Faculty of Electrical Technology and Engineering

DEVELOPMENT OF AN ARDUINO-CONTROLLED BRUSH-BASED SELF-CLEANING PHOTOVOLTAIC SYSTEM

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DEVELOPMENT OF AN ARDUINO-CONTROLLED BRUSH-BASED SELF-CLEANING PHOTOVOLTAIC SYSTEM

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A project report submitted
in partial fulfillment of the requirements for the degree of
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2025

DECLARATION

I declare that this project report entitled "DEVELOPMENT OF AN ARDUINO-CONTROLLED BRUSH-BASED SELF-CLEANING PHOTOVOLTAIC SYSTEM" is the result of my own research except as cited in the references. The project report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I approve that this Bachelor Degree Project 1 (PSM1) report entitled "DEVELOPMENT OF AN ARDUINO-CONTROLLED BRUSH-BASED SELF-CLEANING PHOTOVOLTAIC SYSTEM" is sufficient for submission.

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APPROVAL

I hereby declare that I have checked this project report and in my opinion, this project report is adequate in terms of scope and quality for the award of the degree of Bachelor of Electrical Engineering Technology with Honours.

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Date	:	

DEDICATION

This research paper is lovingly dedicated to our respective parents, who have been our constant source of inspiration. They have instilled in us the drive and discipline to approach any task with enthusiasm and determination. Without their love and support, this research would not have been possible.

I also dedicate this research paper to my supervisor, for the support, guidance, and invaluable insights, which have been instrumental in the completion of this study and never failed to teach or guide me. To my family who supports me in everything, to my friends who helped me complete this project, and most of all to ALLAH SWT, who gives me strength and good health throughout this endeavour.

ABSTRACT

Dust accumulation on photovoltaic (PV) panels significantly reduces their efficiency by obstructing sunlight and hindering energy conversion. Addressing the critical need to maintain optimal performance, this project aims to develop an automated cleaning system to mitigate the issue of dust and dirt coverage on solar panels. The prototype involves designing a self-cleaning mechanism that employs advanced technologies, including mechanical brush, rain sensors, and timers, to initiate regular cleaning cycles. The rain sensor detects natural precipitation, pausing the cleaning process during rain to conserve resources, while the timer ensures periodic activation of the wipers to remove accumulated dust and debris. This system is engineered to operate autonomously, reducing the need for manual maintenance and ensuring continuous, effective cleaning. Based on the analysis of solar panel performance before and after cleaning, using flour as a simulated dust, power output dropped by 40% on average under sunny conditions and 25% under cloudy conditions. Post-cleaning, efficiency improved to near original levels, with power restored by 90-95%. Meanwhile for sand-based cleanliness benchmarks, power output dropped by 50% at fully dirtiness level but was restored to over 95% of baseline levels after the second cleaning cycle. These results confirm the high effectiveness of the automated cleaning mechanism in mitigating soiling impacts. The automated system operates autonomously, reducing manual maintenance and ensuring continuous, effective cleaning. It significantly enhances panel efficiency by minimizing dust accumulation, thereby improving the performance and longevity of solar PV systems. This innovation makes solar energy more reliable and cost-effective, particularly in dust-prone regions, promising to advance the viability of solar power as a sustainable energy source.

ABSTRAK

Pengumpulan habuk pada panel fotovoltaik (PV) mengurangkan kecekapannya dengan ketara dengan menghalang cahaya matahari dan menghalang penukaran tenaga. Menangani keperluan kritikal untuk mengekalkan prestasi optimum, projek ini bertujuan untuk membangunkan sistem pembersihan automatik untuk mengurangkan isu liputan habuk dan kotoran pada panel solar. Prototaip ini melibatkan mereka bentuk mekanisme pembersihan diri yang menggunakan teknologi canggih, termasuk berus mekanikal, penderia hujan dan pemasa, untuk memulakan kitaran pembersihan biasa. Penderia hujan mengesan pemendakan semula jadi, menghentikan proses pembersihan semasa hujan untuk menjimatkan sumber, manakala pemasa memastikan pengaktifan berkala pengelap untuk membuang habuk dan serpihan terkumpul. Sistem ini direka bentuk untuk beroperasi secara autonomi, mengurangkan keperluan untuk penyelenggaraan manual dan memastikan pembersihan yang berterusan dan berkesan. Berdasarkan analisis prestasi panel solar sebelum dan selepas pembersihan, menggunakan tepung sebagai habuk simulasi, output kuasa menurun sebanyak 40% pada purata dalam keadaan cerah dan 25% dalam keadaan mendung. Selepas pembersihan, kecekapan dipertingkatkan kepada hampir tahap asal, dengan kuasa dipulihkan sebanyak 90-95%. Untuk penanda aras kebersihan berasaskan pasir, output kuasa menurun sebanyak 50% pada tahap kekotoran sepenuhnya tetapi telah dipulihkan kepada lebih 95% tahap garis dasar selepas kitaran pembersihan kedua. Keputusan ini mengesahkan keberkesanan tinggi mekanisme pembersihan automatik dalam mengurangkan kesan kekotoran. Sistem automatik beroperasi secara autonomi, mengurangkan penyelenggaraan manual dan memastikan pembersihan yang berterusan dan berkesan. Ia meningkatkan kecekapan panel dengan ketara dengan meminimumkan pengumpulan habuk, dengan itu meningkatkan prestasi dan jangka hayat sistem PV solar. Inovasi ini menjadikan tenaga solar lebih dipercayai dan menjimatkan kos, terutamanya di kawasan yang terdedah kepada habuk, menjanjikan untuk memajukan daya maju tenaga solar sebagai sumber tenaga lestari.

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LIST OF SYMBOLS

G	-	Irriadiance (W/m^2)
P	-	Power (W)
Isc	-	Short Circuit Current (A)
Voc	-	Open Circuit Voltage (V)
FF	-	Fill Factor
Tmod	-	Module Temperature
Tamb	-	Ambient Temperature
Vm	-	Voltage at maximum power (V)
γ	-	Power temperature coefficient
β	-	Voltage temperature coefficient
α	-	Current temperature coefficient
mm	-	Module dimensions
Pmax	-	Maximum power at STC (W)
Vmp	-	Maximum operating voltage (V)
Imp	-	Maximum operating current (A)
Kmm	-	derating factor due to solar module mismatch
Kg	-	derating factor due to solar irradiance
Ktemp_avg	-	derating factor due to solar temperature average
W	-	Watt

LIST OF ABBREVIATIONS

PV	-	Photovoltaic
WS	-	Wind Speed
ML	-	Multilayer
SC	-	Self-cleaning
AR	-	Anti-reflection
RAEL	-	Relative annual energy losses
MPPT	-	Maximum power point tracker
MPP	-	Maximum power point
TCT	-	Total cross tied
SS	-	Simple series
SP	-	Series parallel
BL	-	Bridge linked
HC	-	Honey comb
DOE	-	Design of experiments
IDE	-	Integrated development environment
IEC	-	International Electrotechnical Commission

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Photovoltaic (PV) systems are a rapidly growing renewable energy technology, offering a clean and sustainable way to generate electricity. However, their efficiency can be significantly reduced by the accumulation of dust, dirt, and debris on the panels, especially inoutdoor environments. This soiling acts like a film, blocking sunlight from reaching the solarcells and hindering their ability to convert light into electricity. Dust buildup can significantly reduce solar panel efficiency. Studies have shown that uncleaned panels can experience efficiency losses ranging from 5% to up to 50% depending on the severity of dust accumulation and the type of dust particles [1] [2].

Traditional cleaning methods for solar panels are often manual and labor-intensive, requiring personnel to physically access and clean the panels. This can be expensive and time-consuming, particularly for large-scale solar farms. Additionally, manual cleaning for high- mounted panels can pose safety hazards and may not be feasible in remote locations. Water- based cleaning methods, while effective, can be a concern in areas with limited water resources.

Therefore, there is a growing need for more efficient and automated cleaning solutions for PV systems. Recent research has explored various self-cleaning mechanisms that can address these challenges. These mechanisms aim to automatically remove dust and debris from the panel surface, minimizing efficiency losses and reducing reliance on manual cleaning methods. Some approaches involve passive techniques, specially coated surfaces that repel dust or self-clean through natural phenomena like rain. Others explore active cleaning mechanisms like automated brushes, wipers, or air jets controlled by sensors that detect the level of soiling.

This project builds upon this existing research by proposing an Arduino-controlled self- cleaning mechanism for PV panels. By utilizing Arduino technology, the system can automate the cleaning process based on sensor data, offering a cost-effective and efficient solution compared to traditional methods. The project aims to contribute to the development of practical and reliable self-cleaning technologies that can improve the overall performance and maintenance efficiency of PV system.

1.2 Problem Statement

PV systems are susceptible to the buildup of dust, dirt, and debris. This can include fine particles like windblown soil and air pollution, as well as grime, bird droppings, and even leaves or twigs. This accumulation acts like a film, blocking sunlight from reaching the solar cells and hindering their ability to convert light into electricity. Furthermore, dust particles can absorb sunlight and raise panel temperatures, which can further reduce efficiency and even create hotspots that damage the cells permanently. Traditional cleaning methods are often manual and water-intensive, creating challenges for large installations. This situation calls for innovation in automated cleaning solutions, which align perfectly with SDG 9. By developing efficient and automated cleaning technologies, we can ensure optimal solar panel performance, promote sustainable practices within the solar industry, and potentially create new jobs in this growing sector.

1.3 Project Objective

The aim of this project is to propose a systematic and effective methodology to clean solar PV Panel using Arduino.

Specifically, the objectives are as follows:

a) To design an Arduino-controlled, brush-based self-cleaning mechanism for PV panels.

b) To develop an automated brush-based self-cleaning mechanism for PV panels.

c) To analyse the performance enhancement and cleaning efficiency of PV systems using a brush-based mechanism.

1.4 Scope of Project

The scope of this project are as follows:

- Selecting and integrating appropriate sensors or timer for the self-cleaning mechanism.
- Designing and building a cleaning mechanism using actuators and timer controlled by Arduino.
- focus on a single panel or a small number of panels for initial development and testing.
- Environmental factors like wind, rain, and extreme temperatures might not be explicitly addressed in the initial development stage. These factors could be considered for future improvements based on the initial testing location.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section provides an overview of existing literature on the development of an Arduino- controlled self-cleaning mechanism for photovoltaic (PV) systems and investigates what research has been conducted to avoid redundancy. Studies have explored how dust and soil buildup affect the efficiency of solar PV systems. According to Mohamed and Hassan (2012), dust accumulation can lead to a rapid decline in efficiency of 36% loss within one month, 60% within two months, and complete loss of efficiency within a year. Their research, conducted in the Sahara environment, focused on the impact of weekly cleaning on PV modules from February to May. Results showed a steady decline in power output, with weekly water washing able to mitigate performance losses of between 2 to 2.5%. Similarly, Ali et al. (2019) investigated dust's influence on PV performance, concluding that it significantly affects installations [3].

Regular cleaning of solar PV panels is essential to ensure maximum energy production and efficiency. Dust, dirt, and debris accumulation on the panel surfaces create a barrier that reduces sunlight absorption, leading to decreased electricity generation. By keeping the panels clean, shading is minimized, preventing efficiency losses and maintaining peak performance. Additionally, cleaning helps to extend the lifespan of the panels by protecting them from damage and corrosion, ultimately maximizing the return on investment in solar technology.

2.2 PV Panel Efficiency Degradation Factors

2.2.1 Environmental factors

2.2.1.1 Effect of Solar irradiance

Irradiance refers to the energy that impacts a unit horizontal area per unit wavelength interval per unit time. The performance of PV panels is heavily influenced by solar power or irradiance, given the highly fluctuating nature of solar resources [4]. The level of variability is linked to the time resolution, increasing with finer time scales [5]. Irradiance typically fluctuates due to factors like weather conditions, seasonal shifts, geographical location, time of day, and the position of the sun in the sky [6]. Changes in sun altitude cause the sun's position to shift throughout the day. Cloudy conditions primarily contribute to variations in irradiance values, as indicated in Figure 2.1.

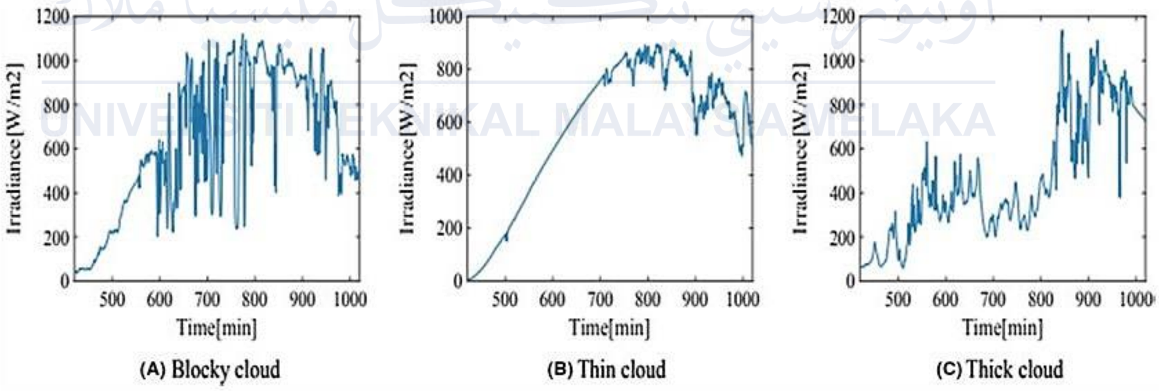


Figure 2.1 Irradiance value changes with different cloudy conditions [7]

PV modules capture both direct sunlight from the sun and scattered light from various sources such as the sky, ground, and nearby objects. However, the primary contribution to irradiance comes from direct solar radiation. Estimating incident irradiance becomes complex when nearby objects cast shadows or reflect sunlight onto the PV modules [8]. To maximize irradiance reception, solar panels are typically tilted to face the sun. The optimal tilt angle depends on the latitude angle (ϕ) of the location, deviating approximately -15° from the latitude angle in summer and +15° in winter. Various solar tracking mechanisms are employed to align PV panels with the direct component of solar irradiance [9]. Each degree of deviation from due south in azimuth orientation results in a 0.08% loss in irradiance [10]

The output of PV modules increases with higher irradiance levels. PV modules can gauge irradiance using the G-P (sun radiation-output maximum power) curve, as it follows an approximately linear pattern [11]. Therefore, the impact of solar irradiance on PV panel performance cannot be quantified by a specific percentage due to the linear correlation between module current and irradiance value, as indicated in the literature [12].

2.2.1.2 Effect of Temperature

The efficient generation of electricity from a PV panel is closely linked to its module temperature. As module temperature rises, electrical efficiency declines due to the fact that PV modules only convert about 20% of solar energy into electricity, with the remaining 80% being converted into heat [13]. There exists a significant correlation between module temperature and the bandgap energy of the PV cell material, with bandgap energy typically decreasing under high operating temperature conditions. This influences the cell to absorb longer wavelength photons and generally extends the lifetime of minority carriers. However, these factors result in a slight increase in the light-generated current (Isc), leading to a decrease in the open-circuit voltage (Voc) and subsequently reducing the cell fill factor (FF). The fill factor quantifies the amount of series and shunt resistance present in a solar cell and its circuit. Electricity generation in the PV module relies on both the short-circuit current (Isc) and the open-circuit voltage (Voc), as the maximum power is determined by Equation (1) [14].

$$P = Vm\ X\ Im = (FF)\ X\ Voc\ X\ Isc \qquad \textbf{Eq 1}$$

According to existing research, module temperature is influenced by various environmental factors, including solar irradiance, wind speed, and ambient temperature, as well as certain PV constructional factors such as materials and glass transmittance. Equation (2) can be used to calculate module temperature [15].

$$Tmod = Tamb + Irradiance\ X\ exp(-a - b\ X\ WS) + \Delta T\ X\ \frac{Irradiance}{1000} \qquad \textbf{Eq 2}$$

In the provided equation, the constants a, b, and ΔT are specified, with values of 3.56, 0.0750, and 3, respectively, for glass/cell/polymer sheet. Here, WS denotes wind speed in meters per second (m/s). According to literature findings, the efficiency of a solar cell experiences a slight increase up to 12% when the cell temperature reaches 36°C. However, beyond this temperature, efficiency begins to decline, as depicted in Figure 2.2 [16].

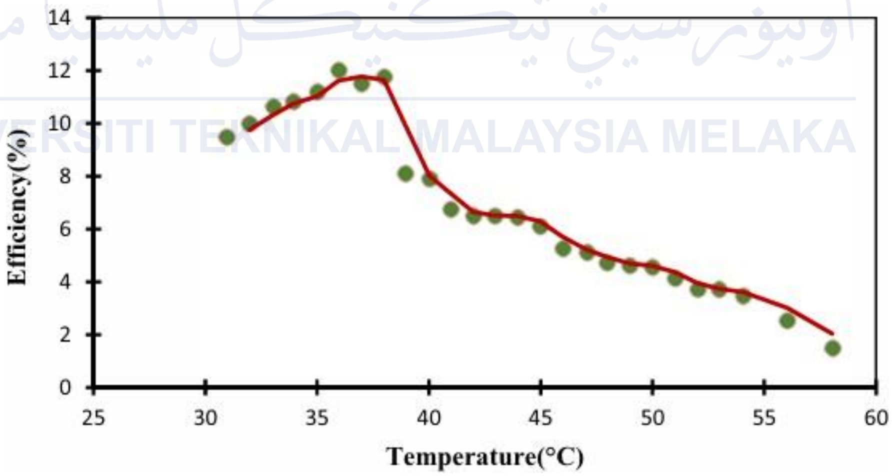


Figure 2.2 Effect of module temperature on efficiency

2.2.1.3 Effect of Dust accumulation

The efficiency of PV modules diminishes due to atmospheric pollutants like dust, water vapor, air molecules, and other contaminants hindering sunlight from reaching the PV panel. Dust particles in the air, larger than the wavelength of incoming solar beams, scatter sunlight, leading to decreased solar irradiation. Additionally, dust accumulation on PV module surfaces can alter optical properties, increasing light reflection and absorption while reducing surface transmissibility, thereby lowering PV module output. The degree of dust accumulation is influenced by environmental factors such as wind speed, humidity, rainfall, dust particle source and type, PV module technology, and surface cover. Desert areas with high dust density and low rainfall are particularly susceptible to severe dust accumulation. Studies conducted in Saudi Arabia indicate an average monthly efficiency degradation rate of 6-7% [17], which can increase to 13% within six weeks without cleaning [18][19].

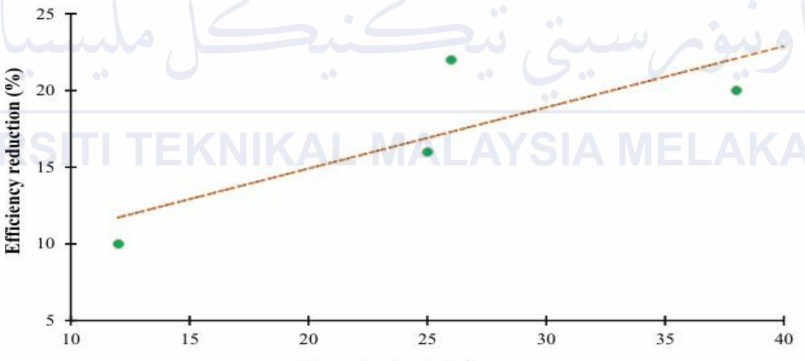


Figure 2.3 Module efficiency reduction vs dust density

Furthermore, the output power generation of PV systems could decline to half of its maximum value (50%) in the absence of cleaning [19]. Elminir et al. found that output power decreases by approximately 17.4% per month in Egypt [20]. This situation worsens in the presence of air pollutants, toxic gases, suspended particles, and dust, resulting in over a 60% reduction in PV energy output [20]. Dust particles settle on module covers due to gravity, absorbing water vapor in humid air and forming adhesive mud on surfaces. Said et al.

demonstrated that a 45-day dust accumulation period reduces overall glass cover transmittance by 20% [19]. The impact of rainfall on dust deposition is notable, as PV power output drops to 60-70% when annual rainfall in Egypt ranges from 18-50 mm [21]. Conversely, studies in the UAE and Qatar, with higher annual rainfall of 80-90 mm and 70-75 mm respectively [22][23], exhibit a lower (10%) deterioration in PV power generation compared to Egypt. Additionally, conversion efficiency decreases with increasing dust density, as depicted in Figure 2.3. In certain regions, dust density may decrease due to factors such as rainfall, wind, and other environmental conditions. Table 2 lists the reduction in PV efficiency resulting from dust accumulation in various climatic regions. Implementing an appropriate cleaning schedule can restore maximum PV module output year-round.

Table 2.1 Performance loss due to dust accumulation on PV module

				Other conditions (average)					
Location	Panel η (%)	Duration	Dust density (g/m^3)	Tilt angle (°)	Ambient temp (°C)	Humidity (%)	Wind velocity (m/s)	Maximum reduction in power (%)	References
Tehran, Iran	15.5	70 days	6.0986	Facing south	34	28	4.6	21.47	68
Santa Clara, USA	7.2	108 days	-	16.4	-	-	-	1.6	69
Thailand	-	60 days	0.425	-	-	-	-	7.28	70
Malaga, Spain	13.4	10 months	-	21	14.7–29.1	52–66	1.2–2.8	12.5	71
Dhahran, Saudi Arabia	11.3	8 months	6.184	26	-	-	-	49	51
Limassol, Cyprus	-	10 weeks	-	31	-	Rainy	-	13	72
Isfahan, Iran	-	70 days	10.3129	15	-	Ignored	2–3	23.83	73
Kuwait	-	30 days	42.5	30	-	-	Low	33	74
Brighton, UK	20.4	3 weeks	0.000815	0	4–4.7	75.6–81	-	5	75

2.2.1.4 Effects of Soiling

Dust accumulation on PV modules can lead to soiling. In humid conditions, dust particles settle on PV surfaces and absorb moisture from the air, forming mud. The adhesive force between dust particles and PV surfaces increases with higher absolute humidity, promoting dust accumulation. Additionally, vapor condensation on the PV module creates capillary bridges between particles and the surface, enhancing dust buildup. Soiling causes both soft and hard shading on PV panels, reducing power output. Soft shading is caused by atmospheric smog, while hard shading results from soil or mud on the panel. Despite hard shading decreasing voltage in some cells of a PV module, the current remains constant as unshaded cells still receive solar irradiance. Similar to dust accumulation, PV power loss due to soiling varies geographically due to different dust types affecting light transmission. The relationship between soiling mass and PV power loss has been extensively studied in the literature.

Table 2.2 Some cooling techniques to enhance the power extraction

Cooling techniques	Conditions	Achieved PV panel temperature range	Energy increases	References
Natural ventilation	-	Reduced to 55.5°C from 76.7°C	Annual electrical energy increased by 2.5%	30
Active ventilation	Forced convection with an airspeed of about 2 m/s	Reduction of cell operating temperatures of 18 K	Electrical output increased by 8%	31
Active cooling by water	Water sprinkle on both sides of PV panel simultaneously	30°C module temperature reduction	7.7% and 5.9% increase in electric power output and efficiency respectively	32
Active cooling by water	Water film cooling on the front surface of the panel	26°C module temperature reduction	15% increase in power output	33
Active cooling by water	Direct water spraying	23°C module temperature reduction	Increases the mean PV cell efficiency, subsystem efficiency and total efficiency by 3.26%, 1.40% and 1.35% respectively	34
Natural vaporization cooling	Installation of panels on the river canals and other places where vaporization exists	39.3–48.3°C	7.3% increase in power output	35
Liquid immersion cooling	A 250X dish concentrator with 940 W/m² direct normal irradiance	Can be cooled to 45°C	Electrical performance degrades after a fairly long time immersion in the de-ionized water	36
Diffusion of water by cotton wicks on PV panel backside	Standalone flat PV modules	20°C decrease in module temperature and cool down to 45°C	15.5% increase in electrical efficiency	37
Thermoelectric cooling	A thermoelectric cooling module is considered to be attached to the backside of a single PV cell	344.41 K (when the ambient temperature is 350.45 K)	0.0704 W extra power output	38
Thermoelectric cooling	Solar insolation range of 0.8–1 kW/m²	Cell temperature 25–45°C	Increases efficiency in the range of 1–18%	39
Thermoelectric cooling	Using Peltier effect	Reduces the operating temperature from 83°C to 65°C	Increases the panel efficiency up to 1.33%	40
Water cooling	2 L/min water through twelve nozzles	Up to 22°C	Net electricity gain increased by 8–9%	41
Radiation and free convection	An open channel is fitted beneath the PV module	10–20°C reduction In module temperature	1–2% gain in efficiency	42
Extended areas	Using lapping fins	Lower the module temperature by 24.6°C	Panel efficiency is 10.68%	43
PVT system	Using CuO nanofluid	Surface temperature drops up to 57.25%	Maximum power reaches up to 51.1% than no cooling system	44
Heat pipe technology	Pulsating heat pipe cooling system	5°C cell temperature reduction	Increasing in electrical efficiency of 0.77%	45
Latent heat sink by PCM	Using $CaCl_2 6H_2O$	25–30°C	Power saving of 13%	46
Latent heat sink by PCM	Two types of PCM are used	42°C	-	47
Latent heat sink by PCM	PCM container is attached to the backside of three 65 W panel	12°C reduction in module temperature	0.4 V gain in voltage	48

In certain instances, the decrease in PV power output correlates directly with the amount of soiling present. As the surface becomes heavily soiled, additional dust settling on existing particles does not further block light. Research indicates that transmittance can decrease by 30% for coated glass and 37% for uncoated glass after 40 days of exposure in Saudi Arabia. Reduction in transmission varies depending on the type of glass material, such as multilayer (ML), self-cleaning (SC), anti-reflection (AR), and regular glass, as tested in Belgium with a 35° tilt angle and average rainfall periods.

2.2.1.5 Effects of shading

Shading refers to any obstruction that blocks light from reaching the PV panel, thereby reducing its power output. Shading can take various forms, such as hard shading, soft shading, and self-shading. Hard shading results from the accumulation of debris like dust, snow, bird droppings, and leaves, as well as obstructions like poles, trees, and buildings that cast clear, defined shadows. Conversely, atmospheric factors like dust, fog, and smoke diminish irradiance intensity, leading to soft shading on the PV module. Self-shading, illustrated in Figure 2.4, occurs when the preceding row of PV modules casts shadows on subsequent rows. Several techniques have been devised to mitigate the effects of self-shading. Brecl, for instance, formulated an empirical equation with a 300° inclination angle to calculate relative annual energy losses (RAEL) due to self-shading, using parameters A and F, where F represents the spacing factor (d/b) with values between (1.5 < F <5).

$$\mathrm{RAEL} = A \times e - 2.3F - 0.001 \times F + 0.01$$

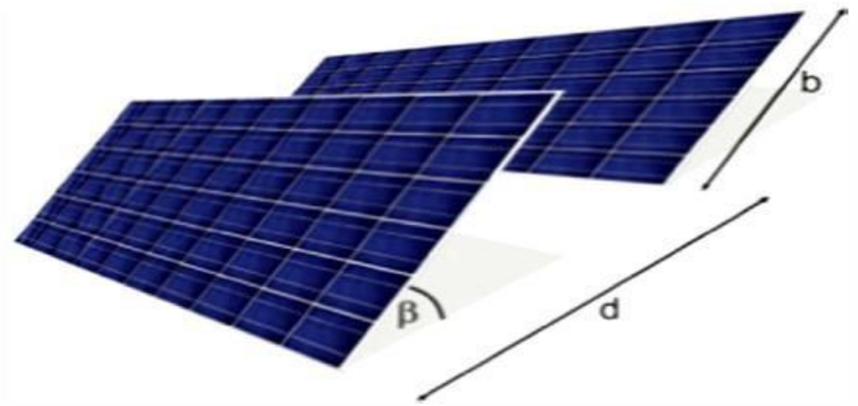


Figure 2.4 Self-shading caused by the proceeding row of PV modules [24]

Partial or complete shading of PV modules depends on factors like module position, array configuration, and shading scenario, resulting in a significant decrease in module output. Partial shading, which obstructs some cells of a PV module, can severely impact module output because shaded

Cells are unable to produce current. Consequently, current from non-shaded cells flows through shaded ones, leading to operation in a negative voltage region and power dissipation instead of generation. Furthermore, shading can cause the maximum power point tracker (MPPT) to shift away from the global maximum power point (MPP), resulting in reduced energy production. Researchers have explored these losses and devised technical solutions to mitigate them. The effects of shading on PV power output are evaluated using various numerical and experimental configurations.

