BJET
(Bayero Journal of Engineering and Technology)
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Research Article
2026, Vol. 21 (3), 1-8

DEVELOPMENT OF AN AUTOMATED PHOTOVOLTAIC PANEL DUST CLEANING ROBOT USING FUZZY LOGIC CONTROLLER

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Received: 23-06-2025
Revised: 05-07-2026
Accepted: 11-07-2026
Published: 01-09-2026

Abstract: *The accumulation of dust particles on solar panels can hinder the transmission of solar energy to the solar cells, resulting in a decrease in overall power generation. If the panels are not cleaned for a month, the power output can be reduced by up to 44.6%. To address this issue, an automatic robot cleaning system has been developed to remove dust from the photovoltaic (PV) panels. This paper focuses on designing an intelligent cleaning system based on fuzzy logic with an Arduino microcontroller. By considering temperature, dust levels, and the output current and voltage of the panel as input variables for the fuzzy logic membership functions, the system is able to operate efficiently. Four membership functions have been determined for each of these input variables. These membership functions determine whether the cleaning robot should be activated or not. The main objective of the design is to minimize efficiency losses caused by dust and dirt on the panel surface and maximize electrical energy production. Evaluation results revealed that the system increases the energy gain by 55.4% when the cleaning robot is deployed to clean the PV panels.*

Key words: Photovoltaic Panel; Irradiance; Dust; Fuzzy Logic Controller; Robot

1 Introduction

In today's era of globalization, the change in climate is one of the toughest challenges facing the planet. Energy production is a main cause for industrial pollution. This is not only a threat to the environment but also risks depletion of the scarce traditional energy sources. This has led to the search of some alternative energy sources, called renewable energy sources, e.g., solar and wind. Renewable sources of energy are natural sources that convert solar radiation, wind, or tide into electrical energy, and the energy that comes from these sources is called renewable energy (RE) (Jha, 2019; Tabachnyk, et al., 2014).

Photovoltaic (PV) cells convert sunlight into electricity by an energy conversion process. In most of the cases of PV cells, photons (light energy) fall on the cells and result in exciting electrons in the atoms of a semiconductor material. Silicon is the main element for making PV systems. The energized electrons result in the generation of an electric voltage and current (Shi, et al., 2013). The problem of dirty PV panel surface contributes significantly to losses in the output power of PV systems (Renewable Green, 2025).

The performance of PV systems is highly affected by internal and external factors such as the structural features, aging, radiation, shading, temperature, wind, pollution and cleanliness. Any type of climatic change that affecting the solar radiations, air quality or the ambient temperature, may cause changes in the solar PV output performance (Rustemli, 2011; Al-Kouz, et al., 2019; Altas and Sharaf, 2007).

This paper focuses on mitigating the effect of dust on PV cell by developing an autonomous cleaning robot. Thus, the work involved software and hardware aspects. While software part is simulated (Alhussain and Yasin, 2020) on MATLAB, a hardware prototype of the system has been developed. The hardware part includes input sensors for dust, voltage and current. The PV module is the power generation source for the system which converts sunlight irradiance into voltage, the research focusing to mitigate the effect of dust casted on PV panel to improve the efficiency.

2 Literature Review

In the literature, a lot of research has been focused on the performance of panels with dust concentration on their surfaces without consideration of how to clean the dust on the PV panels. One of the early works on the effect of dust on solar systems was conducted in 1942 by (Hottel and Woertz, 1942). They reported up to 4.7% degradation in collector performance, with an average loss in incident solar radiation of less than 1%. The work in (Hottel and Woertz, 1942) investigated several parameters that affect PV panel performance. Environmental, PV system, installation, cost issues, and other unspecified factors are among them. Each of these components is divided into new subcategories, as well as the reduction/increase effects of some factors on system output. Some of the system parameters are the panel's I-V characteristics, inverter, battery, and panel efficiency, panel material, atomic structure, and band-gap energy.

