Self-Sustaining Solar Panel Cleaning Solution with Integrated IoT Monitoring

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Abstract

Deposition of dust on photovoltaic panels significantly reduces their power output efficiency, posing a major hindrance to optimal solar energy generation. In this article, the development of a self-sustaining solar panel cleaning system with an inbuilt Internet of Things (IoT) platform for real-time monitoring and control is reported. The system design suggested herein combines a wiper mechanism and a centrifugal air blower powered by a monocrystalline solar panel for effective removal of dust and debris. The cleaning cycle is made automatic using a dust sensor and real-time clock (RTC) module with an override facility through the Blynk IoT interface. Environmental and electrical parameters such as dust density, panel output voltage, current, and power are also monitored by the system. Results indicated a considerable power output increase after cleaning operations, validating the effectiveness and feasibility of the system as a cost-effective, environmentally friendly means of domestic solar panel cleaning.

1. Introduction

Solar power has become one of the world's largest components of renewable energy, offering a clean and sustainable alternative to fossil fuels. The rising energy demand and reducing cost of solar panels mean that PV systems are becoming more widely applied around the world as they have low emissions and are green [1]. Solar panel efficiency is nonetheless influenced by a variety of environmental parameters such as temperature, humidity, wind, and solar irradiance. High temperatures reduce panel efficiency, moderate temperatures and wind speed enhance it. Cloud cover artificially lowers output for a short while but helps clean the panels naturally [2][3].

Non-climatological conditions, such as dust, bird droppings, and organic waste, also affect solar panel performance by blocking sunlight and causing thermal stress. Studies have shown that single dust deposit can reduce energy yield by up to 30%, with repeated abandonment leading to permanent damage [4][5]. Studies in Malaysia have shown significant energy loss due to dust deposits but frequent cleaning effectively restoring efficiency, showing the imperative of regular maintenance [6].

Manual cleaning methods are time-consuming, costly, and impractical for distant or widespread locations. As a result, automated cleaning technology such as robots, water jets, and air blowers have gained attention [7][8][9]. Among them, the combination of wipers with air blowers is an appealing choice, that gives efficient dust removal without water usage—a strong point in water-scarce regions. This method represents solar panel efficiency with minimal human intervention and has been shown to increase power output significantly [8][9].

2. Methodology

In Fig. 1, the system consists of several important components such as an ESP32 microcontroller, GP2Y1010AU0F dust sensor, DS3231 RTC module, DC geared motors, 12V air pump, monocrystalline solar panel, and lead-acid battery. A rubber wiper and centrifugal air blower mounted on a mobile platform constitute the cleaning mechanism. The ESP32 controls the motor direction and timing, sensor inputs, and transmission of data to the Blynk IoT platform via Wi-Fi.

In Fig.2 indicates the process of the proposed system. Cleaning is triggered in one of three ways: at set times according to the RTC, when dust density is higher than a setpoint, or manually through the Blynk interface. Voltage, current, and power readings are measured using an INA219 sensor and sent to the IoT dashboard to be monitored in real time. The system is realized on a testbed that includes a fixed solar panel frame and tested with varying dust conditions.
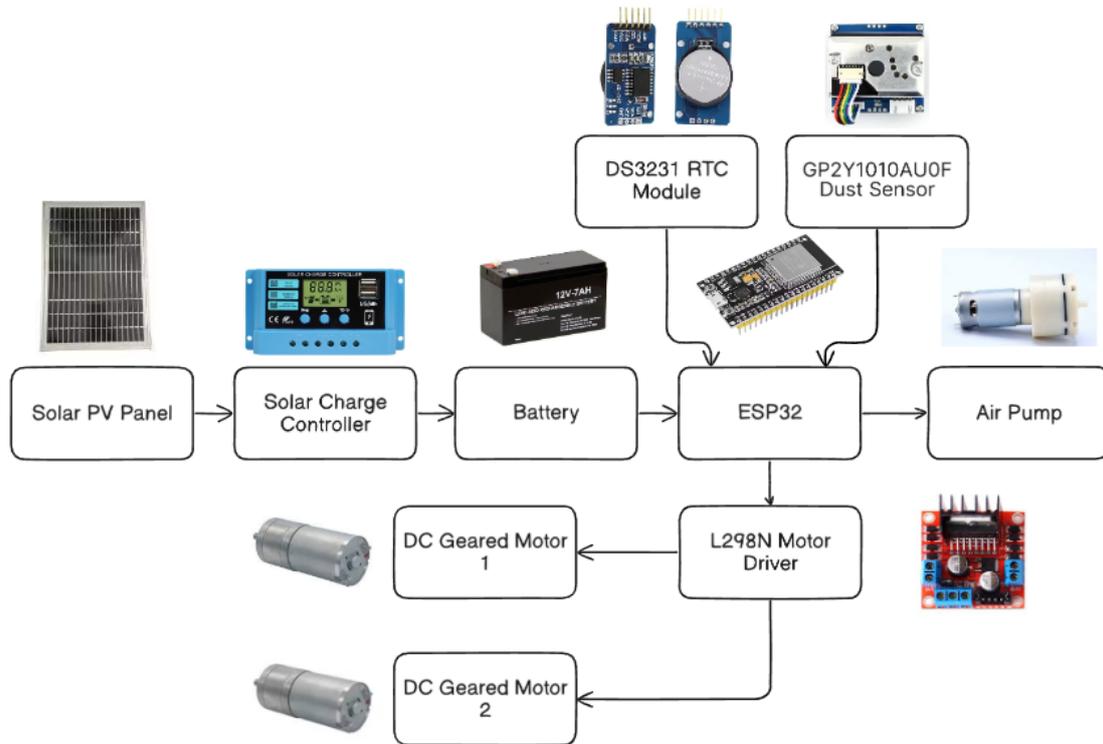

