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Smart Solar Photovoltaic Panel Dust Monitoring System using Internet of Thing (IoT)

Siti Nur Afifah Mohd Suhaimi[1], Mohd Nasri Jasmie[1], Nor Aira Zambri[1,*], Omar Abu Hassan[1], Farahiyah Mustafa[1], Sim Sy Yi[2], Norhafiz Salim[3]

[1] Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussien Onn Malaysia, UTHM Kampus Pagoh, Hab Pendidikan Tinggi Pagoh, KM 1, Jalan Panchor, 84600 Panchor, Johor, Malaysia
[2] Department of Electrical Power Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Batu Pahat, Malaysia
[3] Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Jalan Hang Tuah Jaya,Durian Tunggal, Melaka, 76100, Malaysia

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ABSTRACT

Photovoltaic technology has become one of the most popular ways of generating power from renewable energy sources. Solar panels are solely responsible for generating the maximum amount of electricity. One of the issues that needs to be addressed is the lack of equipment or systematic monitoring of solar panels. Due to their surfaces being covered with dust and not being cleaned for extended periods, solar panels can become damaged and unable to generate electricity. This project investigates the factors of dust that impact photovoltaic module performance and designs an intelligent monitoring system. The project aims to develop a monitoring system that allows users to use their smartphones to monitor the cleanliness of solar panels. This monitoring kit includes a dust sensor component as data input and a NodeMCU ESP32 microcontroller that receives, processes and sends data to the Blynk application. The project enables owners to monitor their solar panels in real-time. The power output decreases to 3.8W, exhibiting an efficiency of 2.41%. This signifies a reduction to less than half of its initial efficiency at 6.16%. This suggests that the solar panel may be dirty, significantly, when the output power dips below the threshold value of 4.85W, corresponding to an efficiency of 3.07%. Experimental findings support the necessity of cleaning the solar panel surface when the output power drops below 50%, specifically at 4.85W. The benefits of this project are that solar panel maintenance will be more systematic, ensuring solar panels can generate the maximum electricity and are not easily damaged, thus increasing the lifespan of solar panels.

1. Introduction

Nowadays, the electricity demand is growing daily due to technological advances and the increasing global population. Burning fossil fuels to meet these needs produces large amounts of CO_2, likely contributing to global warming and climate change [1]. In response to these environmental

* *Corresponding author.*
E-mail address: aira@uthm.edu.my

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concerns, many nations are turning to renewable energy sources, particularly solar energy, which is clean, abundant, and environmentally friendly. Solar photovoltaic (PV) modules function to generate electricity, and people are increasingly recognizing the importance of using photovoltaic solar systems [2]. Malaysia intends to increase the proportion of renewable energy (RE) in its installed capacity to 31% in 2025 and 40% in 2035 [3]. This project aims to monitor solar panels to keep them clean, as panel cleanliness is crucial for efficient electricity generation. The extent to which electrical energy efficiency can be achieved depends on the cleanliness of the panel surface and other related factors. A clean panel can generate much more electrical power. The monitoring process on the surface of the solar panel allows the owner to monitor its cleanliness.

Among the previous projects used as a reference for this project is the Smart IoT-based Solar Panel Cleaning System that monitors and controls the cleanliness of a solar photovoltaic panel [2]. This system includes components such as the GP2Y1010AU0F dust sensor, Arduino UNO, esp8266, wiper, and water pump. The system washes or flushes the solar panel every ten days or whenever the dust sensor detects a significant amount of dust on the panel's surface. The Blynk application is used to control this IoT system. Another system called 'Monitoring of Solar Panel Based on IoT' was created to ensure solar panels produce as much electricity as possible [4]. This system adjusts the solar panel's position as the sun's rays travel from one point to another, ensuring that the panel always faces the sun correctly and generates as much electricity as possible. The system from 'Design of Solar Panels Efficiency Monitoring System' allows the monitoring of voltage, current, humidity, and temperature of a solar photovoltaic system to be monitored systematically. Still, there is no function to detect the solar panel's cleaning state [5].

Furthermore, solar panels are often infrequently maintained and inspected, particularly in residential areas where they are typically installed on rooftops. Without proper and regular maintenance, various issues may arise. If the panels are neglected, their ability to generate power will degrade. The absence of tools or systematic monitoring for solar panels is one significant challenge that requires attention. Additionally, if the panel surfaces accumulate dust and remain uncleaned for an extended period, they can become damaged and lose their capacity to generate optimum power. The primary objectives of this research are to design and develop hardware monitoring for photovoltaic modules, create an IoT platform and mobile apps for monitoring these modules, and integrate both hardware and software monitoring to evaluate the system's performance.

2. Literature Review

2.1 Different Types of PV Panels

In general, this overview is conducted to assist in assessing the relative advantages and disadvantages of each option. It is crucial to evaluate the long-term cost-effectiveness of various PV cell technologies. This overview will focus on and discuss three types of PV cells: monocrystalline, polycrystalline, and thin-film cells. These photovoltaic (PV) panels come with varying efficiency levels. Efficiency refers to the percentage of sunlight a solar panel can convert into electricity. Monocrystalline panels are manufactured from a single crystal structure and are renowned for their high efficiency and sleek black appearance. They perform well under various lighting conditions, with efficiency ranging from 15% to 22%. Some high-end panels achieve even higher efficiency [6]. Additionally, monocrystalline PV panels have a lower environmental impact than others because they are made from abundant, natural silicon and will continue to generate electricity even when some parts of the panel are shaded. In contrast, polycrystalline panels may experience significant efficiency drops in such situations.

Polycrystalline panels, on the other hand, are made from multiple crystal structures and are generally less expensive than monocrystalline panels, with an efficiency range of 13% to 18% [7,8]. However, recent technological advancements have narrowed the efficiency gap between the two types. Finally, thin-film panels employ different semiconductor materials and are renowned for their flexibility, making them suitable for cost-effective applications where rigid panels are not ideal. Their efficiency ranges from 9% to 12% taken from the previous studies [9,10].

In summary, this study utilizes monocrystalline solar panels, chosen for their higher efficiency, space efficiency, durability, temperature performance, and superior performance in low-light conditions. These qualities make them a reliable and efficient choice for various solar energy applications.