Table 2.3 Performance of PV module in partial shading conditions

Conditions	Area shaded	Results
Numerical simulation	2%	70% loss of energy
An arrangement of 33 cells of PV panel	Minimum loss: 24 half-shaded cells Maximum loss: 21 completely shaded cells	Power losses vary from 19% to 79%
Non-transparent materials are used for shading	25% solar radiation	Energy and exergy efficiencies are 7.28% and 5.74%, respectively, compared to 8.19% and 8.05%, respectively, for no shading conditions
An arrangement of 36 solar cells in different configurations are investigated	Partially shading which varies the solar radiation from 0.85 to 1.01 kW/m^2	Highest value of the peak power is obtained for TCT (total-cross-tied) configuration than SS (simple series), SP (series-parallel), BL (bridge-linked) and HC (honey-comb) configurations
Shading effect of wall tree and seasonal variations are considered in both summer and winter	-	Energy degrades about 15% in winter and 1% in summer

2.2.2 Operation and Maintenance Factors

2.2.2.1 Panel degradation

The gradual decline in the performance characteristics of a PV system, known as panel degradation, can impact its power generation capabilities. According to manufacturer recommendations, a panel is considered degraded when its power output falls below 80% of its initial power [25]. Various factors such as temperature, humidity, irradiation, and mechanical shock contribute to the degradation of PV panels. Table 4 outlines different causes of panel degradation. Hot spot formation is a significant concern; as elevated temperatures can damage cells. Hot spots are generated by partially shaded, damaged, or mismatched series-connected cells [26] [27]. Studies have proposed algorithms to mitigate hot spots, with Jerada et al. suggesting an accurate and rapid hot spot detection method. Proper maintenance addressing these issues can prevent unwanted power generation losses [28].

Table 2.4 Degradation of PV Panel

Type	% of loss	Details
Corrosion	19%	Moisture enters into the metallic connections of the panel housing and increases the electrical conductivity, leakage current
Delamination	42%	Adhesion loss between the cells and front glass increases the light reflection and moisture penetration
Discoloration	12%	Glass cover or adhesive material changes their colour and turns into yellow or brown over the years of operation, resulting in a low transmittance of light
Breaking	19%	Glass breakage occurs during installation, screw tightening and maintenance that creates the risk of electrical shock and moisture infiltration
Ribbon crack	8%	Same as glass breaking and produce a low power output

2.3 Classification and Current state of Cleaning Method for Solar PV

2.3.1 Natural removal of dust

The natural removal of dust from solar PV panels relies on environmental forces such as wind, gravity, and rainwater. While these elements can aid in dust removal to some extent, their effectiveness is often limited, especially in areas with low wind or rainfall. Some systems utilize the tilt of the solar panel array during specific times of the day or weather conditions to facilitate easier dust removal, but this approach may not be sufficient for larger arrays due to practical challenges in rotation. The effect of this method is not very well.

2.3.2 Mechanical removal of dust

Among the array of solar panel cleaning methods, mechanical systems are widely employed, with brushes or compressed air commonly utilized to clean the panel surface. However, there is a risk of damaging the glass surface of the panels with brushes, potentially causing scratches or other forms of harm. Following a study on micro-controller-based dust cleaning for photovoltaic systems conducted by Al-Qubaisi et al., power loss was assessed, leading to enhancing panel output energy efficiency [29].

Figure 2.5 Mechanical cleaning system [30]

2.3.3 Electrostatic removal of dust

These systems incorporate a sand-repelling sheet containing parallel electrodes situated beneath the glass of the solar panel. As sand particles descend from the panel, the device induces a back-and- forth motion, effectively dislodging dust particles from the panel surface. Research conducted in Japan achieved impressive cleaning effectiveness through the use of low-frequency, high-voltage application, along with steep panel inclination and minimal initial dust accumulation. Subsequent cleanings resulted in minimal residual dust accumulation, and the system exhibited low power consumption. This advanced technology is anticipated to greatly enhance the efficiency of large-scale solar power plants situated in dusty environments [31].

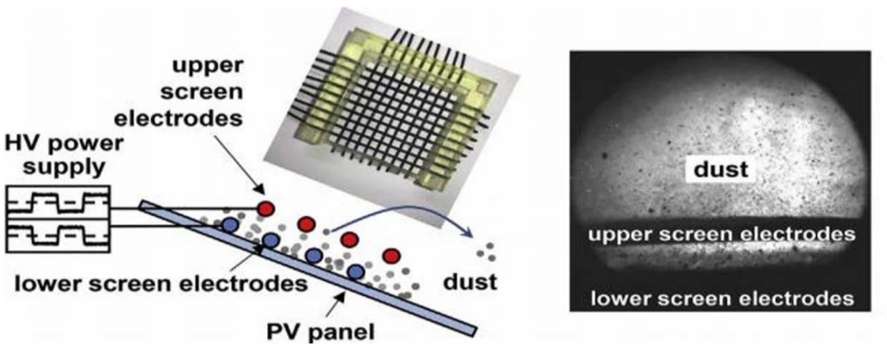


Figure 2.6 System structure of the electrostatic cleaning system [31].

Figure 2.6 illustrates the system architecture of the suggest electrostatic cleaning mechanism. By applying a high AC voltage across the parallel screen electrodes, Coulomb and dielectrophoretic

Forces are generated, affecting the dust particles in proximity to the electrodes. These particles are influenced by the alternating electrostatic field near the electrodes, causing some to pass through the aperture in the upper screen electrode due to their inertial forces

2.3.4 Manual Cleaning method

Manual cleaning is a commonly employed technique for maintaining solar panels. In this method, the assessment of panel cleanliness is determined by personnel. Cleaning typically occurs on a monthly basis, utilizing pure water. Figure 2.7 illustrates a PV cleaning apparatus entirely operated by staff. The primary drawback of manual cleaning systems lies in the reliance on staff to determine the appropriate cleaning schedule. Failure to accurately gauge the timing of cleaning can result in decreased electricity generation from PV panels.

Figure 2.7 Manual Cleaning method

2.4 Concluding remarks on PV Panel Efficiency degradation

This section has comprehensively reviewed various factors that can lead to degradation in PV panel efficiency. Environmental factors like fluctuating solar irradiance, temperature variations, dust accumulation, soiling, and shading were identified as key contributors. In conclusion, understanding and mitigating these degradation factors is crucial for ensuring optimal performance and maximizing the long-term energy production of a solar PV system. By implementing effective maintenance strategies and addressing environmental challenges, solar energy can continue to be a reliable and sustainable source of power.

2.5 Previous Work on development of Self-Cleaning Dust Removal System

Reference	Title	Authors	Application	Main finding
[32]	Smart Dust Detection and Automation Cleaning of Photovoltaics Panel	Muhammad Aiman Mohamad Rafie	ESP32 Dev Module Dust Sensor (GP2Y1010AU0F)	reduced energy losses minimizing manual intervention and maintenance costs.
[33]	Automatic Solar Panel Cleaning System	Manju B	Arduino uno & Timer	Autonomous self-cleaning mechanism and operated without human operation.
[34]	A solar tracking system with light-dependent resistors and a stepper motor controlled by a microcontroller	Bushra Sabir	Arduino Uno & Light Dependent Resistor	71 percent improvement over the static solar panels used in the comparison.

[35]	Automatic solar panel cleaning system based on Arduino for dust Removal	N V NARASIMHARAOL	Arduino Uno & Light Dependent Resistor	Experimental results show that the proposed cleaning system can operate with an efficiency of 60- 70%
[36]	Developing an Automatic Dust Cleaning Unit to Improve the Photovoltaic Panels Productivity	Elmeadawy, M. I.	Arduino Uno Ir sensor and Timer	Improves the energy produced from PV panel by 42.32% compared to the control.
[37]	A Low-Cost and Energy-Efficient Smart Dust Cleaning Technique for Solar Panel System	Nithin Sha Najeeb	(ILC 131 ETH)	Very less human involved in the operation for cleaning the panels in solar farm

[38]	Design of Automatic Cleaning System on Solar Panel Using IoT-based Wiper	Muhammadin Hamid	ESP 8266 RTC	Allowing real-time monitoring of the solar panel surface condition using an Android device
[39]	Smart solar photovoltaic panel cleaning system	Nasib Khadka	Particle Photon (TSL 2561) DHT11 GP2Y1014AU0F	mainly focused on its application in large scale solar farms having uniform solar arrays throughout the plant.
[40]	Design and Construction of an Automatic Solar Panel Cleaning System	Eiche, J. F.	Arduino Wi-Fi module Nodemcu microcontroller	Increase in power output after cleaning, with the power output reaching 53.69 W compared to initial 48.5 W.

[41]	Automatic Solar Panel Cleaning System	Nagesh Maindad	ATmega16A GSM Module	The cost of production is low. No need to purchase heavy machinery. Reduces human efforts.

2.6 Summary

The literature review in Chapter 2 explores various studies and research works related to the development and optimization of self-cleaning mechanisms for photovoltaic (PV) systems. It begins by examining the impact of soiling on the efficiency of PV panels, highlighting how dirt accumulation can significantly reduce energy output. Previous works have demonstrated that regular cleaning can enhance the performance of solar panels, but manual cleaning is labor-intensive and costly. Several studies have proposed automated cleaning solutions, utilizing different technologies such as brushes, wipers, and water sprays. The review notes that while these methods are effective, they often require substantial amounts of water and energy, raising concerns about their environmental impact.

Further, the review delves into the advancements in sensor technologies and microcontroller-based systems, particularly focusing on the use of Arduino for automation. Various authors have successfully implemented Arduino-controlled systems for a range of applications, including environmental monitoring and automation tasks. The incorporation of rain sensors in these systems has shown promise in optimizing cleaning schedules by preventing operation during adverse weather conditions. This integration not only enhances the efficiency of the cleaning process but also conserves resources. The review concludes by identifying gaps in the existing research, such as the need for more energy-efficient and environmentally friendly cleaning mechanisms, setting the stage for the current project’s aim to develop an optimized, Arduino-controlled self-cleaning system for PV panels.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Self-cleaning dust systems have emerged as a pivotal technology aimed at enhancing operational efficiency and environmental sustainability. These systems are designed to automate the removal of dust and particulate matter from various industrial processes, reducing manual labor and ensuring consistent performance. The core principle behind self-cleaning dust systems involves the utilization of advanced filtration technologies and mechanical components that work in synergy to detect, capture, and expel dust particles without interrupting the operational workflow. This automation not only minimizes the risk of equipment damage due to dust accumulation but also significantly improves air quality, aligning with stringent environmental regulations.

The significance of self-cleaning dust systems extends beyond mere operational efficiency. In industries such as manufacturing, mining, and agriculture, where dust generation is inevitable, these systems play a crucial role in safeguarding worker health by mitigating exposure to harmful airborne particles. By incorporating self-cleaning mechanisms, these systems ensure that filters and collectors maintain optimal performance over extended periods, reducing the frequency of maintenance and downtime. Furthermore, the integration of smart sensors and real-time monitoring capabilities allows for proactive management of dust levels, thereby enhancing overall productivity and sustainability.

3.2 Methodology

This project tackles the challenge of maintaining optimal performance in photovoltaic (PV) systems by developing a self-cleaning mechanism controlled by an Arduino microcontroller. Solar panels suffer efficiency drops due to dust, dirt, and debris buildup, especially outdoors. Traditional cleaning methods are labor-intensive and require frequent attention. This project proposes an innovative solution to automate the cleaning process using Arduino technology.

The system will rely on a timer and rain sensor to determine when to clean the PV panels. The timer will schedule regular cleaning intervals, while the rain sensor will detect rainfall and utilize it for natural cleaning. Data from these components will be transmitted to the Arduino board. Arduino will then use this information to decide when to activate the cleaning mechanism. This mechanism could utilize brushes, wipers, or other cleaning tools driven by actuators controlled by the Arduino board. Material selection for these components will be crucial. For instance, brushes may need to be soft enough to avoid scratching the panel surface, while wipers would require a material that effectively removes dirt without leaving streaks.

The overall system operation will be automated. The timer will ensure regular cleaning, and the rain sensor will detect rain to trigger cleaning when appropriate. The Arduino will analyze data from the timer and rain sensor to activate the cleaning mechanism only when necessary, optimizing water usage (if applicable) and minimizing wear on the cleaning components. The control logic programmed onto the Arduino will dictate the movement and operation of the cleaning mechanism, ensuring thorough cleaning of the entire PV panel surface.

3.2.1 Flowchart objective 1

To design and develop an Arduino-controlled, self-cleaning mechanism for PV panels.

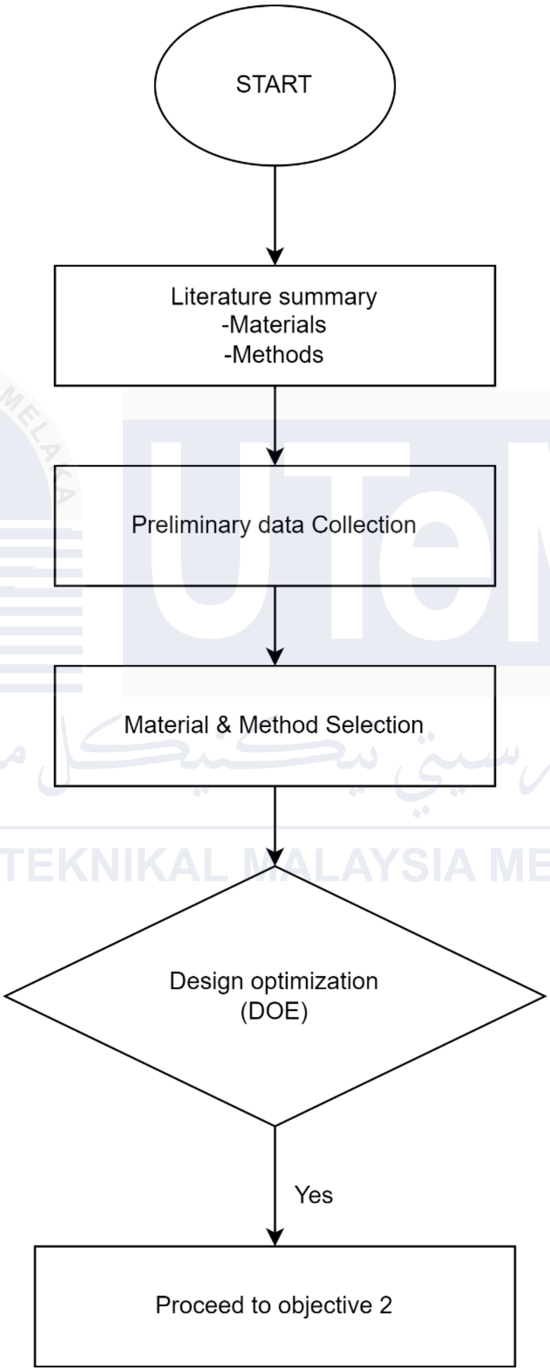


Figure 3.1 Process flowchart of objective 1

3.2.2 Flowchart Objective 2

To develop a self-contained, automated cleaning system for PV panels.

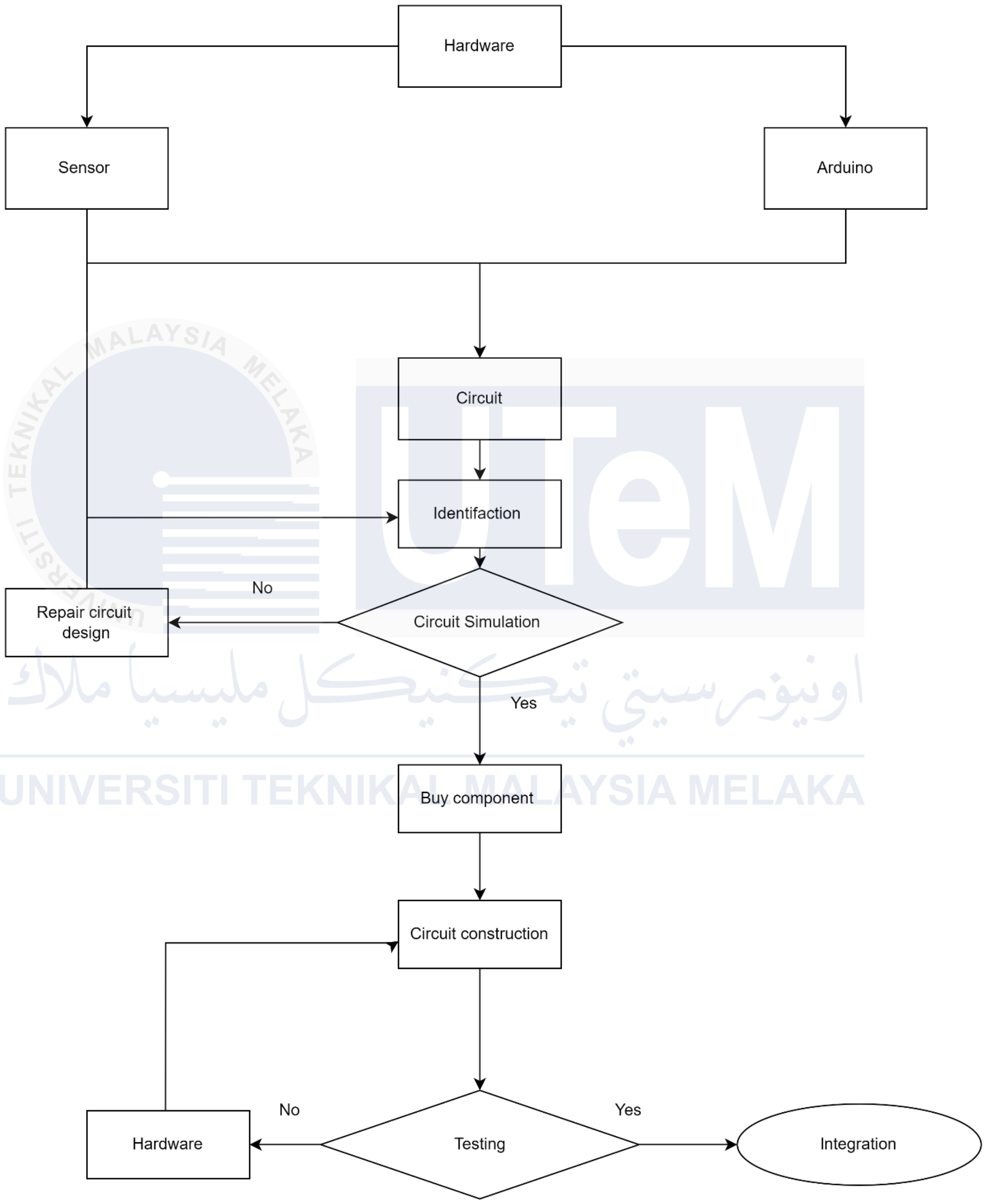


Figure 3.2 Process flowchart of objective 2

3.2.3 Flowchart Objective 3

To analyse the improvement performance and maintenance efficiency of PV systems.

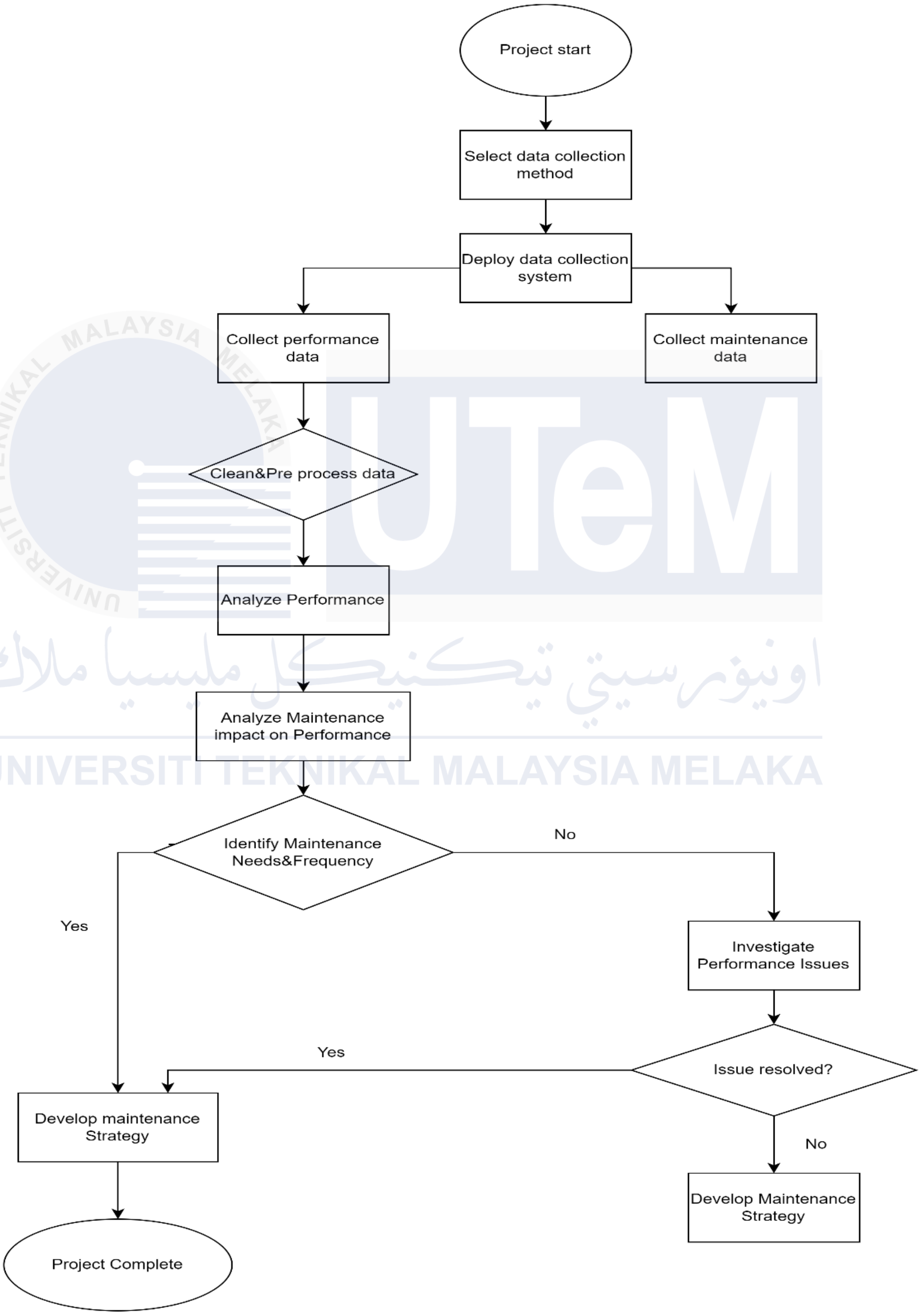


Figure 3.3 Process flowchart of objective 3

3.3 System Design

3.3.1 Mechanical Structural Design

This section explains the project "Development of an Arduino-Controlled Brush-Based Self-Cleaning Photovoltaic System", focusing on the mechanical design of the cleaning mechanism. SolidWorks software was utilized to create a detailed 3D model of the system, as shown in Figure 3.4. The design incorporates several key components a rotating brush powered by a DC motor, a stepper motor for precise movement, a water pump and storage system for delivering water to assist in cleaning, aluminum profile rails for structural support, and a gutter for collecting wastewater.

The cleaning mechanism moves along the solar panel's surface, guided by rails, and is equipped with a rotating brush to remove dust and debris. The water pump ensures consistent water flow to dissolve and wash away dirt, enhancing the cleaning process. Two limit switches are strategically placed at the top and bottom of the system to control and reverse the movement of the cleaning mechanism, ensuring safe and efficient operation.

This innovative design maximizes the efficiency of photovoltaic panels by minimizing energy losses caused by dirt accumulation. It is a sustainable and automated solution for maintaining solar panel cleanliness, reducing the need for manual intervention and improving the overall energy output of the system.