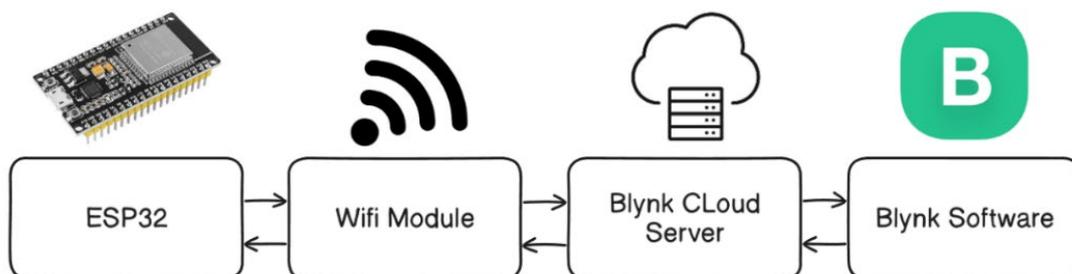**Fig. 1** *Block diagram of the automated cleaning system*

Fig. 2 *Block diagram of the monitoring system*

From Fig. 3, the system developed operates in a loop starting with the initialization of the ESP32 microcontroller, DS3231 RTC module, and GP2Y1010AU0F dust sensor. Once initialized, the system enters a monitoring state where it constantly measures deposited dust and power supplied. The data is then transmitted to the Blynk IoT platform for remote real-time monitoring, such as solar panel cleanliness and system performance, via a web or mobile interface.

