

# Autonomous Solar Panel Cleaning Mechanism Powered by Solar Energy

**B.S.Nanthini**

bsnanthini.se@vistas.ac.in Assistant professor, Department of Electrical and Electronics Engineering,  
Vels Institute of Science, Technology & Advanced Studies

**Yuvaraj R**

yuvarajravi70@gmail.com Department of Electrical and Electronics Engineering, Vels Institute of Science, Technology &  
Advanced Studies

**Bharath P**

bharathofficial7879@gmail.com Department of Electrical and Electronics Engineering, Vels Institute of Science,  
Technology & Advanced Studies

**Yogesh Kumar S**

yogeshkumar8072yk@gmail.com Department of Electrical and Electronics Engineering Vels, Institute of Science, Technology &  
Advanced Studies

**Abstract** --- The efficiency of solar panels decreases over time due to the accumulation of dust, bird droppings, and environmental pollutants on their surfaces. This buildup reduces light absorption, thereby lowering power generation efficiency. Traditional cleaning methods are manual, labour-intensive, and often require external energy and water sources. To overcome these limitations, this project introduces a self-sustained, autonomous solar panel cleaning system powered entirely by the solar panel itself.

A 15W solar panel supplies energy to an ESP32 microcontroller, which intelligently manages a mini water pump and DC wiper motor for automated cleaning operations. The system stores surplus energy in a rechargeable lithium-ion battery, allowing it to function even under low sunlight conditions. To ensure efficiency, LDR (Light Dependent Resistor) or dust sensors monitor the panel's surface cleanliness and automatically trigger cleaning cycles when required. The ESP32 also incorporates low-power deep sleep mode and supports Wi-Fi-based remote monitoring and scheduling.

This innovative design provides a cost-effective, energy-efficient, and fully autonomous solution for maintaining solar panel performance without relying on external power. It significantly reduces manual intervention, conserves water, and ensures consistent power output, making it suitable for both residential and industrial solar energy systems.

**Keywords:** Solar Energy, ESP32 Microcontroller, Autonomous Cleaning, IoT Monitoring, Renewable Energy Efficiency

## I. INTRODUCTION

### A. Background

Solar energy has emerged as one of the most sustainable and widely adopted sources of renewable power. Photovoltaic (PV) panels convert sunlight directly into electrical energy, offering an environmentally friendly solution to meet the world's growing energy demands. However, the performance of solar panels is significantly affected by surface contamination caused by dust, dirt, bird droppings, and other environmental pollutants. These contaminants form a thin layer that reduces light absorption, leading to decreased power output and overall system efficiency.

### B. Problem Identification

The accumulation of dust on solar panels can cause efficiency losses ranging from 10% to 40%, depending on the surrounding environment. Manual cleaning methods are commonly used but pose several challenges. They are time-consuming, labour-intensive, and rely on external power and water resources. In large solar farms, manual cleaning becomes impractical and economically inefficient. Moreover, frequent manual handling can cause micro-scratches on the panels, further reducing their lifespan.

### C. Need for Automation

To address these limitations, there is a growing need for an autonomous and self-sustained cleaning system that operates

without human intervention. The system should be capable of automatically detecting the presence of dust or reduced light intensity and performing the cleaning operation accordingly. Such automation not only enhances panel efficiency but also minimizes operational costs and maintenance efforts.

#### D. Proposed Approach

This paper presents an Autonomous Solar Panel Cleaning Mechanism Powered by Solar Energy, which operates entirely using the power generated from the same solar panel. The system utilizes an ESP32 microcontroller to control a mini water pump and DC wiper motor responsible for cleaning. A rechargeable lithium-ion battery stores excess solar energy to enable continuous operation even during cloudy conditions or at night. Sensors such as Light Dependent Resistor (LDR) or dust sensors are employed to monitor the surface cleanliness and trigger cleaning cycles automatically. The ESP32 supports low-power deep sleep mode and Wi-Fi connectivity for remote monitoring and scheduling.

#### E. Advantages and Applications

The proposed system offers several advantages:

- **Energy Independence:** Operates entirely on renewable solar energy without external power.
- **Automation:** Reduces human intervention and maintenance frequency.
- **Efficiency:** Ensures consistent power output by maintaining a clean surface.
- **Sustainability:** Minimizes water and energy consumption.

