

PERFORMANCE ENHANCEMENT OF PHOTOVOLTAIC SOLAR PANELS BY A CLEANING ROBOT TECHNIQUE

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ABSTRACT

This paper presents a comprehensive approach to integrating Arduino with a current sensor, voltage sensor, two motors, and a motor driver to monitor the output of a solar panel and control a cleaning bot. Interacting the current and voltage sensors with the Arduino allows continuous solar panel power output monitoring. The Arduino is the central control unit to collect data from the current and voltage sensors to monitor the solar panel's performance. Additionally, the same Arduino is used to control the cleaning bot, which is equipped with two motors and a brush-controlled motor driver for effective cleaning of the solar panel surface. Furthermore, the cleaning bot is designed to enhance the solar panel's efficiency by automatically removing dust and rubble using a brush. Additionally, the bot is equipped with a Node MCU, enabling seamless data transmission to a web server, and making it accessible for remote monitoring. An Internet Protocol (IP) camera is integrated to visually inspect the solar panel and the cleaning bot's activities to enhance the system surveillance capabilities.



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I. INTRODUCTION

Various energy sources like coal, nuclear, gas, hydro, and diesel, which are used for generating electricity, may get exhausted within a few years. Due to this, all the researchers are showing interest in sustainable energy production and saving. The power generated by sun radiation is one of the sustainable energy productions. Photovoltaic solar panels use the sun's radiation to generate electricity. When sunlight falls on the solar panel, the sun's radiation penetrates the solar cell to generate electricity more efficiently. If dust forms on the solar PV panel, it acts as a resistance in which the sun radiation may not penetrate properly into the solar cell [1-5]. Due to this, the output from the solar panel is reduced. However, photovoltaic technology faces several obstacles, including cost, the unpredictable nature of the environment, and low solar panel efficiency; it is always evolving in various applications. Since the solar panels are stored in an open environment, various elements, including the effect of clouds, snow, shadow, pollen, high temperatures, dust, bird droppings, and filth, can affect their effectiveness [6-8]. Therefore, keeping the solar panels tidy and clean is the greatest way to reduce dust's effect [9-12]. The main objective of the work is to

- ✓ Develop a solar panel cleaning robot to enhance the efficiency of solar panels power output.
- ✓ Promote the widespread adoption of solar PV panels for remote areas.
- ✓ Simplify and automate the process of cleaning solar PV panels against dust particles.
- ✓ Reduce the need for human intervention in solar PV panel maintenance and operation.
- ✓ Design an environmentally friendly and cost-effective robot for cleaning the solar panels.

In [13], the authors discussed that cleaning and maintenance greatly impact solar panels' efficiency. An 8-panel array shows a 30%–33% increase in efficiency; as a result, we can see that it will be more useful in solar parks with significantly more cells. Thorough cleaning is very beneficial because even a single panel obstructed by dust can reduce the array's overall performance. In [14], the authors proposed recommendations for future automation to lower labor costs and clean recycled water. The project aims to create a smart, completely automated cleaning system that uses less energy and resources. In [15], the author proposed an automatic solar PV panel cleaner robot using IoT. It comprises battery, DC motors, motor driver, microcontroller, IR sensor, and GSM module. In this system, it is possible to increase the peak power output by 10%–30%. The observation suggests that increased energy usage is caused by dust accumulation on the panel. In [16], the authors discussed that floating solar PV panels are typically placed in the center of a body of water. Any human going there to clean them has an extremely difficult time. The cleaning robot moves here and there on the solar PV panel to clean it, serving our objective without having to go there.