2.2 PV Module Efficiency

The efficiency of solar cells is dependent on temperature. Solar cells perform better in cold environments compared to hot climates. While solar panels are rated at 25 degrees Celsius, their actual operating conditions can be significantly different. The exterior temperature can reach 70 to 72 degrees Celsius in the summer. This increased temperature compared to the rated temperature leads to higher losses, up to 25% [11]. It is crucial to position solar cells in a way that avoids any shadows falling on them. Even a tiny portion of shadow on a solar panel can have a significant impact on its power production [12]. Most solar panels have solar cells connected in series, meaning that shaded cells interrupt the current flow across the entire panel [9]. Lastly, dust collection is one of the most challenging issues in operating solar PV systems [13]. Over time, dust accumulation on PV modules leads to power loss. After five months, the power loss in the PV module increased by 12.7%, and the dust density increased by 5.44 g/m^2 [14].

2.3 Dust Accumulation

Dust accumulation is a critical factor leading to efficiency losses in solar photovoltaic (PV) systems, especially in tropical countries with high ambient temperatures and low-frequency rain. The combination of these environmental conditions in tropical regions like Malaysia creates an environment conducive to dust accumulation on the surface of solar panels. Dust particles can block and scatter incoming sunlight, reducing the amount of energy that can be converted into electricity by the PV cells. As a result, the efficiency of the solar power system decreases, leading to a decline in the overall energy output [15].

Dust accumulation on solar panels can reduce the amount of sunlight reaching the photovoltaic (PV) cells. When dust settles on the surface of the solar panels, it acts as a barrier, limiting the amount of light that can penetrate the PV cells. This reduction in light leads to a decrease in the PV current output, which directly affects the power generation capacity of the solar panel system [16,17].

In tropical regions where dust accumulation can be a persistent issue, proper monitoring of the solar power system's performance and timely maintenance become crucial to maximize energy production and overall system efficiency [18]. By addressing the challenges posed by dust accumulation, solar energy installations can continue to be a reliable and sustainable source of electricity in such regions. Rainfall patterns in tropical countries like Malaysia tend to be unpredictable and vary from year to year. Throughout the year, rainfall is abundant and frequent, with most regions receiving over 2,000 millimeters (79 inches) annually and rarely experiencing a month with less than 100 mm (4 inches) of rainfall [19]. However, there are occasional periods with comparatively lower rainfall, although these patterns may differ across different areas.

2.4 Design of a Solar Panels Efficiency Monitoring System

In previous related projects, various methods have been employed to monitor solar panel performance. Table 1 summarizes several projects that share processes similar to the proposed idea. The monitoring system holds significant importance in this project, specifically in tracking the cleanliness of the photovoltaic module, a detail that will be elaborated upon. Much like other projects, this initiative incorporates a dust sensor. However, it sets itself apart by utilizing NodeMCU as its microcontroller, in contrast to the Arduino used in previous projects. Notably, this project offers the advantage of increasing the number of dust sensors to enhance performance and reduce production costs compared to earlier initiatives.

Table 1
Summary of the previous research of the project

Literature	Pros	Cons
Rao *et al.,* [2]	This technology excels in both monitoring and cleaning solar panels.	The drawback of this method is its reliance on an Arduino microcontroller. To enable IoT functionality, an ESP8266 module must be added since Arduino lacks a built-in Wi-Fi module.
Saravanan and Lingeshwaran [4]	The system can adjust the solar panel's position in response to the sun's movement, maximizing solar exposure.	A drawback of this system is the absence of visual monitoring, preventing it from distinguishing between clean and dirty panels.
Lee *et al.,* [5]	This system systematically monitors a solar photovoltaic system's voltage, current, humidity, and temperature.	There is no function to detect the cleaning state of the solar panels.
N. R. E. Laboratory [20]	Proper maintenance enhances the efficiency and lifespan of a photovoltaic system, benefiting its overall performance.	There is currently no systematic monitoring in place. Instead, only regular maintenance is performed.
Songhao *et al.,* [21]	The benefit of this idea is that it can clean solar panels using purely mechanical technology, without requiring any electrical or electronic components.	In a large-scale solar photovoltaic system, the downside of this technology is its high manufacturing costs.

3. Methodology
3.1 System Design and Construction

A block diagram in Figure 1 represents the layout and structure of the system under consideration. The primary purpose of this solar system is to generate electricity, charge the battery, and subsequently deliver electricity from the battery to the DC load. The monitoring system is directly connected to the photovoltaic solar panels to track their cleanliness. A dust sensor detects dust on the solar panel's surface, while the ESP32 CAM provides real-time video of the solar panels. The sensor's output is then forwarded to the NodeMCU ESP32 for data collection.

The IoT system commences with the NodeMCU ESP32 and ESP32 CAM, which collect data and transmit it to a cloud server via Wi-Fi, making it accessible through a dedicated app. A NodeMCU and an ESP32 camera control the Smart Monitoring Dust Detecting System for Photovoltaic Modules. The suggested system is categorized into two components: Photovoltaic Module Dust Monitoring with the NodeMCU ESP32 microcontroller and Camera Monitoring with the ESP32 camera.