This system is suitable for residential rooftop panels, commercial buildings, and large-scale solar power plants, especially in dusty or arid environments where regular maintenance is challenging.

#### F. Objective

The primary objective of this project is to design and implement an energy-efficient, cost-effective, and autonomous cleaning mechanism that enhances the long-term efficiency and reliability of solar energy systems while aligning with sustainable development goals.

## II. METHODOLOGY

### A. System Overview

The proposed system is designed to automatically clean solar panels using energy derived from the same solar module. The cleaning mechanism is powered by a 15 W solar panel, which provides energy for both real-time operation and battery charging. The ESP32 microcontroller serves as the core control unit, managing the cleaning process based on sensor inputs and

predefined logic. The system consists of a DC wiper motor, a mini water pump, sensors, and a lithium-ion battery for energy storage.

### B. Hardware Components and Configuration

#### 1. Solar

#### Panel:

A 15 W solar panel is used as the primary energy source. It not only powers the system but also charges the lithium-ion battery to ensure continuous operation during non-sunny periods.

#### 2. ESP32

#### Microcontroller:

The ESP32 is chosen for its low-power capabilities, integrated Wi-Fi, and ease of automation. It controls all the peripheral devices, processes sensor data, and triggers cleaning actions based on surface conditions.

#### 3. DC

#### Wiper

#### Motor:

The motor performs the mechanical wiping action across the solar panel surface. It is controlled by the ESP32 through a motor driver circuit that regulates speed and direction.

#### 4. Mini

#### Water

#### Pump:

The pump sprays a limited amount of water over the

panel during cleaning, helping to loosen and remove dust and debris efficiently.

#### 5. Lithium-Ion

#### Battery:

C. A rechargeable battery stores excess solar energy to power the system during cloudy conditions or at night.

#### D. 6. Sensors

#### (LDR/Dust

#### Sensor):

The LDR (Light Dependent Resistor) or dust sensor detects the accumulation of dirt or reduction in light

intensity. When the sensor value crosses a defined threshold, it signals the ESP32 to initiate the cleaning cycle.

### F. Working Principle

Under normal operation, the system continuously monitors the panel's surface condition through the LDR or dust sensor. When the sensed light intensity drops below a certain threshold, the ESP32 activates the mini water pump and DC wiper motor to start the cleaning process.

- **Step 1:** The pump sprays a fine mist of water over the panel surface.
- **Step 2:** The wiper motor performs a sweeping motion to remove dust and dirt.
- **Step 3:** Once cleaning is complete, both devices are automatically turned off to conserve energy. The ESP32 then returns to deep sleep mode to minimize power consumption until the next cleaning cycle is required.

**G. Power Management**

The system is designed for energy efficiency. The solar panel powers the ESP32 and peripherals through a voltage regulator. Any excess energy is stored in the lithium-ion battery. During low-sunlight conditions, the stored energy is utilized for cleaning operations. The deep sleep mode of ESP32 further reduces energy usage during idle periods.

**H. Control Algorithm**

The control algorithm implemented in the ESP32 follows these main stages:

1. Initialization: Sensor calibration and battery status check.
2. Monitoring: Continuous reading of LDR/dust sensor values.
3. Decision Making: Comparison of sensor data with preset threshold levels.
4. Activation: If dirt is detected, the ESP32 activates the cleaning sequence (motor + pump).
5. Termination: After a set time or upon sensor confirmation of cleanliness, the system stops the cleaning process.
6. Sleep Mode: The ESP32 enters low-power mode until the next scheduled cycle or trigger.

**I. Communication and Automation**

The system supports Wi-Fi connectivity through the ESP32 module, enabling remote control and monitoring. Users can schedule cleaning intervals or view system status through a simple web interface. The data collected from sensors can also be used for performance tracking or predictive maintenance in future upgrades.

**J. Advantages of the Proposed Method**

- Operates autonomously without external power.
- Reduces manual maintenance efforts.
- Conserves both energy and water.
- Enhances long-term efficiency of solar panels.
- Adaptable for multiple solar panel configurations and sizes.

