# Faculty of Electrical Technology and Engineering

# DEVELOPMENT OF SOLAR PV POWERED OUTDOOR AIR PURIFICATION WITH AIR QUALITY MONITORING SYSTEM

**MUHAMMAD NUR FAIQ BIN NOOR AZIAN**

**Bachelor of Electrical Engineering Technology with Honours**

**2024**

# DEVELOPMENT OF SOLAR PV POWERED OUTDOOR AIR PURIFICATION WITH AIR QUALITY MONITORING SYSTEM

**MUHAMMAD NUR FAIQ BIN NOOR AZIAN**

**A project report submitted**
**in partial fulfillment of the requirements for the degree of**
**Bachelor of Electrical Engineering Technology with Honours**

**Faculty of Electrical Technology and Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**



**2024**

## DECLARATION

I declare that this project report entitled "Development of Solar PV Powered Outdoor Air Purification with Air Quality Monitoring 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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| Date | : | 3/1/2025 |

**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.

Signature :

Supervisor Name : Dr. Azhan Bin Ab Rahman

Date : 27/1/2025

# DEDICATION

*In the name of Allah SWT, the Most Gracious and Most Merciful, I dedicate this humble work, Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System, to those who have been the guiding light of my journey. To Allah SWT, for granting me the strength, patience, and wisdom to embark on and complete this project. Every step I have taken, every challenge I have faced, and every accomplishment I have achieved is by Your grace and blessings. Alhamdulillah, I am forever grateful.*

*To my respected supervisor, Dr. Azhan Bin Ab Rahman, whose guidance, wisdom, and encouragement have been invaluable throughout this project. Your mentorship has been a beacon of knowledge and motivation, and I am honored to have learned under your supervision. Thank you for believing in me and pushing me to achieve my best.*

*To my beloved parents and family, whose unwavering love, sacrifices, and encouragement have been the foundation of my strength and success. Your faith in me has inspired this achievement, and I am deeply grateful for your endless support. May Allah SWT bless you all for your love and contributions to my journey.*

## ABSTRACT

The "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" project addresses concerns over deteriorating air quality and its health effects. Many households own air purifiers, but these devices are often expensive, require external power, and lack integrated air quality monitoring. This project aims to develop an affordable, solar-powered air purifier for both indoor and outdoor use, offering real-time air quality monitoring and eliminating dependency on external power. Simulated using Proteus and Arduino IDE, the system demonstrated accurate pollutant detection by the MQ135 sensor and correct LCD functionality. Hardware analysis focused on evaluating the solar panel's power output, battery charging duration, air quality monitoring, and filtration efficiency. The solar panel generated sufficient power with an average daily output of 2.80 watts under sunny conditions, and the battery fully charged in 8 hours, following two typical SLA charging phases. Air filtration testing revealed significant pollutant reductions, with dust levels reduced by 62.5% ($mg/m^3$), methane by 42.9%, CO by 40%, and $CO_2$ by 33.3%, validating the HEPA + Carbon filter's efficiency. The results confirm the system's capability for sustainable air purification and real-time monitoring, suitable for high-pollution areas or locations with limited power access.

## *ABSTRAK*

*Projek "Sistem Penulenan Udara Luar Berkuasa Solar PV dengan Pemantauan Kualiti Udara" menangani kebimbangan terhadap kemerosotan kualiti udara dan kesannya terhadap kesihatan. Banyak isi rumah memiliki penulen udara, tetapi peranti ini sering mahal, memerlukan kuasa luaran, dan tiada pemantauan kualiti udara yang terintegrasi. Projek ini bertujuan membangunkan penulen udara berkuasa solar yang mampu milik untuk kegunaan dalam dan luar rumah, dengan pemantauan kualiti udara masa nyata dan tanpa bergantung kepada kuasa luaran. Sistem yang disimulasikan menggunakan Proteus dan Arduino IDE menunjukkan pengesanan pencemaran yang tepat oleh sensor MQ135 dan fungsi paparan LCD yang betul. Analisis perkakasan memberi tumpuan kepada penilaian kuasa panel solar, tempoh pengecasan bateri, pemantauan kualiti udara, dan keberkesanan penapisan. Panel solar menghasilkan kuasa yang mencukupi dengan purata output harian sebanyak 2.80 watt dalam keadaan cerah, dan bateri dicas penuh dalam tempoh 8 jam, mengikuti dua fasa pengecasan SLA. Ujian penapisan udara menunjukkan pengurangan bahan pencemar yang ketara, dengan habuk menurun sebanyak 62.5% (mg/m$^3$), metana 42.9%, CO 40%, dan $CO_2$ 33.3%, mengesahkan kecekapan penapis HEPA + Karbon. Hasil ini membuktikan keupayaan sistem untuk penulenan udara mampan dan pemantauan masa nyata, sesuai untuk kawasan pencemaran tinggi atau lokasi dengan akses kuasa yang terhad.*

## ACKNOWLEDGEMENTS

First and foremost, I would like to express my gratitude to my supervisor, Dr. Azhan Bin Ab Rahman for his precious guidance, words of wisdom and patient throughout this project.

I am also indebted to Universiti Teknikal Malaysia Melaka (UTeM) and Yayasan Bank Rakyat (YBR) for the financial support through all semesters which enables me to accomplish the project. Not forgetting my fellow colleague, Mohamad Norafiq Bin Johar for the willingness of sharing his thoughts and ideas regarding the project.

My highest appreciation goes to my parents, and family members for their love and prayer during the period of my study. An honourable mention also goes to Hazeem Faeez Bin Mustapha for all the motivation and understanding. And to Muhammad Danial Bin Ahamad Norddin, thanks for helping me in using Arduino IDE software.

Finally, I would like to thank all fellow colleagues and classmates, the faculty members, as well as other individuals who are not listed here for being co-operative and helpful.

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| | | |
|---|---|---|
| $V$ | - | Voltage |
| A | - | Ampere |
| W | - | Watt |
| CPR | - | Corona Power Ratio |
| SCA | - | Specific Collecting Area |
| AR | - | Aspect Ratio |

## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| WHO | - | World Health Organization |
| SDGs | - | Sustainable Development Goals |
| DALYs | - | Death and Disability Adjusted Life Years |
| PM2.5 | - | Particles Less than 2.5 micrometers in Diameter |
| ESP | - | Electrostatic Precipitator |
| VOCs | - | Volatile Organic Compounds |
| PPM | - | Parts Per Million |
| HEPA | - | High Efficiency Particulate Air |
| PV | - | Photovoltaic |
| BAPV | - | Building-applied Photovoltaic |
| DHT11 | - | Digital Humidity and Temperature Sensor |
| GP2Y1014AU0F | - | Optical Dust Sensor |
| LDR | - | Light Dependent Resistor |
| MQ135 | - | Gas Sensor (Carbon Dioxide) |
| MQ7 | - | Gas Sensor (Carbon Monoxide) |
| MQ9 | - | Gas Sensor (Methane Gas) |
| LCD | - | Liquid Crystal Display |
| LED | - | Light-emitting Diode |
| OLED | - | Organic Light-emitting Diode |
| DC | - | Direct Current |
| AC | - | Alternating Current |
| PID | - | Photoionization Detector |
| Arduino UNO | - | Microcontroller board based on the ATmega328P |
| Arduino Nano | - | Microcontroller board based on the ATmega328 |
| CFM | - | Cubic Feet Per Minute |
| CO2 | - | Carbon Dioxide |
| CO | - | Carbon Monoxide |
| CH4 | - | Methane Gas |
| NO2 | - | Nitrogen Dioxide |
| SO2 | - | Sulphur Dioxide |
| O3 | - | Ozone |
| IoT | - | Internet of Things |

## LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Air quality is a critical aspect of environmental and public health, influenced by various pollutants including particulate matter, nitrogen dioxide, sulphur dioxide, carbon monoxide, and volatile organic compounds. According to the World Health Organization (WHO), air pollution is responsible for an estimated 7.4 million deaths and disability-adjusted life years (DALYs) worldwide each year [1]. Figure 1.1 depicts latest update from WHO regarding fraction of deaths and DALYs attribute in 2016. In Malaysia especially urban areas, vehicular emissions account for up to 25% of particulate matter pollution, while industrial activities contribute significantly to the levels of sulphur dioxide and nitrogen dioxide [2]. However, PM2.5, which consists of fine particulate matter with a diameter of 2.5 micrometres or smaller, is the most critical air pollutant due to its severe health impacts. These particles can deeply penetrate the respiratory system, reaching the lungs and causing short-term health issues such as irritation of the eyes, nose, throat, and lungs, along with symptoms like coughing, sneezing, runny nose, and shortness of breath. Consequently, PM2.5 is commonly monitored in air quality monitoring devices [2]. Moreover, poor air quality can lead to severe health problems such as respiratory diseases, cardiovascular conditions, and even premature death [2]. Figure 1.2 shows analysis of annual PM2.5 in Malaysia in 2021. Therefore, it is imperative to address air pollution through effective measures and technologies to safeguard human health and the environment. One such measure is the use of air purifiers, which can significantly improve indoor air quality.

Air purifiers are devices designed to remove contaminants from the air in a room to improve indoor air quality. They work by filtering out pollutants such as dust, pollen, smoke, and bacteria, using various technologies like HEPA filters, activated carbon, and UV light. These devices are particularly beneficial for individuals with allergies, asthma, or other respiratory conditions. By maintaining cleaner air indoors, air purifiers contribute to better health and overall well-being. However, the effectiveness of air purifiers can be maximized when integrated with air quality monitoring systems that provide real-time data on air pollutant levels.

Air quality monitoring involves the systematic collection of data regarding air pollutants to assess and manage air quality. Advanced monitoring systems use sensors and IoT technology to detect and measure concentrations of various pollutants, providing real-time information and alerts. This data is crucial for understanding pollution sources, trends, and for making informed decisions on air quality management. When air purifiers are connected to these monitoring systems, they can operate more efficiently by adjusting their filtration processes based on the detected air quality levels. Additionally, integrating these systems with renewable energy sources such as Solar Photovoltaic (PV) system can further enhance their sustainability.

A Solar Photovoltaic (PV) system converts sunlight into electricity and offers a renewable, sustainable power source for various applications, including air purifiers and air quality monitoring systems. By harnessing solar energy, air purifiers can operate independently of the traditional power grid, reducing energy costs and environmental impact. This integration not only promotes clean energy use but also ensures that air purification and monitoring systems can function continuously, even during power outages. Combining air purifiers with solar PV systems and real-time air quality monitoring creates a holistic approach to improving indoor air quality sustainably and efficiently.

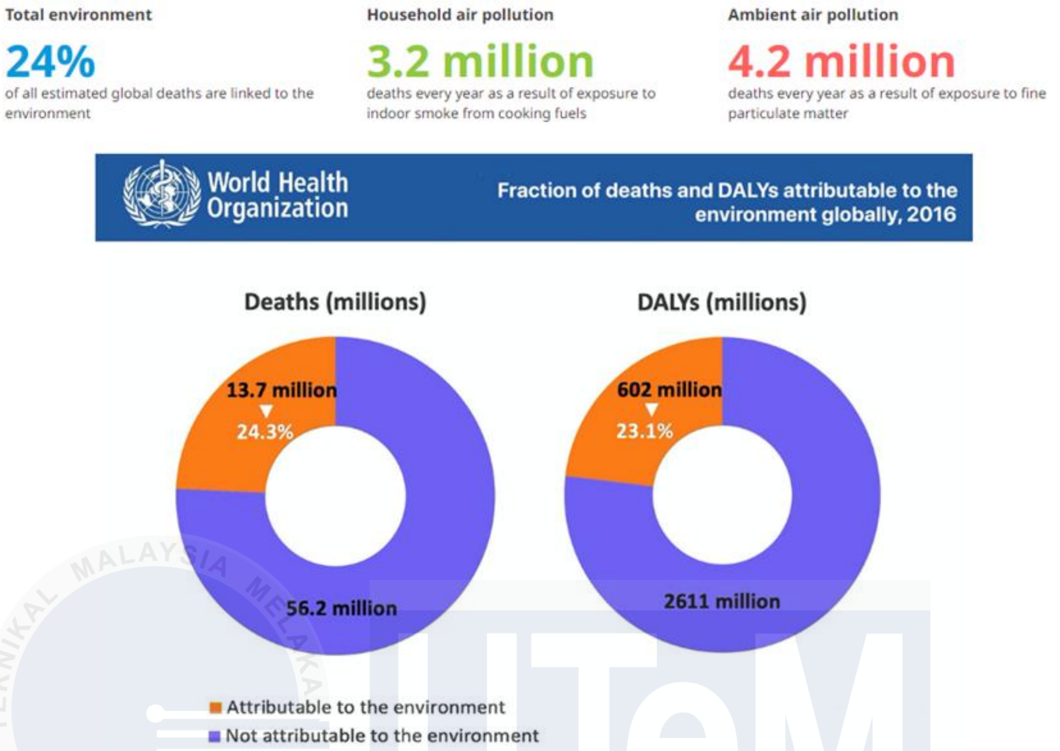



Figure 1.1 Fraction of deaths and DALYs attribute [1].

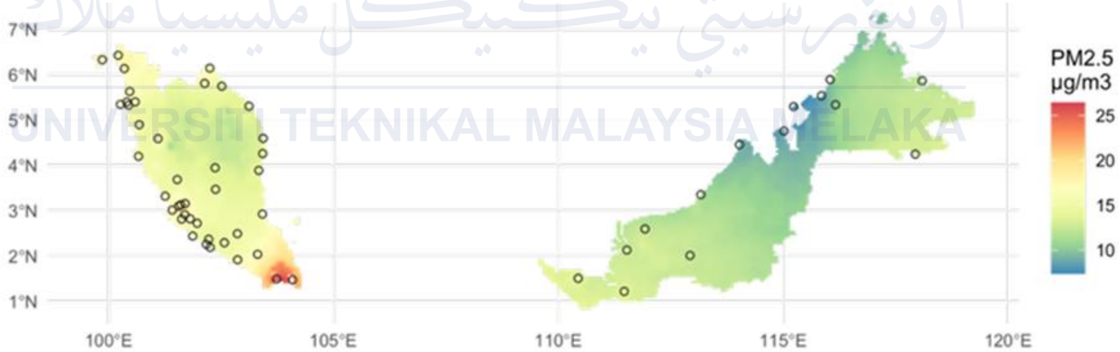



Figure 1.2 Analysis of annual PM2.5 in Malaysia in 2021 [2].

## 1.2 Problem Statement

Air pollution is a significant global issue, adversely affecting human health and the environment. Traditional methods of generating electricity, primarily through the burning of fossil fuels, contribute heavily to air pollution, resulting in numerous health disorders, including respiratory issues, lung cancer, and heart diseases. The World Health Organization (WHO) reports that approximately 4.2 million people die annually from outdoor air pollution, with children living near polluted areas being particularly vulnerable to conditions such as asthma. Furthermore, air pollutants impact water bodies and aquatic life, forcing wildlife to abandon their habitats. Fine dust particles (particulate matter) are particularly dangerous as they can penetrate deep into the lungs, causing severe health problems.

To address these challenges, the "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" project aims to harness solar energy to power an air purification system. By using solar power, the project reduces reliance on fossil fuels, thereby minimizing air pollution. The system includes air quality monitoring components to provide real-time data on pollution levels, enabling proactive measures to improve air quality. This approach aligns with the Sustainable Development Goals (SDGs), particularly:

a) **SDG 3 (Good Health and Well-being):** By reducing air pollution, the project contributes to healthier living conditions, decreasing the prevalence of respiratory and other pollution-related diseases.

b) **SDG 7 (Affordable and Clean Energy):** Utilizing solar power promotes the use of clean, renewable energy sources, reducing dependence on fossil fuels.

c) **SDG 11 (Sustainable Cities and Communities):** Improving air quality and monitoring pollution contributes to making cities and communities more sustainable and liveable.

Air pollution, exacerbated by fossil fuel-based energy production, poses severe health and environmental risks. The innovative solution of using solar-powered air purification addresses these issues by leveraging clean energy and monitoring air quality. This project directly supports SDGs 3, 7, and 11, contributing to healthier populations, sustainable energy use, and more liveable cities. Therefore, by integrating solar PV systems for outdoor air purification and continuous air quality monitoring, this project will fulfil SDG 3, 7, and 11.

## 1.3 Project Objective

This project's primary objective is to create an innovative and sustainable solution for minimizing the harmful effects of air pollution through a Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System. The system aims to:

a) To design and simulate the air purification system and air quality monitoring system by using Arduino IDE software and Proteus software.

b) To develop a prototype of solar-powered air purifier with an integrated air quality monitoring system to continuously track and reduce air pollution, thus promoting a healthier environment.

c) To analyse the performance of the Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System through several classifications.

To achieve these objectives, the project will utilize Proteus and Arduino IDE software for simulation and development, ensuring precise design and efficiency of the system components. This comprehensive approach will help in designing a robust system that not only purifies the air but also keeps track of air quality parameters to optimize performance and impact.

### 1.4 Scope of Project

The scope of the project will be demonstrated considering specific limitations and specifications. This project has the restrictions outlined in this subtopic to safeguard the system hardware and guarantee its proper operation. By utilizing Proteus and Arduino IDE software for simulation and development, we aim to create a reliable and effective Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System. The scope of the project includes:

a) The sensors used in this project, like the MQ135, SHARP GP2Y1010AU0F Dust Sensor, and DHT11, are easy to find, making them simple to replace and maintain.

b) The system does not require an external power supply as it uses solar panels for energy, promoting sustainability. It can be used both during the day and at night. During daylight, it charges the battery while simultaneously operating, and at night, it can be used both indoors and outdoors, drawing power from the charged battery.

c) The MQ135 Gas Sensor measure gases like ammonia, nitrogen oxides, alcohol, benzene, smoke, and carbon dioxide, while the SHARP GP2Y1010AU0F Dust Sensor detects dust particles with a diameter of 2.5 micrometres or smaller. The DHT11 keeps track of temperature and humidity, helping us understand air quality better.

d) The sensor operating voltage will be between 5 - 12 volts, ensuring compatibility with standard components.

e) The 5V DC output is available for additional charging purposes.

f) The system will continuously monitor and update changes in pollutant levels, measured in parts per million (PPM), at an interval of every 0.25 seconds as configured in the Arduino.

g) Only particles and odours that flow through the air can be filtered; stationary pollutants may not be effectively captured.

h) Suitable for both indoor and outdoor air quality monitoring, ensuring a wide range of applications.

i) The air purifier is designed to efficiently clean and improve air quality within a maximum radius of 10 feet, beyond which its effectiveness in air purification significantly diminishes.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter outlines the development of a Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System. This chapter examines the history of an air purification system, concept, component, as well as monitoring and PV system. This segment explores five core principles essential for fulfilling the research objectives. Subsequently, the following section contextualizes the current study by analysing influential research that has shaped the characteristics, evolution, methodologies, applications, and user interfaces of similar tools. Conducting a thorough literature review is imperative for comparing previous works. These earlier endeavours are assessed for their relevance and attributes, thereby contextualizing, and emphasizing the importance and novelty of the research. This chapter closes by pinpointing the shortcomings of the Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System and areas for enhancement, thus positioning this paper to offer innovative solutions and improvements to the field.

## 2.2 Background Study

Recent years have witnessed a surge in innovation driven by the urgent need to combat air pollution, with solar photovoltaic (PV) systems emerging as a promising solution to power outdoor air purification systems while monitoring air quality. This convergence of solar energy and air purification technologies is particularly crucial in urban areas, where pollution poses severe health risks. Air purification systems, evolving in response to escalating pollution from urbanization and industrial activities, employ various techniques to enhance indoor and outdoor air quality. Understanding their background and evolution is essential for guiding future research and policymaking. This research aims to explore the operational mechanisms and potential benefits of solar PV-powered outdoor air purification systems with air quality monitoring, identifying challenges and future directions to enhance their efficiency and scalability. By contributing to the discourse on renewable energy-driven solutions for environmental remediation, the study aims to inform stakeholders in their efforts to mitigate the impacts of air pollution on human health and the environment. Figure 2.1 shows block diagram of basic Solar PV Powered Air Purification with Air Quality Monitoring System by using Arduino UNO. Despite technological advancements, challenges such as solar intermittency and pollutant variability persist, emphasizing the need for further research and development to optimize system performance and ensure long-term effectiveness.

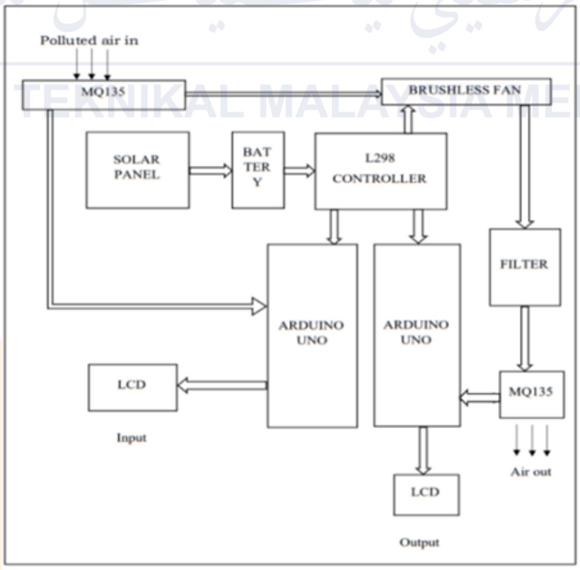



Figure 2.1 Block diagram of basic Solar PV Powered Air Purification with Air Quality Monitoring System by using Arduino UNO [3].

### 2.2.1 History of an Air Purification System

Improving indoor air quality has been a longstanding priority, particularly for allergy sufferers. Over nearly two centuries, the journey toward cleaner indoor air has seen significant innovations. Beginning in the early 19th century with the development of masks for firefighters, advancements such as John Stenhouse's charcoal-based filter design and John Tyndal's respirator marked early milestones. The introduction of HEPA air purifiers in the early 20th century, initially aimed at protecting against atomic fallout, proved crucial in eliminating microscopic pollutants like mould and pollen [4]. Validation by the Department of Energy solidified HEPA filters' effectiveness in removing harmful particles, highlighting their role in safeguarding indoor air quality.

In the late 20th century, home air purifiers transitioned from specialized tools to mainstream household appliances, reflecting growing public awareness of the importance of clean indoor air for health and well-being. This evolution underscores a continuous pursuit of innovation and public welfare in enhancing indoor air quality and alleviating allergy symptoms. From rudimentary masks to sophisticated HEPA filtration systems as shown in figure 2.2 below, the historical progression of air purification technology reflects a concerted effort to address the pressing issue of indoor air pollution.

Figure 2.2 High Efficiency Particulate Air (HEPA) filter.



### 2.2.2 Concept of an Air Purification System

The primary function of an air purification system lies in its ability to effectively remove harmful pollutants from the air, trapping them within its intricate fibre meshes and preventing their re-entry into the environment. Figure 2.3 shows the working principle of an air purification system. This mechanism operates on the basic principle of attracting dust particles towards the air filters, where they are captured and retained.

Beyond this fundamental application, air purifiers serve various other crucial purposes:

1. **Prevention of Nosocomial Infections:** Hospitals are often prone to nosocomial infections due to improper waste handling. These infections pose significant risks to patients' health and must be mitigated. Installing air purifiers can help eradicate such infections by ensuring a cleaner environment [4].

2. **Mitigation of Harmful Diseases:** Air pollution contributes to the onset of numerous diseases, ranging from neurological disorders to respiratory ailments like asthma and bronchitis. Additionally, skin allergies are prevalent due to pollution. Air purifiers effectively remove airborne pollutants, thereby reducing the risk of these diseases and associated symptoms. Respiratory illnesses not only affect physical health but also have adverse mental effects, including stress, anxiety, and depression [4].
3. **Elimination of Toxic Gases**: Air pollution introduces toxic gases such as carbon oxides, nitrogen oxides, and sulphur oxides into the atmosphere, leading to acid rain and smog formation. Air purifiers play a vital role in eliminating these gases, along with volatile organic compounds (VOCs) found in tobacco smoke and other sources, thereby enhancing air quality [4].
4. **Removal of Toxins and Microbes**: Airborne toxins and microbes contribute to pollution and pose health risks. Air purification systems effectively remove these contaminants, making the air safer to breathe. Hospitals, in particular, benefit from air purifiers to maintain clean air, as medical facilities are often more polluted than homes [4].
5. **Control of Bacteria and Viruses**: Air purifiers are deployed in various settings to monitor and sanitize the air by checking for the presence of bacteria and viruses. Utilizing technologies such as HEPA filters and UV light, air purifiers trap and neutralize pathogens, contributing to cleaner and healthier environments [4].

In conclusion, amidst escalating levels of air pollution, air purifiers play a crucial role in ensuring clean and safe air. Utilizing advanced purification technologies and high-quality filters, these systems effectively trap minute pollutants, toxins, and microbes, thus enhancing air quality. Their installation is recommended, especially in homes and healthcare facilities, to promote respiratory health and overall well-being.

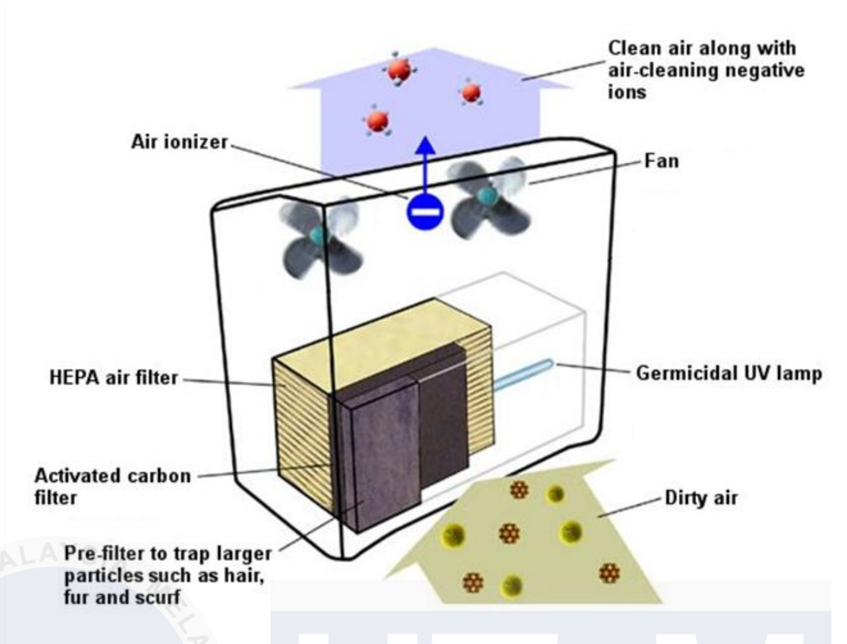



Figure 2.3 A sample Air Purifier that incorporates multiple technologies [4].



### 2.2.3 Component of an Air Purification System

The effectiveness of an air purification system relies fundamentally on its components, each playing a crucial role in the process of removing pollutants from the air. From filters and fans to sensors and control units, these components work synergistically to ensure the delivery of clean and healthy indoor air [4]. Filters, such as HEPA (High Efficiency Particulate Air) filters, activated carbon filters, and UV-C light modules, serve as the frontline defence against airborne contaminants, capturing particles and pathogens of varying sizes [4]. Meanwhile, fans facilitate the circulation of air through the purification system, ensuring that all air within a space is treated efficiently. Sensors and control units monitor air quality parameters in real-time, allowing for dynamic adjustments to purification settings based on the detected levels of pollutants. The integration of these components not only enhances the efficacy and efficiency of air purification systems but also contributes to maintaining optimal indoor air quality, thus promoting the well-being and comfort of occupants in residential, commercial, and industrial settings.

#### 2.2.3.1 Casing

The manufacturing process of air purifier casings involves several steps:

1. **Material Preparation**: Raw materials such as high-impact polystyrene, polyvinyl chloride, high-density polyethylene, or polypropylene are first fed into a hopper. These pellets are then heated to their melting point, typically ranging from 300-590°F (150-310°C) [5].
2. **Injection Moulding**: The molten plastic is injected into a mould of the air purifier case under high pressure. These moulds are typically crafted from tool steel by skilled mould makers. Vents within the mould allow any trapped air to escape as the plastic fills the mould cavity. Ensuring even distribution of plastic within the mould is crucial to prevent defects such as air bubbles or voids in the final product [5].
3. **Cooling and Ejection**: Water channels integrated into the mould facilitate the transfer of heat from the molten plastic to the surrounding environment. Once the plastic has sufficiently cooled, a process that may take up to two minutes, the mould opens. Hydraulically operated pins then push the formed part out of the mould and into a collection bin [5].

This manufacturing process ensures the production of high-quality air purifier casings as shown in figure 2.4 are essential for housing the internal components of the device. By utilizing precise injection moulding techniques and carefully controlling the cooling process, manufacturers can create durable and efficient casings that contribute to the overall performance and reliability of the air purifier.

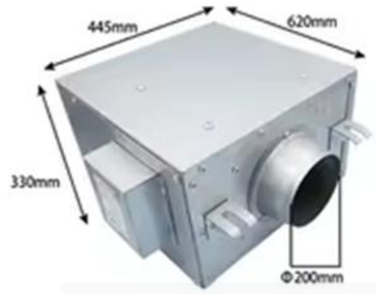



Figure 2.4 Example of an Air Purification System body case.



#### 2.2.3.2 Fan

The functioning of an air purifier relies on an electric fan to draw air through the device. Typically sourced from a specialized supplier of small parts, the fan comprises a compact electric motor connected to metal fan blades. These blades are typically affixed to a collar via spot welding, which is then mounted onto the motor's power take-off and secured in position with bolts. Once integrated into the air purifier casing, the fan is attached securely using steel screws. This component plays a critical role in the air purification process, as it facilitates the movement of air through the device, allowing it to pass through filters and effectively capture airborne pollutants. Figure 2.5 shows an example of a fan used in an Air Purification System. By ensuring a reliable and efficient fan mechanism, air purifiers can maintain consistent performance in providing clean and purified air for users.

Figure 2.5 Example of an Air Purification System fan.



**2.2.3.3 HEPA Filter**

HEPA filters are meticulously constructed using a precise process involving the formation of glass fibres through extrusion of molten glass or plastic through fine pores in a spinning nozzle. These fibres are rapidly cooled and hardened, creating a web-like pattern as the spinning nozzle oscillates back and forth. The resulting fabric, collected onto a moving conveyor belt, is sprayed with a latex binder for structural integrity and customized to various widths before being cut to size and folded into an accordion-like pattern using automated machinery. This unique design allows for a significant amount of filter material to be compactly enclosed in a small space. Subsequently, the folded filter is encased within a wire grid casing to provide support and ensure structural stability during use. This meticulous manufacturing process ensures the efficiency and durability of HEPA filters in capturing microscopic particles and achieving high-quality air purification.

Additionally, A HEPA filter effectively captures a minimum of 99.97% of contaminants sized at 0.3 microns through various mechanisms [6]. Contrary to common belief, HEPA filters do not function like sieves where particles smaller than the largest opening can pass through. Instead, particles are trapped within the filter's fibres due to a combination of interception, impaction, and diffusion as shown in figure 2.6. Interception occurs when particles in the air stream come within the radius of a fibre and adhere to it, while impaction forces larger particles to embed directly into the fibres due to the curving contours of the air stream. Diffusion, particularly impactful for particles below 0.1 µm in diameter, involves collisions with gas molecules, impeding and delaying their path through the filter, similar to Brownian motion [6]. These mechanisms collectively ensure efficient filtration, with diffusion becoming dominant at lower air flow velocities.

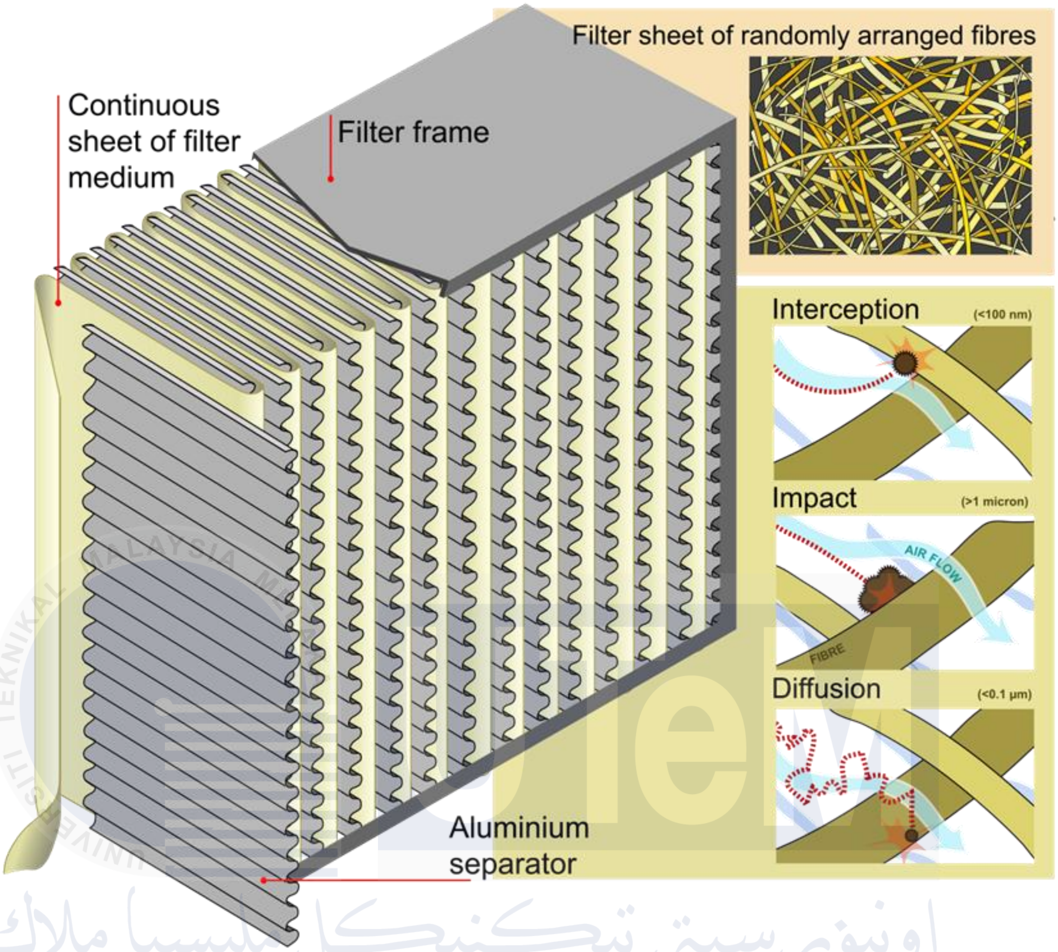



Figure 2.6 HEPA Filter diagram [6].