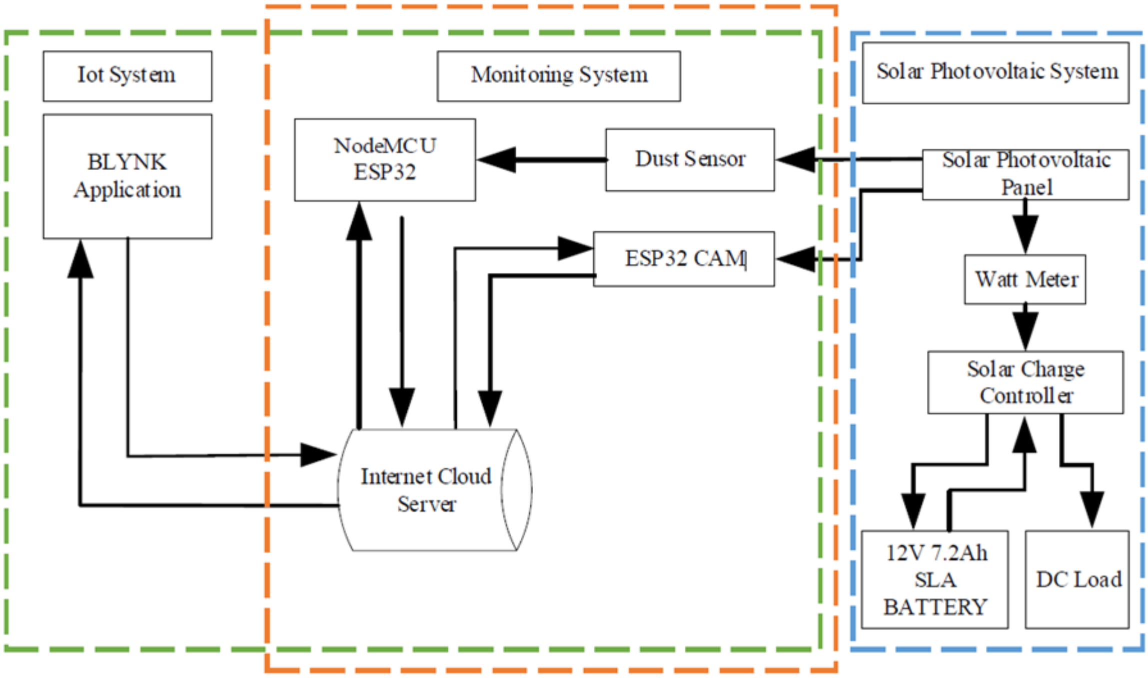

Fig. 1. The block diagram of the system

3.2 Flow Chart

The flow chart for the monitoring system and the monitoring camera are shown in Figure 2 and Figure 3, respectively. Figure 2 illustrates the system architecture for monitoring dust on photovoltaic modules. The dust sensor detects dust particles on the solar module, and the data is transmitted to a microcontroller (NodeMCU ESP32). The microcontroller then sends the dust density data to the Blynk application for display. When the Blynk app runs, the dust density value is compared to the preset dust density level, and the dust status is shown accordingly. These results indicate whether the PV module is clean, dusty, or dirty. Figure 3 explains the process flow of the ESP32 monitoring camera. The ESP32 CAM initially captures live video from the photovoltaic module and sends this video as live data to the Blynk application. The live video is directly displayed on a smartphone until the user turns it off using the Blynk interface.