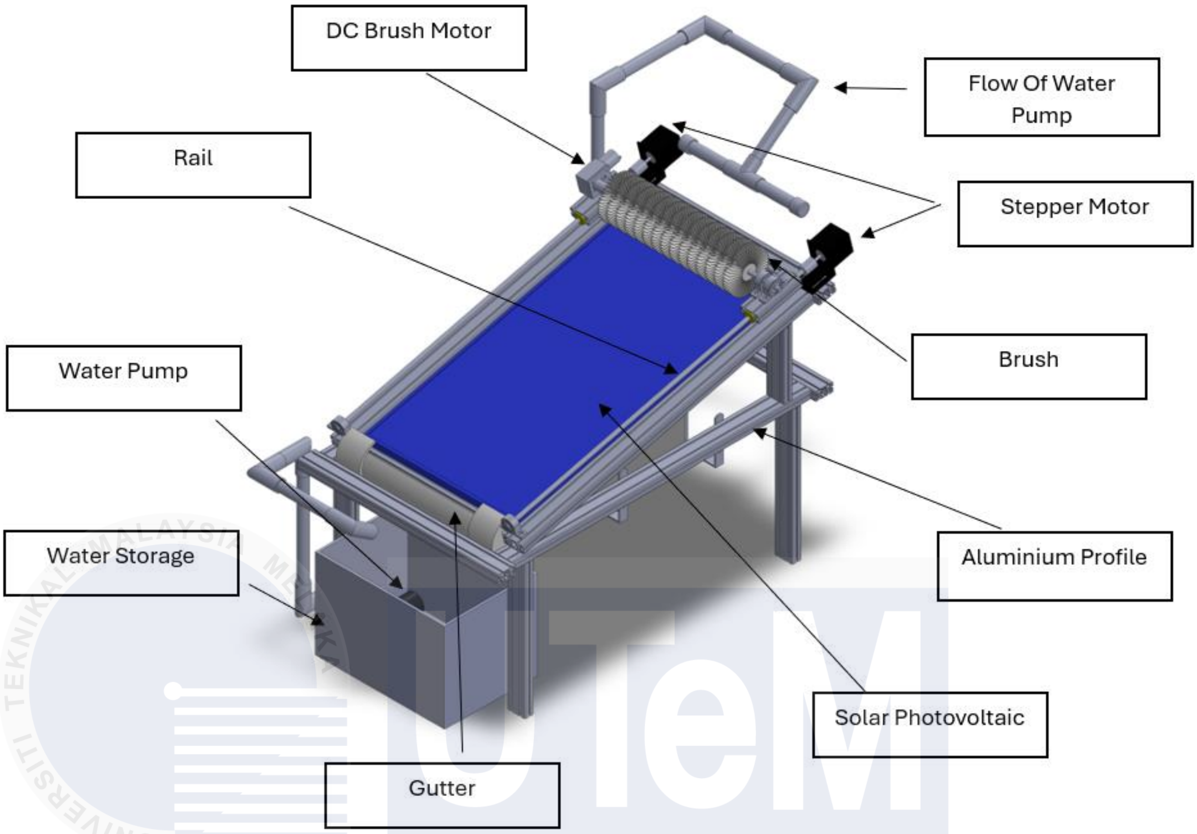


Figure 3.4 Project prototype of Brush-Based Self-Cleaning Photovoltaic System using Solidworks software

3.3.2 Electrical Design

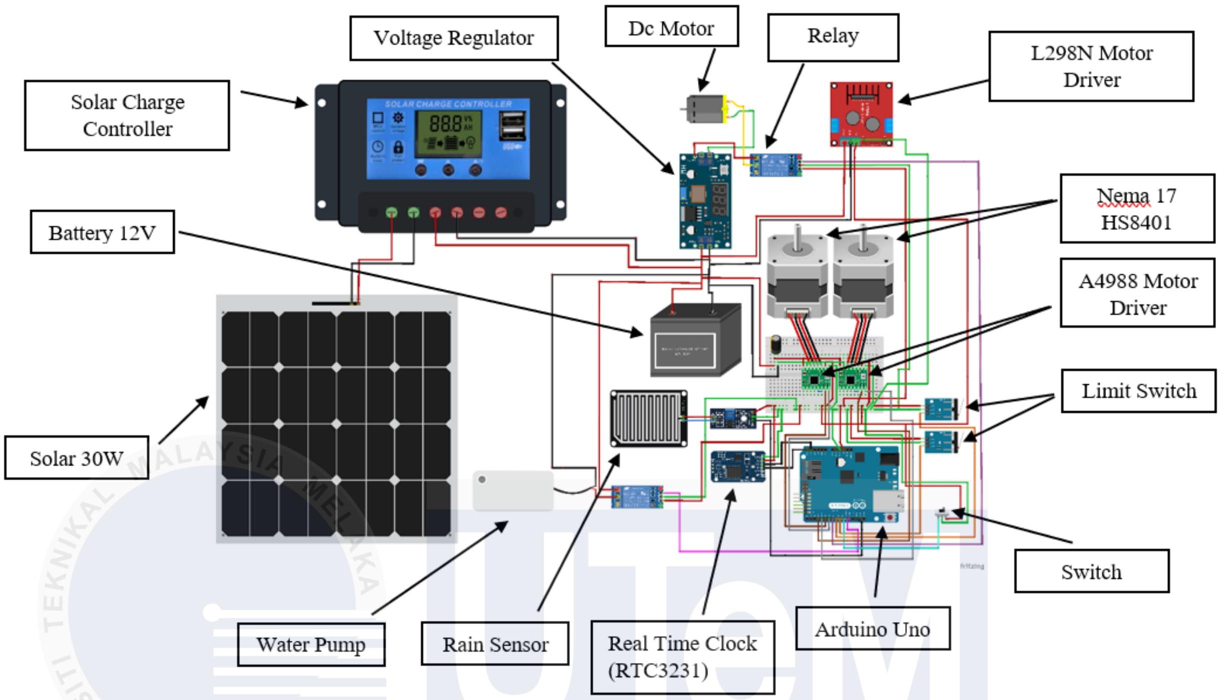


Figure 3.5 Full circuit of Brush Based Self Cleaning Photovoltaic System using Fritzing Software

The electrical circuit of the brush-based self-cleaning photovoltaic system, as depicted in Figure 3.5, integrates several key components to ensure efficient operation. A 30W solar panel powers the system, charging a 12V battery via a solar charge controller to regulate the voltage. The system includes an Arduino Uno microcontroller that manages the cleaning operations, interfacing with various sensors and components. The Real-Time Clock (RTC) module provides accurate timing for scheduled cleaning. A rain sensor detects wet conditions to trigger the cleaning process. The brush mechanism is driven by a Nema 17 stepper motor controlled by an A4988 motor driver, while the movement of the brush is managed by a DC motor linked to an L298N motor driver. Two limit switches are positioned at the top and bottom to define the cleaning brush's range of motion. A water pump is activated to spray water during cleaning. This comprehensive setup ensures the solar panels are regularly cleaned, maintaining their efficiency and performance.

3.3.3 Project Flowchart

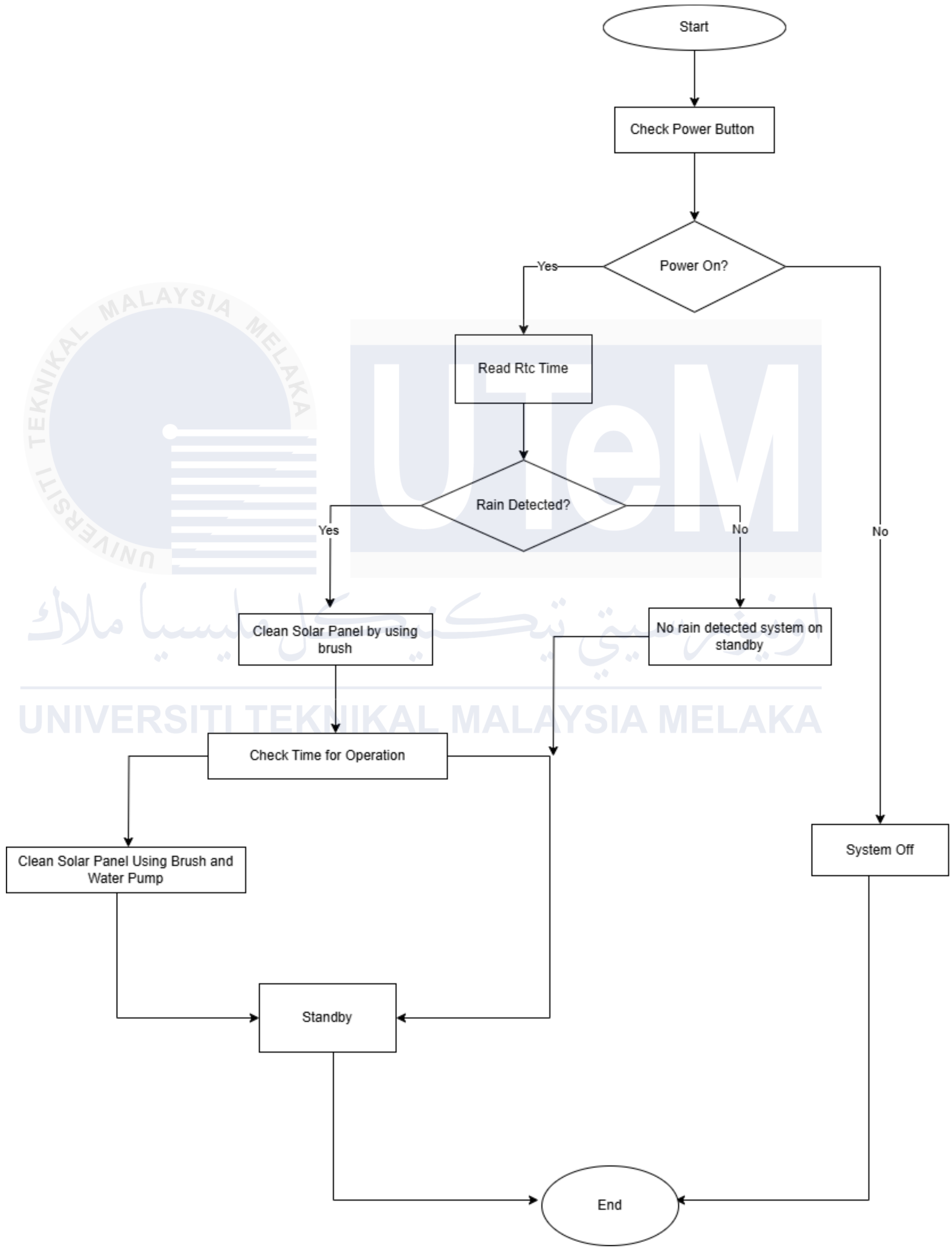


Figure 3.6 Project Flowchart of the sys

The project flowchart outlined in Figure 3.6 details the operational process of an Arduino-controlled self-cleaning photovoltaic (PV) system designed to maintain the efficiency of solar panels by regularly cleaning them. The system initiates its operation by checking the power button to ensure the device is turned on. Once activated, it reads the current time from the Real-Time Clock (RTC) to determine the subsequent actions. A significant feature of the system is its ability to detect rain, which often leaves residues that can reduce the efficiency of solar panels. If rain is detected, the system initiates a cleaning cycle using a brush to remove any debris. If no rain is detected, the system remains on standby, conserving energy until the next scheduled cleaning cycle.

At specified times, the system checks if it is time for operation and, if so, proceeds to clean the solar panels using both a brush and a water pump, ensuring thorough cleaning. This dual approach guarantees that the panels are free of dust and other particles that can hinder their performance. After completing the cleaning process, the system returns to standby mode, ready to reactivate when necessary. This intelligent design ensures that the PV panels operate at maximum efficiency by maintaining their cleanliness, thereby enhancing the overall effectiveness of solar energy production. Figure 3.6 effectively visualizes the logical sequence and decision-making process, showcasing a practical solution for sustainable energy maintenance.

3.3.4 Coding of Simulation System

The Arduino code provided controls a self-cleaning photovoltaic system using a brush and water pump. The system monitors rain using a rain sensor and operates based on a schedule set via a Real-Time Clock (RTC) module. The **Setup** function initializes the pin modes and states for various components, such as the rain sensor, stepper motors, brush motor, water pump, and limit switches. The **Loop** function continuously checks the power button state, rain sensor, and the current time to decide whether to start a cleaning cycle. If rain is detected or if the current time matches the scheduled cleaning time, the system initiates the cleaning process.

During the cleaning process, the YesraincleanSolarPanel and NoraincleanSolarPanel functions control the movement of the brush motor and water pump. These functions move the motors down and up while the brush motor is active, ensuring thorough cleaning of the photovoltaic panels. The moveMotorsDown and moveMotorsUp functions handle the motor movements by setting the appropriate direction and stepping the motors until the respective limit switches are triggered. The stepMotor delay controlling the motor speed. This coordinated operation ensures that the solar panels are cleaned effectively, either when rain is detected or according to the set schedule.function controls the stepping of the motors by toggling the step pins with a specified

Library Inclusions and Pin Definitions

```
#include <Wire.h>
#include <RTClib.h>

// Pin Definitions
#define RAIN_SENSOR_PIN 13
#define MOTOR1_STEP_PIN 5
#define MOTOR1_DIR_PIN 6
#define MOTOR2_STEP_PIN 3
#define MOTOR2_DIR_PIN 4
#define BRUSH_MOTOR_PIN 7
#define WATER_PUMP_PIN 11 // Water pump pin
#define BOTTOM_LIMIT_PIN 8 // Bottom limit switch
#define TOP_LIMIT_PIN 9    // Top limit switch
#define POWER_BUTTON_PIN 10 // Power button pin
```

Figure 3.7 Library and Pin Definition in Arduino Ide Software

The Arduino code begins by including two libraries, Wire.h and RTClib.h, which are essential for I2C communication and real-time clock functionality. The Wire.h library facilitates communication between the Arduino and the RTC module, while RTClib.h provides functions to interact with the RTC, ensuring accurate timekeeping for the system's operations. These libraries are crucial for synchronizing the photovoltaic system's cleaning operations with real-time events.

The code also defines the pin connections for various components using the #define directive. This assigns specific pin numbers to human-readable names, making the code easier to understand and maintain. For example, the rain sensor is connected to pin 13, the stepper motors are controlled via pins 3, 4, 5, and 6, and the brush motor and water pump are connected to pins 7 and 11, respectively. Additionally, the bottom and top limit switches are connected to pins 8 and 9, and the power button is connected to pin 10. These pin definitions allow the Arduino to interact with the hardware components effectively, enabling the automated cleaning process of the photovoltaic system.

Global Variable and Constant

```
bool hasOperatedRain = false;

const int STEPS_PER_REVOLUTION = 200; // Adjust according to your motor specs
const int CLEANING_CYCLES = 1; // Number of cleaning cycles
const int CLEANING_DELAY_MS = 1000; // Delay between movements (adjust as needed)
const int MOTOR_SPEED_DELAY = 1000; // Delay between steps (adjust for speed)

RTC_DS3231 rtc;
bool isPowerOn = false;

// Set the time for the brush motor and water pump to operate
const int START_HOUR = 17; // Set start hour (24-hour format)
const int START_MINUTE = 52; // Set start minute
const int STOP_HOUR = 17; // Set stop hour (24-hour format)
const int STOP_MINUTE = 53; //1 Set stop minute
```

Figure 3.8 Variable and Constant

This section of the code establishes key constants and global variables that define the behavior and timing of the solar panel cleaning system. The variable “hasoperatedrain” is a boolean flag initialized as false, ensuring the system triggers a cleaning operation only once during a rain event. Constants like “steps_per_revolution” define the motor's specifications, while “cleaning_cycles” sets the number of cleaning repetitions during a single operation. Delays such as “cleaning_delay_ms” and “motor_speed_delay” are used to control the timing of motor movements and speed, ensuring smooth and efficient cleaning cycles.

The real-time clock (rtc) module, represented by the rtc variable, tracks the current time for scheduled operations. The boolean is “poweron” monitors whether the system is active, allowing or disabling cleaning functions accordingly. The cleaning schedule is managed using constants like” start_hour” and “start_minute”, which determine the time the system begins operation, and “stop_hour” and “stop_minute”, which specify the stop time. These parameters ensure the system operates only during designated periods, enhancing efficiency while conserving resources.

Parts of the Main Loop

Power State Check

```cpp
if (digitalRead(POWER_BUTTON_PIN) == LOW) {
    isPowerOn = true;
    Serial.println("System is READY to operate.");
} else {
    isPowerOn = false;
    Serial.println("System is OFF.");
}
```

Figure 3.9 Coding of the System Switch

The Power State Check functionality is integral to the Arduino-controlled self-cleaning photovoltaic system. This feature ensures that the system only operates when it is supposed to. It continuously monitors the state of the power button using a digital input pin. If the button is pressed (indicating a low signal), the system sets the isPowerOn flag to true, signaling that the system is ready to operate. Conversely, if the button is not pressed, the isPowerOn flag is set to false, indicating that the system is off. This mechanism prevents the system from running unnecessary operations and conserves energy by ensuring that the cleaning process only initiates when the power button is in the "on" state. This check is crucial for maintaining the system's efficiency and reliability

Check Current Time

```
DateTime now = rtc.now();
Serial.print(now.year(), DEC);
Serial.print('/');
Serial.print(now.month(), DEC);
Serial.print('/');
Serial.print(now.day(), DEC);
Serial.print(" ");
Serial.print(now.hour(), DEC);
Serial.print(':');
Serial.print(now.minute(), DEC);
Serial.print(':');
Serial.print(now.second(), DEC);
Serial.println();
```

Figure 3.10 RTC initialization Coding

The Check Current Time function utilizes the Real-Time Clock (RTC) module to keep track of the current time, which is essential for scheduling the cleaning operations. The RTC provides accurate timekeeping, allowing the system to compare the current time against predefined start and stop times for the cleaning process. The Arduino reads the current time from the RTC module and prints it to the serial monitor for debugging purposes. This time check ensures that the cleaning operations are performed at the correct times each day, enhancing the system's autonomy and ensuring that the photovoltaic panels are cleaned regularly without manual intervention. This feature is vital for maintaining the optimal performance of the solar panels by scheduling cleanings during periods when they are most effective

Rain Sensor Detection

```
if (digitalRead(RAIN_SENSOR_PIN) == LOW && !hasOperatedRain) {
    Serial.println("Rain detected. Starting operation...");
    YesraincleanSolarPanel();
    operateWaterPump();
    hasOperatedRain = true;
}

 if (now.hour() == 0 && now.minute() == 0) {
     hasOperatedRain = false;
 }
 if (now.hour() == 12 && now.minute() == 0) {
     hasOperatedRain = false;
 }
```

Figure 3.11 Rain Sensor Coding

The Rain Sensor Detection mechanism is designed to optimize the cleaning process by leveraging natural rainfall. The rain sensor detects precipitation by reading a digital input pin. When rain is detected (indicated by a low signal), and if the “hasOperatedRain” flag is not set, the system initiates a cleaning cycle using the “YesraincleanSolarPanel” function. This function activates the brush motor and water pump to clean the panels, taking advantage of the rain to assist in the cleaning process. The “hasOperatedRain” flag is then set to prevent repeated triggers from the same rain event. This feature ensures that the system conserves water and energy by utilizing natural rain for cleaning when available, making the system more efficient and environmentally friendly

Scheduled Cleaning

```
if  (now.hour() == START_HOUR && now.minute() == START_MINUTE)  {
    NoraincleanSolarPanel();
    operateWaterPump();
} else {
    Serial.println("No rain detected. System on standby.");
}
```

Figure 3.12 Cleaning Schedule of the System

The Scheduled Cleaning feature ensures that the photovoltaic panels are cleaned at regular intervals, regardless of weather conditions. This is managed by setting predefined start and stop times using constants for hours and minutes. During the main loop, the system checks if the current time matches the scheduled cleaning time. If it does, the "NoraincleanSolarPanel" function is called, which activates the brush motor and water pump to perform the cleaning cycle. This scheduled cleaning operates independently of the rain sensor, ensuring that the panels are cleaned regularly to maintain their efficiency. This autonomous scheduling is crucial for maintaining consistent panel performance, particularly in regions with minimal rainfall, ensuring that dust and debris do not accumulate over time

3.3.5 Experimental setup

This thesis will simulate a functional self-cleaning PV system. A single solar panel will be the test platform for dust accumulation and cleaning. Sensors such as rain detectors will be mounted to detect environmental conditions and transmit data to an Arduino board. The Arduino will be the brain of the system, programmed to activate a cleaning mechanism (brushes, wipers, etc.) based on pre-defined thresholds and a timer. This mechanism will be custom-built to clean the entire panel surface without damage.

The setup will also include a controlled method to simulate dust buildup, such as a dust deposition chamber or a mechanism to sprinkle dust on the panel. The power source (battery pack) will ensure self-powered operation. The modular design allows for easy modification and testing of different components, ensuring a thorough evaluation of the self-cleaning system's effectiveness in maintaining optimal PV panel performance.

3.3.5.1 Parameters

I. Soiling Detection Threshold: This defines the level of dust or dirt accumulation on the PV panel that triggers the cleaning mechanism activation. It can be based on sensor readings (e.g., light intensity drops) or a pre-defined time interval.

II. Cleaning Frequency: This determines how often the cleaning mechanism operates, even if the soiling threshold isn't met. It can be a fixed time interval or adjusted based on environmental factors.

III. Cleaning Mechanism Design: This parameter specifies the type of cleaning method employed (brushes, wipers, etc.) and the design considerations for effective cleaning and minimal panel damage.

IV. Water Usage (if applicable): This defines the amount of water used during the cleaning process, if water is used at all. Optimizing water usage is crucial in water-scarce regions.

V. Power Consumption: This parameter considers the power needed to operate the Arduino board, sensors, and actuators. It influences the choice of power source (battery capacity, solar panel size) and impacts system autonomy.

3.3.5.2 Materials and Equipment

Various tools are used in an experimental setup to collect and analyse data for the design of Self-cleaning PV for dust removal. The essential elements consist of:

I. Photovoltaic Panel: Two identical solar panels are necessary. One serves as the test subject, integrating with the mechanism of cleaning system, while the other acts as a reference panel for comparison.
II. Arduino uno board: Acts as the central processing unit to receive input from the rain sensor, timer, and control the cleaning mechanism
III. Rain sensor: Detects rainfall and triggers the cleaning mechanism accordingly.
IV. Timer: Controls the frequency and timing of the cleaning cycles
V. Cleaning Mechanism: Component such as brushes and wipers can remove dust from the surface of the PV panel.
VI. Power source: Typically, a battery pack to provide power to the Arduino board and cleaning mechanism.
VII. Wiring and Connectors: Connects the components together to enable communication and power supply.

Software:

I. Arduino IDE (Integrated Development Environment) for programming the Arduino board.
II. Solidworks for designing the hardware setup.
III. Fritzing for designing circuits of the system.
IV. Fluke Software

3.4 Hardware and Software Chosen

3.4.1 Hardware Materials and Components

Table 3.1 shows the materials and components used. The materials and components shown in the table are those highlighted main components used for the construction of the prototype.

Table 3.1 Materials and Components Used

No	Component	Quantity
1	Aluminium Profile (20mm x 40mm)	100 mm x 2
2	Aluminium Profile (20mm x 40mm)	400 mm x 4
3	Aluminium Profile (20mm x 20mm)	350 mm x 1
4	Aluminium Profile (20mm x 40mm)	400 mm x 3
5	Aluminium Profile (20mm x 40mm)	670 mm x 4
6	Aluminium Profile (20mm x 40mm)	150 mm x 2 (15°)
7	PVC Pipe D = 28mm , 2440 mm	1
8	PVC Pipe D =80mm , 350 mm	1
9	Stepper Motor Nema 17 HS 8401	2
10	DC Motor 150 RPM	1
11	Water Pump	1
12	Arduino Uno	1
13	Rain Sensor	1
14	RTC DS 3231	1
15	Limit Switch	2
16	Coupling (5mm to 8mm)	2
17	Coupling (4mm to 8mm)	1
18	Stepper Motor Bracket	2
19	DC Motor Bracket	1
20	Ball bearing Pillow Block Mounter (8mm)	4
21	T8 Lead Screw	700mm x 2
22	T8 Lead Screw	400mm x 1
23	Industrial Brush	1
24	Solar Charge Controller	1
25	Voltage Regulator Step Down Buck Converter	1
26	T8 Screw Brass Nut Pitch	6
27	Relay (5V)	2
28	12 Volt Battery	1
29	Cable Connector (5in 1 Out)	2
30	Hose	200mm x 1
31	Water Case Tank	1
32	Junction Box (255mm x 200mm x 100mm)	1
33	Rubber Foot Pad	4
34	A4988 Stepper Motor Driver	2

3.4.2 Software

Three software were used throughout the project. They were the Solidworks, Fritzing, and Arduino IDE. SolidWorks was employed during the design phase to create a detailed 3D model of the self-cleaning photovoltaic system prototype. The software provided an accurate visualization of the system’s mechanical components, enabling precise planning and selection of suitable materials and hardware. SolidWorks allowed the integration of structural elements, such as aluminum profiles, the cleaning mechanism, and motor mounts, ensuring that the overall design was both functional and robust. Figure 3.13 illustrates the SolidWorks interface showcasing the 3D model of the system.

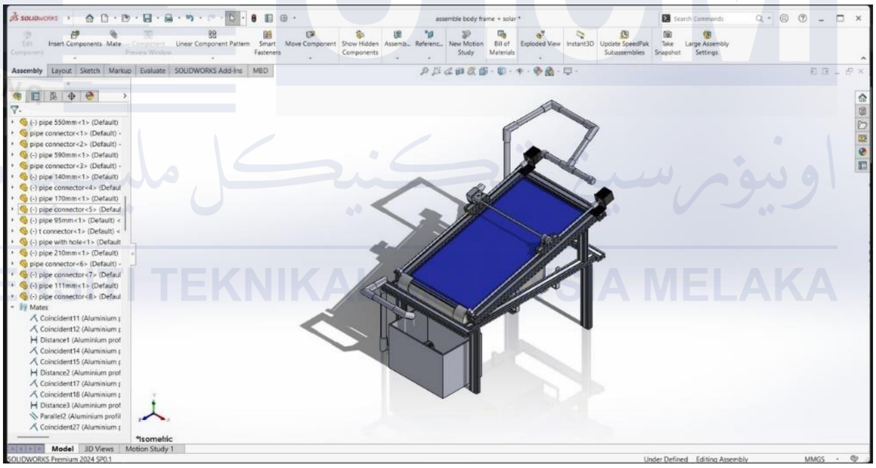


Figure 3.13 Solidworks Software Interface

Fritzing was utilized to design the circuit schematic diagram for the project. The schematic provided a clear representation of the electrical connections between the Arduino controllers, limit switches, motors, and power supply components. It served as a reference for assembling the circuit and ensuring proper pin configurations during the wiring process. Fritzing also helped document the connections to maintain consistency during the system's hardware construction. Figure 3.14 shows the interface of the Fritzing software used to design the circuit.

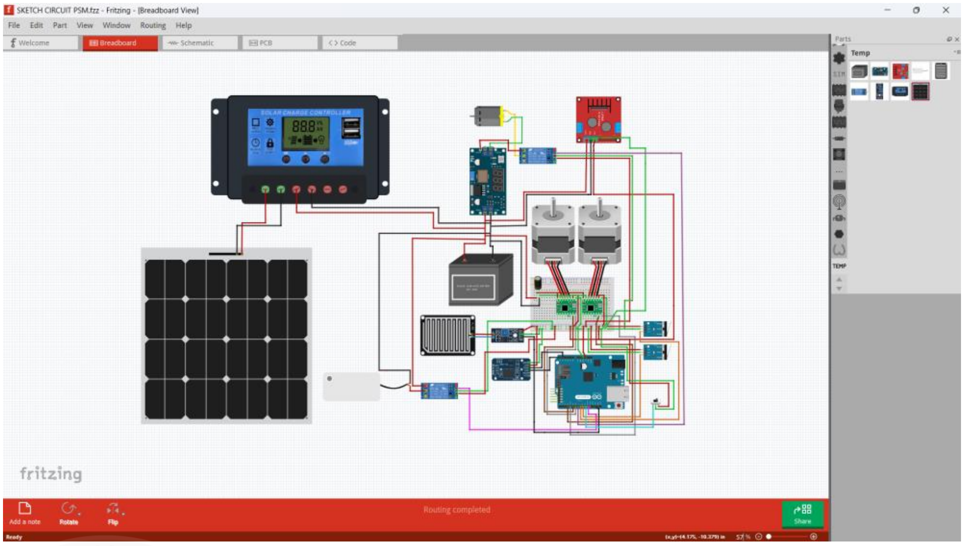


Figure 3.14 Fritzing Software Interface

Finally, Arduino IDE was used for programming the control logic of the system. The software facilitated writing, compiling, and uploading the code to the Arduino Uno microcontrollers. The microcontrollers controlled the movement of the cleaning mechanism, water pump, and limit switches. Arduino IDE's serial monitor feature was also instrumental in debugging and monitoring the system during practical testing, ensuring the proper functionality of the programmed logic. Figure 3.15 presents the Arduino IDE interface used for coding and testing.