#### 2.2.3.4 Electrostatic Precipitator

The electrostatic precipitator (ESP) collection system is meticulously crafted by enclosing steel plates within a plastic casing, often assembled by hand and arranged in parallel to optimize efficiency. To facilitate the electrostatic precipitation process, wires are meticulously connected to alternate plates, serving as conduits for high voltage positive direct current, while the remaining plates are grounded to complete the electrical circuit. The ionizing unit, a crucial component, consists of small diameter wires positioned in front of the collector plates to ensure efficient ionization of particles within the air stream passing through the precipitator. A voltage transformer securely affixed to the casing converts standard household alternating current into high voltage direct current, distributing it to both the positively charged collector plates and ionizing wires for effective particle collection and removal [7],[8]. Figure 2.7 shows the working of Electrostatic Precipitator. Overall, the assembly and operation of electrostatic precipitators require intricate engineering and precise construction to ensure optimal performance in removing particulate matter from the air.

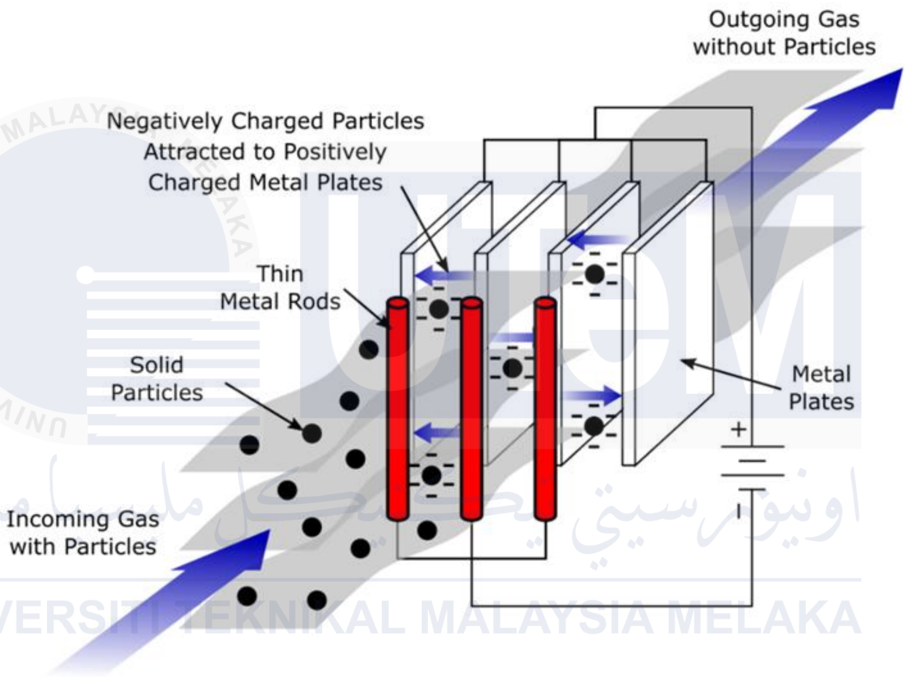



Figure 2.7 The working of Electrostatic Precipitator [7].

Electrostatic Precipitators (ESPs) play a crucial role in mitigating air pollution by efficiently capturing dust particles from flue gases emitted by industrial processes. The efficiency of an ESP hinges upon several key factors. Firstly, the dust collection area of the ESP determines its capacity to trap particles effectively. This effectiveness is further influenced by the size of the dust particles, the volume of flue gas, and the resistivity of the dust present in the gas stream. Moreover, two significant metrics, the Corona Power Ratio

(CPR) and the Specific Collecting Area (SCA), offer insights into the performance of an ESP.

The Corona Power Ratio (CPR) is a vital parameter indicating the energy efficiency of an ESP, calculated as:

$$CPR = \frac{Power\ consumed\ by\ ESP\ in\ watts}{Flue\ gas\ flow\ in\ CFM} \tag{2.1}$$

This ratio provides a measure of the energy expenditure per unit volume of gas treated. A higher CPR typically correlates with improved efficiency, reflecting a more effective utilization of power in dust collection. Similarly, the Specific Collecting Area (SCA) is defined as:

$$SCA = \frac{Total\ collection\ area\ in\ m^2}{Gas\ flow\ rate\ in\ m^3/sec} \tag{2.2}$$

Furthermore, the aspect ratio (AR) of an ESP, defined as the ratio of its length to height, influences its operational performance, calculated as:

$$AR = \frac{Length\ of\ ESP}{Height\ of\ ESP} \tag{2.3}$$

#### 2.2.3.5 Activated Carbon Filter

The activated carbon filter, designed primarily for odour reduction, typically comprises carbon-impregnated cloth or foam. This specialized filter is created through a manufacturing process that involves infusing the raw material with powdered activated carbon, enhancing its adsorption capabilities for capturing odorous molecules and volatile organic compounds (VOCs) as shown in figure 2.8. Once manufactured, the carbon filter is either wrapped around the inside or outside of the HEPA filter or installed in a frame positioned at the inlet or outlet of the electrostatic precipitator as shown in figure 2.9. This strategic placement ensures that air passing through the air purifier encounters the activated carbon filter, where odours and VOCs are effectively trapped and neutralized, resulting in cleaner and fresher-smelling air [9].

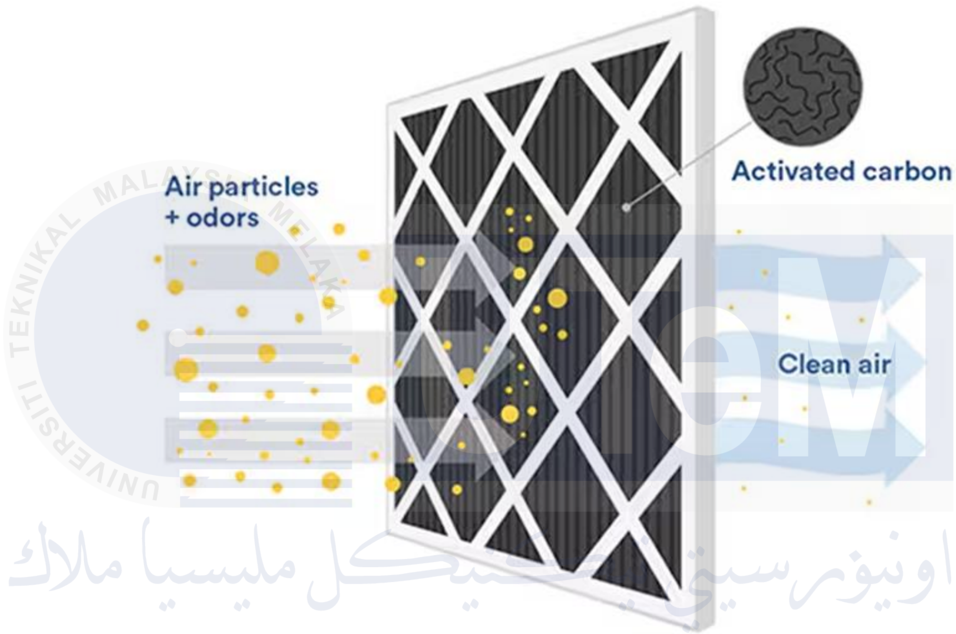





Figure 2.8 The working of Activated Carbon Filter [9].

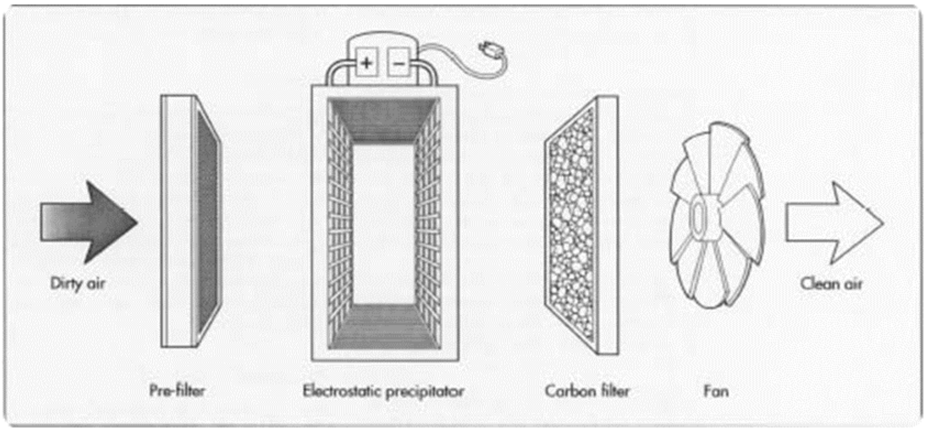



Figure 2.9 An example of an Electrostatic Precipitator and its components with Carbon Filter included.

### 2.2.4 History of an Air Quality Monitoring System

Air quality monitoring has evolved significantly over the past two centuries, transitioning from rudimentary methods involving living organisms like canaries in coal mines to sophisticated sensor technologies and participatory citizen science initiatives. Key milestones include the development of portable gas detection tubes by Dräger in 1937 and the emergence of photoionization detectors (PIDs) in 1974, enabling continuous detection of volatile organic compounds (VOCs). The 21st century witnessed a shift towards participatory sensing and citizen science initiatives, exemplified by projects like Safecast as shown in figure 2.10 and the Air Quality Egg, democratizing monitoring efforts and providing real-time data to communities [10]. This evolution, coupled with advancements in low-cost sensor technologies, underscores the increasing importance of air quality monitoring in addressing public health and environmental justice concerns, particularly highlighted by events like the COVID-19 pandemic. As we continue to innovate and expand monitoring capabilities, we move closer to ensuring clean air as a fundamental right for all.




Figure 2.10 Safecast Air Quality Monitoring System [10].

### 2.2.5 Concept of an Air Quality Monitoring System

The concept of an Air Quality Monitoring System revolves around the idea of continuously assessing the quality of the air in a specific environment to ensure it meets health and safety standards. Such systems utilize various sensors and instruments as shown in figure 2.11 to measure different parameters that contribute to air pollution, including gases, particulate matter, temperature, humidity, and other environmental factors. By collecting and analysing this data in real-time, these systems provide valuable insights into air quality conditions, allowing individuals, communities, and regulatory agencies to make informed decisions and take appropriate actions to mitigate pollution and protect public health.

Key components of an Air Quality Monitoring System typically include:

1. **Sensors:** These are devices that detect and measure specific pollutants or environmental parameters. Different types of sensors are used to measure various aspects of air quality, such as gas sensors for detecting pollutants like carbon monoxide (CO), nitrogen dioxide (NO2), sulphur dioxide (SO2), ozone (O3), and volatile organic compounds (VOCs), as well as particulate matter (PM) sensors for measuring airborne particles of different sizes (PM2.5 and PM10). Additionally, sensors for temperature, humidity, and atmospheric pressure may also be included to provide context for air quality measurements [11].
2. **Data Acquisition System:** This system is responsible for collecting data from the sensors in real-time. It typically consists of microcontrollers or data loggers that interface with the sensors and store or transmit the collected data to a central processing unit for analysis [11].
3. **Data Processing and Analysis:** The collected data is processed and analysed to determine the concentration levels of various pollutants and other environmental

parameters. Algorithms and models may be applied to interpret the raw sensor data and calculate air quality indices or other metrics that provide meaningful insights into air quality conditions [11].

4. **Visualization and Display:** The processed data is presented in a user-friendly format, often through graphical interfaces or displays, to allow users to easily interpret and understand the air quality information. This may include visualizations such as charts, graphs, maps, or color-coded indicators representing different air quality categories [11].
5. **Alerting and Reporting:** Air Quality Monitoring Systems may include features for issuing alerts or notifications when air quality levels exceed predefined thresholds or pose a risk to public health. Additionally, they may generate reports or summaries of air quality data over time for regulatory compliance, research purposes, or public dissemination [11].
6. **Integration with IoT and Connectivity:** Many modern Air Quality Monitoring Systems are equipped with Internet of Things (IoT) capabilities, enabling remote monitoring, data sharing, and connectivity with other smart devices or systems. This allows for centralized monitoring of air quality across multiple locations and facilitates data-driven decision-making at scale [11].

Overall, the concept of an Air Quality Monitoring System is aimed at providing accurate, timely, and actionable information about air quality conditions to support efforts to reduce pollution, protect public health, and promote environmental sustainability. By leveraging advances in sensor technology, data analytics, and connectivity, these systems play a crucial role in monitoring and managing air quality in both indoor and outdoor environments.

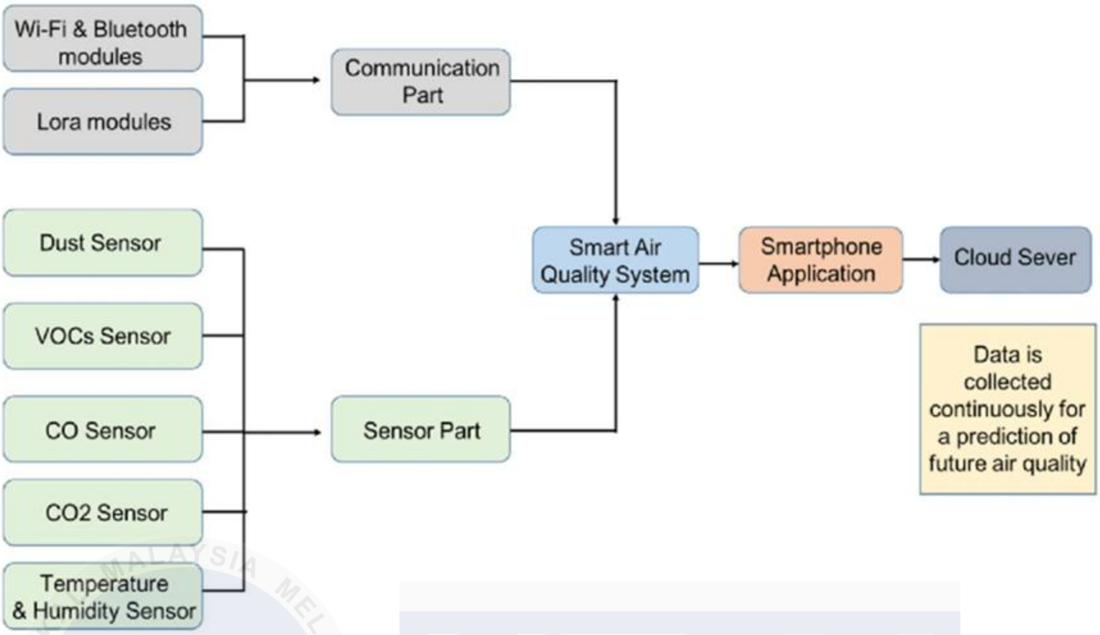



Figure 2.11 Block diagram example of Smart Air Quality Monitoring System [11].



### 2.2.6 Basic Component of an Air Quality Monitoring System by Using Arduino

In our modern era, where environmental concerns are at the forefront of global discourse, the importance of monitoring air quality cannot be overstated. An Air Quality Monitoring System based on Arduino microcontrollers presents a versatile and accessible solution to this imperative. By leveraging the capabilities of Arduino boards and a range of sensors, these systems offer a cost-effective means of measuring, analysing, and visualizing various parameters related to air quality. This essay delves into the fundamental components of such systems, highlighting their significance and potential applications.

### 2.2.6.1 Arduino Board

At the core of an Arduino-based Air Quality Monitoring System is the Arduino board, functioning as the central processing unit. Selection of the Arduino board is based on factors such as processing power, input/output capabilities, and form factor, with popular options including Arduino Uno, Arduino Nano, and Arduino Mega. These boards play a critical role in interfacing with sensors, collecting data, and executing control logic, thus serving as the foundation of the monitoring system. Figure 2.12 provides a comprehensive diagram illustrating all inputs and outputs of an Arduino UNO board, showcasing its versatility and adaptability for various sensor connections and data acquisition tasks within the air quality monitoring system.

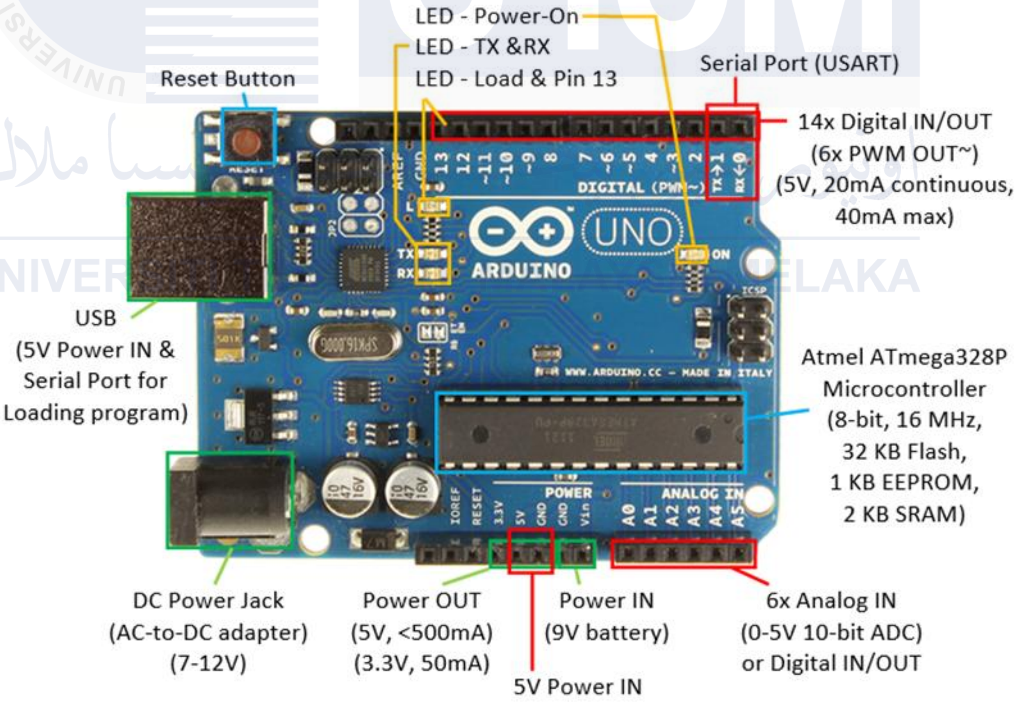



Figure 2.12 Diagram of an Arduino UNO board.

#### 2.2.6.2 Sensor

A diverse array of sensors constitutes a crucial component of the monitoring system, enabling the detection and measurement of various pollutants and environmental parameters. Gas sensors play a pivotal role in measuring concentrations of gases like carbon monoxide (CO), nitrogen dioxide (NO2), sulphur dioxide (SO2), ozone (O3), and volatile organic compounds (VOCs) as shown in figure 2.13. Particulate Matter (PM) sensors quantify airborne particle concentrations, categorized by size (e.g., PM2.5 and PM10) as shown in figure 2.14, while temperature and humidity sensors provide context for air quality measurements and assess indoor air comfort levels. Optional sensors, such as those for atmospheric pressure or UV radiation, may be incorporated based on specific monitoring requirements.

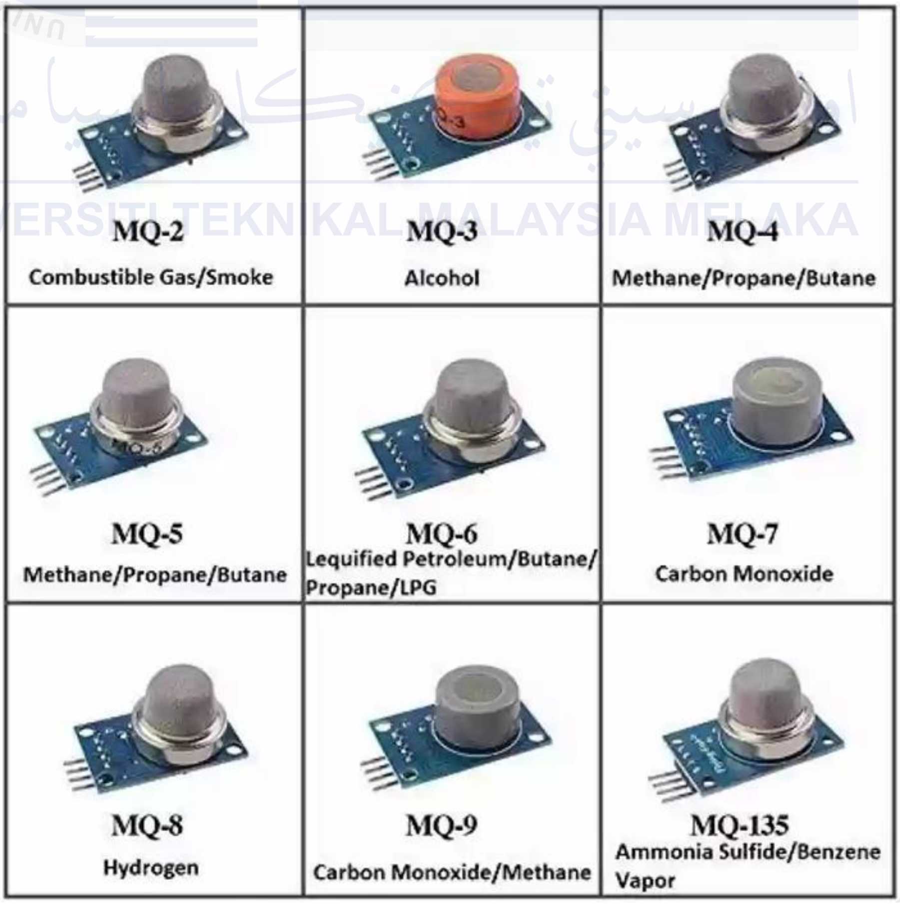



Figure 2.13 All MQ Gas Sensors.

Figure 2.14 GP2Y1010AU0F PM2.5 Dust Particle Sensor.

#### 2.2.6.3 Data Acquisition Circuitry

Efficient data acquisition in air quality monitoring systems relies on circuitry designed to interface seamlessly with sensors, converting their output signals whether analogue or digital into a format readable by the input pins of Arduino boards. This process is essential for gathering accurate and reliable data from the sensors. Signal conditioning components, including amplifiers, filters, and analogue-to-digital converters (ADCs), play a crucial role in this process, as depicted in Figure 2.15. These components ensure that the acquired data is properly conditioned and processed before being fed into the Arduino board, thereby enhancing the overall performance of the monitoring system. By accurately capturing and converting sensor signals, the system can provide precise and actionable insights into air quality conditions, contributing to informed decision-making and effective environmental management strategies.

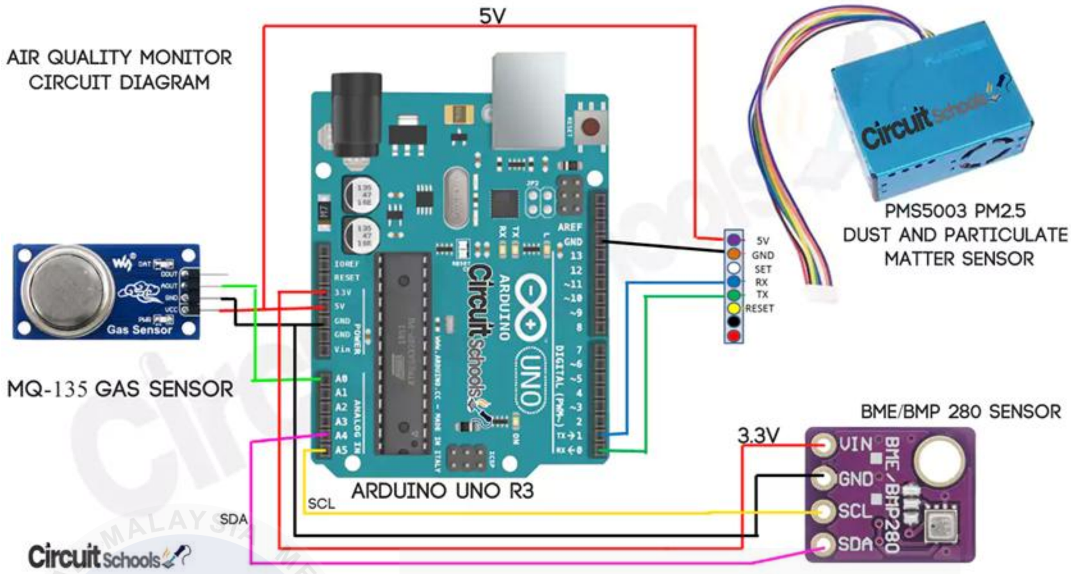



Figure 2.15 Circuit diagram example of IoT Based Air Pollution Monitoring System Using Arduino.

### 2.2.6.4 Power Supply

Ensuring a stable and reliable power source is essential for the uninterrupted operation of air quality monitoring systems. Arduino boards, commonly used in such systems, typically operate at 5VDC, and can be powered through various means such as USB, battery, or an external power adapter. Figure 2.16 illustrates the utilization of a battery to power an Arduino UNO, highlighting the flexibility in power options. To optimize energy efficiency and prolong battery life, especially in portable or remote monitoring applications where continuous power supply may be challenging, power management circuitry may be incorporated. This circuitry plays a crucial role in regulating power consumption and maximizing the utilization of available energy sources, ensuring sustained operation of the monitoring system over extended periods without interruption.


Figure 2.16 Battery Powering Arduino UNO.

#### 2.2.6.5 Display

In air quality monitoring systems, visual feedback of air quality measurements is crucial for users to effectively interpret and respond to changing conditions. This feedback is typically provided through a display module, such as an LCD screen or OLED display, which presents real-time air quality data in an easily understandable format. By offering immediate access to information, these display modules enhance user awareness of air quality conditions and facilitate informed decision-making. Users can quickly assess current air quality levels and take appropriate actions, whether it involves adjusting ventilation systems, avoiding outdoor activities during poor air quality periods, or implementing mitigation measures. The inclusion of visual feedback mechanisms, as depicted in Figure 2.17 with an I2C 20x4 LCD connected to an Arduino UNO, ensures that users have direct access to vital air quality information, ultimately contributing to improved health and well-being.

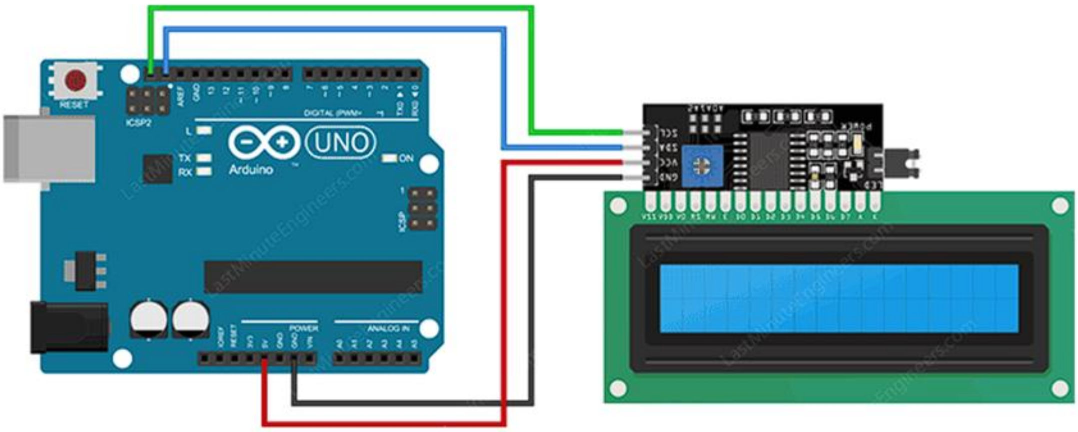



Figure 2.17   I2C 20x4 LCD connected to Arduino UNO.

#### 2.2.6.6 Communication Interface

For remote monitoring or data logging purposes, modern air quality monitoring systems often integrate various communication interfaces such as Wi-Fi, Bluetooth, GSM, or Ethernet. These interfaces play a vital role in facilitating the transmission of air quality data to external devices, cloud platforms, or online dashboards for further analysis and visualization. By enabling seamless connectivity and accessibility, these communication interfaces enhance the system's functionality, allowing users to remotely access real-time air quality information from anywhere. Figure 2.18 illustrates an example of an ESP32 module, showcasing its capability for Wi-Fi and Bluetooth connectivity, which is commonly utilized in air quality monitoring systems to enable wireless data transmission and remote monitoring capabilities.

Figure 2.18 ESP32 module for Wi-Fi and Bluetooth connectivity.

#### 2.2.6.7 Enclosure and Housing

To safeguard monitoring system components from environmental factors and ensure long-term durability, it is common practice to house the system within an enclosure or casing. This enclosure serves multiple purposes: it provides protection against dust, moisture, and physical damage, thereby enhancing the system's longevity and reliability. Additionally, while offering robust protection, the enclosure must also allow for adequate airflow to facilitate sensor operation and prevent overheating [12]. The design of the enclosure is crucial, as it needs to strike a balance between providing sufficient protection and allowing proper ventilation as shown in figure 2.19. By housing the monitoring system within a carefully designed enclosure, it can effectively withstand various environmental conditions and continue to operate reliably over extended periods, ensuring accurate and consistent data collection.

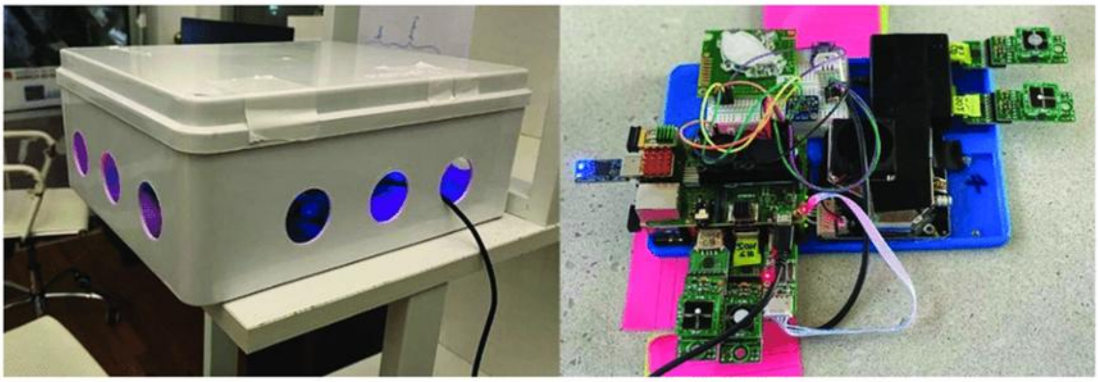


Figure 2.19 Casing for Low-Cost Air Quality Sensor (LCAQS) monitoring system [12].

### 2.2.7 History of Solar PV System

Solar energy technology has a rich history spanning over a century and a half, marked by a continuous stream of advancements in efficiency and aesthetics. The journey began in 1839 when Edmond Becquerel discovered the photovoltaic effect, laying the groundwork for harnessing solar energy. Subsequently, inventors like Augustin Mouchot and Charles Fritts pioneered early solar-powered devices, leading to significant milestones such as the creation of the first solar cell by Fritts in 1883 [13]. Figure 2.20 showcases Charles Fritts installing the first solar panels on a New York City rooftop in 1884, highlighting early adoption efforts. Throughout the late 19th and early 20th centuries, innovators like Edward Weston, Aleksandr Stoletov, and Melvin Severy contributed to the development of solar cells based on the photoelectric effect, furthering our understanding of solar energy conversion [13]. By the 1950s, Bell Laboratories introduced silicon solar cells, which proved more efficient than previous materials like selenium [13]. Despite their initial cost challenges, these silicon cells marked a crucial step towards practical solar energy conversion. Figure 2.21 depicts Edward Weston's "Apparatus for Utilizing Solar Radiant

Energy," patented in 1888, showcasing early innovations in solar technology. In the 1970s, spurred by an energy crisis, governments began investing in solar research and development, culminating in initiatives like the Solar Energy Research, Development and Demonstration Act of 1974 in the United States. Notably, Figure 2.22 illustrates United Solar Systems Corporation's "Photovoltaic Shingle System," patented in 1995, exemplifying ongoing efforts to enhance both the efficiency and aesthetics of solar technology. Over subsequent decades, government support, coupled with technological advancements, propelled the growth of solar energy, with initiatives like the Solar Investment Tax Credit enacted in 2006 playing a significant role in accelerating adoption [13]. However, despite its environmental benefits, traditional solar panels have often been criticized for their visual impact on rooftops. Recognizing this challenge, companies have pursued innovative solutions such as building-applied photovoltaic (BAPV) systems, integrating solar cells into existing architectural elements like roof tiles and facades. Patented inventions from companies like Solus Engineering, Enpulz, Guardian Industries Corporation, and Tesla (formerly SolarCity) underscore ongoing efforts to improve both functionality and visual appeal, promising a bright future for solar energy adoption.

Figure 2.20 Charles Fritts installed the first solar panels on New York City rooftop in 1884.

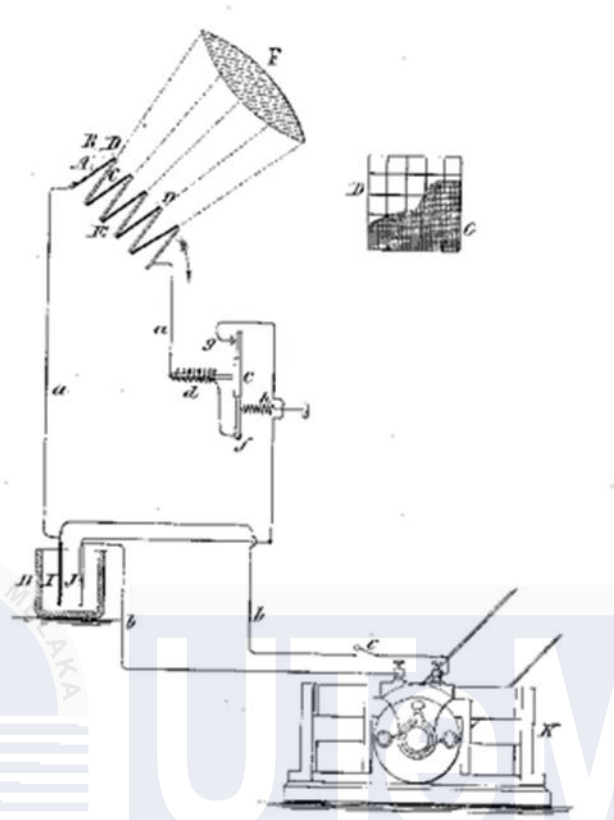



Figure 2.21 Edward Weston's "Apparatus for Utilizing Solar Radiant Energy," patented September 4, 1888.