In (Hussain, 2017), a set of computational models was developed to assess the impact of dust and ambient temperature on the performance of a photovoltaic system established at Jordan's Hashemite University with an azimuth angle of 0 and a tilt angle of 26. The system is connected on-grid. To predict conversion efficiency based on experimental data, the models were created using optimized architectures of artificial neural network (ANN) and extreme learning machine (ELM). Using several criteria, the method of generating models was tested for correctness. Each parameter's effect was discovered to be consistent with the well-known relationship between each parameter and expected efficiency. The improved ELM model was found to have the best accuracy in predicting conversion efficiency, with a Regression of 91.4% (Hussain, 2017).

Similarly, Khadka, et al. (2020) investigated the effect of air dust particles on the performance of photovoltaic (PV) modules. They studied gathered dust samples using a scanning electron microscope, and the pictures acquired were processed to determine the character and topography of the dust sample particles. Data was acquired for dust samples of various weights with changes in power loss in a PV module at three distinct solar irradiation levels of 650, 750, and 850 W/m2. The impact of ambient dust particles on power loss in PV modules was measured using electrical performance indices such as voltage, current, and power. On the accumulation of rice husk on the PV module, a minimum power value of 3.88 W/m2 was observed.

In the same vein, Mutluer (2019) demonstrated the negative impact of temperature and soiling on PV performance.

From the foregoing, previous research efforts have explored the impact of dust deposition on the performance of photovoltaic (PV) panels. A variety of technologies have been deployed to mitigate the dust problems from studies across different regions globally. Because of these variations and discrepancies, it is evident that comparing the results of the relevant investigations is extremely difficult. As a result, this work will incorporate a real-time robotic control system for routine cleaning of dust on PV cells in order to improve power production.

3 Methodology

The design and development of a cleaning robot for PV panel system constitute both software and hardware parts.

3.1. Robot Structure Fabrication

The physical structure of the fabricated robot is shown in Figure 1. The followings components were used to fabricate the PV panels cleaning system: i) Roller ii) Thread iii) Bolt and Nut iv) Aluminum pipe

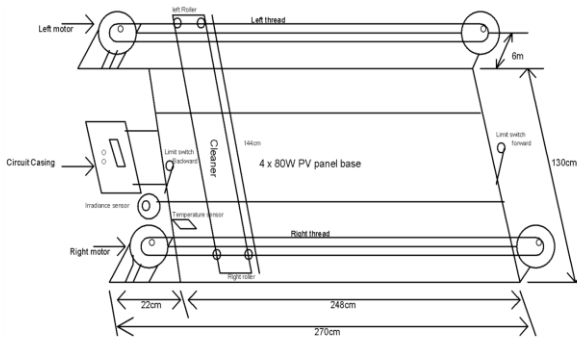

Figure 1: *Mechanical Structure of the Automatic PV Panel Cleaning Robot System*

v) Pulley vi) Iron angle metal.

3.2. Model of PV Cell Plant

Photovoltaic cell is typically modelled (Pandiarajan and Muthu, 2011) as a current source associated with a shunt PN junction diode. A current is corresponding to the power of the light incident on the cell. Photovoltaic framework is affected, specifically by climate conditions and sun-oriented radiation.

The ideal electrical circuit model of a PV cell is shown in Figure 2. It incorporates a current source, a diode, a series arrangement resistance ($\boldsymbol{R_s}$) and a shunt resistance ($\boldsymbol{R_{sh}}$), these two resistances stand for the

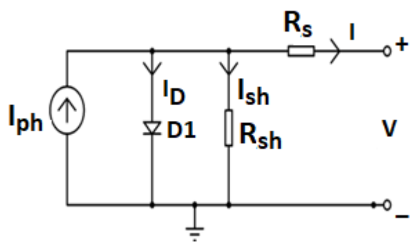

Figure 2: *Diode Model of PV Panel*

internal resistance of the cells since there is no ideal solar cell in practice.

