

**INVESTIGATION OF ENERGY EFFICIENCY
OF A HYBRID PV-T SYSTEM FOR
MALAYSIAN HOUSEHOLD**

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**INVESTIGATION OF ENERGY EFFICIENCY OF A HYBRID PV-T
SYSTEM FOR MALAYSIAN HOUSEHOLD**

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**A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Mechanical
Engineering with Honours**

**Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman**

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ABSTRACT

Malaysia's reliance on fossil fuels and the push for renewable energy face challenges in tropical climates, where high ambient temperatures degrade standard photovoltaic (PV) module efficiency. This study investigates the electrical and thermal efficiency of a hybrid photovoltaic-thermal (PV-T) system designed for Malaysian residential households to simultaneously generate electricity and usable hot water. An experimental prototype was fabricated using a monocrystalline PV panel and tested under natural outdoor conditions in Bandar Sungai Long. The study evaluated two active front-surface water cooling configurations: Setup A, an evaporative sprinkler system, and Setup B, a continuous direct-contact water film. Both configurations were compared against a baseline standalone PV module. Results demonstrate that active thermal management significantly mitigates efficiency losses. Setup A achieved a maximum panel temperature reduction of 17.2 °C compared to the standalone unit, successfully preventing thermal degradation and recovering electrical efficiency. However, Setup B exhibited superior overall stability and heat extraction, reaching a peak combined system efficiency of 91.9% and a peak thermal power of 310.0 W. Economic analysis confirms that Setup B is the more practical and viable solution for real-world scaling due to minimal environmental water loss, capable of offsetting approximately 13.78% of a typical four-person household's daily water heating load. The findings conclude that PV-T systems offer an economically sound, dual-benefit energy solution that maximizes solar utilization and supports sustainable residential energy transition in tropical climates.

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LIST OF SYMBOLS / ABBREVIATIONS

$\dot{m}$	Mass Flow Rate of Water, kg/s
c_p	Specific Heat Capacity of Water, J/kg·K
T_{out}	Outlet Water Temperature, °C
T_{in}	Inlet Water Temperature, °C
G	Solar Irradiance, W/m ²
A	Surface Area of PV-T Collector, m ²
V	Output Voltage of PV Module, V
I	Output Current of PV Module, A
η_{tot}	Total Efficiency, %
η_e	Thermal Efficiency, %
η_{th}	Electrical Efficiency, %

CHAPTER 1

INTRODUCTION

1.1 General Introduction

One of the crucial things that drives a country's development is energy. Gross Domestic Product (GDP) is closely related to the energy to nation's demand. It is important not only for economic expansion but also maintaining long-term national advancement. Energy is vital for daily life, economic growth, and innovation in modern technologically advanced society. To strive as a country for Malaysia, it requires a highly reliable sources of energy.

Historically, Malaysia has heavily relied on fossil fuels, primarily natural gas and coal for electricity generation. As of 2025, most of the Malaysia's power is currently generated using fossil fuels, with 43.05% coming from coal, 36.68% from natural gas, and 0.6% from oil, contributing for about 80.33% of total energy production. While renewable energy only contributes to 19.68%, being 16.86% from hydropower, 2.08% from solar, and 0.78% from bioenergy (Our World in Data, 2024). Despite having a diverse energy resources and while being a net energy exporter, Malaysia's energy structure is heavily skewed towards conventional fuels as can be seen from Figure 1-1.

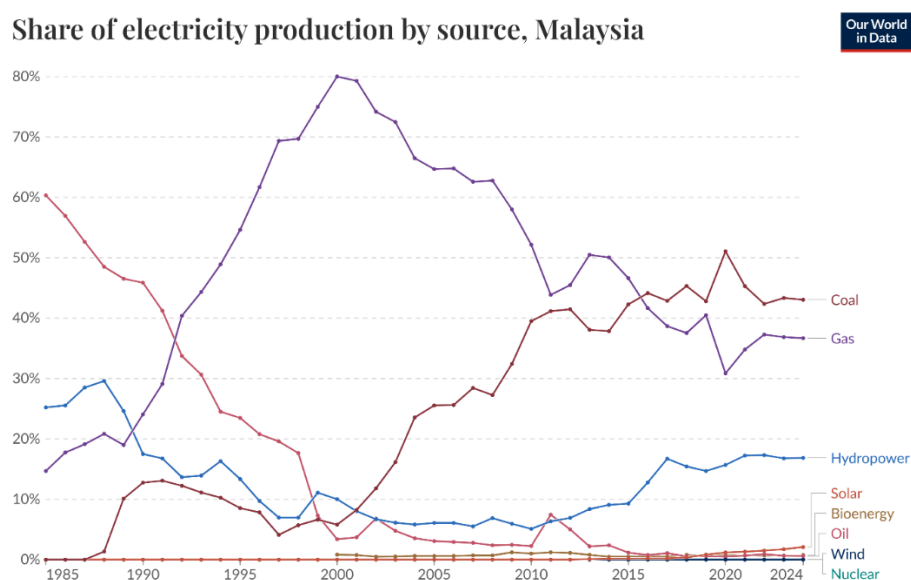


Figure 1-1: Statistical Review of Malaysia Energy Source (Our World in Data, 2024)

This over dependence greatly adds to environmental problems in along with depleting limited resources. One of the main causes of climate change and global warming is the huge emissions of carbon dioxide (CO₂) from the combustion of fossil fuels. Furthermore, sulphur dioxide and nitrogen oxides released by power plants and vehicles cause acid rain, which damages infrastructure, public health, and ecosystems (Consensus, 2024). The continuous reliance on conventional fuels exacerbates environmental issues, particularly greenhouse gas emissions and air pollution. The latest value for carbon dioxide emissions per capita in Malaysia has reached 8.07 metric tons as of 2023, an increase from 7.91 metric tonnes in 2022 (The Global Economy, 2024). The increasing trend indicates that it's a worrying figure that continues to rise with urbanization.

The reliance on natural resources deemed Malaysia as one of the largest oil and gas producers in the Asia-Pacific region while also being titled as the world's fifth biggest exporter of LNG in 2023. However, according to National Energy Transition Roadmap, announced by Prime Minister Anwar Ibrahim, Malaysia has pledged to gradually phase out fossil fuel dependence and achieve net-zero greenhouse gas emissions by 2050 (Ministry of Economy Malaysia, 2023).

Energy consumption in the Malaysia residential sector has increased dramatically because of the increased ownership of appliances, changes in lifestyle, and urbanization (Daud et al., 2023). Average monthly electricity consumed in urban households is noted at approximately 648.31 kWh, with income level, house sizes, and number of rooms being the main contributors (Ali et al., 2021). In the last decade, PV policies such as Feed-in Tariff and Net Energy Metering policies have been implemented to encourage solar PV adoption by households (Husain et al., 2021).

1.2 Importance of the Study

Investigating the viability of photovoltaic–thermal (PV-T) systems for households helps improves in terms energy security, savings, and the nation's climate goals. Malaysia remains largely dependent on fossil fuels for electricity production, gas and coal and petroleum (Our World in Data, 2024). Dependence on these fuels exposes us to price fluctuations, and it is highly carbon intensive.

Being a tropical country with plentiful solar irradiance, it opens opportunities to explore this resource more efficiently, using household PV-T systems. (Sarker et al., 2023)

PV-T technology is desirable because it does not only produce electricity but captures heat to use for household purposes. This adds a layer of efficiency above a normal PV system. Evidence suggests households in Malaysia are beginning to adopt solar more frequently, but overall adoption is still low compared to potential. However, studies have shown that the challenges to adoption are high initial costs, a lack of awareness and certainty in government support (Alam et al., 2021). In exploring efficiency of a PV-T system, this study can show clearer benefits in term of energy savings, payback periods, and reliability of daily use, which influence decisions for most households.

Malaysia has initiatives, including Feed-in Tariff (FiT) and Net Energy Metering (NEM), that aim to foster the adoption of solar. However, the effectiveness of these programs depends heavily on real performance data. As earlier studies have shown that real efficiency outcomes derived from actual households that can help enrich these incentives and enhance their chances of implementation (Sarker et al., 2023). In short, showing that PV-T systems can function adequately within local and actual environments will serve to reassure homeowners and consider space utilization for government policy makers.

Finally, large-scale rooftop PV projects in Malaysia have demonstrated that when said systems are successfully deployed, there will be reductions in carbon emissions, and the provide long-term financial savings (Govindarajan et al., 2024). Ordinary Malaysians can practically contribute to national targets for carbon emissions reduction, while achieving the prospect of savings on their utility bill. This project is not only filling a gap in the research but connecting household benefits to national energy transition targets.

1.3 Problem Statement

Malaysia recognizes the importance of increasing renewable energy generation, but solar photovoltaic (PV) systems face challenges in tropical environments. Standard PV panels, on average, only convert about 15–20% of the solar energy they receive into energy, and the rest is lost as heat. The excess heat on the PV

cells increases the temperature and can mean PVs will lose efficiency by about 0.4–0.5% for every 1 °C above standard test conditions. The hot and humid Malaysian climate, with an average daily temperature of between 27–33 °C and solar irradiance from 4.21–5.56 kWh/m²/day annually, making these losses worse.

Several designs and mechanisms have been proposed to solve this issue, including fluid cooling channels, advanced absorber materials, and hybrid photovoltaic–thermal (PV-T) collectors. Although there have been limited studies adapting PV-T systems for Malaysia's weather conditions, including heavy rainfall on the east coast of the country and high humidity levels in the central parts of the states, there has been less research into the road to adopting this technology to meet consumer needs. Throughout Malaysia, consumers not only require stable electricity but also a significant volume of hot water, with hot water comprising up to 20% of household energy usage.

Furthermore, cost remains a key barrier. Global PV module prices have decreased by 80% since 20, but the addition of PV-T technology and water circulation systems may incur additional capital costs. The challenge is thus to develop an affordable, efficient, and climate-resilient PV-T system that is affordable and meets consumer needs, as well as supporting the reduction in our reliance on fossil fuels.

1.4 Aim and Objectives

This study aims to evaluate the energy efficiency and viability of a hybrid photovoltaic-thermal (PV-T) system for households in Malaysia by analysing its electrical and thermal performance and its potential to meet household energy requirements. The objectives of the study are to:

- (i) Design a hybrid photovoltaic-thermal (PV-T) system incorporating front-surface water cooling.
- (ii) Assess the overall energy efficiency of the PV-T system under real Malaysian outdoor environmental conditions.
- (iii) Evaluate the feasibility of the PV-T system in meeting household energy demands for residential applications in Malaysia.

1.5 Scope and Limitation of the Study

The study aims to evaluate the performance of a hybrid photovoltaic-thermal (PV-T) system, focusing on the Malaysian climate. The PV-T system will be investigated outdoors to observe real variations in solar irradiance, ambient temperature, humidity, and rainfall. The measurements will consist of solar irradiance, PV module surface temperature, inlet and outlet temperatures of the water, ambient conditions, and electrical output such as voltage and current. The measured parameters will be used to assess the electrical efficiency of the PV module and thermal efficiency of the complete heat recovery system. The study will include variations in the weather patterns in Malaysia, including clear, cloudy, rain, the research aims to present an understanding of how climate and environment affect the efficient performance of PV-T systems for household use.

However, the study poses some challenges and limitations. The PV-T system used in this study was built and assembled as a prototype making it difficult to recreate the same conditions and quality as a commercial household system. Therefore, results may not accurately reflect performance on a large-scale or during long-term installations. The testing was limited to some months of the year, and while seasonal changes of the data were observed, it may not accurately represent the entire year. Although the PV-T system could consider several enhancement methods to improve heat transfer, the study could not consider testing all available due to resource constraints. The focus of the study is mainly on technical performance, where a large-scale economic analysis, including installation and maintenance costs, is beyond the scope of this study. Finally, performance data is measured in real outdoor conditions, which may be affected by uncontrollable events, such as sudden changes in environmental conditions or uncertainty in measurements.

1.6 Contribution of the Study

The study makes both academic and practical contributions to renewable energy research. It provides new performance data on hybrid photovoltaic-thermal (PV-T) systems that were tested under a tropical climate in Malaysia. There are still limited localized research data in the existing literature base, and this study

contributes to fill that gap in demonstrating how PV-T technology performs in hot, humid, and unpredictable weather conditions.

The research demonstrates how PV-T systems can improve overall energy utilization. As they collect and recover the waste heat that usually degrades PV performance, the system produces useful thermal energy in addition to maintaining electrical generation. The dual benefits demonstrate that PV-T can be a more effective means of energy production compared to traditional PV modules, particularly in climates where overheating is an issue and a major concern.

Moreover, the findings are important for households' application, as the system satisfies two demands (electricity and hot water) at once. Since the hot water sector will tend to consume a relatively large proportion of residential energy use, the dual-purpose of PV-T systems can provide an effective way to decrease household energy costs while improving self-sufficiency.

1.7 Outline of the Report

The report is structured into five chapters. Chapter One covers the introduction where background, problem statement, objectives, scope, limitations and contributions of the study are discussed. Chapter Two discusses the literature review of the work related to photovoltaic-thermal (PV-T) systems, energy efficiency and their application in the Malaysian households which lays down the components for this project. Chapter Three outlines the methodology which includes the system configuration, experimental setup, data collection and performance evaluation that were undertaken in this study. Chapter Four describes the results of the experiments and analysis undertaken in this project, along with discussion and comparison to past research in this field. Finally, Chapter Five provides a closing to the report outlining and summarizing the key findings, the contributions of the work, and suggestions for improvement and future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Hybrid photovoltaic–thermal (PV-T) systems are an advanced solar technology that combines generation of electrical power with heat recovery. In this section, the basic idea of PV-T technology, the historical development and characteristics of major types of PV-T collectors and why it is considered promising to utilize solar energy more effectively will be discussed.

2.2 Hybrid PV-T Technology

Photovoltaic Thermal Collectors (PV-T) are known as hybrid solar collectors, where power generation technologies from solar panels convert solar radiation into usable thermal and electrical energy. PV-T combines the ability to generate electricity along with thermal absorber to produce both heat and power simultaneously. The concept of using solar energy to produce heat energy and electrical energy are summarized as shown in Figure 2-1. The concept of PV-T dates to the mid-1970s when Kern and Russell first proposed integrating photovoltaic (PV) modules with thermal collectors to reduce overheating and efficiency losses in solar cells. For typical photovoltaic (PV) modules, only 5% to 25% of solar radiation are converted into electricity while up to 80% are dissipated as heat, leading to increased cell temperature and efficiency drops. The goal of PV-T systems is to capture wasted heat using air or water as working fluid to improve the overall solar energy utilization (Tiwari et al., 2023). Figure 2-1 shows the overview of the PV-T system extracted starting from solar energy.

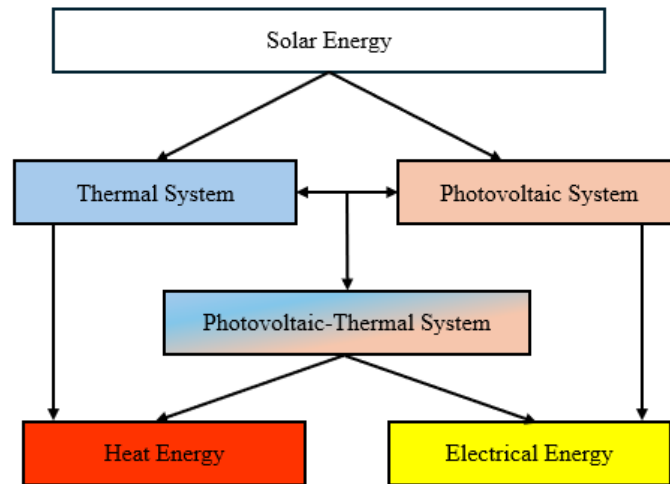


Figure 2-1: Overview of PV-T System

Solar energy generally can be harnessed in two forms of energy, thermal energy where sunlight is converted into heat and electrical energy is convert through PV modules. PV-T combines these processes into a single system by using a working fluid, either air or water to flow near the PV modules to extract the excess heat, which can then be circulated for applications such as domestic hot water supply or space heating. Over the 1990s and 2000s, research expanded to include more advanced configurations such as building-integrated photovoltaic-thermal (BIPVT) systems, concentrator collectors and heat-pipe-based units (Herrando et al., 2023). Over the last decades, significant improvement has been shown in both modelling and experimental validation where studies have shown that PV-T systems can achieve combined thermal and electrical efficiencies exceeding 60% to 70% (Chhugani et al., 2019). Innovations such as absorber materials, selective coatings and working fluid such as nanofluids and phase-change materials, have bought PV-T to one of the most versatile and efficient solar technologies available today (Tiwari et al., 2023).

2.2.1 Potential of PV-T System

A photovoltaic–thermal (PV-T) system is a hybrid device that integrates a photovoltaic module with a thermal collector to generate electricity and uses heat for other uses simultaneously. Conventional PV modules often suffer from efficiency losses due to high operating temperatures. Hence, PV-T systems address this limitation by removing the excess heat or also known as waste heat

to a heat transfer medium such as air, water or refrigerant to be put into practical use. This process can keep PV cells operate at a lower temperature to sustain higher electrical output and provide a secondary source of energy in the form of hot water or warm air for domestic, commercial or industrial uses (Herrando et al., 2023). The dual-output system makes PV-T systems a highly promising solution in terms of overall energy efficiency, where combined outputs often reaching more than 70%, significantly outperforming separate PV and solar thermal technologies (Tiwari et al., 2023). Furthermore, PV-T systems optimize energy output per unit area, which is beneficial when roofs are limited in urban areas. PV-T systems do more than just basic heating. They help with desalination, building-integrated energy solutions, cooling via desiccant or absorption systems, and even help produce hydrogen. PV-T systems' plays an important role in lowering greenhouse gas emissions and works well for net-zero energy building (NZEB) plans highlights how important and useful they are to advancing global decarbonization efforts (Herrando et al., 2023). Therefore, PV-T systems is a primary role as a sustainable energy solution by addressing the concerns about the environment and spatial use while improving shortcomings the efficiency of a standalone PV.