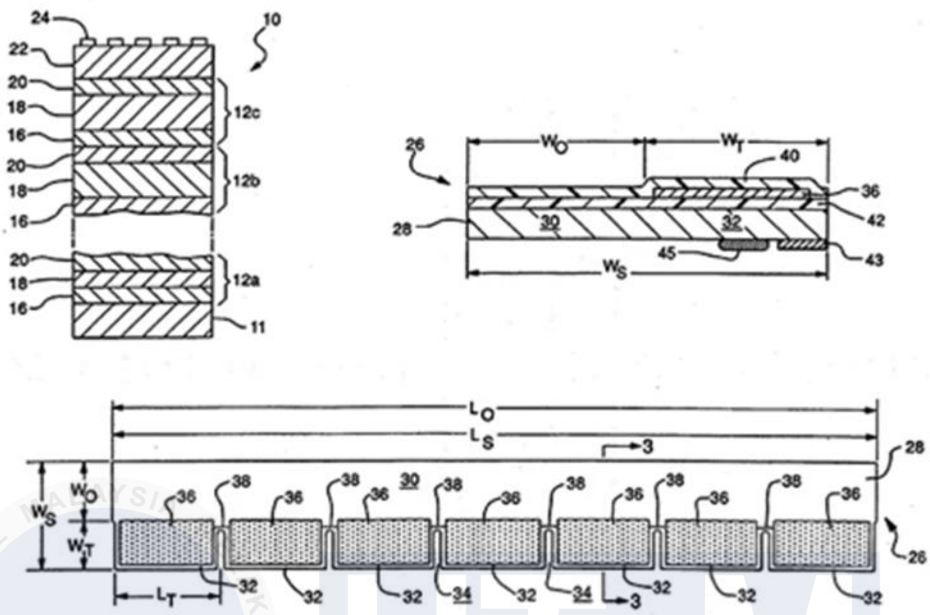



Figure 2.22 United Solar Systems Corporation's "Photovoltaic Shingle System," patented August 1, 1995.

### 2.2.8 Concept of Solar PV Power Generation

Solar photovoltaic (PV) power generation is a sustainable energy solution that utilizes solar panels to convert sunlight into electricity, with systems capable of either connecting to the main power grid or operating independently. The key components of solar PV systems include solar panels, inverters, optimizers, and disconnects, while grid-connected setups may incorporate additional features such as batteries and meters. Table 2.1 shows an Advantage and disadvantage of solar PV power generation. Despite its environmental benefits and reduced reliance on fossil fuels, solar PV faces challenges such as intermittency, installation costs, and maintenance requirements. However, ongoing technological advancements and cost reductions are steadily overcoming these obstacles, making solar PV increasingly feasible for meeting residential and commercial energy needs [14]. As a result, solar PV contributes significantly to environmental preservation and promotes energy sustainability by harnessing renewable energy sources.

Table 2.1 Advantage and disadvantage of solar PV power generation.

| Advantage | Disadvantage |
|---|---|
| • Sunlight is free and readily available in many areas of the country. | • PV systems have a high initial investment. |
| • PV systems do not produce toxic gas emissions, greenhouse gases, or noise. | • PV systems require large surface areas for electricity generation. |
| • PV systems do not have moving parts. | • The amount of sunlight can vary. |
| • PV systems reduce dependence on oil. | • PV systems require excess storage of energy or access to other sources, like the utility grid, when systems cannot provide full capacity. |
| • PV systems can generate electricity in remote locations that are not linked to a grid. | |
| • Grid-connected PV systems can reduce electric bills. | |

Grid-connected PV systems are the predominant configuration owing to their straightforward design and comparatively lower cost when contrasted with off-grid systems, which necessitate battery storage. These systems empower homeowners to diminish their dependence on the grid by harnessing solar power and can even channel surplus electricity back into the utility grid. The setup and magnitude of the system vary depending on its intended application; residential installations typically range below 20 kW, while commercial systems span from 20 kW to 1 MW, and utility-scale energy storage systems surpass 1 MW in capacity [14]. Essentially, grid-connected PV systems furnish a pragmatic solution for trimming electricity bills and reducing carbon footprint while accommodating diverse scales of energy requirements, from individual residences to expansive utility-scale installations. Figure 2.23 shows A common configuration for a PV system is a grid-connected PV system without battery backup.

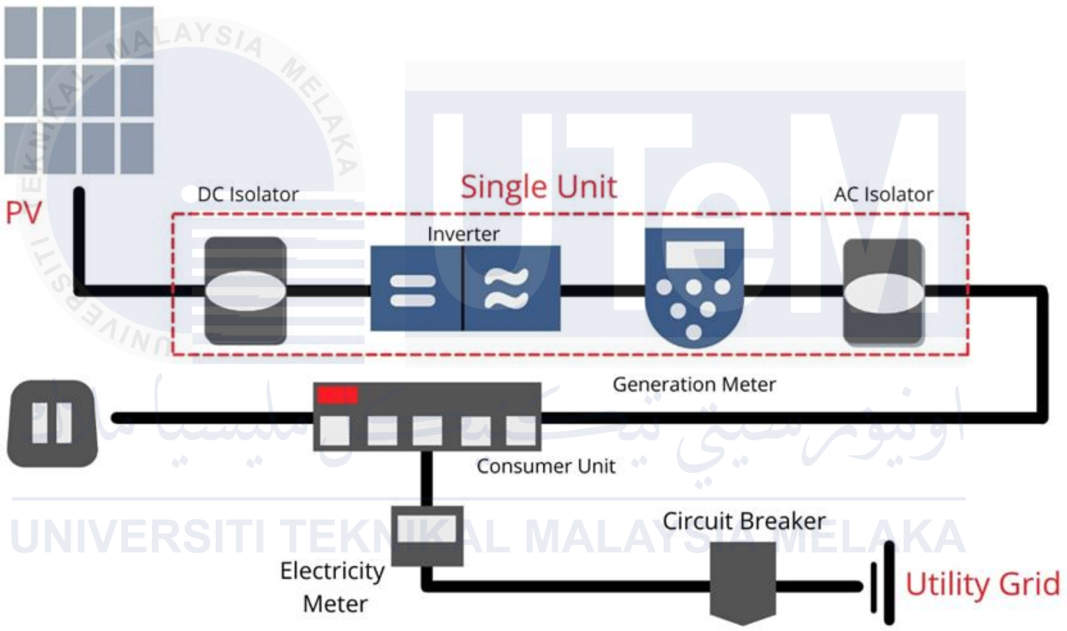



Figure 2.23 A common configuration for a PV system is a grid-connected PV system without battery backup.

Off-grid (stand-alone) PV systems employ solar panels to charge rechargeable batteries during daylight hours, ensuring a continuous power supply even when sunlight is unavailable, such as during nighttime. These systems offer benefits such as reduced energy costs, resilience against power outages, the production of clean energy, and the attainment of energy independence. Key components of off-grid PV systems include battery banks, inverters for converting DC to AC power, charge controllers to regulate charging, battery disconnects for safety, and optional generators for backup power generation [14]. Overall, off-grid PV systems provide a sustainable and reliable solution for remote locations or areas with unreliable grid infrastructure, offering autonomy and environmental benefits.

Solar panels utilized in PV systems consist of solar cells typically made of silicon, encased within a rigid flat frame. These panels are interconnected in series to create strings, and these strings are further linked in parallel to form arrays, allowing for efficient electricity generation. Rated by their DC output, solar panels require periodic inspection to maintain optimal performance, including cleaning to remove debris and snow and ensuring secure electrical connections. However, shading can significantly diminish power output, highlighting the importance of unobstructed sunlight exposure. With a typical guaranteed lifespan ranging from 10 to 25 years, solar panels' power output is measured in watts, with ratings typically spanning from 200 W to 350 W under ideal conditions [14].

Solar arrays, crucial components of PV systems, require strategic mounting to maximize sunlight absorption. Installation typically involves mounting the arrays at an angle to optimize sunlight exposure. Various mounting options exist, including roof, freestanding, and directional tracking mounts as depicts in figure 2.24. Roof-mounted arrays offer the advantage of integrating seamlessly with existing architectural designs while conserving yard space. Freestanding mounts provide flexibility in positioning but may require more land area. Directional tracking mounts dynamically adjust the angle of the panels to follow the sun's path throughout the day, enhancing energy capture efficiency [14]. Overall, the choice of mounting method depends on factors such as available space, architectural considerations, and desired energy output.

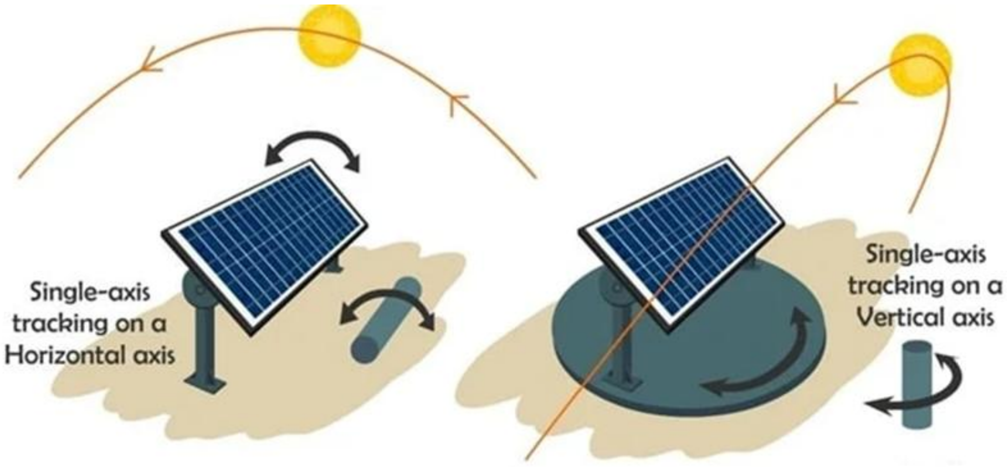



Figure 2.24 Typical solar array mounts include roof, freestanding, and directional tracking mounts on the roof or on the ground. Image courtesy of Greensarawak.

Roof-mounted solar arrays are designed to withstand the same environmental conditions as the rooftop itself, with composition shingles being the easiest roofing material for mounting, while slate and tile pose greater challenges. While these arrays integrate well with existing structures, they require accessibility for maintenance. In contrast, freestanding arrays offer easier maintenance access but demand significant space and should be avoided in snow-prone regions. Solar array mounts come in fixed or tracking varieties, with fixed mounts maintaining a set position and tracking mounts adjusting to follow the sun's path. Although directional tracking arrays can boost energy output by 25% to 40%, the complexity and cost of the mounting system may outweigh the benefits for some installations [14]. Ultimately, the choice between roof-mounted, freestanding, fixed, or tracking mounts depends on factors such as space availability, maintenance considerations, and budget constraints.

PV combiner boxes play a crucial role in PV system installations by consolidating the output from multiple solar panel strings into a single main power feed directed to the inverter. Typically situated near the solar panels and preceding the inverter, these boxes can incorporate various protective features such as overcurrent and surge protection, as well as pre-wired fuse holders and connectors, facilitating installation and ensuring operational safety. Periodic inspection is essential to detect leaks or loose connections. While not mandatory for every PV system, combiner boxes are essential for systems with multiple panel strings, streamlining wiring and enhancing overall system efficiency. In instances where only a few strings of solar panels are utilized, direct connection to the inverter may suffice, eliminating the need for a combiner box [14].

PV inverters are essential components in photovoltaic systems, tasked with converting DC power generated by solar panels into AC power suitable for household or grid use. In addition to this primary function, inverters maintain the AC frequency at 60 cycles per second and regulate voltage fluctuations to ensure stable electricity output [14]. The market offers various types of inverters, including micro-inverters, string inverters, and power optimizers, each catering to different system requirements and configurations. Micro-inverters operate at the panel level, string inverters handle multiple panels within a string, while power optimizers optimize the performance of individual panels [14]. These inverters play a critical role in maximizing energy efficiency and system reliability in PV installations. Figure 2.25 shows Microinverters are connected to each solar panel, which are connected in parallel, and convert DC directly to AC. String inverters are used with multiple solar panels connected in series. Power optimizers are installed on each solar panel, which are connected in parallel.

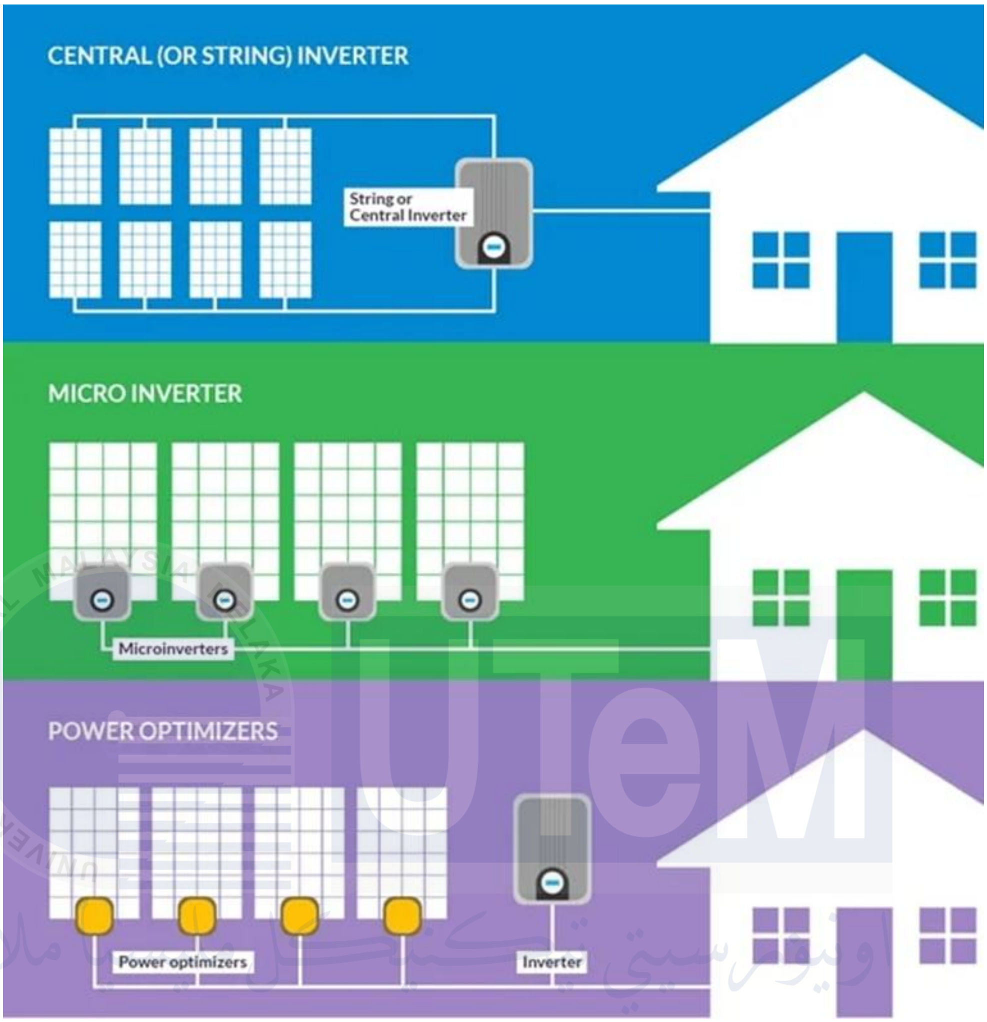





Figure 2.25 Microinverters are connected to each solar panel, which are connected in parallel, and convert DC directly to AC. String inverters are used with multiple solar panels connected in series. Power optimizers are installed on each solar panel, which are connected in parallel. Image courtesy of Letsgosolar.

PV disconnects play a crucial role in ensuring the safety and functionality of photovoltaic systems by protecting wiring and components from power surges and equipment malfunctions. These disconnects, available in both automatic and manual configurations, enable safe shutdown of the system for maintenance or repair purposes. In grid-connected systems, they serve to isolate generating equipment from the grid, ensuring the safety of utility personnel. Each power source or energy storage device within the PV system requires a disconnect, with an AC disconnect typically installed indoors before the main electrical panel and an exterior lockable AC disconnect placed near the utility meter for accessibility by utility personnel [14]. Ultimately, PV disconnects are essential components that safeguard both the system and personnel, ensuring reliable operation and maintenance procedures.

### 2.2.9 Component of Solar PV System

Solar photovoltaic (PV) systems have emerged as a leading renewable energy solution, harnessing the power of sunlight to generate electricity. Central to the operation of these systems are a range of components meticulously engineered to capture, convert, and manage solar energy efficiently [14]. From solar panels that capture sunlight to inverters that transform it into usable electricity, each component plays a critical role in the seamless functioning of PV systems. This introduction provides an overview of key PV components, delving into their functions, types, and significance in the broader context of renewable energy adoption and sustainability efforts. Through understanding these components, we gain insight into the intricate mechanisms driving the transition towards cleaner and more sustainable energy sources.

#### 2.2.9.1 Solar Panel

Solar panels are the cornerstone of a solar power system, responsible for converting sunlight into electricity. While numerous components contribute to the success of a photovoltaic system, the quality of the solar panel is paramount. These panels vary in size, price, output rating, and subtype, typically comprising 60 or 72 photovoltaic cells, with some models featuring 120 or 144 cells [15]. The output of a single panel ranges from 10 to 300 watts, with higher wattage panels being more efficient. Efficiency ratings typically fall between 15 and 20 percent, with higher efficiency panels offering greater output in relation to their size [15]. Investing in panels with higher efficiency can result in smaller panels meeting the energy needs of a household more effectively.

There are two primary types of electric panels: polycrystalline and monocrystalline. Monocrystalline panels feature cells manufactured from a single source of silicone, making them the most efficient technology available. In contrast, polycrystalline PV cells are made from various sources of silicone, offering a cheaper alternative with slightly lower efficiency. Both types are readily accessible on the market, allowing consumers to weigh the trade-off between cost and efficiency when making a decision. The price of solar cells in the United States typically ranges from $2.40 to $5 per watt, depending on panel characteristics and manufacturer [15]. To optimize panel performance, proper placement is essential. Figure 2.26 shows the difference between monocrystalline and polycrystalline panel.

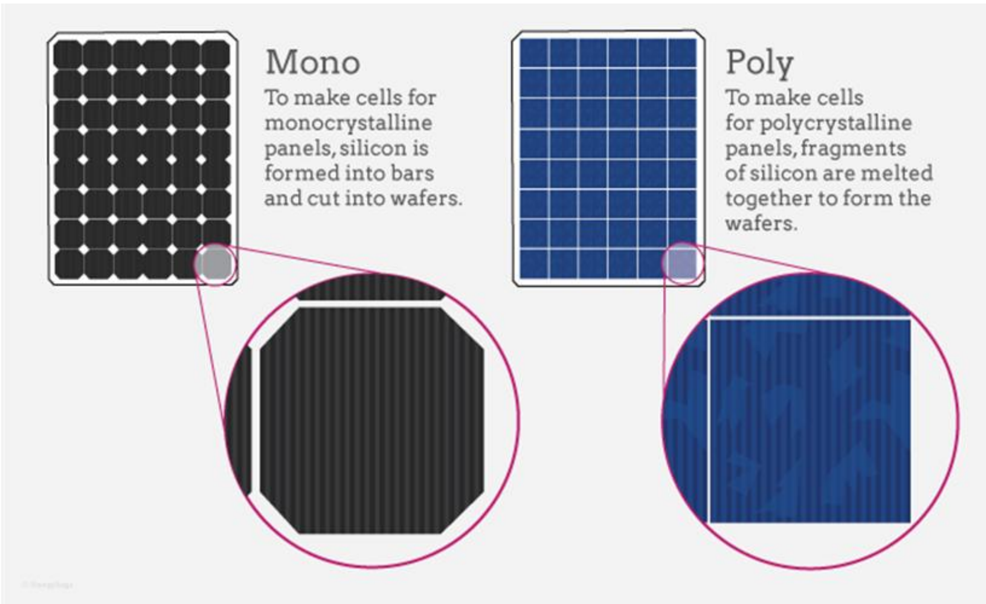



Figure 2.26 Monocrystalline vs Polycrystalline Solar PV panels.

A solar panel is a device composed of multiple photovoltaic cells connected in series, with the voltage output determined by the number of cells in series. These cells harness sunlight to generate electricity through the photovoltaic effect. When multiple panels are connected in series, they form a "string," and when these strings are connected in parallel, they create an "array." This modular design allows for scalability and flexibility in designing solar power systems to meet varying energy needs, with arrays capable of generating larger amounts of electricity suitable for residential, commercial, and utility-scale applications. Overall, solar panels serve as the fundamental building blocks of solar power systems, enabling the conversion of sunlight into clean and renewable energy. Figure 2.27 and figure 2.28 shows solar cell and panel diagram respectively.

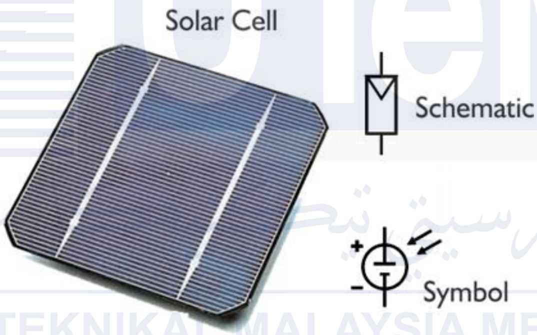



Figure 2.27   Solar cell diagram.

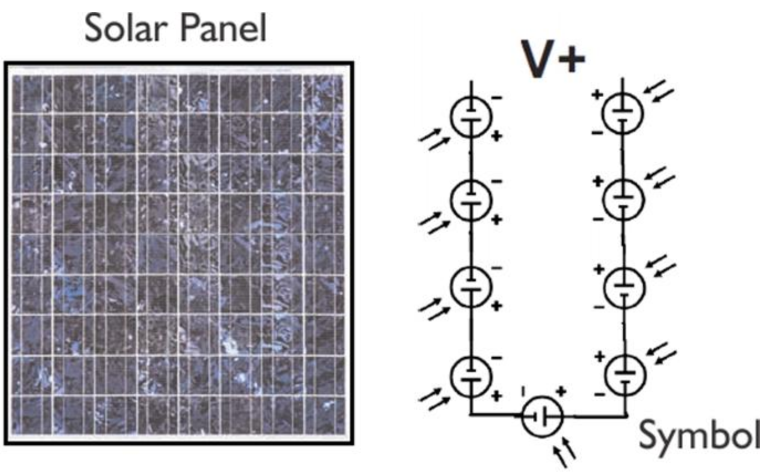



Figure 2.28   Solar panel diagram.

#### 2.2.9.2 Solar Mounting Structure

Solar mounting systems play a critical role in ensuring the optimal performance and longevity of solar power systems by strategically positioning panels to capture maximum sunlight throughout the year. It's imperative to utilize high-quality mounting systems and seek professional installation, as solar panels are expected to remain intact and functional for at least 25 years. Typically installed at angles of 30 or 45 degrees facing south, solar panels rely on the mounting system to secure them in place and maximize exposure to sunlight [16].

Mounting systems come in various subtypes, including fixed and tracking systems. Fixed systems remain stationary throughout their lifespan, while tracking systems dynamically adjust the angle of the panels to follow the sun's path. Although less common, tracking systems are employed when solar panels are installed on the ground, allowing for optimal sunlight capture.

Depending on the location of solar panels, mounting systems can be roof-mounted or ground-mounted. Roof-mounted systems are the norm and are often mandated by local regulations. They offer an efficient solution for most households, allowing panels to harness sunlight effectively while minimizing space usage. Ground-mounted systems, although more expensive initially, provide an alternative for those unable to install panels on rooftops. However, they may pose challenges in regions prone to snow or adverse weather conditions, complicating maintenance efforts. Overall, the choice between roof and ground mounting systems depends on factors such as available space, local regulations, and environmental considerations. Figure 2.29 illustrates variety of solar mounting structures.

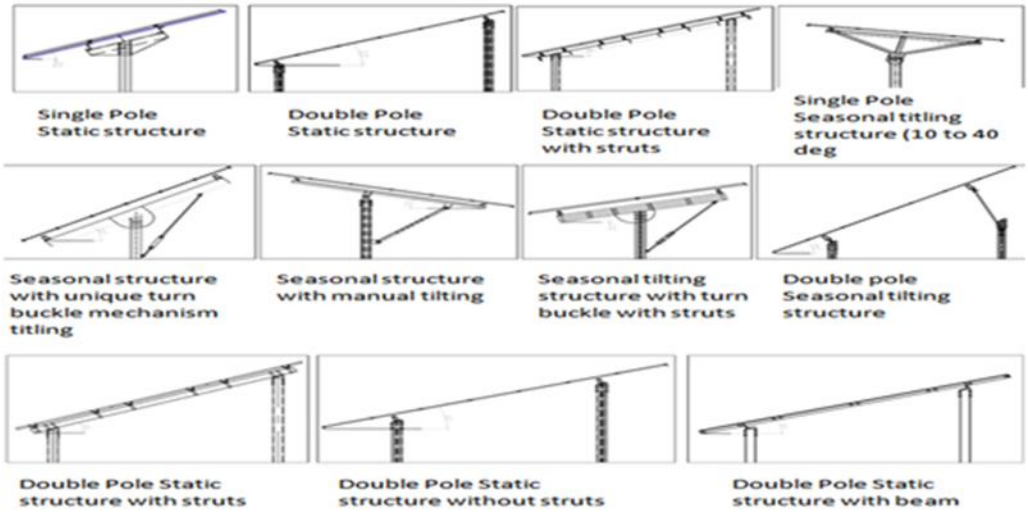



Figure 2.29 Solar Mounting structures.

### 2.2.9.3 Solar Power Inverter

Solar power inverters are essential components of photovoltaic systems, converting the DC energy generated by solar cells into the AC electricity utilized in homes as shown in figure 2.30. There are several common subtypes of inverters, each offering unique advantages and considerations. String centralized inverters, the most prevalent type, connect all solar panels to a single electrical panel, making them cost-efficient and commonly found in residential areas. These inverters are ideal for installations where panels are closely spaced, and shading is minimal.

Microinverters, on the other hand, are installed individually with each solar panel, maximizing the efficiency of every PV cell. While more costly than string inverters, microinverters offer increased efficiency, typically ranging from 20 to 25 percent higher than traditional string inverters [17]. They are particularly suitable for installations where shading affects panels unevenly throughout the day, ensuring optimal performance under varying conditions.

Power optimizers represent a hybrid solution between string inverters and microinverters, attaching to each photovoltaic cell individually but transmitting converted DC power to a centralized string inverter. This compromise allows for the benefits of a string inverter while providing attention to each PV cell. Power optimizers offer cost savings compared to microinverters while still enhancing system performance, making them a viable option for those seeking efficiency without the higher cost associated with microinverter technology. Ultimately, the choice of inverter type depends on factors such as shading patterns, installation layout, and budget considerations.

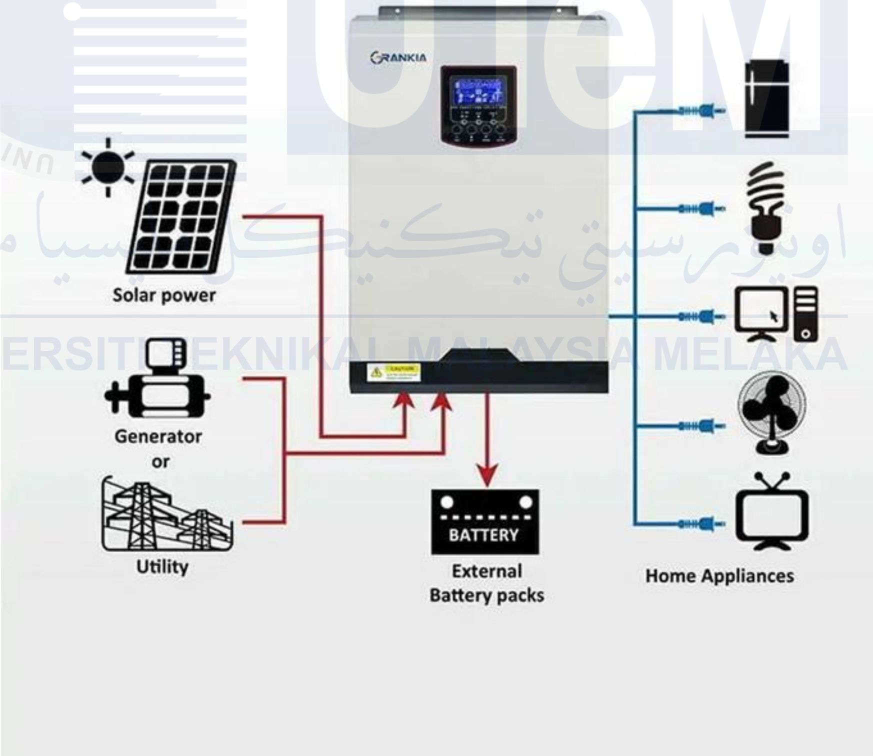



Figure 2.30 Solar PV Inverter.

#### 2.2.9.4 Electrical Protection Equipment

Solar photovoltaic (PV) systems have undergone significant advancements over the past five decades, emerging as a mature and sustainable technology with increasing efficiency and aesthetic appeal. With solar cells now achieving between 15% and 20% efficiency conversion rates, and the size of PV systems expanding, ensuring circuit protection against overcurrent is crucial for safe operation and component preservation [18]. These systems work by harnessing sunlight through photovoltaic cells, which convert photons into clean DC electricity. The generated electricity is then fed into a power inverter (PV inverter) that converts and regulates the DC source into usable AC power, which can be utilized locally or fed back into the power grid as renewable energy as depicts in figure 2.31. As solar power continues to gain acceptance and affordability, prioritizing circuit protection measures becomes paramount for the long-term reliability and safety of PV systems.

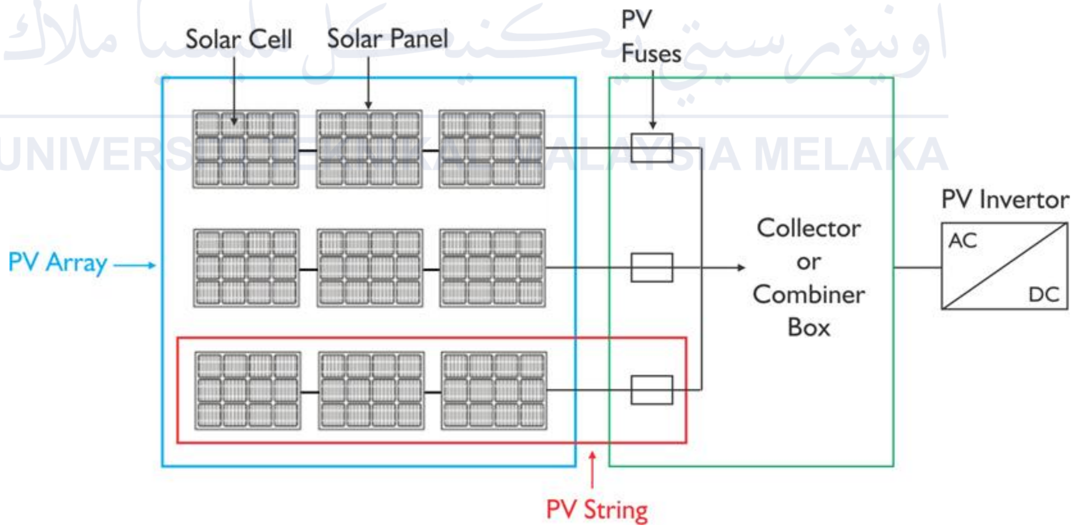



Figure 2.31 Block diagram of Solar PV system.

As the deployment of PV systems grows alongside increasing demand for renewable energy, ensuring effective electrical protection becomes imperative. Just like any electrical power system, PV systems require appropriate overcurrent protection for both equipment and conductors to safeguard against potential hazards such as short circuits or overloads. With a global trend towards higher voltages, aiming for efficiencies beyond 1000Vdc, the necessity for circuit protection as illustrates in figure 2.32 becomes even more critical [18]. This emphasis on circuit protection is essential to ensure the safety, reliability, and longevity of PV systems as they continue to evolve and expand in scale and complexity to meet the world's growing energy needs sustainably.

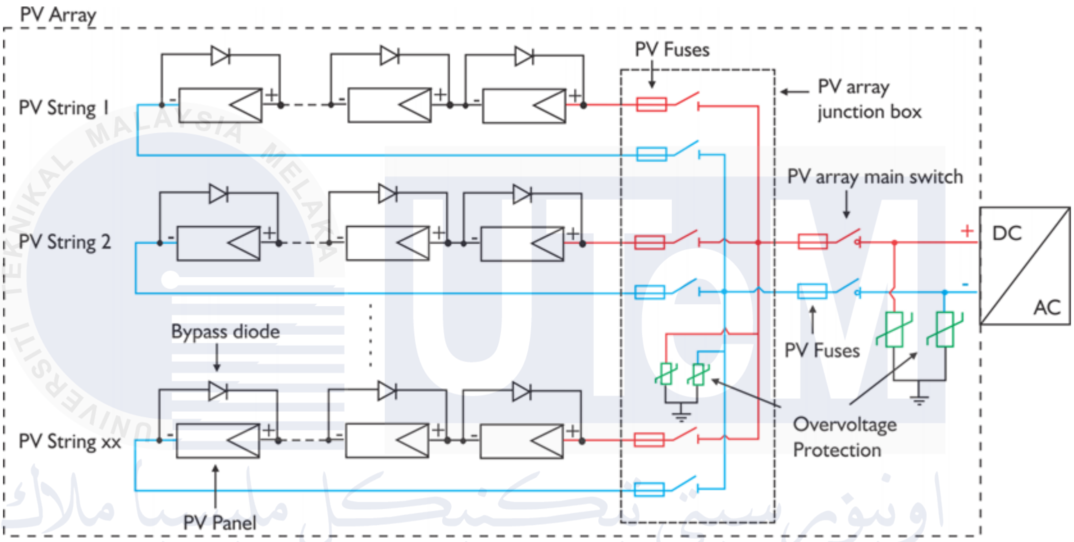





Figure 2.32 Block diagram of Solar PV system with protection equipment.

Not all PV systems require circuit protection, as those with less than three strings connected in parallel may not generate sufficient fault current to pose safety hazards or damage conductors/equipment if properly sized according to local code requirements. However, systems with three or more strings connected in parallel necessitate individual protection for each string. Fuses installed on each string serve to safeguard conductors from damage, isolate any faults to the affected string, and ensure the continued generation of electricity by the rest of the PV system. This targeted circuit protection is crucial for maintaining the safety and integrity of PV systems, particularly in installations with multiple parallel strings where fault currents can pose significant risks if left unmitigated. Figure 2.33 shows sample of solar PV system protection equipment.