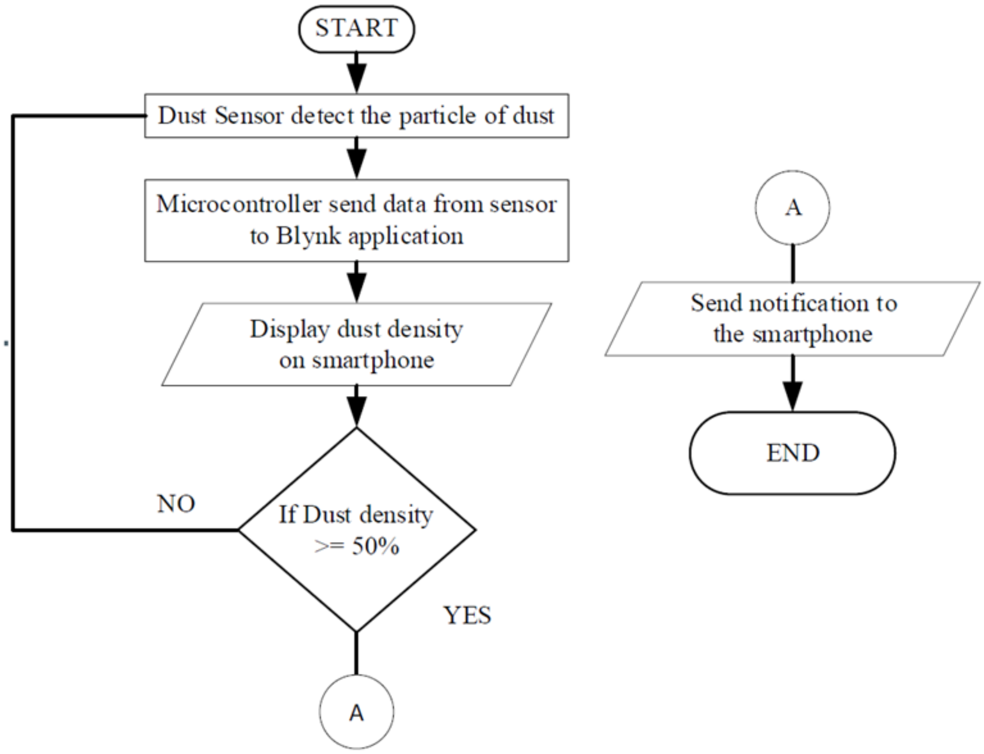

Fig. 2. Monitoring system flowchart

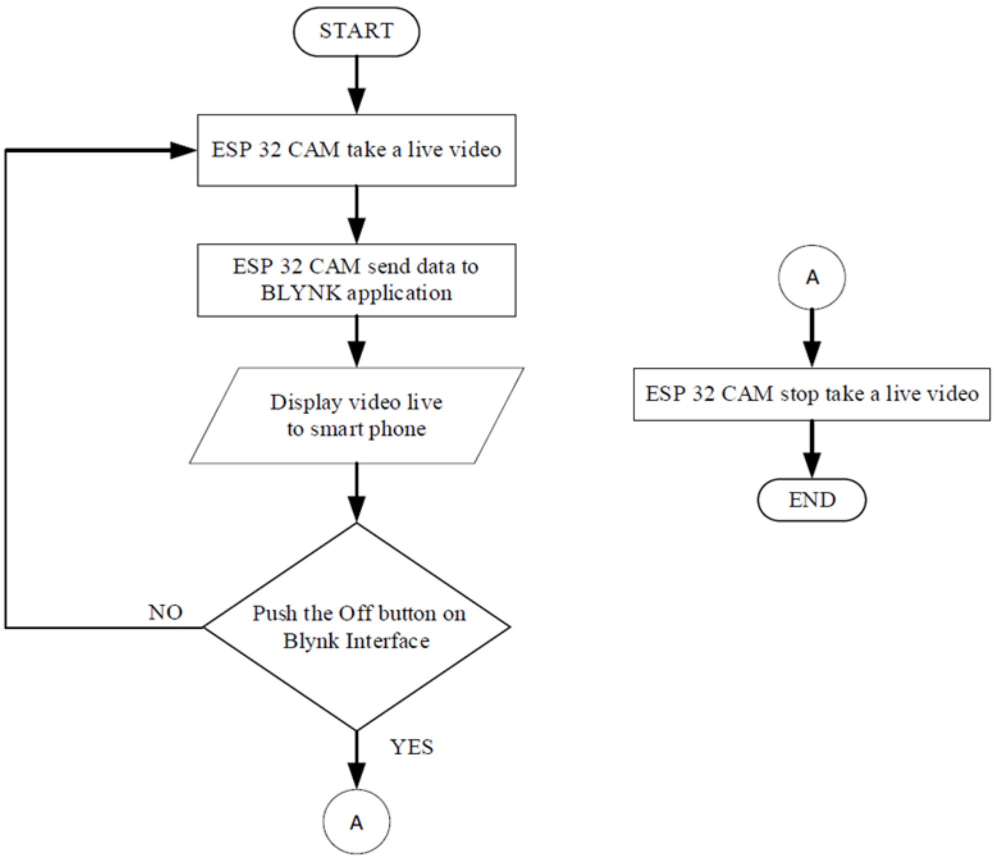

Fig. 3. Process flow of ESP32 Monitoring Camera

3.3 Hardware Development

Table 2 presents a compilation of components necessary for creating the off-grid solar prototype, encompassing electrical and electronic parts. The electrical components include the solar panel module, battery, wattmeter, and charge controller. On the other hand, the electronic components comprise the microcontroller, dust sensor, and ESP32 camera.

Table 2
List of components

Component	Item	Description
Electrical component	Solar Panel Module	20W, 18V, Mono, 0.35m x 0.45m
	Battery	12V, 7Ah
	Wattmeter	8 V
	Charge Controller	12V, 10A
Electronic Component	Microcontroller	NodeMCU ESP32
	Dust Sensor	3.3V – 5V
	ESP32 CAM	5V

Figure 4 shows a block diagram for the electrical components of this project. The components include a 20W 18V Monocrystalline PV module, wattmeter, solar charge controller, 12V 7Ah battery. Figure 5 shows a block diagram for the electronic components of this project. The components include NodeMCU ESP32, Dust Sensor, and ESP32 Camera.