Studies have shown that a water-cooled PV-T panel in Germany produced 4.3% more electricity and delivered 1.8–1.87 kWh/m² per day of thermal energy compared with an uncooled PV module (Chhugani et al., 2019). In Malaysia, it was reported that a water-based PV-T operating at 0.5 L/min achieved 67.4% thermal efficiency and delivered outlet water at 45.8 °C, where it is sufficient to meet the daily hot-water demand of a three-person household (Basuhaib et al., 2024). Likewise, it was found that raising water flow to 3 L/min lowered PV surface temperature to 30.7 °C and stabilised outlet water at 38–39 °C under 1000 W/m² irradiance (Gomaa et al., 2022).

These mechanisms have been further refined by recent developments and studies conducted. Phase-change materials (PCMs) absorb heat peaks and keep PV at stable temperatures. Nanofluids containing metallic or oxide nanoparticles improve heat transfer by raising thermal conductivity and circulates heat more efficiently (Tiwari et al., 2023). Spectral-splitting concentrators work at roughly 60% efficiency by sending infrared light to thermal absorbers for visible light for electricity and heat. Collectively, these

strategies improve PV cells through conduction and convection, lower radiation losses, and gives more precise temperature control. This way, PV-T system can turn waste heat into useful heat, while producing more electricity simultaneously.

2.2.2 Working Principle and Mechanism of PV-T Systems

Photovoltaic-thermal (PV-T) systems are a hybrid device that convert incident solar radiation into both electricity and heat. It involves the pairing a PV module with a thermal extraction unit mounted on its rear surface. Under normal function, only up to 20% of the irradiation is converted to electricity, while the rest is absorbed as heat or lost through reflection in the cell material and the substrate (Goh et al., 2024). This resulted in the increase of cell temperature, internal resistance that directly lowers the voltage output of the PV module. Field measurements in Malaysia shown that efficiency typically falls by 0.4- 0.5% with every one-degree Celsius rise in temperature, highlighting the importance of cooling strategies in tropical climates (Gomaa et al., 2022).

To address the issue, PV-T systems integrate a thermal absorber and fluid circuit behind the PV panel. The excess heat moves by conduction from the PV laminate into the absorber plate, which is usually made of a highly conductive material such as aluminium or copper (Tiwari et al., 2023). From there, the heat is transferred through conduction from the PV laminate to an absorber plate, followed by convection into a working fluid, typically water, air or nanofluid that circulates beneath or around the module. Part of the absorbed energy are lost by radiation to the environment. To minimize these losses, glazing and selective coating are used to limit unwanted radiation transfer along with insulation at the back and sides of the collector to reduce conductive and convective heat escape (Herrando et al., 2023).

In contrast, front-surface mechanism, such as thin-film water glazing and evaporative spray, extracts heat directly from sun-facing glass via active conduction and evaporation. By applying a thin surface of water directly onto the PV Module, it allows for heat transfer and latent heat of vaporization. The water effectively strips excess thermal energy from the panel before it can penetrate and heat the semiconductor layers underneath. Consequently, the PV cells are maintained at a lower and more stable operating temperature, while

heated water is simultaneously collected for domestic applications, thereby maximising the total energy utilization of the entire system (Chaich et al., 2026).

This combined mechanism ensures that PV cells operate at a lower, more stable temperatures while converting a portion of the waste heat into useful thermal energy. In summary, PV-T systems convert incoming solar energy into electricity while using conduction, convection and insulation and radiation control strategies to maximize the remaining heat in the most efficient way possible.

2.2.3 Types of PV-T

PV-T systems are classified according to the heat transfer medium and collector design. Common categories for PV-T system are air-based, water-based, heat-pipe, concentrator PV-T (CPVT), and building-integrated PV-T (BIPVT) (Tiwari et al., 2023).

Air-based PV-T collectors use forced or natural air circulation to remove heat from the PV panel. They are simple, cost-effective, and resistant to leakage or corrosion, but the low thermal capacity of air decreases their performance in the system. Thermal efficiencies of 30–50% are typical, but different designs such as double-pass channels, fins, glazing, and insulation can improve recovery (Herrando et al., 2023). Enhancement may include increment of turbulence and rounded channels may further enhance convective transfer (Herez et al., 2025).

Water-based PV-T collectors are the most widely studied because water has a higher heat capacity and conductivity than air. Flat-plate designs often employ sheet-and-tube, serpentine, or spiral channels. Herez et al. (2025) compared different layouts and found that spiral and serpentine flows outperform direct and web flows due to improved turbulence and residence time, achieving efficiencies above 65% (Herez et al., 2025). To control losses, water-based collectors are often glazed and insulated at the back and sides. With these measures, overall efficiencies above 70% are achievable (Tiwari et al., 2023).

However, recent PV-T technology has shifted focus to front-surface water cooling, bypassing thermal resistance from the rear surface of a PV module (Mostakim et al, 2024). Instead of circulating fluid behind the panel, these systems distribute water directly over the sun-facing photovoltaic glass

using atomized spray nozzles or open-channel falling film (Raad et al, 2025). Furthermore, applying a continuous thin film of water creates a highly favourable optical matching layer. Because water has a refractive index of 1.33, positioning it between the air and the glass minimizes the reflection of solar radiation, increasing solar penetration into the cells while simultaneously absorbing heat to generate useful thermal energy (Mostakim et al., 2024). To maximize this cooling performance and prevent localized hot spots, Wibowo et al. suggested that full cone spray nozzle provide a more even distribution of water across the PV surface compared to hollow cone or flat fan alternatives. Figure 2-2 shows the application of water-based PV-T for household uses.

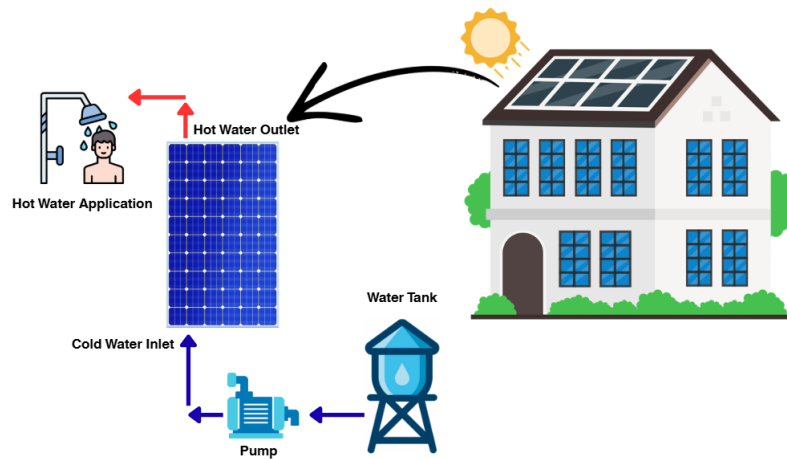


Figure 2-2: Household Water-based PV-T System

Heat-pipe PV-T collectors transfer heat via a two-phase cycle of evaporation and condensation inside sealed pipes. This passive operation eliminates the need for pumps, providing reliability, although costs are higher. Recent studies confirm that heat-pipe solar collectors achieve more uniform fluid flow, near-isothermal heat absorption, and high outlet temperatures compared to conventional systems (Li et al., 2022). Moradgholi et al. (2014) demonstrated that incorporating heat pipes in PV-T panels improved both thermal and electrical performance under experimental conditions. Similarly, Deng et al. (2015) reported that micro-heat-pipe arrays integrated in household PV-T systems in Beijing achieved stable thermal outputs and extended PV lifespan. These findings confirm that heat-pipe designs deliver stable outputs

comparable to water-based systems while supporting PV efficiency (Herrando et al., 2023).

Concentrator PV-T systems (CPVT) focus solar radiation onto smaller PV surfaces by using parabolic troughs, Fresnel lenses, or other optics. This approach boosts both electrical and thermal outputs, but it requires robust cooling and insulation to handle high fluxes (Lucio et al., 2023). Herez et al. (2025) simulated a Fresnel CPVT system with spectral splitting, achieving total efficiencies above 60%, where PV cells captured the visible spectrum while absorbers converted infrared to produce useful heat. Experiments have been conducted on spectral-splitting CPVT collectors showing that it could yield electrical efficiencies around 20% along with thermal efficiencies exceeding 70% (Wang et al., 2023).

Building-integrated PV-T (BIPVT) systems integrated PV-T modules into roofs, façades, or shading devices. It allows them to serve as construction materials while generating energy simultaneously. However, the effectiveness of BIPVT depends strongly on insulation and glazing (Tiwari et al., 2023). It has been further highlighted that BIPVT is promising for net-zero urban buildings, as it provides dual functionality while saving space (Herrando et al., 2023). Architectural studies confirm that semi-transparent PV and selective coatings can enhance energy efficiency while maintaining building aesthetics recently (Liu et al., 2022).

2.3 Components of PV-T System

This section will mainly focus on the key components to build a PV-T system suitable for residential application in Malaysia as well as focusing on enhancements approaches to enhance thermal management techniques.

2.3.1 Solar Cells and Photovoltaic Modules

A PV module, also known as a solar panel, is a device that captures sunlight and converts it into electrical energy through the photovoltaic (PV) effect. The process involves a material that raises an electron to a higher energy state from the absorption of light. The movement of this high energy electron from the solar cell is then flowed into an external circuit to generate electric power, dissipating its energy in the external circuit and returning to the solar cell. The

photovoltaic energy conversion typically uses semiconductor materials in the form of p-n junction.

When light shines on the surface of the photovoltaic (PV) cell, photons from the sunlight are absorbed and provide energy to the electrons inside a semiconductor material. The energized electrons will leave their positions and create an electrical flow into an external circuit. A solar cell typically is built with two semiconductor layer, n-type that are n-type and p-type. N-type layer has an excess of electrons where p-type layer consists of excess positively charged holes, forming a p-n junction and internal electric field at the interface when the two layers are brought in contact. The free electrons are then driven to the n-side and holes to the p-side in field, preventing them from recombination. Once the separation occurs, the electrons will flow through an external circuit to recombine with holes on the other side, produce usable electrical power. The region where this separation occurs is known as the depletion zone, where the actual generation of current takes place here. In simple terms, the photon's energy excites electrons, p-n junction is the force to drive the separation of charges, and the external circuit provides the means for current to flow, which we can use as electricity (Gundogdu et al., 2021).

Solar cells are divided into 3 generations based on their characteristics and technical advancements. First generation includes both single and multi-crystal variations, typically monocrystalline and polycrystalline. Despite being more expensive, it provides a high level of efficiency and contributes to more than 90% of the PV industry (Soonmin et al., 2023). Monocrystalline silicon cells are manufactured using highly purified silicon and are characterized by their uniform crystal structure. They are known for achieving the highest efficiencies among silicon-based technologies, with records of 26.1% and even 27.6% under concentrator systems (Lu, 2023). Their main advantages include high power output per unit area, excellent durability, and long lifespan, making them ideal in applications where space is limited. Moreover, these cells work well in low sunlight conditions, where it is ideal for cloudy conditions (Mdallal et al., 2025). However, their precise and energy-intensive manufacturing processes makes them significantly unaffordable, resulting a longer payback period (Lu, 2023). On the other hand, Polycrystalline silicon cells are made from multiple silicon crystals, resulting in lower production costs and simpler

fabrication (Kant and Singh, 2022). However, they achieve slightly lower efficiencies, up to 23.3%, with low performance ratio and efficiency. Their main drawbacks are lower efficiency compared to monocrystalline cells, larger space requirements, and more thermal losses with higher temperature increase (Lu, 2023).

Second generation solar cells use thin films technologies, that were developed to address the cost and material intensity of crystalline wafers. Despite having lower efficiency than first-generation cells, second-generation cells are considered cost-effective by using micrometre-thick semiconductor layers. Amorphous silicon (a-Si) is lightweight and cheap but achieves only 13.8% efficiency with higher degradation rate. Cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) provides higher efficiencies of around 23%, with CdTe being especially more expensive and cadmium are toxic (Lu, 2023; Mdallal et al., 2025). Thin films hold less than 10% of the market but are used in applications where flexibility and low weight are crucial.

Lastly, third generation are still emerging but demonstrate rapid progress in solar cells development. Perovskite solar cells (PSC) have risen from below 10% efficiency in 2009 to 25.7% today, while tandem designs such as perovskite/Si and III–V/Si have achieved 34–36% efficiencies (Mdallal et al., 2025). Other technologies such as organic, dye-sensitized, and quantum dot solar cells offer unique benefits like flexibility and tunable absorption but with lack of stability and short lifetimes. Multi-junction devices currently hold the efficiency record at 47.6% under concentrated light, but high costs only allow for niche uses (NREL, 2023). Table 2-1 shows the comparison of mainstream solar cell type in the current market.

Table 2-1: Comparison of Mainstream Solar Cell Type

Sources	Types	Efficiencies	Pros	Cons
Lu (2023)	Monocrystalline Si	26.1	Highest efficiency, long lifespan, stable	High cost, energy-intensive manufacturing

Lu (2023)	Polycrystalline Si	23.3	Lower cost, easier to produce, widely available	Slightly lower efficiency, larger area needed
Lu (2023), Mdallal et al. (2025)	Thin-Film (a-Si, CdTe, CIGS)	a-Si: 13.8%; CdTe: 23.3%; CIGS: 23.4%	Lightweight, flexible, cheaper, scalable	Lower stability, Cd toxicity, variable efficiency
Mdallal et al. (2025)	Perovskite (PSC)	25.7%	High efficiency growth, low-cost potential	Poor stability, not yet commercial
Mdallal et al. (2025)	Tandem (Perovskite/Si, III–V/Si)	34-36%	Very high efficiency	Complex, costly
NREL (2023)	Multi-junction	47.6% (with concentrator)	Record efficiency, wide spectrum absorption	Very expensive, niche uses

In summary, monocrystalline silicon remains the most efficient and reliable technology, while polycrystalline provides a cheaper alternative at slightly lower performance. Thin films offer cost and flexibility advantages but has issues with efficiency and stability, and third-generation cells highlight the future direction of PV research though they are not yet ready for widespread commercial deployment.

2.3.2 Thermal Absorber Plate

The thermal absorber plate is a crucial component in PV-T systems; it transfers unused solar energy in the form of waste heat from PV laminate into a working fluid. The choice of materials used strongly affects both thermal and electrical

efficiency of the system (Korkut et al., 2022). Metals with high thermal conductivity, such as copper and aluminium are widely used to minimize resistive heat losses and stabilize PV-T system. Copper has a very high conductivity and provides superior thermal transfer, but it costs more while aluminium offers as a cheaper and lightweight alternatives, particularly in roll-bond configurations (Colombini et al., 2021).

However, front surface cooling does not use conventional metallic backplate for heat extraction. Instead, the protective front glass cover of the PV module functions directly as the primary thermal absorber and heat exchange interface. This design significantly reduces the thermal resistance path, as heat no longer needs to conduct through the encapsulation and rear structural layers before interacting with the working fluid (Mostakim et al., 2024).

Furthermore, using a water layer over the glass surface allows for better optical properties that benefit electrical generation. Water contains a refractive index of approximately 1.33, which acts as an intermediate optical matching layer between the ambient air (refractive index of 1.0) and the panel glass (refractive index of 1.52). This optical matching reduces reflection losses and enhances the transmission of the visible light spectrum into the solar cells (Raad et al., 2025). Concurrently, the water film actively absorbs the infrared portion of the solar spectrum, converting it directly into useful thermal energy without reducing the photovoltaic effect, thus establishing a highly efficient dual-purpose mechanism (Mostakim et al., 2024)

2.3.3 Fluid Flow Channels

The arrangement and setup of fluid distribution channels are important to determine the uniformity of the cooling process and the required pumping power. While traditional systems utilize internal serpentine copper tubing, front-surface PV-T uses external distribution mechanisms, primarily atomized spray nozzles or perforated header pipes. Experimental investigations have demonstrated that full cone nozzles provide superior cooling capabilities compared to hollow cone or flat fan nozzles, as they ensure a more even distribution of water droplets across the entire surface area, thereby minimizing localized hot spots (Wibowo et al., 2024).

In addition to the nozzle type, the diameter of the nozzle significantly influences the droplet size and the overall cooling effectiveness. Research indicates that using a full cone nozzle with a 2 mm diameter hole can effectively reduce photovoltaic panel temperatures from 61.96°C down to 36.51°C under high solar radiation, outperforming 3 mm nozzles by providing a more consistent spray coverage at the same mass flow rate (Wibowo et al., 2024). By optimizing the system with flow rate, the system can achieve uniform conductive and convective heat transfer without the pressure drops due to complex internal piping.

2.3.4 Working Fluid

Selection of working fluid is crucial in determining the thermal and electrical performance of a PV-T system. Water and air are more commonly used fluids. Water generally provides superior cooling and heat transfer to its high specific heat capacity and thermal conductivity (Şirin et al., 2023). It helps to decrease the temperature of PV modules to operate at lower temperatures, yielding higher thermal efficiencies, typically in the range of 60-65%. In contrast, air is a simpler option that avoids issues such as corrosion or scaling. However, air has a lower heat capacity that limits thermal efficiency to 20-40% range, and unable to be used to require hot water supply (Attia et al., 2025).

Nanofluids are used to enhance heat transfer beyond conventional fluids such as Al_2O_3 , CuO , TiO_2 or SiC in a base fluid. Nanofluids improve the thermal conductivity and convective heat transfer coefficient of the fluid, leading to the better cooling of PV modules and higher energy yield. For example, a CuO and water nanofluid achieved a thermal efficiency increase of 3.3% and an electrical efficiency improvement of 1.1% compared to pure water at a flow rate of 60 kg/h (Madas et al., 2023). Similarly, SiC –water nanofluid used with micro-finned tubes to enhance the thermal efficiency to 77.5% and stabilized the PV temperature, resulting in an electrical efficiency of 9.6% (Bassam et al., 2023).

Moreover, further improvements have been made through bi-fluid systems that circulate two different coolants simultaneously such as air and nanofluid. Attia et al. (2025) reported that a PV-T module using a CuO and water nanofluid with air in a double heat exchanger with fins reached a thermal

efficiency of 78.19%, compared to the same system without fins with only 63.28%. This configuration also led to lower PV surface temperatures and improved electrical output (Lebbi et al., 2021).