Figure 2.33   Sample of Solar PV system protection equipment [18].

Operating conditions for fuses as shown in figure 2.34 in PV systems can be more challenging when fault currents are low, especially in circuits where breaking is necessary under direct voltage. In such scenarios, fuses may experience longer melting times and face difficulties in breaking the circuit. To address this issue, manufacturers have developed specialized fuses explicitly designed and tested to effectively protect PV systems with high DC voltages and low fault currents. These specially designed fuses are engineered to withstand the unique operating conditions of PV systems, ensuring reliable and safe protection against faults while maintaining system integrity and performance.




Figure 2.34   Sample of fuse protection of PV strings.

In Photovoltaic (PV) systems, where multiple sub-arrays are connected in parallel to enhance current and power capacity, fuse protection plays a crucial role in safeguarding conductors from current faults and minimizing safety hazards. Each sub-array is equipped with a fuse link as shown in figure 2.35 to isolate faults and ensure uninterrupted electricity generation by the rest of the system. Additionally, if multiple sub-arrays are combined, an array fuse link is incorporated to provide further protection. Specialized NH size fuse links designed for PV array combiners and disconnected are capable of interrupting low overcurrent associated with faulted PV systems, ensuring efficient and reliable protection. It's essential to consider the varying characteristics of PV modules with changes in temperature and irradiance levels, as fuse links' operation can be influenced by ambient temperature. As a result, a wide range of solar circuit protection devices, including fuses, blocks, and carriers, are available to meet the diverse needs of PV system installations.


Figure 2.35 Sample of fuse protection for PV arrays.

### 2.2.9.5 Battery Bank

A battery bank serves as a crucial component in photovoltaic systems, allowing excess energy generated by the PV array to be stored for later use, particularly during periods of low sunlight or at night. While optional, integrating a battery bank significantly enhances the usability and efficiency of solar energy utilization. With a battery system in place, homes can maximize their consumption of solar energy, utilizing up to 80 percent of the generated energy compared to just 40 percent without one [19]. This capability not only reduces reliance on grid electricity but also enhances energy resilience and sustainability, making battery storage a valuable addition to photovoltaic installations. Figure 2.36 illustrates how battery bank works.

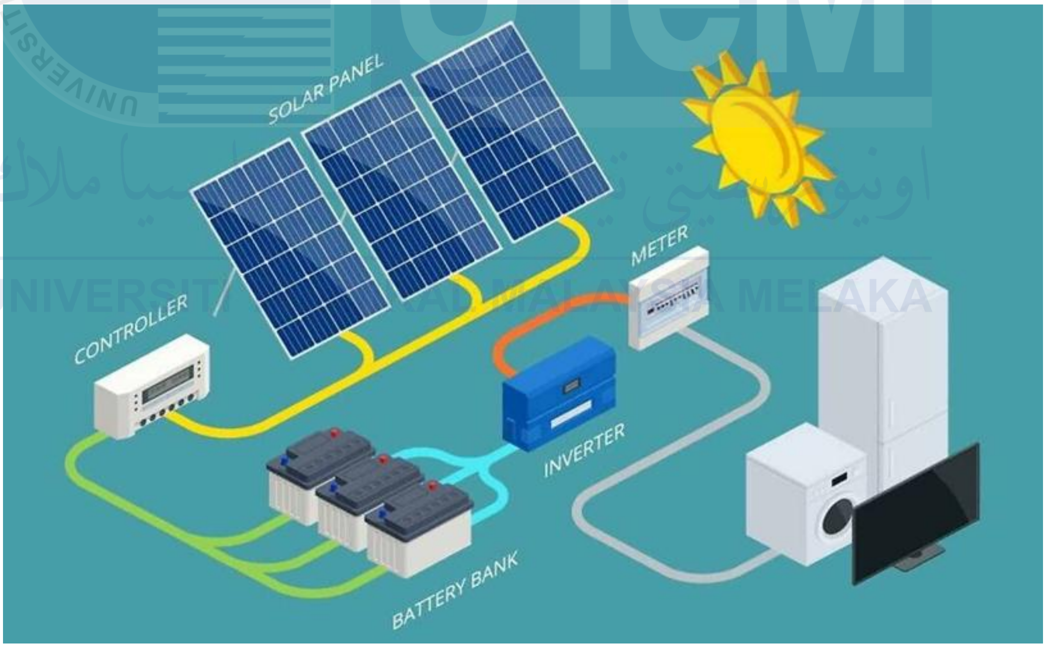



Figure 2.36 How battery bank works.

## 2.3 Previous Work on Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System by Others

### 2.3.1 Design A Solar Powered Air Purifier with Air Quality Monitoring System

The innovative solar-powered air purifier with an integrated air quality monitoring system represents a crucial advancement in combating indoor air pollution. By harnessing renewable solar energy through photovoltaic panels, the system operates independently of grid power, significantly reducing carbon emissions and offering a sustainable solution. Cutting-edge filtration technologies efficiently eliminate harmful particles, allergens, and volatile organic compounds (VOCs) from indoor air, while real-time monitoring of parameters such as PM2.5, PM10, CO2 levels, VOCs, temperature, and humidity ensures constant awareness of air quality conditions [20]. The system's intelligent control mechanism dynamically regulates purification processes based on real-time sensor readings, optimizing energy consumption, and enhancing indoor air quality. With features such as adjustable fan speeds and automated alerts, users can effortlessly monitor air quality trends and ensure optimal performance even in the face of fluctuating environmental conditions [20]. This holistic approach to air purification not only improves health and well-being but also contributes to environmental sustainability by mitigating the adverse effects of indoor air pollution.

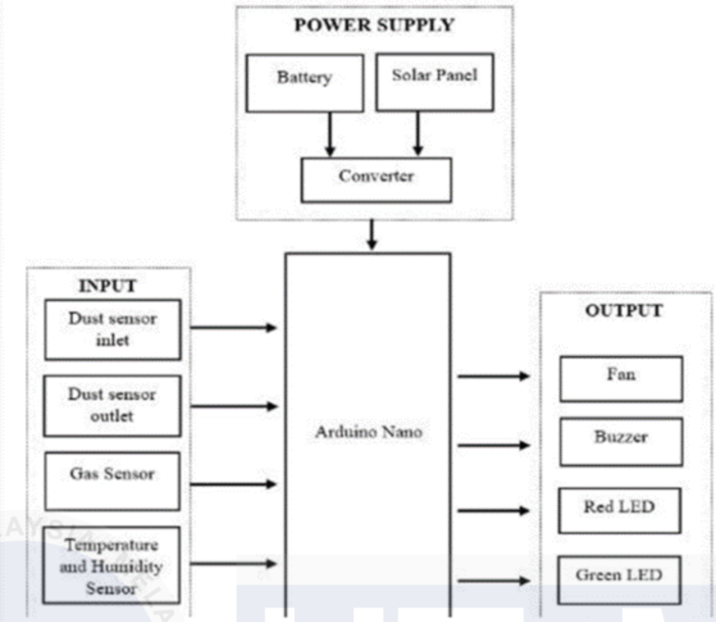



Figure 2.37 Block diagram of Solar Powered Air Purifier with Air Quality Monitoring System [20].



### 2.3.2 Development of an IoT-Based Indoor Air Quality Monitoring Platform

This paper introduces an innovative IoT-based indoor air quality monitoring platform called "Smart-Air," accompanied by a web server, offering a comprehensive solution for real-time air quality assessment accessible remotely. Leveraging IoT and cloud computing technologies, Smart-Air collects air quality data through a microcontroller and pollutant detection sensors, transmitting it to a web server via LTE connectivity. The device integrates various sensors, including those for aerosol, volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO2), temperature, and humidity, enabling precise monitoring of indoor air quality [21]. Rigorous testing confirmed the reliability of the device, which was implemented successfully at Hanyang University in Korea [21]. Cloud computing is seamlessly integrated into the web server for data analysis, classification, and visualization based on government standards, facilitating swift identification of air quality issues and timely interventions. An accompanying mobile application enables authorized personnel to track indoor air quality remotely. The platform's adaptability allows for customization of air quality thresholds and comfort parameters, ensuring relevance in diverse indoor environments. Overall, Smart-Air represents a significant advancement in indoor air quality monitoring, offering real-time insights and empowering users to take proactive measures to enhance indoor air quality and safeguard public health [21].

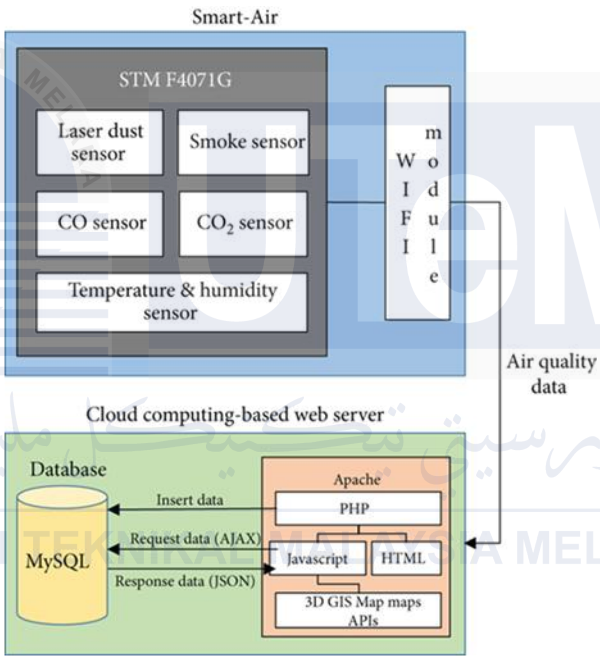





Figure 2.38 Configuration diagram for the IoT-Based Indoor Air Quality Monitoring Platform [21].

### 2.3.3 Development of an IoT-Enabled Air Pollution Monitoring and Air Purifier System

This paper proposes the development of an IoT-enabled air pollution monitoring and air purifier system to address the critical hazard of air pollution in urban environments. The system utilizes a combination of sensors, including PM sensors like PMSA003 and gas sensors like MQ2 and MQ135, alongside a Raspberry Pi 3 B+ microcontroller, to monitor pollutants such as CO, CO2, NH4, LPG, smoke, and particulate matter ranging from 0.3 to 10 microns [22]. The system comprises a pre-filter unit, a filtering unit with primary, activated carbon, and HEPA filters, an IoT-based sensing unit, and a control unit [22]. Through step-by-step filtration, the system targets various particle sizes and gas pollutants, with real-time monitoring facilitated by transmission of data to the ThingSpeak Cloud platform [22]. The paper details the hardware components used, including the pre/primary filter, activated carbon filter, HEPA filter, Raspberry Pi, PM sensor, and gas sensors, along with their specifications and operational principles [22]. Python programming language is employed for data processing and transmission, while ThingSpeak Cloud Platform enables real-time monitoring and analysis [22]. The prototype structure and implementation, as well as experimental results and discussions, are comprehensively presented, demonstrating the system's effectiveness in sensing and filtering air pollutants under various conditions. The paper concludes by highlighting the prototype's cost-efficiency, adaptability, and potential for meeting green energy standards, while suggesting future enhancements for augmenting its filtering capabilities and performance validation under high air speed conditions [22].

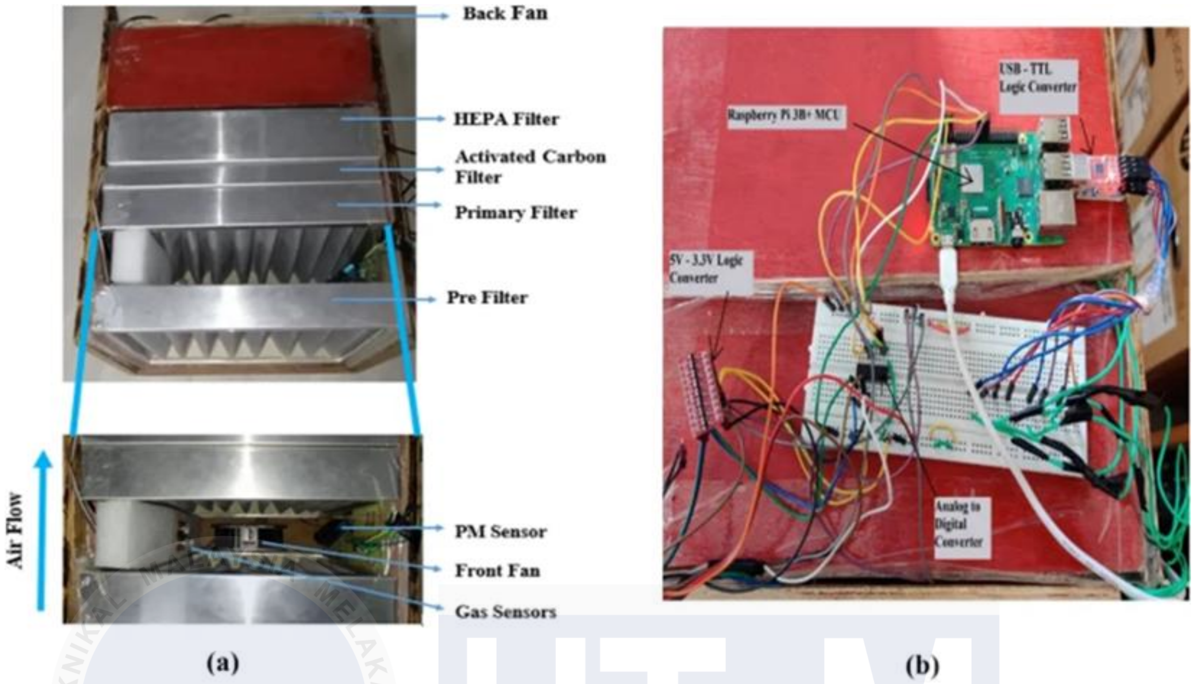



Figure 2.39 Complete setup and connections for an IoT-Enabled Air Pollution Monitoring and Air Purifier System [22].

### 2.3.4 Design and Development of Air Purification

The proposed system aims to combat dust pollution by introducing an innovative air purification solution tailored for small spaces, particularly relevant in regions like India where urban air pollution poses significant health risks. Integrating IoT technology, the system incorporates Arduino Nano and ESP8266 Wi-Fi module for data processing and transmission to a real-time Firebase database, enabling remote monitoring and control via an Android application [23]. The system employs various sensors for air quality, temperature, and humidity monitoring, with the Arduino Nano processing sensor data and the ESP8266 module facilitating data transmission to the Firebase database [23]. The Android application provides users with real-time updates on environmental conditions and enables control over the air purifier's operation, enhancing convenience and usability.

Furthermore, the system's potential for future enhancements, such as compact size, IoT integration, and artificial intelligence for intelligent control, underscores its adaptability and commitment to advancing air purification technologies to safeguard public health amidst evolving environmental threats like air pollution and airborne pathogens [23].

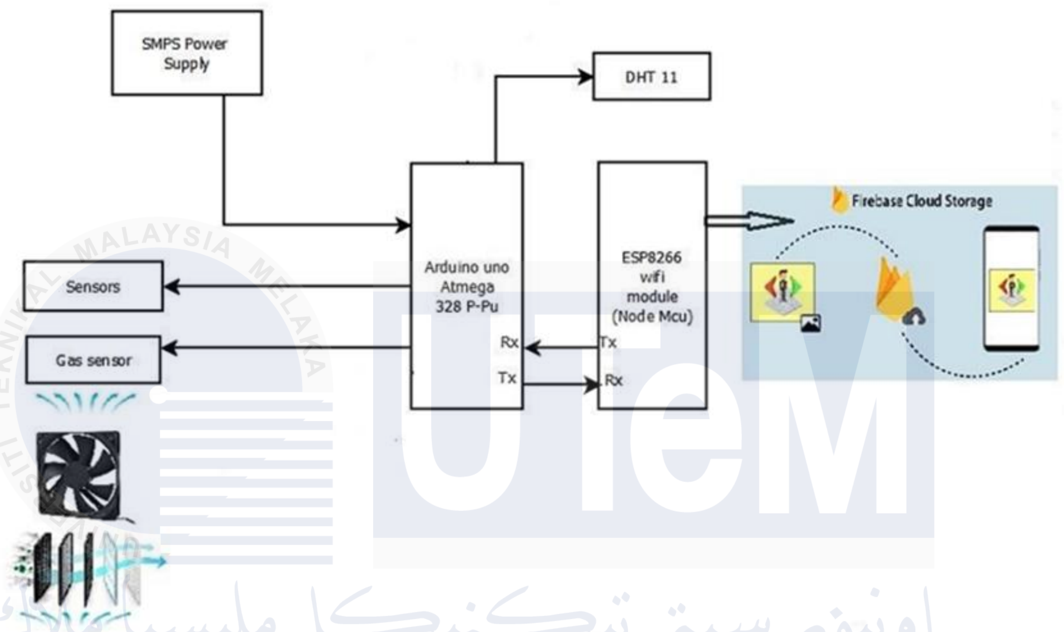



Figure 2.40 Proposed work design of the Air Purification project [23].

### 2.3.5 Solar Air Purifier & Air Monitoring

The proposed system addresses the pressing issue of air pollution by introducing a cost-effective solar-powered air purifier designed to improve indoor air quality. Utilizing a multi-stage filtration process incorporating filters and activated carbon technology, the system efficiently captures and eliminates various pollutants, providing occupants with a continuous supply of clean and purified air. The block diagram illustrates the integration of components such as solar panels, batteries, Arduino Uno boards, MQ135 gas sensors, and LCD displays to measure and visualize air quality data. With the solar panel harnessing sunlight to charge the battery, which powers the system, the brushless fan draws in polluted air for filtration through the carbon filter. The MQ135 gas sensors measure air quality, while the Arduino Uno boards process and display the input and output data on LCD displays [3]. This setup offers a tangible solution to combat indoor pollution, particularly relevant for individuals with respiratory ailments, and underscores the importance of environmental monitoring in safeguarding public health and promoting a healthier lifestyle. Additionally, the discussion on air environmental parameters highlights the significance of monitoring air quality in addressing the adverse impacts of air pollution, with a specific focus on particulate matter 2.5 (PM2.5) and its associated health risks [3]. The hardware implementation of the system demonstrates its feasibility and potential for future enhancements, while the conclusion emphasizes the system's contribution to improving air quality, reducing respiratory issues, and ensuring economic sustainability.

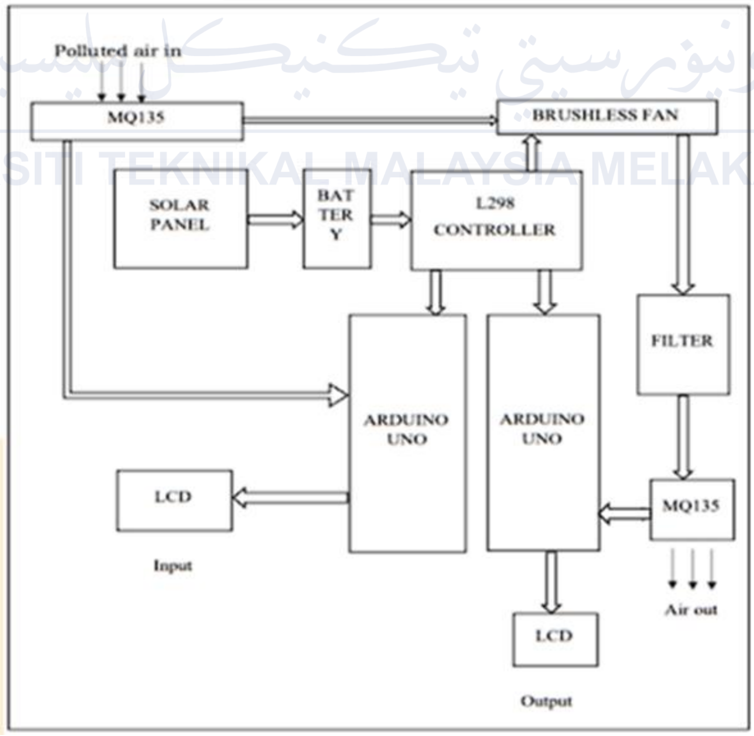



Figure 2.41 Block diagram of Solar Air Purifier and Air Monitoring [3].

### 2.3.6 Design Methodology of Off-Grid PV Solar Powered System

Solar energy offers a transformative solution to global energy needs, with its abundance and sustainability making it an attractive option for diverse applications. In this research, methodologies for designing off-grid photovoltaic (PV) systems are proposed, with a focus on practical implementation exemplified through the design of an off-grid bus shelter [24]. The design process begins with a thorough site assessment, considering factors such as sunlight exposure, shading, and local climate conditions to optimize system efficiency. Energy calculations are then performed to determine the wattage requirements of the equipment to be powered by the PV system, facilitating accurate sizing of solar panels and batteries. Panel sizing involves accounting for internal losses and variations in solar irradiance throughout the day and seasons, ensuring optimal energy capture [24]. Battery sizing considerations include cycle life, maintenance costs, and planned system lifespan, with careful attention to financial viability [24]. Inverter selection is guided by system voltage and power output requirements, while charge controllers are chosen based on battery management needs and efficiency considerations [24]. The proposed methodologies emphasize the importance of system optimization and financial feasibility, with the designed off-grid PV system showcasing versatility and applicability beyond bus shelters. Ultimately, this research underscores the potential of off-grid PV systems to reduce dependence on centralized grids and promote self-sufficiency, contributing to sustainable energy solutions for diverse communities and applications.

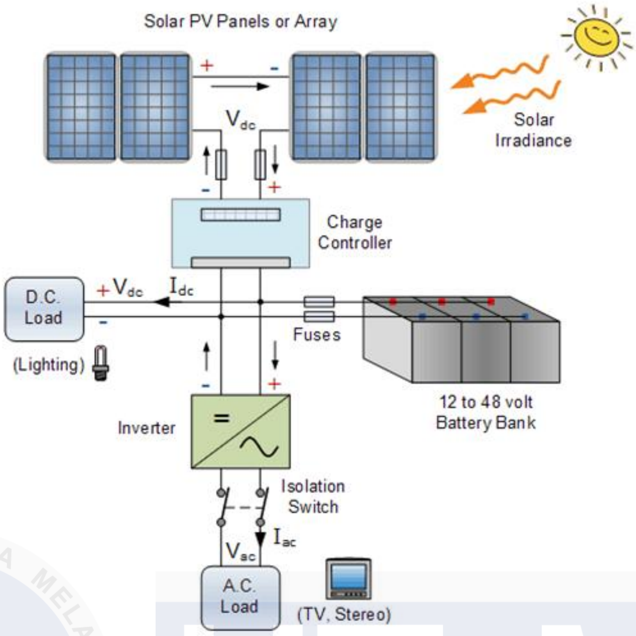



Figure 2.42 Block diagram of an Off-Grid PV Solar Powered System [24].

### 2.3.7 Solar Powered Air Quality Monitoring and Filtering System

This research paper advocates for the development of a solar-powered air quality monitoring and filtration system designed to combat air pollution, particularly focusing on hazardous particulate matter. Employing an innovative approach, the system integrates various sensors such as MQ135, MQ2, and MQ6, connected to an Arduino Uno microcontroller, to monitor specific air quality parameters [25]. When pollution levels exceed predefined thresholds, corresponding sensors trigger a relay to activate a fan, drawing air into a filter chamber for purification [25]. Real-time data on gas concentrations is displayed on an LCD screen, enabling users to monitor air quality continuously. The system's reliance on solar energy, coupled with battery storage, ensures autonomous operation and sustainability [25]. This intelligent solution not only raises awareness about air quality but also facilitates proactive measures to mitigate pollution, thus contributing to environmental conservation efforts. Additionally, the system's potential for future enhancements, including the integration of additional sensors and advanced features like data storage and GPS modules, underscores its adaptability and potential for broader impact in public health and environmental conservation endeavours.

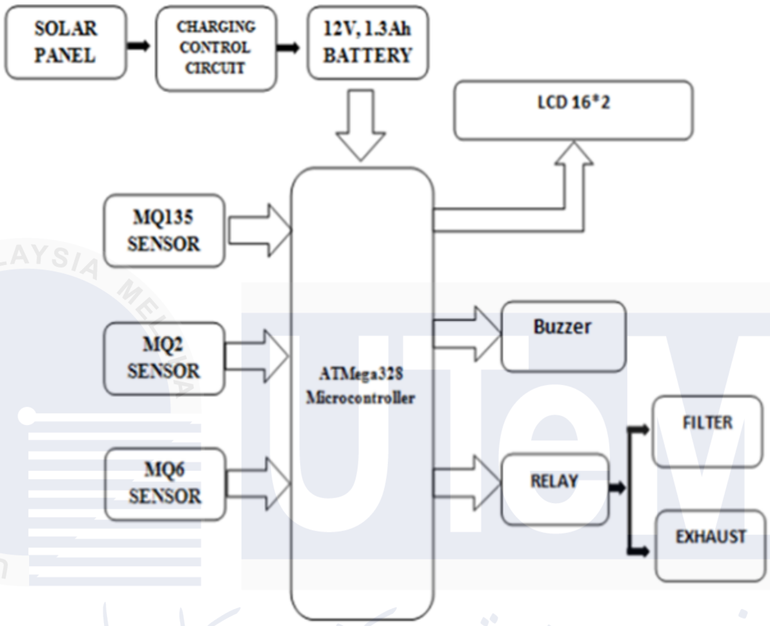



Figure 2.43 Block diagram of Solar Powered Air Quality Monitoring and Filtering System [25].



### 2.3.8 Solar Outdoor Air Purifier with Air Quality Monitoring Using IOT

The research paper proposes the development of a solar-powered outdoor air purification and monitoring system to address the pressing issue of air pollution in contemporary times, particularly in urban areas. The system integrates various components including sensors, filtration elements, a Wi-Fi module, and a solar panel to effectively monitor and filter air pollutants. Through a multi-stage filtration process involving HEPA filters and activated carbon, the system aims to remove harmful particles and gases from outdoor environments, thereby reducing the risk of airborne diseases and improving overall air quality. Real-time monitoring capabilities facilitated by the Wi-Fi module enable users to track air quality parameters remotely, while the portability of the system allows for versatile deployment in industrial areas, bus stops, railway stations, and other high-traffic locations prone to pollution [26]. By harnessing solar energy and incorporating efficient filtration technologies, the system offers a cost-effective and sustainable solution to mitigate air pollution and promote public health and environmental sustainability in outdoor settings.

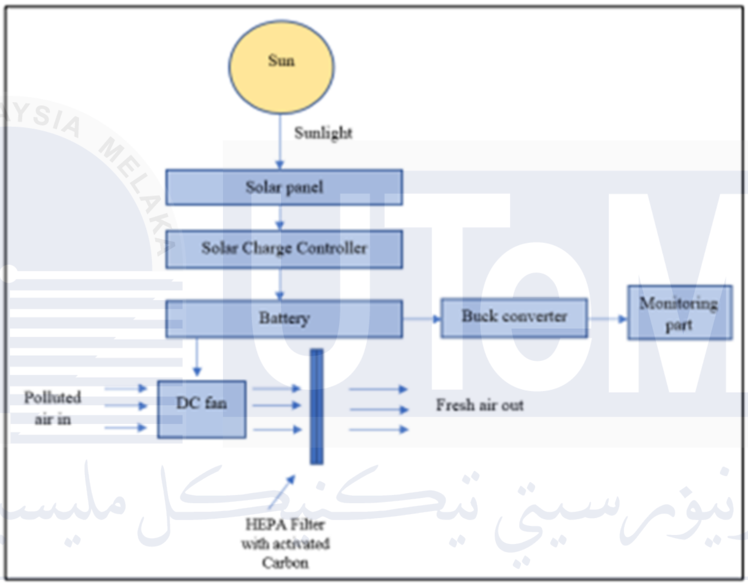



Figure 2.44 Block diagram of Solar Outdoor Air Purifier with Air Quality Monitoring Using IOT [26].

### 2.3.9 Solar Powered Air Purifier with Air Quality Monitor

Amidst escalating global concerns regarding air pollution, the development of a solar-powered outdoor air purifier emerges as a groundbreaking solution to combat harmful pollutants effectively. Unlike conventional purifiers reliant on external power sources, this innovative design ensures energy independence, rendering it suitable for diverse outdoor environments. By incorporating a multi-stage purification process involving HEPA, Active

Carbon, and UV filters, the purifier efficiently targets PM10 and PM2.5 pollutants along with harmful gases, offering a comprehensive solution to outdoor air pollution challenges [27]. Utilizing components such as the MQ135 gas sensor, DHT22 temperature and humidity sensor, and PM2.5 dust sensor interfaced with an Arduino Uno microcontroller, the purifier monitors air quality parameters in real-time, facilitating informed decision-making and ensuring optimal performance [27]. The effectiveness of solar-powered air purifiers in reducing particulate matter, smoke particles, and other pollutants underscores their significance in promoting public health and environmental sustainability. Moreover, their economic benefits and longevity without frequent component replacements further enhance their appeal, emphasizing their pivotal role in providing access to clean and pure air, essential for human health and well-being.

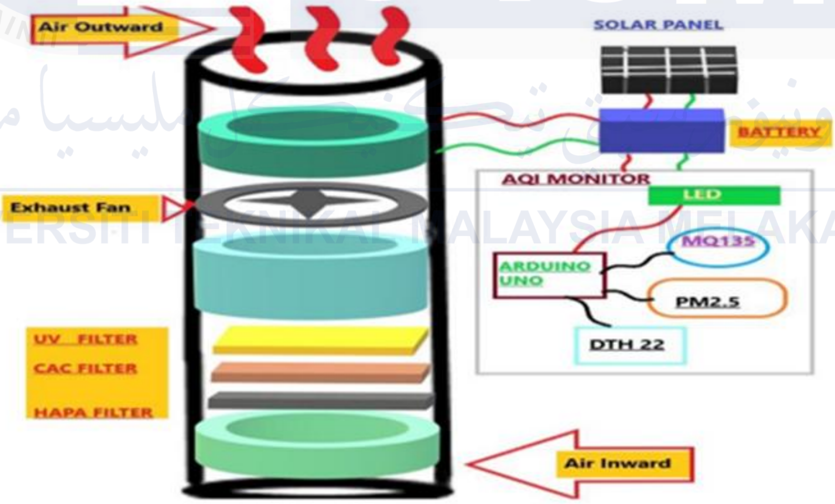



Figure 2.45 Block diagram of Solar Powered Air Purifier with Air Quality Monitor [27].

### 2.3.10 Air Purification by Using Solar Power Resolving Air Pollution Problem

Amidst the escalating global concern over air pollution, exacerbated by factors such as increased fossil fuel consumption and industrial activities, the development of a solar-powered air purification system emerges as a crucial solution. This innovative system, designed for outdoor environments like highways and factory settings, addresses the challenge of fine dust particulates through a multi-stage purification process, leveraging solar energy and advanced sensing technology [28]. By incorporating components such as solar panels, charge controllers, high-voltage electrodes, and gas sensors, the system operates seamlessly to detect, ionize, and filter pollutants, ensuring efficient air purification. Its adaptability, sustainability, and cost-effectiveness make it a promising tool in combatting air pollution and safeguarding public health. Additionally, ongoing development efforts aim to further enhance the system's efficiency and functionality, underscoring its potential to contribute significantly to environmental conservation efforts and the promotion of clean and healthy living environments.



Solar panel power = 20 watts Solar panel voltage = 12V
Hence,
Load current = power/voltage = 20/12 = 1.67A
Battery charging time = Battery current hour/ load current
= 7.5/1.67
= 4.49 Hrs

Figure 2.46 Calculations for Air Purification by Using Solar Power Resolving Air Pollution Problem [28].

### 2.3.11 Design & Fabrication of Solar Powered Air Filtration and Ventilation System

The development of an advanced air filtration and ventilation system tailored for diverse industrial environments such as machine workshops, cement factories, and food processing plants addresses the critical need for ensuring clean and comfortable air for workers. This innovative system integrates multiple stages of filtration and ventilation, utilizing a two-way path for faster and more efficient removal of unwanted particles and contaminants [29]. Powered by solar energy, the system operates sustainably and cost-effectively, eliminating the need for external power sources. By actively extracting heat, moisture, odours, and harmful gases while simultaneously filtering out dust, debris, and pollens, the system creates a healthier and more comfortable working atmosphere for individuals within these industrial sectors. Its modular design allows for easy installation and modifications, ensuring adaptability and longevity in evolving industrial environments, thus making it an efficient and practical solution for enhancing indoor air quality and promoting the well-being of workers.

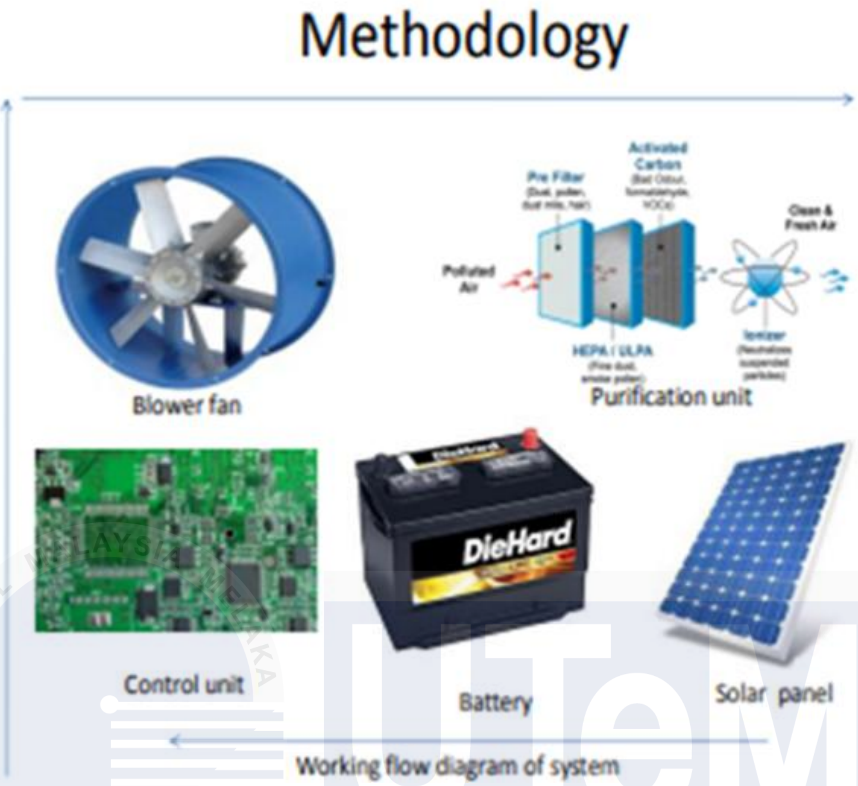



Figure 2.47 Flow diagram with components for Solar Powered Air Filtration and Ventilation System [29].