3.3. Simulink Model of PV Module

There are four fundamental equations describing the PV Module:

i. PV Module Photo Current I_{ph}

An ideal Photovoltaic cell consists of a single diode connected in parallel with a light generated current source, I_{ph} (1)

$$I_{ph} = \left[I_{sc} + K_i(T - 298) \times \frac{G}{1000}\right] \quad (1)$$

ii. PV Module Reverse Sat. Current Irs

$$I_{rs} = \frac{I_{scr}}{\left[exp\left(q.\frac{V_{oc}}{N_s}.k.A.T\right)\right]} \quad (2)$$

iii. PV Module Saturation Current Is

The module saturation current I_s varies with the cell temperature, which is given by:

$$I_s = I_{rs}.\left[\frac{T}{Tr}\right]^3 exp\left[q.E_{go}\left\{\left(\frac{1}{Tr}\right) - \left(\frac{1}{T}\right)\right\}\right] \quad (3)$$

iv. PV Shunt Current Ish

The Simulink model of Shunt Current (I_{sh}) obtained from equation (4).

$$I_{sh} = \frac{V + I.R_s}{R_{sh}} \quad (4)$$

3.4. Reference Model

An 80W solar panel is taken as the reference module for simulation and the detailed parameters of module is given in Table 1. The test condition electrical specifications are: cell temperature at 25°C; spectrum at 1.5 air mass; and irradiance at 1 kW/m2.

***Table 1:** Electrical Specifications of PV panel*

Name	Values
Rated	80Watt
Open circuit Voltage Voc	22.3V
Voltage at max power	18.0V
Current at max power	4.44A
Short circuit current	4.851A
Total number of cell in series Ns	72
Total number of cell in parallel Np	2

3.5. Fuzzy Logic Controller for PV Cleaning Robot

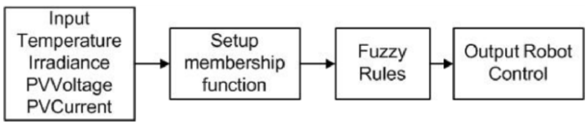

***Figure 3:** Block Diagram of the Fuzzy Logic Algorithm*

Figure 3 presents the general block diagram of a Fuzzy logic controller, illustrating how fuzzy variables together with the rule base fuzzy output to derive the PV panel cleaning robot.

3.6. Fuzzy Logic Structure of the Cleaning System

In this design, an artificial intelligence method based on fuzzy logic system was utilized. The input parameters for fuzzification include Irradiance, temperature, PV output current, and voltage.

Table 2 is used based on empirical experiment to set-up the range of values for inference engine (Rule base table). This was then used to establish fuzzy rules for appropriate defuzzification, determining PV state of dust as well as the robot action at the output as shown in Table 3. The complete Fuzzy Logic representation for the inputs and output of the system is shown in

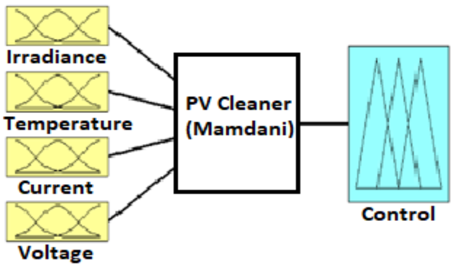

***Figure 4:** Design of fuzzy logic system inputs & outputs*

Figure 4.

3.6.1 Membership Functions

Three membership functions, namely LOW, MEDIUM, and HIGH, were defined for the inputs of temperature, irradiance, voltage, and current based on Table 2. Similarly, for the output, two membership functions, namely CLEAN and DO NOT CLEAN, were defined according to Tables 3.

***Table 2:** Fuzzy logic controller input design*

Input Parameters	Low	Medium	High
Irradiance *W/m2*	0-400	400-800	>800
Temperature °C	0-35	35-60	>60
PV Current (A)	0-2.5	2.5-3.5	>3.5
Voltage (V)	0-20	0-20	0-20

***Table 3:** Fuzzy logic controller output design*

SN	Irradiance	PV output Current	Fuzzy output	Robot Action
1	: 800	≤ 2.5	9	Do clean
2	≥ 800	≥ 3.5	0	Do not Clean

3.6.2 Rule Base

The rule base table in Table 3 is designed according to the input data for the accurate solution of the fuzzy problem. The purpose of creating this rule base table is to obtain the rule editor. **I** is a PV current, **V** is PV voltage, **Ir** is Irradiance and **T** is Temperature. Then, **L** stands for Low, **M** for Medium, **H** for High and **N** for Normal voltage (open circuit voltage). Also, **C** is to Clean and **D** is do not clean. A proportional (P) controller is designed to control the speed control of a DC motor when the fuzzy logic controller is set to clean a PV panel. Figure 5 illustrates the block diagram of this unit.