A camera installed on the robot allows for monitoring of the cleaning process. Additionally, the robot increases the effectiveness of the PV module. In [17], the author proposed an automatic solar PV panel cleaning system which will increase the solar PV module's efficiency. With the introduction of the Arduino Uno and driver circuit, they demonstrated the cleaning and control of the solar PV module cleaning mechanism along with the water pump and soft material. In [18], authors have developed and tested an automated solar panel cleaning robot to reduce dust-related efficiency losses. Experimental results showed improved PV output and reduced maintenance effort. In [19], an optimized grid-integrated hybrid AC/DC microgrid for rural electrification has been developed for location. The work demonstrated technical feasibility, cost-effectiveness, and improved reliability using renewable energy and storage systems. In [20], an experimentally investigated power enhancement techniques for partially shaded PV systems, showing improved output performance under non-uniform irradiance conditions. It is concluded that above studies advance photovoltaic system efficiency, operational reliability, and sustainable energy integration by introducing innovations in automated maintenance systems, optimized hybrid microgrid design, and effective partial shading mitigation techniques.

II. COMPONENTS REQUIRED

To overcome the limitations of conventional methods, an innovative approach is proposed, which leverages the use of embedded systems and automation. By interfacing Arduino with current and voltage sensors, the proposed method enables continuous real-time monitoring of solar panel performance. The embedded system provides live data and logs and stores historical data for detailed analysis. This ensures that any drop in efficiency or issues with the solar panel can be promptly detected and addressed, thus maximizing energy production, and minimizing downtime. Moreover, integrating an Arduino-controlled cleaning bot equipped with two motors and a brush motor driver offers significant advantages. The brush-controlled motor ensures consistent and thorough cleaning, enhancing the solar panel's overall performance. Additionally, the bot's integration with a Node MCU facilitates seamless data transmission to a web server, enabling remote monitoring and management. Users can gain visual insights into the solar panel's condition and the bot's cleaning activities through the web server and an IP camera. Due to its remote accessibility, operators can plan maintenance, make data-driven decisions, and maximize cleaning results, all contributing to increased solar panel efficiency. The components required for cleaning the solar panel are based on hardware and software requirements, and Figure 1 depicts the list of components used in the work for designing the proposed system.

II.1 HARDWARE REQUIREMENTS

The components used in the proposed system are as follows:

- Rechargeable Battery:

A rechargeable battery is an energy-storage gadget that can be charged once again by connecting DC current to its terminals.

- Arduino UNO:

It is a microcontroller board manufactured by Arduino. Cc and introduced in 2010. It is designed according to the Microchip ATmega328P microprocessor (MCU). The microcontroller board has sets of analogue and digital input/output (I/O) pins that interface with various expansion boards, shields, and other electrical/electronic circuits. The board can be programmed by using a USB cable and the Arduino integrated development environment (IDE). It is equipped with six analogue and fourteen digital input/output pins, with six capable of generating pulse-width modulation (PWM) output.

- Current Sensor:

A current sensor is a device capable of accurately measuring and calculating the current passing through a conductor without impacting system performance. This linear integrated circuit sensor operates on the principle of the Hall effect.

- Voltage Sensor:

A voltage sensor is a device used for measuring voltage. Voltage sensors can measure voltage using several methods, including detecting low voltage levels and measuring high voltages.

- DC Motor:

A motor is necessary for a robot to turn a wheel or carry out a certain task. A DC Motor is one such electric machine that converts electrical energy into mechanical energy. Two windings are found in a DC motor: the stator core consists of field winding and the rotor core consists of armature winding.

The field winding creates the magnetic field, whereas the armature winding acts as a conductor for current flow. According to the electromagnetic induction law, a current-carrying conductor experiences a force that produces torque when placed in a magnetic field. As a result, the shaft rotates.

- **L293D Motor Driver:**

The 16-pin L293D Motor Driver IC controls the two DC motors simultaneously, protecting the microcontroller from the high current required to operate the motor. It also works as an amplifier, boosting the microcontroller's low-power signal until it produces sufficient power to turn on the motor.