### 2.3.12 Application Design of an Integrated Outdoor Air Quality Monitoring Device Based on Solar Power

This paper presents a novel integrated outdoor air quality monitoring device powered by solar energy, addressing the latest application requirements. By integrating advanced technologies such as digital control, wireless communication, and LED display, the device enables real-time monitoring of multiple air quality parameters in outdoor settings. The device's structure comprises a modular LED display and a monitoring control cabinet, allowing for flexibility in installation methods to suit diverse environments [30]. Through a dual control chip design, the device ensures efficient management and control of functions, including air quality parameter acquisition, real-time clock management, and information display [30]. Experimental tests confirmed the device's stability, reliability, and accuracy in monitoring air quality parameters, validating its potential for practical application. With its green solar-powered technology and innovative design approach, the device offers a sustainable and effective solution for addressing outdoor air quality monitoring needs, fulfilling market demands for reliable monitoring systems while contributing to environmental conservation efforts.

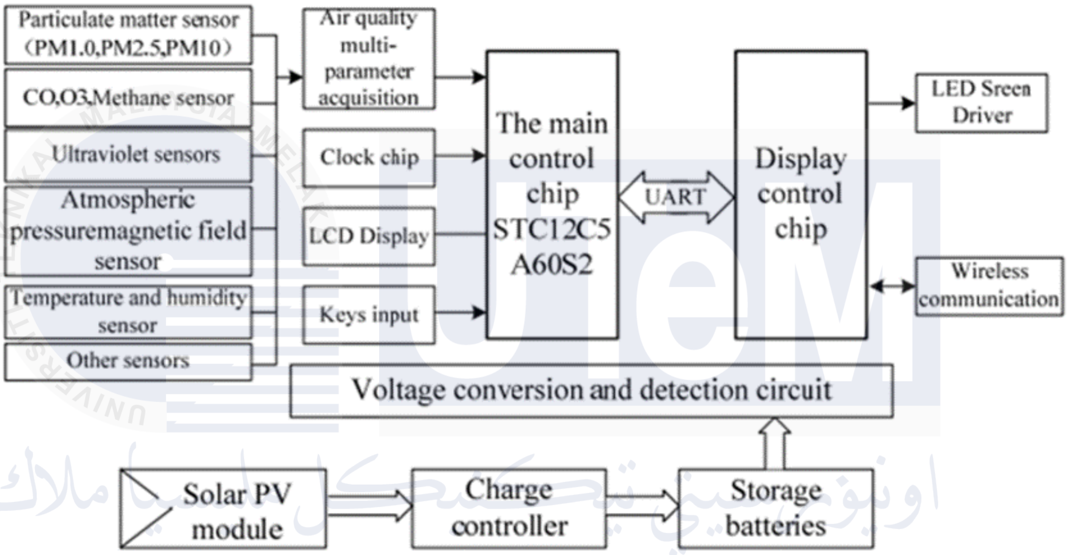





Figure 2.48 The block diagram of the circuits for Integrated Outdoor Air Quality Monitoring Device Based on Solar Power [30].

## 2.4 Comparison of Previous Work by Others

Table 2.2 This is a comparison of previous work on solar PV powered outdoor air purification with air quality monitoring system by others.

| No. | Author | Title | Application | Remark (Special Feature) |
|---|---|---|---|---|
| **1** | Pooja M, Bhagya P K, Anil Kumar N, and Niveditha M U | Design A Solar Powered Air Purifier with Air Quality Monitoring System. | To develop an affordable solar-powered air purifiers with built-in air monitoring devices | 1. Indoor system.<br><br>2. Runs on solar energy during the day.<br><br>3. Continues operating during power outages. |
| **2** | JunHo Jo, ByungWan Jo, JungHoon Kim, SungJun Kim, and WoonYong Han | Development of an IoT-Based Indoor Air Quality Monitoring Platform. | To efficiently monitor the data and alert users and related personnel. | 1. Development of an IoT-based indoor air quality monitoring<br><br>2. Wirelessly transmits data to a web server for real-time indoor air quality monitoring. |
| **3** | M. Anitha, and Lakshmi Sutha Kumar | Development of an IoT-Enabled Air Pollution Monitoring and Air Purifier System. | To develop a smart air pollution monitoring and purification system using IoT technology. | 1. Customizable gas detection capabilities, affordability, and the potential for integration with renewable energy sources. |
| **4** | Shayank Verma, and Devendra Dohare | Design and Development of Air Purification. | To develop a portable and efficient air purification system capable of filtering air pollutants in small spaces. | 1. Automatically detects air quality and can be monitored and controlled remotely using a user-friendly Android application. |

| No. | Author | Title | Application | Remark (Special Feature) |
|---|---|---|---|---|
| **5** | Mrs. Thanuja K, and Mr. Swaroop N S | Solar Air Purifier & Air Monitoring. | To efficiently clean indoor air by filtering out contaminants such as dust, smoke, and pollutants. | 1. Offers real-time measurement of air parameters. |
| **6** | Ayaz A. Khamisani *et. al.* | Design Methodology of Off-Grid PV Solar Powered System. | To design and implement an off-grid PV solar-powered system. | 1. Calculations for energy usage, wattage of solar panels, battery sizing, inverter sizing, and charge controller sizing. |
| **7** | Khaja Jamaluddin *et. al.* | Solar Powered Air Quality Monitoring and Filtering System. | To develop a solar-powered air quality monitoring and filtering system. | 1. MQ135 for overall air quality, MQ6 for other gases, and MQ2 for combustible gas connected with an LCD.<br><br>2. includes a filter fan controlled by threshold values set for the sensors. |
| **8** | Dr Nagendra Kumar M, Darshan K Gowda, Suprith S, and Vinay N | Solar Outdoor Air Purifier with Air Quality Monitoring Using IOT. | To develop a solar-powered outdoor air purifier equipped with air quality monitoring using IoT. | 1. To utilize solar energy and incorporating HEPA and activated carbon filters.<br><br>2. The IoT integration enables remote monitoring of air quality parameters. |

| No. | Author | Title | Application | Remark (Special Feature) |
|---|---|---|---|---|
| **9** | Satyam Ray *et. al.* | Solar Powered Air Purifier with Air Quality Monitor. | To mitigate rising air pollution levels by effectively removing PM10 and PM2.5 pollutants as well as harmful gases from the air. | 1. Utilizing a combination of HEPA, Active Carbon, and UV filters.<br><br>2. The system operates independently of external power sources. |
| **10** | Rohit.B. Madane, Aniket.D. Hatkar, Sapna.N. Rathod, and Suraj.R. Gillurkar | Air Purification by Using Solar Power Resolving Air Pollution Problem. | To address the problem of air pollution, particularly focusing on the removal of fine dust particles. | 1. Calculations for solar PV panel and battery concluded. |
| **11** | Deep Vanpariya, Vyom Vyas, Sujal Rana, and Harshit Shah | Design & Fabrication of Solar Powered Air Filtration and Ventilation System. | To design and fabricate a solar-powered air filtration and ventilation system. | 1. Simple and easy installation process.<br><br>2. Embedded with solar power. Incorporates solar-powered fans. |
| **12** | Wang Yiwang *et. al.* | Application Design of an Integrated Outdoor Air Quality Monitoring Device Based on Solar Power. | To design an integrated outdoor air quality monitoring device powered by solar energy, featuring real-time multi-parameter monitoring. | 1. The integration of solar power for sustainable energy supply, combined with digital control technology, allowing real-time online collection of various air quality parameters, and scrolling display through an LCD screen. |

## 2.5 Summary

The literature review delves into the integration of solar photovoltaic (PV) technology with outdoor air purification systems coupled with air quality monitoring. It encompasses a comprehensive exploration of various aspects, including the technical feasibility, environmental impact, efficiency, and effectiveness of such integrated systems. Key topics covered include the design and implementation of solar PV-powered air purification units, the selection of appropriate air filtration technologies, the integration of real-time air quality monitoring sensors, and the potential benefits in terms of energy savings, pollutant removal, and public health improvements. Furthermore, the review examines case studies, research findings, and advancements in the field, highlighting both the opportunities and challenges associated with deploying solar PV-powered outdoor air purification systems with integrated monitoring capabilities.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This chapter outlines the implementation of the "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" and elucidates how the project aims will be realized. It provides a broad perspective on the approach taken in constructing the system for this project. The chapter delves into the development process, offering detailed explanations and visual aids. Additionally, it outlines the optimal strategy employed to attain the desired outcome.

## 3.2 Methodology

The methodology adopted in this study entails a comprehensive approach to the development and implementation of the "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System." Initially, extensive attention is dedicated to the meticulous design phase, wherein the system's fundamental requirements are delineated, and the overarching architecture is conceptualized to ensure seamless integration of key components. This phase involves a thorough analysis of system functionality and operational dynamics to establish a robust foundation for subsequent stages. After design, a meticulous component selection process ensues, prioritizing criteria such as performance optimization, compatibility, and energy efficiency. This stage involves sourcing and evaluating various components, including solar PV panels, air purification units, air quality sensors, and ancillary hardware, to assemble a cohesive system framework that aligns with project objectives and specifications.

### 3.2.1 General Flowchart

Following component selection, the methodology progresses to the prototype development stage, where the theoretical designs are translated into tangible prototypes through meticulous assembly and integration of selected components. The prototype serves as a tangible manifestation of the envisioned system, allowing for practical testing and validation of design concepts. Rigorous testing procedures are then undertaken to assess the prototype's performance across various operational parameters, including air purification efficacy, air quality monitoring accuracy, solar PV power generation reliability, and overall system responsiveness. This phase facilitates the identification of potential bottlenecks or areas for optimization, paving the way for iterative refinement and enhancement of system functionality. Additionally, validation protocols are implemented to ensure that the developed system meets predefined performance standards and objectives, with field testing conducted under real-world conditions to evaluate practical usability and effectiveness in outdoor environments. Throughout the methodology, meticulous documentation is maintained to provide a comprehensive record of the design process, component selection rationale, prototype development iterations, testing procedures, optimization efforts, and validation outcomes. Figure 3.1 depicts the subsequent phases of product design and fabrication. Using a flowchart, Figure 3.1 illustrates the process used to construct this project. This strategy was used to describe the execution procedure for the project. In addition, it assists in determining which tasks must be prioritised and completed in order of importance.

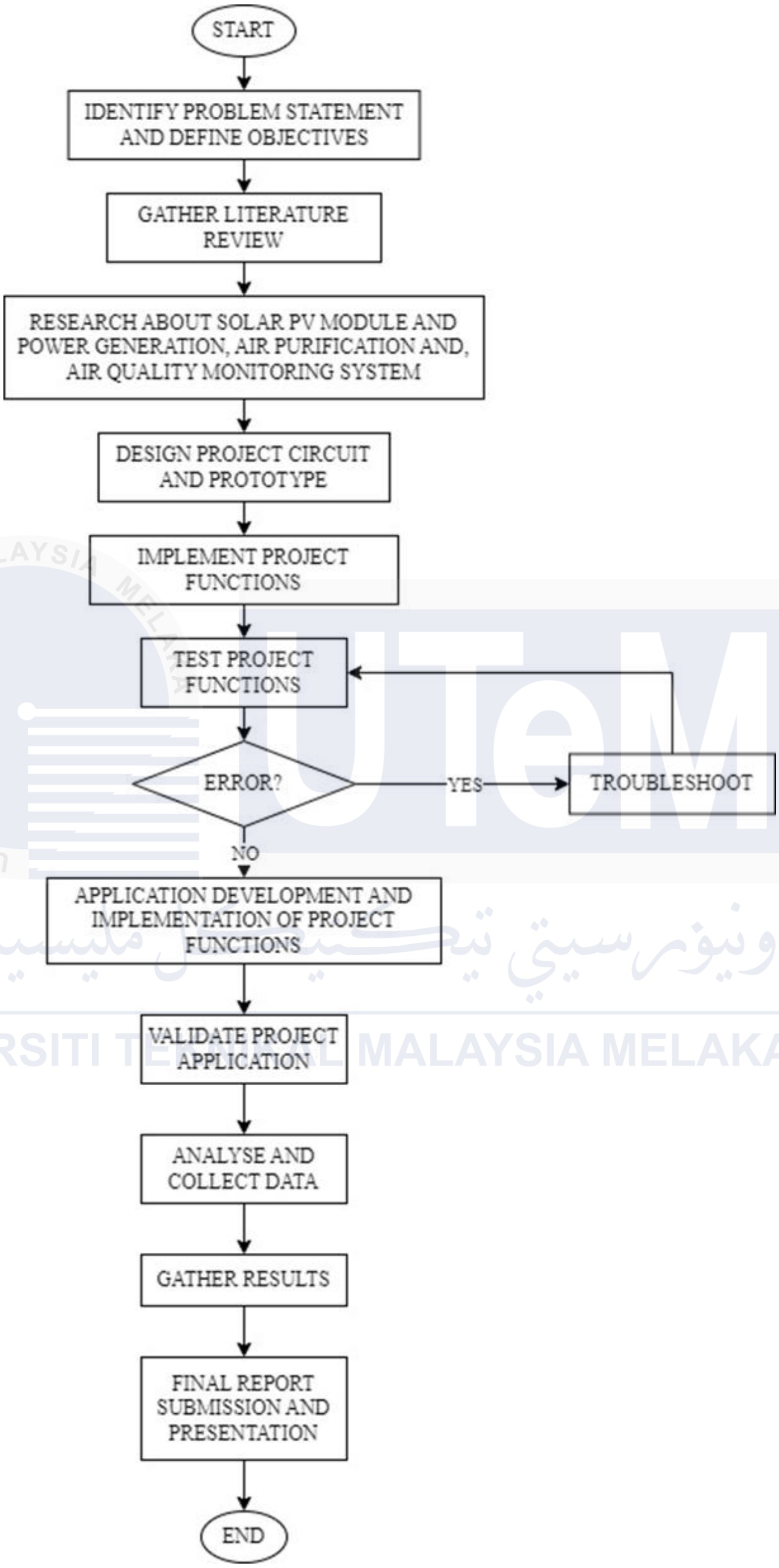



Figure 3.1 Flowchart of the whole project.

### 3.2.2 Project Flowchart

This project flowchart outlines the development of an outdoor air purification system powered by solar photovoltaic (PV) panels as shown in figure 3.2. The system incorporates an air quality monitoring system to assess real-time air quality.

The process begins with initializing the power generation module. This module controls the solar panels and ensures they are functioning correctly. The solar panels convert sunlight into direct current (DC) electricity.

For air quality monitoring, the system takes readings from a trio of calibrated sensors, each designed to measure a specific type of pollution. The first sensor, an MQ-135, is calibrated to detect carbon dioxide ($CO_2$) and other volatile organic compounds (VOCs), which are harmful airborne organic chemicals. The second sensor, an MQ-7, focuses on detecting carbon monoxide (CO), a dangerous gas commonly associated with vehicle emissions and incomplete combustion. The third sensor, an MQ-9, is optimized to detect methane ($CH_4$), a flammable gas that contributes to air pollution. Additionally, a SHARP GP2Y1014AU0F sensor is used to measure particulate matter such as dust and (PM) 2.5 – tiny particles that can penetrate deep into the lungs and pose significant health risks. A DHT11 sensor complements the setup by monitoring temperature and humidity, creating a comprehensive dataset for assessing air quality.

The readings from the MQ-135, MQ-7, MQ-9, and SHARP GP2Y1014AU0F sensors are typically in analog format, while the DHT11 sensor outputs digital readings. The system converts all analog data into digital format to ensure compatibility with the microcontroller for seamless processing.

The system compares the collected data to predetermined threshold values. If the readings are below the threshold values, indicating good air quality, the fan remains off.

Conversely, if any sensor readings exceed the threshold, signalling poor air quality, the fan is activated to improve air conditions.

This solar-powered outdoor air purification system with air quality monitoring demonstrates a potential solution to mitigating outdoor air pollution. The system's reliance on solar energy makes it sustainable, while the air quality monitoring system allows for real-time assessment of air quality.

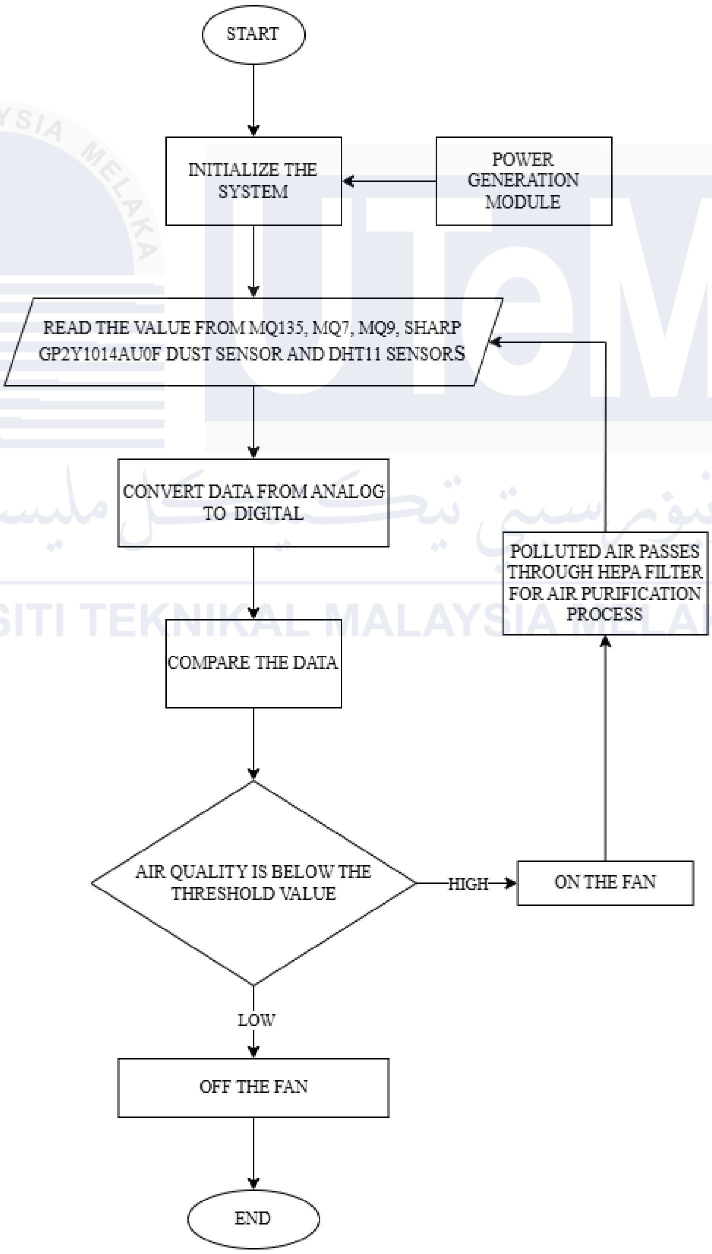



Figure 3.2 Flowchart of project functions.

## 3.3 Project Architecture

This is a block diagram depicting the operation of the project. According to the Figure 3.3, The solar panel harnesses solar radiation to generate power, which is then boosted by the solar charge controller to charge the battery. Once power is supplied to the Arduino Uno, the DHT11 and SHARP GP2Y1014AU0F Dust sensors initiate detection of harmful gases and dust particles in their vicinity [31],[32]. When the air quality is detected as very low by the MQ-135, MQ-7, and MQ-9 sensors it triggers a green-light indicator and activates an alarm. Subsequently, the fans are turned on, and they work to purify the surrounding air to the best of their capability. If the sensor data indicates that the air quality is within safe parameters, the fans are stopped, and a green light is displayed. This process repeats continuously. During daylight hours, the solar panel provides power for battery charging and circuit operation. In the absence of sunlight, the L298N Motor Driver is activated, and the circuit is powered by the battery. Utilizing solar power enhances the device's energy efficiency and environmental friendliness. It harnesses solar energy during daylight hours to both operate the air purification system and recharge any batteries present. Consequently, the device remains operational even in situations of power outages or in regions with restricted electricity access.

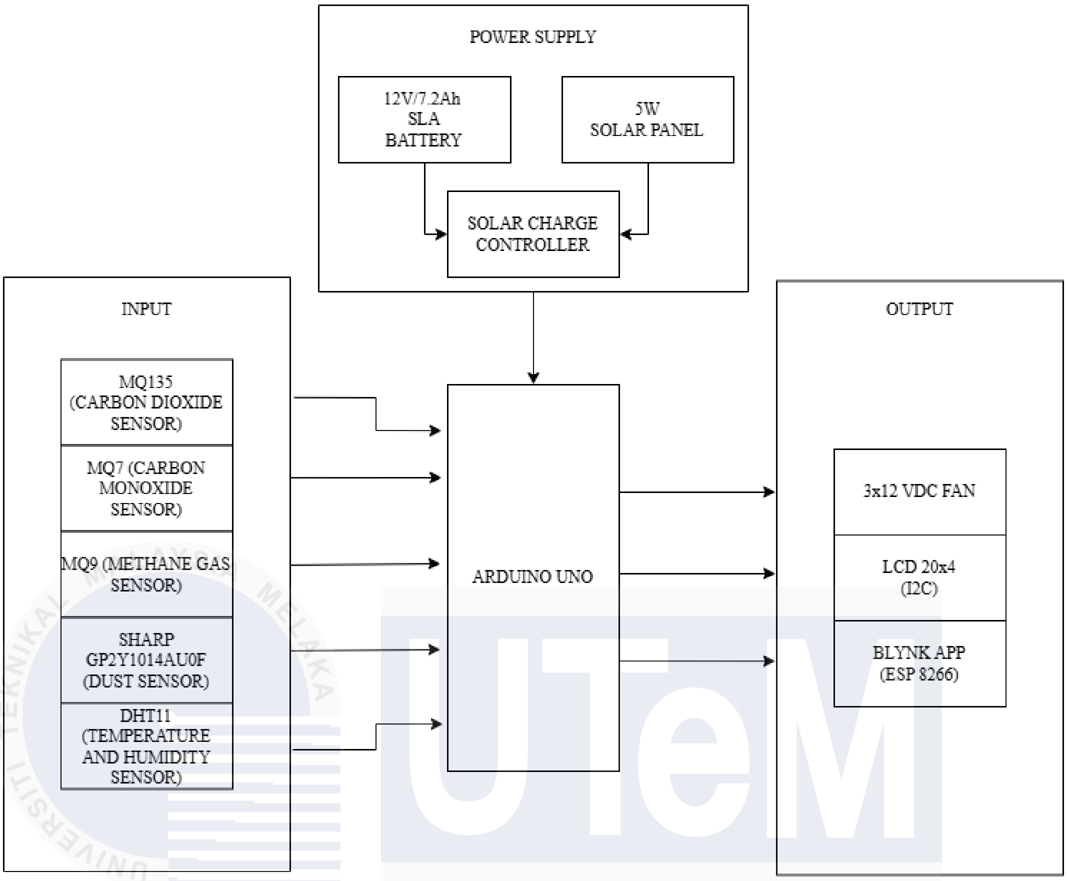



Figure 3.3 Project block diagram.

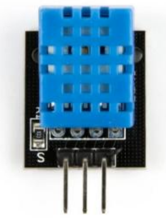
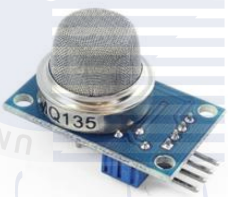
At its core, the system relies on a single solar panel for the generation of electrical energy, regulated by a solar charge controller to efficiently charge a battery for energy storage. Control and monitoring of the system are facilitated by an Arduino Uno microcontroller, which interfaces with various sensors including the DHT11 and SHARP GP2Y1014AU0F Dust sensors for real-time air quality monitoring. Additionally, an air inlet sensor is employed to trigger alerts and initiate actions in response to detected low air quality, signified visually through red and green light indicators and audibly through an alarm. The purification process is driven by a fan, activated when air quality is compromised, circulating, and purifying the surrounding air. Moreover, light-dependent resistor (LDR) sensing enables the system to adjust power sources between solar panels and batteries based on ambient light conditions. Crucially, voltage conversion is managed by a DC-DC converter, while a DC-AC inverter facilitates the conversion of battery power into usable AC power for devices within the system. This comprehensive array of components ensures the system's energy efficiency, environmental sustainability, and continuous operation, even in challenging conditions such as power outages or limited electricity access.

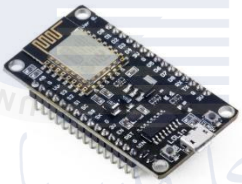
## 3.4 Component

In the pursuit of developing a groundbreaking project entitled "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System," meticulous efforts were undertaken to procure essential components within Malaysia's dynamic technological ecosystem. This endeavour encompassed the acquisition of pivotal elements crucial for the project's realization, including solar panels for sustainable energy generation, Arduino Nano microcontrollers for precise system control, DH11 and SHARP GP2Y1014AU0F Dust sensors for comprehensive air quality assessment, alongside strategic acquisitions of the MQ135 gas sensor and LCD 20x4 display. Each component acquisition not only facilitated the materialization of the project but also underscored Malaysia's commitment to technological advancement and environmental sustainability. Table 3.1 presents a comprehensive overview of the components essential for the implementation of the "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" project.

Table 3.1 Component used and their application.

| No. | Component | Quantity | Application | Description |
|---|---|---|---|---|
| **1** | 5W Solar Panel  | 1 | Power Generation | Converts solar radiation into electrical energy to power the system and charge batteries [29]. |
| **2** | Solar Charge Controller  | 1 | Power Regulation | Regulates the voltage and current from the solar panel to efficiently charge the batteries [24]. |
| **3** | 12V/7.2Ah SLA Battery  | 1 | Energy Storage | Stores excess energy from the solar panel for use during periods of low sunlight or at night [29]. |
| **4** | Arduino UNO  | 1 | Control and Monitoring | Microcontroller used for data processing, control of sensors, and monitoring air quality parameters [20]. |

| No. | Component | Quantity | Application | Description |
|---|---|---|---|---|
| **5** | DHT11 Humidity Sensor<br> | 1 | Air Quality Monitoring | Measures temperature and humidity levels in the surrounding air to assess air quality [20]. |
| **6** | SHARP GP2Y1014AU0F Dust Sensor<br> | 1 | Air Quality Monitoring | Detects harmful gases and dust particles in the air, providing real-time air quality data [27]. |
| **7** | MQ135 Gas Sensor<br> | 1 | Air Quality Monitoring | Detects various harmful gases in the air, such as carbon dioxide and benzene, to assess air quality [20]. |
| **8** | MQ7 Gas Sensor<br> | 1 | Air Quality Monitoring | Detects carbon monoxide (CO) with a 5V operating voltage, an analog output, and a range of 10–500 ppm, suitable for CO detection and air quality monitoring. |
| **9** | MQ9 Gas Sensor<br> | 1 | Air Quality Monitoring | Detects both carbon monoxide (CO) and combustible gases (methane, LPG) with a 5V operating voltage, analog output, and a range of 10–1000 ppm for CO and 100–10000 ppm for other gases, ideal for gas leak detection. |

| No. | Component | Quantity | Application | Description |
|---|---|---|---|---|
| **10** | 80x80 12VDC Fan   | 3 | Air Purification | Circulates and purifies the surrounding air to improve air quality when triggered by low-quality readings [20]. |
| **11** | LCD 20x4 w/I2C Controller  | 1 | Data Visualization | Displays real-time air quality data for user visualization and monitoring [20]. |
| **12** | Wi-Fi Module ESP-8266  | 1 | Wireless Connectivity | Enables wireless communication and data transmission, facilitating remote monitoring and control of the system. |
| **13** | Jumper Wires M-M, M-F  | - | Electrical Connections | Provide connections between various components for seamless electrical conductivity and communication. |
| **14** | Castor Wheel  | 4 | Project Mobility | A castor wheel is a small wheel mounted on a swivel frame, allowing objects to move easily in any direction. |

| No. | Component | Quantity | Application | Description |
|---|---|---|---|---|
| **15** | HEPA + Carbon Filter  | 1 | Air Purification | A HEPA filter catches tiny particles like dust and pollen, while a carbon filter gets rid of odours and gases [6]. |

## 3.5 Project Quotation

In the realm of sustainable technology, the project titled "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" emerges as a beacon of innovation and environmental consciousness. This endeavour epitomizes a holistic approach towards addressing pressing issues of air quality and energy sustainability. By harnessing the power of solar photovoltaics and integrating cutting-edge sensor technologies, the project aims to create a robust system capable of purifying outdoor air while providing real-time monitoring of air quality parameters. Grounded in principles of sustainability and technological ingenuity, this project embodies a proactive response to the challenges posed by environmental degradation and underscores the imperative of advancing towards a cleaner, greener future. Table 3.2 shows the quotation of project. The investment made in this project reflects a commitment to sustainability, with the allocated funds utilized judiciously to procure essential components, conduct research and development, and ensure the successful implementation of the innovative solution.

Table 3.2 Quotation of project.

| No. | Component | Description | Quantity | Estimated Cost (RM) |
|---|---|---|---|---|
| **1** | 5W Solar Panel | RM 58.00 / piece | 1 | 58.00 |
| **2** | Solar Charge Controller | RM 25.00 / set | 1 | 25.00 |
| **3** | 12V/7.2Ah SLA Battery | RM 45.00 / set | 1 | 45.00 |
| **4** | Arduino UNO | RM 38.00 / set | 1 | 38.00 |
| **5** | DHT11 Humidity Sensor | RM 12.50 / piece | 1 | 12.50 |
| **6** | SHARP GP2Y1014AU0F Dust Sensor | RM 40.00 / piece | 1 | 40.00 |
| **7** | MQ135 Gas Sensor | RM 12.00 / piece | 1 | 12.00 |
| **8** | MQ7 Gas Sensor | RM 12.00 / piece | 1 | 12.00 |
| **9** | MQ9 Gas Sensor | RM 12.00 / piece | 1 | 12.00 |
| **10** | 80x80 12VDC Fan | RM 9.50 / piece | 3 | 28.50 |
| **11** | LCD 20x4 w/I2C Controller | RM 38.00 / set | 1 | 38.00 |
| **12** | WiFi Module ESP-8266 | RM 25.00 / set | 1 | 25.00 |
| **13** | Jumper Wires M-M, M-F | RM 4.00 / set | 2 | 8.00 |
| **14** | 9mm Plywood | RM 3.80 / piece | 6 | 22.80 |
| **15** | Castor Wheel | RM 12.00 / set | 2 | 24.00 |
| **16** | HEPA + Carbon Filter | RM 35.90 / set | 1 | 35.90 |
| **17** | **Total =** | - | - | **436.7** |



## 3.6 Project Design

This section explains the project "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" prototype development to create a comprehensive solution. Tinker CAD software is employed for designing the physical prototype, integrating components such as a photovoltaic panel, air quality sensors, and an air purifier as shown in figure 3.4. The photovoltaic panel serves as the primary power source, converting solar energy into electricity for the system, while the air quality monitoring system measures pollutant levels in real-time, facilitating proactive intervention. The air purifier, utilizing multi-stage filtration, removes harmful pollutants, ensuring cleaner air. This innovative approach aligns form and function, promoting environmental sustainability and addressing outdoor air quality concerns effectively.

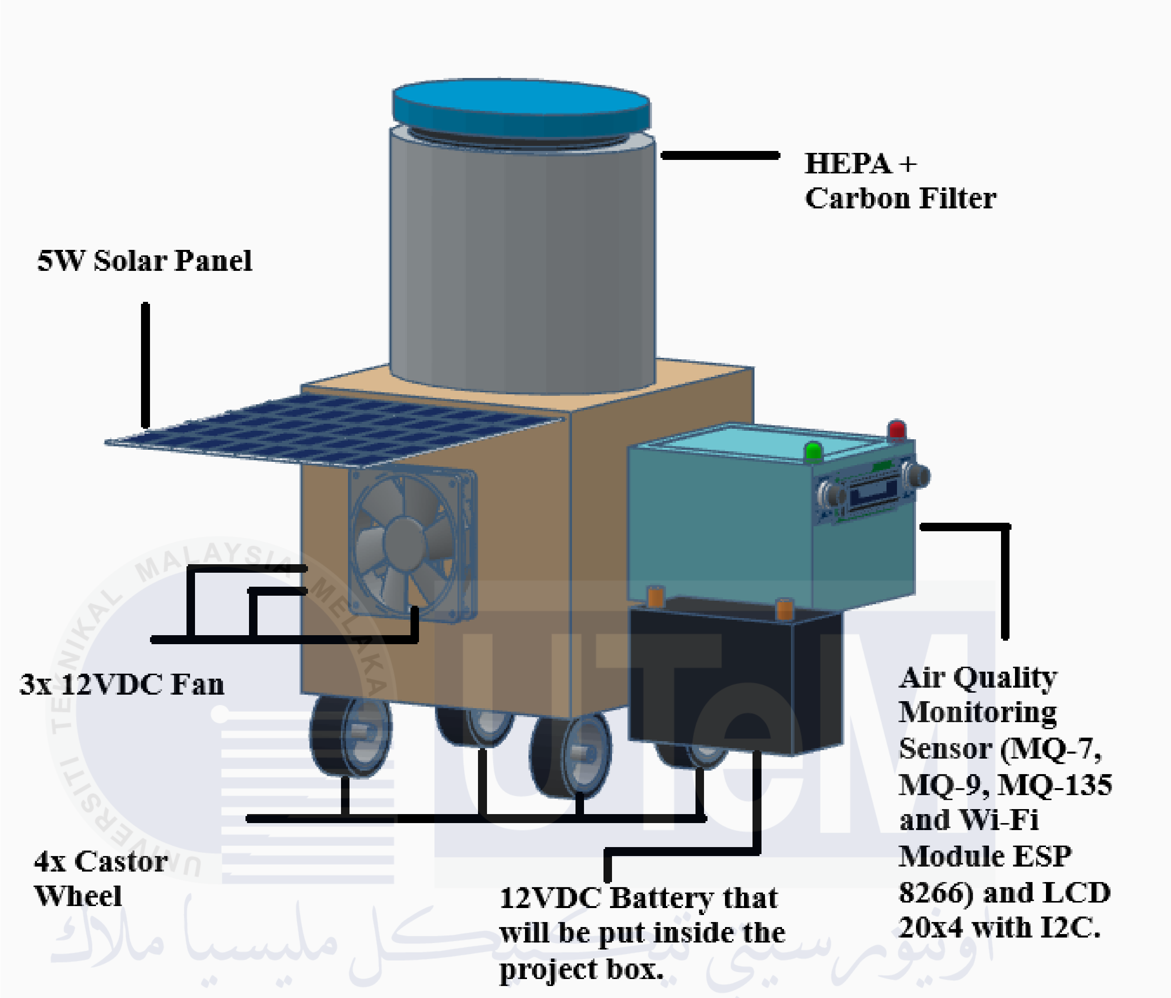



Figure 3.4 Project prototype of Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System using Tinker CAD software.

