuit Diagram for proposed system

The major hardware components used in the proposed system are:

1. Microcontroller/control unit
2. Solar panel
3. Multi-axis motor mechanism
4. Motor driver/driver circuitry
5. Water sensor
6. Vibration sensor
7. Protective solar panel cover
8. Power supply unit
9. Supporting mechanical frame

10. Connecting wires and electronic components The overall hardware arrangement is represented through the system block diagram. The block diagram should be placed immediately after this section to provide a clear representation of the interconnection between the sensing, control, actuation, and solar-panel protection units.

The hardware implementation can be divided into the following functional units.

4.2.1 Control Unit

The control unit is responsible for processing the signals obtained from the water and vibration sensors and generating appropriate control signals for the motor mechanism. The microcontroller continuously monitors the sensor inputs and executes the programmed decision-making logic.

When normal operating conditions are detected, the controller maintains the solar panel in its intended operating position. When water or significant vibration is detected, the controller activates the corresponding motor mechanism to move the panel toward the predefined protected position.

The control unit also provides the interface between the sensing section and the mechanical actuation section. Appropriate driver circuitry is used wherever required because the current supplied directly by the microcontroller may not be sufficient to operate the motors.

4.2.2 Solar Panel

The solar panel is the primary energy-generating component of the system. It converts incident solar radiation into electrical energy through photovoltaic conversion. The panel is mounted on a mechanically movable frame so that its position can be changed using the multi-axis mechanism.

The mounting arrangement allows the panel to be repositioned without manually operating the system. The mechanical structure is designed to provide sufficient support while allowing the required movement of the panel.

4.2.3 Multi-Axis Movement Mechanism

A multi-axis movement mechanism is used instead of a conventional dual-axis arrangement. The purpose of the mechanism is to provide movement of the solar panel along multiple required axes

according to the control logic and mechanical configuration of the prototype.

The motors are mechanically coupled to the panel-supporting frame. The controller generates the required motor control signals, while the driver circuitry provides the necessary electrical interface between the controller and motors.

The multi-axis arrangement provides greater flexibility in positioning and allows the solar panel to be moved from its normal operating position to the protected position when an environmental event is detected.

4.2.4 Water Sensor

A water sensor is incorporated to detect the presence of water on or around the solar-panel protection mechanism. The sensor provides an electrical signal to the microcontroller when water is detected.

The water-sensing information is primarily used for automatic protection of the solar panel. When the predefined water-detection condition is satisfied, the controller initiates the covering sequence. The motor mechanism then moves the protective cover or solar-panel assembly to the required position.

This arrangement reduces the need for manual intervention during unexpected water exposure and helps protect the panel and associated components.

4.2.5 Vibration Sensor

The vibration sensor is used to identify significant mechanical vibrations affecting the system. Such vibrations may occur due to external disturbances or mechanical conditions surrounding the solar-panel structure.

The sensor output is monitored by the microcontroller. When the detected vibration exceeds the programmed threshold or satisfies the defined detection condition, the controller initiates the protection sequence.

The vibration sensor therefore acts as an additional environmental/mechanical safety input. Its integration with the water sensor allows the system to respond to more than one external condition rather than depending on a single sensing parameter.

4.2.6 Motor Driver Circuit

The motor driver circuit provides the electrical interface between the microcontroller and the motors used in the multi-axis mechanism. Since motors generally require higher current than the microcontroller can directly supply, the driver circuit is used to control motor operation safely.

The controller provides the required control signals to the motor driver. Depending on the received command, the driver operates the corresponding motor in the required direction. This enables controlled movement of the solar panel and its protective mechanism.

The motor driver also helps isolate the low-power control circuitry from the higher-current motor section.

4.2.7 Protective Cover Mechanism

The protective cover is an important part of the proposed system. Its function is to cover or protect the solar panel when the controller identifies a predefined environmental condition through the water or vibration sensor.

The cover is mechanically connected to the multi-axis actuation mechanism. When a protection command is generated, the motors move the mechanism until the cover reaches the required protected position.