3.7. Design of the Robot Cleaner Speed Control Unit

A proportional (P) controller is designed to control the speed control of a DC motor when the fuzzy logic

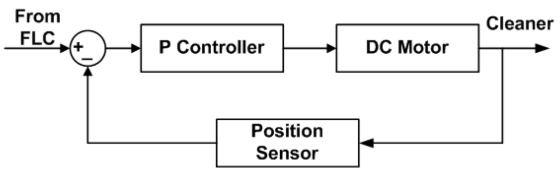

Figure 5: *PV Cleaning Robot Speed Control System*

controller is set to clean a PV panel. Figure 5 illustrates the block diagram of this unit.
The transfer function $G(s)$ of the DC motor is

$$G(s) = \frac{\theta(s)}{v(s)} = \frac{K}{(Ls+R)(Js+B)+K^2} \qquad (5)$$

Substituting the motor parameter values (Almatheel, and Abdelrahman, 2017) gives,

$$\frac{\theta(s)}{v(s)} = G(s) \;= 0.0663K \,/((1.17\times10^{-3}\, s + 2.73)(1.15s + 0.0138) + 4.36\times10^{-3}\,)$$

Now, with the gain controller, closed-loop characteristic equation compared with the standard second order characteristic equation, we assume a peak overshoot of $M_p = 5\%$, damping ratio $\zeta = 0.7$

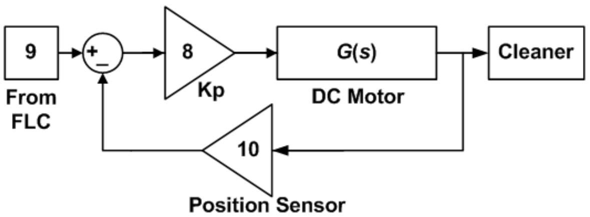

Figure 6: *Simulink Model for the PV Cleaning Robot Speed Control System*

and settling time of $T_s = 5sec$. The gain of the designed P controller is $K \approx 8$.
The complete model is shown in see Figure 6.

3.8. Hardware Design of the Robot Cleaner

The proposed prototype method consists of PV panels dust sensing unit, Real time clock monitoring unit, DC motor control and a microcontroller unit (Arduino). The time interval for cleaning PV panel. A dc motor driver circuit drives the robotic cleaner as PV cleaning system. A geared DC motor is used to drive the robotic cleaner for a clean a PV panel. An ultrasonic sensor is used to provide feedback to the microcontroller input as a position sensor for the cleaning robot to- and fro-

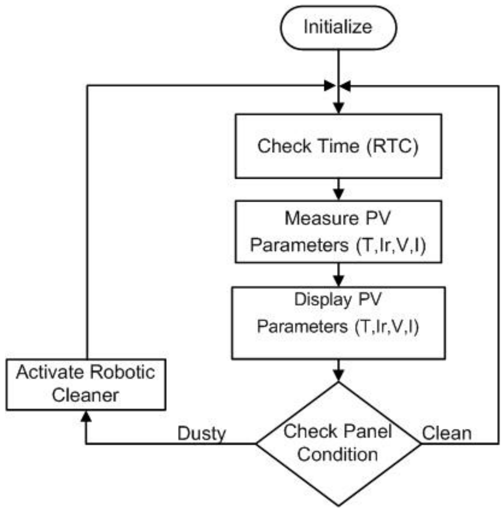

Figure 7: *Flow chart of the PV Panel Cleaning Robot*

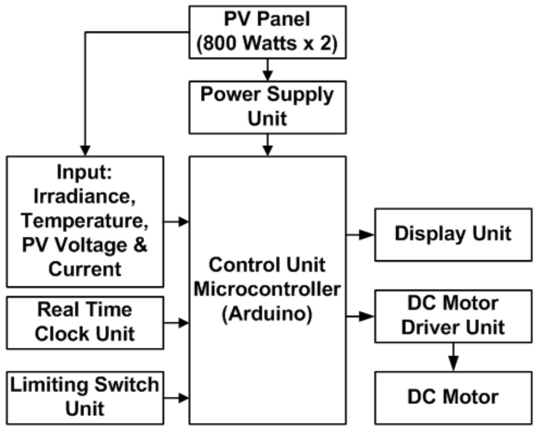

Figure 8: *Block Diagram of the PV Panel*

movements. Figure 7 shows a flowchart which describes the software implementation of the complete system. The complete block diagram is shown in Figure 8.