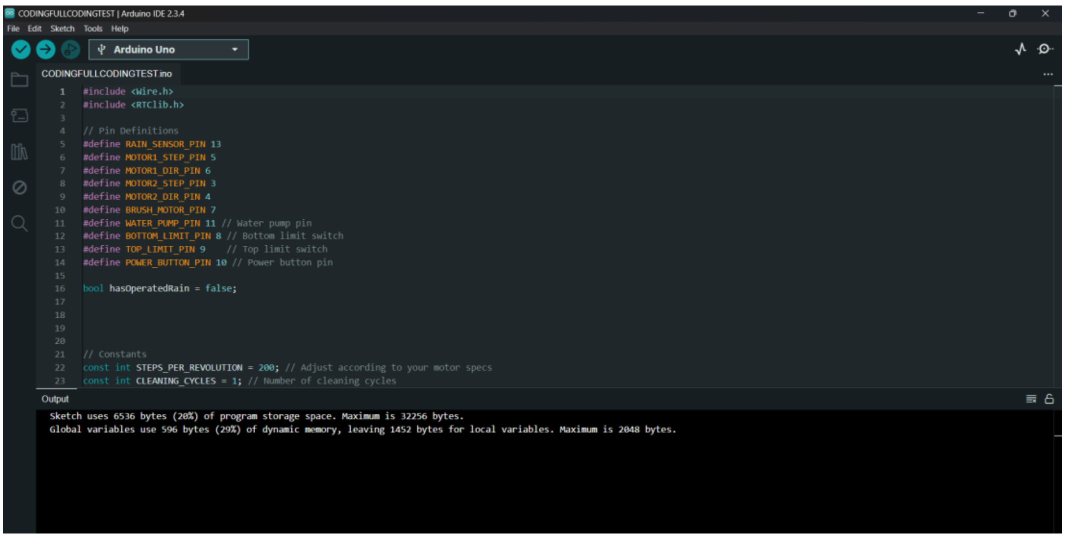


Figure 3.15 Arduino Software Interface

3.5 Quotation for project

In the context of advancing renewable energy technologies, the project titled "Development of an Arduino-Controlled Brush-Based Self-Cleaning Photovoltaic System" stands as a testament to innovation in solar energy maintenance. This initiative addresses a critical challenge faced by photovoltaic (PV) systems: efficiency losses due to dust and debris accumulation. By integrating an Arduino-controlled mechanism with industrial brushes and sensor technologies, the project seeks to automate the cleaning process of solar panels, thereby enhancing energy output and reducing manual maintenance.

The system's design reflects a commitment to sustainability and technological advancement. It incorporates components such as a stepper motor-driven cleaning rail, rain sensors for weather-adaptive operation, and a water pump for optimal cleaning efficiency. As highlighted in Table 3.2, the investment in this project emphasizes the judicious allocation of resources towards essential hardware, research, and development. This endeavor not only demonstrates the potential for automated solutions to improve solar energy reliability but also aligns with the broader goals of promoting renewable energy and environmental sustainability.

Table 3.2 Quotation of project

No	Component	Description	Quantity	Estimated Cost (RM)
1	Aluminium Profile (20mm x 40mm)	10mm / RM0.25	100 mm x 2	RM 5
2	Aluminium Profile (20mm x 40mm)	10mm / RM0.25	400 mm x 4	RM40
3	Aluminium Profile (20mm x 20mm)	10mm / RM0.25	350 mm x 1	RM 8.75
4	Aluminium Profile (20mm x 40mm)	10mm / RM0.25	400 mm x 3	RM 30
5	Aluminium Profile (20mm x 40mm)	10mm / RM0.25	670 mm x 4	RM 67
6	Aluminium Profile (20mm x 40mm)	10mm / RM0.25	150 mm x 2 (15°)	RM 7.5

7	PVC Pipe D = 28mm , 2440 mm	RM 1.50 /1 Feet	1	RM 12.20
8	PVC Pipe D =80mm , 350 mm	RM 3.60 / 1 Feet	1	RM 4.20
9	Stepper Motor Nema 17 HS 8401	Rm 44.90/ piece	2	RM89.8
10	DC Motor 150 RPM	RM 29.90/piece	1	Rm 29.90
11	Water Pump	28.99/piece	1	28.99
12	Arduino Uno	42.90/piece	1	42.90
13	Rain Sensor	6.50/piece	1	6.50
14	RTC DS 3231	RM 6.99	1	RM 6.99
15	Limit Switch	RM 2.00/piece	2	RM 4.00
16	Coupling (5mm to 8mm)	RM 5.50/piece	2	RM11.00
17	Coupling (6mm to 8mm)	RM 5.50/piece	1	RM 5.50
18	Stepper Motor Bracket	RM 8.00/piece	2	RM 16.00
19	DC Motor Bracket	RM 5.29/piece	1	RM 5.29
20	30W Monocrystalline Solar Panel	RM 80.37/piece	1	RM 80.37
21	Ball bearing Pillow Block Mounter (8mm)	RM 3.65/piece	4	RM 14.60
22	T8 Lead Screw	RM 21.51/piece	400mm x 1	RM 21.51
23	T8 Lead Screw	RM 38.61/piece	700mm x 2	RM 77.22
24	Industrial Brush	RM 61.05/piece	1	RM 61.05
25	Solar Charge Controller	RM 12.50/piece	1	RM 12.50
26	Voltage Regulator Step Down Buck Converter	RM 9.50/piece	1	RM 9.50
27	T8 Screw Brass Nut Pitch	RM 2.76/piece	6	RM 16.56
28	Relay (5V)	RM 3.29/piece	2	RM 6.58
29	12 Volt Battery	RM 38.50/piece	1	RM38.50
30	Cable Connector (5in 1 Out)	RM 1.62/piece	2	RM 3.24
31	Hose	RM 4.00/meter	1	RM 4.00

32	Water Case Tank	RM 12.30/piece	1	RM 12.30
33	Junction Box (255mm x 200mm x 100mm)	RM 13.52/piece	1	RM 13.52
34	Rubber Foot Pad	RM 2.50/piece	4	RM 10.00
35	Switch	RM 0.40/piece	2	RM 0.80
36	Screw Cap M5	RM 0.20/piece	36	RM 7.20
37	Screw Cap M4	RM 0.20/piece	14	RM 2.8
38	Screw Cap M3	RM 0.20/piece	12	RM 2.4
39	**Total**	**-**	**-**	**RM 786**

3.6 Limitation of proposed methodology

Using a time-based soiling detection system for the automatic cleaning of photovoltaic (PV) panels presents several limitations. Cleaning based on a fixed schedule rather than real-time soiling conditions can lead to inefficiencies. This approach may trigger the cleaning mechanism when the panels are not significantly dirty, wasting resources and potentially reducing the lifespan of the cleaning components due to unnecessary usage. Conversely, it might also fail to clean the panels promptly during periods of unexpected heavy soiling, leading to reduced energy output and efficiency. Additionally, the integration of rain sensors, which trigger the cleaning mechanism based on rainfall, can be problematic. Rain sensors might not accurately distinguish between light rain and heavy, effective cleaning rainfall, and in regions with infrequent or unpredictable rainfall, this could result in inadequate cleaning and reliance on manual intervention or alternative cleaning schedules.

Moreover, the dependency on water availability and the potential for water wastage are significant concerns, especially in arid regions. Optimizing water usage is crucial, but without precise control, this can be challenging. The integration of rain sensors and time-based cleaning schedules requires careful calibration and maintenance to ensure accuracy and reliability over time, adding complexity and potential points of failure to the system. Finally, the power consumption of the Arduino board, sensors, and cleaning actuators must be carefully managed to ensure system autonomy, particularly in off-grid installations. If the cleaning mechanism operates too frequently or inefficiently, it could drain the battery, compromising the overall functionality of the PV system. Thus, while a time-based soiling detection and rain sensor approach can provide a straightforward solution, it necessitates careful consideration of these limitations to achieve optimal performance and resource utilization.

3.7 Gantt Chart

Table 3.3 Gantt Chart for PSM 1 and PSM 2

	TASK	PSM1														PSM2													
NO	WEEK	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	Briefing for PSM 1 by JK,PSM,FTKEE																												
2	Project title conformation and registration																												
3	Briefing with supervisor																												
4	Study the project background																												
5	Drafting chapter1 : Introduction																												
6	Task progress evaluation 1																												
7	Drafting chapter 2 : Literature Review																												
8	Table summary Literature review																												
9	Drafting Chapter 3: Methodology																												
10	Work on the software/hardware																												
11	First draft submission to supervisor																												
12	Task progress evaluation 2																												
13	Submission Report to the panel																												
14	Presentation of BDP1																												
15	Drafting Chapter 4: Analyse Data and result																												
16	Data Analyse and result																												
17	Record the result																												
18	Drafting Chapter 5: Conclusion and recommendation																												
19	Compiling Chapter 4 and 5																												
20	Submit latest report to supervisor																												
21	Finalize the report																												
22	Presentation of BDP2																												

3.8 Summary

This project addresses the challenge of maintaining optimal efficiency in solar panels by developing a self-cleaning system controlled by Arduino. Dust buildup significantly reduces solar panel output, and traditional cleaning methods are labor-intensive. The proposed solution automates the cleaning process using sensors, an Arduino board, and a custom-designed cleaning mechanism (brushes, wipers, etc.).

The system will rely on sensors and timer to detect dust accumulation and trigger cleaning based on pre-defined thresholds or sensor readings. This optimizes water usage (if applicable) and minimizes wear on the cleaning components. The Arduino's control logic ensures thorough cleaning of the entire panel surface. An experimental setup will simulate a functional system using a single solar panel, dust simulation methods, and a power source (battery or solar panel). This modular design allows for testing different components and evaluating the system's effectiveness in maintaining optimal PV panel performance. However, limitations exist such as sensor accuracy, cleaning mechanism effectiveness in all weather, and resource management (water usage, power consumption).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, we delve into the preliminary data collected to assess the impact of cleaning on the performance of solar panels. The efficiency of solar panels can significantly diminish due to the accumulation of dust, dirt, and other environmental contaminants on their surfaces. This reduction in efficiency directly affects the electricity output and overall productivity of solar power systems. Therefore, understanding the extent of these effects and evaluating the potential benefits of regular cleaning schedules is crucial for optimizing the performance of solar installations. The preliminary data gathered in this investigation provides a foundational understanding of how various factors influence the cleanliness and efficiency of solar panels.

The data collection process involved measuring the performance of solar panels under different conditions, both before and after cleaning, using a combination of advanced tools such as PV reference cells, pyranometers, and thermal imagers. These measurements were complemented by environmental data, including weather patterns, dust deposition rates, and local air quality indices. By analyzing this data, we aim to establish a clear correlation between cleanliness and solar panel efficiency. This chapter presents the methodology, tools, and initial findings from the preliminary data, setting the stage for a more detailed analysis in subsequent sections of the project. Through this investigation, we seek to provide actionable insights that can inform best practices for maintaining solar panel cleanliness and maximizing energy output.

4.2 PV Panel specification

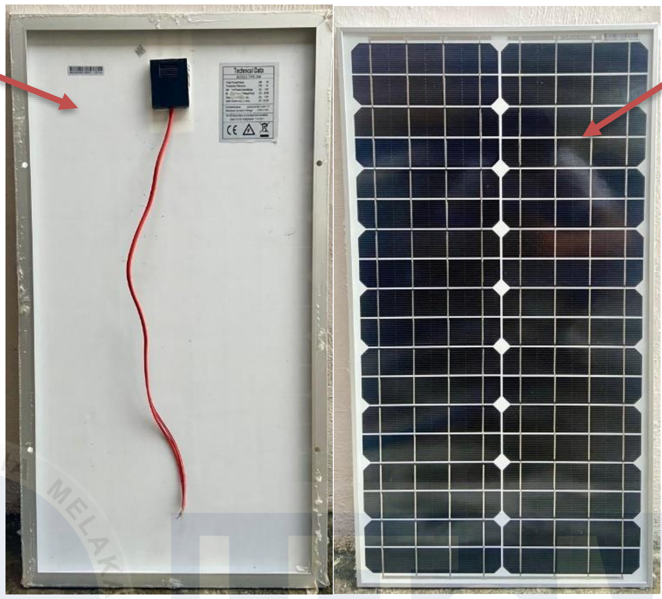


Figure 4.1 Monocrystalline PV Module (IBC30Wp)

Table 4.1 Technical specification of the tested PV module

Parameters	Value
Maximum power at STC (Pmax)	30 W
Open-circuit voltage (Voc)	22.3 V
Short-circuit current (Isc)	1.82 A
Maximum operating voltage (Vmp)	18.00 V
Maximum operating current (Imp)	1.67 A
Operating temperature	-20 °C to +65 °C
Module dimensions (mm)	630 x 340 x 317
Weight	2.5 kg

4.3 Prototype Development

The prototype design incorporates a 30W Monocrystalline PV module with an automated cleaning system. The cleaning module features a rotary brush engineered to sweep vertically, efficiently eliminating dirt and debris from the module's surface. The mounting structure is fabricated from robust aluminium profiles, offering a lightweight yet resilient framework to support the photovoltaic module and cleaning apparatus. The system operates via an Arduino microcontroller equipped with rain sensors that autonomously engage the cleaning brush upon detecting precipitation. This design leverages free rainwater to enhance cleaning efficiency and reduce water wastage. The configuration also incorporates a water distribution system and a collection bin to efficiently manage the cleaning process. The design is refined for efficiency, simplicity of assembly, and versatility in various environmental conditions.

4.3.1 Prototype Overview

Figure 4.2 shows the overall prototype of the solar panel cleaning system. The cleaning mechanism is mounted on a moving frame, which is driven by a T8 lead screw powered by a stepper motor. This moving frame ensures the cleaning mechanism can traverse along the length of the solar panel during the cleaning task. The lead screw mechanism provides precise and smooth linear motion, while the cleaning brush, powered by a DC motor, rotates to remove dirt and debris from the solar panel surface effectively. Limit switches are installed at the top and bottom of the moving frame to define the endpoints of travel, ensuring safe and controlled operation. The wheels of the cleaning mechanism run along the frame, while the rotating brush extends downward to clean the solar panel surface. This setup enables efficient and reliable cleaning, ensuring the solar panel remains free of dirt for optimal performance.

Figure 4.2 Brush-Based Self-Cleaning Photovoltaic System Prototype

4.3.1.1 Self-Cleaning Brush Mechanism on a Moving rail by a Stepper Motor

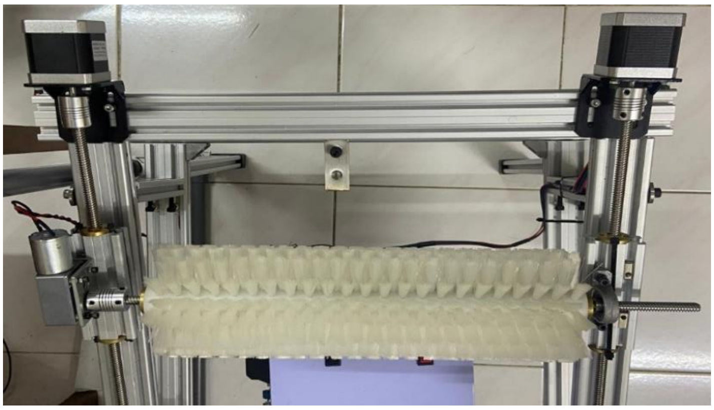


Figure 4.3 Cleaning Mechanism on Moving rail

Figure 4.3 shows the cleaning mechanism positioned on the moving rail system, while Figure 4.4 provides a top view of the cleaning mechanism. From these figures, it can be observed that the cleaning mechanism is guided by the lead screw system, with the aluminum profile positioned on top serving as a supporting structure. The lead screw ensures precise and controlled linear motion, allowing the cleaning mechanism to traverse along the rail efficiently. The cleaning mechanism is securely attached to the lead screw, which provides stability and eliminates the risk of the mechanism deviating or falling off during operation. This design ensures that the cleaning process remains smooth and consistent, as the lead screw controls the movement with high precision.

The integration of the cleaning mechanism with the lead screw and aluminum profile introduces a potential challenge: occasional contact between the moving parts of the cleaning mechanism and the rail structure may increase friction and cause wear over time. To address this issue, adjustments or cushioning materials can be added to minimize contact and ensure smoother motion. By doing so, the system maintains efficient operation while extending the durability of the components.

Figure 4.4 Top View of the Self-Cleaning Photovoltaic System

4.3.2 Cleaning Mechanism Design

4.3.2.1 Overview of the Industrial Brush

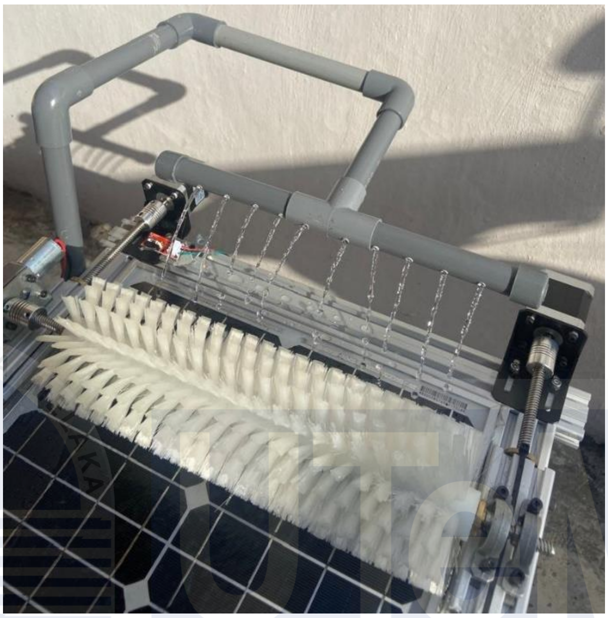


Figure 4.5 Industrial Brush Placement

The cylindrical cleaning brush is made of nylon, selected for its durability, flexibility, and resistance to wear. Nylon bristles are stiff enough to clean effectively but gentle enough to avoid scratching the solar panel surface. The hollow core of the brush reduces its weight, making it easier to integrate into the cleaning mechanism without adding excessive load.

The brush is moved across the solar panel surface by a rail system, with the cleaning mechanism traveling along the rail. This movement is powered by motors that drive the system, ensuring consistent motion. To address slight deviations in the motor speeds that could cause unwanted contact with the supporting frame, the brush acts as a cushioning element. Its bristles absorb impacts and reduce friction, providing smoother operation and protecting both the solar panel and the cleaning mechanism.

4.3.2.2 Water Pump

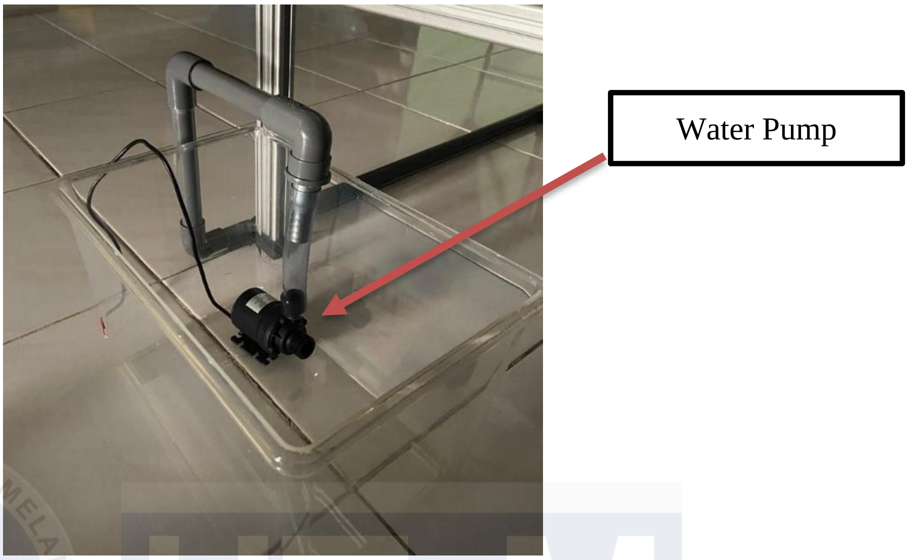


Figure 4.6 Water Pump Placement

The water pump in a self-cleaning photovoltaic system plays a crucial role in improving cleaning efficiency. It circulates water or cleaning solution across the solar panel surface, effectively removing dust, dirt, and debris. Using water helps reduce friction between the cleaning mechanism and the panel, minimizing the risk of scratching. The pump ensures an even distribution of water, creating a controlled flow that aids in cleaning while conserving energy. It’s quiet and brushless design enhances system reliability, making it ideal for continuous operation without disrupting the surrounding environment.

4.3.3 Flow of the water pump

The flow of water in the self-cleaning photovoltaic system begins at the water storage tank, where the water is held for cleaning operations. The water pump, a crucial component of the system, is designed to draw water from the storage tank and push it through a network of PVC pipes. These pipes are laid out strategically to ensure uniform distribution of water across the photovoltaic panel's surface.

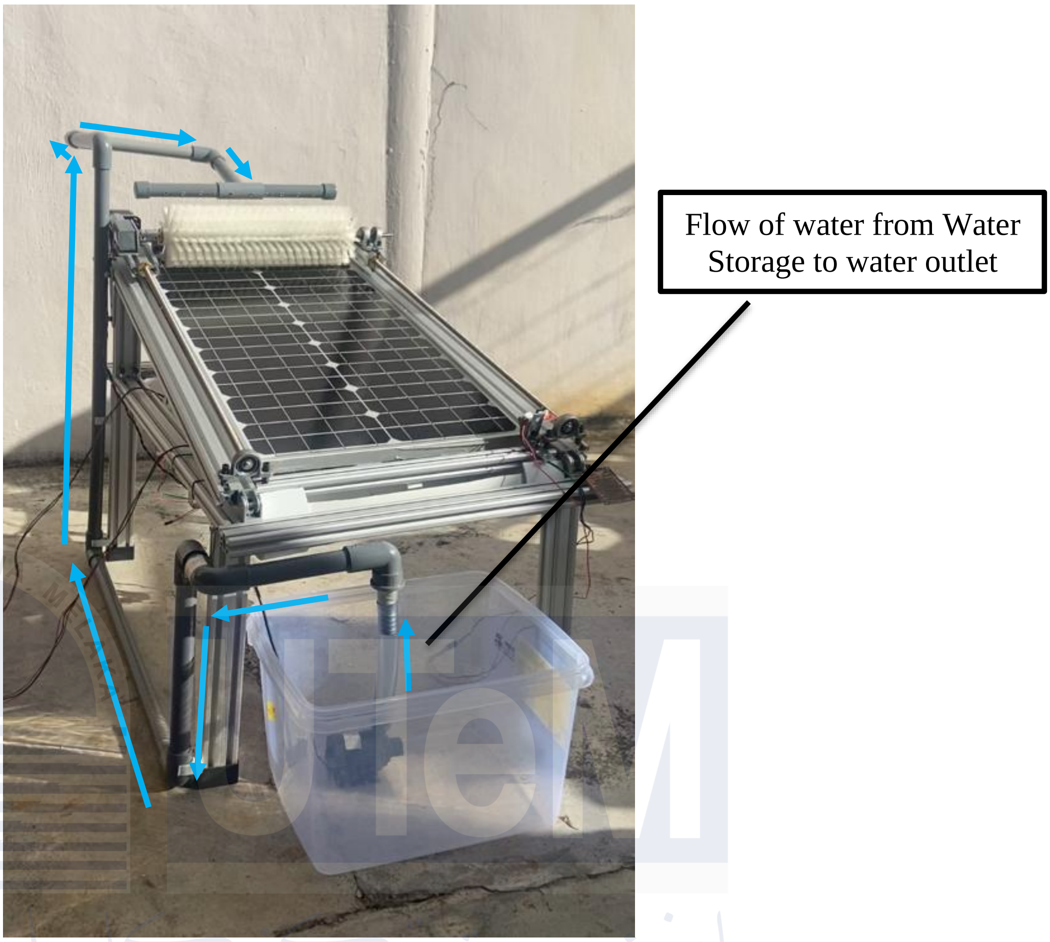


Figure 4.7 Flow of water pump using PVC Pipe

Flow of Water Process:

1. **Water Storage Tank**: Water is initially stored in a tank, typically made of durable and corrosion-resistant material, to ensure longevity and ease of maintenance.
2. **Pump Activation:** The Arduino controller triggers the water pump based on cleaning schedules or environmental conditions detected by sensors (e.g., rain sensor or dust level sensors).
3. **Water Flow Through Pipes**: The water pump forces the water through PVC pipes, directing it towards the water outlet holes. The flow rate is carefully calibrated to provide adequate pressure for effective cleaning without causing water wastage.
4. **Application on PV Panel Surface**: The water exits the pipes through strategically positioned outlet holes, ensuring an even spread across the entire surface of the PV panel. This design prevents dry spots and maximizes cleaning efficiency.

Figure 4.8 Water Outlet Hole

The water outlet system is designed with precision to ensure effective cleaning of the solar panel surface. It consists of 10 evenly spaced holes or nozzles along the PVC pipe network, with a uniform distance between each hole to guarantee consistent water distribution. The spacing between the holes is calculated to maximize coverage, ensuring that the entire panel surface receives an adequate water flow for efficient dirt and debris removal.

Each hole is carefully angled to direct the water stream evenly across the panel, preventing dry spots and ensuring thorough cleaning. The uniform spacing and controlled flow rate from the 10 holes are optimized to minimize water wastage, reduce runoff, and promote sustainable water usage while maintaining the panel's cleanliness and efficiency.

4.3.4 Gutter and Water storage

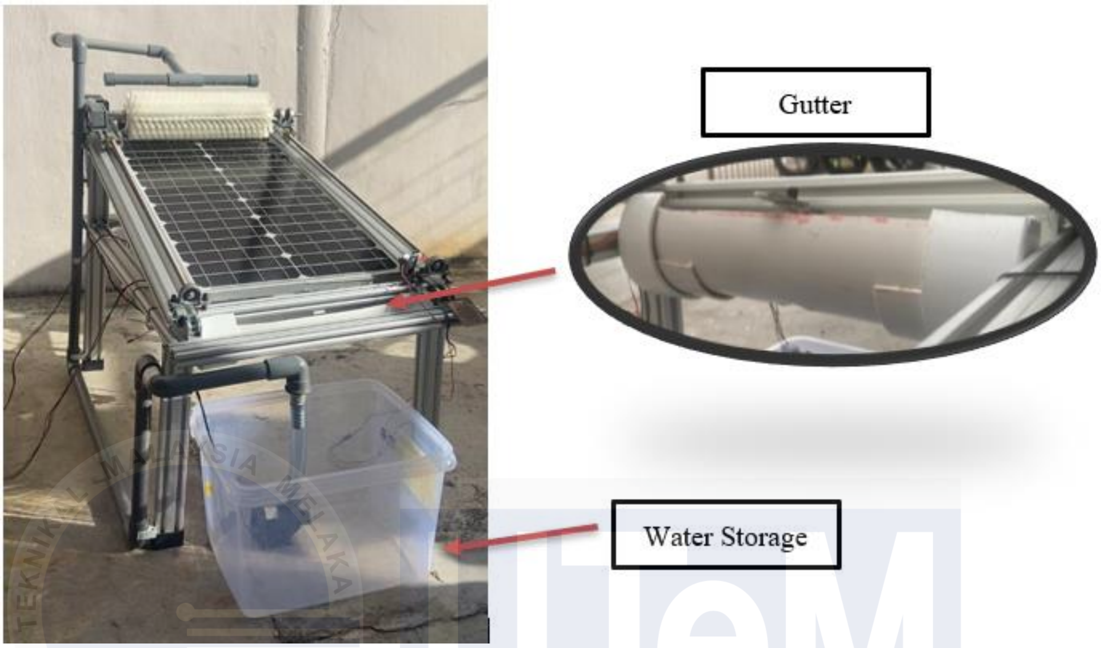


Figure 4.9 Water management

The gutter system collects wastewater after the cleaning process, directing it to a storage area or drainage system. This design minimizes water spillage and maintains the cleanliness of the surrounding area. The storage tank integrates seamlessly with the water pump, creating a closed-loop system to optimize water usage. Such a setup is particularly beneficial in regions where water conservation is critical, as it allows for potential reuse of collected water.