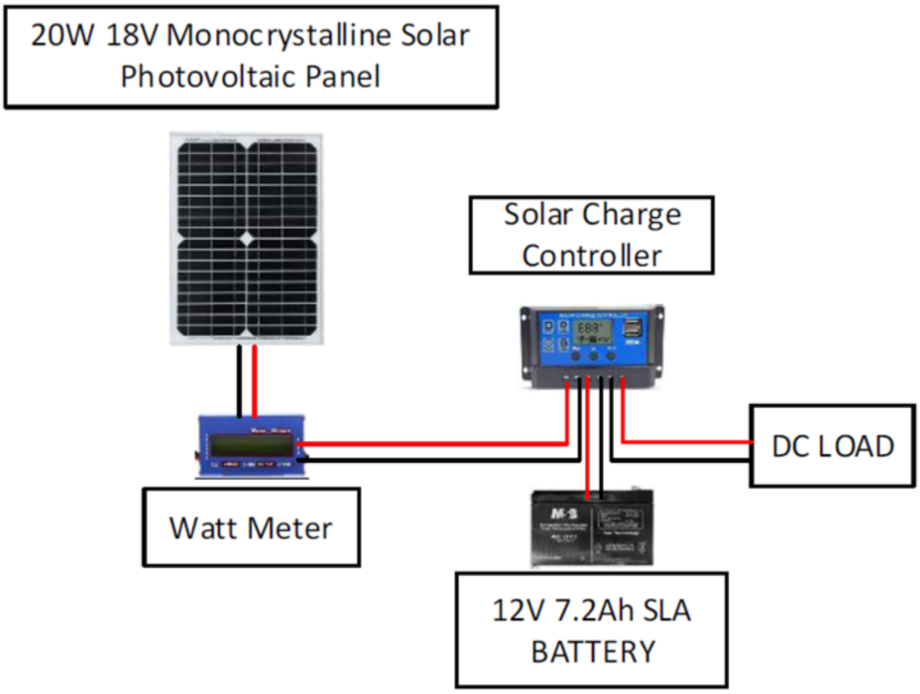

Fig. 4. Block diagram for electrical component of this project

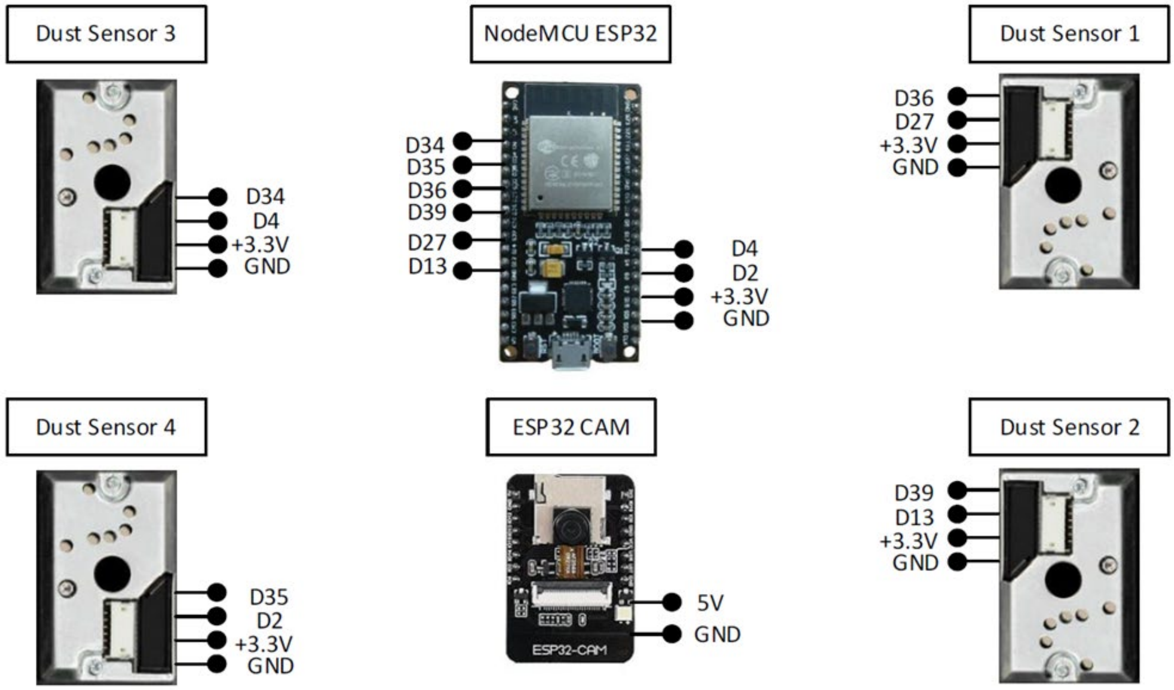

Fig. 5. Electronic component diagram

Figure 6 illustrates the design circuit of this project. The monitoring dust detection system for the photovoltaic module comprises numerous components. ESP32 microcontroller, dust sensor, and ESP32 CAM. The ESP32 receives the dust sensor signal from the solar panel and interfaces with the Blynk app to monitor the PV module system's sensors. Through this application, users can view the dust density and live video feed of the PV module's surface, increasing awareness of the module's cleanliness. Consequently, the solar PV module operates more efficiently, providing electric energy.

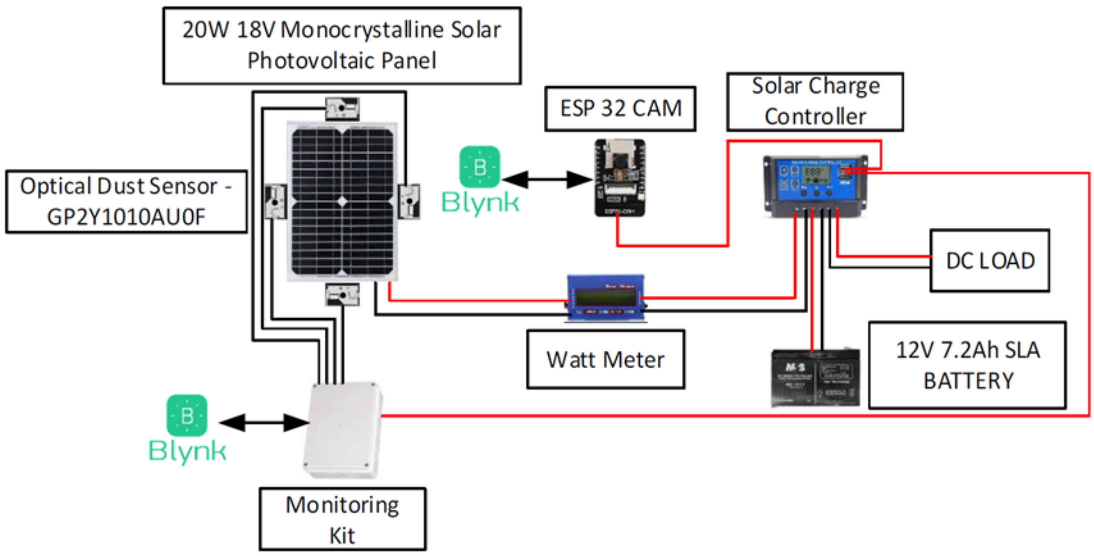

Fig. 6. Design circuit of the project system

3.4 Software Development

To gather data and information while the solar PV module is in operation, software development plays a crucial role in this project. The project uses the Arduino software (IDE) and the Blynk application. The Blynk app is the user interface for monitoring and sending notifications, while the Arduino IDE is employed for creating and designing the programming code. Figure 7 provides a visual representation of the interface for monitoring the solar PV module system using the Blynk application.

The testing phase commences with the integration of code into the ESP32. Once the code is successfully incorporated into the ESP32, it can be connected to the Blynk application. Establishing a connection between the ESP32 and the Blynk app is crucial because it enables the ESP32 to transmit data from the dust sensor, which can then be displayed on a smartphone.

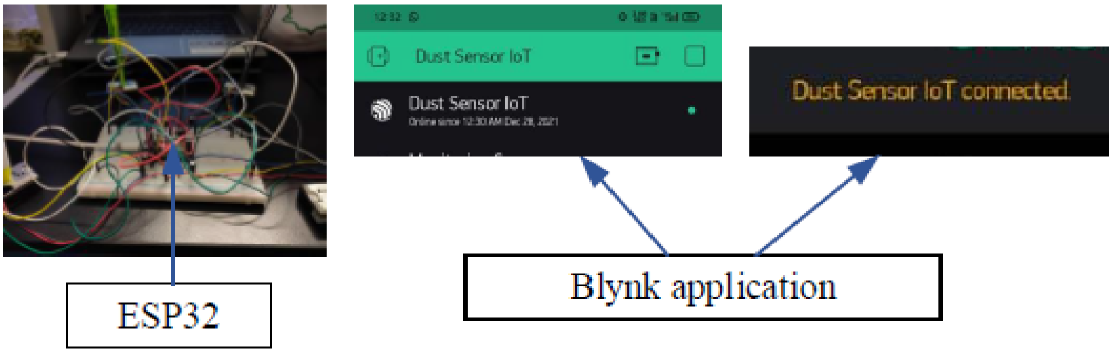

Fig. 7. ESP32 successfully linked to the Blynk application

ESP32 CAM is required to incorporate with the Blynk. The coding was installed into the ESP32 CAM and was successfully connected to the Blynk application, as in Figure 8. It is ensured that the ESP32 CAM can send video data directly to the Blynk app, as shown in Figure 9, from the solar panel and will be able to be displayed using the Blynk app available on the smartphone.