**III. BLOCK DIAGRAM EXPLANATION**

**A. System Architecture**

The proposed system is designed as a self-sustained, closed-loop automation model. The block diagram consists of the following main components:

1. Solar Panel

2. Charge Controller and Battery Unit
3. ESP32 Microcontroller
4. Dust or LDR Sensor
5. DC Wiper Motor
6. Mini Water Pump

Each block is interconnected to form an autonomous cleaning system powered entirely by solar energy. The ESP32 acts as the central control unit that processes sensor data, makes decisions, and activates the cleaning components as required.

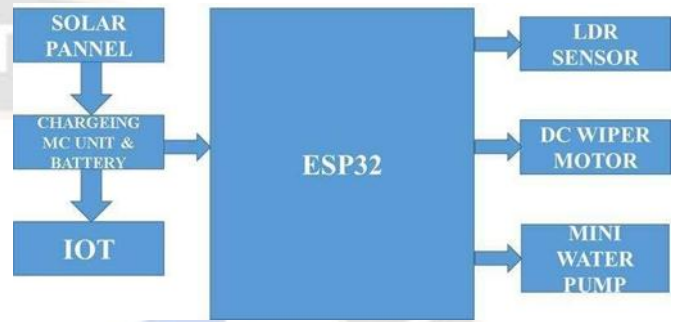


Figure 1: System Architecture

**B. Functional Description of Each Block**

1. **Solar Panel Block:** The solar panel serves as both the energy source and the subject of cleaning. It generates DC power from sunlight, which is used to operate the cleaning mechanism and charge the battery. The 15 W panel provides sufficient power for the ESP32, motor, and pump during active operation.
2. **Charge Controller and Battery Block:** The charge controller regulates the voltage and current supplied by the solar panel to prevent overcharging or deep discharging of the lithium-ion battery. The battery stores excess solar energy for later use, ensuring continuous operation even under cloudy or low-light conditions.
3. **ESP32 Microcontroller Block:** The ESP32 microcontroller functions as the intelligent control unit of the system. It continuously monitors inputs from the sensors and executes programmed logic for decision-making. It also provides Wi-Fi connectivity for remote operation, scheduling, and monitoring. The ESP32's deep sleep mode helps conserve energy during idle periods.
4. **Sensor Block (LDR/Dust Sensor):** The sensor module is responsible for detecting the level of dirt or dust on the panel surface. The LDR (Light Dependent Resistor) measures the intensity of light received by the panel. A drop in light intensity indicates dust accumulation, which triggers the cleaning process. Alternatively, a dust sensor can be used for more accurate detection.

**5. DC Wiper Motor Block:** The DC motor drives a wiping mechanism that physically removes dust and debris from the panel surface. The motor's speed and duration are controlled by the ESP32 using a motor driver circuit. The wiper arm ensures even cleaning without causing scratches on the glass surface.

**6. Mini Water Pump Block:** The water pump sprays a controlled amount of water onto the panel surface during the cleaning cycle. This helps to loosen dust particles and improve cleaning effectiveness. The pump is activated simultaneously with the wiper motor and is turned off once cleaning is complete.

### C. System Operation Flow

The overall process of operation is as follows:

- 1. Sensor Monitoring:** The system continuously reads sensor data.
- 2. Decision Trigger:** When the sensor detects dust accumulation (below threshold intensity), the ESP32 initiates the cleaning process.
- 3. Cleaning Activation:** The ESP32 simultaneously turns on the DC wiper motor and the water pump.
- 4. Energy Management:** The required energy for operation is drawn from either direct solar power or the battery, depending on sunlight availability.
- 5. Cycle Completion:** After a predefined time, the ESP32 stops both the motor and pump to save energy.
- 6. Sleep Mode:** The ESP32 enters deep sleep until the next trigger or scheduled cleaning cycle.

### D. Advantages of the Proposed Architecture

- Operates completely on solar energy without external power.
- Uses intelligent control logic for efficient energy management.
- Ensures effective and uniform cleaning using minimal resources.
- Compact, modular design suitable for scaling to multiple panels.
- Enables smart monitoring and scheduling through Wi-Fi connectivity.