4.3.5 Electronic Junction Box of the Self-Cleaning Photovoltaic System

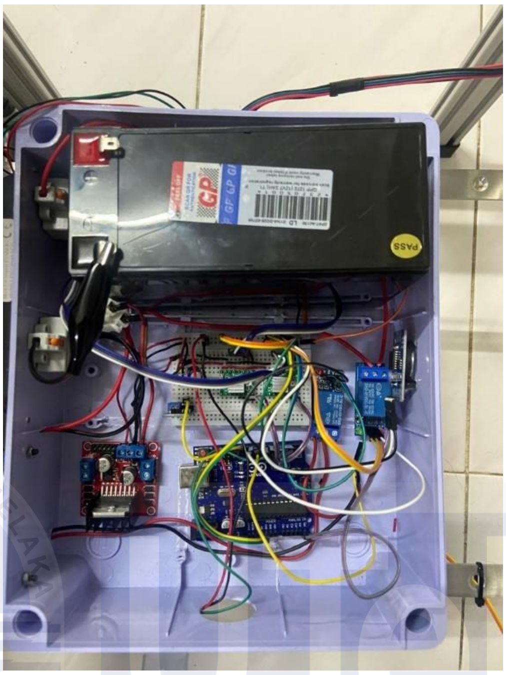


Figure 4.10 Electrical arrangement inside junction Box

The electronic junction box acts as the central hub for the system's electrical components, housing the solar charge controller, voltage regulator, and other critical elements. It ensures safe and organized wiring, protecting the system from environmental factors such as dust and moisture. The junction box is designed to facilitate easy access for maintenance and troubleshooting, ensuring the reliability and longevity of the photovoltaic cleaning system.

Figure 4.11 Side view of junction box

4.3.6 Wire Handling Method

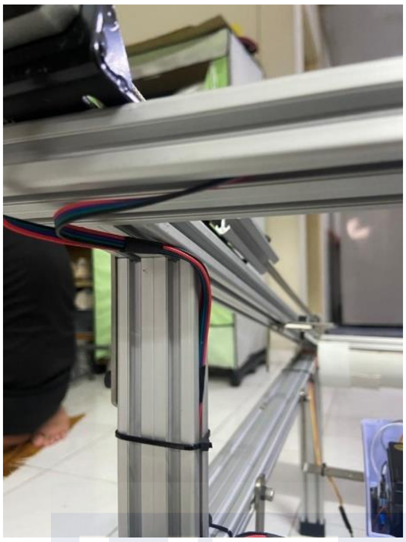


Figure 4.12 Stepper Motor wire handling

Efficient wire handling is essential for the reliable and safe operation of the self-cleaning photovoltaic system. For the stepper motor in figure 4.12 which moves the cleaning mechanism along the rail, wires are routed through flexible conduits to accommodate its motion while preventing stress or wear. These wires are securely fastened to the frame using cable ties and clamps, with sufficient slack provided near moving parts to avoid tension or disconnections during operation. Proper labelling further simplifies troubleshooting and maintenance. As in the figure 4.13 the water pump wiring is routed from the pump to the Arduino-controlled relay module, with wires secured along the pipe structure using clips or adhesive mounts. To ensure durability, the wires are insulated with waterproof sleeving to protect them from moisture and environmental exposure, while proper grounding is implemented for safety.

Figure 4.13 Water Pump wire handling

The rain sensor wires, which transmit environmental data to the Arduino, are carefully routed and kept separate from high-power lines to minimize electromagnetic interference. These wires are secured with cable clips along the system structure and protected with weather-resistant tubing to shield them from rain and UV exposure. Labeling the wires and using a dedicated connector for the sensor ensures easy replacement or servicing without disturbing other connections. Together, these wire-handling practices reduce clutter, enhance safety, and ensure the system's components operate seamlessly over time.

Figure 4.14 Rain sensor wire handling

4.3.7 Use of Wire Connector

Figure 4.15 Lever Wire Connector 1 in 5 out

Wire connectors play a vital role in organizing and securing electrical connections within the self-cleaning photovoltaic system. As shown in Figure 4.15, the system utilizes two lever wire connectors, one for the positive terminal of the battery and the other for the negative terminal. Each connector has a single input from the battery and multiple outputs to distribute power effectively to the connected components.

The positive wire connector supplies power to the stepper motor driver, rain sensor, cleaning mechanism circuit, and LN298 motor driver, while the negative connector serves as a common ground for all these components. This setup ensures a clean and organized wiring system, minimizing the risk of connection issues or short circuits. The lever mechanism of these connectors allows for easy assembly and disassembly, streamlining maintenance and enabling quick system upgrades. The design is optimized for reliability and safety, ensuring efficient power distribution throughout the system.

4.3.8 Sensor Application

4.3.8.1 Rain Sensor

The rain sensor detects precipitation and adjusts the cleaning schedule accordingly. During rainfall, the system halts operation to conserve energy and water, relying on the natural cleaning effect of rain. This sensor adds intelligence to the system, optimizing its efficiency by adapting to environmental conditions.

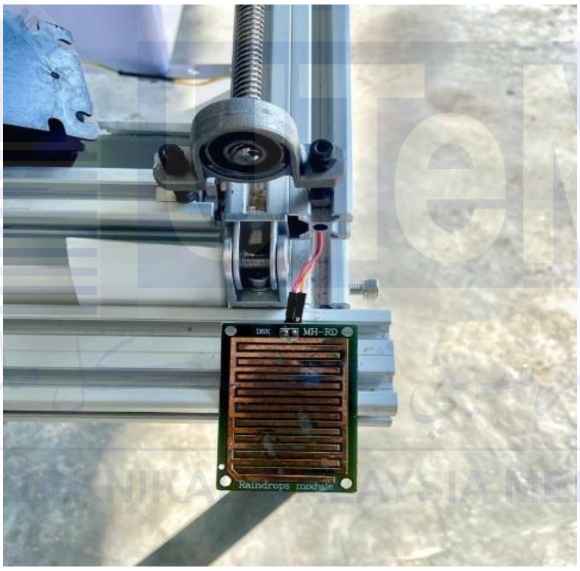


Figure 4.16 Rain Sensor placement

4.3.8.2 Real Time Clock Module

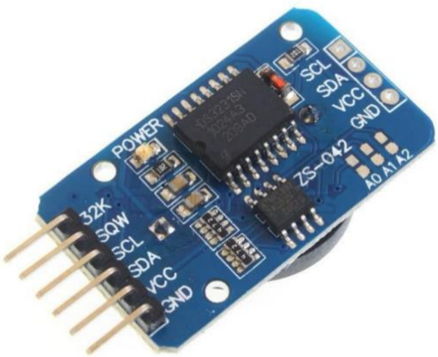


Figure 4.17 Real Time Clock

The RTC module provides accurate timing for scheduling cleaning operations. It ensures that the cleaning mechanism operates at pre-determined intervals, maintaining the PV panel's efficiency without manual intervention. By integrating the RTC module, the system aligns its operations with environmental factors, further enhancing its autonomy and resource management.

4.3.8.3 Limit Switch

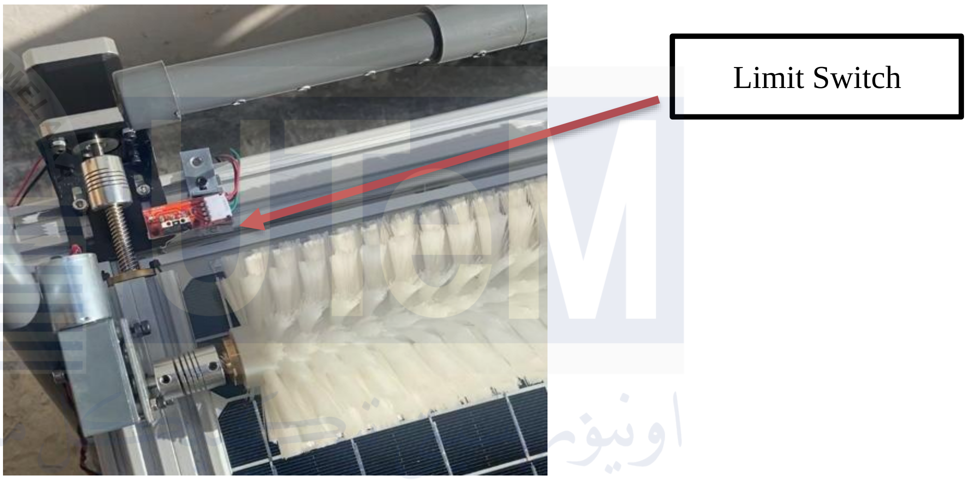


Figure 4.18 Limit Switch placement

In the self-cleaning photovoltaic system utilizing a brush mechanism, two limit switches are strategically placed at the top and bottom ends of the brush's travel path to ensure efficient and safe operation. The top limit switch as in figure 4.18 is positioned at the uppermost point and stops the upward movement of the brush when triggered, preventing it from moving beyond the designated cleaning area and causing potential damage. Conversely, the bottom limit switch is located at the lowest point and halts the downward movement of the brush upon activation, ensuring it doesn't exceed its cleaning range. Both switches send signals to the control system to reverse the brush's direction, allowing for continuous cleaning. Proper alignment, protection from environmental factors, and secure wiring are essential for the reliable functioning of these limit switches.

4.4 Understanding the PV module behaviour under real operating conditions

In this section, we examine how the photovoltaic (PV) module performs in actual environmental conditions, as opposed to controlled laboratory settings. This involves analyzing how factors such as temperature fluctuations, varying sunlight intensity, and dust accumulation impacts the efficiency and overall functionality of the PV module. By monitoring the module's performance in real-world scenarios, we can gain valuable insights into its reliability, identify potential issues, and assess its effectiveness in generating power under diverse and dynamic conditions. This understanding is crucial for optimizing PV system design and maintenance strategies to ensure consistent and efficient energy production.

4.4.1 PV module Acceptance test

The acceptance test is carried out at the testing site to confirm that the PV module operates according to the manufacturer's specifications and to validate its functionality. Throughout the experimental study, reference is made to the International Electrotechnical Commission (IEC) standards for PV systems, which are published under the IEC TC82, as well as Malaysian standards. Guidance on PV modules can be derived from various International Standards, the details of which are provided in the Appendix section for further clarification. The following International Standards provide guidelines related to PV modules in (Table 4.2).

Table 4.2 International Standards that are relevant to solar PV modules

No	Standard	Title
1	IEC 61215	Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval
2	IEC 61646	Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type of approval
3	IEC 61730 – Part 1	Photovoltaic (PV) modules safety qualification Part 1: Requirement for construction
4	IEC 61730 – Part 2	Photovoltaic (PV) modules safety qualification Part 2: Requirements for testing
5	IEC 61701	Salt mist corrosion testing of photovoltaic (PV) modules
6	IEC 628041	System voltage durability test for crystalline silicon modules – Design qualification and type approval
7	IEC 627162	Photovoltaic (PV) modules – Ammonia corrosion testing

The fundamental measurement for PV systems is to determine their functionality. Initially, this is conducted through visual inspection as outlined in IEC 61215 and IEC 61646, as shown in Table 4.3. No visible defects were detected, and subsequently, both PV modules were subjected to technical acceptance tests.

Table 4.3 Typical failures during visual inspection

PV module by part	Type of failures
Front surface	Browning, delamination, bubbles
Solar cells	Cell cracking/broken, discolouration
Metallization contacts	Oxidized, burnt marks
Aluminium frame	Misaligned, bend
Back surface	Delamination, bubbles, burnt marks, browning
Junction box	connectors Corrosion, loose, oxidation, detached/exposed wires

Two specific tests were conducted: (i) the open-circuit test and (ii) the short-circuit test. These tests are crucial for identifying any hidden manufacturing defects, such as internal cell cracks or grid defects, by comparing the expected and actual measurements of voltage and current. Additionally, these tests enhance the accuracy of measurements and ensure the proper dynamic behavior of the selected PV module.

According to MS 1837:2018 (12.3.2), it is recommended that all measurements be conducted under specific irradiance conditions, ideally during the daytime without rain. The minimum requirement for performing the acceptance test is that solar irradiance levels should be at least 350 W/m². Additionally, the percentage difference between expected and measured values for Voc and Isc should fall within ±5%. If the values exceed this 5% threshold, the PV modules must be replaced. The expected values for Voc and Isc were analytically determined using equations provided by Omar et al. (2009).

$$\boldsymbol{Voc_{expected} = Voc_{stc}\ X\ Kmm\_{}_{v}\ X\ Ktemp\_v} \quad \textbf{Eq 3}$$

$$\boldsymbol{Isc_{expected} = Isc_{stc}\ X\ Kmm\_i\ X\ Kg} \quad \textbf{Eq 4}$$

Where *Voc_stc* is the module open-circuit voltage at standard test conditions (STC), *kmm_v* is the module mismatch derating factor for voltage, *ktemp_v* is the temperature derating factor for voltage, *Isc_stc* is the module short-circuit current at STC, kmm_i is the module mismatch derating factor for current, and *Kg* is the derating factor due to solar irradiance. Comparing the measured and expected values of *Voc_stc* and *Isc_stc* offers a reliable indication of potential technical issues. For both modules, *Voc_measured* and *Isc_measured* were assessed under realistic operating conditions. The results of the acceptance tests are documented in Table 4.4 and Table 4.5.

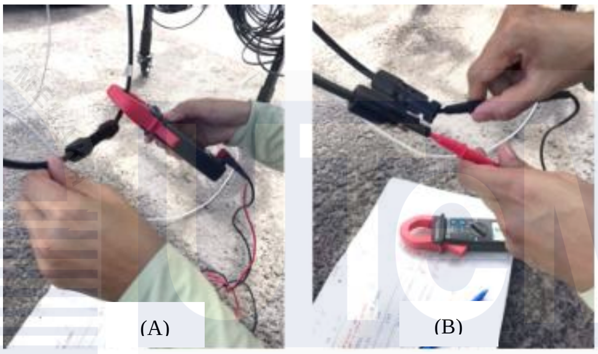


Figure 4.19 Methods for measuring (a) short-circuit current and (b) open-circuit voltage

Table 4.4 Measurement data for short-circuit current test

Irradiance (W/m^2)	PV temperature (ºC)	Isc-measured (A)	Isc-expected (A)	% Different	Results
905	57.54	5.62	5.83	0.21	Accept
898	57.02	5.57	5.76	0.19	Accept
745	52.44	4.62	4.85	0.23	Accept

Table 4.5 Measuremnet data for open-circuit voltage test

Irradiance (W/m^2)	PV temperature (ºC)	Voc-measured (A)	Voc-expected (A)	% Different	Results
905	57.54	22.29	22.91	0.62	Accept
898	57.02	22.13	22.71	0.57	Accept
745	52.44	18.36	19.17	0.81	Accept

The recorded data showed that the percentage differences between the measured and expected values were within ±5%. Consequently, the functionality of both PV modules has been confirmed to align with the specifications listed in the manufacturer's datasheet.

4.4.2 Thermal behaviour

4.4.2.1 Temperature measurement Using Fluke Ti100 Series Thermal Imager

The Fluke T100 Infrared Thermal Imager is a precision instrument designed for capturing detailed thermal images, enabling users to detect and analyze temperature variations and heat patterns in various environments. It is commonly used in industrial, electrical, and building inspections to identify issues such as overheating components, insulation deficiencies, and other thermal anomalies. The device offers high-resolution imaging, user-friendly interface, and advanced features like real-time image processing, extensive temperature range measurements, and accurate pinpointing of heat sources, making it an essential tool for preventive maintenance, troubleshooting, and quality control.

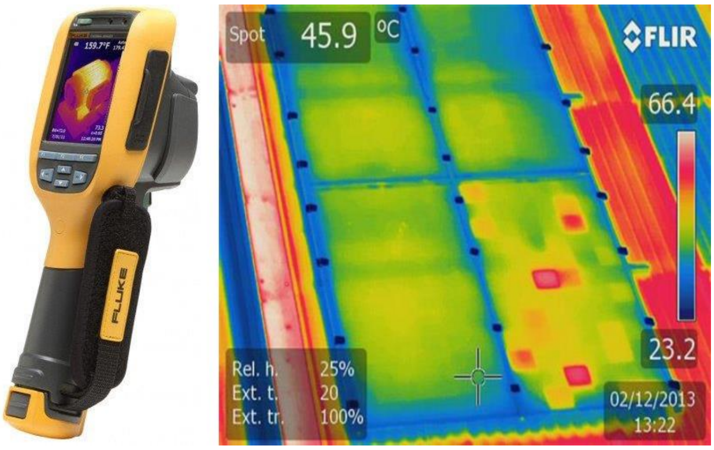


Figure 4.20 Infrared thermal imager Fluke T100

To collect data from photovoltaic (PV) solar modules, the Fluke thermal imager software is an indispensable tool. Accurate performance evaluation is achieved by first capturing thermal images of the PV modules. These images are then processed using the Fluke thermal imager software, which employs color coding to display temperature distribution across the PV module. The color scheme, ranging from colder (blue) to hotter (red), highlights temperature variations, while adjusting the temperature range helps detect minute changes more precisely. The software's IR-Fusion® technology, which merges thermal and visual images, provides a more contextualized view of anomalies on the actual PV module. This analysis is further enhanced by adjustable blending settings, offering a comprehensive assessment of the PV module's performance.

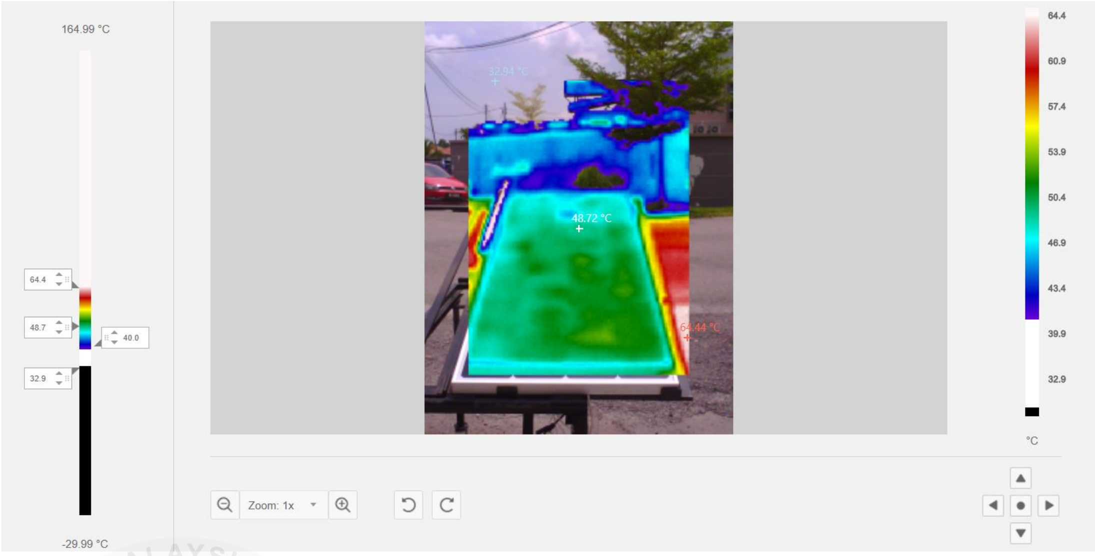
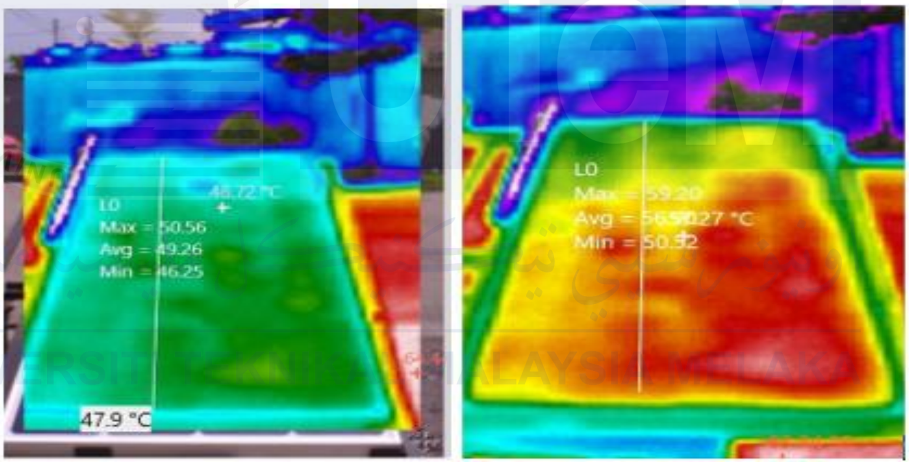


Figure 4.21 Fluke connect software interface

4.4.2.2 Measurement of PV temperature under real operating conditions

Identifying hot spots and examining temperature distribution are crucial aspects of interpreting thermal data. Hot spots, indicated by higher temperatures, can signal issues such as electrical resistance problems, shading, or damaged cells. The software allows users to mark these areas and record their temperatures for further analysis. Evaluating the overall temperature distribution helps assess the level of heat dissipation, with irregular patterns potentially indicating efficiency problems. By comparing images over time, patterns and changes can be uncovered, providing insights into performance dynamics under different conditions.



(a) (b)

Figure 4.22 Thermal images captured subsequently examined utilizing Fluke Connect Software

The thermal images show the condition of a solar PV panel before and after an intervention. As shown in Figure 4.22 (a), the panel exhibits relatively uniform temperature distribution with a maximum temperature of 50.56°C, an average of 49.26°C, and a minimum of 46.25°C, indicated by cooler colors (blue and green). In contrast, Figure 4.22 (b) reveals a significant increase in temperatures, with a maximum of 59.20°C, an average of 56.59°C, and a minimum of 50.52°C, represented by warmer colors (yellow and red). The emergence of hot spots and higher overall temperatures in the after image suggests potential issues such as increased electrical resistance, shading, or damage to the cells, leading to decreased efficiency and impaired heat dissipation of the PV panel.

4.4.2.3 Data analysis setup

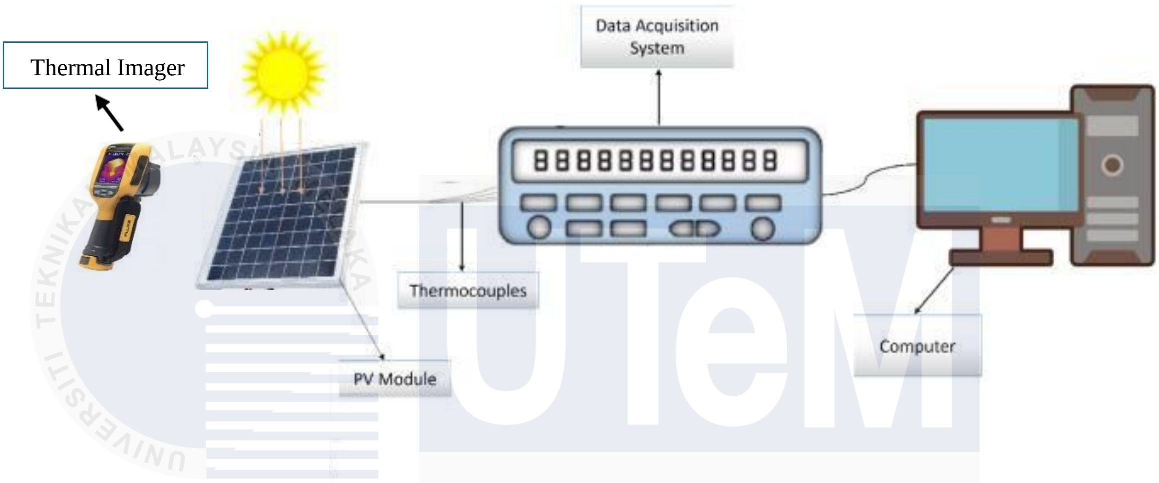


Figure 4.23 Equipment setup for measuring irradiance and temperature

This setup is designed to monitor and analyze the thermal and electrical performance of a photovoltaic (PV) module exposed to sunlight. At the heart of the system is the PV module, which converts sunlight into electrical energy. To understand how efficiently the module operates and to identify any potential thermal issues, several K-type thermocouples are attached to the module. These thermocouples measure the temperature at specific points on the module's surface, providing precise data on its thermal distribution. The temperature data collected by the thermocouples is then sent to a data acquisition system, specifically a model -4019+, which processes and consolidates this information.

Complementing this data collection, a Fluke T100 thermal imager is used to capture thermal images of the PV module. The thermal imager provides a visual representation of temperature variations across the module, allowing for easy identification of hot spots or areas with potential performance issues. The processed temperature data from the data acquisition system, along with the thermal images from the Fluke T100, are sent to a connected computer. This computer is equipped with software to analyze and visualize the data, offering detailed insights into the PV module's performance and thermal characteristics. This comprehensive setup ensures accurate and efficient monitoring, facilitating better understanding and optimization of the PV module's operation.

4.4.2.4 Instrument calibration

Table 4.6 List of Instrument for calibration

Instrument	Image	Model	Specification
Irradiance Meter		Seaward Solar Survey 200R	Uncertainty:0.5% Accuracy: (±1.0%)
Thermal Imager		Fluke TR100	Accuracy: ± (3% + 5 digit)
Thermocouples		K-Type (chromel-alumel) Fibreglass insulated	Uncertainty:0.2% Accuracy: (±2.0ºC) Range: 200ºC~300ºC
Digital Multimeter		SANWA DCM400AD	Uncertainty: 0.5% Accuracy: DCA: ±(2.5%±10) Resolution: DCA: 0.01A

Figure 4.24 Software Fluke connect Desktop

Fluke Connect Desktop allows you to import thermal images captured by your Fluke camera. Within the software, you can edit these images to enhance clarity and highlight key temperature points. This includes adjusting color palettes to better represent temperature variations, adding measurement cursors and isotherms (areas of similar temperature), and inserting annotations for reporting purposes. Fluke Connect Desktop goes beyond basic editing by allowing you to analyze temperature data from the image. You can set alarms for exceeding specific temperature thresholds and generate reports with thermal images and relevant data visualizations. This software equips you to effectively analyze thermal images for temperature detection and create professional reports for maintenance or troubleshooting purposes

4.4.2.5 PV inclination angle and irradiance measurement

The Seaward Solar Survey 200R is a handy all-in-one meter designed specifically for solar site assessments. This includes the roof's orientation (using a digital compass) and tilt angle (via a digital inclinometer). It even has dual temperature sensors, one for the environment and another specifically for the solar panel itself. Additionally, the 200R can log this data over time, allowing for in-depth analysis and the creation of comprehensive solar installation reports.

Figure 4.25 Seaward Solar Survey 200R

4.4.2.6 Temperature and irradiance

Figure 4.26 K-Type Thermocouple wire

K-type thermocouple wire stands out as the preferred choice for measuring solar panel temperature for several reasons. Firstly, it boasts an impressive operating range, typically spanning from -270°C to 1370°C. This comfortably covers the spectrum of temperatures experienced by solar panels, ensuring accurate readings even in harsh weather conditions. Secondly, K-type thermocouples are champions of durability.