3.8.1 System Circuit Diagram

After designing the interfaces for the various sensors to the Arduino microcontroller, a simulation was carried out in PROTEUS ISIS to optimize the circuit parameters prior to practical construction of the designed system. Each component was picked by selecting the PROTEUS schematic capture and component mode from the library's toolbar. The complete circuit schematic is presented in Figure 9 showing the placement and interconnection of all the essential components.

4 Result

4.1. Simulation of Robotic Cleaning System using MATLAB

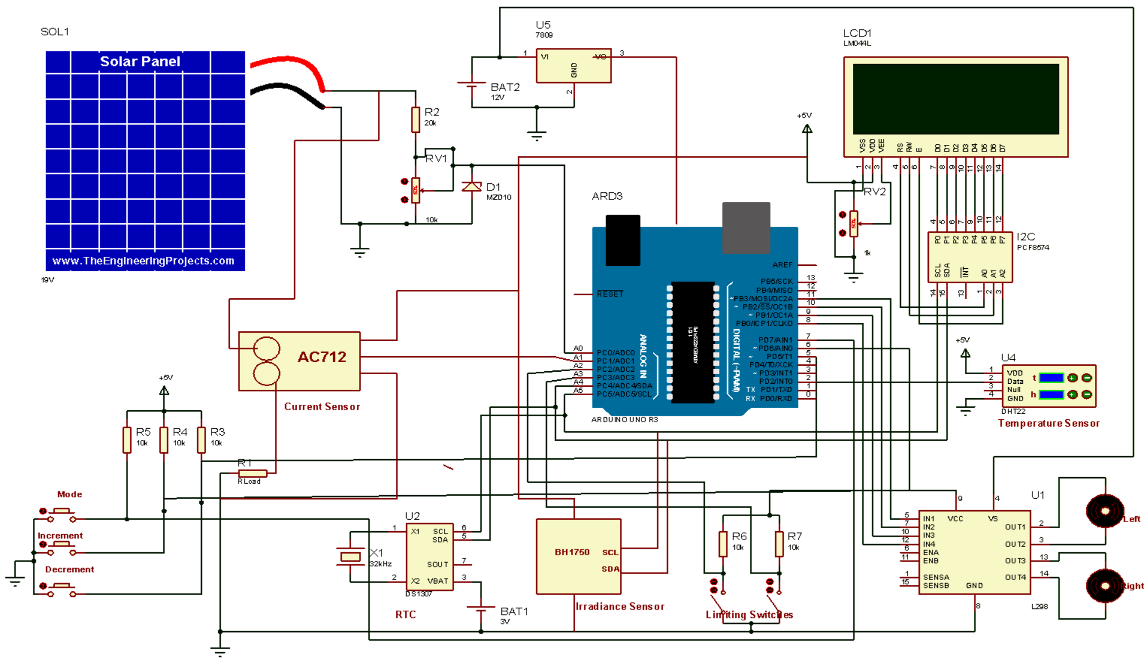

Figure 9: Circuit Diagram of the Automatic PV Panel Cleaning Robot System

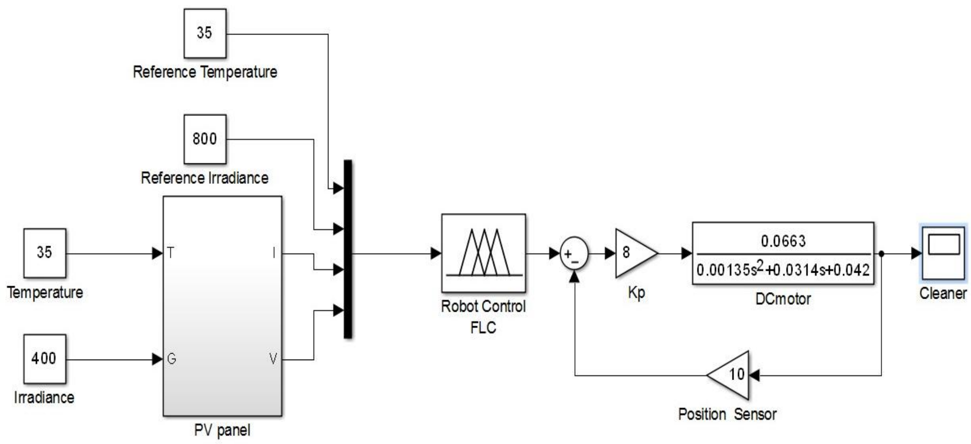

Figure 10: Simulation Model of the Cleaning Robot System in Simulink

The complete simulation model of the system is designed on MATLAB Simulink to ensure the system workability as shown in Figure 10.

The source code of the project is debugged from the Arduino IDE software to generate the hex file and simulate a circuit on ISIS Proteus software to confirm the system workability. As shown in Figure 11.

4.3. Current Consumption of the system