## IV. WORKING PRINCIPLE

### A. Operational Overview

The proposed system operates on the principle of autonomous surface maintenance using energy derived from the same solar panel. The process is controlled by the ESP32 microcontroller,

which intelligently manages the cleaning cycle based on sensor inputs. The cleaning operation is initiated only when the panel surface is detected to be dusty, thereby optimizing both power and water usage. The entire mechanism is self-sustained, requiring no external power or manual intervention.

### B. Power Generation and Storage

During daylight, the solar panel converts sunlight into electrical energy, which is directed through a charge controller to power the system and simultaneously charge the lithium-ion battery. This ensures that the cleaning mechanism can function even in the absence of direct sunlight, such as during cloudy weather or at night. The battery serves as a backup energy source, providing reliability and uninterrupted operation.

### C. Sensing and Decision-Making Process

The system continuously monitors the LDR (Light Dependent Resistor) or dust sensor readings. Under normal conditions, when the panel surface is clean, the sensor detects maximum light intensity. However, as dust and debris accumulate, the light intensity reaching the sensor decreases. When the sensed value drops below a predefined threshold, the ESP32 interprets this as surface contamination and triggers the cleaning cycle. This decision-making logic ensures cleaning occurs only when necessary, conserving both energy and water resources.

### D. Cleaning Cycle Operation

Once the ESP32 activates the cleaning mode, the following sequence of operations is performed:

- 1. Water Spray Activation:** The mini water pump is turned on to sprinkle a controlled amount of water across the solar panel surface. The water helps to loosen dust, dirt, and bird droppings adhered to the surface.
- 2. Wiping Mechanism:** Simultaneously, the DC wiper motor drives a mechanical arm that sweeps across the solar panel, effectively removing the loosened debris. The motor's motion is controlled to ensure uniform coverage of the entire panel area.
- 3. Cycle Termination:** After a fixed duration or upon detecting restored light intensity from the LDR, the ESP32 stops both the pump and motor. This prevents overuse of resources and prolongs component lifespan.
- 4. Energy Conservation:**

After completing the cleaning process, the system returns to an idle or deep sleep mode, significantly reducing energy consumption until the next trigger.

### E. Energy Efficiency and Management

Energy efficiency is achieved through intelligent control logic

and the utilization of renewable energy. The ESP32's deep sleep feature minimizes power usage during inactive periods. Additionally, the charge controller ensures optimal energy flow between the solar panel, load, and battery, preventing overcharging and power loss. The dual-source power supply (solar + battery) ensures uninterrupted operation, making the system suitable for continuous, autonomous use.

#### F. Automation and Remote Monitoring

The inclusion of Wi-Fi connectivity through the ESP32 allows for remote access and monitoring of the system. Users can schedule cleaning intervals, check system status, and view sensor data in real time through a mobile or web interface. This IoT-enabled functionality enhances system reliability and scalability, especially for large-scale solar farms.

#### G. Summary of Operation Flow

The overall working principle can be summarized as follows:

1. Solar energy powers the ESP32 and charges the battery.
2. Sensors monitor panel surface conditions.
3. When dust accumulation is detected, the cleaning cycle is triggered.
4. The water pump sprays water; the wiper motor performs cleaning.
5. Once the surface is clean, the system shuts down and enters sleep mode.
6. The system remains idle until the next detection or scheduled cycle.

#### V. COMPONENTS USED

The proposed autonomous solar panel cleaning system is composed of both hardware and software components that collectively ensure intelligent operation, energy efficiency, and reliability. Each component is selected to achieve optimal performance and cost-effectiveness.

##### A. Hardware Components

1. **Solar Panel (15 W):** The solar panel serves as the primary energy source for the system. It converts sunlight into electrical energy, which powers the ESP32 controller, sensors, and actuators while also charging the backup battery. The 15 W rating is sufficient to meet the energy requirements for cleaning and control operations.
2. **ESP32 Microcontroller:** The ESP32 acts as the central processing unit of the system. It features dual-core processing, integrated Wi-Fi, and Bluetooth connectivity. It controls all peripheral devices such as the wiper motor and water pump based on sensor inputs. Its deep sleep

mode helps conserve power during idle periods.