According to Fig. 3, the system requires three conditions to start cleaning, in which the scheduled time specified by the RTC, a level of dust higher than a certain value of the sensor, manual trigger from physical push button or remote trigger from Blynk. When cleaning is initiated, the system starts both air pump and motor-operated wiper to clean the panel surface. After cleaning, it logs vital details such as cleaning time and dust state, which are sent to the Blynk server for monitoring purposes. Meanwhile, the system also recharges the battery from solar panel if the need arises or returns to standby mode for continued monitoring until the next cycle.
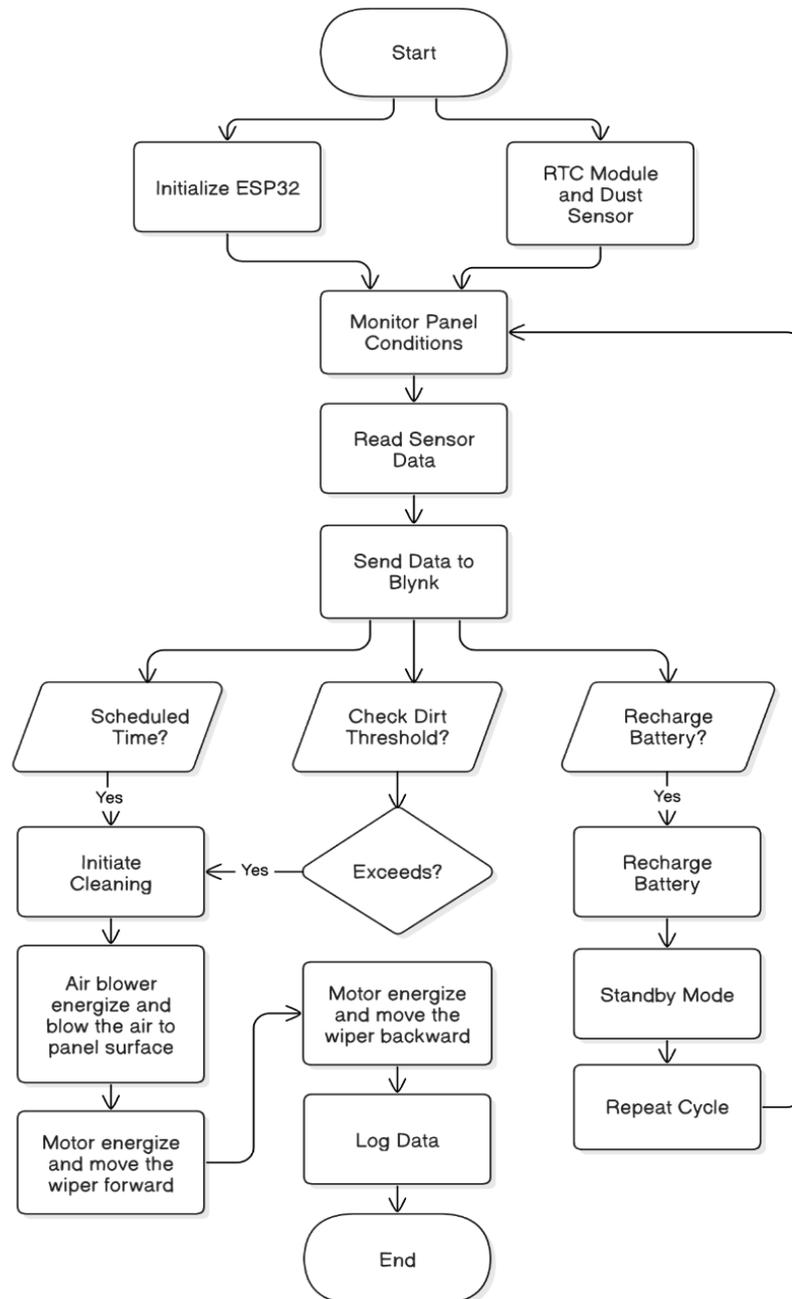

Fig. 3 *Flowchart of the proposed system*

2.1 Hardware Implementation

The schematic diagram of whole proposed system's arrangement and connection is shown in Fig. 3, meanwhile Fig. 4 depicts the completed implementation of hardware base design. Based on Fig.3, the core of the system is an ESP32 microcontroller that manages all sensors, actuator, and source communication. The primary energy source is a 40W monocrystalline solar panel, which is linked to a solar charge controller that manages battery charging and overcharge or deep discharge. Backup power to ensure consistent operation when the amount of sunlight is low is given by a 12V lead-acid battery.

ESP32 is supplied with regulated power from the solar charge controller and talks to significant peripheral devices. They include the DS3231 RTC for scheduling of timely cleaning work and GP2Y1010AU0F dust sensor, whose function is to detect surface dust accumulation. ESP32 invokes cleaning based on sensor readings or according to scheduled timing.