To assess the current consumption of the overall system, Table 4 shows the measured current consumption by each active components as well as the total current consumed by the circuit. A 12V, 7AH battery was used to drive this unit. The total current

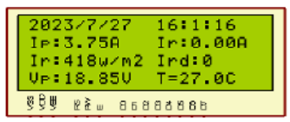

Figure 11: Circuit simulation Test Result

consumption with robot idling is 100.62mA, when robot is actively cleaning it consumes 5900.62mA.

Table 4: Current Consumption of each Components

SN	Name	Qty	Current (mA)	Total Current(mA)
1	Arduino	1	40	40
2	LCD20x4	1	4	4
3	Bh1750	1	0.12	0.12
4	DHT11	1	2.5	2.5
5	L298	1	36	36

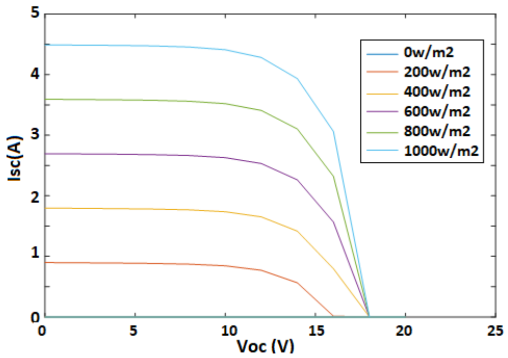

Figure 12 (a): *I-V characteristics of PV panel*

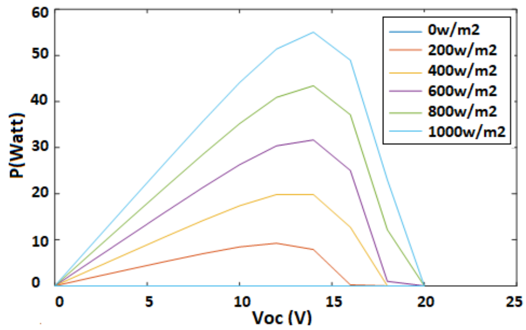

Figure 12 (b): *P-V characteristics of PV panel*

6	DC motor	2	2900	5800
7	I2c module	3	3	3
			Total	5885.62mA

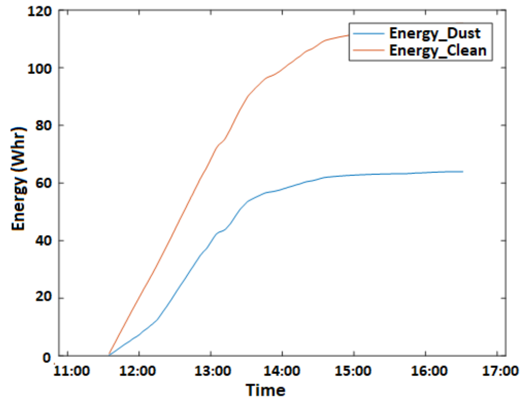

Figure 13: *PV Energy Generation under Clean and Dusty Conditions*

4.4. Model of PV simulation

The simulation results for the mathematical model of the PV are presented in this section. The plots in Figure 12 (a and b) present the I-V and P-V characteristics of the PV panel under a constant temperature of T= 25°C on the surface of the PV panel with different solar irradiance levels: 1000, 800, 600, 400, and 200 W/m^2.