Although advanced working fluid improves thermal and electrical performance of PV-T system, there are accompanied by several limitations. Conventional water is the simplest option, but it is typically used in closed loops and cannot be consumed directly due to risk of contamination and scaling. Corrosion in pipes is another concern if water quality is not controlled (Alshibil et al., 2023). On the other hand, the addition of nanoparticles in nanofluids increases viscosity and pressure drop, causing stronger pumps to be needed, leading to higher energy consumption. Furthermore, stability issues such as agglomeration, sedimentation, and fouling in narrow flow channels can reduce system reliability, where abrasive nanoparticles may erode surfaces at higher concentrations (Awais et al., 2021). Bi-fluid systems that combines air and nanofluid coolants improves efficiency but consist of complex system and higher capital cost due to dual heat exchangers and the need for optimized design parameters (Attia et al., 2025). Table 2-2 shows the comparison of different working fluid and the efficiencies. These limitations cause the need of careful considerations when selecting working fluids for household-scale PV-T systems. Table 2-3 shows the advantages and disadvantages of each working fluid.

Table 2-2: Comparison of Different Working Fluid and their Efficiencies

Source	Working Fluid	Thermal Efficiency	Electrical Efficiency
Şirin et al. (2023)	Water	60–65%	Moderate
Attia et al. (2025)	Air	20–40%	Low-Moderate
Madas et al. (2023)	Nanofluids	70–77%	+1–2% above water
Attia et al. (2025)	Bi-Fluid	72–78%	Higher than single fluid

Table 2-3: Advantages and Disadvantages of Different Working Fluid

Source	Working Fluid	Advantages	Disadvantages
Alshibil et al. (2023)	Water	High specific heat, widely available, low cost.	Risk of scaling & corrosion, typically closed loop and unsuitable for consumption.
Attia et al. (2025)	Air	Simple design, no corrosion risk, can work passively.	Poor heat transfer capacity, unsuitable for domestic hot water.
Madas et al. (2023)	Nanofluids	Higher thermal conductivity, better PV cooling.	Higher pumping power, stability issues, fouling/clogging in tubes, costly preparation.
Attia et al. (2025)	Bi-Fluid	Dual cooling mechanisms increase overall efficiency.	Complex design, high capital cost.

2.3.5 Water Flow Setup Configurations

The type of water flow setup configurations highly affects the thermal recovery and the electrical improvement of a hybrid PV-T system. Among active water-cooling strategies applied to the front surface of photovoltaic modules, the common methodologies are continuous laminar film flow and forced sprinkler systems (Mostakim et al., 2024).

In a continuous laminar flow configuration, water is directed over the front surface of the photovoltaic panel to establish a thin, uniform cooling layer. Experimental and computational fluid dynamics (CFD) modelling by Menacer et al. (2025) showed that by applying a top-down laminar water flow on to the

PV module, it facilitated rapid and even heat dissipation. Because the water maintains consistent direct contact with the glass interface, this laminar flow mechanism is effective, reducing cell surface temperatures by over 35°C under peak radiation. Consequently, this thermal extraction significantly improved the panel's overall performance, boosting the net electrical power output by 30.9%, even when factoring in the parasitic energy consumption of the circulation pump. Similarly, Jailany et al. (2016) utilized a forced-water technique where a thin film of water flowed down from the top of the panels, which successfully decreased solar cell temperatures by 9.07°C and resulted in a power gain of 9.27%.

Conversely, forced circulation using a sprinkler or misting system uses pressurized nozzles to distribute water droplets across the PV surface. Wibowo et al. (2024) conducted an experimental to compare various type of nozzle and found that full cone provides better cooling performance compared to flat fan or hollow cone nozzles. The full cone design delivers a more uniform and consistent spray distribution across the panel, minimizing localized thermal gradients; using a full cone nozzle with a 2 mm diameter successfully reduced the panel temperature from 61.96°C to 36.51°C and increased efficiency from 10.98% to 14.47%.

Misting nozzles can effectively reduce operating panel temperatures from 45.08°C down to 34.12°C by spraying it onto the panel's surface. Operating at an optimal mass flow rate of 1.56 L/min, this specific cooling effect yielded peak electrical efficiency enhancements of 16.78%. Furthermore, besides thermal management, intermittent water spraying serves as an automatic self-cleaning mechanism. The regular removal of accumulated dust and atmospheric soiling has been proven to restore and boost PV panel efficiency by approximately 2.53% (Mostakim et al., 2024).

However, they exhibit major operational drawbacks, primarily excessive water consumption and the continuous parasitic electrical draw of the pumps. To address these inefficiencies, recent advancements have introduced smart cooling automation. Chaich et al. (2026) developed an intelligent cooling system utilizing an Arduino-based microcontroller to regulate water spraying based on real-time thermal feedback. The controller was programmed to activate the water pump only when the panel's rear surface temperature

exceeded a predefined threshold of 40°C. The system achieved a maximum instantaneous efficiency gain of 28.8%, dropping the panel surface temperature from 58.6°C to 36.7°C. Most importantly, the automated smart cooling system delivered a 15.5% average efficiency improvement while consuming 84% less water than a typical continuous cooling setup. This massive reduction in water usage, decreased pump operation time, significantly lowers the annual levelized cost of power production, establishing smart spray systems as a highly economically viable and sustainable solution for high-temperature climates. Table 2-4 shows different configurations of front-surface water cooling.

Table 2-4: Front-Surface Water Cooling Configurations from Literature

Source	Configuration	Setup	Thermal Performance	System Performance
Menacer et al. (2025)	Continuous	Top-down	Reduced PV	Improved net
	Laminar Film	laminar water flows over the front surface.	cell temperature by over 35°C under peak radiation.	electrical output by 30.9%.
Jailany et al. (2016)	Continuous	Thin film	Decreased solar	Achieved a
	Laminar Film	of water flowing down from the top of the panel.	cell temperature by 9.07°C	power gain of 9.27%
Wibowo et al. (2024)	Forced	Compared	Reduced panel	Increased
	Sprinkler (Nozzle Comparison)	full cone, hollow cone, and flat fan nozzles.	temperature from 61.96°C to 36.51°C.	electrical efficiency from 10.98% to 14.47%.

Mostakim et al. (2024)	Forced Sprinkler (Misting)	Front-surface misting nozzles operating at a mass flow rate of 1.56 L/min.	Reduced operating panel temperatures from 45.08°C to 34.12°C	Improved by 16.78%. Self-cleaning dust removal boosted efficiency by 2.53%
Chaich et al. (2026)	Smart Cooling Automation	Arduino-controlled system activates spraying when the panel exceeds 40°C.	Surface temperature dropped from 58.6°C to 36.7°C.	Maximum efficiency gain of 28.8% (average of 15.5%). Consumed 84% less water than continuous cooling.

2.3.6 Forced versus Passive Circulation

Hydraulic configurations significantly influence the performance and applicability of hybrid PV-T and solar water heating system. Forced circulation (FC) employs pumps to regulate mass-flow rate and outlet temperature. It allows precise thermal control and integration with large storage volumes. In contrast, natural circulation (NC) or thermosyphon relies on buoyancy forces to eliminate the use of pumps and reduce operational cost and complexity.

The basic principle of natural circulation is that solar heating reduces the density of the working fluid in the collector, causing it to rise into the storage tank while denser cold fluid sinks to replace it. This passive loop is a continuous operation if there is a temperature gradient between the collector and tank. In forced circulation, a small pump drives the fluid regardless of buoyancy forces. It allows a more precise control and stable flow rates, but it requires electricity

and introduces mechanical components that requires maintenance (Sakellariou et al., 2023).

An experimental comparison was conducted between FC and NC system under continuous operations. Results shown that FC system outperformed the thermosyphon design with a solar fraction (SF) of 0.62 against 0.48 and thermal efficiency of 68.2% against 53.53% (Sakellariou et al, 2023). PV-T systems also note that FC configurations are generally more effective in reducing PV cells temperature that maintains electrical efficiency. Building-integrated PV-T systems with forced circulation system achieved lower average and peak PV cell temperatures compared to naturally ventilated ones, with electrical efficiency gains up to 5.3%. However, natural ventilation can only be effective if the inlet temperature and insolation were both high (Bandaru et al., 2021).

2.3.7 Insulation

In PV-T systems, insulation is a crucial role in reducing heat losses from the rear and the sides of the module to the environment. It is unlike glazing, which is already integrated into standard PV modules and does not need to be separately considered here, the rear and edge insulation determines how effectively the system can retain its thermal energy. Without proper insulation, convective and conductive heat losses may occur to the surroundings which will result in both thermal yield and decrease of overall system efficiency and system life (Joo et al., 2023). Materials such as polyurethane (PU) foam and mineral wool are commonly employed due to their low thermal conductivity and durability (Ebrahim, 2021).

Different insulation materials have been tested in PV-T applications. EPDM foamed rubber has been used because it is lightweight and flexible. It is easy to laminate to the collector back sheet and provides moderate insulation, but it is not fire resistant (Joo et al., 2023). Mineral wool is another common option, valued for its fire resistance and stability at elevated temperatures. Mineral wool maintains reliable insulating performance even under thermal stress with conductivity in the range of 0.030–0.046 W/m·K. Hence, making it suitable for long-term applications (Ablaoui et al., 2023).

A study from Basuhaib et al. (2024) used a different approach with epoxy resin to be applied in a Malaysian water-based PV-T study. Epoxy resin was poured as the final backside layer to provide both physical protection and thermal insulation. Epoxy has a conductivity at around $0.20 \text{ W/m}\cdot\text{K}$, higher compared to foams or mineral wool. It eliminates air gaps, bonds strongly to copper tubes, and reduces convective losses that enhances thermal transfer to the fluid path.

Lastly, polyurethane (PU) foam is also the most widely used insulation materials in solar collectors with a very low conductivity at about $0.022\text{-}0.030 \text{ W/m}\cdot\text{K}$ range (Soloveva et al., 2022). It is an excellent thermal barrier while being lightweight and cost-effective. However, PU foams can degrade under prolonged heat exposure and are flammable unless treated with additives. Although PU foams are highly effective for insulation, its usage in hot climates may be a concern. Table 2-5 compares different insulation materials properties.

Table 2-5: Comparison of Different Insulation Materials

Sources	Material	Thermal Insulation ($\text{W/m}\cdot\text{K}$)	Pros	Cons
Joo et al. (2023)	EPDM Foam	0.25-0.30	Lightweight, flexible, easy to laminate.	Moderate insulation, not fire resistant.
Ablaoui et al. (2023)	Mineral Wool	0.030-0.046	Fire resistant, stable at high temperature, durable.	Heavier, handling safety needed for fibers.
Basuhaib et al. (2024)	Epoxy Resin	0.2	Good bonding, reduces air gap, structural protection.	Higher conductivity than foams/wool, may degrade under heat.

Soloveva et al. (2022)	PU Foam	0.022-0.03	Very low conductivity, lightweight, cost-effective.	Flammable without additives, degrades under high temperature.
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2.3.8 Thermal Energy Storage

Thermal Energy Storage (TES) plays a critical role capturing and holding heat for later use, instead of wasting excess thermal energy when available. In renewable energy systems, especially solar often do not line up availability with consumption. TES enables surplus energy heat collected during sunny hours to be used later at night or during cloudy periods. TES systems are known as three categories: sensible heat storage (SHS), latent heat storage (LHS) using phase change materials (PCMs), and thermochemical storage (TCS) (Chavan et al., 2022). Figure 2-3 illustrates a closed-loop thermal energy storage system used for domestic water heating.

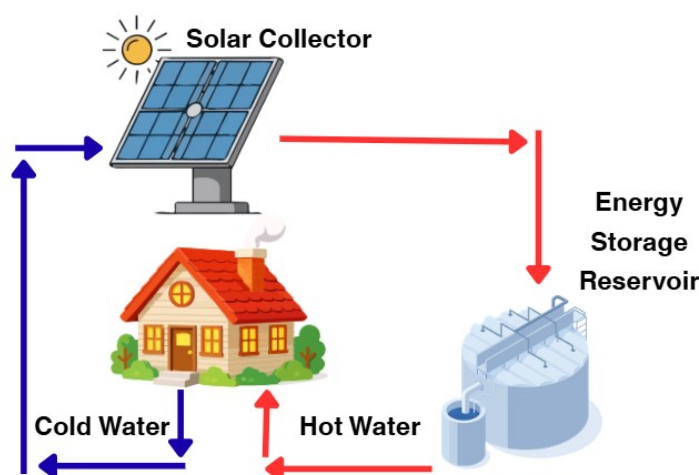


Figure 2-3: Thermal Energy Storage System Schematic

The cycle begins with cold water flowing from the house to solar collectors where it is heated by the sun's energy. This heated water is then directed to an energy storage reservoir, where it is held until needed. Finally, the hot water is distributed back into the house for consumption, and the cooled water returns to the solar collection to repeat the continuous process.

Sensible heat storage (SHS) stores energy by raising the temperature of storage media such as water, rocks or molten salts. Water is widely used due to its high specific heat, low cost and availability. However, it has drawbacks of having high vapor pressure and corrosivity. In Europe, water-based tanks are often used in residential area and district systems to allow large-scale seasonal storage, particular during winter (Zsiborács et al., 2024).

Latent heat storage stores energy during a phase of a material such as from solid to liquid. Phase Change Materials (PCM) are used due to its higher storage density and a near constant temperature, making it suitable for solar heating and building applications. For examples, in solar water heating, PCMs were integrated to maintain collector temperatures of ~ 63 °C for up to 15 hours without sunlight, achieving storage efficiencies of 75% compared to 57% for conventional systems (Eze et al., 2024). However, PCMs has a low thermal conductivity and material stability with high costs.

Thermochemical storage (TCS) provides the highest potential energy density and long-term storage capability without heat loss. Current studies explore salt hydrates and adsorption systems for integration with solar thermal power and district heating. However, their complexity and cost limits deployment of the system (Chavan et al., 2022).

For solar hybrid systems, integration of TES with PV-T collectors has been shown to improve both thermal and electrical performance. Studies demonstrated that PV-T systems integrated with TES tanks closely matches real-world data, with percentage error for storage temperatures kept under 8% (Sredenšek et al., 2021). Similarly in the Europe, linking PV systems with 200-L domestic electric water heaters provides a cost-effective TES option that increases self-consumption of PV energy, reducing the dependency on the power grid (Zsiborács et al., 2024). The wide-ranging applications of TES in solar water heating, PV/T systems, building energy efficiency, and industrial waste heat recovery proves a vital role to advance sustainable energy transition.

2.4 Temperature on PV-T Energy Efficiency

The performance of photovoltaic (PV) modules is highly affected by temperature changes. Typical crystalline silicon panels can yield efficiencies in the range of 14–20% under standard testing conditions. However, as cell

temperatures rise, their efficiency drops by about 0.40–0.50% for every degree above standard test conditions (Goh et al., 2024). This issue becomes even more serious in hot climates, where module surfaces can reach 60 °C or more, leading not only to immediate efficiency losses but also long-term material degradation (Herrando et al., 2023).

To counter these losses, hybrid photovoltaic–thermal (PV-T) systems have been developed. By circulating a fluid behind the PV module, excess heat can be removed, helping the PV cells to run cooler while the captured heat is used for domestic applications such as hot water or space heating (Tiwari et al., 2023).

A well-known outdoor study by Chhugani et al. (2019) tested this concept using two identical systems at ZAE Bayern in Germany. One module was connected to a water-circulated thermal collector while the other acted as a standard PV panel. The cooled panel is about 10 °C lower than the reference, resulting in 4.3% higher electrical output, while delivering 1.8–1.9 kWh/m² worth of thermal gain per day from the water circulation that captured heat. On certain days, the total efficiency reached more than 50%, significantly higher compared to the uncooled panel, yielding roughly 15%. These results clearly highlight the strong link between temperature control and overall system efficiency.

Colombini et al. (2021) showed that aluminium roll-bond PV-T absorbers can achieve thermal efficiencies above 80% while also lowering material costs compared to copper. Recent studies have reported that coatings and glazing improved thermal yields with combined efficiencies in the 60–70% range (Herrando et al., 2023). Similarly, it was estimated that household PV-T systems could reach overall efficiencies of 77% with payback periods of under seven years (Hui et al., 2025). Besides efficiency, by controlling temperature through PV-T, it helps to reduce thermal stress on PV cells and extend the lifespan. (Tiwari et al., 2023).

In short, temperature greatly impacts PV efficiency, but PV-T systems provide a practical way to turn other known as wastes into something more useful. By cooling the modules, electrical output is improved while useful thermal energy is recovered, making PV-T technology valuable in hot and humid regions like Malaysia.

2.5 Seasonal Variations in Malaysia

Tropical climates like Malaysia's offer abundant solar sources but come with complex factors, including humidity, monsoon rains, and haze. This section discusses local practices of PV-T systems, advantages and disadvantages of their implementation in homes, and their role in sustainable energy goals.

2.5.1 Monsoon and Dry Season Irradiance

Malaysia's equatorial location allows an abundant of solar radiation throughout the year. However, the magnitude and consistency of irradiance are strongly influenced by the country's monsoon cycles. There are two dominant regimes, the Northeast Monsoon that occurs from November to March and the Southwest Monsoon that occurs from May to September, along with two short inter-monsoon periods in April and October. The Southwest Monsoon are drier and brings shorter, less intense rain compared to Northeast Monsoon which brings heavy rains and wet weather. As a results, monsoon season in Malaysia generate distinct seasonal variations in rainfall, cloud cover, and atmospheric conditions that directly influence solar energy availability (Tan, 2018).

Studies conducted in Malaysia have demonstrated that irradiance levels are generally higher during the drier periods associated with the Southwest Monsoon, while the Northeast Monsoon brings persistent rainfall and cloudiness, reducing incoming solar energy. A year-long analysis was conducted at Kota Kinabalu, reported that solar radiation peaked in March and April, reaching more than 400 W/m², but dropped to 278.52 W/m² in January during the Northeast Monsoon. However, it has been noted rainfall and solar radiation do not always exhibit a simple inverse relationship, as different rainfall events and short-term meteorological fluctuations may affect daily radiation balance (Teong et al., 2017)

Similar findings were observed in Peninsular Malaysia, where rainfall regimes tied to the monsoon cycles affects monthly irradiance profiles. Kedah's average annual precipitation of 2,562 mm from 2007 to 2016 shows that seasonal rainfall patterns dominate, with the Northeast Monsoon limiting sun availability and creating larger wet season totals than the Southwest Monsoon (Tan, 2018). A study applied a modified Daneshyar model to estimate daily irradiation across Peninsular Malaysia that obtain values between 13.67 and

17.18 MJ/m²/day. The highest irradiation occurred in January (19.28 MJ/m²/day) in the relatively dry northern states, whereas the lowest was observed in November (10.53 MJ/m²/day) during peak monsoon rainfall (Shavalipour et al., 2013). These results confirm that the east coast that are dominated by the Northeast Monsoon, is less favourable for solar applications compared to the more stable northern and inland regions.