II.1.1 Software Requirements:

- **Arduino IDE:** The Integrated Development Environment application is compatible with various operating systems using the free and open-source Arduino IDE software. It provides support for programming languages such as C++. This is known as the Integrated Development Environment ITR, IDE for short.
- **Adafruit:** This library offers a user-friendly, device-independent interface for engaging with Adafruit IO using Arduino. It simplifies the transition between Wi-Fi, Ethernet, and cellular (32u4 FONA).

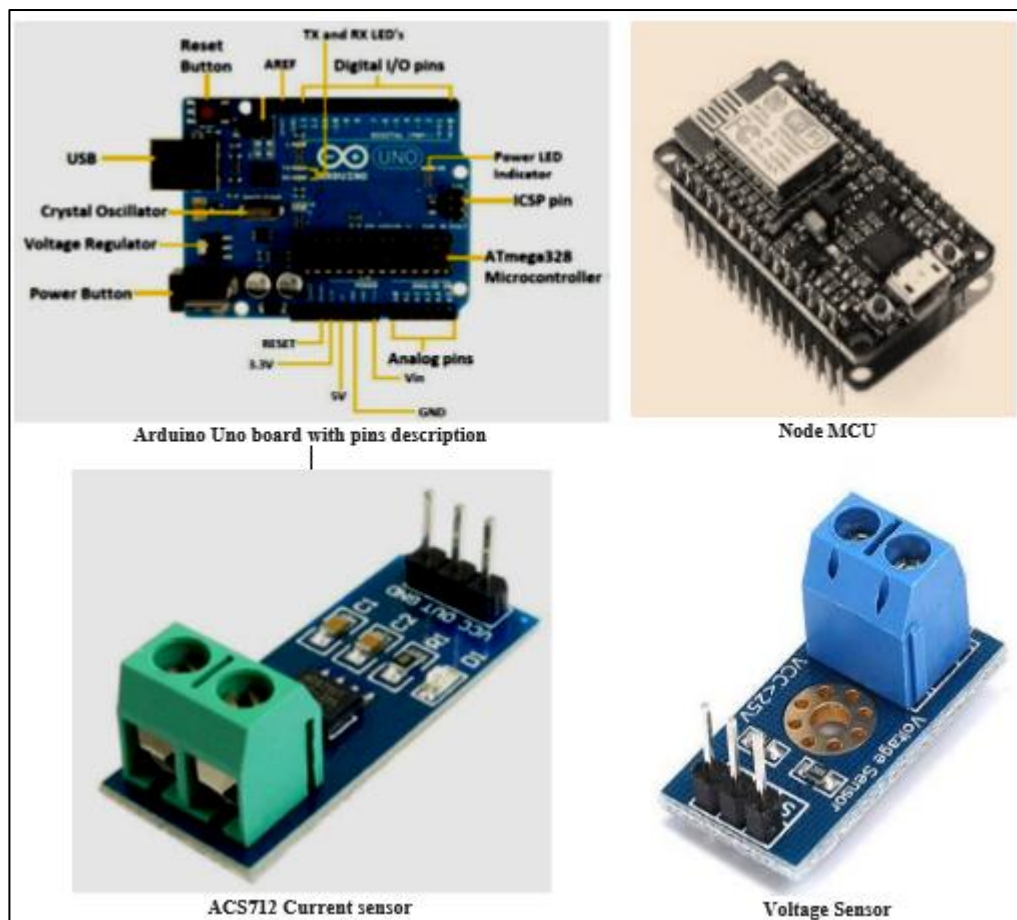


Figure 1: List of hardware components used in proposed work.

Source:Authors, (2026).