4.5. Results of Dust Impact on PV Panels Output

An experimental setup was made to facilitate data collection. The results obtained from the sensors, including temperature, irradiance, and PV panel output voltage, current, and power, are recorded in Table 5.

While this experiment was run for several months, the data presented in Table 5 corresponds to one-day data record. Additionally, Figure 13 compares the performance of the PV panel based on energy generation under clean and dusty PV panel surface conditions. The comparison between PV Energy with clean and dusty conditions is presented in both Table 5 and Figure 13, where the energy form a clean PV (Ec (Whr)) represents the energy output under clean conditions, while Ed (Whr) under dust cover.

4.6. Evaluation of Energy and Cost Savings

Using a single 80W PV panel, the energy produced from a clean and dusty PV are recorded. In the presence of dust, from 11AM-4PM, the cumulative Energy output of the solar panel is 1446.23Whr in Table 5. However, the cumulative Energy output at EC (Whr) when the PV panel is clean is 2587.42Whr This decrease in Energy output can be attributed to the presence of dust. Hence, the percentage Energy gains $(E_{gain})$is:

$$E_{gain} = \frac{E_c - E_D}{E_c} = \frac{115.38 - 63.94}{115.38} = 55.4\%$$

Hence, the energy loss (E_{loss}) due to dust is 44.6%.

4.7. Discussion of Result

A cleaning robot was employed to clean the dust accumulated on PV panels, as the energy output from these panels greatly varies based on surface cleanliness. Each cleaning round lasted for 10 seconds. Table 5 presents the energy generated after the panel surfaces were cleaned, in comparison to the energy produced prior to the cleaning process, specifically in relation to dust density.

Figure 13 compares the energies produced from the two test cases. The results showed that the dust enveloped solar panels delivered the lowest energy to the load per day, as data shows between 11 AM and 4 PM. The cumulative energy output had increased from 1446.23Whr before cleaning to 2587.42Whr after just one cleaning round. Table 5 highlights the energy output for PV panels before and after cleaning, compared to clean PV solar panels. The PV panels with intense dust accumulation had the lowest energy output, indicating the negative impact of a thick dust layer.

The difference (ΔE) between the clean and dusty PV panel samples revealed an energy loss of 44.6% as derived from Figure 13. To address this issue, a cleaning robot was used to clean the PV panels. This improved the energy gain of the solar PV panels to 55.4%. This improvement can be attributed to the removal of dust droppings that were attached to the surfaces of the solar cells, which required a cleaning cycle.

Table 5: *Sample of Daily Data Collection Records for Dust Assessment on PV Panel Performance*