These seasonal difference in Malaysia are measured with ground-based radiation. According to Muhammad et al. (2020), the highest monthly average of irradiance was recorded in February (282 W/m²/day) at Seri Iskandar in Perak, with a maximum daily irradiance of 1,068 W/m² in September. On the other hand, November, when there was a lot of monsoon rainfall, had the lowest monthly mean (209.2 W/m²/day). Similar trends were recorded in Pekan, Pahang, where it was discovered lowest measurement at 469.2 W/m² in December and peaks of 874 W/m² in April (Saad et al., 2019). According to the analysis, the drier Southwest Monsoon consists of higher and more stable radiation, while the Northeast Monsoon months of November to January consistently produce the lowest irradiance mainly because their high humidity, cooler temperatures, and dense cloud cover.

Malaysia receives an average of 4.21 to 5.56 kWh/m²/day, or roughly 1,643 kWh/m²/year worth of irradiance. (Saad et al., 2019). While there are still regional variations, the Malaysian Energy Statistics Handbook also emphasizes solar availability in both Peninsular and East Malaysia, with the northern and inland states displaying more constant irradiance than the eastern coastal regions where monsoon impacts tend to be the greatest (Energy Commission Malaysia, 2020).

These seasonal dynamics are also noticeable in large-scale photovoltaic (PV) systems. In an analysis of the performance of a 50 MW solar farm in eastern Peninsular Malaysia, it was found that, higher solar input from irradiance during the Northeast Monsoon raised PV module temperatures and increases system stress, causing degradation and decreased efficiency. On the other hand, the Southwest Monsoon has a lower irradiance, limiting its potential for generation but it operates at favourable temperatures (Jamaludin et al., 2025). This further emphasizes pm how thermal stress and seasonal irradiance can both affect system performance.

This indicates that Malaysia has an abundant of solar resources but seasonally fluctuate. The Northeast Monsoon generates the lowest irradiance due to its high levels of humidity, cloud cover, and rainfalls compared to the Southwest Monsoon and inter-monsoon seasons can generate higher irradiance due to clearer skies. Therefore, to maximize yield and reliability, seasonal variations must be considered during system design.

2.5.2 Haze Events and Solar Energy Reduction

In Malaysia, haze events are one of the main barriers to solar energy use in Southeast Asia. Instead of conventional cloud cover, haze is composed of fine particulate matter and gaseous pollutants that absorb and disperse incoming solar radiation, significantly reducing solar irradiance and photovoltaic (PV) output.

The 2013 Southeast Asian haze crisis proofed that solar energy losses are related to haze. An empirical evaluation was conducted by using two photovoltaic configurations which are fixed flat plate (FFP) and tracking flat plate (TFP) that is installed at Universiti Putra Malaysia (Maghami et al., 2015). The results have showed that haze significantly decreased solar irradiance, where the FFP system experienced greater energy yield losses compared to the TFP system. The results showed that haze significantly reduced irradiance, with the FFP system suffering greater energy yield losses compared to the TFP system. This highlighted the combined impact of soiling and decreased solar transmittance. Ash and soot from Indonesian forest fires with particulate sizes below $12\text{ }\mu\text{m}$, where Air Pollution Index (API) during this time exceeded 200 at its highest point, making it hazardous (Maghami et al., 2015).

Moreover, average daily solar energy input for Terengganu was analysed and found that it was found that average daily solar energy input was $18.92\text{ MJ m}^{-2}\text{ day}^{-1}$, with significant fluctuations throughout the northeast monsoon because of elevated air visibility (Muzathik et al., 2010). Haze-related attenuations often cause extended low-irradiance periods that are difficult to predict. It is more abrupt and severe compared to seasonal monsoon that causes reductions of solar irradiance. Hence, it is crucial to take the difference into account during system sizing and performance forecasting of PV and PV-T hybrid systems.

Haze-induced irradiance loss has significant negative effects on the economy and environment. According to Bashir et al. (2015), Malaysian solar water heating and PV-T systems rely heavily on steady levels of solar radiation, and haze lengthens payback periods by lowering the number of effective solar days. The reliability of PV-T hybrids is dependent on irradiance levels between 230 and 800 W m⁻², with mean values of approximately 500 W m⁻² under clear conditions, (Tang et al., 2025) Irradiance is often suppressed below these thresholds by haze events, which limits thermal and electrical outputs.

Furthermore, national goals for the use of renewable energy are often challenged by declining solar resource availability. Even though Malaysia's renewable energy mix is still relatively small, rooftop solar PV are known as a major contributor to decarbonization strategies. The overestimation generation and savings could be resulted from assuming haze influence is minimal despite educational institutions having a large amount of rooftop PV potential (Kahiri et al., 2022). As a results, haze episodes increase dependency on grid-based fossil fuel generation and reduce capacity factors. It was warned by Islam et al. (2010) that atmospheric pollution continues to be a barrier to the expansion of solar energy in Malaysia, despite having abundant solar resources.

In conclusion, Malaysia's solar energy performance is often affected and limited by haze events. Physical losses in energy yield are caused by the direct decrease in irradiance, surface soiling, and possible deterioration of PV glass. These haze effects would jeopardize larger renewable energy goals and reduced PV returns at the household and institutional levels. Efficient mitigation techniques are encouraged to be applied such as optimal panel orientation, consistent cleaning schedules, and hybrid energy integration are crucial to maintain solar energy reliability.

2.5.3 PV-T System Design under Tropical Climate Conditions

Malaysia's position at the equator offers abundant solar energy potential, with average daily irradiation levels ranging from 4–6 kWh/m² across most regions (Mohammad et al., 2020). However, monsoon rains and cloud cover often reduce availability seasonally, as shown in Kota Kinabalu where southwest monsoon months saw lower radiation despite high rainfall variability (Teong et al., 2017).

In contrast to cooler climates, PV modules in tropical climates experience faster degradation and greater efficiency losses. The primary issues are dust, high cell temperatures, and humidity, all of which gradually lower output from PV modules. Certain thin-film alternatives function better in these circumstances, but crystalline silicon panels are most impacted. Henceforth, to maintain the systems' stability, practical measures like improved cooling, more robust encapsulation, and regular cleaning are required. Overall, studies indicate that when it comes to making PV function well in tropical regions, maintenance are equally as crucial as solar resources (Ogbomo et al., 2016).

The high humidity and temperature from tropical climates, influencing the efficiency of PV. According to empirical research conducted in Malaysia, module output decreases by 0.40- 0.50% for each degree Celsius that standard test conditions (STC) are raised. Besides that, Outdoor experiments in Perlis reported that PV surface temperatures exceeded 60 °C at peak irradiance, leading to significant efficiency drops from 15.4% at 25 °C to 12.3% at 65 °C (Amelia et al., 2016). Meanwhile, grid-connected systems at UKM averaged module temperatures at 39.5 °C and achieved a performance ratio of only 63.6% (Sopian et al., 2007)

Malaysia has enormous, untapped potential in residential settings. However, adoption is still low due to high installation costs, insufficient incentives despite having an area that receives 6-8 hours of sunshine per day and an average irradiation of 4-5 kWh/m² (Goh et al., 2024). Policy frameworks from government incentives such as the Feed-in Tariff (FiT) and Net Energy Metering (NEM) schemes have encouraged some adoption, but usage is still below potential (Goh et al., 2024). PV-T systems that can easily connect to the grid under these schemes or offer quick payback through savings on both electricity and hot water. Local PV manufacturing already exists in Malaysia, and this industrial base can support the development of PV-T systems at lower cost (Islam et al., 2010).

PV-T technologies are seen as promising technology in tropical countries such as Malaysia. By extracting heat from PV modules, PV-T systems can simultaneously enhance electrical efficiency and provide hot water where it is in demand for Malaysian households (Ogbomo et al., 2017). By making better

use of available solar energy, PV-T systems can improve energy efficiency and offer more value compared to standalone PV panels.

To keep up with Malaysia's sustainability goals, PV-T systems can offer plentiful environmental advantages. Carbon emissions have skyrocketed due to our country's heavy reliance on coal, reaching 118 million tonnes in 2006 and are expected to double by 2020 if no actions are taken (Shafie et al., 2011). Each household PV-T installation can save 3-4 tonnes of CO₂ per year if fossil fuel water heating is replaced with PV-T along with offsetting grid electricity (Goh et al., 2024). At the national scale, PV-T could save more than 2 million tonnes of emissions annually if only 10% of Malaysia's 7.5 million residential users adopted it (Abdullah et al., 2019). Apart from reducing carbon emissions, PV-T provides exceptional land-use efficiency by generating thermal and electrical energy from a single surface area where it is a crucial benefit in Malaysian cities with constrained rooftop space. Table 2-6 shows the difference in system performance tested in Malaysia.

Table 2-6: PV, Solar Thermal, and PV-T Hybrid System Performance in Malaysia

Sources	System Type	Primary Output	Typical Efficiency in Malaysia	CO ₂ savings per House
Amelia et al. (2016)	PV	Electricity	12–15% electrical (drops at >60°C)	2–3 tonnes/year
Jing et al. (2015)	Solar Thermal	Heat (Hot Water)	40–60% thermal (depending on design)	1–2 tonnes/year
Goh et al. (2024)	PV-T Hybrid	Electricity + Heat	12–14% electrical + 40–50% thermal	3–4 tonnes/year

2.6 Summary

Hybrid photovoltaic-thermal (PV-T) systems combines both electricity production and heat recovery to optimize solar energy use and achieve higher efficiencies relative to PV or thermal systems alone. Studies show that absorber materials, flow configurations, insulation, and advanced fluids such as nanofluids greatly enhance performance, with water-based systems in Malaysia

achieving around 70% thermal efficiency and enough hot water to provide a household. However, the unique challenges of a tropical environment, including high levels of humidity, changing incoming radiation due to the monsoon, and haze, limit PV efficiency and require optimized designs. Therefore, a clear research gap exists in the experimental evaluation and optimization of PV-T system configurations tailored to tropical environments. Addressing this gap is essential to fully realize the potential of PV-T technology in improving energy utilization, supporting residential applications, and advancing renewable energy and decarbonization efforts in Malaysia. For this reason, PV-T technologies may have excellent potential for supporting panel utilization, renewable energy, and decarbonization goals in Malaysia, but localized performance studies still need to be conducted.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter focuses on methodology adopted for the investigation of energy efficiency in a hybrid photovoltaic-thermal (PV-T) system for Malaysia households. The research uses both experimental and analytical approaches. It will begin with identification of suitable locations, followed by the design and fabrication of a prototype and collection, analysis, and evaluation of the thermal and electric performance. Literature review conducted was to scope and plan experiments to evaluate the performance of a PV-T System. The flowchart of workplan is as shown Figure 3-1 below.

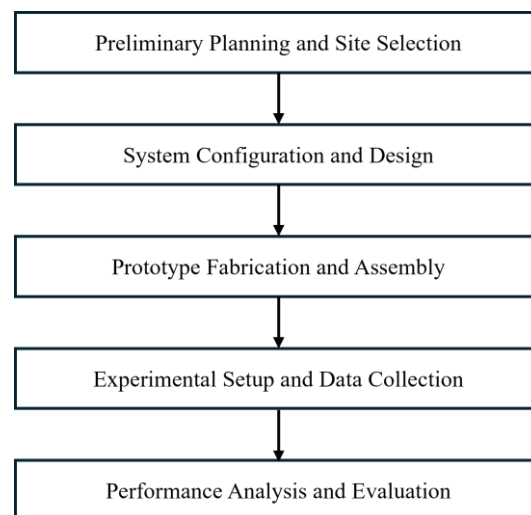


Figure 3-1: Flowchart of Experimental Workplan

3.2 Configuration of PV Systems

This section highlights the parameters for the setup of the PV-T prototype are before the testing. The geographical location chosen to maintain a consistent site testing, and the azimuth and tilt angles represented optimal solar exposure conditions under Malaysia. The pre-testing procedure also ensured that the prototype was appropriately orientated and had up-to-date baseline conditions of environmental parameters that had a direct impact to the testing.

3.2.1 Study Geographical Locations

Bandar Sungai Long is chosen to be geographical sites in Peninsular Malaysia to evaluate the performance. This site was selected based on their observable climatic differences, even though they are all located in the same tropical band, this site experiences abundant solar irradiance, heavy rainfalls and haze events. Previous research has shown that humidity and rainfall have an impact on PV output through its modification to irradiance, temperature, and module degradation in humid conditions Previous studies confirm that solar irradiance in Malaysia ranges from 4.21–5.56 kWh/m²/day depending on the region, with seasonal fluctuations due to monsoon events. (Mohammad et al., 2020; Teong et al., 2017). The aim is to capture the system's efficiencies under seasonal differences associated with the seasonal and regional availability of solar resource.

3.2.2 Azimuth and Tilting Angle

The azimuth angle indicates how and which direction the PV modules should be oriented to capture the higher amount of solar energy from the module. Results have shown that facing south-direction is the ideal orientation for Malaysia. This southerly direction can guarantee that the PV panels is able to capture the highest average irradiance throughout the entire year. Even though the azimuth angle is not as critical in tropical climates as it is at higher latitudes, it has been found that an azimuth angle error of about 10° to 15° will translate into a reduction in annual energy yield of about 3% to 5% annually (Sultan & Efzan, 2018). Figure 3-2 shows the PV module with azimuth and tilt angles.

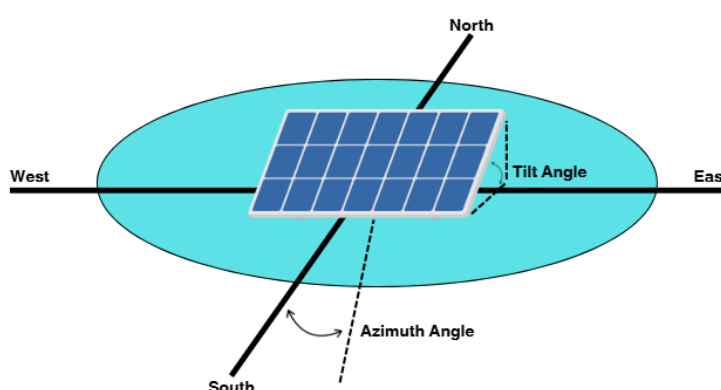


Figure 3-2: PV Module with Azimuth and Tilt Angles

Solar collectors can be affected by the amount of energy generated at specific times of the day as well. While a true south orientation can generate the most annual daily output from the panels, by slightly adjusting the azimuth position of the solar collectors to the east or the west, the collector(s) will be generating more for either the use in the morning or the afternoon core usage of residential households. Nevertheless, for residential household applications, the overall energy generation will be most equally distributed with a southern orientation system (Mohammad et al., 2020).

The azimuth position is associated with the azimuth angle. In this study, an angle of 10° - 15° was adopted, which is reasonable considering the latitude of Malaysia. This orientation provides good exposure during the year, and rain will wash the surface of the panels to limit losses in production due to soiling. In Malaysia, where the changes in season alter the angle of the sun as it sets in the spring and summer seasons at the equinox and solstice, these seasonal changes in solar path are less important, and allowing the azimuth angle to be fixed will be adequate. While solar trackers can also improve energy production, and would be possible to use in residential situations, they require an additional amount of capital investment and effort to manage.

3.2.3 Pre Testing Steps

Before deploying the PV-T prototype, a series of pre-testing measurements were conducted to establish baseline environmental and operational conditions. 2 solar panels, PV-T and standalone PV will be used to compare side by side.

The first phase of pre-testing will begin with the geometric alignment. The intended tilt angle to set for the PV modules will be between 10° and 15° , which is in keeping with Malaysia's latitude. A digital inclinometer will be utilized to measure and set tilt, ultimately deciding upon 10° tilt angle due to it allowing for optimal annual irradiance capture plus promoting natural panel cleaning during rainfall. The azimuth angle will orient to 180° (true south), as research suggests in equatorial locations this will produce a maximized year's energy yield. Validation and verification will be determined with a compass calibrated with GPS and carefully adjusted to minimize the error of misalignment. South-facing panel orientation will provide good balance of sun exposure on panels throughout the year, with the possibility of exploring west

orientation during planning, as in the past seasons west orientation appeared to be a better energy yield orientation as it aligns with highest peak household demand of load being air conditioners and lighting in later afternoons.

The next part is measurement of environmental parameters. Solar irradiance will be measured using a digital meter for solar power, which has sufficient resolution for quick variations under cloudy conditions. A HT-9815 Thermocouple will be used to measure initial temperature of both panels and the initial inlet water temperature. 2 methods of measurement will be used, with the first being manual collection and cross validated with custom-built Arduino data loggers.

3.3 Design Work for PV-T System Model

This section discusses the design and construction of the PV-T hybrid prototype used in this study. It details the PV modules, frame structure, fluid channel arrangement, working fluid and circulation system, insulation strategies, and the data collection process. Design decisions were based on literature review and suitability for small-scale households in Malaysian conditions. Figure 3-3 is the overview of the PV-T system configuration.