The cleaning process is driven by two DC geared motors controlled by a motor driver module. The motors power a mechanical wiper that sweeps the panel surface. A 12V air pump further assists in the removal of loose dust. ESP32 also offers Wi-Fi-based communication and transmits real-time data to the Blynk IoT platform for remote control and monitoring. This configuration of the integrated circuit ensures stable power supply to all the devices and enables automated and remotely controlled solar panel cleaning. Fig. 5 shows a complete prototype of project.
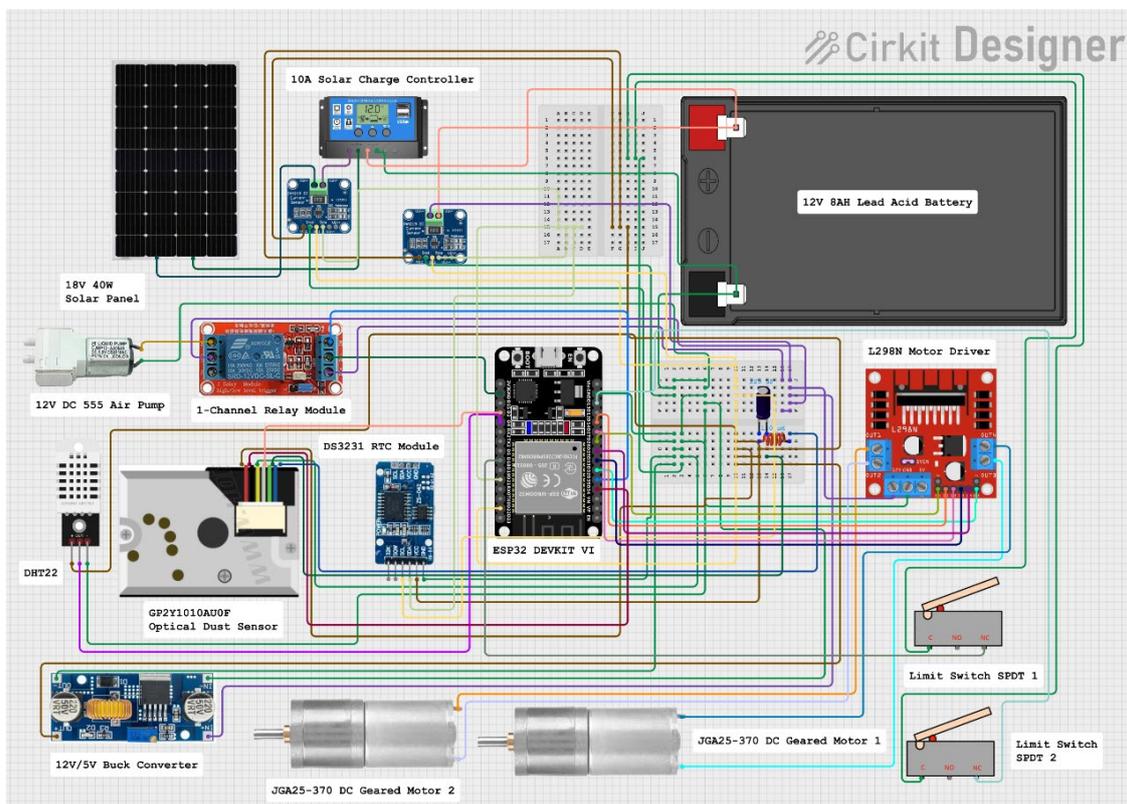

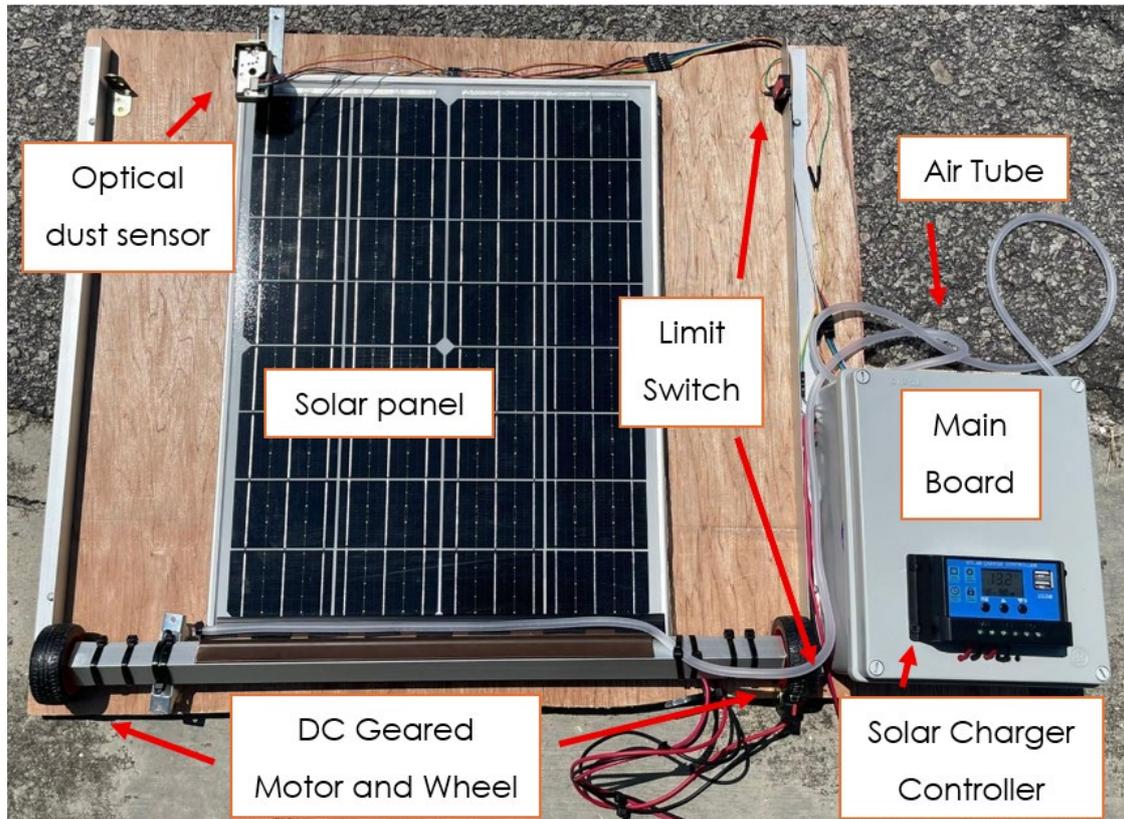**Fig. 4** *Schematic diagram of the proposed system*