4.4.2.7 Data acquisition (DAQ) unit

A crucial component of this experiment is the data acquisition system. This system, comprised of Advantech ADAM modules (ADAM-4520 and ADAM-4019+) chosen for their affordability, compact size, and customizability, will be responsible for capturing and recording all the measurement data from the solar irradiance and thermocouple sensors throughout the experiment. These ADAM modules feature built-in microprocessors that enable independent signal conditioning, further enhancing the system's functionality. The complete data acquisition system also includes four core communication cables and a host computer for data processing.

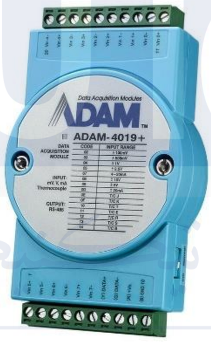


Figure 4.27 Data acquisition ADAM -4019+

4.4.2.8 Ambient Temperature and Irradiance

Figure 4.28 Graph temperature ambient and irradiance over time

This chart illustrates the relationship between ambient temperature and solar irradiance over a specific time period. The blue line represents ambient temperature (°C) on the left axis, while the red line represents irradiance (W/m²) on the right axis. Initially, both ambient temperature and irradiance rise, peaking around 13:46:30, before both start to decline.

The correlation between irradiance and ambient temperature is clear. As irradiance increases, ambient temperature also rises, indicating that higher solar energy levels contribute to a temperature increase. This relationship is important for photovoltaic systems, as both irradiance and temperature impact their efficiency. The sharp drop in irradiance towards the end corresponds with a decrease in ambient temperature, reflecting reduced solar energy input. Understanding this relationship helps optimize photovoltaic system performance by considering environmental

4.4.2.9 Expected Power Output

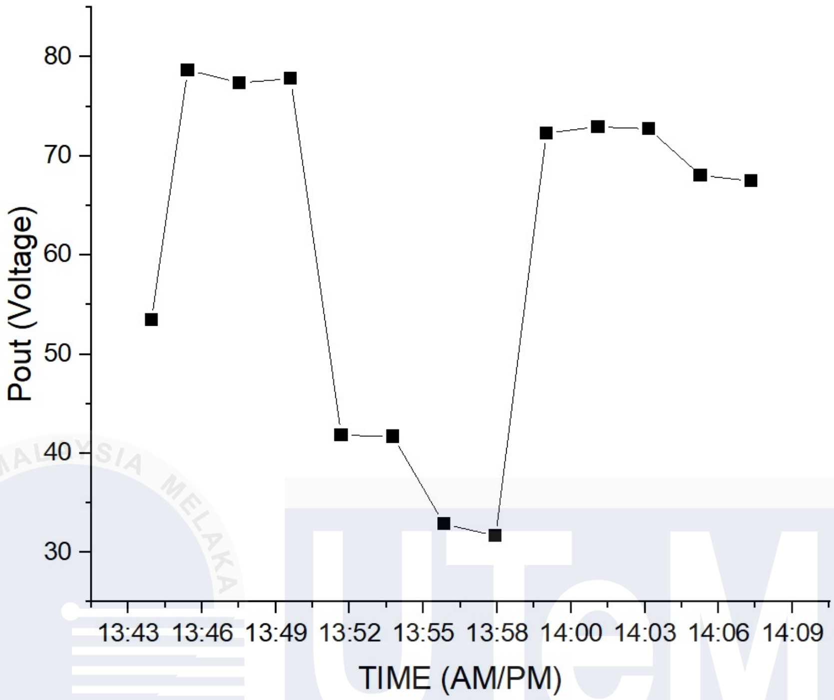


Figure 4.29 Graph Pout vs Time

This is a line graph showing a zoomed-in section of a solar panel’s power output over a short period of time. The x-axis is labeled "Time" and shows timestamps ranging from 13:43:41 to 14:09:19. The y-axis is labeled "Pout" which likely refers to "Power Output" and is measured in watts (W). The data points show that the solar panel's power output fluctuates slightly over the course of the 22 minutes depicted in the graph. It starts at around 53 watts and increases to a peak of around 80 watts at 13:48:00. The power output then dips slightly before ending at around 78 watts at 13:52:18. From this graph, we can see that the solar panel produced the most power around 1:48 PM, and the power output fluctuated a little around an average of 80 watts during this time.

4.5 Environmental Performance of Solar Panels Simulated with Flour as Dust

This study investigates the impact of flour as a simulated dust agent on the performance of solar panels under varying weather conditions. Flour was chosen due to its fine particulate size, which closely resembles environmental dust in terms of adhesion and light-blocking properties. The experiment aims to evaluate how dust affects solar panel efficiency under sunny and cloudy conditions. Additionally, the analysis highlights the importance of implementing a self-cleaning brush system to restore and maintain optimal performance.

4.5.1 Experimental Setup and Methodology

The experiment aimed to assess the percentage enhancement in photovoltaic module performance pre- and post-cleaning, utilizing a 30W Mono-crystalline PV module tested in Melaka (latitude 2.2797°N). The module was positioned at a 15° angle towards the south, and flour was utilized to replicate dust accumulation. Cleaning was performed using a rotary brush coupled with a water pump integrated with a rain sensor. When it rains, the automated brush operates to utilize free rainwater while cleaning the PV module. The experimental setup included the PV module securely mounted on a frame with the rotary brush and water pump positioned for effective cleaning, while the PROVA 1011 analyzer was connected to the module for data acquisition. Data was gathered at three time points: 1:00 PM, 1:30 PM, and 2:00 PM, under both sunny and cloudy weather conditions. The I-V characteristics of the module were measured with a PROVA 1011 analyzer to quantify essential parameters, including short-circuit current, open-circuit voltage, and maximum power output.

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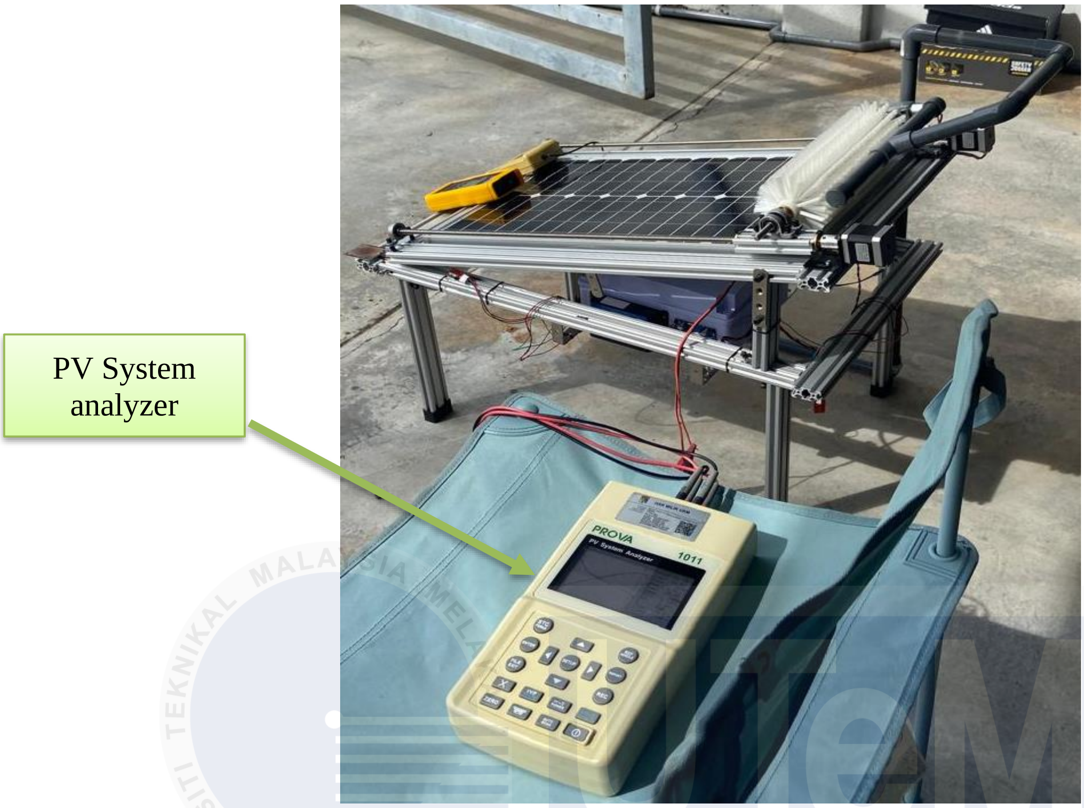


Figure 4.30 Experimental Setup of Environmental Performance of Solar Panel

Measurements were recorded during peak sunlight hours to ensure consistency. The data collected allows for a detailed comparison of the performance degradation caused by dust under different weather conditions.

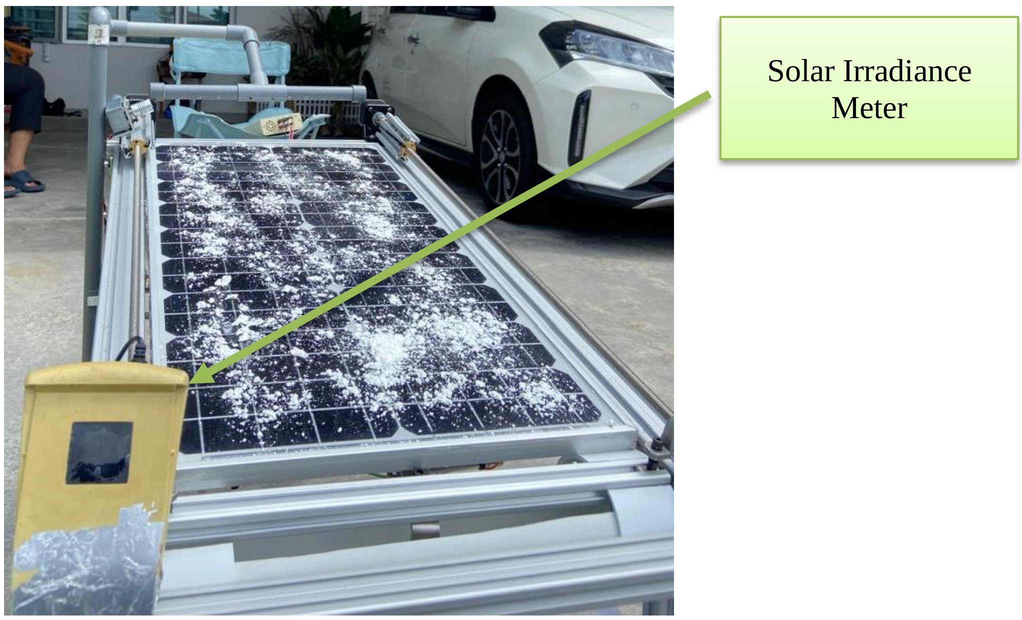


Figure 4.31 Irradiance Meter Placement

4.1 Quantification of Performance Improvement After PV Cleaning

To assess the efficacy of the cleaning robot, the percentage enhancement in critical performance metrics, including short-circuit current, open-circuit voltage, and maximum power output, was determined using the formula:

$$Percentage\ Improvement\ (\%) = \frac{After\ cleaning\ value - Before\ cleaning\ value}{Before\ cleaning\ value} \times 100 \quad \textbf{Eq 3}$$

The notable enhancements in these metrics unequivocally confirm the cleaning mechanism efficacy in reinstating the PV module's performance to optimal standards. The findings highlight that the buildup of dirt and pollutants on the surfaces of photovoltaic modules significantly impairs their electricity generation capacity, diminishing both current flow and voltage output. This directly affects the overall power generation and efficiency of the solar modules, resulting in potential energy losses and diminished system reliability over time. By efficiently eliminating the layers of grime with an automated brush and water, the cleaning mechanism not only reinstates the electrical performance of the PV modules but also guarantees their operation near rated specifications. This procedure mitigates the adverse impacts of shading and surface contamination, prevalent challenges in outdoor installations subjected to environmental factors.

4.5.2 Solar Panel Performance on Sunny Days:

4.5.2.1 Clean Solar Panels

Figure 4.32 Clean Solar Panel

Under sunny conditions, clean solar panels exhibited optimal performance due to high irradiance levels and the absence of dust. At 1:00 PM, the panels achieved a maximum power output (Pmax) of 35.11 W, with a fill factor of 0.664 and an irradiance level of 1012 W/m². These results confirm the efficiency of the panel in converting solar energy into electrical energy under ideal conditions.

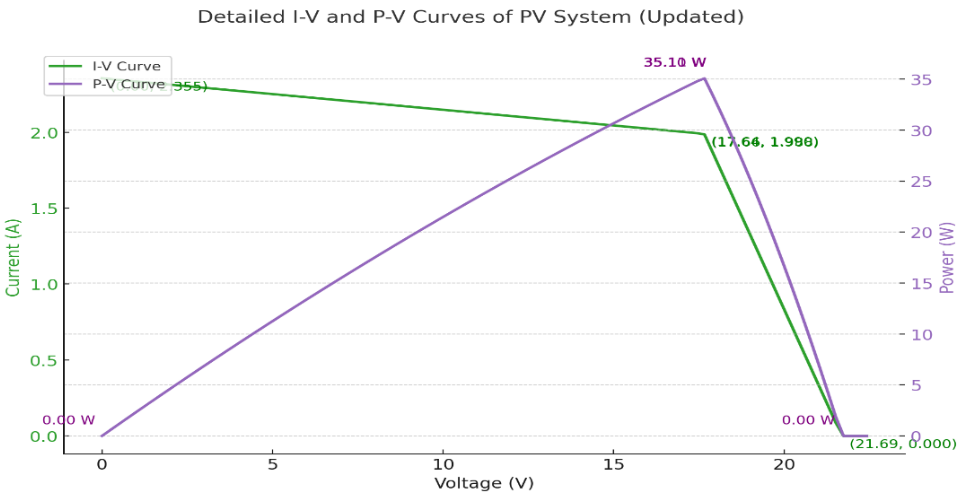


Figure 4.33 Graph I-V and P-V Curves of PV system after cleaning on sunny weather

4.5.2.2 Solar Panels with Flour Dust

The presence of flour dust on the solar panels significantly impacted their performance, leading to a notable reduction in efficiency. The maximum power output (Pmax) decreased to 28.75 W, accompanied by a fill factor of 0.661 and an irradiance level of 510 W/m². This decline illustrates how dust obstructs sunlight from reaching the solar cells, thereby diminishing their ability to convert solar energy into electricity effectively. The findings emphasize the critical need for regular maintenance or self-cleaning mechanisms to mitigate the adverse effects of dust accumulation on energy generation.

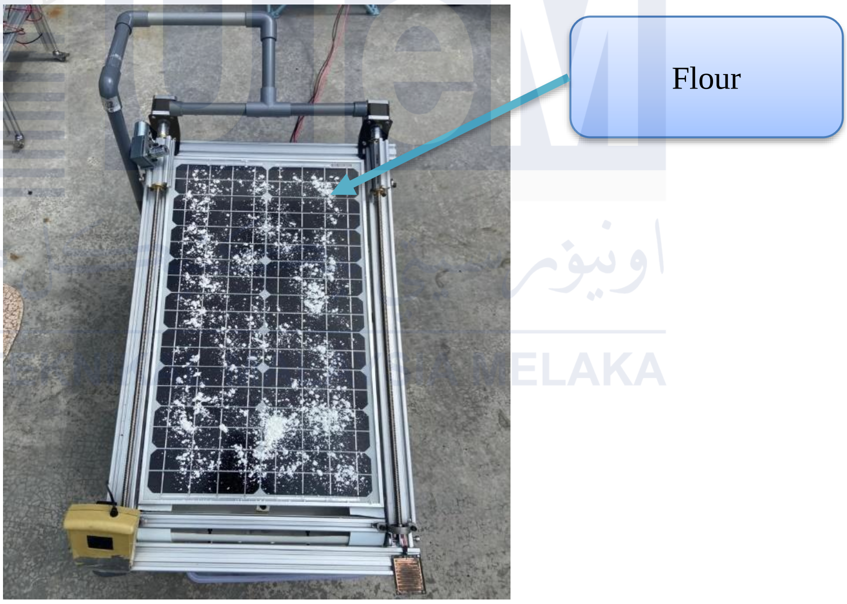


Figure 4.34 Solar Panel with flour

4.5.2.3 Comparison of Clean vs. Dusty Panels on Sunny Days

The presence of flour dust on solar panels caused a significant reduction in performance, with an 18.1% decrease in power output under sunny conditions. This decline demonstrates how even a thin layer of dust can obstruct sunlight, reducing the effective irradiance that reaches the photovoltaic cells. The dust particles create a physical barrier that scatters and absorbs incoming light, thereby decreasing the amount of energy available for conversion into electricity. This not only impacts the energy output but also reduces the efficiency of the panels, as evidenced by the decline in key parameters such as the maximum power output (Pmax) and fill factor. These findings highlight the sensitivity of solar panels to surface contamination, even under high irradiance conditions typically associated with sunny weather.

The degradation in performance due to dust accumulation underscores the critical need for regular cleaning and maintenance of solar panels to ensure consistent energy generation. Frequent cleaning becomes essential in dusty environments where such obstructions are common, as prolonged exposure to dust can compound performance losses over time. Furthermore, the study's findings reinforce the value of self-cleaning mechanisms, such as brush-based systems, which can automate the removal of dust and reduce maintenance efforts. By maintaining a clean surface, these systems ensure that the panels operate at their optimal capacity, maximizing energy generation and improving the overall efficiency of solar power installations. This is particularly important in regions where solar energy serves as a primary source of renewable energy.

Table 4.7 Performance Metrics of Clean vs. Dusty Solar Panels Under Sunny Conditions

Condition	Voc (V)	Isc (A)	Pmax (W)	Irradiance (W/m^2)	Fill Factor
Clean	22.42	2.355	35.11	1012	0.664
Dusty	21.75	1.995	28.75	510	0.661

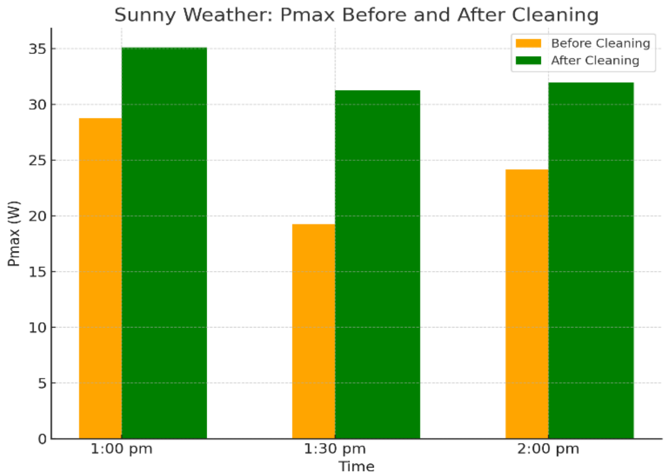


Figure 4.35 Comparison of Photovoltaic Panel Power Output (Pmax) Before and After Cleaning Under Sunny Conditions"

Figure 4.35 shows a significant difference in photovoltaic panel performance before and after cleaning under both sunny and cloudy conditions. Under sunny weather, the maximum power output (Pmax) before cleaning ranged from 19.28 W to 28.75 W. After cleaning, the Pmax increased substantially, ranging from 31.27 W to 35.11 W. This improvement in power output can be attributed to the removal of dust and debris, which likely impeded the panels' ability to absorb solar irradiance effectively. For example, at 1:00 pm, the Pmax increased from 28.75 W before cleaning to 35.11 W after cleaning. This increase highlights the effectiveness of the cleaning mechanism in enhancing the performance of the solar panels, even when the irradiance varied.

4.5.3 Solar Panel Performance on Cloudy Days

4.5.3.1 Clean Solar Panels

In cloudy conditions, clean solar panels exhibited a commendable level of performance despite reduced irradiance levels, demonstrating their adaptability to low-light environments. At 2:00 PM, the panels achieved a maximum power output (Pmax) of 12.01 W, with a fill factor of 0.714 and an irradiance of 371 W/m². This capability to generate electricity efficiently in suboptimal weather conditions highlights the effectiveness of maintaining clean panel surfaces, ensuring maximum exposure to available sunlight.

These findings emphasize the importance of regular maintenance, particularly in regions where cloudy weather is frequent or prolonged. Clean solar panels can maintain a steady energy output even under limited sunlight, making them a reliable source of renewable energy in varying environmental conditions.

Figure 4.36 Clean solar Panel on Cloudy weather

Table 4.8 Solar Panel performance data on cloudy weather based on time

Time	Voc (V)	Isc (Amp)	Pmax (W)	Irradiance (W/m2)	Fill Factor	Tc °C
1:30 pm	21.61	680m	10.64	340	0.722	37.1
2:00 pm	21.77	771m	12.01	371	0.714	37.1
2:30 pm	21.76	747m	11.57	360	0.711	37.1

4.5.3.2 Solar Panels with Flour Dust

Figure 4.37 Solar Panels with flour as dust on cloudy weather

The performance of solar panels under cloudy conditions declined significantly when covered with flour dust. The maximum power output (Pmax) dropped to 5.89 W, with a fill factor of 0.711 and an irradiance level of 311 W/m². This reduction demonstrates how the combined effects of low light and dust accumulation severely impact panel efficiency. Dust particles create an additional barrier that obstructs the already limited sunlight in cloudy conditions, further reducing the energy available for conversion into electricity.

Table 4.9 Solar Panel with flour as dust performance data on cloudy weather based on time

Time	Voc (V)	Isc (Amp)	Pmax (W)	Irradiance (W/m2)	Fill Factor	Tc °C
1:30 pm	21.42	361m	5.02	299	0.648	39.6
2:00 pm	21.38	386m	5.89	311	0.711	39.6
2:30 pm	21.51	444m	6.96	315	0.727	39.6

These findings underscore the compounded challenges that solar panels face in low-light environments when dust is present. Regular maintenance or the use of automated self-cleaning systems becomes vital to minimize these losses and ensure consistent performance. In environments prone to frequent dust accumulation, such solutions can help maintain optimal energy generation, even during adverse weather conditions.

4.5.3.3 Comparison of Clean and Dusty Panels under Cloudy Conditions

The presence of flour dust caused a 50.9% reduction in power output under cloudy conditions. This significant performance loss demonstrates that dust has a more pronounced effect on energy generation in low-light environments compared to sunny conditions, as it scatters and absorbs the already limited sunlight, reducing the efficiency of the solar panel.

Table 4.10 Comparison of Clean vs. Dusty Panels on Cloudy Days Weather

Condition	Voc (V)	Isc (A)	Pmax (W)	Irradiance (W/m^2)	Fill Factor
Clean	21.77	0.771	12.01	371	0.714
Dusty	21.38	0.386	5.89	311	0.711

Table 4.10 presents the comparison of key performance parameters between clean and dusty solar panels. When clean, the panels recorded a maximum power output (Pmax) of 12.01 W, with an open-circuit voltage (Voc) of 21.77 V, a short-circuit current (Isc) of 0.771 A, and a fill factor (FF) of 0.714 under an irradiance of 371 W/m^2. These results highlight the ability of clean panels to function efficiently by maximizing light capture and energy

In contrast, when covered with flour dust, the solar panel's maximum power output dropped to 5.89 W. The open-circuit voltage (Voc) fell slightly to 21.38 V, and the short-circuit current (Isc) dropped significantly to 0.386 A.

The irradiance also decreased to 311 W/m², which compounded the impact of dust accumulation. The fill factor (FF) of 0.711 reflects the reduced electrical performance. These results illustrate how dust reduces light transmission to the solar cells, causing a significant decrease in energy output.conversion, even under reduced sunlight.

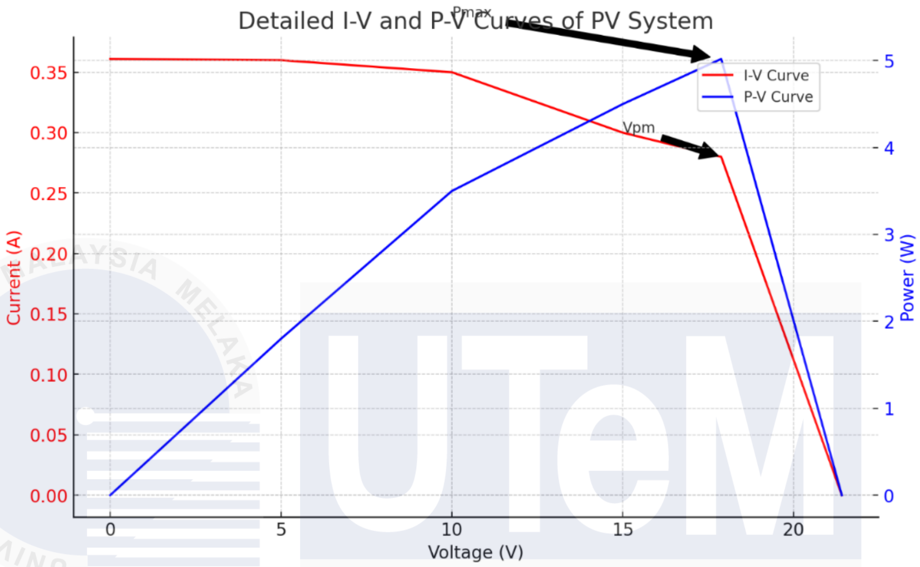


Figure 4.38 Graph I-V and P-V Curves of PV system before cleaning on cloudy weather

The detailed IV and PV curves provide further insights into the panel performance before and after cleaning. Figure 4.38 shows a peak power of 5.89W at a voltage of approximately 21.38 V and current of 0.386A. However, this output is markedly lower compared to the figure 4.39 where the peak power reaches 12.01W at a voltage of approximately 21.77 V and current of 0.771A. This stark difference underscores the importance of cleaning solar panels to restore their full energy-generating potential, especially in environments with frequent dust accumulation.

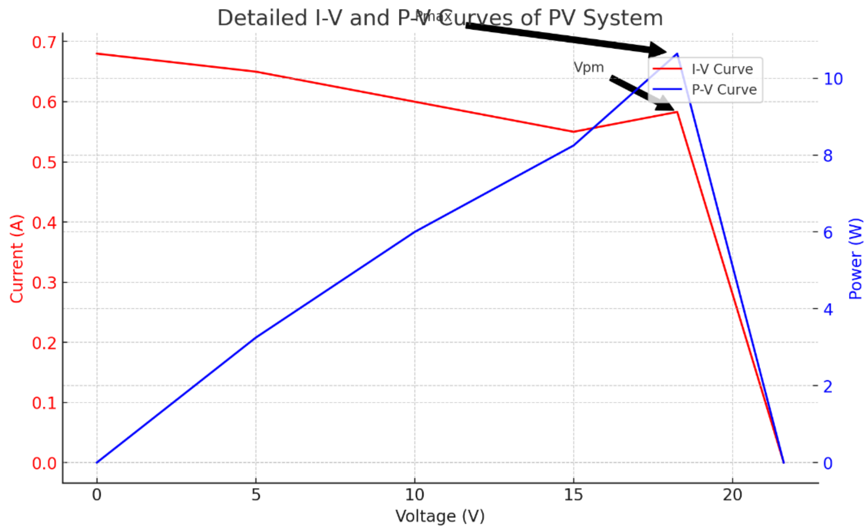


Figure 4.39 Graph I-V and P-V Curves of PV system after cleaning on cloudy weather

Under cloudy conditions, the improvement in performance is also evident, although the overall power output is lower compared to sunny conditions due to reduced irradiance. Before cleaning, the Pmax ranged from 5.02 W to 6.96 W, whereas after cleaning, it increased to a range of 10.64 W to 12.01 W. Despite the lower irradiance levels, the cleaning process significantly enhanced the panels' efficiency. For instance, at 2:00 pm, the Pmax before cleaning was 5.89 W, which increased to 12.01 W after cleaning. This substantial improvement underlines the importance of maintaining clean surfaces on photovoltaic panels to maximize energy production, regardless of weather conditions. The data clearly demonstrates that regular cleaning is essential for optimizing the performance and efficiency of solar panels, ensuring they operate at their full potential in both sunny and cloudy environments.