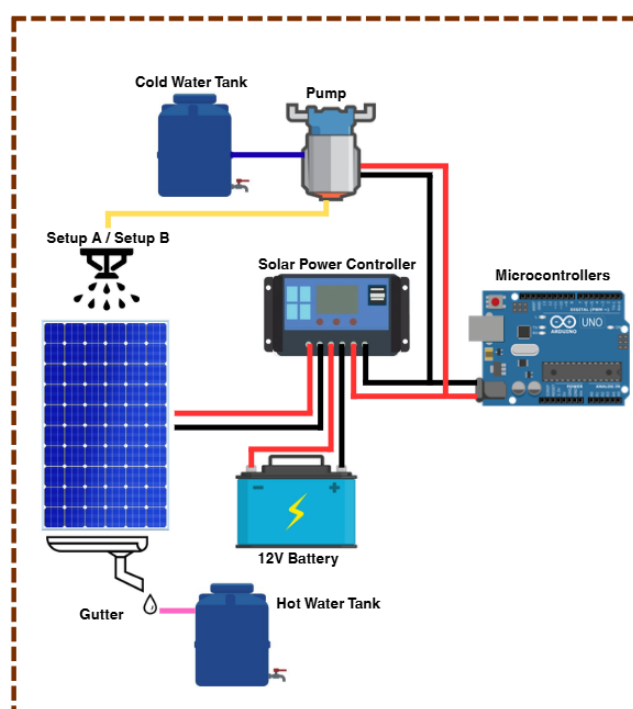


Figure 3-3: Overview of PV-T System Configuration

3.3.1 PV Module Selection

A monocrystalline solar panel from One-Sun is selected for this study. All technical data are tested by manufacturer at Standard Test Condition (STC): 1000 W/m², AM 1.5, 25°C. Table 3-1 shows the specifications of PV module used.

Table 3-1: PV Module Specifications

Description	Specifications
Name	Monocrystalline Solar Panel
Solar Module	0S-100M
Maximum Power (P_{max})	100 W
Maximum Power Voltage	18.24 V
Maximum Power Current	5.5 A
Open Circuit Voltage (V_{oc})	21.8 V
Short Circuit Current (I_{sc})	6.05 A
Power Tolerance	0~ + 6 W
Module Dimension	680 × 760 × 30 mm

3.3.2 Frame

The frame serves as a structural support for the PV module and ensures proper alignment for tilt and azimuth angle. In this project, the frame will be constructed of perforated steel angle bars, which are common, easy to assemble, and sufficiently sturdy to hold the PV-T system for brief periods of testing. The use of perforated bolts and nuts will allow flexibility in adjustment by relocating bolts and nuts to adjust tilt angles or additional reinforcement of structural joints. The frame design follows a triangular A-frame pattern for stability and to evenly distribute the load of the PV module. Figure 3-5 will be used as reference. The upper section will support the PV panel with a tilt angle that will remain between 10°, consistent with Malaysia's latitude and considering what the project recommends-testing conditions. The frame will contain cross-brace elements to reduce wobble and assist in a minding external factor such as wind or handling during setup. The frame used for testing is as shown in Figure 3-4.



Figure 3-4: Frame Assembly using Perforated Steel Members

The frame will support the PV module and maintain correct orientation of the PV module in regard to tilt and azimuth angles. For this project, the frame is to be built from perforated steel angle bars that are easy to find and assemble and are strong enough to hold the PV-T system during testing. In addition, the perforated bars include predrilled holes for ease of assembly, providing flexibility for multiple configurations. Although steel is heavier and more prone to rust than aluminium, it is practical to use for prototype development due to its strength, rigidity, and ease of construction. The frame will be coated in anti-rust paint to help protect the steel frame from humidity and rain during outdoor testing. The modular design utilizing bolts, nuts, and perforated bars is advantageous for later adjustments or transport.

Moreover, the angle of the panel is tested to ensure that water is able to be flowed down on to a designated gutter that is positioned at the bottom to be sent into a tank storing the water. The gutter is attached by drilling holes and using steel bar to be secured together onto the frame to ensure stability during data collection phase as shown in Figure 3-5 and 3-6.



Figure 3-5: Gutter System for Water Flow



Figure 3-6: Attached Gutter on Frame

3.3.3 Water Flow Configuration

To evaluate the cooling effects on the photovoltaic (PV) modules, two distinct water flow configurations were incorporated as Setup A and Setup B. Despite using different delivery methods, a standardized baseline was maintained for both systems to ensure a controlled testing environment. Both setups use an electronically controlled pump system programmed with Arduino to deliver a consistent water flow rate at 1.5 Liters per Minute and was set to an intermittent operating cycle, activating for exactly 30 seconds every 30 minutes. Furthermore, the glass surface of the PV panels in both setups was clean from dust or debris and coated with anti-fog spray. It is a critical step to reduce surface tension and preventing water from beading up to ensure it could spread smoothly and evenly across the entire face of the panels.

The first configuration, Setup A, was designed as a sprinkler system positioned above the PV panel. In this setup, water was forced through a sprinkler nozzle to create a continuous mist that falls onto the surface. The height of the sprinkler head was carefully calibrated and adjusted to ensure that the spray covers the entire panel without leaving dry zones. Figure 3-7 and Figure 3-8 shows the configuration of both setups used for testing.



Figure 3-7: Setup A Configuration



Figure 3-8: Setup B Configuration

On the other hand, Setup B utilized a flowing water mechanism to produce a sheet of water directly over the PV panel. This was achieved by installing a customized PVC header pipe horizontally along the top edge of the solar panel with holes on the pipe. Water was pumped into this pipe and allowed to cascade down on to the module, creating a thin, continuous film for direct contact cooling. To ensure that this water film was perfectly uniform and did

not channel into streaks of water, the drilled holes were distributed along the length of the PVC pipe and adjusted. This allows the water to be distributed equally across the width of the panel and effectively covering the whole surface area with a consistent layer of cooling water.

3.3.4 Working Fluid

The working fluid chosen for the hybrid PV-T system in this project would be plain water. It was chosen because the heated water obtained could be used for bathing, washing, or other household applications. While the research has shown that nanofluids enhance heat transfer, there are potential health risks associated with their use, as well as doubts regarding filtration and disposal of nanofluids. From a household perspective, plain water is the safest and most cost-effective approach to considering fluid types because it can be repurposed and does not require special disposal considerations.

The circulation loop consists of pumping water into PVC Piping to distribute water directly over the front surface of the PV module, replacing traditional rear-mounted copper channels. After flowing across the panel and absorbing the thermal energy, the water is collected into a storage tank by the gutter. The insulated storage tank is not used as the ambient solar heating of the tank would create inaccuracies during the thermal data collection. Instead, the thermocouples are placed at the edge of the gutter, allowing for precise monitoring of the outlet temperature immediately after the water exists the panel. Flowchart of the PV-T system is shown in Figure 3-9.

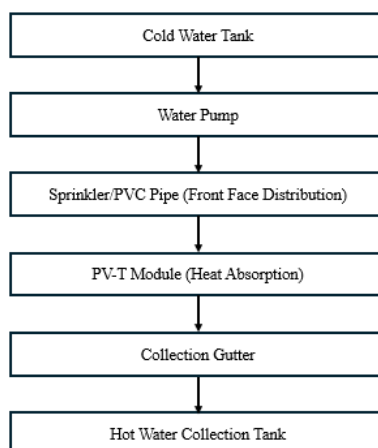


Figure 3-9: Flowchart of PV-T System Prototype

3.3.5 Water Pump

A water pump is utilized to circulate the water, operating at a constant flow rate of 1.5 L/min. This specific flow rate was selected to align with the output of the sprinkler system and is maintained consistently across both testing configurations (Setup A and Setup B) to standardised as a constant variable. The specifications of the pump used is as shown in Table 3-2:

Table 3-2: Pump Specifications

Description	Specifications
Name	Agricultural Electric Water Pump
Model ID	DP-521
Maximum Pump Pressure	0.48 MPa
Maximum Flow Rate	3.5 L/min
Rated Voltage	12 V
Rated Current	2 A

The flow rate of the pump was kept constant at 1.5 L/min using Arduino microcontroller. The Arduino is programmed to execute a strict intermittent cooling schedule, activating the pump for exactly 30 seconds at 30-minute intervals. To ensure self-sufficient operation, the pump and its associated control circuits draw power from a 12 V lead-acid battery. This battery is continuously recharged by the photovoltaic panel through a solar charge controller, making the system fully autonomous. It consists of a manual override switch, bypassing the automated sequence for manual operation as well. Pump controls with Arduino microcontroller can be seen in Figure 3-10.

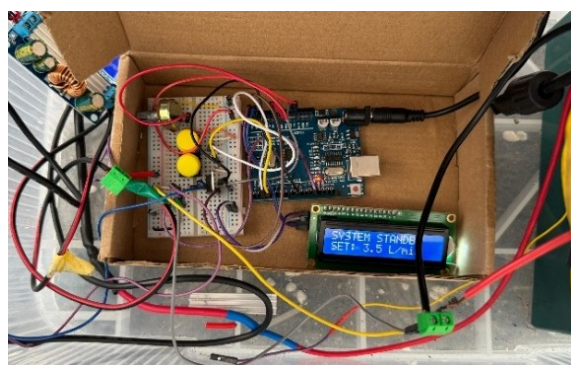


Figure 3-10: Pump Controls

3.3.6 Water Storage and Collection Tank

The experimental setup uses two storage containers to manage the cooling water cycle effectively. The primary reservoir for the unheated water is a 25-litre jerry can. The capacity was specifically chosen to ensure a sufficiency and uninterrupted supply of water throughout the entire duration of the daily testing period. The cold-water source tank is shaded to maintain a consistent baseline temperature. By protecting it from direct exposure to solar irradiance, the setup prevents unwanted ambient heating before the water is actively pumped over the PV module.

After the water flows across the solar panel, the heated water is directed into a separate, smaller container designated to be the hot water collection tank through the gutter. A filter funnel is installed at the top of the inlet to provide a direct flow into the container. The secondary tank has a smaller volume than the cold-water source tank. Hence, it's not used for long-term storage and only serves as a temporary catchment that is emptied regularly throughout the day to prevent overflow.

3.4 Data Collection Process

The data collection process is focused on obtaining both thermal and electrical performance indicators of the PV-T system in realistic operating conditions. Testing will take place during a complete day cycle, from 10:00 a.m. to 5:00 p.m., to observe variations based on weather and solar irradiance. This specific timeframe was selected to ensure the solar panel absorbs sufficient solar irradiance to reach operating temperature that allows effective heat transfer to the cooling water. Solar irradiance will also be recorded alongside system outputs.

For the thermal performance, the water temperature at the inlet and the outlet of the collector will be occupied throughout the entire testing period. This indicates the temperature rise achievable prior to sending the water for domestic use. The data that is collected, along with the measured flow rate and water collected after spraying, will allow for the calculation of useful thermal energy, and the system thermal efficiency.

The temperature of the PV cells will also be recorded to assess the cooling effect on the electrical performance. For electrical performance, the

open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) of the PV module will be collected throughout the day, allowing for the determination of electrical power and calculation of the electrical efficiency.

Figure 3-11 below shows the target parameters for data collection.

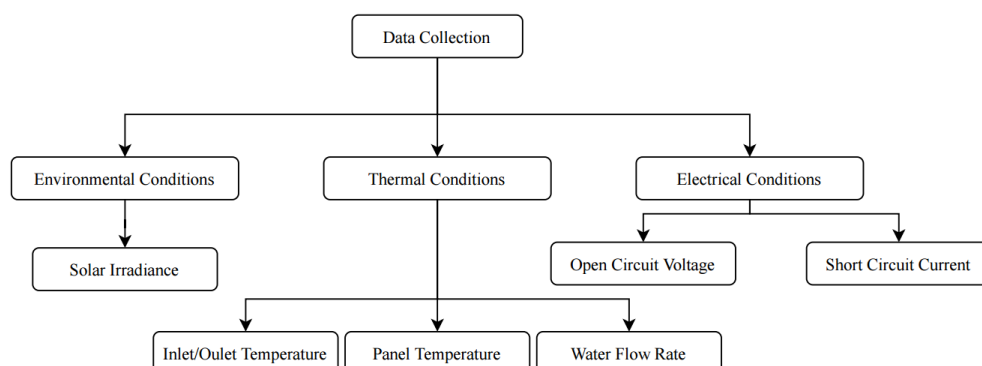


Figure 3-11: Data Collection Target Parameters

3.4.1 Data Measurement

The data measurement phase runs continuously from 10:00 a.m. to 5:00 p.m. The performance of the PV-T setup is directly evaluated against a conventional, standalone PV panel operating under identical environmental conditions. Standalone PV will be a control variable to establish a baseline, measuring relative thermal and electrical improvements. Furthermore, the water collected at the end of the gutter will be captured and measured to determine the average water that is collected after flowing down the panel.

Primary measurements will be conducted manually at 30-minute intervals and be compared with secondary automated data loggers. A digital multi meter and a clamp meter will be utilized to manually verify the open-circuit voltage and short circuit current. Additionally, handheld thermocouples will be used for inlet, outlet and panel temperature. A solar power meter is used to manually record the solar irradiance received. The data loggers will log real-time solar irradiance, inlet, outlet and panel temperature, open-circuit voltage and short-circuit voltage, recording data into a SD card.

To ensure accuracy and reliability, data will be recorded concurrently using fully automated data logging system and manual measurements. The results from the data loggers will then be directly compared against the manual

data to validate and verify the integrity of the finds. All the measurements will be recorded at consistent time intervals, and the data that is acquired will be utilized to determine daily variations, when peak performance is achieved, and the overall effectiveness of the PV-T system in a domestic household.

3.5 Performance and Efficiency Measurement

This section details the process for evaluating the hybrid PV-T system in real outdoor conditions. The evaluation will consist of monitoring solar irradiance, temperature, and thermal and electrical outputs of the system. The evaluation will cover several sites and testing conditions to ensure a range of seasonal and climate variation that affect the performance of PV-T systems in Malaysia. Standard equations for efficiency will be applied to the thermal, electrical, and overall efficiency to allow a consistent assessment of the performance of the system among all sites and operating conditions. Both PV-T and Standalone PV is measured and evaluated for accurate comparison.

3.5.1 Solar Irradiance

Solar irradiance data will be recorded over the testing duration using dual-measurement approach. Manual readings will be taken using a dedicated solar power meter to provide physical data points as shown in Figure 3-12 below.



Figure 3-12: Solar Power Meter

Simultaneously, continuous automated data logging will be conducted using an Arduino microcontroller equipped with a BH1750 light sensor. To prevent sensor saturation from direct and intense sunlight, a Neutral Density (ND) filter is attached above the sensor for accurate and properly scaled irradiance measurements as can be seen in Figure 3-13 below.



Figure 3-13: Solar Irradiance Data Logger

3.5.2 Panel Performance

During the testing period, the electrical performance of the solar panels will be evaluated under fluctuating environmental conditions. Manual measurement of open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) is recorded with a digital multimeter and clamp meter as shown in Figure 3-14 and Figure 3-15. These parameters are critical for determining the maximum power output generated by the PV modules based on the standard electrical power equation:

$$P_{max} = V_{oc} \times I_{sc} \quad (3.1)$$

where

V_{oc} = Open-circuit Voltage, V

I_{sc} = Short-circuit Current, A



Figure 3-14: Multimeter



Figure 3-15: Clampmeter

An automated logging system controlled by an Arduino microcontroller is used as a secondary measurement. The setup utilizes INA226 power sensor integrated with relay module to safely alternate between measurements states. To measure V_{oc} , the first relay connects to the panel to the sensor while the second relay remains open, allowing the Arduino to read the potential different without current flow. Once the Arduino triggers the second relay to close, it creates a short circuit that directs the I_{sc} through the sensor's internal shunt for measurement. By incorporating a Data Logger Shield the microcontroller autonomously logs the time-stamped voltage, current and calculate power values directly into an SD card. The dataset is then exported to Excel to analyse the power output to visualize the performance differences between PV-T and standalone PV throughout the day. Figure 3-16 shows the data logger to measure power output.

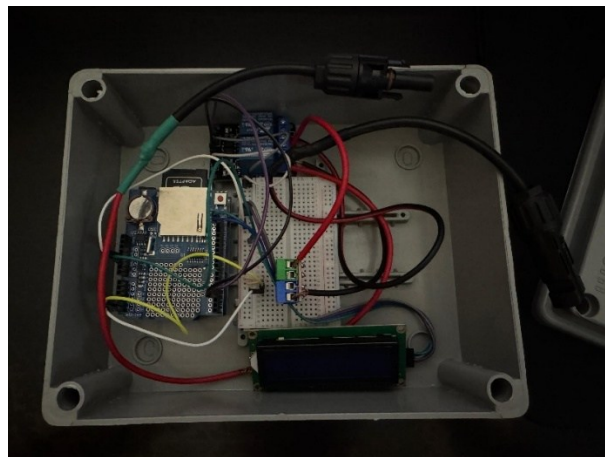


Figure 3-16: Power Output Data Logger

3.5.3 Mass Flow Rate Measurement

To accurately determine the mass flow rate of the cooling water circulating through the PV-T system, gravimetric measurement was used by measuring the physical mass of the water entering the inlet and exiting the outlet. This was achieved by collecting the water in a designated container for a specific timed duration. The collected water was then weighted using a digital scale. The outlet mass flow rate formula is calculated as shown:

$$\dot{m} = \frac{m}{t} \quad (3.2)$$

where

m = Mass of Outlet Water, kg

t = Duration of Water Flow, s

3.5.4 Efficiency of PV-T

The mass flow rate from the outlet is used is to potentially assess their effects on outlet water temperature and on thermal efficiency and PV cooling. In addition to inlet and outlet water temperature, PV cell surface temperature will be logged with HT-9815 K-type thermocouple (Figure 3-17) and Arduino controlled MAX6675 K-type thermocouples (Figure 3-18).



Figure 3-17: HT-9815 Thermocouple

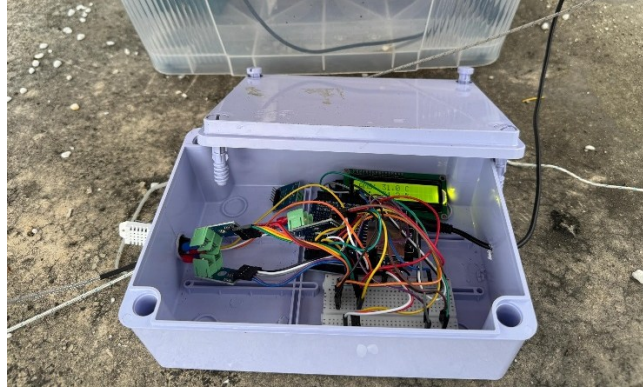


Figure 3-18: Temperature Data Logger

These surface readings allow for the average temperature reduction to be directly observed based on thermal regulation from circulating water, in comparison without cooling.