Figure 2 presents the block diagram of the proposed system. The system operation is initiated by turning ON the battery slide switch, which supplies power to the Arduino UNO, NodeMCU, and motor driver circuits. Under normal operating conditions, when the solar PV panel is clean, the LED remains in the ON state, and the voltage and current sensors continuously measure the electrical parameters of the panel. The sensed data are processed by the Arduino UNO and transmitted to NodeMCU, which uploads information to a cloud server, enabling real-time monitoring of the solar PV panel's voltage and current. Table 1 lists the specifications of the various components used in the proposed system design [21], [22]. When dust accumulation occurs on the solar PV panel, a reduction in voltage and current is detected and the LED turns OFF. In response, the Arduino UNO generates a control signal to activate the robotic cleaning mechanism. The robot is then automatically engaged to clean the solar PV panel. During this operation, a "Cleaning" status message is displayed on the cloud server, followed by a "Cleaned Successfully" message upon completion of the cleaning process. The cloud server continuously monitors system parameters, including voltage, current, and cleaning status. The proposed architecture integrates sensing, actuation, communication, and power management modules in an IoT-enabled embedded framework. Motor driver circuits ensure reliable control of the cleaning motor and auxiliary motors, while an IP camera provides visual monitoring of the solar panel and robotic operation. Overall, the system demonstrates a scalable and efficient solution for automated solar PV panel maintenance with real-time monitoring and remote supervision capabilities.

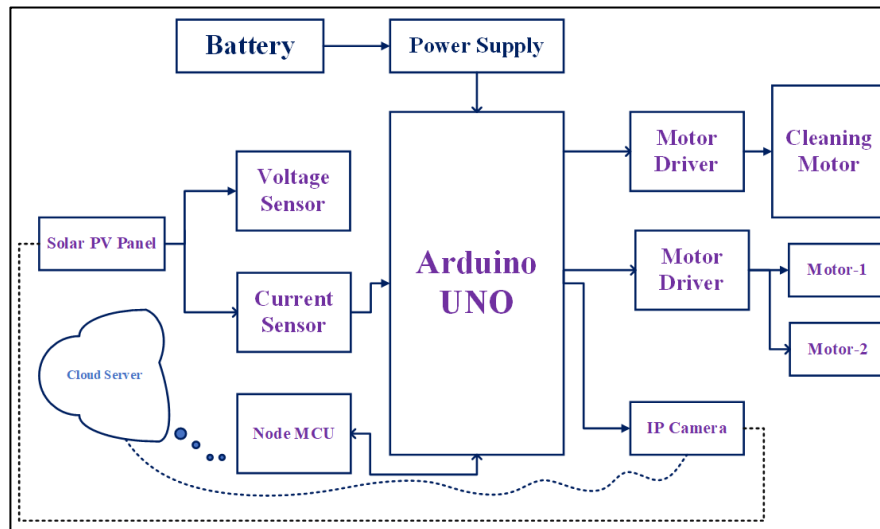


Figure 2: Block Diagram of proposed design model.

Source: Authors, (2026).

Table 1: The specifications of the various components used in the proposed system model.

Components	Specifications	Components	Specifications
Voltage Sensor	Input Voltage: 0-25 V	Node MCU	Operating Voltage: 4.5V-9V, typically 5V
	Voltage Detection: 0.02445 V-25 V		Flash Size: 4MB
	Analog Voltage Resolution: 0.00489 V		Transfer Rate: 110-460800 bps
ACS712 Current Sensor	Input Voltage: 4.5 V-5.5 V DC	Motor Driver	Working Temperature: -40 to +125 degree Celsius
	Measure current Range: 20 A		Driver Model: L29D Motor Driver
	Sensitivity: 100 mV/A		Operating voltage: 4.5 V-12 V
Solar Panel	Type: Polycrystalline	DC Motor	Maximum Supply Current: 600 mA per motor
	Maximum Power Output: 5Watt		Peak Current: 0.6 A
			Motor type: Permanent Magnet Dc Motor (PMDc)
Arduino Uno Board	Operating Voltage: 5V	Wi-Fi Smart Net Camera	Operating Voltage: 12V
	Input Voltage (Recommended): 7-12V		Rated Speed: 200 RPM
	Input Voltage (Limit): 6 V-20 V		Load Current: 0.3 A
	Microcontroller: ATmega328P	360-degree rotation CCTV Camera	12 LED IR Night Vision
	Flash Memory: 32KB (ATmega 328P of which 0.5KB used by bootloader)		1080P resolution video recording
	SRAM: 2KB		
	EEPROM: 1KB		
	DC Current per I/O Pin: 20mA		
	DC Current for 3.3V Pin: 50mA		

Source: Authors, (2026).