Fig. 5 *Complete protyotype of project*

3. Results and Discussion

3.1 Sensor Readings and Analysis

The system was tested using GY-INA219 modules to record voltage and current on both input and output terminals of the solar panel. Both input and output power calculations are as in Eq. (1) and (2). The measurements were used to calculate power values both pre-clean and post-clean to enable assessment of the performance of the cleaning mechanism. Five readings were taken daily from 10:00 AM to 2:00 PM to capture changes under varying solar irradiance levels. Fig.6, Fig.7 and Fig. 8 illustrate the experimental setup of automated solar panel cleaning system; before, during and after respectively.

Before cleaning, the output power from the panel was consistently lower due to dust accumulation as shown in Table 1. Voltage was very stable once the automatic cleaning process was started, but current and power output were improved visibly as in shown in Table 2. This showed that wiper and blower mechanism cleaned dust efficiently and allowed better light absorption and energy conversion.

From Table 3, the efficiency of cleaning was determined as percentage increase in power output after the cleaning process by using Eq. (3). Results indicated maximum efficiency in the early morning when dust had a greater effect on solar performance. Towards the noonday and with an increase in sunlight intensity, the impact of cleaning started to diminish. This is in accordance with solar performance in tropical climates, where solar irradiance is highest at midday.

Overall, the data concurred that the proposed cleaning system significantly improved power output during low irradiance periods and guaranteed consistent panel performance during the day. The results validate the effectiveness of employing mechanical wipers and an air blower in automated, dry solar panel cleaning using Equation (1), (2) and (3).

$$Pin = Vin \times Iin \tag{1}$$

$$Pout = Vout \times Iout \tag{2}$$

$$\eta = \left(\frac{Pout(after\ cleaning) - Pout(before\ cleaning)}{Pout(before\ cleaning)} \right) \times 100\% \tag{3}$$

Table 1 *Readings of voltage, current and power before cleaning*

No.	Time	Voltage (V)	Current (A)	Formula Used	Power (W)
1	10:00 AM	13.25	1.00	13.25 × 1.00	13.25
2	11:00 AM	13.32	1.03	13.32 × 1.03	13.72
3	12:00 PM	13.47	1.08	13.47 × 1.08	14.55
4	1:00 PM	13.43	1.07	13.43 × 1.07	14.37
5	2:00 AM	13.21	1.05	13.21 × 1.05	13.87

Table 2 *Readings of voltage, current and power after cleaning*

No.	Time	Voltage (V)	Current (A)	Formula Used	Power (W)
1	10:00 AM	13.35	1.09	13.35 × 1.09	14.55
2	11:00 AM	13.38	1.10	13.38 × 1.10	14.72
3	12:00 PM	13.49	1.14	13.49 × 1.14	15.37
4	1:00 PM	13.45	1.12	13.45 × 1.12	15.06
5	2:00 AM	13.25	1.08	13.25 × 1.08	14.31