Thermal Efficiency of water is as calculated (Hu et al., 2025):

$$\eta_{th} = \frac{\dot{m}c_p(T_{out}-T_{in})}{G \times A} \quad (3.3)$$

where

$\dot{m}$ = Mass Flow Rate of Water, kg/s

c_p = Specific Heat Capacity of Water, J/kg·K

T_{out} = Outlet Water Temperature, °C

T_{in} = In Water Temperature, °C

G = Solar Irradiance, W/m²

A = Surface Area of PV-T Collector, m²

Electrical Efficiency for PV Module is as calculated (Tan et al., 2017):

$$\eta_e = \frac{V_{oc} \times I_{sc}}{G \times A} \quad (3.4)$$

where

V_{oc} = Open Circuit Voltage of PV Module, V

I_{sc} = Short Circuit Current of PV Module, A

Total Efficiency is as calculated (Basuhaib et al., 2024):

$$\eta_{tot} = \eta_e + \eta_{th} \quad (3.5)$$

where

η_e = Thermal Efficiency, %

η_{th} = Electrical Efficiency, %

With the reduction PV temperature to the electrical efficiency trends, we can connect how improved thermal management with higher electrical output under Malaysian climate condition. Hourly solar irradiance (W/m²) and logged environmental conditions data will be used to normalize performance and allow fair comparison between sites and weather conditions.

3.5.5 Economic Analysis

Economic analysis is conducted to compare Setup A and Setup B to translate the measured thermal and electrical performance of the prototype into monetary savings based on local utility area.

The thermal energy harnessed by the system is first quantified using the specific heat capacity formula:

$$Q = \dot{m}c\Delta T \quad (3.6)$$

where

$\dot{m}$ = Mass Flow Rate of Water, kg/s

c = Specific Heat Capacity of Water, J/kg°C

ΔT = Temperature Difference, °C

The calculation assumes an average of 4.5 Peak Sun Hours per day (Muzathik et al., 2010) over a standard 30-day billing cycle to project monthly energy savings. The equivalent energy savings are then monetized using the current Tenaga Nasional Berhad (TNB) domestic electricity tariff of RM0.334/kwh (Sustainable Energy Development Authority Malaysia, n.d.). By applying the tariff to both the thermal heat recovered, it offsets electric wate

heat and direct electrical power generated. The monthly savings for both configurations can then be calculated.

3.6 Summary

An experimental framework is employed in this research to assess the energy performance of a hybrid photovoltaic–thermal (PV-T) system in a household context in Malaysia. The prototype PV-T system was made up of a monocrystalline PV module, copper tubes as water channels, a storage tank, and insulation (like PU foam). The prototype was mounted on a frame of steel with a tilt of 10–15° and a south-facing azimuth tilt for maximum irradiance capture. Water was used as the working fluid for the system due to its practicality in household applications. Proper orientation, calibration of measuring devices and establishing baseline readings were completed before testing the system. The thermal and electrical performance of the PV-T was captured through readings of inlet and outlet water temperature, PV surface temperature, voltage and current outputs, while environmental variables of irradiance, temperature, and humidity were captured continuously in the same timeframe of 7 a.m. to 7 p.m. at different flow rates (range of 0.3–0.7 L/min). This research methodology provided an objective means to compare the energy performance of the PV-T during varying weather conditions, seasons and locations, while providing results pertinent to real household application and energy performance.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the experimental findings and performance analysis of PV-T system in comparison to a standard standalone PV Panel. The objective of these tests is to evaluate how effectively the cooling mechanism manage panel temperature and to prevent the efficiency losses while obtaining hot water for Malaysian household use. The data analysed was collected over multiple days but only days with usable results were selected. 2 configurations (Setup A and Setup B) were focused on with a standalone PV panel serving a baseline. Throughout the following sections, the system's performance is characterized with solar irradiance, electrical and thermal efficiency. Additionally, this chapter includes an analysis of the mass flow rate derived from water collection and an economic evaluation to assess the system's long-term feasibility.

4.2 Environmental Conditions

For this project, the performance of the hybrid PV-T system was evaluated under the tropical climate conditions of Malaysia. To ensure comprehensive analysis of the system's efficiency, data was collected in relation to solar irradiance profiles for both experimental setups. These environmental factors serve as the primary input variables for the thermal and electrical efficiency calculations

4.2.1 Solar Irradiance Profile

In this experiment, the irradiance levels were recorded at 30-minute intervals from 10:00 to 17:00 to capture the full progression of the solar window. Figure 4-1 and Figure 4-2 show the solar irradiance for both setup's day.

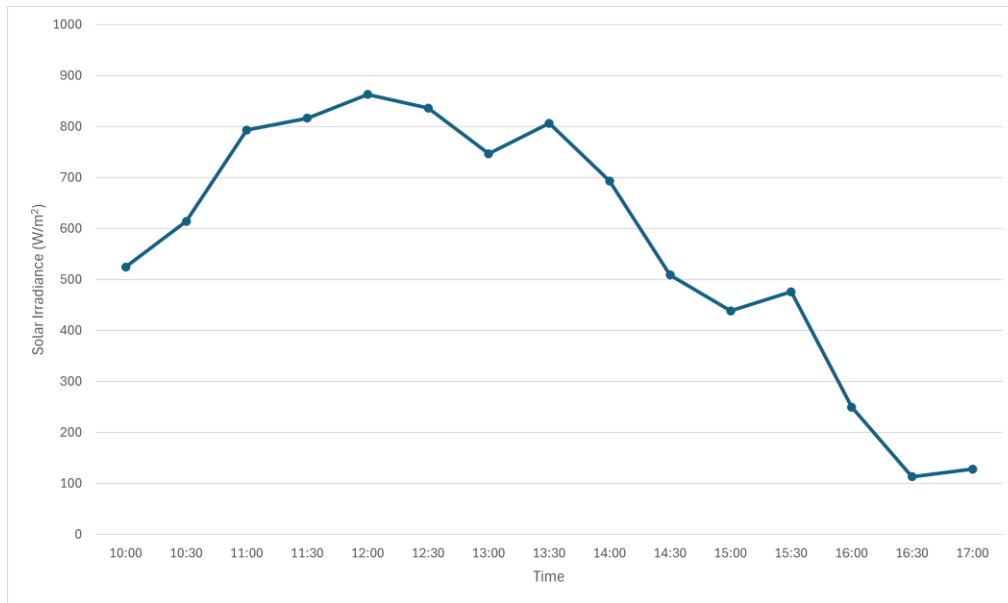


Figure 4-1: Solar Irradiance for (Setup A)

As shown in Figure 4-1, the testing day for Setup A (31/03/2026) exhibited a relatively consistent irradiance curve throughout the day. The irradiance climbed steadily from 524.5 W/m² at 10:00, reaching a peak of approximately 863.1 W/m² at 12:30. After the peak, the irradiance followed an afternoon decline with minimal fluctuations, providing an ideal baseline for evaluating the efficiency of the panel for Setup A under solar load.



Figure 4-2: Solar Irradiance (Setup B)

In contrast, Figure 4-2 showed the irradiance profile for Setup B (02/04/2026). While the morning trend reached a peak 787.7 W/m^2 at 11:30, sharp and drastic dip occurred at 12:00, where the irradiance decreased to 220.3 W/m^2 , followed by a recovery to 793.8 W/m^2 at 13:00, showing that the sunlight is blocked by clouds, representing an accurate depiction of Malaysian climate.

Setup A was testing under more idealized and consistent sun conditions while Setup B was subjected to real-world weather fluctuations. It helps to demonstrate the system's operational ability under the unpredictable conditions that are most likely to be encountered in domestic Malaysian applications.

4.2.2 Mass Flow Rate

The time measured is 30 seconds. Table 4-1 shows the mass flow rate for Setup A while Table 4-2 shows the mass flow rate for Setup B.

Table 4-1: Mass Flow Rate (Setup A)

Setup A					
Inlet Water Mass (kg)			Outlet Water Mass (kg)		
Before	After	Difference	Before	After	Difference
0	-0.79	0.79	0	0.55	0.55
0	-0.67	0.67	0	0.56	0.56
0	-0.71	0.71	0	0.51	0.51
Average (kg)		0.72	Average (kg)		0.54
Mass Flow Rate (kg/s)		0.024	Mass Flow Rate (kg/s)		0.018

Table 4-2: Mass Flow Rate of (Setup B)

Setup B					
Inlet Water Mass (kg)			Outlet Water Mass (kg)		
Before	After	Difference	Before	After	Difference
2.22	1.66	0.56	0	0.58	0.58
2.39	1.81	0.58	0	0.52	0.52
2.37	1.58	0.79	0	0.65	0.65
Average (kg)		0.64	Average (kg)		0.58
Mass Flow Rate (kg/s)		0.021	Mass Flow Rate (kg/s)		0.019

The mass flow rate for both configurations was determined over 30-second measurement. As shown in the experimental data, the outlet mass for both systems were lower than the corresponding inlet mass. Setup A recorded an average inlet mass of 0.72 kg but only recovered 0.54 kg at the outlet, resulting in the flow rate of 0.018 kg/s. In contrast, Setup B, despite having a lower inlet mass of 0.64 kg, recovered 0.58 kg, yield a higher outlet mass flow rate of 0.01 kg/s.

The significant loss in Setup A can be attributed to its spray cooling design. Since the test were conducted on an open rooftop, environmental wind likely dispersed the water droplets as it comes out from the sprinkler head before they could reach the collection tank. Setup B's design proved more robust against wind, capturing higher amount of inlet water. Discrepancies between the inlet of both setups are likely influenced by system factors such as pump cavitation or air pocket in the piping despite setting the same inlet flow rate for both setups. To ensure accuracy and reliability of data, all measurements were averaged across 3 measurements.

4.3 Thermal Performance Analysis

This section evaluates the thermal performance and behaviour of 2 PV-T configurations, Setup A and Setup B. Both are tested on 2 separate days, 31 March 2026 and 2 April 2026. The analysis focuses on the temperature distribution across the panels and the working fluid (water) to determine heat extraction efficiency between spray cooling method and the thin film contact method under Malaysian climate conditions. The inlet, outlet and panel temperatures (before and after) of Setup A and Setup B are evaluated against a standalone PV panel used as a control baseline.

4.3.1 PV Panel Temperature

Table 4.3 and Table 4.4 present the recorded panel temperatures for Setup A (tested on 31/03/2026) and Setup B (tested on 02/04/2026), respectively, compared against a standalone PV panel. Both setups are graphed to represent the trend as shown in Figure 4-3 and Figure 4-4.

Table 4-3: Panel Temperature of Setup A vs Standalone PV

Time	Solar Irradiance (W/m ²)	PV-T (Setup A)			Standalone PV	
		Before (°C)	After (°C)	Difference (°C)	Temp (°C)	Difference with PV-T
10:00	524.5	44.2	35.3	8.9	49.7	14.4
10:30	614.2	48.3	41.9	6.4	50.2	8.3
11:00	793.3	50.3	46.4	3.9	51.8	5.4
11:30	816.5	54.4	43.2	11.2	60.1	16.9
12:00	863.1	56.6	42.5	14.1	59.7	17.2
12:30	836.2	55.3	42.7	12.6	57.3	14.6
13:00	746.8	54.3	43.7	10.6	55.2	11.5
13:30	806.2	54.4	48.3	6.1	54.6	6.3
14:00	693.3	56.1	47.0	9.1	56.3	9.3
14:30	508.8	49.7	45.8	3.9	52.1	6.3
15:00	438.3	43.80	36.6	7.2	45.3	8.7
15:30	475.8	46.10	38.2	7.9	49.6	11.4
16:00	249.7	42.50	37.1	5.4	46.2	9.1
16:30	113.2	34.10	33.4	0.7	34.9	1.5
17:00	128.1	33.70	32.1	1.6	49.7	0.7

As observed in Table 4-3, Setup A demonstrated a significant amount of cooling during peak solar irradiance. While the standalone PV temperature reached a maximum of 60.1°C, Setup A maintained the panel temperature at approximately 42.5°C to 43.7°C. The maximum temperature difference from standalone PV to PV-T achieved was 17.2°C at 12:00.

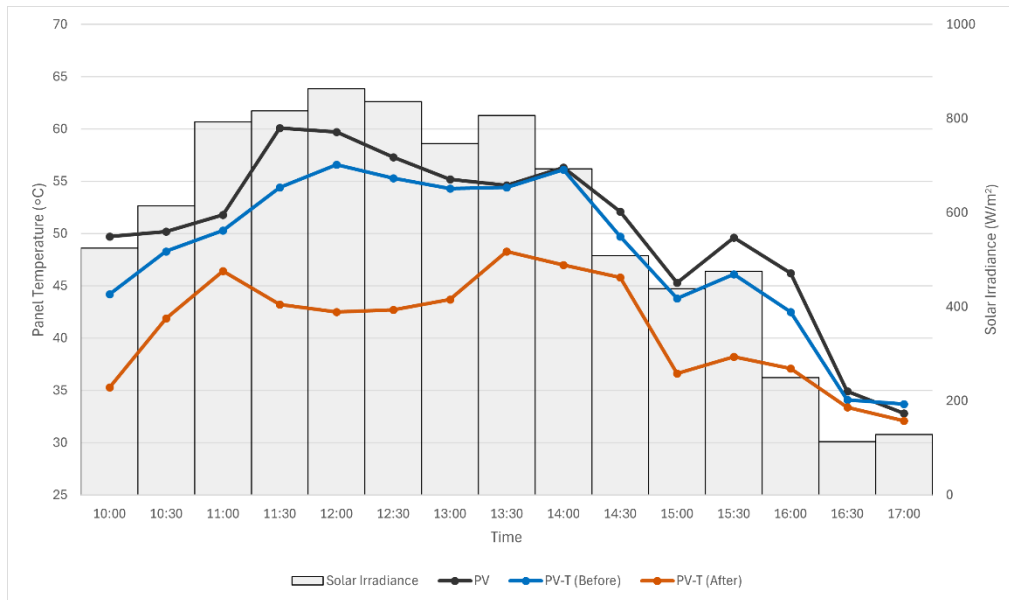


Figure 4-3: Graph of Panel Temperature against Time (Setup A)

The relationship between these variables is further illustrated in Figure 4-3 as the graph clearly displays the temperature gap between the standalone PV and the state of Setup A after spraying. This reduction is primarily due to evaporating cooling, where the spray mechanisms promote the absorption of latent heat from the panel surface as the water evaporates.

Table 4-4: Panel Temperature of Setup B vs Standalone PV

Time	Solar Irradiance (W/m ²)	PV-T (Setup B)			Standalone PV	
		Before (°C)	After (°C)	Difference (°C)	Temp (°C)	Difference with PV-T
10:00	506.8	43.8	41.2	2.6	44.2	3.0
10:30	649.2	44.3	40.3	4.0	44.7	4.4
11:00	710.8	44.9	40.2	4.7	45.2	5.0
11:30	787.7	50.2	47.2	3.0	50.6	3.4
12:00	220.3	40.4	37.4	3.0	42.1	4.7
12:30	644.3	52.4	49.9	2.5	53.1	3.2
13:00	793.8	57.3	51.0	6.3	53.2	2.2
13:30	616.1	48.7	47.3	1.4	48.9	1.6
14:00	687.9	51.5	44.4	7.1	50.1	5.7
14:30	663.1	46.4	44.8	1.6	46.4	1.6

15:00	223.1	43.1	42.3	0.8	45.0	2.7
15:30	228.0	41.8	40.5	1.3	40.9	0.4
16:00	356.3	38.8	37.7	1.1	39.2	1.5
16:30	344.0	36.3	36.1	0.2	37.3	1.2
17:00	226.5	37.0	36.7	0.3	37.4	0.7

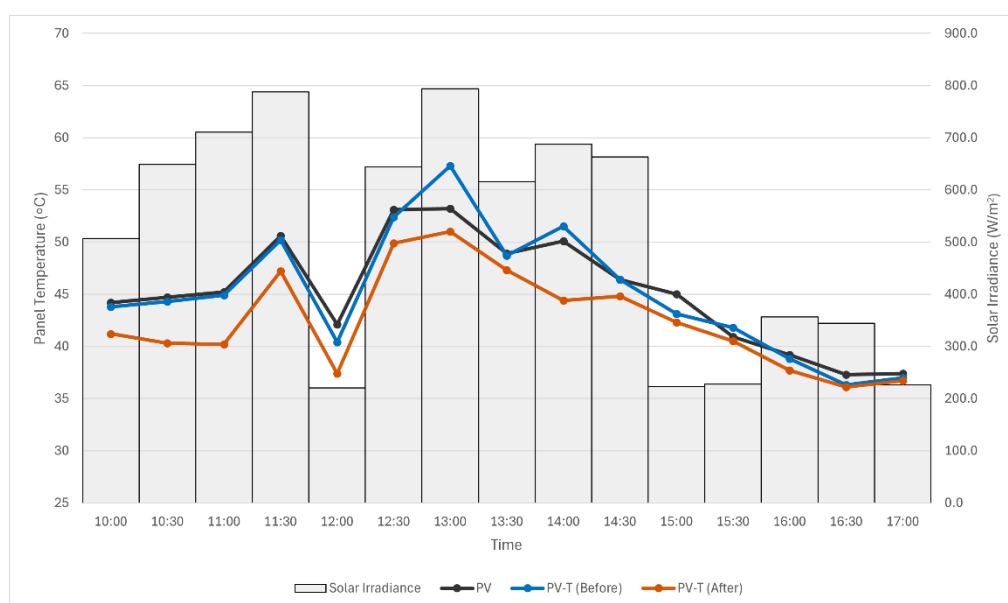


Figure 4-4: Graph of Panel Temperature against Time (Setup B)

For Setup B, the cooling effect was evident as shown in Table 4-4 and Figure 4-4, though the temperature differences were lesser compared to Setup A's peak performance. Setup B uses a direct contact that consists of thin film of water to cool. The lower temperature difference is also partly due to the solar irradiance on a different day, causing a lower ambient solar irradiance on a testing day compared to Setup A's.