III. EXPERIMENTAL RESULTS AND DISCUSSION

To work with the proposed designed system, a code has been written in Arduino and NodeMCU software, as shown in Table 2. After writing the codes for Arduino UNO and NodeMCU, install the ESP8266WIFI library and save the codes. Connect the Arduino board and Node MCU to the laptop or computer using the USB and Micro USB cables, respectively. The USB cable has two connectors: a type-A connector on one end and a type-B connector on the other. Connect the Arduino UNO to the USB type-A connector, and link the USB type-B connector to the power source or programming device, such as a computer or laptop. The next step is to compile the code and then upload the code. While uploading the code for Node MCU, remove the RX pin and then upload the code by selecting the board and port to which the Arduino and Node MCU are connected at tools. Now, turn on the battery slide switch. The Arduino, Node MCU, and motor driver receive the power when the dust accumulates on the solar panel, as shown in Figure 3. The Connections for the proposed model are given as:

- Battery red terminal and black terminal are given as input to the power supply board.
- One pin of the 9V/12V output pin of the power supply board is connected to the Vin pin of the nodemcu, and another pin is connected to the ground.
- Another set of 9V/12V output pins is connected to the Arduino board's Vin and GND pins.
- One set of 5V pins of the power supply board is connected as input pins of the motor driver.
- A0 pin of the Arduino uno board is connected to the signal pin of the voltage sensor. 5V pin of the Arduino uno board is connected to the positive pin of the voltage sensor. GND pin of the Arduino uno board is connected to negative pin of the voltage sensor.
- The Arduino Uno board's A2 pin is connected to the current sensor's output pin. The current sensor's VCC pin is connected to another 5V pin of the Arduino board, and the current sensor's GND pin is connected to the Arduino board's GND pin.

- 2 Wires are connected to the solar panel. One wire i.e., positive wire is connected to the VCC pin of the Voltage Sensor, Positive pin of the current sensor and to the LED
- Another Wire from the solar panel is connected to the GND pin of the voltage sensor, current sensor, and LED
- TX, RX pins of the arduino uno board are connected to TX, RX pin of the nodemcu.
- D1, D2, D3, D4, D5, and D6 pins of the nodemcu are connected to the motor driver.

Table 2: Arduino and Nodemcu code used in the proposed system model.