Table 3 *Cleaning efficiency of proposed system*

No.	Time	Power Before Cleaning, Pout (W)	Power After Cleaning, Pout (W)	Efficiency, η (%)
1	10:00 AM	13.25	14.55	9.81
2	11:00 AM	13.72	14.72	7.29
3	12:00 PM	14.55	15.37	5.64
4	1:00 PM	14.37	15.06	4.80
5	2:00 AM	13.87	14.31	3.17

Fig. 6 *Solar panel condition before cleaning*

Fig. 7 *Solar panel condition during cleaning*

Fig. 8 *Solar panel condition after cleaning*

3.2 IoT Interface and Monitoring

All the critical performance metrics such as voltage, current, power, temperature, efficiency, and dust level were sent to the Blynk platform via virtual pins successfully. The user interface as shown in Fig. 9 provided features such as a cleaning button and real-time plots of data with historical logs. The operations carried out in cleaning were timestamped through the DS3231 RTC and sent to Blynk for remote monitoring. This remote access capability allows users to control and monitor the system without on-site interaction, promoting ease and system monitoring.
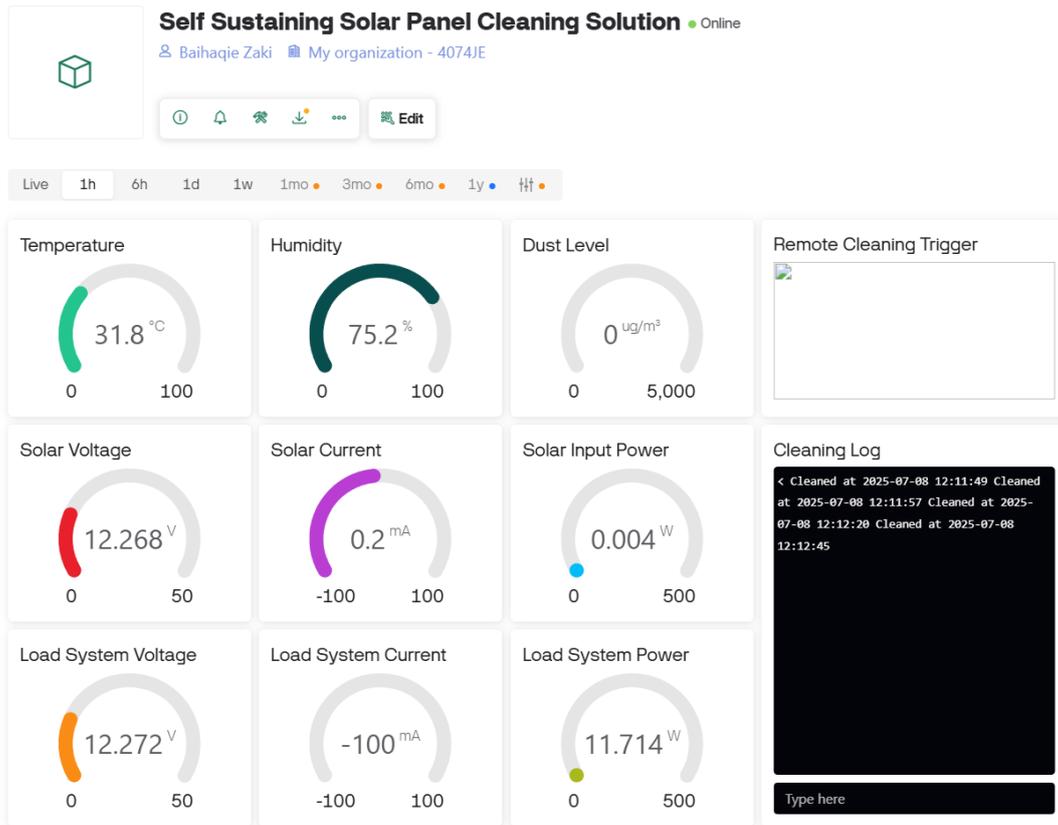
Fig. 9 *Schematic diagram of the proposed system*

3.3 Key Function of Cleaning System Control Logic

The main control logic of the solar panel cleaning system provides both automatic and manual cleaning modes. The system accepts input from environmental sensor data, cleaning schedule time, and user input via the Blynk IoT platform.