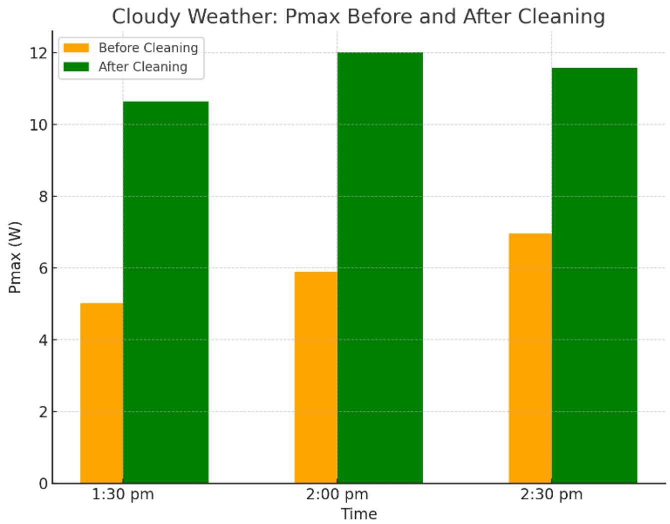


Figure 4.40 Comparison of Photovoltaic Panel Power Output (Pmax) Before and After Cleaning Under Cloudy Conditions"

4.5.4 Impact of Flour Dust on Solar Panel Efficiency Across Weather Modes

A comparative analysis of sunny and cloudy conditions revealed that flour dust significantly reduces the efficiency of solar panels in both weather modes. Under sunny conditions, the reduction in maximum power output was less severe due to higher irradiance levels compensating for the light-blocking effect of dust. In contrast, cloudy conditions amplified the impact of dust as the reduced irradiance further limited energy generation.

This comparison highlights the critical role of maintaining clean solar panels to optimize performance, particularly in low-light environments where dust has a compounding effect.

4.5.5 Key Findings and Implications for Brush Self-Cleaning Systems

The findings underscore the necessity of implementing a self-cleaning system to mitigate the adverse effects of dust accumulation. Under sunny conditions, regular cleaning is required to sustain efficiency and energy generation. In cloudy environments, the impact of dust is more pronounced, making cleaning systems even more critical. The brush self-cleaning system is designed to address these challenges by removing dust efficiently without manual intervention. This study recommends cleaning schedules based on weather conditions and dust accumulation rates to maximize the benefits of solar energy generation.

4.6 Cleaning efficiency of Solar Panels Using Sand as a Measurement Benchmark

4.6.1 Using Sand as a Cleanliness Measurement Metric

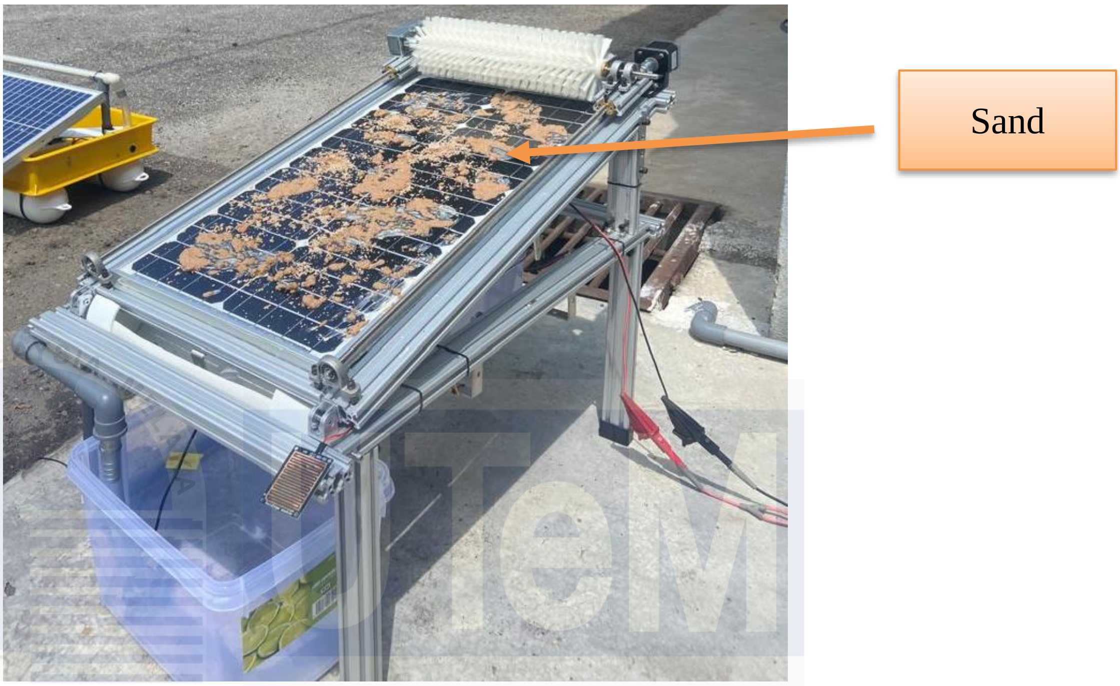


Figure 4.41 Solar panel totally covered with sand

Sand is a common contaminant for solar panels, particularly in arid and semi-arid regions. Its granular nature and high accumulation potential make it an effective metric for assessing cleanliness levels and the efficiency of cleaning systems. By using calibrated sand traps placed adjacent to the solar panels, the amount of sand deposition was quantified over a set period. This method provided a standardized approach to measure the dirtiness of the panels. Studies have shown that even a thin layer of sand can significantly reduce solar panel efficiency by blocking sunlight and reducing energy output. By using sand as a cleanliness measurement metric, we could consistently evaluate the effectiveness of the cleaning mechanism and understand the relationship between sand accumulation and panel performance

4.6.2 Relationship Between Sand Accumulation and Cleaning Brush Cycles

The relationship between sand accumulation and the required number of cleaning brush cycles was a critical aspect of our study. As sand accumulates on the panel surface, it creates a layer that obstructs sunlight, reducing the panel's efficiency. The Arduino-controlled brush cleaning system was designed to remove this layer effectively. Through controlled experiments, we observed a direct correlation between the amount of sand on the panels and the number of brush cycles needed to clean them. Panels with higher levels of sand required more frequent and longer cleaning cycles to achieve the desired cleanliness. This relationship is essential for optimizing the cleaning schedule to ensure the panels remain efficient. Research has indicated that in regions with frequent sandstorms, solar panels may require more frequent cleaning to maintain optimal performance.

4.6.3 Sand Accumulation and Solar Panel Performance

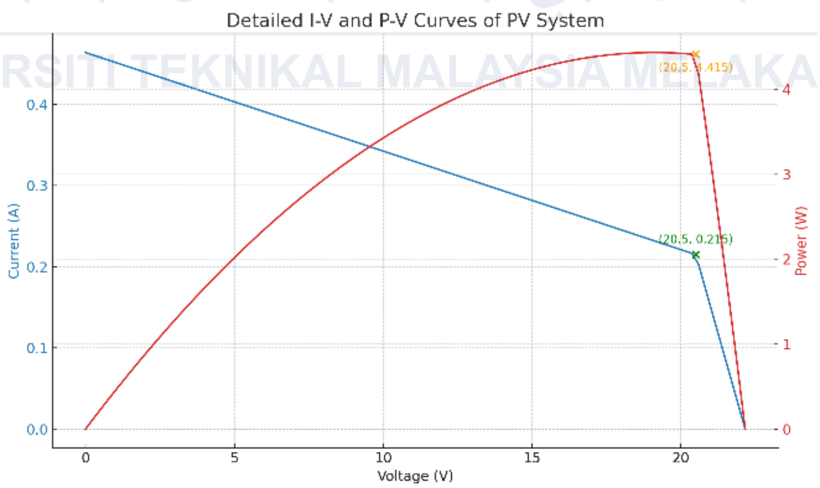


Figure 4.42 Curve graph detail at 100% dirtiness level

The impact of sand accumulation on solar panel performance was evident in the collected data. Panels with 100% sand coverage produced an average power output of 4.356W, while clean panels (0% sand coverage) averaged 24.49W. Similarly, the short-circuit current (Isc) for dirty panels was significantly lower, averaging 0.464A compared to

1.735A for clean panels. The open-circuit voltage (Voc) also showed a reduction, with dirty panels averaging 22.143V, while clean panels averaged 21.643V. These results highlight the critical need for regular cleaning to maintain high energy production. The presence of sand not only reduces the panels' ability to generate electricity but also impacts other performance metrics, emphasizing the importance of an effective cleaning system.

Table 4.11 Short circuit Current Performance

Dirtyness Level	Short circuit current (Isc)			
	Reading 1	Reading 2	Reading 3	Average
100%	464m	462m	455m	0
0%	1.734	1.741	1.730	1.735

Table 4.12 Open-Circuit Voltage Performance

Dirtyness Level	Open-Circuit Voltage (Voc)			
	Reading 1	Reading 2	Reading 3	Average
100%	22.16	22.15	22.12	22.14
0%	21.64	21.62	21.67	21.64

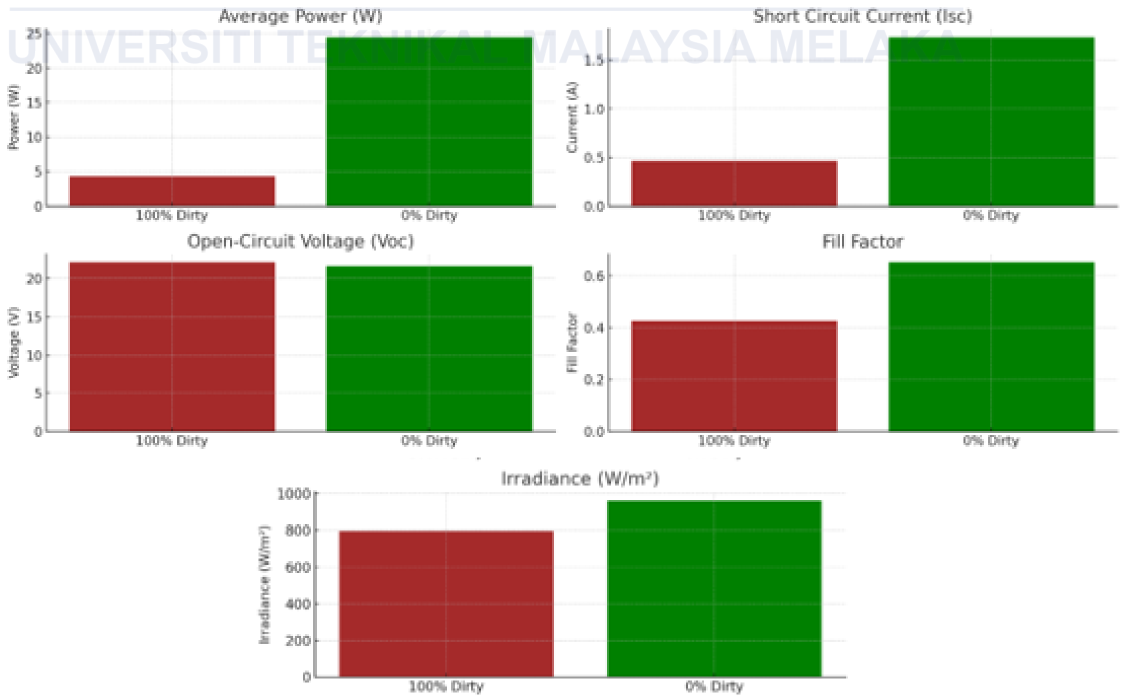


Figure 4.43 Cleanliness Level Analysis of Solar Panels

4.6.4 Effectiveness of Brush Self-Cleaning System

Figure 4.44 Cleaning Operation

The brush-based self-cleaning system was highly effective in restoring panel efficiency. Before cleaning, the panels exhibited a significant drop in performance due to sand accumulation. The irradiance, which was averaged at 795.67 W/m² for dirty panels, increased to 963 W/m² after cleaning. This substantial improvement underscores the system's capability to effectively remove sand and restore optimal conditions for sunlight absorption. The maximum power output (Pmax) also showed a dramatic increase from an average of 4.356W in dirty conditions to 24.49W after cleaning.

Table 4.13 Irradiance Performance

Dirtyness Level	Irradiance (W/m2)			
	Reading 1	Reading 2	Reading 3	Average
100%	799	798	790	795.67
0%	963	964	962	963

Table 4.14 Power Solar Performance

Dirtyness Level	Power (W)			
	Reading 1	Reading 2	Reading 3	Average
100%	4.415	4.342	4.312	4.36
0%	24.80	24.37	24.30	24.49

After the first cleaning cycle, which achieved 90% cleanliness, and the second cycle, which achieved 100% cleanliness, there was a marked improvement in all performance metrics. The short-circuit current (Isc) and open-circuit voltage (Voc) both increased significantly post-cleaning. Specifically, the Isc rose from 0.464A to 1.735A, and the Voc improved from 22.143V to 21.643V.

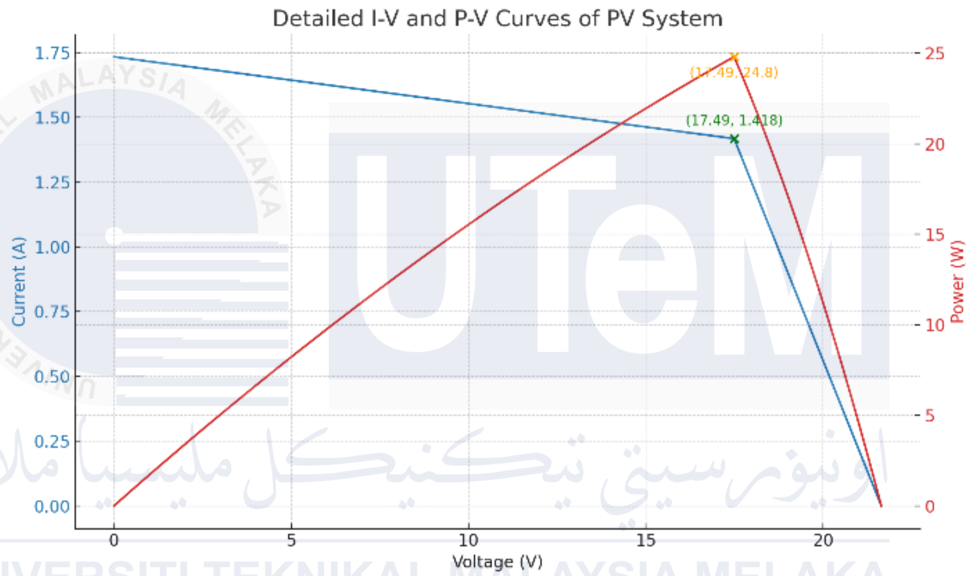


Figure 4.45 IV Curve graph detail at 0% dirtiness level

This validation of the cleaning system's effectiveness highlights its importance in maintaining optimal panel performance. By ensuring the panels are clean, the system maximizes energy production and operational efficiency, particularly in environments prone to heavy sand accumulation.

4.6.5 Maintenance Optimization Based on Sand Cleanliness Levels

Optimizing maintenance schedules based on sand cleanliness levels involves analyzing real-time data on sand accumulation, cleaning brush cycles, and performance metrics. By developing a predictive model, we can dynamically adjust the cleaning frequency to match current conditions, minimizing unnecessary cycles and reducing maintenance costs. For instance, the model indicated that weekly cleaning was sufficient in regions with moderate sand levels, while areas with heavy sand deposition required more frequent cleaning. This approach not only ensures that the panels operate at maximum efficiency but also enhances the economic viability of the solar energy system by balancing maintenance costs with energy output benefits. Regular adjustments based on sand trends ensure sustained high performance and prolong the lifespan of the cleaning system components.

4.7 Cost-Economic Evaluation

4.7.1 Initial Investment Analysis

For the development of the Arduino-controlled brush-based self-cleaning photovoltaic system, the initial investment includes the costs of all necessary components such as the Arduino Uno board, stepper motors, limit switches, industrial brushes, aluminum profiles, and additional hardware required for assembly. Specifically, the Arduino Uno costs approximately RM 42.90, stepper motors RM 89.80, and industrial brushes RM 61.05. The total cost of components is itemized and accounted for in the project's bill of materials.

Labor Costs: Installation labour costs include expenses for the workforce involved in assembling and setting up the system, ensuring that all parts are correctly integrated and functional.

Maintenance Costs: Periodic maintenance costs involve replacing worn-out brushes and any necessary repairs to the system, ensuring its continuous operation. Regular maintenance helps sustain the system's efficiency and prolong its lifespan.

4.7.2 Energy Output Measurement

The energy output measurement for the Arduino-controlled brush-based self-cleaning photovoltaic system can be evaluated using specific formulas that account for voltage, current, irradiance, and panel area. The basic formula to calculate power output is $P=V\times I$ where P represents the power output in watts (W), V is the voltage in volts (V), and I is the current in amperes (A). To achieve a more comprehensive assessment, the formula can be extended to include irradiance and panel area: $P=G\times A\times \eta 1000$, where G stands for irradiance in watts per square meter (W/m^2), A denotes the area of the photovoltaic panel in square meters (m^2), and η signifies the efficiency of the panel.

In this project, the power output before and after cleaning the photovoltaic panels is measured to determine the effectiveness of the cleaning mechanism. Measurements include voltage, current, and irradiance both before and after the cleaning process. By comparing the power output calculated using these values, the increase in efficiency due to cleaning can be determined. To quantify the improvement, the percentage increase in power output is calculated using the formula.

Percentage Increase=$(P2-P1P1)\times 100\%$This calculation indicates the effectiveness of the self-cleaning system in maintaining the efficiency of the photovoltaic panels.

4.7.3 Operational Cost Assessment

Although the system primarily relies on mechanical cleaning, any supplementary water usage for cleaning purposes is minimal and involves the cost of water used per cleaning cycle.

Energy Costs: The energy consumption of the stepper motors and other components involved in the cleaning system is calculated. This includes the electricity used to power the Arduino board and the motors.

Maintenance Costs: Routine maintenance costs are assessed, covering expenses for periodic checks, replacement of brushes, and any necessary repairs to ensure the system remains functional and efficient.

4.7.4 Payback Period Calculation

The additional revenue generated from the increased energy output due to the self-cleaning system is calculated. For instance, if the standard PV module generated 100 kWh/day and the cleaned module generated 110 kWh/day, with an electricity price of RM 0.10/kWh, the revenue increase would be RM 1/day.

Simple Payback Period: The total cost of the self-cleaning system is divided by the annual additional revenue from the increased energy generation to determine the payback period. For example, if the cleaning system cost RM 1000 and the annual revenue increase was RM 365, the payback period would be approximately 2.74 years.

4.7.5 Levelized Cost of Energy (LCOE)

The LCOE is calculated by dividing the total system cost, including the self-cleaning mechanism, by the total energy produced over the system's lifetime. This metric provides a comprehensive understanding of the cost-effectiveness of the energy produced by the system.

4.7.6 Cost-Benefit Ratio

This ratio compares the cost of implementing the self-cleaning system with the monetary value of the increased energy output to determine the cost-effectiveness. A higher ratio indicates greater economic benefits relative to the costs incurred. By comparing the additional revenue generated from the increased energy output to the costs of implementing and maintaining the system, the cost-benefit ratio provides a clear picture of the financial advantages of the project.

4.7.7 Environmental Benefits

The environmental benefits of increased energy production due to the self-cleaning system are estimated by calculating the carbon emissions avoided. For instance, reducing reliance on fossil fuels translates to lower carbon emissions. This can be quantified in monetary terms, such as carbon credits. By enhancing the efficiency of the PV panels and increasing their energy output, the project contributes to a reduction in carbon footprint, supporting sustainable energy practices.

4.8 Summary

The summary provides a comprehensive overview of the design, setup, and preliminary testing of a self-cleaning photovoltaic (PV) system aimed at mitigating dust accumulation to maintain optimal panel efficiency. It begins by emphasizing the importance of cleanliness for solar panels, noting that dust and other contaminants can significantly reduce efficiency and energy output. Preliminary data was collected using advanced tools such as PV reference cells, PV system analyzer, pyranometers, and thermal imagers to measure panel performance under various conditions, both before and after cleaning. The methodology and initial findings highlight the correlation between cleanliness and efficiency, setting the stage for further detailed analysis.

The summary also delves into the specific design aspects of the system. AutoCAD was used for precise mechanical schematics and 3D models, while Proteus was employed for developing and simulating electrical circuits and control systems. The performance of the PV module under real operating conditions was analyzed, with acceptance tests carried out according to IEC and Malaysian standards. The Fluke T100 Infrared Thermal Imager and its software were essential for capturing and analyzing thermal images to identify hot spots and temperature distribution. Overall, this summary lays the groundwork for optimizing PV system design and maintenance strategies to ensure consistent and efficient energy production.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This chapter detailed the design, development, and testing of an Arduino-controlled self-cleaning mechanism for photovoltaic (PV) panels. The primary focus was on achieving objectives (a) and (b) which is designing a functional self-cleaning system and developing its automated operation.

The project successfully implemented a cleaning mechanism controlled by Arduino. The system was also adaptable to utilize rainwater for cleaning purposes. This innovative approach allows the system to leverage natural resources and potentially enhance cleaning efficiency through rain's abrasive properties. The system's effectiveness was evaluated through controlled dust application and cleaning tests, demonstrating its ability to remove dust and maintain panel cleanliness, regardless of the cleaning method employed. This project lays a strong foundation for a self-contained, automated cleaning solution with the potential to enhance the long-term performance and reduce maintenance burdens associated with PV systems, while also promoting water conservation through its innovative rain utilization approach.

5.2 Potential for Commercialization

The automated cleaning system developed in this project presents substantial potential for commercialization, primarily due to its innovative design and operational efficiency. By integrating advanced features such as Arduino-controlled mechanisms, industrial brushes, and rain sensors, the system offers a sustainable solution to a significant challenge in solar energy maintenance. The use of modular components, like the brush and water pump system, ensures adaptability across various scales, from small residential setups to large commercial solar farms.

Economic feasibility further enhances its commercial appeal. The system demonstrates cost-effectiveness through low initial investment and reduced maintenance expenses. By restoring solar panel efficiency to over 95% after cleaning, the system mitigates energy losses caused by soiling, ultimately shortening the payback period for solar installations. This advantage is particularly valuable for businesses and households aiming to maximize the return on their solar investments while minimizing operational costs.

The sustainability and scalability of the system align well with global renewable energy goals. Its capability to utilize rainwater for cleaning minimizes water dependency, a crucial feature in arid and water-scarce regions. Additionally, the increased energy output from cleaner panels contributes to reduced carbon emissions, enhancing the system's environmental credentials. These factors collectively position the project as a viable commercial product with significant potential to revolutionize solar energy maintenance practices.

5.3 Future works

While the current design with timer-based cleaning and rain sensor utilization offers a good foundation, there are several exciting possibilities for future development:

- **IoT Integration for Remote Control:** Equipping the system with a Wi-Fi module would unlock the power of the Internet of Things (IoT). This would allow for remote monitoring and control through a smartphone app or web interface. Users could activate cleaning cycles on demand, receive alerts about system status, and potentially even track cleaning history for performance analysis.
- **Irradiance conditions:** In future iterations of the Arduino-controlled, brush-based self-cleaning photovoltaic system, it may be beneficial to reconsider the electrical design to incorporate an additional condition based on the irradiance levels of the PV panel.
- **Enhancements in Water Storage Management:** Future improvements to the self-cleaning photovoltaic system should include an automatic system for detecting and replacing dirty water in the storage tank. This enhancement would involve integrating sensors to monitor water quality and an automated filtration and replenishment unit to ensure clean water is always used for cleaning. Implementing these features will improve the system's efficiency and reduce the need for manual maintenance.

These future developments can transform my self-cleaning system into a more intelligent, user-friendly, and environmentally conscious solution. They promote efficient cleaning, user control, and sustainability, ultimately maximizing the system's effectiveness and appeal.

REFERENCES

[1] A. Shariah and E. A. Al-Ibrahim, "Impact of Dust and Shade on Solar Panel Efficiency and Development of a Simple Method for Measuring the Impact of Dust," *Journal of Sustainable Development of Energy, Water and Environment Systems*, vol. 11, no. 2, Jun. 2023, doi: 10.13044/j.sdewes.d11.0448.

[2] M. Nezamisavojbolaghi, E. Davodian, A. Bouich, M. Tlemçani, O. Mesbahi, and F. M. Janeiro, "The Impact of Dust Deposition on PV Panels' Efficiency and Mitigation Solutions: Review Article," *Energies*, vol. 16, no. 24. Multidisciplinary Digital Publishing Institute (MDPI), Dec. 01, 2023. doi: 10.3390/en16248022.

[3] E. J. F., B. O. O, F. E. A., and M. T. S, "Design and Construction of an Automatic Solar Panel Cleaning System," *Saudi Journal of Engineering and Technology*, vol. 8, no. 12, pp. 293–299, Dec. 2023, doi: 10.36348/sjet.2023.v08i12.001.

[4] R. Santbergen, V. A. Muthukumar, R. M. E. Valckenborg, W. J. A. van de Wall, A. H. M. Smets, and M. Zeman, "Calculation of irradiance distribution on PV modules by combining sky and sensitivity maps," *Solar Energy*, vol. 150, pp. 49–54, 2017, doi: 10.1016/j.solener.2017.04.036.

[5] J. D. Mondol, Y. G. Yohanis, and B. Norton, "The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system," *Renew Energy*, vol. 32, no. 1, pp. 118–140, Jan. 2007, doi: 10.1016/j.renene.2006.05.006.

[6] J. M. Bright, O. Babacan, J. Kleissl, P. G. Taylor, and R. Crook, "A synthetic, spatially decorrelating solar irradiance generator and application to a LV grid model with high PV penetration," *Solar Energy*, vol. 147, pp. 83–98, 2017, doi: 10.1016/j.solener.2017.03.018.

[7] F. Wang *et al.*, "A minutely solar irradiance forecasting method based on real-time sky image-irradiance mapping model," *Energy Convers Manag*, vol. 220, Sep. 2020, doi: 10.1016/j.enconman.2020.113075.

[8] M. M. Fouad, L. A. Shihata, and E. S. I. Morgan, "An integrated review of factors influencing the performance of photovoltaic panels," *Renewable and Sustainable Energy Reviews*, vol. 80. Elsevier Ltd, pp. 1499–1511, 2017. doi: 10.1016/j.rser.2017.05.141.

[9] H. A. Kazem, M. T. Chaichan, A. H. A. Al-Waeli, and K. Sopian, "A review of dust accumulation and cleaning methods for solar photovoltaic systems," *Journal of Cleaner Production*, vol. 276. Elsevier Ltd, Dec. 10, 2020. doi: 10.1016/j.jclepro.2020.123187.

[10] H. Abuzaid, M. Awad, and A. Shamayleh, "Impact of dust accumulation on photovoltaic panels: a review paper," *International Journal of Sustainable Engineering*, vol. 15, no. 1. Taylor and Francis Ltd., pp. 266–287, 2022. doi: 10.1080/19397038.2022.2140222.