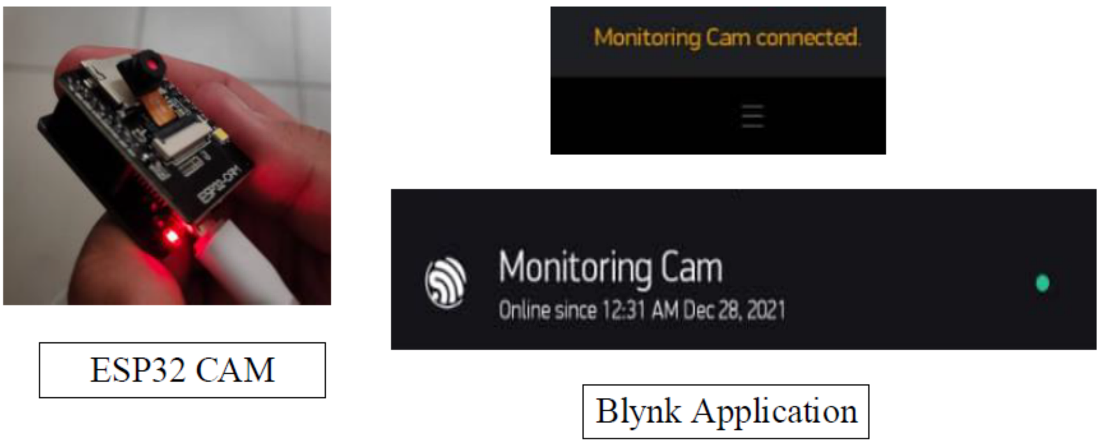

Fig. 8. ESP32 CAM successful linked to the Blynk application

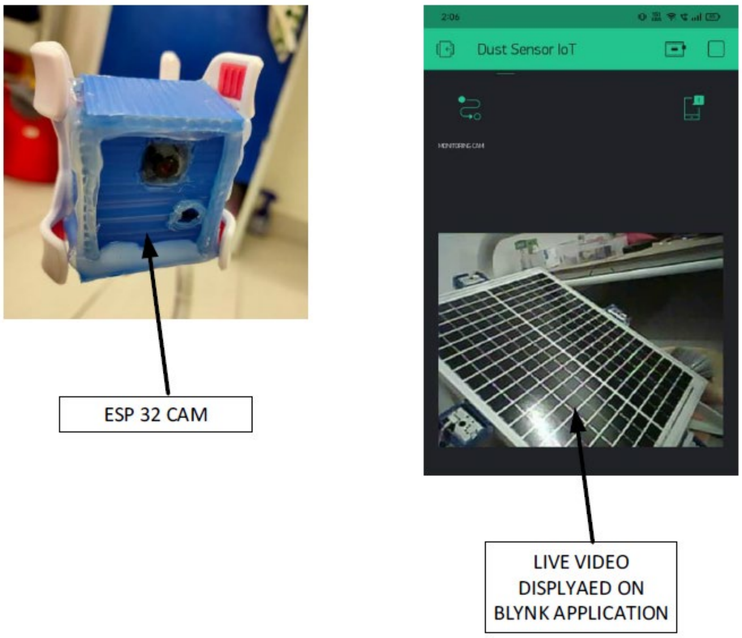

Fig. 9. Monitoring Camera

3.5 Prototype Design and Setup

This project utilized an 18V 20W monocrystalline solar panel, a Sharp GP2Y1010AU0F Dust Sensor for detecting dust on the solar panel's surface, an ESP32 CAM for live video feed from the solar panels, and a wattmeter to display the solar panel's power generation. Inside a solar monitor box, a NodeMCU ESP32 microcontroller receives data input from the dust sensors, processes it, and sends it to the Blynk application. Both the ESP32 NodeMCU and ESP32 CAM require 5V DC to operate. Figure 10 displays the final hardware development of the solar PV system. As shown in the figure, dust sensors are positioned at each side of the solar panel to ensure that all four dust sensors can effectively cover the entire panel surface. For this research, it is assumed that the dust is evenly distributed.

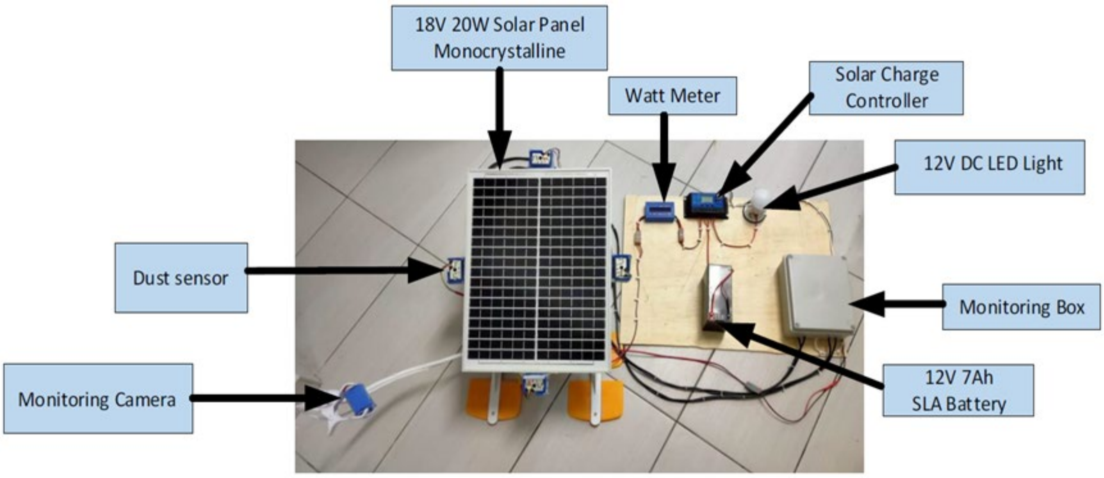

Fig. 10. Final design of the project

Figure 11 displays the electronic components used for monitoring the dust detection circuit with the ESP32 microcontroller module. This circuit incorporates four dust sensors that measure the dust density, and their values serve as input signals to the ESP32, which then displays the data on the Blynk application. The Blynk application interfaces with the circuit's operation and sends notifications to users when dust is detected on the surface of the solar PV module.