## 3.7 Hardware Analysis

This chapter discusses the components used in the project, their roles, and the testing methods employed. Each section examines the hardware's functionality, efficiency, and contributions to the overall system's objectives.

The hardware analysis chapter details the comprehensive examination of the system components used in this project, which include a 5W solar panel, battery charging mechanism, multiple air quality sensors, and a HEPA + Carbon filter. This chapter explores each component's role, methodology of testing, and analytical approach, contributing to an understanding of the system's efficiency, operational capacity, and suitability for outdoor air purification powered by solar energy.

The primary objectives of this analysis are to (1) evaluate the solar panel’s ability to produce sufficient power to run the purification system, (2) determine the battery charging duration, (3) assess the air quality levels based on pollutants detected by different sensors, and (4) measure the pollutant reduction effectiveness of the HEPA + Carbon filter. Each section addresses a specific component or test, examining both the methodology and the data collection approach.

### 3.7.1 5W Solar Panel Power Output Analysis

The 5W solar panel was tested to evaluate its ability to generate power under varying environmental conditions. This testing was conducted outdoors in Serendah, Selangor, where the panel was exposed to different levels of solar irradiance throughout the day. Data collection spanned multiple days to ensure accuracy and consistency in observations.

Solar irradiance was measured at intervals between 8:00 AM and 6:00 PM, with attention given to diverse weather conditions, such as sunny, cloudy, and partly cloudy skies. Voltage and current outputs were recorded during each interval, and these measurements were used to calculate power output. The analysis revealed that the solar panel performed optimally under clear skies, achieving a peak power output of 4.5W around midday. On average, the daily power output was calculated to be 2.80W. However, efficiency dropped significantly during overcast conditions, highlighting the dependency of solar panels on sunlight availability as shown in figure 3.5.

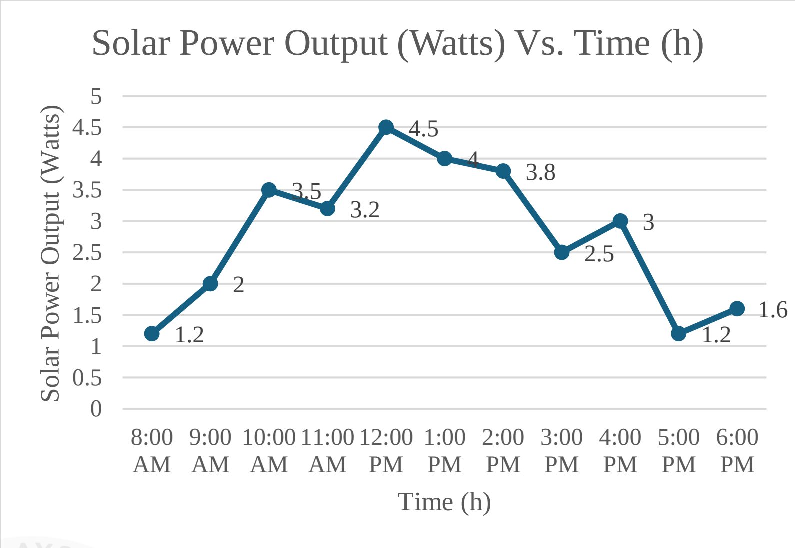



Figure 3.5 Solar panel power output at different times of the day.

The power output was calculated using the standard formula:

$$Power(W) = Voltage(V)\ x\ Current(A) \tag{3.1}$$

### 3.7.2 Solar Charging Duration by Using 5W Solar Panel Analysis

The analysis focuses on the charging performance of the 12V Sealed Lead Acid (SLA) Battery using the solar panel and solar charge controller. The battery voltage chart was used as a reference to determine the battery's State of Charge (SOC).

#### 3.7.2.1 Battery Voltage and State of Charge (SOC)

The SLA battery voltage chart, shown in Figure 3.6, provides crucial reference points for interpreting the battery's charge level:

- 12.89V: Fully charged (100% SOC).
- 12.41V to 12.78V: Moderate charge levels (60% to 90% SOC).

- 11.96V: Low charge level (30% SOC).
- 11.63V and below: Fully discharged (0% SOC).

| 12V Sealed Lead Acid Battery Voltage Chart | |
|---|---|
| **Voltage** | **Capacity** |
| 12.89V | 100% |
| 12.78V | 90% |
| 12.65V | 80% |
| 12.51V | 70% |
| 12.41V | 60% |
| 12.23V | 50% |
| 12.11V | 40% |
| 11.96V | 30% |
| 11.81V | 20% |
| 11.70V | 10% |
| 11.63V | 0% |

Figure 3.6 SLA battery voltage chart.

The charging process commenced at various initial voltage levels, with real-time measurements logged to observe changes over time. The solar charge controller effectively managed the flow of current and voltage, protecting the battery from overcharging and excessive discharge.



#### 3.7.2.2 Methodology of Solar Charging Duration Analysis

1. **Setup:** A 12V SLA battery was connected to the solar charge controller, which facilitated efficient charging and displayed real-time battery voltage. An Arduino microcontroller and sensors monitored the charging current and battery voltage at hourly intervals.
2. **Measurements:** Battery voltage was recorded starting from 11.60V (0% SOC) at the beginning of the test and continued until it reached 12.90V (100% SOC)

over an 8-hour duration. The charging current was also logged to determine the rate of energy transfer to the battery.

3. **Reference Chart:** The SLA battery voltage chart was used to correlate the recorded voltage with the battery's capacity percentage (SOC).

#### 3.7.2.3 Findings of Solar Charging Duration Analysis

- **Battery Voltage and Capacity:** At the beginning of the charging process, the battery voltage was 11.60V, corresponding to 0% SOC. As the solar charging continued, the battery voltage gradually increased, reaching 12.90V after 8 hours, signifying a full charge (100% SOC).
- **Charging Current:** The charging current started at an average of 4.0A and increased progressively, peaking at 6.0A when the battery was nearly full. The average current throughout the charging process was approximately 5.11A.
- **Charging Duration:** The battery charging performance aligns with the expected SLA voltage behavior. The solar charge controller effectively managed the charging process, slowing the current as the battery neared full capacity to prevent overcharging and reduce internal resistance.

The solar charge controller played an important role by dynamically adjusting the input current based on sunlight conditions and displaying real-time voltage readings. This feedback was critical for ensuring the battery's health and monitoring its progression towards full charge.

### 3.7.2.4 Graph and Analysis of Solar Charging Duration

A graphical representation of the charging chart, illustrating voltage vs. time, highlights the non-linear charging process. Early-stage charging showed a steep slope, while the chart flattened as the battery approached full charge as shown in figure 3.7.

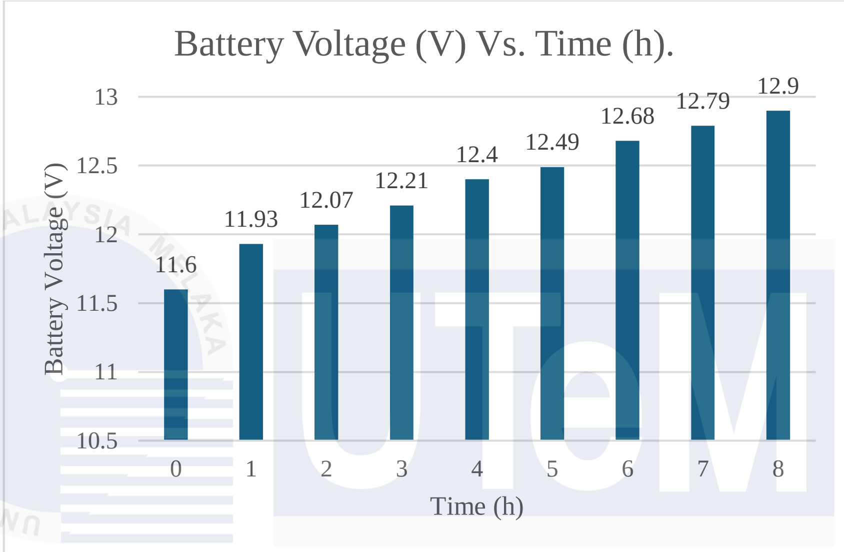



Figure 3.7 Charging curve showing voltage vs. time.

In summary, the integration of the solar charge controller and reference to the SLA battery voltage chart ensured a reliable and efficient charging process, optimized for the system's solar power capabilities. Furthermore, figure 3.8 shows charging curve showing voltage levels.

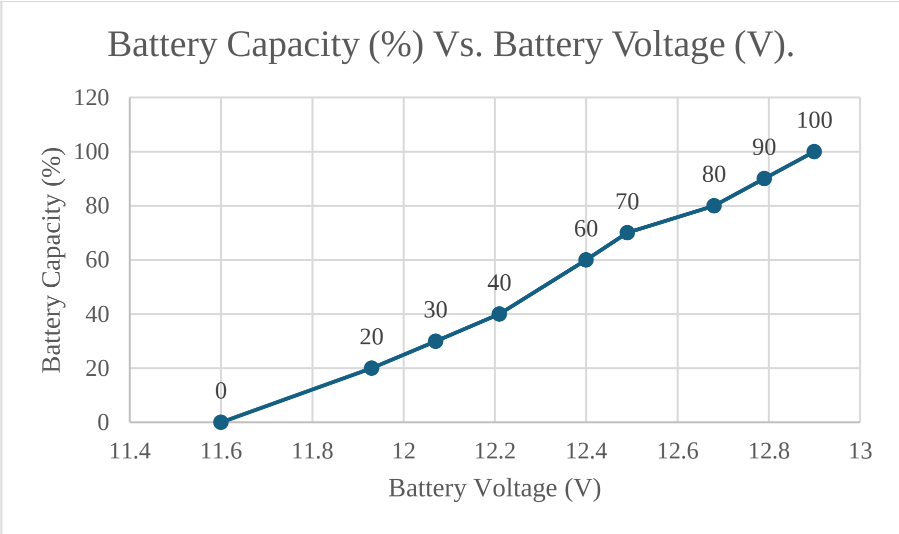



Figure 3.8 Charging curve showing voltage levels.

### 3.7.3 Exposure Level Measured by MQ135, MQ7, MQ9, and Sharp GP2Y1014AU0F Dust Sensor Using Arduino IDE Serial Monitor

To monitor exposure level, four sensors were used, each calibrated to detect a specific pollutant. These sensors included the MQ135 for Carbon Dioxide ($CO_2$), MQ7 for Carbon Monoxide (CO), MQ9 for Methane ($CH_4$), and the Sharp GP2Y1014AU0F Dust Sensor for particulate matter.

Table 3.3 summarizes the permissible exposure levels (measured in parts per million, ppm, or micrograms per cubic meter, $\mu g/m^3$) and corresponding effects of three key gases—carbon monoxide (CO), carbon dioxide ($CO_2$), and methane ($CH_4$)—along with dust particles detected by the GP2Y1014AU0F Dust Sensor. The data presented in this table is based on standards and guidelines from authoritative sources such as OSHA, WHO, EPA, and NIOSH. Each gas or dust particle's safety level is categorized into different thresholds, ranging from normal to extremely dangerous, based on its impact on human health and safety. For carbon monoxide (CO), levels below 9 ppm are considered normal and safe for outdoor environments. As the concentration increases, the effects range from mild discomfort to life-threatening conditions. Carbon dioxide ($CO_2$) levels of 400 ppm are typical for outdoor air, while indoor concentrations above 1,000 ppm can lead to poor air quality and health risks. Methane ($CH_4$), although non-toxic at lower concentrations, becomes flammable and potentially explosive when it exceeds 5% (50,000 ppm) in enclosed spaces. The GP2Y1014AU0F Dust Sensor measures particulate matter, where levels below 0.075 mg/m³ are considered normal, while levels exceeding 0.3 mg/m³ are hazardous to human health. This table provides a concise reference for assessing air quality and ensuring safety, particularly in environments where these gases or dust particles are commonly present.

Table 3.3 Permissible exposure levels.

| **Gas/Sensor** | **PPM Level** | **Effects** |
|---|---|---|
| **Carbon Monoxide (CO)** | 0-9 ppm | Normal [1] |
| | 10-50 ppm | Above Normal [1] |
| | 51-200 ppm | Poor Air Quality [1] |
| | 201-400 ppm | Very Dangerous [1] |
| | 400+ ppm | Extremely Dangerous [1] |
| **Carbon Dioxide ($CO^2$)** | 0-599 ppm | Normal [9] |
| | 600-1000 ppm | Above Normal [9] |
| | 1001-2000 ppm | Poor Air Quality [10] |
| | 2001-5000 ppm | Dangerous [11] |
| | 5000+ ppm | Extremely Dangerous [11] |
| **Methane Gas ($CH_4$)** | 0-5000 ppm | Normal [20] |
| | 5001-50000 ppm (5%) | Flammable [21] |
| | 50000+ ppm (above 5%) | Explosive [22] |
| **GP2Y1014AU0F Dust Sensor** | 0-0.075 mg/m³ | Normal [31] |
| | 0.076-0.15 mg/m³ | Above Normal [32] |
| | 0.16-0.3 mg/m³ | Poor Air Quality [1] |
| | 0.3+ mg/m³ | Dangerous [1] |

The MQ135 sensor measured $CO_2$ concentrations in parts per million (ppm) by detecting changes in electrical resistance caused by $CO_2$ gas interactions with the sensor's surface. These resistance changes were processed as voltage signals and converted into ppm using calibration formulas provided in the datasheet. So to measure the appropriate $CO_2$

concentration values, you have to replace the 1KΩ resistor with a 22KΩ resistor as shown in figure 3.9 circuit schematic.

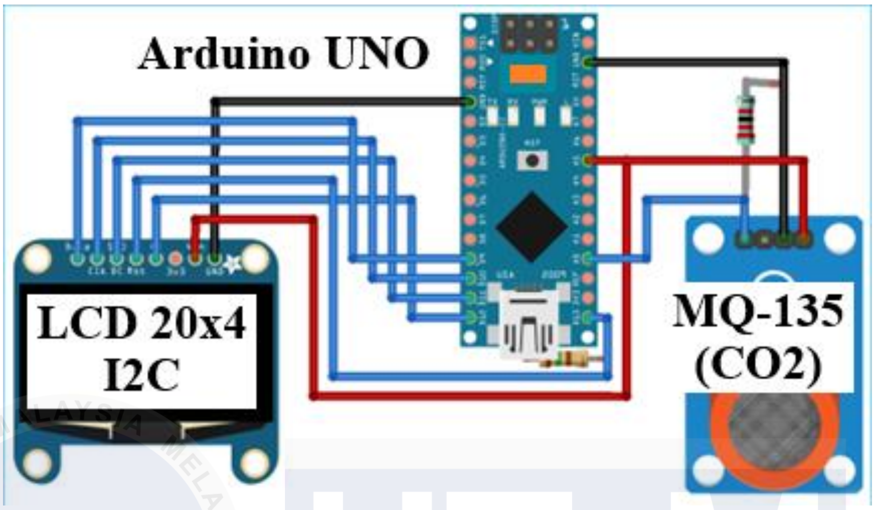



Figure 3.9 MQ135 circuit schematic.

The MQ7 sensor detected CO concentrations, leveraging a dual heating mode to improve accuracy. CO presence influenced the internal resistance of the sensor, and this resistance variation was processed to determine ppm values. The dual heating mechanism reduced interference from other gases, making it highly effective for CO detection. Figure 3.10 shows average CO levels over 8 hours (Weekdays Vs. Weekends).

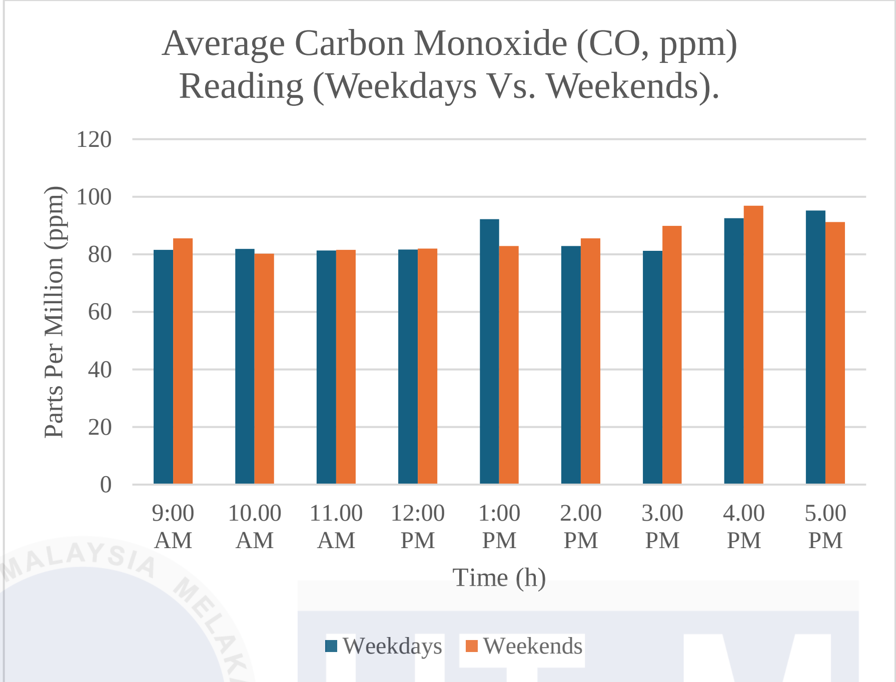



Figure 3.10 Average CO levels over 8 hours (Weekdays Vs. Weekends).

Methane concentrations were measured using the MQ9 sensor, which calculated $CH_4$ levels based on resistance changes. When methane interacted with the sensor, it altered its resistance, which was then converted to ppm using a resistance-to-ppm relationship defined in the datasheet. This sensor effectively detected methane spikes associated with human activities such as cooking or industrial emissions. Figure 3.11 shows average $CH_4$ levels over 8 hours (Weekdays Vs. Weekends).

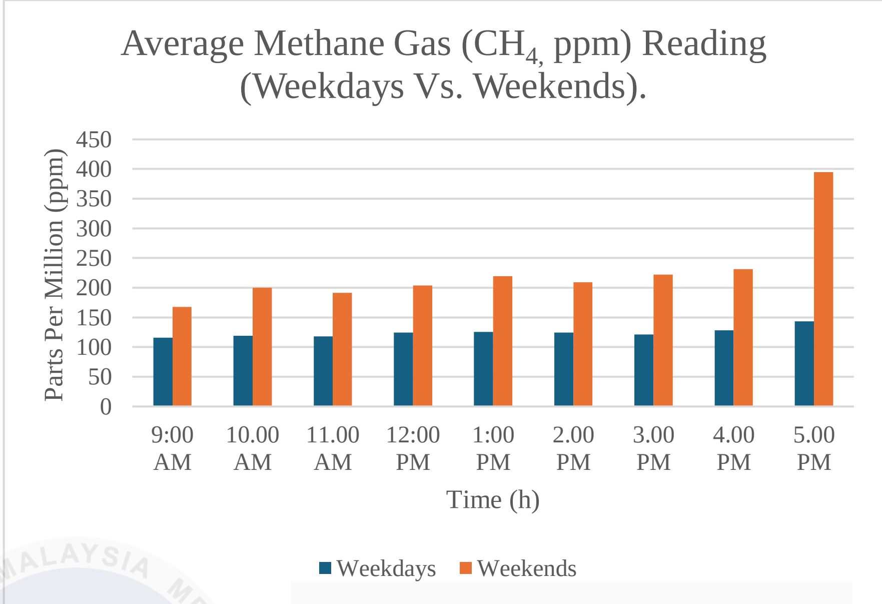



Figure 3.11 Average $CH_4$ levels over 8 hours (Weekdays Vs. Weekends).

For particulate matter, the Sharp GP2Y1014AU0F Dust Sensor was used to measure dust concentration levels in milligrams per cubic meter ($mg/m^3$). This sensor employs optical scattering technology, where light is emitted inside the sensor and scattered by particulate matter in the air. The scattered light intensity is detected by a photodiode, which quantifies the concentration of dust in the environment. This method provides accurate and real-time measurements of fine particulate matter levels.

All sensors were mounted at a fixed outdoor location and connected to an Arduino microcontroller for real-time data acquisition as shown in figure 3.12. Hourly readings were recorded to track fluctuations in pollutant concentrations, providing insights into temporal variations influenced by environmental and human activities as shown in figure 3.13.

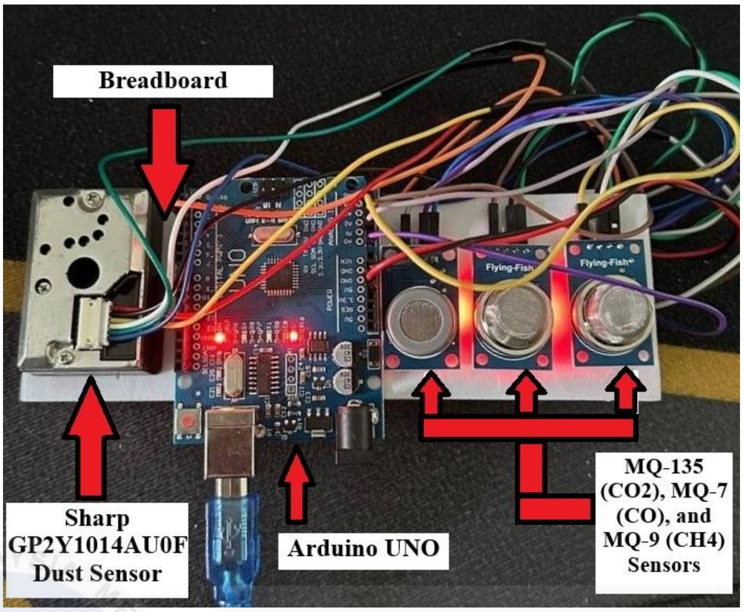



Figure 3.12 Complete sensor setup for air quality monitoring.

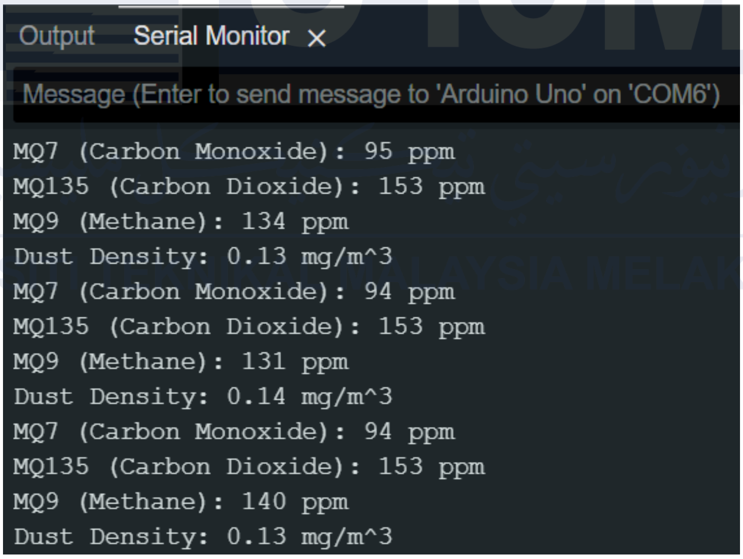



Figure 3.13 Average readings taken from each sensors observed on Arduino IDE serial monitor.

### 3.7.4 HEPA + Carbon Filter Effectiveness

Finally, to determine the system's air purification effectiveness, we evaluated the HEPA + Carbon filter's ability to reduce pollutant concentrations. The HEPA filter captures particulate matter, while the carbon filter absorbs gaseous pollutants, making this combination effective for outdoor applications with mixed contaminants.

Testing involved taking pollutant readings before and after passing air through the filter. Each pollutant ($CO_2$, CO, $CH_4$, and dust) was measured to quantify the reduction percentage achieved by the filtration process. This setup allowed us to calculate the filter's efficiency using the formula for percentage reduction:

$$Reduction(\%) = \frac{(Before - After)}{Before} \, x \, 100 \tag{3.2}$$



This analysis provides quantitative evidence of the filter's capacity to improve air quality by removing harmful pollutants from the ambient air. The data illustrates the filter's effectiveness under typical conditions encountered at the test site, emphasizing its value in enhancing the system's impact on air quality.

This completes the analysis of hardware components, each tailored to assess the performance, efficiency, and effectiveness of the outdoor air purification system powered by a small solar panel as shown in figure 3.14.

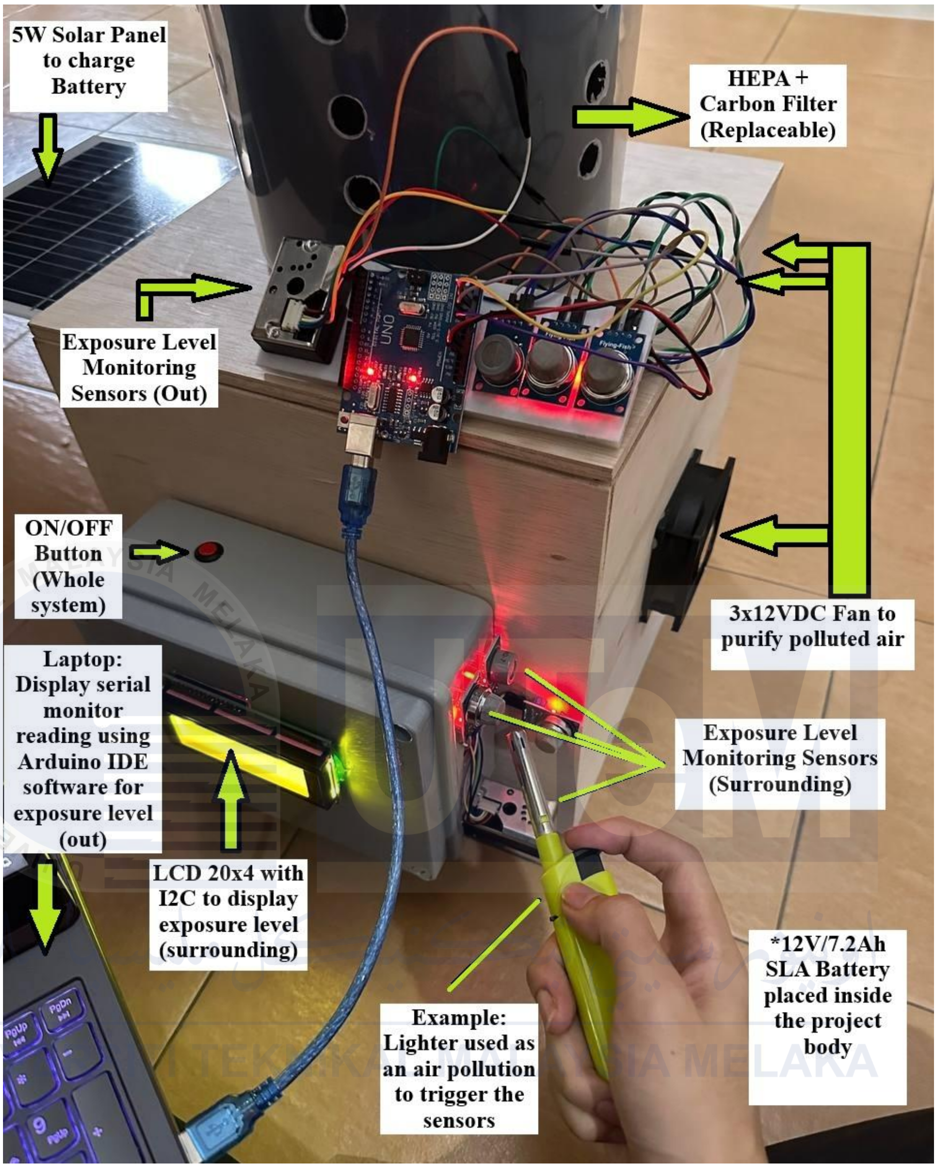



Figure 3.14 Complete sensor setup for HEPA + Carbon Filter effectiveness.

### 3.8 Gantt Chart

The Gantt Chart illustrated the progression of the project schedule in terms of date and task, thereby ensuring that the project stays on track. Time management is more effective and conducive when it is planned from the outset.

| No. | Task/ | PSM1 | | | | | | | | | | | | | | PSM2 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 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 confirmative and registration | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | Briefing with supervisor | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | Study the project background | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | Drafting Chapter 1: Introduction | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | Task progress evaluation | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | Drafting Chapter 2: Literature Review | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8 | Table of 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 | Report submission to the panel | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 14 | Presentation pf BDP1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 15 | Drafting Chapter 4: Analysis Data and Result | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 16 | Data Analysis and Results | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 17 | Record the result | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 18 | Drafting Chapter 5: Conclusion and Recommendation | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 19 | Compiling Chapter 4 and Chapter 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 20 | Submit the report to supervisor | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 21 | Finalise the report | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 22 | Presentation pf BDP2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

## 3.9 Summary

This chapter presents the methodology for the development and deployment of the Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System, which combines renewable energy and air purification technologies to address environmental concerns. The methodology focuses on the step-by-step approach required to achieve the project's objectives, starting with system design and continuing through integration and testing. It includes the identification and selection of key components, such as the solar panel, air purification system, and air quality sensors, to ensure optimal functionality. To evaluate the system's feasibility and performance, a thorough hardware analysis was conducted. The analysis primarily focused on assessing the solar panel's power output, battery charging duration, and the efficiency of the air filtration system. The solar panel's performance was tested under typical sunny conditions, producing an average daily output of 2.80 watts, which was sufficient to power the system. The battery charging process was analyzed in two phases, with a complete charge achieved within 8 hours, confirming the system's capability to operate on solar power for extended periods. In terms of air quality monitoring, the system was tested for its ability to detect and quantify various pollutants. The air filtration system, incorporating a combination of HEPA and Carbon filters, was subjected to pollutant reduction tests. The results indicated that the filtration system effectively reduced dust levels by 62.5% (mg/m$^3$), methane by 42.9%, carbon monoxide (CO) by 40%, and carbon dioxide ($CO_2$) by 33.3%. These reductions confirm the system's efficiency in purifying air and its potential to address air quality concerns in environments with significant pollution. The real-time air quality monitoring system was also analyzed for its ability to continuously measure air quality parameters, providing valuable data for users to monitor pollution levels. The combined results of these analyses validate the system's ability to deliver sustainable air purification and continuous monitoring, making it suitable for use in high-pollution areas or regions with limited access to grid power. A flowchart was created to provide a visual representation of the system's sequential processes, from the solar panel's energy generation to the air purification and monitoring stages. This flowchart outlines the key milestones and steps involved in deploying the system. Additionally, a block diagram was included to showcase the operational framework of the system, clearly illustrating how the individual components work together to achieve the desired outcomes. This chapter serves as a comprehensive guide to understanding the implementation process and the system's potential to provide an innovative solution to environmental challenges.

# CHAPTER 4

# RESULT AND ANALYSIS

## 4.1 Introduction

This chapter will provide an in-depth exploration of the progress and outcomes of the "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" project. It will comprehensively detail the entire system. This section discusses many of the obstacles and advancements that are faced as the project developed. Furthermore, it will elucidate the expected outcomes and limitations inherent in the system's design and implementation. Additionally, this chapter will delve into the testing and analysis of the system's application, highlighting the output results and the influence of the application on varying input parameters. Through rigorous testing and analysis, this chapter aims to provide valuable insights into the performance and efficacy of the innovative system in purifying outdoor air while monitoring air quality, thereby contributing to a deeper understanding of its practical implications and potential for real-world deployment.

## 4.2 Results and Analysis

The solar-powered air purification unit integrates a Light Dependent Resistor (LDR) to switch power sources between solar panels and batteries based on sunlight availability, ensuring continuous operation. Sensor readings, including dust levels, temperature, humidity, and gas concentrations, are displayed on an LCD screen, with the system activating fans and adjusting filtration based on detected air quality. The photovoltaic panel generates electricity for daytime use and charges the battery for nighttime operation. Air quality monitoring relies on various sensors detecting pollutants like PM2.5, PM10, CO, NO2, and VOCs, with data analysed by a microcontroller and displayed in real-time. The air purifier employs a multi-stage filtration system, consisting of a pre-filter, HEPA filter, and activated carbon filter, to remove particles and odours from the air, with adjustable fan speeds for user preference. Parts per million (ppm) is the unit used to measure air quality, indicating the concentration of pollutants in the air relative to the total volume of air. Additionally, there are two sets of results obtained: one from Proteus simulation and the other from manual testing, providing comprehensive validation of the system's performance.

### 4.2.1 Proteus Simulation by Using Arduino IDE

This section will utilize an MQ135 air quality sensor, DHT11 for temperature and humidity readings, and an LCD 20x4 display, presenting a cost-effective solution for real-time air quality monitoring. The code consists of two main functions: "sendSensor()" retrieves temperature and humidity data using the DHT library and displays it on the LCD 20x4, while "air_sensor()" reads analogue values from the air quality sensor, assigning corresponding quality levels based on predefined thresholds. Proper calibration of the air quality sensor is essential, requiring a 24-hour "burn-in" period to clean the sensor for accurate results. Gas level values may need adjustment based on environmental conditions, achieved through initial outdoor testing and calibration. It's worth noting that the coding was done using Arduino IDE software and validated through simulation in Proteus software. Figure 4.1 depicts the coding for air quality monitoring using the Arduino IDE.

```
#include <LiquidCrystal.h>
#include <dht.h>

#define DHTPIN 2          // Digital pin 2
#define DHTTYPE DHT11     // DHT 11

#define sensor A0
#define LCD_COLS 20
#define LCD_ROWS 4

LiquidCrystal lcd(12, 11, 5, 4, 3, 2); // RS, E, D4, D5, D6, D7

int gasLevel = 0;         //int variable for gas level
String quality = "";
dht DHT;

void sendSensor()
{
  float h = DHT.humidity;
  float t = DHT.temperature;

  lcd.setCursor(0, 2);
  lcd.print("Temp  : ");
  lcd.print(t);
  lcd.print(" C");

  lcd.setCursor(0, 3);
  lcd.print("RH    : ");
  lcd.print(h);
  lcd.print("%");
}

void air_sensor()
{
  gasLevel = analogRead(sensor);

  if (gasLevel < 181) {
    quality = " AQ Level low";
  }
  else if (gasLevel > 181 && gasLevel < 225) {
    quality =  "  Poor!";
  }
  else if (gasLevel > 225 && gasLevel < 300) {
    quality = "Very bad!";
  }
  else if (gasLevel > 300 && gasLevel < 350) {
    quality = "ur dead!";
  }
```

```
  else {
    quality = " AQ Level HIGH";
  }

  lcd.setCursor(0, 0);
  lcd.print("Air Quality:");
  lcd.setCursor(0, 1);
  lcd.print(quality);
}

void setup() {
  Serial.begin(9600);
  lcd.begin(LCD_COLS, LCD_ROWS);
  lcd.clear();
  lcd.setCursor(4, 0);
  lcd.print("Air Quality");
  lcd.setCursor(3, 2);
  lcd.print("Quality monitor");
  delay(2000);
  lcd.clear();
}

void loop() {
  lcd.clear();
  air_sensor();
  sendSensor();
  delay(2000);
}
```

Figure 4.1 Air quality monitoring code.