3.1.1 Blynk Remote Trigger and User Control

From Fig. 10, the remote control of the cleaning system is facilitated by the application of the Blynk IoT platform. Users can manually start cleaning through a virtual button assigned to pin V9 from the app interface. Clicking it triggers a signal that goes to the ESP32 microcontroller, which checks system status to avoid duplicate operation. If the system is idle, the cleaning cycle is initiated. This functionality allows users to control the system remotely wherever there is internet connectivity, which is convenient and accessible, especially for remote or unmanned solar installations.

```
114   // === Remote clean trigger from Blynk ===
115   BLYNK_WRITE(V9) {
116     int cleanTrigger = param.asInt();
117     if (cleanTrigger == 1 && !isRunning) {
118       startCleaning();
119     }
120   }
```

Fig. 10 *Code section of Blynk remote trigger function*

3.1.2 Dust Sensor-Based Auto Cleaning Trigger

From Fig. 11, the system incorporates a GP2Y1010AU0F dust sensor that is utilized to sense particulate density on the panel. The sensor provides analog readings that are converted to dust density in $\mu g/m^3$. If the sensed value is greater than a predetermined value ($150 \, \mu g/m^3$), ESP32 will automatically trigger the cleaning procedure. This

autonomous aspect allows the system to adapt to the outside environment without the need for input from the operator, and thus it is smart and adaptable. It ensures maximum panel performance is maintained by triggering cleaning just in time when required because of dust accumulation.

```
195     // === Dust Sensor ===
196     int dustRaw = 0;
197     float dustVoltage = 0;
198     float dustDensity = 0;
199
200     digitalWrite(LED_PIN, LOW);
201     delayMicroseconds(280);
202     dustRaw = analogRead(DUST_SENSOR_PIN);
203     delayMicroseconds(40);
204     digitalWrite(LED_PIN, HIGH);
205     delayMicroseconds(9680);
206
207     dustVoltage = dustRaw * (3.3 / 4095.0);
208     dustDensity = (dustVoltage - 0.9) * 1000.0 / 0.5;
209     if (dustDensity < 0) dustDensity = 0;
210
211     Serial.print("Dust: "); Serial.print(dustDensity); Serial.println(" µg/m³");
212     Blynk.virtualWrite(V2, dustDensity);
213
214     const float DUST_THRESHOLD = 150.0;
215     if (dustDensity >= DUST_THRESHOLD && !isRunning) {
216       Serial.println("📛 Dust level high! Triggering cleaning...");
217       startCleaning();
218       }
219  }
220
```

Fig. 11 *Code section of dust sensor trigger function*

3.3.2 Schedule-Based Cleaning Trigger

From Fig.12, the system employs the DS3231 RTC module for timed cleaning based on time periods. It compares the present time with the previous cleaning time, and it will start a new cleaning process if a predetermined time duration (three minutes for testing) is passed and the system is in idle state. This offers regular maintenance, even in low dust conditions, which helps remove sticky deposits or dampness.

```
221     DateTime now = rtc.now();
222
223     // === Auto clean every 3 minutes ===
224     if (!isRunning && (now.unixtime() - lastCleanTime.unixtime() >= CLEAN_INTERVAL_SECONDS)) {
225       startCleaning();
226     }
```

Fig. 12 *Code section scheduled cleaning logic trigger function*

4. Conclusion

The developed self-cleaning solar panel system with IoT integration effectively maintains solar panels clean, thereby maximizing energy output and system efficiency. The project demonstrates a low-maintenance and scalable home solar installation solution. The system can potentially be further optimized with AI-based decision algorithms, water-spray hybrid capabilities, or used in large solar farms.

The test analysis indicated a clear improvement in power output after cleaning, validating the mechanism's effectiveness. The integration with IoT guaranteed reliable real-time monitoring and user control. Overall, the system offers an efficient and effective means of maintaining solar panel efficiency, especially in household or rural environments. Future development can involve better cleaning techniques and predictive automation using weather information.

Acknowledgement

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Ahmad Baihaqie Yusoff Zaki, Mohammad Faiz Liew Abdullah; **data collection:** Ahmad Baihaqie Yusoff Zaki; **analysis and interpretation of results:** Ahmad Baihaqie Yusoff Zaki, Mohammad Faiz Liew Abdullah; **draft manuscript preparation:** Ahmad Baihaqie Yusoff Zaki, Mohammad Faiz Liew Abdullah. All authors reviewed the results and approved the final version of the manuscript.*

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