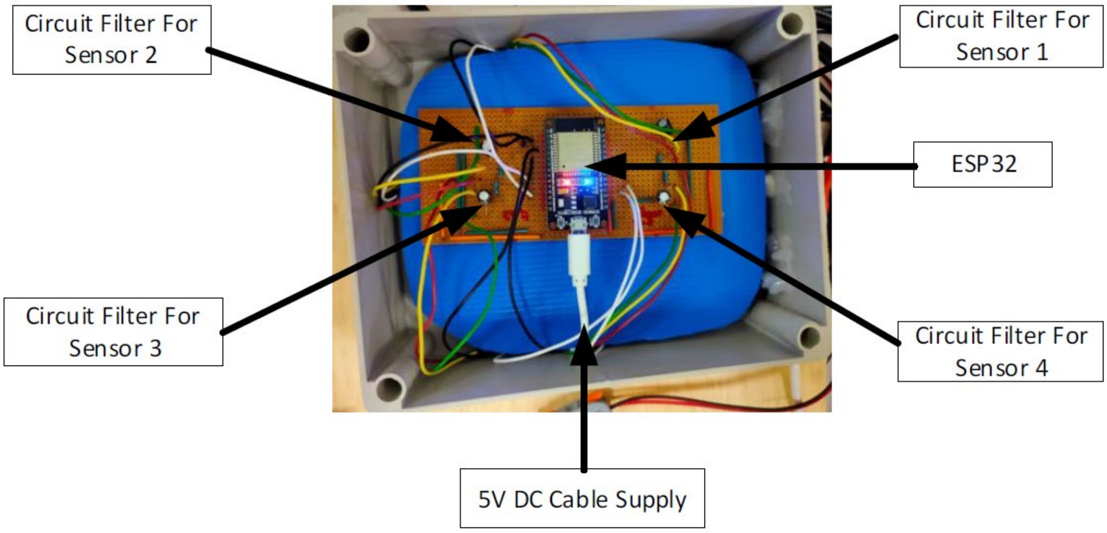

Fig. 11. Monitoring Box

4. Results

4.1 Experimental Validation and Result Analysis

The data results for the PV solar systems were collected to monitor the performance of the developed system. Real-time dust density readings were compared with the power provided by the PV module. Figure 12 illustrates the photovoltaic (PV) solar system tested under direct sunlight in UTHM Pagoh Campus.

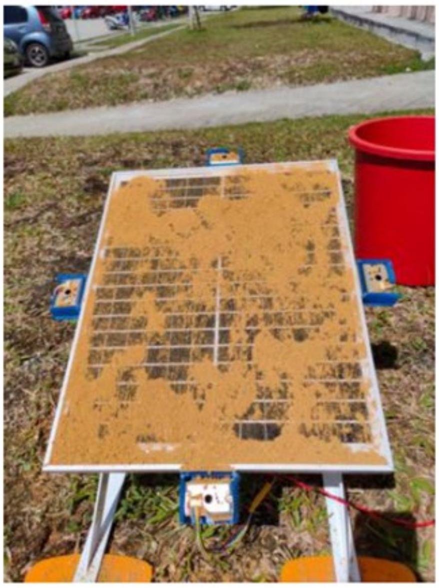

Fig. 12. Outdoor Solar System testing

4.2 Dust Density and Power Provided from PV module

The unit value of dust density will be converted into a percentage value by dividing the current dust density reading by the maximum value recorded during the section. After this division, the resulting value will be multiplied by 100% to obtain the percentage data. Based on a study conducted before testing the performance of solar panels against dust, reference results showed that dirty panels generate, on average, 9% less solar energy than clean panels. This indicates that as more dust accumulates on the solar panel's surface, its ability to produce power decreases [22]. Table 3 presents the data collected from all dust sensors.

Table 3
Data collection from all sensors and solar PV modules

Sensor 1	Sensor 2	Sensor 3	Sensor 4	Group	Power	Solar Power Condition
0%	13%	0%	23%	A	76%	Clean
47%	30%	53%	50%	B	39%	Dusty
50%	53%	55%	62%	C	22%	Dusty
50%	100%	100%	100%	D	19%	Very Dirty

Figure 13 presents a graph depicting data collected from all sensors and solar PV modules. The testing began with the solar panel in a clean state, where it recorded the highest output power value at 76%. Data readings from all sensors ranged from 0% to 23%, indicating a small quantity of dust on the solar panel. As dust gradually accumulated on the solar panel, the power provided by the solar panel decreased to 39%, with the dust sensor readings ranging from 30% to 53%. With further dust accumulation, the power value dropped to 22%, and the dust density readings were between 50% and 62%. The power decreased to 19%, with the dust sensors reading nearly 100%. The dust density percentages were divided into groups A, B, C, and D. Group A represents the clean condition of the solar PV module. In contrast, groups B and C represent the solar panels in dusty conditions, and group D indicates very dirty condition. In summary, the results indicate that as solar panels become dustier, their performance in generating electricity diminishes. The values of voltage, current, and output power for the solar panel with the dust density are tabulated in Table 4.

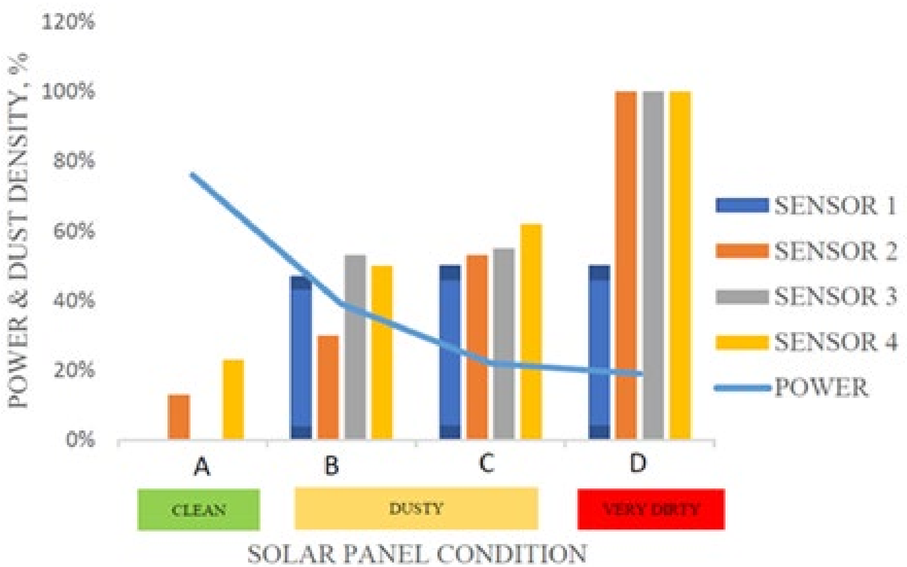

Fig. 13. Graph for data collection from all sensor and solar PV module

Table 4
Calculation for panel efficiency

Sensor 1	Sensor 2	Sensor 3	Sensor 4	Voltage (V)	Current (A)	Power (W)	Panel Efficiency
0%	0%	0%	0%	13.05	0.75	9.7	6.16%
0%	13%	0%	23%	12.93	0.58	7.4	4.69%
47%	30%	53%	50%	12. 71	0.3	3.8	2.41%
50%	53%	55%	62%	12.68	0.17	2.1	1.33%
50%	100%	100%	100%	12.67	0.15	1.9	1.20%

Formula to calculate the panel efficiency

$$Efficiency\ (\eta) = \frac{Panel\ power}{Panel\ length\ x\ Panel\ width\ (in\ m)\ x\ irradiance}\ x\ 100\% \quad (1)$$

Based on the formula and data tabulated in Table 4, it is evident that the efficiency of the solar PV module diminishes to approximately 50% by the end of the data analysis, which is deemed unacceptable for normal operation [23]. To address this issue, a specific output power value has been established as the threshold point beyond which any further reduction in current is considered unacceptable. This critical power output level is the "threshold value," set at 9.7W.