ARDUINO CODE:	NODEMCU CODE:	NODEMCU CODE:
<pre>const int sensorPin=A0; //Analog input pin for the voltage sensor float voltage; float voltage2; float r1=30000.0; float r2=7500.0; float vin=0; const int currentPin=A2; int sensitivity=66; int offsetVoltage=2500; double advoltage=0; double currentValue=0; void setup() { Serial.begin(115200); // Initialize Serial Communication } void loop() { int sensorValue = analogRead(sensorPin); // Read the analog voltage from the sensor voltage = sensorValue * (5.0 / 1023.0); // Convert the analog value to voltage (assuming a 5V reference voltage) vin= voltage /(r2/(r1+r2)); delay(1000); // Wait for a second adcValue = analogRead(currentPin); adcVoltage = (adcValue / 1024.0) * 5200; currentValue = ((adcVoltage - offsetVoltage) / sensitivity); delay(2500); String solarvalues= "a" + String(vin) + "b" + String(currentValue)+"c" ; Serial.println(solarvalues); }</pre>	<pre>#include<AdafruitIO_WiFi.h> #include<ESP8266WiFi.h> // Replace with your own Wi-Fi and Adafruit IO credentials #define WIFI_SSID "Goud" #define WIFI_PASS "supraja.26" #define AIO_USERNAME "Supraja_Goud" #define AIO_KEY "aio_Dwix706HNCG9zEITB5ehfL7DMwUp" #include <AdafruitIO.h> AdafruitIO_WiFi io(AIO_USERNAME, AIO_KEY, WIFI_SSID, WIFI_PASS); // Your WiFi credentials. // Set password to "" for open networks. char ssid[] = "Goud"; char pass[] = "supraja.26"; String sub2; String sub; String dataa="cleaned successfully"; int Motor1 = D1; int Motor2 = D2; int Motor3 = D3; int Motor4 = D4; int Motor5 = D5; int Motor6 = D6; int Ampere = 0; int val1 = 0; int val2 = 0; int val3 = 0; int val4 = 0; AdafruitIO_Feed *temp = io.feed("amphere"); AdafruitIO_Feed *hum = io.feed("voltage"); AdafruitIO_Feed *reading = io.feed("date"); void setup() { // Debug console Serial.begin(115200); // Blynk.begin(BLYNK_AUTH_TOKEN, ssid, pass); pinMode(Motor1, OUTPUT); pinMode(Motor2, OUTPUT); pinMode(Motor3, OUTPUT); pinMode(Motor4, OUTPUT); pinMode(Motor5, OUTPUT); pinMode(Motor6, OUTPUT); pinMode(14, OUTPUT); io.connect(); while(io.status() < AIO_CONNECTED) { Serial.print("."); delay(500); } } void loop() { if (Serial.available() > 0) { //wait for data available String solareadings = Serial.readString(); //Serial.println("Enter your data:");</pre>	<pre>Serial.println(solareadings); val1 = solareadings.indexOf('a'); val2 = solareadings.indexOf('b'); String sub2 = solareadings.substring(val1 + 1, val2); Serial.println(sub2); val3 = solareadings.indexOf('b'); val4 = solareadings.indexOf('c'); String sub = solareadings.substring(val3 + 1, val4); Serial.println(sub); //Blynk.virtualWrite(V0, sub2); //Blynk.virtualWrite(V1, sub); if (sub2 < "2") { dataa="cleaning"; Serial.println("Sensorvalue"); digitalWrite(Motor1, HIGH); digitalWrite(Motor2, LOW); digitalWrite(Motor3, HIGH); digitalWrite(Motor4, LOW); delay(1500); digitalWrite(Motor1, LOW); digitalWrite(Motor2, LOW); digitalWrite(Motor3, LOW); digitalWrite(Motor4, LOW); delay(7000); digitalWrite(Motor5, HIGH); digitalWrite(Motor6, LOW); delay(500); digitalWrite(Motor5, LOW); digitalWrite(Motor6, HIGH); delay(500); digitalWrite(Motor5, LOW); digitalWrite(Motor6, LOW); delay(1000); digitalWrite(Motor1, LOW); digitalWrite(Motor2, HIGH); digitalWrite(Motor3, LOW); digitalWrite(Motor4, HIGH); delay(1500); digitalWrite(Motor1, LOW); digitalWrite(Motor2, LOW); digitalWrite(Motor3, LOW); digitalWrite(Motor4, LOW); delay(7000); } else { dataa="cleaned successfully"; } temp->save(sub); hum->save(sub2); reading->save(dataa); }</pre>

Source: Authors, (2026).