#### 4.2.1.1 High Air Quality Level Detection and Alert Mechanism

In this system, air quality is assessed in terms of parts per million (ppm). If the ppm exceeds a predetermined threshold, the LED flashes, the buzzer activates, and "AQ LEVEL HIGH" is displayed, indicating high levels of particulate matter and impurities in the air, signalling the need for purification as shown in figure 4.2.

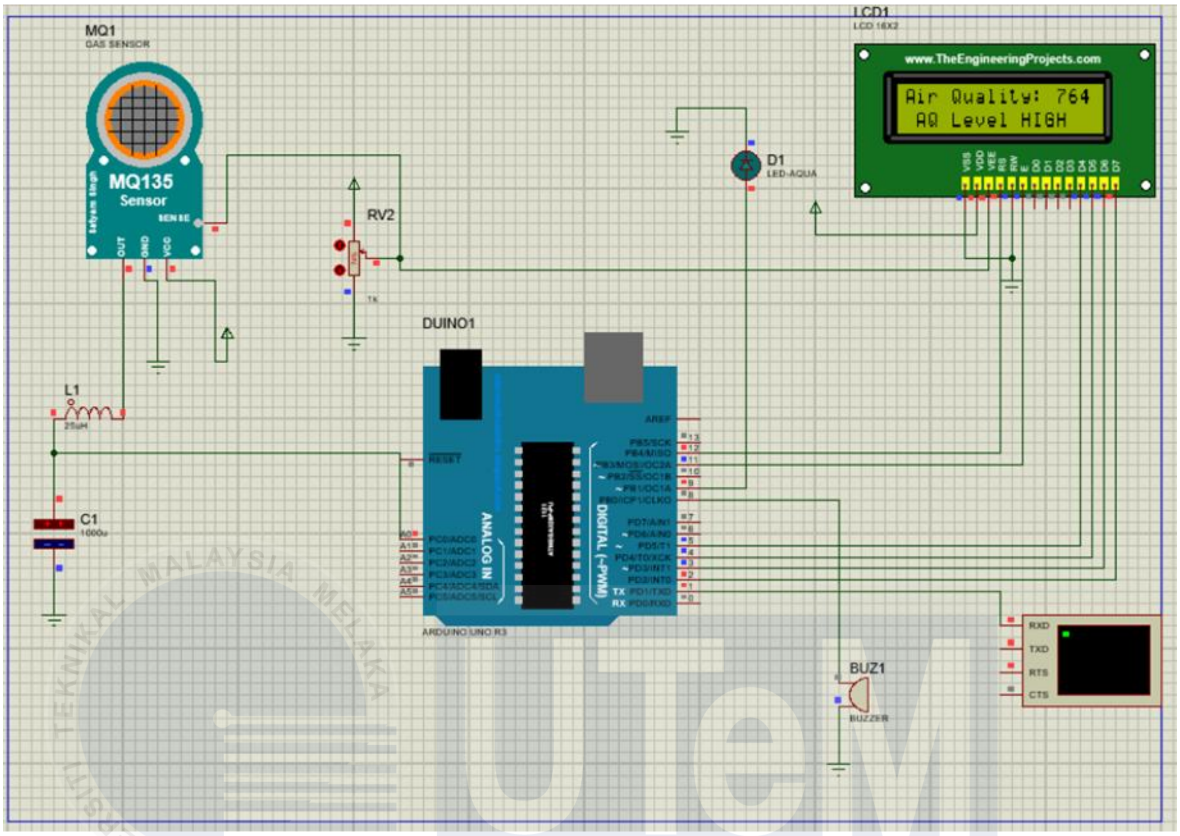



Figure 4.2 Shows the example of an air purifier needs to be activate.



#### 4.2.1.2 Low Air Quality Level Detection and Status Indication

When the ppm falls below the set threshold, the LED is switched off, the buzzer activates, and "AQ LEVEL LOW" is displayed, indicating that the particulate matter is low and the air is relatively clean, thus indicating no need for purification as shown in figure 4.3.

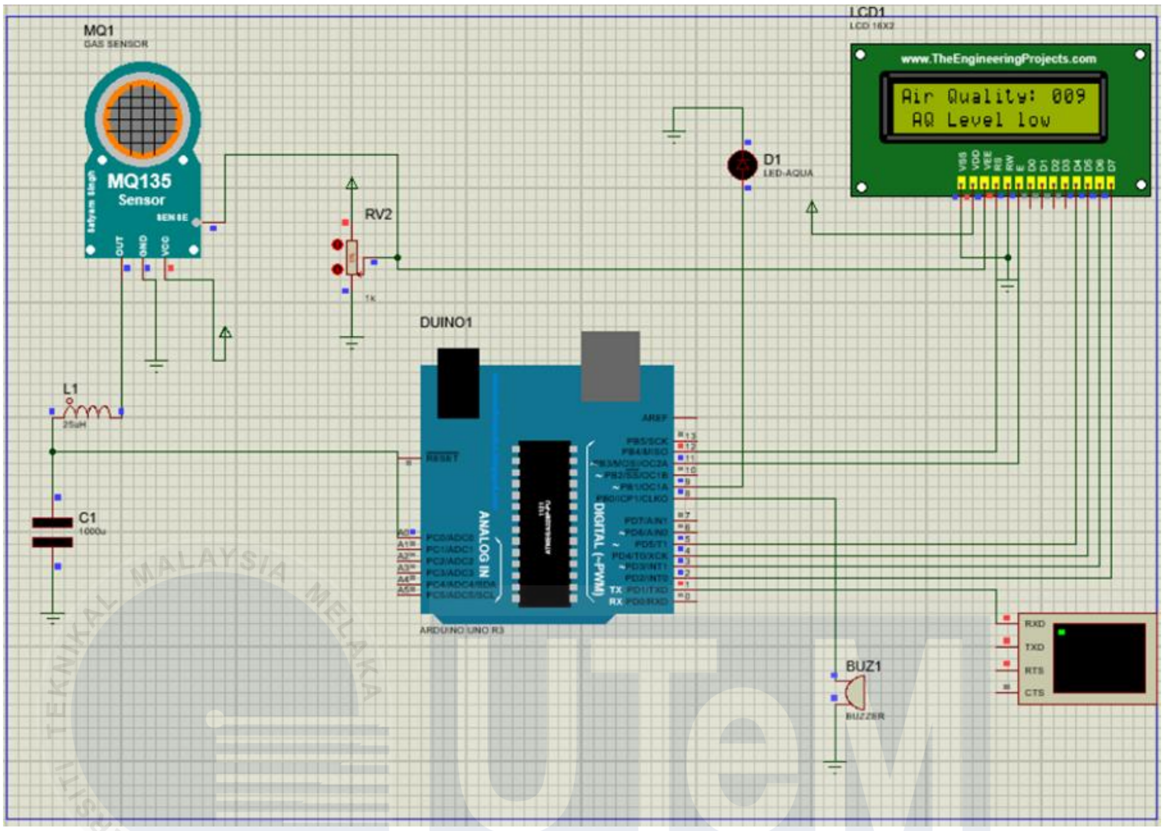



Figure 4.3 Shows the example of an air purifier does not need to be activate.

### 4.2.2 Manual Testing

The values depicted in the chart represent actual readings from the air-quality sensor, ranging from 0 to 300 ppm. In terms of breathable clean room air, it typically contains up to 10% or approximately 20 ppm of air quality sensor readings [33]. To assess the sensor's accuracy, a smoke concentration of around 200 ppm was artificially generated within a home environment. These readings were obtained from an MQ135 air quality sensor positioned at the rear of the purifier, capturing the quality of polluted air entering the purifier, and another sensor placed at the front, measuring the quality of purified air released from the purifier as shown in table 4.1 and figure 4.4. Additionally, figure 4.5 shows test result using matches on burned paper.

Table 4.1 Air quality readings from polluted air going in and out using matches on burned paper.

| **Polluted Air In (ppm)** | **Polluted Air Out (ppm)** |
|---|---|
| 20.0 | 18.4 |
| 20.6 | 18.0 |
| 20.8 | 19.3 |
| 23.0 | 19.4 |
| 23.9 | 18.2 |
| 35.7 | 18.5 |
| 42.5 | 19.4 |
| 79.9 | 19.4 |
| 41.0 | 19.0 |
| 195.0 | 19.6 |
| 108.0 | 19.7 |
| 87.0 | 21.0 |
| 86.0 | 22.3 |
| 43.0 | 22.2 |
| 52.0 | 22.5 |
| 112.0 | 27.0 |
| 109.0 | 28.0 |
| 148.0 | 25.0 |
| 181.0 | 23.0 |
| 178.0 | 24.0 |
| 205.0 | 23.0 |
| 117.0 | 24.0 |
| 133.0 | 22.0 |
| 203.1 | 21.0 |

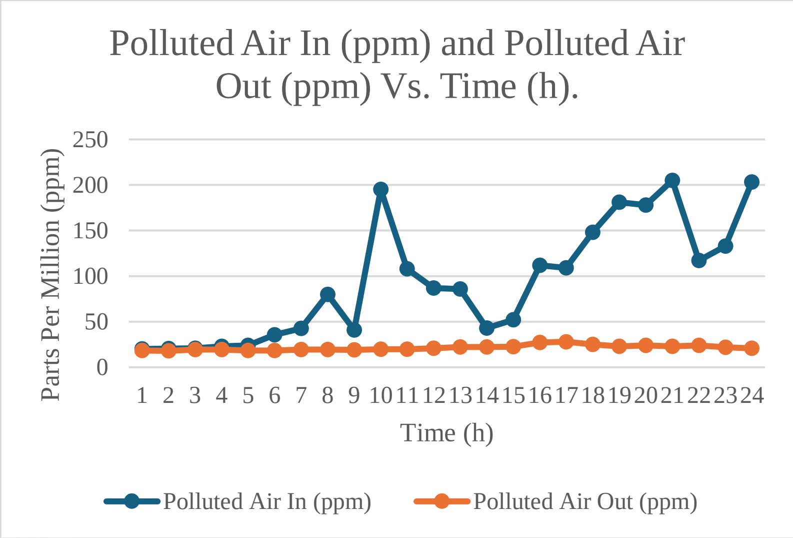



Figure 4.4 Air quality results from fabricated air purifier.


Figure 4.5 Test result using matches on burned paper.

The maximum air index value recorded is 205 ppm, with the corresponding filter air index value estimated at 18 ppm, factoring in an approximate 6 ppm error due to polluted air interference. This suggests an air purification percentage of approximately 92%, calculated as ((205-18)/205)*100. This solar-powered air purifier is designed not only to deliver clean air but also to address concerns about excessive electricity consumption. Operating for up to

14 hours on an average day with 5 to 6 hours of sunlight, it offers an efficient solution, particularly in areas without access to electricity. Additionally, it can be adapted into a portable unit and remotely controlled. Further enhancements, such as temperature-controlled cooling using a DHT11 sensor and a timed fragrance dispenser, contribute to its versatility, making it an attractive, cost-effective option in the market.

### 4.2.3 Complete Circuit Diagram

During daylight hours, the Light Dependent Resistor (LDR) detects sunlight, allowing the input power for battery charging and circuit operation to be sourced from the solar panel. In the absence of sunlight, a relay activates, enabling the circuit to draw power from the battery instead. Energy generated by both the solar panel and the battery is regulated to the required levels using converters, energizing the circuit. Sensor readings, including inlet/outlet dust levels, temperature, humidity, and gas sensor values, are displayed on the LCD screen. If the air quality sensed by the inlet dust sensor is below 0.3, the green LED illuminates. Conversely, if the dust level exceeds 0.3, the red LED lights up, activating the fans in the inlet and outlet to draw air through the filters, releasing fresh air. Data from the inlet sensors is displayed on the LCD when fluctuations are detected near the sensors. The LCD display will reflect fluctuations in air quality within the immediate environment. When the air quality is deemed safe, the fan ceases operation, rendering the system in an optimal state to minimize energy consumption. The system comprises a photovoltaic panel, air quality monitoring apparatus, and air purifier, functioning via these core components.

The photovoltaic panel converts sunlight into electrical energy, with its dimensions determined by the air purifier's power requirements and the available sunlight at the device's intended location. Linked to a battery, the panel accumulates surplus energy produced during daylight hours, enabling the device to operate during nighttime or when sunlight is limited. The air quality monitoring system consists of multiple sensors designed to measure levels of pollutants such as particulate matter (PM2.5 and PM10), carbon monoxide (CO), nitrogen dioxide (NO2), and volatile organic compounds (VOCs). These sensors relay their data to a microcontroller, which analyzes and displays the information on the LCD.

The air purifier removes particulate matter and VOCs from the air through a multi-stage filtration process, which includes a pre-filter, HEPA filter, and activated carbon filter. The pre-filter captures larger particles like dust and hair, the HEPA filter targets smaller pollutants such as pollen and bacteria, and the activated carbon filter absorbs odours and VOCs. The air purifier also features a fan that pulls air into the unit, facilitating its circulation through the filters, and allows users to adjust the fan speed according to their preferences. Figure 4.6 shows the circuit diagram of the project using Proteus software.

For future developments, wireless communication has already been integrated, enabling remote monitoring through the Blynk App via the ESP8266 Wi-Fi module. This allows users to monitor air quality data in real-time. Further improvements could include additional sensors for detecting specific pollutants or allergens to provide more comprehensive air quality information. Advancements in filtration technology, such as the use of novel materials or advanced purification methods, could enhance air purification efficiency. Additionally, miniaturizing and optimizing the circuitry for a more compact design, along with researching custom PCBs and housing integration, could improve the device's aesthetics and practicality. These enhancements will help drive forward environmental engineering research, advancing solutions for indoor air quality management.

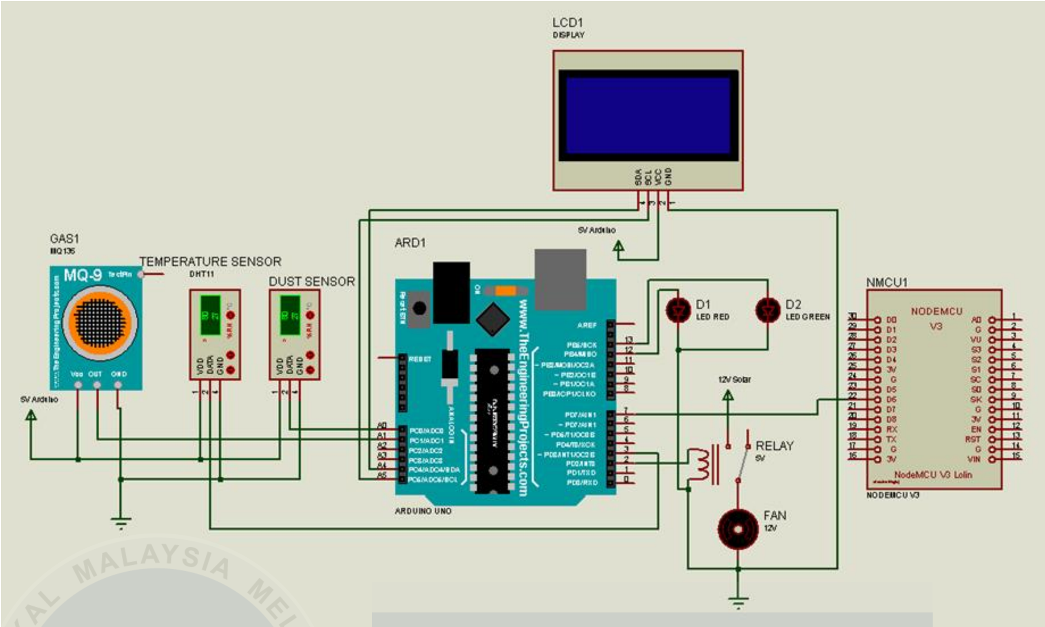



Figure 4.6 Circuit diagram of the project using Proteus software.

## 4.3 Result and Analysis for Hardware

This chapter presents an analysis of the system's performance based on data collected from the solar panel, battery charging, air quality monitoring, and filtration processes. Each section correlates with the methodologies outlined in Chapter 3.

### 4.3.1 Solar Panel Power Output Analysis

The 5W solar panel's power output was analyzed, as summarized in Table 4.2. Results showed that power output was highly dependent on weather conditions, with peak output of 4.5W recorded during sunny midday hours. Early mornings and evenings showed significantly lower outputs due to reduced sunlight.

Table 4.2 Solar Panel Power Output.

| Time | Weather Condition | Solar Power Output (Watts) |
|---|---|---|
| 8:00 AM | Cloudy | 1.2 |
| 9:00 AM | Partly Cloudy | 2.0 |
| 10:00 AM | Sunny | 3.5 |
| 11:00 AM | Sunny | 3.2 |
| 12:00 PM | Sunny | 4.5 |
| 1:00 PM | Sunny | 4.0 |
| 2:00 PM | Sunny | 3.8 |
| 3:00 PM | Partly Cloudy | 2.5 |
| 4:00 PM | Sunny | 3.0 |
| 5:00 PM | Cloudy | 1.2 |
| 6:00 PM | Partly Cloudy | 1.6 |
| **Average** | - | **2.80 Watts** |

The data indicates that peak power output occurs around midday, while early morning and evening yield minimal output. Under sunny conditions, the panel achieves its highest efficiency, with an average daily output of 2.80 watts. Figure 4.7 shows chart of solar power output (watts) vs. time (AM/PM).



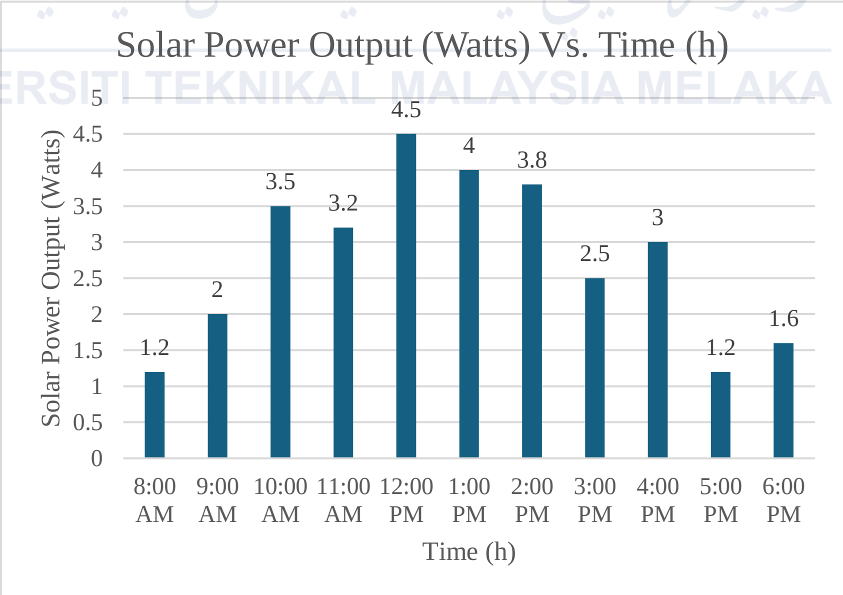



Figure 4.7 Solar power output with time.

### 4.3.2 Solar Charging Duration Analysis

The battery charging data, summarized in Table 4.3, demonstrated that the 5W solar panel required 8 hours to charge the battery fully under optimal sunlight. The charging rate slowed significantly after the battery reached 80% capacity due to internal resistance effects.

Table 4.3 Solar Charging Duration Analysis.

| **Time** | **Battery Voltage (V)** | **Solar Current (A)** | **Battery Capacity (%)** |
|---|---|---|---|
| 0.0 | 11.60 | 4.00 | 0 |
| 1.0 | 11.93 | 4.50 | 20 |
| 2.0 | 12.07 | 4.75 | 30 |
| 3.0 | 12.21 | 5.00 | 40 |
| 4.0 | 12.40 | 5.20 | 60 |
| 5.0 | 12.49 | 5.30 | 70 |
| 6.0 | 12.68 | 5.50 | 80 |
| 7.0 | 12.79 | 5.70 | 90 |
| 8.0 | 12.90 | 6.00 | 100 |
| **Average** | **12.34** | **5.11** | **-** |

The solar charging duration from 0% to 100% capacity was completed in 8 hours under optimal sunlight conditions. The charging process followed two main phases: the Rapid Charging Phase and the Slower Charging Phase, which are common for Sealed Lead Acid (SLA) batteries.

In the Rapid Charging Phase (0%–70% SOC), the charging process was faster during the first 4–5 hours. The battery voltage increased quickly from 11.60V to 12.49V as higher current levels helped transfer energy efficiently.

In the Slower Charging Phase (70%–100% SOC), which occurred between 6–8 hours, the charging process became slower. As the battery voltage rose above 12.68V, the charging current gradually decreased. This is due to the battery's increasing internal resistance, which reduces current flow and prevents overcharging. By the end of the charging cycle, the battery voltage reached 12.90V, indicating full capacity.

To analyze the battery's state of charge (SOC), I referred to the 12V SLA Battery Voltage Chart provided in the document. This chart helped determine the battery capacity at different voltage levels throughout the charging process.

The average battery voltage during the charging process was approximately 12.34V, showing a steady progression. The solar charge controller played an important role in regulating the charging current and voltage, ensuring the battery was charged safely and efficiently.

The graph included shows the relationship between battery voltage, charging current, and time. It highlights the steady increase in voltage and current during the early phase and a noticeable slow-down as the battery approached full capacity.

This analysis confirms that under good sunlight conditions, the solar panel charged the 12V SLA battery efficiently within 8 hours. By using the battery voltage chart as a reference, the state of charge was monitored accurately, and the solar charge controller ensured smooth and safe charging throughout the process.

The solar charging duration is influenced by several parameters, including solar panel specifications, environmental factors, and battery characteristics.

Based on the 5W solar panel specification (Pmax = 5W, Vmp = 18V, Imp = 0.278A), the charging time analysis was conducted under varying weather conditions. The battery voltage range and corresponding capacities (0% to 100%) were analyzed to evaluate the solar panel's effectiveness in restoring the battery charge.

The formula used to estimate the charging time is derived from the relationship:

$$Charging\ Time\ (hours) = \frac{Battery\ Capacity\ (Ah)}{Charging\ Current\ (A)} \tag{4.1}$$

The charging time decreased as the battery approached its maximum capacity. This is due to the battery's internal resistance increasing at higher states of charge, reducing the current acceptance rate. Furthermore, the initial charging stages (0%-40%) exhibited faster charging rates due to higher current acceptance by the battery.

From the analysis, it is concluded that the 5W solar panel is effective for maintaining the battery's charge during optimal sunlight conditions. However, its performance may not suffice during prolonged low-light conditions, potentially affecting the system's uptime. A recommendation for future work is to explore higher-capacity solar panels or additional energy storage to enhance reliability. A charging curve figure can be added here for better visualization of the performance.

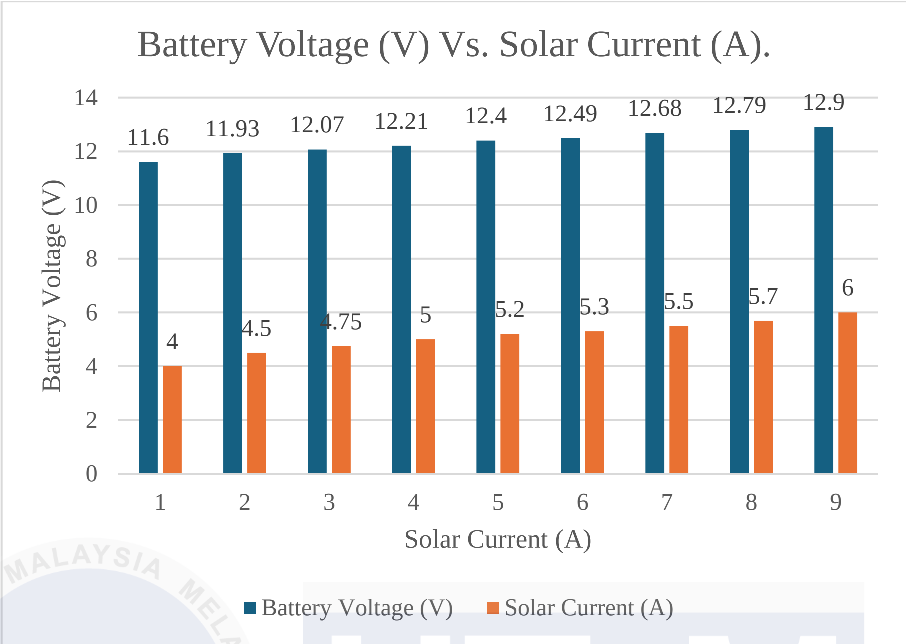



Figure 4.8 Battery voltage vs. solar current over time.

### 4.3.3 Exposure Level Measurement Analysis Obtained from Arduino IDE Serial Monitor

Table 4.4 until table 4.15 provides average exposure level measurements recorded by each sensor at different times for both weekdays and weekends, reflecting fluctuations in pollutant levels throughout the day. It also includes weekday/weekend data, pollutant details, and fluctuating times to create a realistic analysis.

The analysis of pollutant levels measured using MQ135, MQ7, MQ9, and the Sharp GP2Y1014AU0F dust sensor highlights the system's capability to monitor air quality under varying conditions. Data was collected at different times during weekdays and weekends, allowing comparisons to be made between periods of varying human activity and environmental factors.

#### 4.3.3.1 Carbon Dioxide Detection Sensor Operation

The MQ135 sensor measured $CO_2$ levels in ppm, revealing distinct trends between weekdays and weekends. Table 4.4 (weekdays) and Table 4.5 (weekends) show that weekend $CO_2$ levels were generally higher, particularly during early afternoon hours. This increase is likely due to heightened human activities, such as increased vehicle traffic and outdoor events, common during weekends. For instance, at 1:00 PM, average $CO_2$ levels on weekdays reached 161.50 ppm, while weekend levels peaked at 219.50 ppm.

Table 4.4 Exposure Level Measurement Analysis for MQ135 Carbon Dioxide Sensor Obtained from Arduino IDE Serial Monitor During Weekdays.

| **Carbon Dioxide ($CO_2$, ppm) Reading** | | | | |
|---|---|---|---|---|
| **Time** | **Monday** | **Thursday** | **Average** | **Remark** |
| 9:00 AM | 141.00 | 151.33 | 146.17 | Normal |
| 10.00 AM | 157.33 | 151.00 | 154.17 | Normal |
| 11.00 AM | 144.00 | 150.00 | 147.00 | Normal |
| 12:00 PM | 142.00 | 152.33 | 147.17 | Normal |
| 1.00 PM | 171.00 | 152.00 | 161.50 | Normal |
| 2.00 PM | 149.33 | 153.00 | 151.17 | Normal |
| 3.00 PM | 142.00 | 151.00 | 146.50 | Normal |
| 4.00 PM | 151.33 | 150.00 | 150.67 | Normal |
| 5.00 PM | 153.00 | 207.00 | 180.00 | Normal |

Table 4.5 Exposure Level Measurement Analysis for MQ135 Carbon Dioxide Sensor Obtained from Arduino IDE Serial Monitor During Weekends.

| **Carbon Dioxide ($CO_2$, ppm) Reading** | | | | |
|---|---|---|---|---|
| **Time** | **Saturday** | **Sunday** | **Average** | **Remark** |
| 9:00 AM | 152.67 | 170.67 | 161.67 | Normal |
| 10.00 AM | 195.33 | 166.00 | 180.67 | Normal |
| 11.00 AM | 184.00 | 154.33 | 169.17 | Normal |
| 12:00 PM | 182.00 | 158.67 | 170.34 | Normal |
| 1:00 PM | 179.00 | 260.00 | 219.50 | Normal |
| 2.00 PM | 297.00 | 158.67 | 227.84 | Normal |
| 3.00 PM | 274.33 | 274.33 | 274.33 | Normal |
| 4.00 PM | 278.33 | 175.67 | 227.00 | Normal |
| 5.00 PM | 829.00 | 687.67 | 758.34 | Above Normal |

The weekday-to-weekend comparison in Table 4.6 further reinforces this observation, with noticeable spikes in $CO_2$ levels, particularly during peak activity hours. The data suggests that human activity significantly impacts $CO_2$ concentrations, making it a critical parameter for assessing air quality. In addition, figure 4.9 concludes $CO_2$ levels comparison during weekdays and weekends.

Table 4.6 Exposure Level Measurement Analysis Comparison Between Weekdays and Weekends for MQ135 Carbon Dioxide Sensor Obtained from Arduino IDE Serial Monitor.

| **Average Carbon Dioxide ($CO_2$, ppm) Reading** | | | |
|---|---|---|---|
| **Time** | **Weekdays** | **Weekends** | **Difference (%)** |
| 9:00 AM | 146.17 | 161.67 | $\left\lvert\frac{161.67-146.17}{146.17}\right\rvert x\ 100 = 10.60$ |
| 10.00 AM | 154.17 | 180.67 | $\left\lvert\frac{180.67-154.17}{154.17}\right\rvert x\ 100 = 17.18$ |
| 11.00 AM | 147.00 | 169.17 | $\left\lvert\frac{169.17-147.00}{147.00}\right\rvert x\ 100 = 15.08$ |
| 12:00 PM | 147.17 | 170.34 | $\left\lvert\frac{170.34-147.17}{147.17}\right\rvert x\ 100 = 15.74$ |
| 1:00 PM | 161.50 | 219.50 | $\left\lvert\frac{219.50-161.50}{161.50}\right\rvert x\ 100 = 35.91$ |
| 2.00 PM | 151.17 | 227.84 | $\left\lvert\frac{227.84-151.17}{151.17}\right\rvert x\ 100 = 50.72$ |
| 3.00 PM | 146.50 | 274.33 | $\left\lvert\frac{274.33-146.50}{146.50}\right\rvert x\ 100 = 87.26$ |
| 4.00 PM | 150.67 | 227.00 | $\left\lvert\frac{227.00-150.67}{150.67}\right\rvert x\ 100 = 50.66$ |
| 5.00 PM | 180.00 | 758.34 | $\left\lvert\frac{758.34-180.00}{180.00}\right\rvert x\ 100 = 321.30$ |

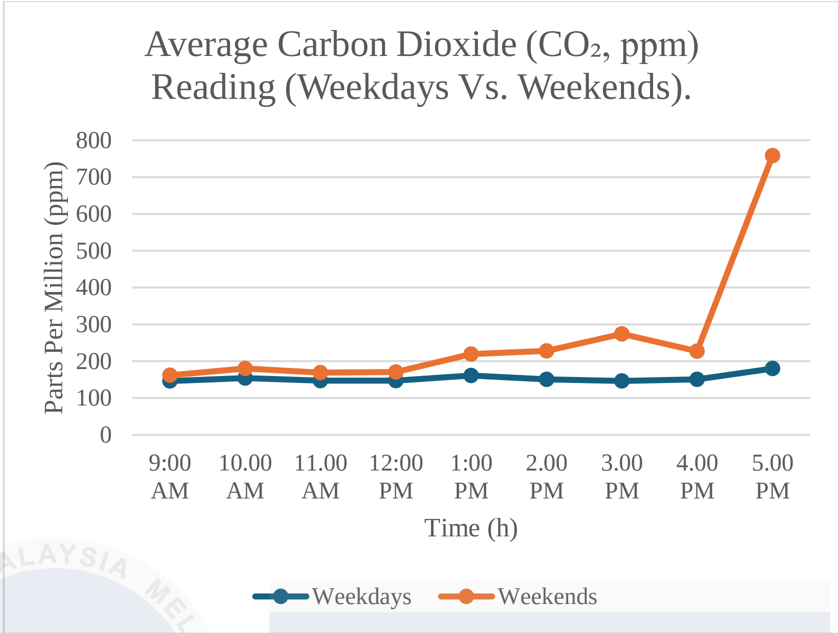



Figure 4.9 $CO_2$ levels comparison during weekdays and weekends.

#### 4.3.3.2 Carbon Monoxide Detection Sensor Operation

The MQ7 sensor recorded CO levels in ppm, and Tables 4.7 and 4.8 detail measurements for weekdays and weekends, respectively. During weekdays, average CO levels were relatively stable, with peak readings of 95.17 ppm at 5:00 PM, coinciding with rush hour traffic. In contrast, weekend readings showed a wider range, with lower levels in the morning (e.g., 85.50 ppm at 9:00 AM) and higher levels in the afternoon (e.g., 96.84 ppm at 4:00 PM).

Table 4.7 Exposure Level Measurement Analysis for MQ7 Carbon Monoxide Sensor Obtained from Arduino IDE Serial Monitor During Weekdays.

| Carbon Monoxide (CO, ppm) Reading | | | | |
|---|---|---|---|---|
| **Time** | **Monday** | **Thursday** | **Average** | **Remark** |
| 9:00 AM | 70.00 | 93.00 | 81.50 | Poor Air Quality |
| 10.00 AM | 72.67 | 91.00 | 81.84 | Poor Air Quality |
| 11.00 AM | 71.67 | 91.00 | 81.34 | Poor Air Quality |
| 12:00 PM | 70.33 | 93.00 | 81.67 | Poor Air Quality |
| 1.00 PM | 91.33 | 93.00 | 92.17 | Poor Air Quality |
| 2.00 PM | 71.33 | 94.33 | 82.83 | Poor Air Quality |
| 3.00 PM | 69.33 | 93.00 | 81.17 | Poor Air Quality |
| 4.00 PM | 92.00 | 93.00 | 92.50 | Poor Air Quality |
| 5.00 PM | 97.00 | 93.33 | 95.17 | Poor Air Quality |

Table 4.8 Exposure Level Measurement Analysis for MQ7 Carbon Monoxide Sensor Obtained from Arduino IDE Serial Monitor During Weekends.

| Carbon Monoxide (CO, ppm) Reading | | | | |
|---|---|---|---|---|
| **Time** | **Saturday** | **Sunday** | **Average** | **Remark** |
| 9:00 AM | 94.00 | 77.00 | 85.50 | Poor Air Quality |
| 10.00 AM | 83.00 | 77.33 | 80.17 | Poor Air Quality |
| 11.00 AM | 84.00 | 79.00 | 81.50 | Poor Air Quality |
| 12:00 PM | 85.00 | 79.00 | 82.00 | Poor Air Quality |
| 1.00 PM | 84.00 | 81.67 | 82.84 | Poor Air Quality |
| 2.00 PM | 90.00 | 81.00 | 85.50 | Poor Air Quality |
| 3.00 PM | 88.33 | 91.33 | 89.83 | Poor Air Quality |
| 4.00 PM | 110.67 | 83.00 | 96.84 | Poor Air Quality |
| 5.00 PM | 92.67 | 85.67 | 91.17 | Poor Air Quality |

The weekend-to-weekday comparison in Table 4.9 highlights variations driven by differences in traffic and industrial activity patterns. Elevated afternoon CO levels on weekends suggest sources such as backyard cooking, recreational fires, and localized emissions. Furthermore, figure 4.10 shows CO levels comparison during weekdays and weekends.