Furthermore, when the power output drops to 3.8W with an efficiency of 2.41%, the efficiency decreases to more than half of its initial efficiency value, which is 6.16%. This leads to the assumption that the solar panel is dirty when the output power is approximately lower than the threshold value of 4.85W, corresponding to an efficiency of 3.07%. Experimental evidence has corroborated the need to clean the solar panel surface when the output power falls below 50%, which is 4.85W. This cleaning action is essential for increasing the output voltage, increasing the system stability and ensuring proper performance under load conditions [24].

4.3 Real Situation

To enable the solar panel owner to monitor its output performance, data can be tracked using the process depicted in Figure 14. In practical scenarios, solar panels, dust sensors, and even cameras will be positioned outdoors, while components such as the Watt Meter, monitoring box, batteries, and solar charge controller will be located within the house. If the dust sensor detects dust accumulation on the solar panel's surface, as illustrated in Figure 15, the Blynk application will promptly notify the user.

Upon receiving a notification from the Blynk application, the user can access the Watt Meter reading. The primary objective is to verify whether the solar panel is performing optimally and capable of generating maximum power output. Subsequently, the user can utilize the monitoring camera feature within the Blynk application to visually inspect the condition of the solar panel. If it is determined that the solar panel is contaminated, the user should undertake cleaning measures to restore the panel's ability to produce power at its peak capacity.

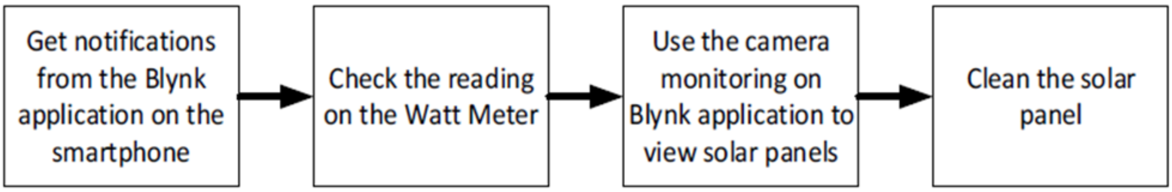

Fig. 14. Block diagram of monitoring system in real situation

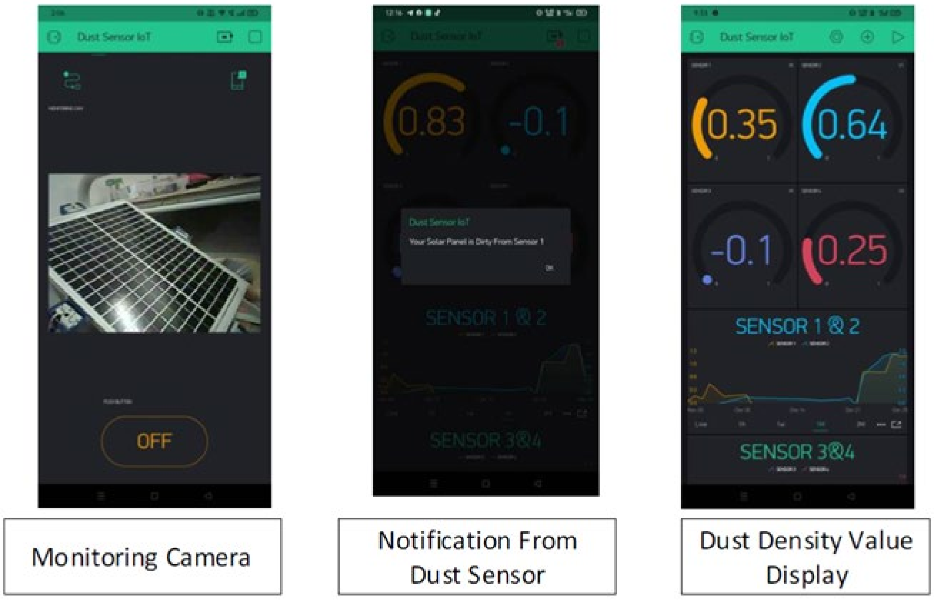

Fig. 15. Blynk app interface

5. Conclusion

A Smart Monitoring Dust Detecting System for Photovoltaic Modules is a relevant system to be developed, as it can help monitor the cleanliness of solar PV modules. This project enables users to monitor the dust density on the surface of solar PV modules. The main components include NodeMCU ESP32, a dust sensor, and ESP32 CAM, which is used for visual monitoring of the solar PV module. The project successfully detects the dust density on the solar PV module surfaces using a dust sensor and sends notifications when the dust density value exceeds or reaches 47% for sensor 1, 30% for sensor 2, 53% for sensor 3, and 50% for sensor 4, indicating an unclean condition of the PV module at that time. Considering the widespread use of PV systems in the country, developing a prototype for a Smart Monitoring Dust Detecting System for Photovoltaic Modules is deemed necessary. Tests were conducted by gradually staining the solar PV module to analyze its performance, and the system proved successful. Users can receive notifications through the Blynk interface when the solar PV module requires cleaning. The Blynk interface also provides a live monitoring camera feed of the solar PV module. For future improvements, the project can benefit from the addition of a control system that can clean solar panels, as the current project can only monitor the cleanliness condition of solar panels. With the integration of a control element, the system would become more systematic and practical, aligning with the Malaysia Sustainable Development Goals (SDGs) aimed at increasing green energy production.

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