Time	Vc (V)	Ic (A)	Pc (W)	Ec (Wh)	Vd(V)	Id (A)	Pd (w)	Ed (whr)	Temp (C)	Irrad (W/m^2)	Cum Ed (whr)	Cum Ec (whr)
11:34:50	16.8	2.65	44.52	0.76	8.4	1.8	15.12	0.26	43.9	839.56	0.26	0.76
11:44:55	17.2	2.85	49.02	8.64	9.6	1.8	17.28	3.11	45	776.76	3.37	9.4
11:54:00	16.8	2.9	48.72	15.71	9.8	2	19.6	5.7	42.9	717.61	9.07	25.11
12:04:05	15.8	2.8	44.24	23.36	9.3	1.9	17.67	8.78	41.5	601.14	17.85	48.47
12:14:10	17	2.85	48.45	30.88	10.2	2.15	21.93	12.12	43.1	681.39	29.97	79.35
12:24:15	16.9	2.95	49.86	39.06	14.5	2.6	37.7	17.87	44	778.86	47.84	118.41
12:34:21	16.8	3	50.4	47.52	14.7	2.55	37.49	24.28	43.2	741.85	72.12	165.93
12:44:26	16.6	3	49.8	55.83	14.2	2.7	38.34	30.58	42.9	691.33	102.7	221.76
12:54:31	14.8	2.9	42.92	63.91	10.9	2.2	23.98	36.41	44.5	581.44	139.11	285.67
13:04:36	15.2	2.8	42.56	72.04	11.5	2.3	26.45	42.22	43	605.26	181.33	357.71
13:14:42	15.9	2.95	46.9	77.39	12.8	2.4	30.72	45.03	42.9	648.38	226.36	435.1
13:24:47	15.8	2.95	46.61	85.61	12.8	2.5	32	50.93	44.2	660.39	277.29	520.71
13:34:52	10.8	2.35	25.38	91.82	7	1.7	11.9	54.46	41.3	477.03	331.75	612.53
13:44:57	9.2	2.25	20.7	95.94	6.1	1.4	8.54	56.42	41.3	440.8	388.17	708.47
13:54:02	6.8	2	13.6	97.81	4.1	1.1	4.51	57.18	41.4	376.47	445.35	806.28
14:04:07	9.3	2.25	20.93	100.82	5.7	1.5	8.55	58.4	42.5	445.3	503.75	907.1
14:14:12	8.2	2.05	16.81	103.83	5.2	1.5	7.8	59.63	41.4	415.89	563.38	1010.93
14:36:24	5.3	1.7	9.01	109.54	3.3	1.05	3.46	61.95	41.7	325.55	625.33	1120.47
14:34:23	6.4	1.85	11.84	109.17	3.9	1.1	4.29	61.81	41.2	367.52	687.14	1229.64
14:44:28	3.9	1.45	5.66	110.36	2.3	1	2.3	62.28	38.5	280.55	749.42	1340
14:54:33	3.2	1.3	4.16	111.18	1.9	0.75	1.42	62.6	39.5	255.48	812.02	1451.18
15:04:39	2.5	1.3	3.25	111.78	1.5	0.65	0.97	62.82	38.9	232.29	874.84	1562.96
15:14:44	2.2	1.05	2.31	112.22	1.2	0.7	0.84	62.99	38.3	215.64	937.83	1675.18
15:24:49	1.9	1	1.9	112.57	1.1	0.65	0.71	63.11	38.1	205.64	1000.94	1787.75
15:34:54	1.2	0.85	1.02	112.82	0.5	0.5	0.25	63.19	38.1	180.18	1064.13	1900.57
15:44:59	2.1	1.2	2.52	113.01	0.9	0.6	0.54	63.25	38.1	229.03	1127.38	2013.58
15:54:04	2.8	1.25	3.5	113.78	1.7	0.6	1.02	63.47	39.9	271.95	1190.85	2127.36
16:04:09	3.7	1.5	5.55	114.37	1.7	0.75	1.28	63.66	39.4	308.97	1254.51	2241.73
16:14:14	2.6	1.05	2.73	114.99	1.2	0.8	0.96	63.85	40.4	270.33	1318.36	2356.72
16:24:19	1.1	0.8	0.88	115.32	0.6	0.45	0.27	63.93	39.7	196.67	1382.29	2472.04

4.8 Prototype of the Robotic Cleaning System

The system was made in a plastic adaptable case to provide protection attached to the frame of the system.

(a) System with Dust (b) System after cleaning

Figure 14: *PV Dust Cleaning Robot System configurations*

The dimensions of the system were chosen to suit the application and provide enough space as demonstrated in Figure 14.

5. Conclusion

This paper presented the design and development of an automatic PV panel cleaning robot. It also investigated the impact of pollution (dust coating) on the efficiency of PV panels. As part of the study, a fuzzy logic-based intelligent system was designed and implemented on Arduino microcontroller to automatically clean the surfaces of the panels. The fuzzy logic system took into account the output current of the PV panel, and irradiance factors as inputs, which were defined using two membership functions for each of the four-input data. The research findings revealed that dust and dust derivative particles deposited on the panel surface led to panel energy loss of 44.6%. However, by utilizing the fuzzy logic-based cleaning robot, an average improvement of 55.4% in the energy of the photovoltaic panel was achieved. Thus, more energy can be harnessed from a limited number of panels.

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