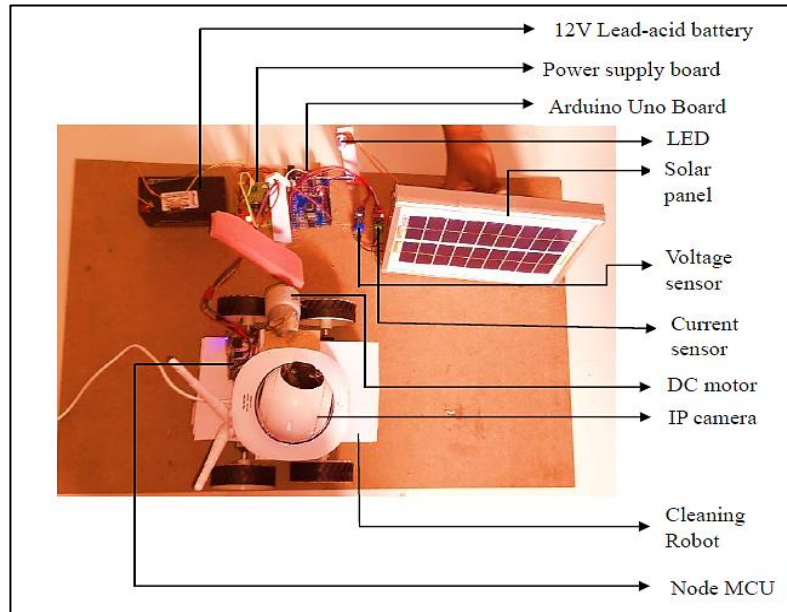


Figure 3: Experimental setup of robot cleaning the Solar panel.

Source: Authors, (2026).

To monitor the values of voltage and current, create an account in Adafruit software. It is open-source software. When the robot is cleaning the panel the values of current, voltage and message cleaning are uploaded in the Adafruit software as shown in Figure 4(a) and 4(b).



Figure 4: (a) The values of Voltage and Current before Cleaning (b) The values of Voltage and Current after Cleaning.

Source: Authors, (2026).

After completing the cleaning process, the voltage and current values increase, and a message is displayed as shown in Figure 4 b. The data is collected and tabulated in Table 3 at different timings in a day; from this, it can be concluded that solar radiation increases the output of the solar PV panel. A mobile application named V380 Pro will be downloaded from the Play Store on mobile to set the camera position and perform the visual inspections on the solar panel. To set up a V380 Wi-Fi Camera on an Android Phone.

Table 3: Obtained results data of solar PV panel before cleaning and after cleaning for the proposed system.

Time	Before Cleaning		After Cleaning	
	Current (Amp)	Voltage (V)	Current (Amp)	Voltage (V)
8:00 AM	0.21	0.46	2.52	1.12
9:00 AM	2.21	0.81	2.59	1.47
10:00 AM	2.62	0.49	2.75	1.64
11:00 AM	2.30	1.52	2.88	1.82
12:00 PM	1.75	1.80	1.82	2.47
1:00 PM	1.90	2.45	2.05	2.55
2:00 PM	1.94	2.50	2.24	2.67
3:00 PM	2.15	2.63	2.41	2.79
4:00 PM	2.30	2.77	2.63	2.98

Source: Authors, (2026).

IV. CONCLUSIONS

In this proposed work, a functional robot for cleaning solar panels has been developed. It draws attention to how the efficiency of solar PV systems is impacted by dust, filth, pollen, sea salt, and bird droppings. The performance and efficiency of the solar panels power output are significantly impacted by dust and moisture contain particles. Due to this peak power generation by PV panel can be reduced by 10% to 30%. Dust deposition on the panels were shown to cause a power generation decrease, a robotic cleaning technique can fix this issue. This technique can enhances the solar panels ability to generate more power. Some advantages of this approach are low cost, easy maintenance, and reduced power use. Furthermore, this cleaning technique can overcome the decrease in peak power generation.

V. AUTHOR'S CONTRIBUTION

Conceptualization: N Chinna Alluraiah, Pujari Harish Kumar, Reshma Gopi and K Harinath Reddy.

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Investigation: N Chinna Alluraiah, Pujari Harish Kumar.

Discussion of results: N Chinna Alluraiah, Pujari Harish Kumar, Swetha Shekarappa G.

Writing – Original Draft: Pujari Harish Kumar.

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Resources: Pujari Harish Kumar.

Supervision: N Chinna Alluraiah and Swetha Shekarappa G.

Approval of the final text: N Chinna Alluraiah, Pujari Harish Kumar.

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