After the environmental condition is no longer detected, the controller can execute the programmed recovery operation and return the mechanism to its normal operating configuration, depending on the implemented control logic.

4.2.8 Power Supply Unit

A regulated power supply is provided to operate the microcontroller, sensors, motor driver, and other electronic components. Separate voltage/current requirements are considered for the control electronics and motor section.

The power supply section should provide stable voltage to the controller and sensors, while the motor supply should be capable of delivering the current required during motor operation. Proper grounding is maintained between the different hardware sections to ensure reliable signal communication.

4.2.9 Hardware Interconnection

The hardware interconnection follows a sensor–controller–actuator architecture. The water sensor and vibration sensor are connected to the input pins of the microcontroller. The microcontroller processes the sensor signals according to the programmed control conditions.

The output control signals are supplied to the motor driver circuitry. The motor driver subsequently controls the motors responsible for the multi-axis movement and protective covering operation.

4.2.10 Hardware Working Sequence

The implemented hardware operates according to the following sequence:

1. The system is powered through the regulated power supply.
2. The microcontroller initializes the connected sensors and motor-control circuitry.
3. The water sensor and vibration sensor are continuously monitored.
4. Under normal conditions, the solar panel remains in its predefined operating configuration.
5. When water is detected, the corresponding sensor signal is provided to the controller.
6. When significant vibration is detected, the vibration sensor provides the corresponding signal to the controller.
7. The controller evaluates the received sensor conditions according to the programmed threshold and decision logic.
8. If a protection condition is identified, the controller sends control signals to the motor driver.
9. The motor driver activates the required motor(s) of the multi-axis mechanism.

10. The mechanism moves the solar panel/protective cover to the predefined protected position.
11. After the required condition is cleared, the controller can return the mechanism to its normal position according to the programmed recovery logic.



Fig. 4.2.10 Realtime Model Working

CONCLUSION AND FUTURE SCOPE

Conclusion

The proposed system presents an automated approach for solar-panel positioning and protection using a microcontroller, water and vibration sensing, and a multi-axis mechanical mechanism. The developed prototype demonstrates the feasibility of automatically responding to detected environmental conditions and moving the solar panel or protective cover accordingly.

The practical implementation combines sensing, control, and actuation into a compact system and provides a foundation for further development of automated and protective solar-energy systems.

Future Scope

The system can be further enhanced by integrating additional environmental sensors, wireless monitoring, IoT-based data logging, improved mechanical positioning, and remote control facilities. Future versions may also incorporate advanced tracking algorithms and predictive environmental monitoring to improve the overall automation and reliability of the system.

REFERENCES

1. International Energy Agency (IEA), *Renewables 2024: Analysis and Forecast to 2030*. Paris, France: IEA, 2024.
- A. Luque and S. Hegedus, Eds., *Handbook of Photovoltaic Science and Engineering*, 2nd ed. Chichester, U.K.: Wiley, 2011.
2. M. A. Green, *Solar Cells: Operating Principles, Technology, and System Applications*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1982.
3. N. M. Pearsall, *Photovoltaic Systems: Fundamentals and Applications*. Cambridge, U.K.: Cambridge University Press, 2017.
4. T. Esmar and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, Jun. 2007.
5. D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithms," *Progress in Photovoltaics: Research and Applications*, vol. 11, no. 1, pp. 47–62, 2003.
6. R. Messenger and J. Ventre, *Photovoltaic Systems Engineering*, 3rd ed. Boca Raton, FL, USA: CRC Press, 2010.
7. M. A. Green, "The path to 25% silicon solar cell efficiency: History of silicon cell evolution," *Progress in Photovoltaics: Research and Applications*, vol. 17, no. 3, pp. 183–189, 2009.
8. J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, 4th ed. Hoboken, NJ, USA: Wiley, 2013.
9. S. A. Kalogirou, "Solar energy engineering: Processes and systems," Academic Press, 2014.