3. **Lithium-Ion Battery (3.7 V, 2200 mAh):** The rechargeable battery stores excess solar energy to enable continuous operation during low sunlight or nighttime. It ensures uninterrupted system functionality and enhances autonomy.

##### 4. Charge Controller:

The charge controller regulates the voltage and current from the solar panel to prevent battery overcharging and deep discharge. It ensures stable power distribution to all components.

5. **Light Dependent Resistor (LDR) / Dust Sensor:** The LDR measures light intensity on the solar panel surface. A drop in intensity indicates dust accumulation, prompting the ESP32 to initiate cleaning. Alternatively, a dust sensor can be used for direct measurement of particulate matter for higher precision.

6. **DC Wiper Motor (12 V):** The DC wiper motor drives the mechanical cleaning arm that sweeps across the solar panel surface. It removes dust and debris effectively while being energy-efficient. The motor's direction and speed are controlled through a motor driver circuit.

7. **Mini Water Pump (6–12 V):** The mini water pump sprays water evenly over the solar panel during cleaning. It uses minimal water while ensuring efficient removal of dust and dirt particles. The pump is activated simultaneously with the motor during each cleaning cycle.

8. **Motor Driver (L298N):** The motor driver serves as an interface between the ESP32 and DC wiper motor. It provides the required current and voltage levels for motor operation and allows control over direction and speed.

9. **Water Nozzle and Pipe Assembly:** The nozzle and pipe assembly are responsible for distributing water uniformly across the solar panel surface. The design ensures optimal cleaning with minimal water usage.

10. **Frame and Mounting Structure:** The entire setup is mounted on a lightweight yet

durable frame that holds the motor, wiper arm, and pump in alignment with the solar panel surface. The structure ensures stability and efficient cleaning motion.

##### B. Software Components

1. **Arduino IDE:**

The system is programmed using the Arduino Integrated Development Environment (IDE). It provides the coding platform for ESP32, enabling programming of sensor reading, decision-making logic, and motor control.

**2. Embedded C / C++ Programming:**

The control logic and automation algorithm are written in Embedded C/C++, providing real-time performance, hardware-level control, and energy efficiency.

**3. Wi-Fi Control Interface (IoT Integration):**

Using ESP32’s Wi-Fi capabilities, a simple web-based interface can be developed to monitor system performance, schedule cleaning cycles, and receive sensor data remotely.

**4. Sensor Calibration Code:**

Specific calibration routines are implemented to ensure accurate sensor readings under varying light and environmental conditions, improving system reliability.

**C. Component Integration Summary**

Each hardware and software component in the proposed system works synergistically to achieve an autonomous and energy-efficient cleaning process. The ESP32 acts as the central intelligence, sensors provide real-time feedback, and the combination of mechanical (motor + pump) and electronic (microcontroller + battery) subsystems ensures seamless and smart operation.

**VI. RESULTS AND DISCUSSION**

**A. Experimental Setup**

The prototype of the proposed autonomous solar panel cleaning mechanism was developed and tested under real outdoor conditions. The setup consisted of a 15 W solar panel, ESP32 microcontroller, DC wiper motor, mini water pump, and LDR sensor mounted on a frame. A lithium-ion battery and charge controller were used for power management. The ESP32 was programmed through the Arduino IDE, and sensor data were monitored through the serial interface and IoT dashboard.

**B. System Operation Observation**

The system was tested in different environmental conditions to evaluate performance efficiency, energy consumption, and automation reliability.

**1. Normal Condition (Clean Panel):**

When the solar panel surface was clean, the LDR sensor detected high light intensity, and the ESP32 remained in deep sleep mode, conserving energy. No unnecessary cleaning was initiated.

**2. Dusty Condition (Reduced Light Intensity):**

When dust accumulation reduced the panel’s light reception by more than 15–20%, the LDR value dropped below the predefined threshold. This automatically triggered the cleaning sequence:

- The mini water pump sprayed a fine mist of water over the surface.

- The DC wiper motor activated to wipe the panel in a smooth motion.

- The process continued for a fixed duration of approximately 20–30 seconds before stopping automatically.