[11] O. Zogou, "UNIVERSITY OF THESSALY-SCHOOL OF ENGINEERING DEPARTMENT OF MECHANICAL ENGINEERING Experimental and computational investigation of the thermal and electrical performance of a new building integrated photovoltaic concept," 2011.

[12] S. Shapsough, R. Dhaouadi, I. Zualkernan, and M. Takrouri, "Power Prediction via Module Temperature for Solar Modules Under Soiling Conditions," in *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, LNICST*, Springer, 2020, pp. 85–95. doi: 10.1007/978-3-030-49610-4_7.

[13] M. M. Rahman, M. Hasanuzzaman, and N. A. Rahim, "Effects of operational conditions on the energy efficiency of photovoltaic modules operating in Malaysia," *J Clean Prod*, vol. 143, pp. 912–924, Feb. 2017, doi: 10.1016/j.jclepro.2016.12.029.

[14] "[14]".

[15] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world - A review," in *Energy Procedia*, Elsevier Ltd, 2013, pp. 311–321. doi: 10.1016/j.egypro.2013.05.072.

[16] R. Moretón, E. Lorenzo, A. Pinto, J. Muñoz, and L. Narvarte, "From broadband horizontal to effective in-plane irradiation: A review of modelling and derived uncertainty for PV yield prediction," *Renewable and Sustainable Energy Reviews*, vol. 78. Elsevier Ltd, pp. 886–903, 2017. doi: 10.1016/j.rser.2017.05.020.

[17] F. Wang *et al.*, "A minutely solar irradiance forecasting method based on real-time sky image-irradiance mapping model," *Energy Convers Manag*, vol. 220, Sep. 2020, doi: 10.1016/j.enconman.2020.113075.

[18] S. A. M. Said and H. M. Walwil, "Fundamental studies on dust fouling effects on PV module performance," *Solar Energy*, vol. 107, pp. 328–337, 2014, doi: 10.1016/j.solener.2014.05.048.

[19] S. A. M. Said, N. Al-Aqeeli, and H. M. Walwil, "The potential of using textured and anti-reflective coated glasses in minimizing dust fouling," *Solar Energy*, vol. 113, pp. 295–302, Jan. 2015, doi: 10.1016/j.solener.2015.01.007.

[20] E. A. Almuhanna, "Dustfall Associated with Dust Storms in the Al-Ahsa Oasis of Saudi Arabia," *Open Journal of Air Pollution*, vol. 04, no. 02, pp. 65–75, 2015, doi: 10.4236/ojap.2015.42007.

[21] K. Hasan, S. B. Yousuf, M. S. H. K. Tushar, B. K. Das, P. Das, and M. S. Islam, "Effects of different environmental and operational factors on the PV performance: A comprehensive review," *Energy Science and Engineering*, vol. 10, no. 2. John Wiley and Sons Ltd, pp. 656–675, Feb. 01, 2022. doi: 10.1002/ese3.1043.

[22] "[23]".

[23] F. Touati, A. Massoud, J. A. Hamad, and S. A. Saeed, "Effects of environmental and climatic conditions on PV efficiency in qatar," *Renewable Energy and Power Quality Journal*, vol. 1, no. 11, pp. 262–267, Mar. 2013, doi: 10.24084/repqj11.275.

[24] K. Brecl and M. Topič, "Self-shading losses of fixed free-standing PV arrays," *Renew Energy*, vol. 36, no. 11, pp. 3211–3216, Nov. 2011, doi: 10.1016/j.renene.2011.03.011.

[25] M. A. Munoz, M. C. Alonso-García, N. Vela, and F. Chenlo, "Early degradation of silicon PV modules and guaranty conditions," *Solar Energy*, vol. 85, no. 9, pp. 2264–2274, Sep. 2011, doi: 10.1016/j.solener.2011.06.011.

[26] M. Waqar Akram *et al.*, "Study of manufacturing and hotspot formation in cut cell and full cell PV modules," *Solar Energy*, vol. 203, pp. 247–259, Jun. 2020, doi: 10.1016/j.solener.2020.04.052.

[27] J. Gosumbonggot and G. Fujita, "Global maximum power point tracking under shading condition and hotspot detection algorithms for photovoltaic systems," *Energies (Basel)*, vol. 12, no. 5, 2019, doi: 10.3390/en12050882.

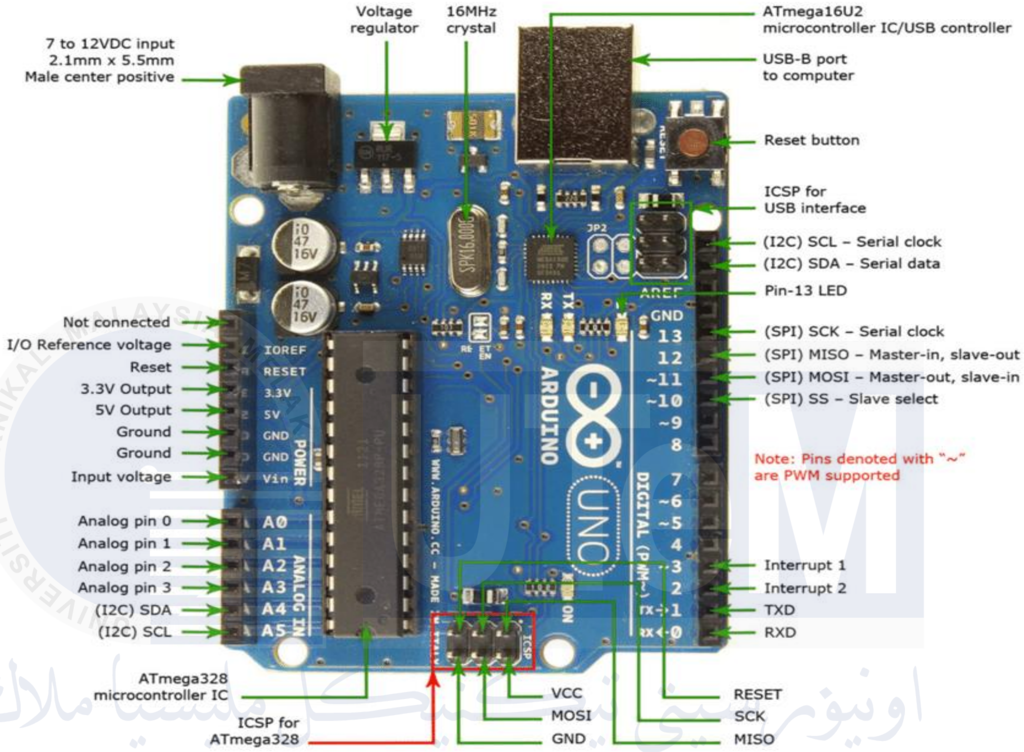
[28] Y. Jiang, L. Lu, and H. Lu, "A novel model to estimate the cleaning frequency for dirty solar photovoltaic (PV) modules in desert environment," *Solar Energy*, vol. 140, pp. 236–240, Dec. 2016, doi: 10.1016/j.solener.2016.11.016.

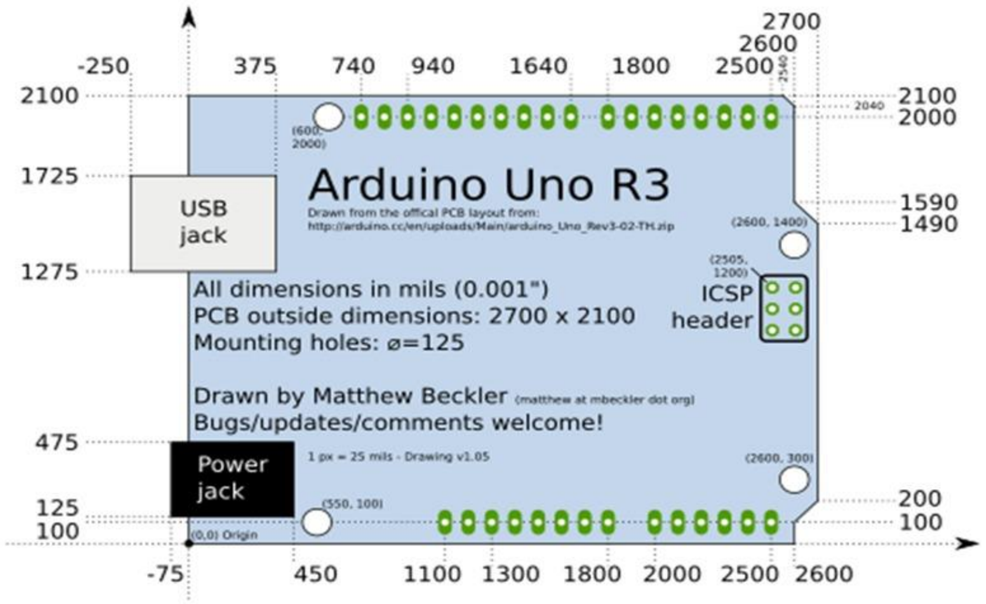
[29] H. Kawamoto, "Electrostatic cleaning equipment for dust removal from soiled solar panels," *J Electrostat*, vol. 98, pp. 11–16, Mar. 2019, doi: 10.1016/j.elstat.2019.02.002.

[30] A. E. Özçelik and G. N. Güğül, “Renewable Energy Sources Energy Policy and Energy Management journal homepage Photovoltaic panels: A review of Cleaning Systems ARTICLE INFO ABSTRACT,” *Renewable Energy Sources Energy Policy and Energy Management*, vol. 1, no. 2, pp. 9–17.
[31] “[32]”.
[32] M. Aiman Mohamad Rafie and S. Sy Yi, “Smart Dust Detection and Automation Cleaning of Photovoltaics Panel,” *Evolution in Electrical and Electronic Engineering*, vol. 4, no. 2, pp. 423–432, 2023, doi: 10.30880/eeee.2023.04.02.052.
[33] M. B, A. Bari, and P. C M, “Automatic Solar Panel Cleaning System,” *International Journal of Advances in Scientific Research and Engineering*, vol. 4, no. 7, pp. 26–31, Jul. 2018, doi: 10.31695/ijasre.2018.32778.
[34] Sayeedurrahman, B. Sabir, R. A. Khan, D. Masood, and A. Nat, “A solar tracking system with light-dependent resistors and a stepper motor controlled by a microcontroller,” in *2023 International Conference on Computer, Electronics and Electrical Engineering and their Applications, IC2E3 2023*, Institute of Electrical and Electronics Engineers Inc., 2023. doi: 10.1109/IC2E357697.2023.10262787.
[35] “8”.
[36] M. I. Elmeadawy, “Developing an Automatic Dust Cleaning Unit to Improve the Photovoltaic Panels productivity,” *Journal of Soil Sciences and Agricultural Engineering*, vol. 11, no. 11, pp. 647–651, Nov. 2020, doi: 10.21608/jssae.2020.135709.
[37] D. A. Asoh and N. N. Awangum, “Low-Cost Automated PV Panel Dust Cleaning System for Rural Communities,” *Smart Grid and Renewable Energy*, vol. 13, no. 08, pp. 173–199, 2022, doi: 10.4236/sgre.2022.138011.
[38] M. Hamid, M. F. Simamora, M. D. E. Vania, and P. Cholillah, “Design of Automatic Cleaning System on Solar Panel Using IoT-based Wiper,” in *Journal of Physics: Conference Series*, Institute of Physics, 2024. doi: 10.1088/1742-6596/2733/1/012024.
[39] N. Khadka, A. Bista, B. Adhikari, A. Shrestha, and D. Bista, “Smart solar photovoltaic panel cleaning system,” in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics Publishing, Apr. 2020. doi: 10.1088/1755-1315/463/1/012121.
[40] E. J. F., B. O. O, F. E. A., and M. T. S, “Design and Construction of an Automatic Solar Panel Cleaning System,” *Saudi Journal of Engineering and Technology*, vol. 8, no. 12, pp. 293–299, Dec. 2023, doi: 10.36348/sjet.2023.v08i12.001.
[41] N. Maindad, A. Gadhave, S. Satpute, and B. Nanda, “International Conference on Communication and Information Processing Automatic Solar Panel Cleaning System,” 2020. [Online]. Available: https://ssrn.com/abstract=3646147

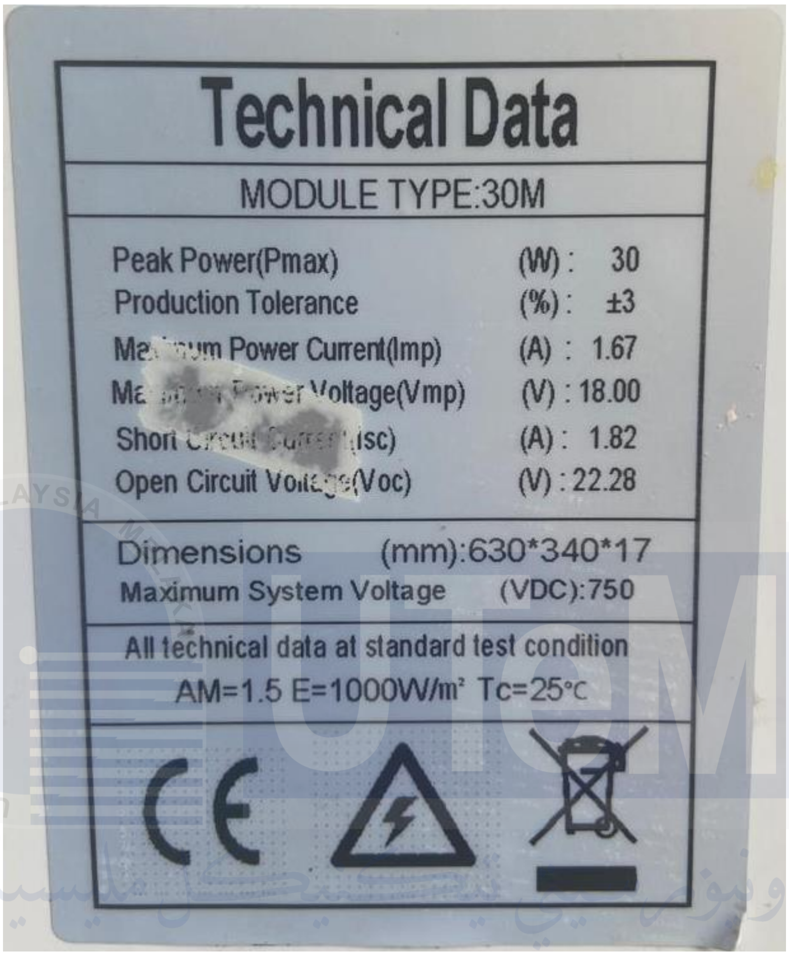
APPENDICES

Appendix 1 Arduino Uno

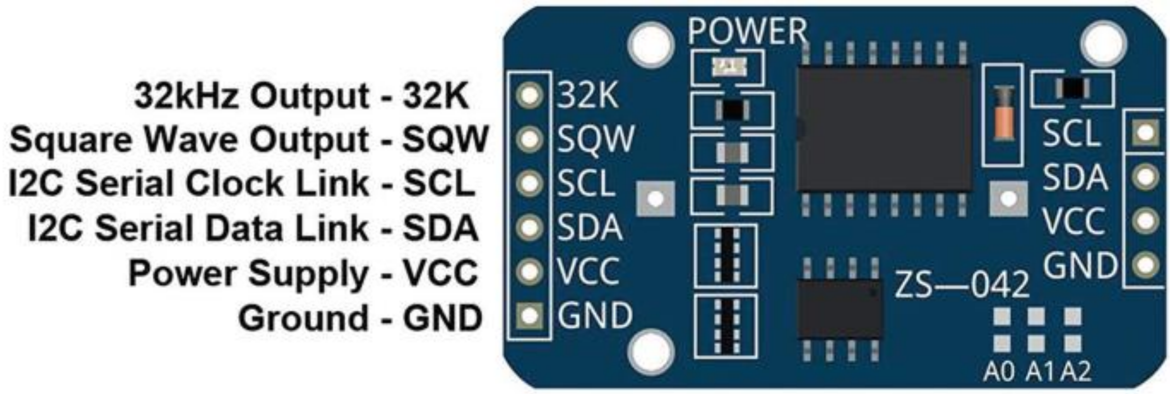




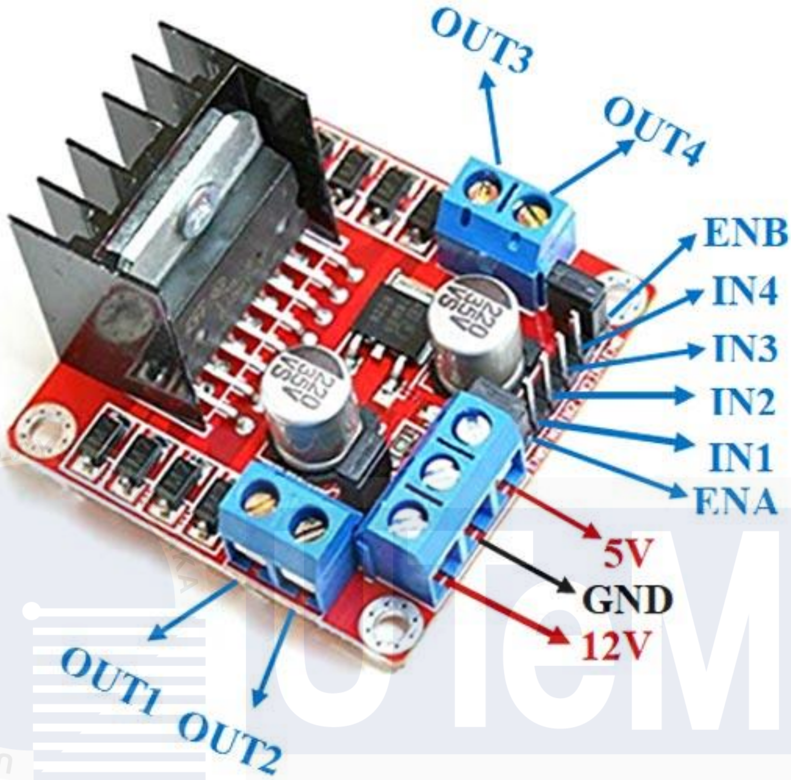
Appendix 2 Solar Panel Monocrystalline PV Module (IBC30Wp)



Appendix 3 RTC 3231 Module



Appendix 4 L298N Motor Driver Module



Appendix 5 Full Coding System

```
#include <Wire.h>
#include <RTClib.h>

// Pin Definitions
#define RAIN_SENSOR_PIN 13
#define MOTOR1_STEP_PIN 5
#define MOTOR1_DIR_PIN 6
#define MOTOR2_STEP_PIN 3
#define MOTOR2_DIR_PIN 4
#define BRUSH_MOTOR_PIN 7
#define WATER_PUMP_PIN 11 // Water pump pin
#define BOTTOM_LIMIT_PIN 8 // Bottom limit switch
#define TOP_LIMIT_PIN 9    // Top limit switch
#define POWER_BUTTON_PIN 10 // Power button pin

bool hasOperatedRain = false;



// Constants
const int STEPS_PER_REVOLUTION = 200; // Adjust according to your motor specs
const int CLEANING_CYCLES = 1; // Number of cleaning cycles
const int CLEANING_DELAY_MS = 1000; // Delay between movements (adjust as
needed)
const int MOTOR_SPEED_DELAY = 1000; // Delay between steps (adjust for speed)

// Global Variables
RTC_DS3231 rtc;
bool isPowerOn = false;

// Set the time for the brush motor and water pump to operate
const int START_HOUR = 17; // Set start hour (24-hour format)
const int START_MINUTE = 52; // Set start minute
const int STOP_HOUR = 17; // Set stop hour (24-hour format)
const int STOP_MINUTE = 53; //1 Set stop minute

void setup() {
  Serial.begin(9600);
  rtc.begin();

  // Pin Modes
  pinMode(RAIN_SENSOR_PIN, INPUT);
  pinMode(MOTOR1_STEP_PIN, OUTPUT);
  pinMode(MOTOR1_DIR_PIN, OUTPUT);
  pinMode(MOTOR2_STEP_PIN, OUTPUT);
  pinMode(MOTOR2_DIR_PIN, OUTPUT);
  pinMode(BRUSH_MOTOR_PIN, OUTPUT);
  pinMode(WATER_PUMP_PIN, OUTPUT); // Set water pump pin as output
```

```
  pinMode(BOTTOM_LIMIT_PIN, INPUT_PULLUP);
  pinMode(TOP_LIMIT_PIN, INPUT_PULLUP);
  pinMode(POWER_BUTTON_PIN, INPUT_PULLUP);

  // Initialize power state
  digitalWrite(BRUSH_MOTOR_PIN, HIGH); // Brush motor off
  digitalWrite(WATER_PUMP_PIN, HIGH); // Water pump off
}

void loop() {
  // Check switch button state
  if (digitalRead(POWER_BUTTON_PIN) == LOW) { // Switch button HIGH means
system is ready to operate
    isPowerOn = true; // Set power state to ON
    Serial.println("System is READY to operate.");
  } else {
    isPowerOn = false; // Set power state to OFF
    Serial.println("System is OFF.");
  }

  if (isPowerOn) {

    DateTime now = rtc.now();

    Serial.print(now.year(), DEC);
    Serial.print('/');
    Serial.print(now.month(), DEC);
    Serial.print('/');
    Serial.print(now.day(), DEC);
    Serial.print(" ");
    Serial.print(now.hour(), DEC);
    Serial.print(':');
    Serial.print(now.minute(), DEC);
    Serial.print(':');
    Serial.print(now.second(), DEC);
    Serial.println();

    // Check rain sensor
    if (digitalRead(RAIN_SENSOR_PIN) == LOW && !hasOperatedRain) { // LOW
means rain is detected
      Serial.println("Rain detected. Starting operation...");
      YesraincleanSolarPanel();
      operateWaterPump();
      hasOperatedRain = true; // Set the flag to true to prevent re-triggering
    }

    // Optional: Reset the hasOperatedRain flag at a specific time or condition
    // For example, reset it at midnight (00:00)
    if (now.hour() == 0 && now.minute() == 0) {
      hasOperatedRain = false;
```

```
    }
    if (now.hour() == 12 && now.minute() == 0) {
      hasOperatedRain = false;
    }



    // Check if the current time matches the set time for operation
    if  (now.hour() == START_HOUR && now.minute() == START_MINUTE)  {
      NoraincleanSolarPanel();
      operateWaterPump();


    }else {
      Serial.println("No rain detected. System on standby.");
    }
  } else {
    Serial.println("System is OFF. No operations will be performed.");
  }

  delay(500); // Add delay to prevent rapid state changes
}

void YesraincleanSolarPanel() {
  // Start the brush motor
  digitalWrite(BRUSH_MOTOR_PIN, LOW);
  digitalWrite(WATER_PUMP_PIN, HIGH);
  Serial.println(" AA");
  delay(5000); // Run the brush motor for 5 seconds (adjust as needed)

  for (int cycle = 0; cycle < CLEANING_CYCLES; cycle++) {
    // Move down
    moveMotorsDown();
    delay(CLEANING_DELAY_MS); // Delay between down and up movements

    // Move up
    moveMotorsUp();
    delay(CLEANING_DELAY_MS); // Delay between cycles
    Serial.println(" BB");
  }

  // Stop the brush motor after cleaning
  digitalWrite(BRUSH_MOTOR_PIN, HIGH);
  digitalWrite(WATER_PUMP_PIN, HIGH);
  Serial.println(" CC");
}

void NoraincleanSolarPanel() {
  // Start the brush motor
  digitalWrite(BRUSH_MOTOR_PIN, LOW);
```

```
   digitalWrite(WATER_PUMP_PIN, LOW);
   Serial.println(" AA");
   delay(5000); // Run the brush motor for 5 seconds (adjust as needed)

   for (int cycle = 0; cycle < CLEANING_CYCLES; cycle++) {
      // Move down
      moveMotorsDown();
      delay(CLEANING_DELAY_MS); // Delay between down and up movements

      // Move up
      moveMotorsUp();
      delay(CLEANING_DELAY_MS); // Delay between cycles
      Serial.println(" BB");
   }

   // Stop the brush motor after cleaning
   digitalWrite(BRUSH_MOTOR_PIN, HIGH);
   digitalWrite(WATER_PUMP_PIN, HIGH);
   Serial.println(" CC");
}

void operateWaterPump() {
   // Start the water pump
   //digitalWrite(WATER_PUMP_PIN, LOW);
   //delay(5000); // Run the water pump for 5 seconds (adjust as needed)
   //Serial.println(" PUMP ON");
   //digitalWrite(WATER_PUMP_PIN, HIGH); // Stop the water pump
}

void moveMotorsDown() {
   // Set motor direction down
   digitalWrite(MOTOR1_DIR_PIN, LOW);
   digitalWrite(MOTOR2_DIR_PIN, LOW);

   while (digitalRead(BOTTOM_LIMIT_PIN) == HIGH) { // Continue until bottom limit
is hit
      stepMotor(MOTOR1_STEP_PIN);
      stepMotor(MOTOR2_STEP_PIN);
   }
}

void moveMotorsUp() {
   // Set motor direction up
   digitalWrite(MOTOR1_DIR_PIN, HIGH);
   digitalWrite(MOTOR2_DIR_PIN, HIGH);

   while (digitalRead(TOP_LIMIT_PIN) == HIGH) { // Continue until top limit is hit
      stepMotor(MOTOR1_STEP_PIN);
      stepMotor(MOTOR2_STEP_PIN);
   }
```

```
}

void stepMotor(int stepPin) {
  digitalWrite(stepPin, HIGH);
  delayMicroseconds(MOTOR_SPEED_DELAY);
  digitalWrite(stepPin, LOW);
  delayMicroseconds(MOTOR_SPEED_DELAY);
}
```

Appendix 6 Materials and Components used

No	Component	Quantity
1	Aluminium Profile (20mm x 40mm)	100 mm x 2
2	Aluminium Profile (20mm x 40mm)	400 mm x 4
3	Aluminium Profile (20mm x 20mm)	350 mm x 1
4	Aluminium Profile (20mm x 40mm)	400 mm x 3
5	Aluminium Profile (20mm x 40mm)	670 mm x 4
6	Aluminium Profile (20mm x 40mm)	150 mm x 2 (15°)
7	PVC Pipe D = 28mm , 2440 mm	1
8	PVC Pipe D =80mm , 350 mm	1
9	Stepper Motor Nema 17 HS 8401	2
10	DC Motor 150 RPM	1
11	Water Pump	1
12	Arduino Uno	1
13	Rain Sensor	1
14	RTC DS 3231	1
15	Limit Switch	2
16	Coupling (5mm to 8mm)	2
17	Coupling (4mm to 8mm)	1
18	Stepper Motor Bracket	2
19	DC Motor Bracket	1
20	Ball bearing Pillow Block Mounter (8mm)	4
21	T8 Lead Screw	700mm x 2
22	T8 Lead Screw	400mm x 1
23	Industrial Brush	1
24	Solar Charge Controller	1
25	Voltage Regulator Step Down Buck Converter	1
26	T8 Screw Brass Nut Pitch	6
27	Relay (5V)	2
28	12 Volt Battery	1
29	Cable Connector (5in 1 Out)	2
30	Hose	200mm x 1
31	Water Case Tank	1
32	Junction Box (255mm x 200mm x 100mm)	1
33	Rubber Foot Pad	4
34	A4988 Stepper Motor Driver	2