4.3.2 Water Temperature Gain

To determine the feasibility of PV-T system for Malaysian household hot water applications. This section focuses on the temperature rise of the cooling water as it circulates both setups, using the temperature difference between inlet and outlet to quantify heat absorption. The water temperature gain for Setup A can be observed in Table 4-5 and Figure 4-5 while Table 4-6 and Figure 4-6 represented Setup B.

Table 4-5: Water Temperature Gain (Setup A)

Time	Solar Irradiance (W/m ²)	PV-T (Setup A)			
		Inlet Temperature (°C)	Outlet Temperature (°C)	Difference (°C)	Thermal Power (W)
10:00	524.5	37.3	39.6	2.3	171.5
10:30	614.2	33.9	36.8	2.9	217.2
11:00	793.3	33.4	36.8	3.4	254.6
11:30	816.5	34.7	38.2	3.5	259.1
12:00	863.1	34.4	38.1	3.7	277.1
12:30	836.2	33.8	37.3	3.5	262.1
13:00	746.8	33.7	36.6	2.9	217.2
13:30	806.2	35.1	38.3	3.2	239.7
14:00	693.3	37.1	39.2	2.1	157.3
14:30	508.8	35.8	37.2	1.4	104.9
15:00	438.3	35.6	36.8	1.2	89.9
15:30	475.8	35.4	36.8	1.4	104.9
16:00	249.7	36.3	36.9	0.6	48.7
16:30	113.2	27.0	27.2	0.2	15.0
17:00	128.1	28.7	28.9	0.2	17.2

For Setup A, the maximum heat gain, Q reached approximately 277.1 W. While the spray-cooling allows for greater panel temperature drop via evaporative cooling, the thermal energy captured in the water is limited because much of the heat is dissipated as latent heat during evaporation rather than being stored in the collecting water. Furthermore, the environmental losses caused by wind on the rooftop reduced the effective volume of water available for heat recovery.

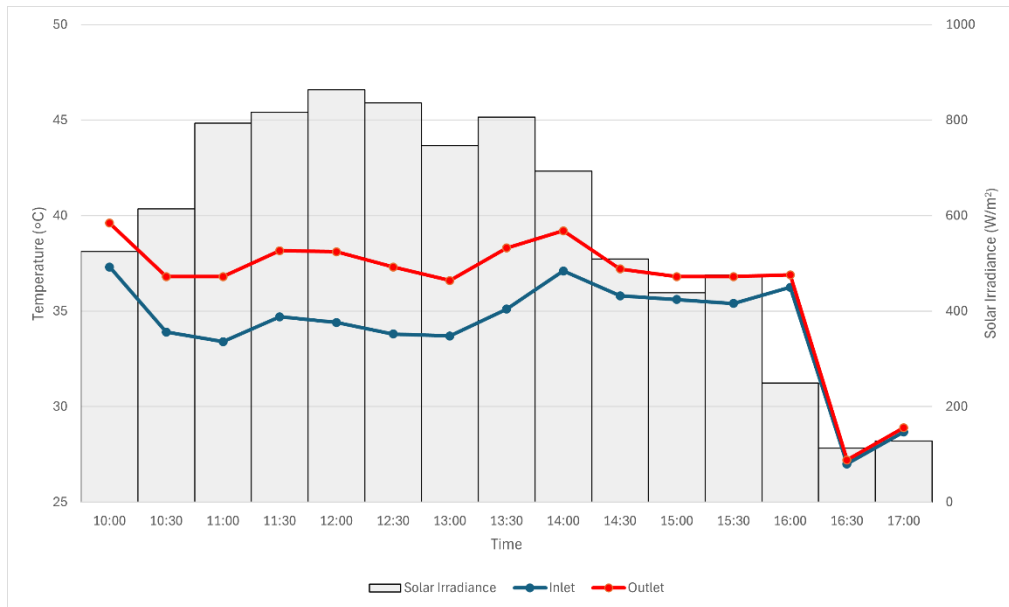


Figure 4-5: Graph of Inlet and Outlet Temperature against Time (Setup A)

Table 4-6: Water Temperature Gain (Setup B)

Time	Solar Irradiance (W/m ²)	PV-T (Setup B)			
		Inlet Temperature (°C)	Outlet Temperature (°C)	Difference (°C)	Thermal Power (W)
10:00	506.8	30.5	32.4	1.9	151.0
10:30	649.2	30.8	33.6	2.8	222.6
11:00	710.8	34.2	37.5	3.3	262.3
11:30	787.7	34.7	38.6	3.9	310.0
12:00	220.3	37.9	38.8	0.9	71.5
12:30	644.3	42.0	44.5	2.5	198.7
13:00	793.8	40.2	43.7	3.5	278.2
13:30	616.1	38.7	41.2	2.5	198.7
14:00	687.9	38.9	41.6	2.7	214.6
14:30	663.1	38.4	41.4	3.0	238.5
15:00	223.1	38.0	38.6	0.6	47.7
15:30	228.0	38.6	39.4	0.8	63.6
16:00	356.3	35.0	36.4	1.4	111.3
16:30	344.0	35.3	36.3	1.0	79.5
17:00	226.5	36.9	36.2	0.0	0.0

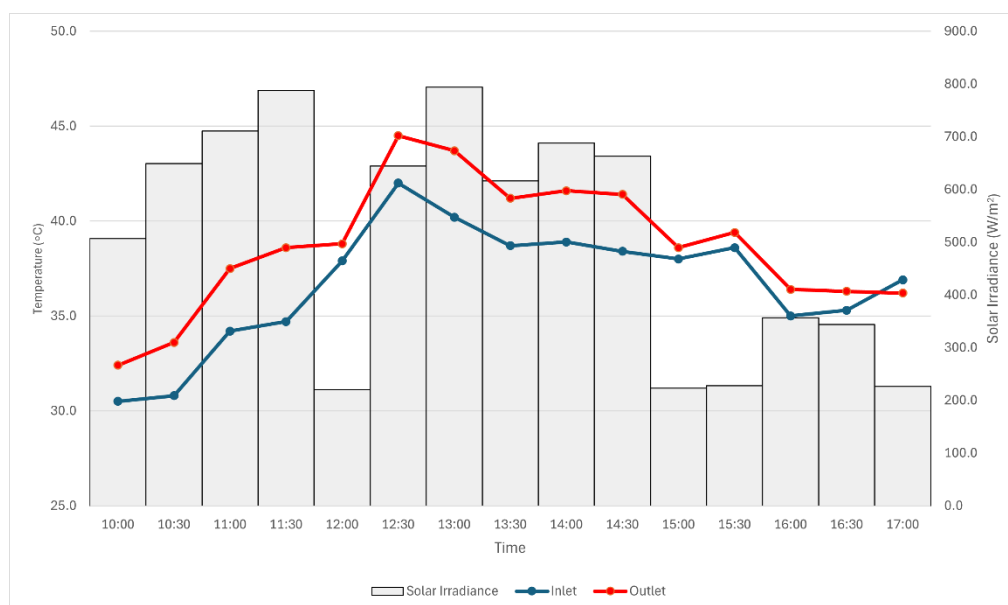


Figure 4-6: Graph of Inlet and Outlet Temperature against Time (Setup B)

Setup B achieved a higher peak thermal power of approximately 310.10 W. This is because of the direct contact of water, allowing more heat transfer compared to Setup A. By maintaining a sheet of water over the panel, Setup B maximises conductive heat transfer. However, when the panel rises excessively the film breaks in streaks, which hinders the thermal gain during peak afternoon period.

4.3.3 Thermal Efficiency

Thermal efficiency measures the system's effectiveness in converting incident solar radiation into useful thermal energy. This parameter is crucial for evaluating the potential of the PV-T system to meet the domestic hot water demands of a Malaysian Household while cooling the PV cells for better efficiency at the same time. Table 4-7 and Figure 4-7 shows the thermal efficiency throughout the day for Setup A while Table 4-8 and Figure 4-8 represented Setup B.

Table 4-7: Thermal Efficiency (Setup A)

Time	Solar Irradiance (W/m ²)	PV-T (Setup A)
		Thermal Efficiency (%)
10:00	524.5	63.3
10:30	614.2	68.5
11:00	793.3	62.2
11:30	816.5	61.5
12:00	863.1	62.2
12:30	836.2	60.7
13:00	746.8	56.3
13:30	806.2	57.6
14:00	693.3	43.9
14:30	508.8	39.9
15:00	438.3	39.7
15:30	475.8	42.7
16:00	249.7	37.8
16:30	113.2	25.6
17:00	128.1	26.0

As shown in Table 4-7, Setup A produced a higher thermal efficiency initially, peaking at 68.5% during the mid-morning interval. However, a noticeable downward trend was observed as the day progresses into the afternoon. Because the water is atomized and sprayed from a height, the windy conditions on the rooftop likely caused the water to be blown away, preventing a portion of water from reaching the panel. Furthermore, as the panel becomes extremely hot, the energy absorbed is to the latent heat of evaporation instead of increasing the water temperature, leading to a lower recorded thermal efficiency value.

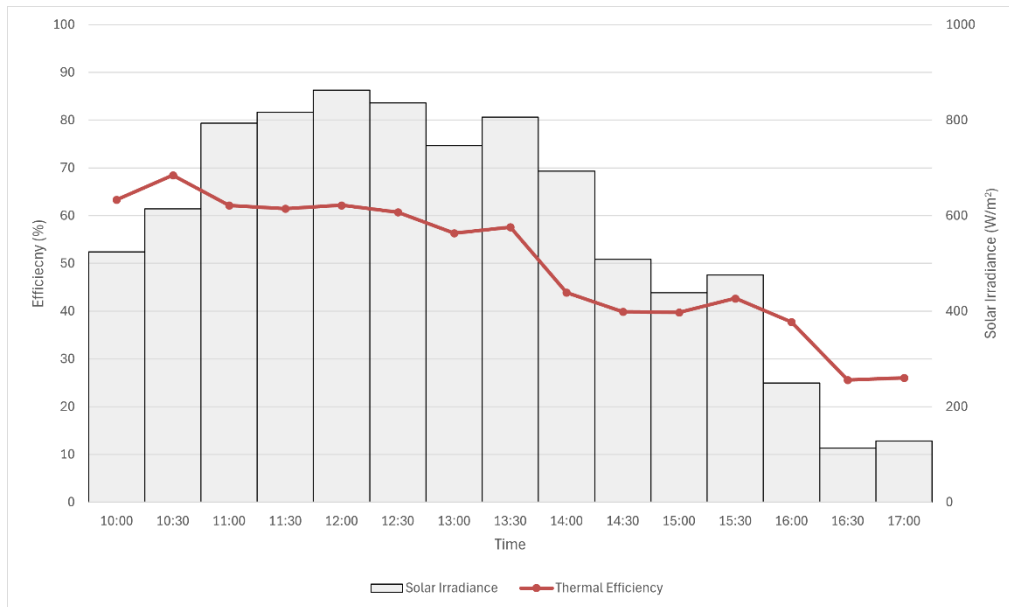


Figure 4-7: Graph of Thermal Efficiency against Time (Setup A)

Table 4-8: Thermal Efficiency (Setup B)

Time	Solar Irradiance (W/m ²)	PV-T (Setup B)
		Thermal Efficiency (%)
10:00	506.8	57.7
10:30	649.2	66.4
11:00	710.8	71.5
11:30	787.7	76.2
12:00	220.3	62.9
12:30	644.3	59.7
13:00	793.8	67.9
13:30	616.1	62.5
14:00	687.9	60.4
14:30	663.1	69.6
15:00	223.1	41.4
15:30	228.0	54.0
16:00	356.3	60.5
16:30	344.0	44.8
17:00	226.5	0.0

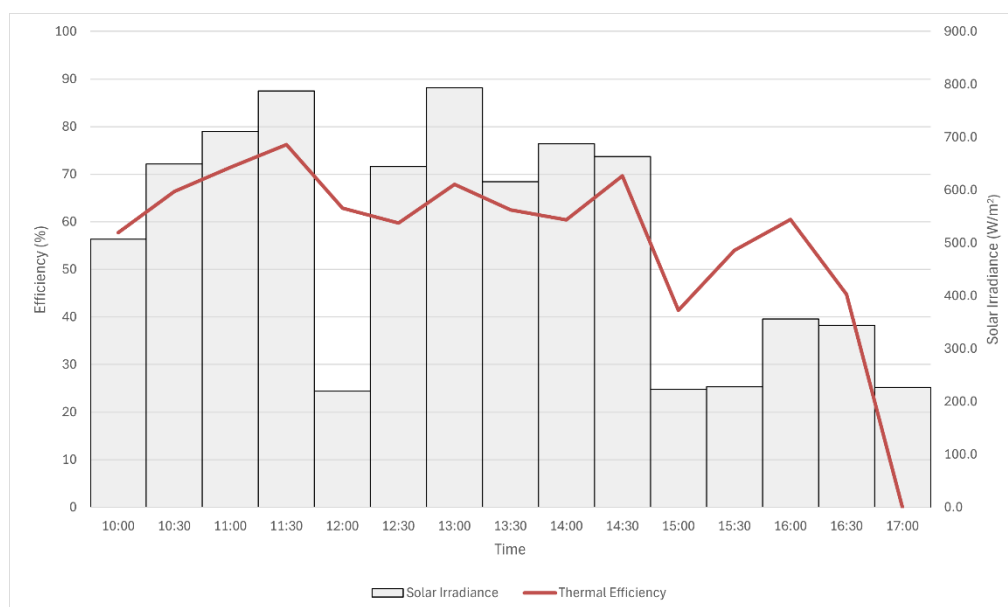


Figure 4-8: Graph of Thermal Efficiency against Time (Setup B)

In contrast, Setup B has a generally higher and more stable thermal efficiency profile, reaching a peak of 76.2% at 11:30. The primary reason is because of the direct contact of water; the system maximizes conductive heat transfer and minimizes the environmental losses that affected Setup A.

Despite its overall higher efficiency, the efficiency may fluctuate if the water film becomes unstable. If the panel temperature rises too rapidly, the water may form streaks of water instead of a uniform layer, temporarily reduces the heat exchange area. However, data from Setup B proved that it's able to maintain high efficiency even in the late afternoon. This high efficiency ensures that the system provides sufficient hot water for household use while reducing the temperature of PV module.

4.4 Electrical Performance Analysis

This section focuses on the power output of the PV cells to determine the relationship with the temperature and efficiency. The electrical performance of Setup A and Setup B is evaluated by comparing their maximum power output ($P_{\max}$) against a standalone PV panel. The cooling system is aimed to recover the voltage drop due to overheated panels, increasing the total electrical efficiency.

4.4.1 Power Output Comparison

Table 4-9 and Table 4-10 represents the electrical parameters for both setups with comparison to standalone PV, including Short Circuit Current (I_{sc}), Open Circuit Voltage (V_{oc}) and Maximum Power (P_{max}). The trend comparison for both setups can be observed in Figure 4-9 and Figure 4-10.

Table 4-9: Power Output Comparison (Setup A)

Time	Solar Irradiance (W/m^2)	PV-T (Setup B)							Standalone PV			
		Short Circuit Current (A)		Open Circuit Voltage (V)		Maximum Power (W)		Difference	Short Circuit Current (A)	Open Circuit Voltage (V)	Maximum Power (W)	Difference with PV-T
		Before	After	Before	After	Before	After					
10:00	524.5	2.4	2.6	19.8	20.5	46.6	53.4	6.8	2.5	19.9	50.5	2.9
10:30	614.2	2.8	2.9	19.8	20.5	56.2	58.4	2.2	2.8	19.9	56.1	2.3
11:00	793.3	3.6	3.7	19.9	20.2	72.3	74.4	2.0	3.6	19.9	72.3	2.1
11:30	816.5	3.7	3.8	19.5	20.1	72.7	76.9	4.2	3.6	19.6	71.0	5.9
12:00	863.1	3.8	3.7	19.7	20.2	74.0	74.8	0.8	3.6	19.8	70.9	3.9
12:30	836.2	3.4	3.7	19.6	20.2	66.8	73.7	7.0	3.5	19.6	69.1	4.6
13:00	746.8	3.5	3.7	19.6	20.2	68.7	75.6	6.9	3.2	19.9	62.6	13.0
13:30	806.2	3.6	3.8	19.6	20.3	71.1	76.2	5.0	3.2	19.6	62.9	13.2
14:00	693.3	3.5	3.5	18.3	20.3	63.4	71.4	8.0	2.2	19.4	42.9	28.5
14:30	508.8	1.8	2.3	19.1	20.2	35.0	46.6	11.6	2.1	19.2	39.5	7.1

15:00	438.3	2.0	2.1	19.9	20.6	40.6	43.8	3.2	1.9	18.5	34.9	8.8
15:30	475.8	2.4	2.4	19.9	20.1	47.4	48.4	1.0	1.7	19.7	34.3	14.0
16:00	249.7	1.2	1.3	19.2	19.4	23.4	24.4	0.9	1.0	19.3	18.8	5.6
16:30	113.2	0.4	0.5	18.6	18.9	7.3	8.7	1.4	0.4	18.7	8.0	0.7
17:00	128.1	0.4	0.5	19.0	19.1	8.0	9.2	1.2	0.6	9.1	5.2	3.9

As shown in Table 4.11, Setup A is consistently outperforming the standalone PV panel during the peak solar irradiance hours. At 14:00, the standalone PV power dropped to 42.9 W, while cooled Setup A maintained the output of 71.4 W, representing a power gain of 28.5 W. This confirms that the evaporative spray cooling effectively prevents thermal degradation of the solar cells.