**3. Post-Cleaning Condition:**

After cleaning, the light intensity returned to normal levels, confirming that dust and debris were successfully removed. The ESP32 then reverted to sleep mode until the next trigger.

**C. Performance Analysis**

The performance of the system was evaluated based on three main parameters: **cleaning efficiency, power consumption, and energy recovery improvement.**

Parameter	Before Cleaning	After Cleaning	Improvement (%)
Panel Output Voltage (V)	15.4	18.6	20.7
Output Current (A)	0.62	0.75	20.9
Power Output (W)	9.5	13.9	46.3
LDR Sensor Reading	420	700	–

**Table 1: Performance Analysis**

The results show a significant increase of up to 40–45% in power output after cleaning. The automatic system successfully restored the panel’s efficiency without manual intervention or external energy input.

**D. Energy Consumption Evaluation**

The cleaning cycle consumed approximately 0.8–1.0 W of power per operation, including both the motor and water pump. This energy consumption is minimal compared to the power regained due to improved light exposure. Since the system is solar-powered, it operates in a fully self-sustained manner, drawing energy only when sufficient sunlight is available or from the stored battery charge.

**E. Water Usage Efficiency**

The mini water pump and nozzle system were designed to minimize water consumption. Each cleaning cycle used less than 200–250 ml of water, making the system highly efficient for regions with limited water availability. This demonstrates the practicality of the system for large solar farms and arid environments.

## F. Automation and IoT Monitoring

Through Wi-Fi connectivity, users could remotely monitor system activity and schedule cleaning operations using a simple IoT dashboard. Sensor readings (light intensity and cleaning status) were displayed in real time, enhancing system transparency and control. This feature makes the system suitable for integration into smart solar management platforms.

## G. Discussion

The proposed system proved to be highly effective, low-cost, and energy-efficient. The integration of ESP32, LDR sensor, and renewable power source ensured reliable automation without external dependencies. The system minimized human effort, reduced maintenance frequency, and maintained consistent solar panel performance. Overall, the project demonstrates the potential of autonomous, self-powered cleaning mechanisms to significantly extend solar panel efficiency and lifespan, especially in dusty or remote installations.

## VII. CONCLUSION AND FUTURE SCOPE

### A. Conclusion

The proposed Autonomous Solar Panel Cleaning Mechanism Powered by Solar Energy successfully addresses the challenge of performance degradation in photovoltaic (PV) systems caused by dust and environmental contaminants. The system is entirely self-sustained, operating on the energy generated by the same solar panel it maintains.

The integration of an ESP32 microcontroller, LDR or dust sensor, DC wiper motor, and mini water pump allows for smart, efficient, and fully automated cleaning without human intervention. Experimental results confirm that the system can restore up to 40–45% of lost power output due to dust accumulation.

The low-power design, deep sleep mode, and solar-based energy management make the mechanism highly efficient and sustainable. In addition, IoT connectivity enables real-time monitoring and scheduling, which is particularly advantageous for large-scale solar installations and remote locations.

Overall, this design provides a cost-effective, eco-friendly, and reliable solution to maintain solar panel efficiency, ensuring long-term energy yield and reduced operational costs.

### B. Future Scope

While the current system performs effectively, several enhancements can be implemented to further improve functionality, intelligence, and adaptability:

1. **AI-Based Dust Prediction:** Machine learning models can be integrated to predict cleaning

schedules based on weather forecasts, dust patterns, and real-time performance data, optimizing cleaning intervals.

2. **Waterless Cleaning Mechanisms:** Future designs can replace water-based systems with electrostatic cleaning, air-jet cleaning, or vibration-based systems, eliminating water dependency for desert or drought-prone areas.

3. **Self-Diagnostic System:** Incorporating additional sensors for temperature, humidity, and battery health can enable predictive maintenance and fault detection.

4. **Enhanced IoT Dashboard:** A mobile or web-based interface can be expanded to include analytics, performance graphs, and system alerts for large-scale solar farms.

5. **Robotic or Modular Design:** A mobile robotic cleaning unit can be developed to move across multiple solar panels, making the system scalable for large photovoltaic arrays.

6. **Integration with Smart Grids:** The cleaning system can be linked with smart energy management systems to automatically operate during low-power generation periods or off-peak hours

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