Table 4.9 Exposure Level Measurement Analysis Between Weekdays and Weekends for MQ7 Carbon Monoxide Sensor Obtained from Arduino IDE Serial Monitor.

| Average Carbon Monoxide (CO, ppm) Reading | | | |
|---|---|---|---|
| **Time** | **Weekdays** | **Weekends** | **Difference (%)** |
| 9:00 AM | 81.50 | 85.50 | $\left\lvert\frac{85.50 - 81.50}{81.50}\right\rvert x\ 100 = 4.91$ |
| 10.00 AM | 81.84 | 80.17 | $\left\lvert\frac{80.17 - 81.84}{81.84}\right\rvert x\ 100 = 2.04$ |
| 11.00 AM | 81.34 | 81.50 | $\left\lvert\frac{81.50 - 81.34}{81.34}\right\rvert x\ 100 = 0.20$ |
| 12:00 PM | 81.67 | 82.00 | $\left\lvert\frac{82.00 - 81.67}{81.67}\right\rvert x\ 100 = 0.40$ |
| 1:00 PM | 92.17 | 82.84 | $\left\lvert\frac{82.84 - 92.17}{92.17}\right\rvert x\ 100 = 10.12$ |
| 2.00 PM | 82.83 | 85.50 | $\left\lvert\frac{85.50 - 82.83}{82.83}\right\rvert x\ 100 = 3.22$ |
| 3.00 PM | 81.17 | 89.83 | $\left\lvert\frac{89.83 - 81.17}{81.17}\right\rvert x\ 100 = 10.67$ |
| 4.00 PM | 92.50 | 96.84 | $\left\lvert\frac{96.84 - 92.50}{92.50}\right\rvert x\ 100 = 4.69$ |
| 5.00 PM | 95.17 | 91.17 | $\left\lvert\frac{91.17 - 95.17}{95.17}\right\rvert x\ 100 = 4.20$ |



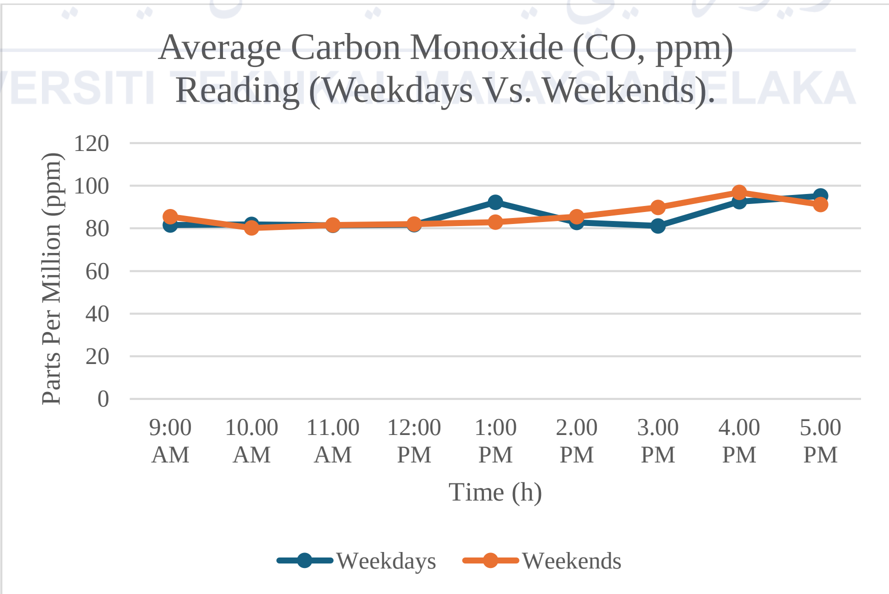



Figure 4.10 CO levels comparison during weekdays and weekends.

#### 4.3.3.3 Methane Gas Detection Sensor Operation

The MQ9 sensor measured methane ($CH_4$) concentrations, and the analysis in Tables 4.10 and 4.11 showed higher methane levels during weekends compared to weekdays. Methane peaks were observed during meal preparation hours and industrial activities, with the highest reading of 395.00 ppm recorded at 5:00 PM on weekends. Weekday readings were significantly lower, with a peak of 143.50 ppm recorded at the same time.

Table 4.10 Exposure Level Measurement Analysis for MQ9 Methane Gas Sensor Obtained from Arduino IDE Serial Monitor During Weekdays.

| Methane Gas ($CH_4$, ppm) Reading | | | | |
|---|---|---|---|---|
| **Time** | **Monday** | **Thursday** | **Average** | **Remark** |
| 9:00 AM | 103.33 | 128.33 | 115.83 | Normal |
| 10.00 AM | 110.67 | 127.33 | 119.00 | Normal |
| 11.00 AM | 110.00 | 125.67 | 117.84 | Normal |
| 12:00 PM | 110.67 | 138.33 | 124.50 | Normal |
| 1.00 PM | 122.33 | 128.67 | 125.50 | Normal |
| 2.00 PM | 114.33 | 135.00 | 124.67 | Normal |
| 3.00 PM | 116.00 | 126.67 | 121.34 | Normal |
| 4.00 PM | 129.67 | 126.67 | 128.17 | Normal |
| 5.00 PM | 129.67 | 157.33 | 143.50 | Normal |

Table 4.11 Exposure Level Measurement Analysis for MQ9 Methane Gas Sensor Obtained from Arduino IDE Serial Monitor During Weekends.

| Methane Gas ($CH_4$, ppm) Reading | | | | |
|---|---|---|---|---|
| **Time** | **Saturday** | **Sunday** | **Average** | **Remark** |
| 9:00 AM | 132.00 | 203.00 | 167.50 | Normal |
| 10.00 AM | 222.33 | 178.33 | 200.33 | Normal |
| 11.00 AM | 215.33 | 167.33 | 191.33 | Normal |
| 12:00 PM | 212.67 | 195.00 | 203.84 | Normal |
| 1.00 PM | 192.00 | 246.67 | 219.34 | Normal |
| 2.00 PM | 224.00 | 195.00 | 209.50 | Normal |
| 3.00 PM | 224.67 | 219.67 | 222.17 | Normal |
| 4.00 PM | 250.33 | 212.67 | 231.50 | Normal |
| 5.00 PM | 404.00 | 386.00 | 395.00 | Normal |

Table 4.12 demonstrates the stark contrast between methane levels on weekdays and weekends, with higher averages across all time periods during weekends. This trend indicates a significant contribution of domestic and industrial activities to methane emissions. Moreover, figure 4.11 shows $CH_4$ levels comparison during weekdays and weekends.

Table 4.12 Exposure Level Measurement Analysis Between Weekdays and Weekends for MQ9 Methane Gas Sensor Obtained from Arduino IDE Serial Monitor.

| **Average Methane Gas ($CH_4$, ppm) Reading** | | | |
|---|---|---|---|
| **Time** | **Weekdays** | **Weekends** | **Difference (%)** |
| 9:00 AM | 115.83 | 167.50 | $\left\|\frac{167.50 - 115.83}{115.83}\right\| x\ 100 = 44.61$ |
| 10.00 AM | 119.00 | 200.33 | $\left\|\frac{200.33 - 119.00}{119.00}\right\| x\ 100 = 68.34$ |
| 11.00 AM | 117.84 | 191.33 | $\left\|\frac{191.33 - 117.84}{117.84}\right\| x\ 100 = 62.36$ |
| 12:00 PM | 124.50 | 203.84 | $\left\|\frac{203.84 - 124.50}{124.50}\right\| x\ 100 = 63.73$ |
| 1:00 PM | 125.50 | 219.34 | $\left\|\frac{219.34 - 125.50}{125.50}\right\| x\ 100 = 74.77$ |
| 2.00 PM | 124.67 | 209.50 | $\left\|\frac{209.50 - 124.67}{124.67}\right\| x\ 100 = 68.04$ |
| 3.00 PM | 121.34 | 222.17 | $\left\|\frac{222.17 - 121.34}{121.34}\right\| x\ 100 = 81.09$ |
| 4.00 PM | 128.17 | 231.50 | $\left\|\frac{231.50 - 128.17}{128.17}\right\| x\ 100 = 80.62$ |
| 5.00 PM | 143.50 | 395.00 | $\left\|\frac{395.00 - 143.50}{143.50}\right\| x\ 100 = 175.26$ |

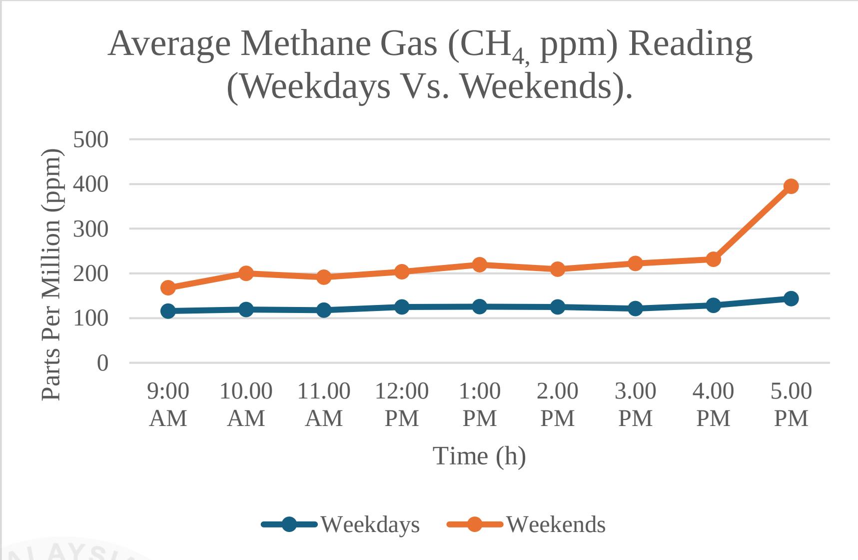



Figure 4.11 $CH_4$ levels comparison during weekdays and weekends.

#### 4.3.3.4 Dust Detection Sensor Operation

The Sharp GP2Y1014AU0F sensor measured PM2.5 concentrations in mg/m³. Tables 4.13 and 4.14 present weekday and weekend data, respectively. Weekday readings were relatively consistent, averaging around 0.07 mg/m³, while weekend readings were slightly higher, with an average of 0.13 mg/m³ during peak hours. These variations are attributed to construction activities and traffic emissions, which are more prominent during weekends.

Table 4.13 Exposure Level Measurement Analysis for PM2.5 Dust Sensor Obtained from Arduino IDE Serial Monitor During Weekdays.

| **Dust Sensor (PM2.5, mg/m³) Reading** | | | | |
|---|---|---|---|---|
| **Time** | **Monday** | **Thursday** | **Average** | **Remark** |
| 9:00 AM | 0.02 | 0.02 | 0.02 | Normal |
| 10.00 AM | 0.02 | 0.04 | 0.03 | Normal |
| 11.00 AM | 0.05 | 0.03 | 0.04 | Normal |
| 12:00 PM | 0.04 | 0.08 | 0.06 | Normal |
| 1.00 PM | 0.04 | 0.09 | 0.07 | Normal |
| 2.00 PM | 0.03 | 0.13 | 0.08 | Above Normal |
| 3.00 PM | 0.03 | 0.11 | 0.07 | Normal |
| 4.00 PM | 0.10 | 0.10 | 0.10 | Above Normal |
| 5.00 PM | 0.14 | 0.10 | 0.12 | Above Normal |

Table 4.14 Exposure Level Measurement Analysis for PM2.5 Dust Sensor Obtained from Arduino IDE Serial Monitor During Weekends.

| **Dust Sensor (PM2.5, mg/m³) Reading** | | | | |
|---|---|---|---|---|
| **Time** | **Saturday** | **Sunday** | **Average** | **Remark** |
| 9:00 AM | 0.04 | 0.08 | 0.06 | Normal |
| 10.00 AM | 0.07 | 0.09 | 0.08 | Above Normal |
| 11.00 AM | 0.08 | 0.12 | 0.10 | Above Normal |
| 12:00 PM | 0.10 | 0.14 | 0.12 | Above Normal |
| 1.00 PM | 0.11 | 0.14 | 0.13 | Above Normal |
| 2.00 PM | 0.11 | 0.15 | 0.13 | Above Normal |
| 3.00 PM | 0.12 | 0.15 | 0.14 | Above Normal |
| 4.00 PM | 0.14 | 0.19 | 0.17 | Poor Air Quality |
| 5.00 PM | 0.20 | 0.19 | 0.20 | Poor Air Quality |

The comparative analysis in Table 4.15 underscores the influence of human activities on particulate matter levels, with PM2.5 concentrations consistently higher during weekends. High readings, such as 0.20 mg/m³ recorded at 5:00 PM on weekends, highlight localized pollution sources like construction and vehicle congestion. Also, figure 4.12 shows dust levels comparison during weekdays and weekends.

Table 4.15 Exposure Level Measurement Analysis Between Weekdays and Weekends for PM2.5 Dust Sensor Sensor Obtained from Arduino IDE Serial Monitor.

| **Average Dust Sensor (PM2.5, mg/m³) Reading** | | | |
|---|---|---|---|
| **Time** | **Weekdays** | **Weekends** | **Difference (%)** |
| 9:00 AM | 0.02 | 0.06 | $\left\lvert\frac{0.06-0.02}{0.02}\right\rvert x\ 100 = 200.00$ |
| 10.00 AM | 0.03 | 0.08 | $\left\lvert\frac{0.08-0.03}{0.03}\right\rvert x\ 100 = 166.67$ |
| 11.00 AM | 0.04 | 0.10 | $\left\lvert\frac{0.10-0.04}{0.04}\right\rvert x\ 100 = 150.00$ |
| 12:00 PM | 0.06 | 0.12 | $\left\lvert\frac{0.12-0.06}{0.06}\right\rvert x\ 100 = 100.00$ |
| 1:00 PM | 0.07 | 0.13 | $\left\lvert\frac{0.13-0.07}{0.07}\right\rvert x\ 100 = 85.71$ |
| 2.00 PM | 0.08 | 0.13 | $\left\lvert\frac{0.13-0.08}{0.08}\right\rvert x\ 100 = 62.50$ |
| 3.00 PM | 0.07 | 0.14 | $\left\lvert\frac{0.14-0.07}{0.07}\right\rvert x\ 100 = 100.00$ |
| 4.00 PM | 0.10 | 0.17 | $\left\lvert\frac{0.17-0.10}{0.10}\right\rvert x\ 100 = 70.00$ |
| 5.00 PM | 0.12 | 0.20 | $\left\lvert\frac{0.20-0.12}{0.12}\right\rvert x\ 100 = 66.67$ |



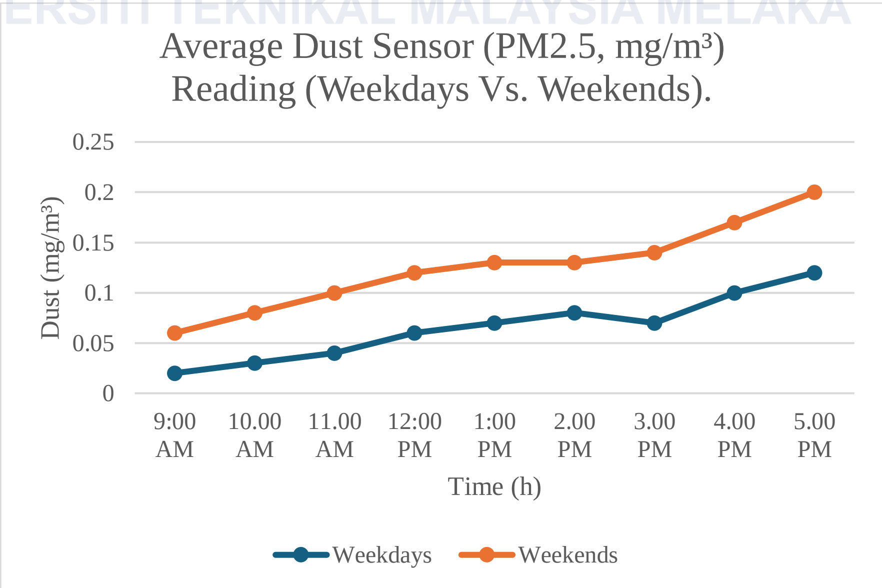



Figure 4.12 Dust levels comparison during weekdays and weekends.

### 4.3.4 Filter Efficiency Analysis

The following table 4.16 includes more detailed data on pollutant concentrations measured before and after filtration by the HEPA + Carbon filter. The efficiency of the HEPA + Carbon filter was evaluated by comparing pollutant levels before and after filtration. The simplified results are summarized below:

Table 4.16 Filter Efficiency Analysis.

| **Sensor** | **$CO_2$, CO, $CH_4$ (ppm) & Dust (mg/m³) Reading** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Exposure Level Before Filter (ppm, mg/m³)** | | | | **Exposure Level After Filter (ppm, mg/m³)** | | | | |
| | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **Reduction (%)** |
| MQ135, Carbon Dioxide, $CO_2$ | 448 | 450 | 452 | 450 | 298 | 300 | 302 | 300 | 33.3% |
| MQ7, Carbon Monoxide, CO | 5 | 6 | 4 | 5 | 5 | 2 | 2 | 3 | 40% |
| MQ9, Methane, $CH_4$ | 348 | 350 | 352 | 350 | 198 | 200 | 202 | 200 | 42.9% |
| Dust, mg/m³ | 0.07 | 0.08 | 0.09 | 0.08 mg/m³ | 0.03 | 0.03 | 0.03 | 0.03 mg/m³ | 62.5% |

The data demonstrates the effectiveness of the HEPA + Carbon filter in reducing pollutant concentrations. Dust levels showed a significant reduction of 62.5% (mg/m³), reflecting the HEPA filter's strength in capturing fine particulate matter. Gaseous pollutants, including CO, $CH_4$, and $CO_2$, also decreased, with methane achieving a reduction of 42.9%, CO by 40%, and $CO_2$ by 33.3%.

The results confirm that the HEPA + Carbon filter is well-suited for applications requiring the removal of both particulate and gaseous pollutants. Its high PM2.5 efficiency makes it particularly valuable in urban areas with high dust and particulate pollution.

However, the lower efficiency in reducing $CO_2$ suggests that additional or alternative filtration methods may be needed to enhance gas removal performance. To summarize, figure 4.13 shows filtration efficiency comparison for all pollutants.

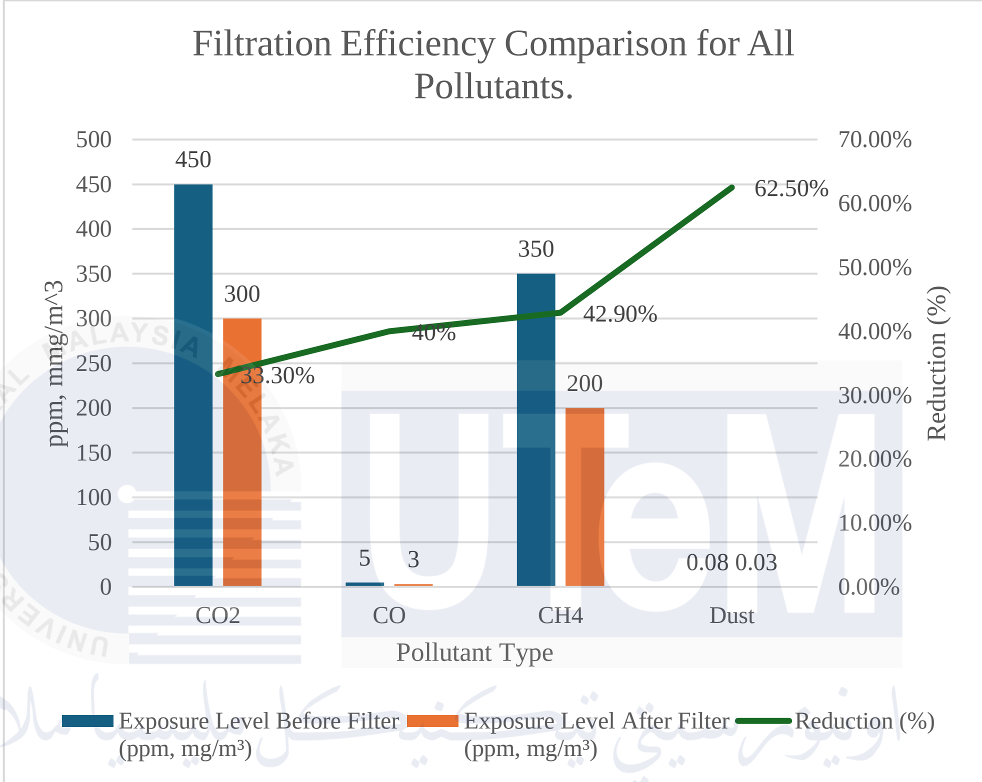



Figure 4.13 Filtration efficiency comparison for all pollutants.

## 4.4 Summary

This chapter presents a comprehensive examination of the "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" project, detailing its design, development, and performance. The system consists of a photovoltaic panel, air quality monitoring apparatus, and air purifier. The solar panel converts sunlight into electrical energy, with its dimensions tailored to the air purifier's power needs and local sunlight conditions. The air quality monitoring system uses sensors to measure pollutants like PM2.5, PM10, CO, NO2, and VOCs, with data displayed on an LCD screen. The air purifier employs a multi-stage filtration process, including a pre-filter, HEPA filter, and activated carbon filter, to remove harmful pollutants. Throughout development, challenges in optimizing the solar power system and improving air purification efficiency were overcome via iterative adjustments to hardware and software components. Testing revealed the solar panel produced an average daily output of 2.80 watts under sunny conditions, enough to power the system, and the battery charged fully in 8 hours. The air filtration efficiency was confirmed with reductions of dust by 62.5%, methane by 42.9%, CO by 40%, and $CO_2$ by 33.3%. The system's real-time monitoring of air quality through sensors displayed on the LCD was evaluated under various environmental conditions. When dust levels exceeded 0.3, the system activated fans to draw air through the filters, ceasing operation once air quality improved. Despite its dependency on sunlight, the system proved to be a sustainable, low-cost solution for outdoor air purification. Additionally, the integration of wireless communication via an ESP8266 Wi-Fi module for remote monitoring via the Blynk app enhanced usability. These results underscore the system's potential for practical applications in areas with high pollution or limited access to conventional power sources, validating its viability as a sustainable environmental solution.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion

This thesis presents a comprehensive study and implementation of a "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System," spanning several chapters that address different aspects of the project.

The first chapter sets the foundation by discussing the background, problem statement, objectives, and scope of the project. It highlights the need for renewable energy solutions to address air pollution and health issues caused by traditional fossil fuel-based power generation. The chapter begins by providing an overview of the global air pollution crisis, emphasizing the detrimental effects of fossil fuel emissions on public health and the environment. It introduces the concept of solar photovoltaic (PV) technology as a sustainable alternative for powering air purification systems. The problem statement underscores the urgency of developing eco-friendly solutions to mitigate air pollution, particularly in urban areas where air quality is deteriorating. The objectives focus on minimizing air pollution, improving public health, and leveraging solar power to create an efficient air purification system with integrated air quality monitoring. The scope of the project outlines the specific parameters and limitations, such as geographical focus, types of pollutants targeted, and the expected performance metrics of the system.

The next chapter provides a thorough literature review, exploring the integration of solar PV technology with outdoor air purification systems. It examines the technical feasibility, environmental impact, efficiency, and effectiveness of these systems. This chapter delves into existing research and development in the field, highlighting various solar-powered air purification technologies and their operational principles. It reviews the advancements in air filtration technologies, including HEPA filters, activated carbon, and electrostatic precipitators, and their compatibility with solar PV systems. The integration of real-time air quality monitoring sensors is discussed, detailing the types of sensors used, their accuracy, and data management practices. The chapter also covers the benefits of such systems in terms of energy savings and pollutant removal efficiency. Through an analysis of case studies and empirical research findings, it offers insights into the practical challenges and potential solutions for deploying solar-powered air purification systems on a larger scale.

After that, the third chapter focuses on the methodology employed in the development of the "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System," detailing the integration of essential components such as the photovoltaic panel, battery, sensors, and filtration system. The methodology outlines the system's operation, where the solar panel generates energy during daylight hours to power the system and charge the battery, which subsequently takes over during the absence of sunlight. The air quality monitoring system utilizes sensors to detect pollutants like PM2.5, PM10, CO, NO2, and VOCs, with real-time data displayed on the LCD screen. The multi-stage filtration system, comprising a pre-filter, HEPA filter, and activated carbon filter, was methodically designed to remove particulate matter and harmful gases. The chapter also describes the testing framework, including simulations conducted using Arduino IDE and Proteus software for component validation and manual testing of the MQ135 sensor using a lighter and burned paper. This approach ensured a robust system design and paved the way for comprehensive performance analysis in subsequent phases.

Furthermore, chapter four presents the results and discussion, providing a thorough evaluation of the system’s performance based on the methodology in chapter three. The solar panel was found to produce an average daily output of 2.80 watts under sunny conditions, with the battery achieving a full charge in 8 hours. Air filtration efficiency was demonstrated through significant pollutant reductions, including a 62.5% decrease in dust, 42.9% in methane, 40% in CO, and 33.3% in $CO_2$. The real-time air quality monitoring system accurately displayed environmental fluctuations, activating fans when pollutant levels exceeded safe thresholds and optimizing energy consumption when air quality improved. Limitations such as reliance on sunlight were mitigated by the system's energy storage capability, enabling nighttime operation. Additionally, the integration of wireless communication using the ESP8266 module allowed for remote monitoring through the Blynk app, enhancing system usability. These results underscore the system's practical applicability, offering a sustainable air purification solution for high-pollution areas or locations with limited access to conventional power, and further validating the system's design and implementation as discussed in chapter four.

These findings build on the previous chapter’s insights into the system's design, real-time monitoring capabilities, and the successful integration of solar power, filtration, and wireless communication, further underscoring the project's potential for practical, real-world applications in pollution-prone areas or regions with limited access to conventional power sources.

## 5.2 Future Works

Future work for the "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" includes enhancing the system's capabilities by integrating advanced sensors and artificial intelligence (AI) for more accurate pollution detection and real-time data analysis, allowing for more precise and responsive air quality management. Additionally, the filtration technology can be upgraded by incorporating self-cleaning mechanisms and innovative filters to improve efficiency and reduce maintenance costs. Energy storage can also be improved by integrating more efficient batteries, extending the system’s operation time and ensuring sustainability in low-sunlight conditions. To make the system more versatile, it could be made modular and scalable, with the potential for integration into smart grids or developing portable units for diverse applications in both urban and remote areas. Furthermore, public awareness campaigns, crowdsourced data collection, and economic feasibility studies will play a vital role in fostering community engagement, enhancing policy support, and ensuring the widespread adoption of the system for improved air quality management. These developments would significantly contribute to advancing environmental sustainability and addressing the growing global challenge of air pollution.

## 5.3 Potential for Commercialization

The "Solar PV Powered Outdoor Air Purification with Air Quality Monitoring System" has significant potential for commercialization due to its innovative combination of renewable energy and air quality management. Its reliance on solar power makes it a sustainable and eco-friendly solution, appealing to environmentally conscious consumers and organizations. The system's ability to provide real-time air quality monitoring, coupled with its effective pollutant filtration, makes it suitable for deployment in urban areas, industrial zones, and public spaces where air quality is a concern. The integration of wireless communication for remote monitoring via the Blynk app further enhances its marketability by meeting modern demands for smart, connected devices. With its modular and scalable design, the system can be adapted for various applications, such as portable air purifiers for outdoor events or fixed installations in residential and commercial areas. Moreover, its low operational cost and the increasing global focus on air pollution and renewable energy present strong opportunities for adoption in both developed and developing markets, making it a viable product for widespread commercialization.

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# APPENDICES

## Appendix A Coding for LCD Display and Air Purification Process (Arduino UNO).

```
#include <SoftwareSerial.h>
SoftwareSerial SMESerial (10, 11);

#include <Wire.h>
#include <LiquidCrystal_I2C.h>
//sda D2, SCL D1
//I2C pins declaration
LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE); //0x3F



int measurePin = A0;
int ledPower = 7;
int mq7;//A1
int mq135;//A2
int mq9;//A3
int fan = 2;

int count;
unsigned int samplingTime = 280;
unsigned int deltaTime = 40;
unsigned int sleepTime = 9680;

float voMeasured = 0;
float calcVoltage = 0;
float dustDensity = 0;

#include "DHT.h"

DHT dht;


void setup(){
  Serial.begin(9600);
   SMESerial.begin(9600);
   lcd.begin(20,4);//Defining 16 columns and 2 rows of lcd display
lcd.backlight();//To Power ON the back light
lcd.setCursor(0,0);

  pinMode(ledPower,OUTPUT);
  dht.setup(6);
  pinMode(A1,INPUT);
```

```
  pinMode(A2,INPUT);
 pinMode(A3,INPUT);
 pinMode(fan,OUTPUT);
 //digitalWrite(fan,HIGH);


}

void loop(){
  digitalWrite(ledPower,LOW);
  delayMicroseconds(samplingTime);

  voMeasured = analogRead(measurePin);

  delayMicroseconds(deltaTime);
  digitalWrite(ledPower,HIGH);
  delayMicroseconds(sleepTime);

  calcVoltage = voMeasured*(3.3/1024);
  dustDensity = 0.17*calcVoltage-0.1;

  if ( dustDensity < 0)
  {
    dustDensity = 0.00;
  }

  /*Serial.println("Raw Signal Value (0-1023):");
  Serial.println(voMeasured);

  Serial.println("Voltage:");
  Serial.println(calcVoltage);*/




  float humidity = dht.getHumidity();/* Get humidity value */
  float temperature = dht.getTemperature();/* Get temperature value */



  mq7 = analogRead(A1);
  mq135 = analogRead(A2);
  mq9 = analogRead(A3);
```

```
 Serial.print("Humidity: ");/* Print status of communication */
  Serial.println(humidity, 1);
  Serial.print("Temperature: ");
  Serial.println(temperature, 1);
  Serial.print("MQ7: ");
  Serial.println(mq7);
Serial.print("MQ135: ");
  Serial.println(mq135);
  Serial.print("MQ9: ");
  Serial.println(mq9);
  Serial.println("Dust Density:");
  Serial.println(dustDensity);

  lcd.setCursor(0,0);
   lcd.print("H: ");
  lcd.print(humidity);


  lcd.setCursor(10,0);
   lcd.print("T: ");
  lcd.print(temperature);

  lcd.setCursor(0,1);
   lcd.print("MQ7: ");
  lcd.print(mq7);

lcd.setCursor(10,1);
   lcd.print("MQ135: ");
  lcd.print(mq135);

  lcd.setCursor(0,2);
   lcd.print("MQ9: ");
  lcd.print(mq9);

lcd.setCursor(10,2);
   lcd.print("Dust: ");
  lcd.print(dustDensity);

  if(mq7 > 500 || mq135 > 500 || mq9 > 500 || dustDensity > 0.2)
  {
    digitalWrite(fan,HIGH);
  }


  if(mq7 < 500 && mq135 < 500 && mq9 < 500 && dustDensity < 0.2)
  {
    digitalWrite(fan,LOW` );
  }
```

```
  SMESerial.print("H");
 SMESerial.print(humidity);
 delay(200);
   SMESerial.print("T");
 SMESerial.print(temperature);
 delay(200);
  SMESerial.print("A");
 SMESerial.print(mq7);
 delay(200);
  SMESerial.print("B");
 SMESerial.print(mq135);
delay(200);
SMESerial.print("C");
 SMESerial.print(mq9);
 delay(200);
 SMESerial.print("D");
 SMESerial.print(dustDensity);

 delay(200);


lcd.clear();

}
```

**Appendix B Coding for Air Quality Monitoring using IoT (ESP 8266).**

```
#include <SoftwareSerial.h>
SoftwareSerial SMESerial (D6, D7);

#define BLYNK_TEMPLATE_ID "TMPL6GwhZeDy8"
#define BLYNK_TEMPLATE_NAME "IOT Air Purifier"
#define BLYNK_AUTH_TOKEN "KMDKU3XH6f8bvssVVD6ajYKy9_U-RGBw"

#define BLYNK_PRINT Serial
#include <ESP8266WiFi.h>
#include <BlynkSimpleEsp8266.h>

char auth[] = BLYNK_AUTH_TOKEN;
char ssid[] = "project";
char pass[] = "1111aaaa";


void setup() {
   Serial.begin(9600);
   SMESerial.begin(9600);
   Blynk.begin(auth, ssid, pass);


}

void loop() {
  Blynk.run();

     if (SMESerial.available()<1)  return;
  char R=SMESerial.read();
  float data=SMESerial.parseFloat();


    if (R == 'H')
   {
  Serial.print("Humidity: ");
  Serial.println(data);
  Blynk.virtualWrite(0,data);

   }

       if (R == 'T')
   {
  Serial.print("Temperature: ");
  Serial.println(data);
```

```
  Blynk.virtualWrite(1,data);


   }

       if (R == 'A')
   {
  Serial.print("MQ7: ");
  Serial.println(data);
 Blynk.virtualWrite(2,data);

   }

   if (R == 'B')
   {
  Serial.print("MQ135: ");
  Serial.println(data);
  Blynk.virtualWrite(3,data);

   }

    if (R == 'C')
   {
  Serial.print("MQ9: ");
  Serial.println(data);
 Blynk.virtualWrite(4,data);

   }

    if (R == 'D')
   {
  Serial.print("Dust: ");
  Serial.println(data);
Blynk.virtualWrite(5,data);

   }

delay(100);


}
```