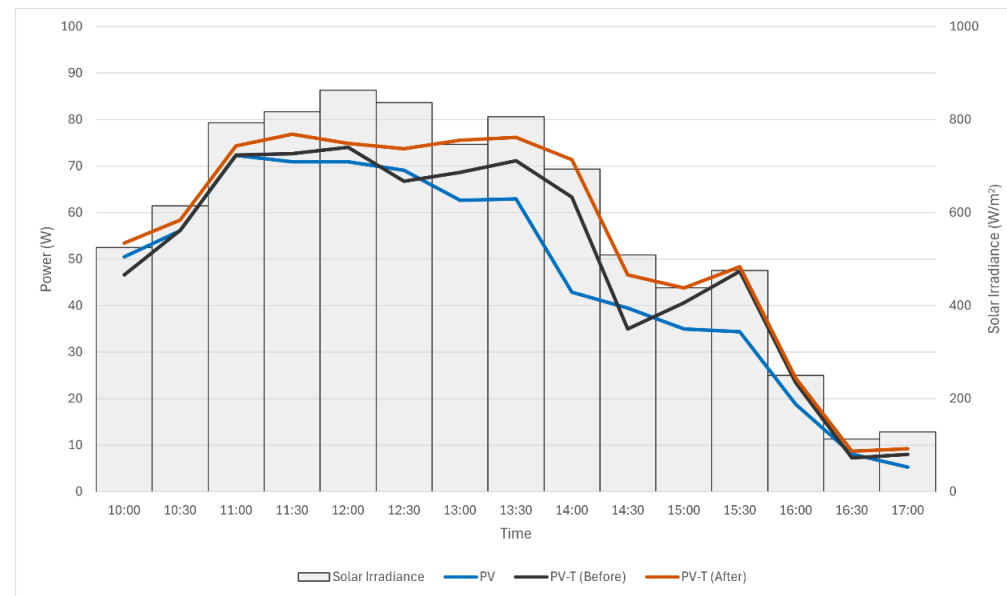


Figure 4-9: Graph of Power Output against Time (Setup A)

Table 4-10: Power Output Comparison (Setup B)

Time	Solar Irradiance (W/m ²)	PV-T (Setup B)							Standalone PV			
		Short Circuit Current (A)		Open Circuit Voltage (V)		Maximum Power (W)		Difference	Short Circuit Current (A)	Open Circuit Voltage (V)	Maximum Power (W)	Difference with PV-T
		Before	After	Before	After	Before	After					
10:00	506.8	2.6	2.7	19.7	20.2	52.0	54.4	2.5	2.7	19.6	52.8	1.6
10:30	649.2	2.9	3.1	19.8	20.4	58.1	62.5	4.4	2.9	19.6	56.7	5.8
11:00	710.8	3.0	3.1	19.9	20.1	60.1	61.5	1.3	3.0	19.8	58.9	2.6
11:30	787.7	3.1	3.2	19.8	20.1	61.7	63.6	1.9	3.0	19.7	59.3	4.4
12:00	220.3	1.0	1.1	19.4	19.8	19.7	22.2	2.5	0.6	19.6	11.6	10.6
12:30	644.3	2.8	2.9	19.9	20.1	55.5	58.4	2.9	2.3	19.7	45.4	13.0
13:00	793.8	2.2	2.5	19.4	20.1	42.2	49.3	7.1	1.9	19.6	37.3	12.1
13:30	616.1	1.7	1.9	20.3	20.3	35.1	39.4	4.3	1.5	20.3	30.4	8.9
14:00	687.9	2.9	3.5	19.4	19.7	57.0	69.2	12.2	2.9	19.5	56.6	12.6
14:30	663.1	3.2	3.4	19.0	19.8	61.5	67.9	6.4	2.9	19.6	57.0	11.0
15:00	223.1	0.9	1.1	20.1	19.5	18.5	21.3	2.7	0.9	19.1	17.6	3.7
15:30	228.0	1.0	1.0	19.3	19.6	18.9	19.8	0.8	1.0	19.5	19.7	0.1
16:00	356.3	1.6	1.6	19.7	20.2	30.6	33.0	2.4	1.5	19.8	30.1	2.9
16:30	344.0	1.6	1.7	20.3	20.3	33.3	35.1	1.9	1.3	20.2	26.2	8.9
17:00	226.5	1.0	1.0	20.1	19.3	19.3	19.9	0.6	0.7	19.9	13.3	6.5

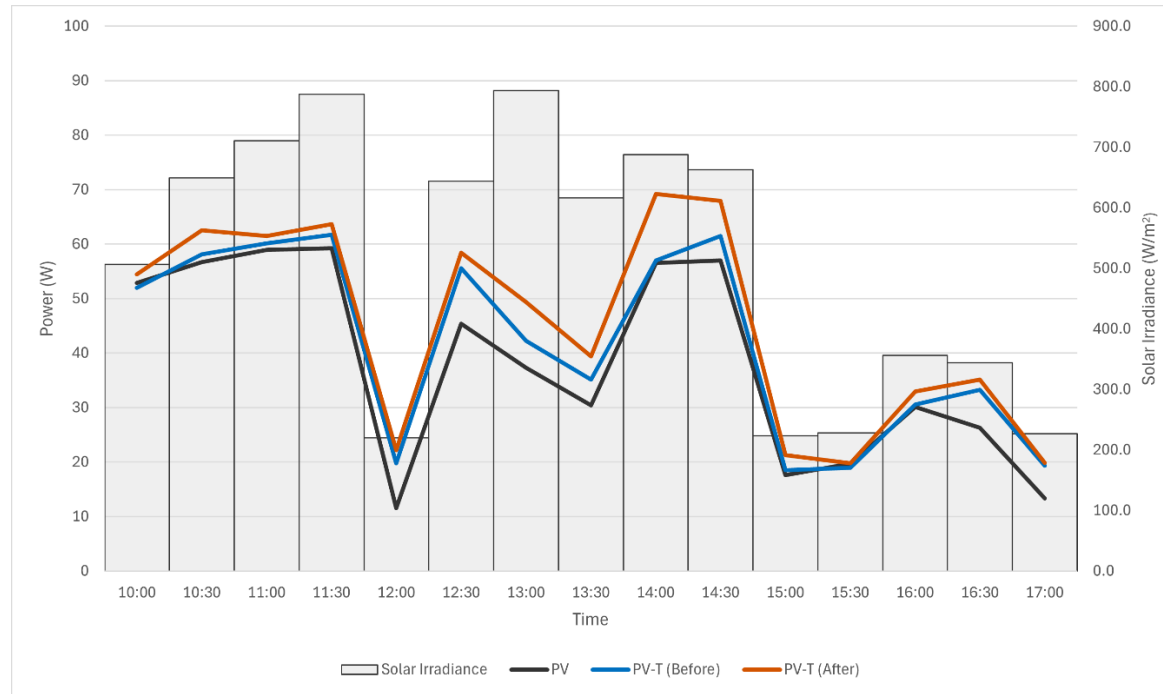


Figure 4-10: Graph of Power against Time (Setup B)

For Setup B, the standalone PV experienced a massive drop to 45.5 W at 12:30 while Setup B maintained at 58.4 W, resulting in power difference of 13 W. The consistent increase in power validates the theory that cooling recovers power loss due to heat.

Both Setups demonstrate that active cooling is essential for maintaining power stability in the Malaysian Climate. While the standalone PV suffers drastic power fluctuations as it heats up, the PV-T configuration improves its electrical output. Setup B's contact cooling showed a slightly electrical gain than Setup A, as the uniform water layer provides consistent thermal contact across the PV module

4.4.2 Electrical Efficiency

Electrical efficiency is to quantify how effectively the PV modules convert solar energy into electricity. Since solar cell efficiency is inversely proportional to temperature, the cooling mechanisms in both setups are expected to maintain higher efficiency levels compared to the standalone PV. Table 4-11 and Figure 4-11 shows the electrical efficiency for Setup A and Table 4-12 and Figure 4-12 represented Setup B.

Table 4-11: Electrical Efficiency (Setup A)

Time	Solar Irradiance (W/m ²)	PV-T (Setup A)			Standalone PV	
		Before (%)	After (%)	Difference (%)	Efficiency (%)	Difference with PV-T
10:00	524.5	17.2	19.7	2.5	18.7	1.1
10:30	614.2	17.7	18.4	0.7	17.7	0.7
11:00	793.3	17.7	18.2	0.5	17.7	0.5
11:30	816.5	17.2	18.2	1.0	16.8	1.4
12:00	863.1	16.6	16.8	0.2	15.9	0.9
12:30	836.2	15.5	17.1	1.6	16.0	1.1
13:00	746.8	17.8	19.6	1.8	16.3	3.4
13:30	806.2	17.1	18.3	1.2	15.1	3.2
14:00	693.3	17.7	20.0	2.2	12.0	8.0
14:30	508.8	13.3	17.8	4.4	15.0	2.7
15:00	438.3	18.0	19.4	1.4	15.5	3.9
15:30	475.8	19.3	19.7	0.4	14.0	5.7
16:00	249.7	18.2	18.9	0.7	14.6	4.4
16:30	113.2	12.4	14.9	2.5	13.8	1.2
17:00	128.1	12.1	13.9	1.8	7.9	6.0

As shown in Table 4-11, Setup A demonstrated a consistent efficiency advantage over the standalone PV. At 14:00, the standalone reached an efficiency of 12% due to excessive heat while Setup A reached at efficiency of 20%, resulting in 8% increase in efficiency. This highlights that evaporative cooling is stripping away heat that would cool the panel and increase efficiency.

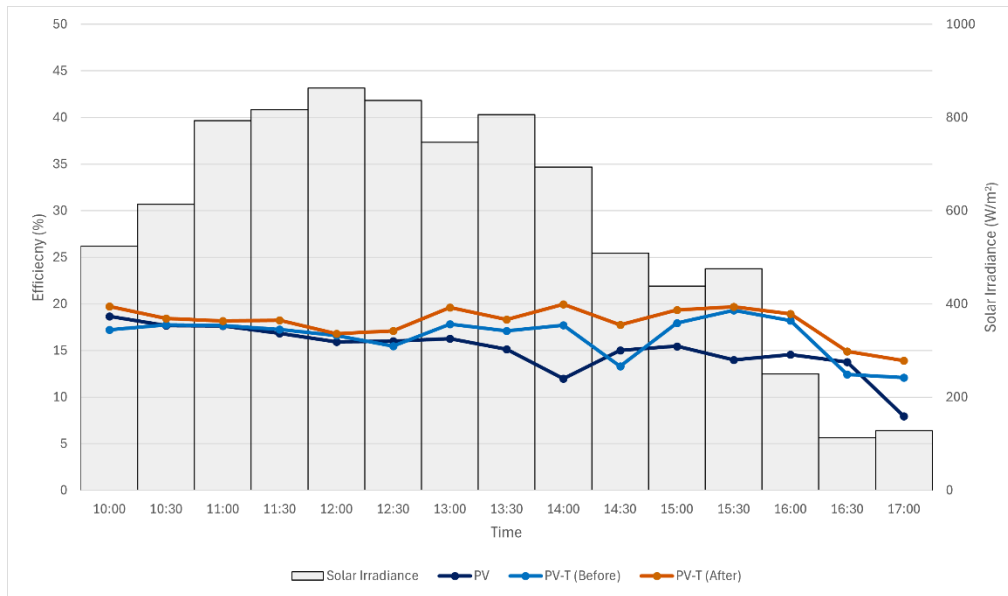


Figure 4-11: Graph of Electrical Efficiency against Time (Setup A)

Table 4-12: Electrical Efficiency (Setup B)

Time	Solar Irradiance (W/m ²)	PV-T (Setup B)			Standalone PV	
		Before (%)	After (%)	Difference (%)	Efficiency (%)	Difference with PV-T
10:00	506.8	19.9	20.8	0.9	20.2	0.6
10:30	649.2	17.4	18.7	1.3	16.9	1.7
11:00	710.8	16.4	16.8	0.4	16.1	0.7
11:30	787.7	15.2	15.7	0.5	14.6	1.1
12:00	220.3	17.4	19.5	2.2	10.2	9.4
12:30	644.3	16.7	17.6	0.9	13.7	3.9
13:00	793.8	10.3	12.0	1.7	9.1	2.9
13:30	616.1	11.0	12.4	1.4	9.6	2.8
14:00	687.9	16.1	19.5	3.4	15.9	3.6
14:30	663.1	18.0	19.9	1.9	16.6	3.2
15:00	223.1	16.1	18.5	2.4	15.3	3.2
15:30	228.0	16.1	16.8	0.7	16.7	0.1
16:00	356.3	16.6	17.9	1.3	16.4	1.6
16:30	344.0	18.8	19.8	1.0	14.8	5.0
17:00	226.5	16.5	17.0	0.5	11.4	5.6

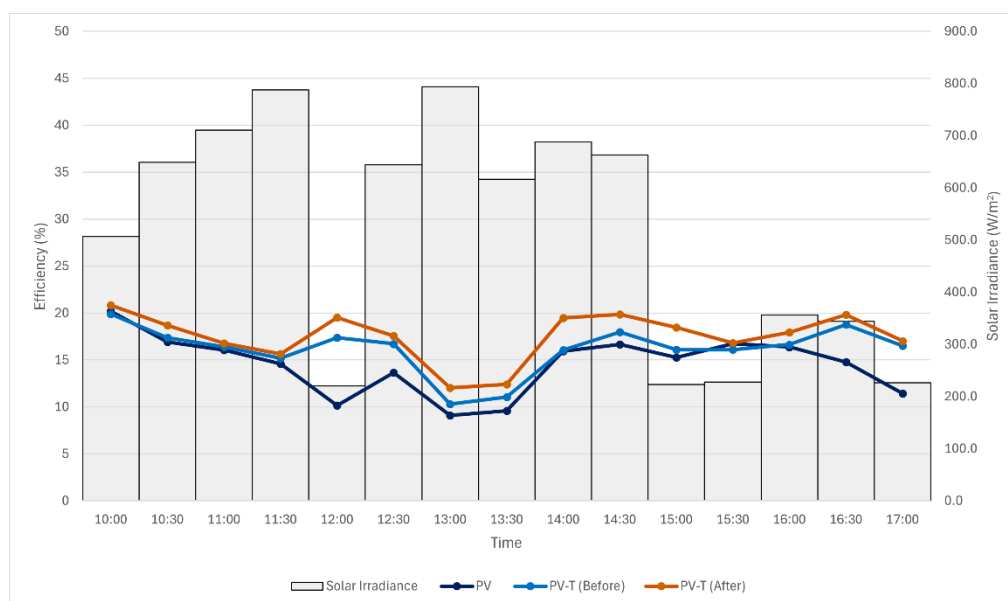


Figure 4-12: Graph of Electrical Efficiency against Time (Setup B)

For Setup B, the direct cooling provides an efficiency boost compared to standalone PV. At 12:00, Setup B is at 19.5% compared to only 10.2% for standalone PV with a 9.3% difference. Despite the standalone PV experiencing reduced efficiency from temperature climb, Setup B managed to keep the PV module operating near their optimal operating range.

The comparison across both testing days concluded that thermal management is vital for PV systems in Malaysia. While both setups outperform the baseline standalone PV, Setup B provided a more stabilized efficiency curve during periods of lower irradiance, whereas Setup A is more suitable for dissipating heat to recover lost power.

4.5 Combined PV-T Efficiency

The true value of a hybrid Photovoltaic-Thermal (PV-T) system lies in its ability to harvest a significantly larger portion of the solar spectrum than a conventional solar panel. While a standard PV panel treats excess thermal energy as a waste product that actively degrades its performance, the PV-T system converts this heat into a secondary energy source. This section evaluates the combined performance by aggregating the electrical and thermal yields to determine the overall system efficiency.

4.5.1 Overall System Efficiency

The overall system efficiency is obtained from summing the electrical efficiency and thermal efficiency. It highlights the total energy utilization of the system from solar irradiance. Table 4-13 and Figure 4-13 highlights the total efficiency obtained for Setup A and Table 4-14 and Figure 4-14 represented Setup B.

Table 4-13: Total Efficiency for Setup A

Time	Solar Irradiance (W/m ²)	PV-T (Setup A)			Standalone PV	
		Thermal (%)	Electrical (%)	Total (%)	Efficiency (%)	Difference with PV-T
10:00	524.5	63.3	19.7	83.1	18.7	64.4
10:30	614.2	68.5	18.4	86.9	17.7	69.2
11:00	793.3	62.2	18.2	80.3	17.7	62.7
11:30	816.5	61.5	18.2	79.7	16.8	62.9
12:00	863.1	62.2	16.8	79.0	15.9	63.1
12:30	836.2	60.7	17.1	77.8	16.0	61.8
13:00	746.8	56.3	19.6	75.9	16.3	59.7
13:30	806.2	57.6	18.3	75.9	15.1	60.7
14:00	693.3	43.9	20.0	63.9	12.0	51.9
14:30	508.8	39.9	17.8	57.7	15.0	42.6
15:00	438.3	39.7	19.4	59.1	15.5	43.6
15:30	475.8	42.7	19.7	62.4	14.0	48.4
16:00	249.7	37.8	18.9	56.7	14.6	42.1
16:30	113.2	25.6	14.9	40.5	13.8	26.8
17:00	128.1	26.0	13.9	39.9	7.9	32.0



Figure 4-13: Graph of Efficiency against Time (Setup A)

Setup A demonstrated effective energy harvesting, reaching a peak 86.9% at 10:30 while standalone PV was only operating at 17.7% efficiency, meaning nearly 82% of the solar energy hitting on the PV module was entirely wasted. It shows that Setup A consistently outperformed the standalone PV throughout the day.

However, in the morning, the total efficiency of Setup A dropped to 57.7% (14:30) and further declined to 40.5% at 16:30. The decline is heavily influenced by the environmental factors due to the spray cooling design. Rooftop wind blew the sprayed water before it could be collected. However, electrically efficiency is not affected as thermal efficiency decreases due to the reduced ambient temperature decreasing the temperature of PV module and reducing heat transfer.

Table 4-14: Total Efficiency for Setup B

Time	Solar Irradiance (W/m ²)	PV-T (Setup B)			Standalone PV	
		Thermal (%)	Electrical (%)	Total (%)	Efficiency (%)	Difference with PV-T
10:00	506.8	57.7	20.8	78.5	20.2	58.3
10:30	649.2	66.4	18.7	85.1	16.9	68.1
11:00	710.8	71.5	16.8	88.2	16.1	72.2

11:30	787.7	76.2	15.7	91.9	14.6	77.3
12:00	220.3	62.9	19.5	82.4	10.2	72.3
12:30	644.3	59.7	17.6	77.3	13.7	63.6
13:00	793.8	67.9	12.0	79.9	9.1	70.8
13:30	616.1	62.5	12.4	74.9	9.6	65.3
14:00	687.9	60.4	19.5	79.9	15.9	64.0
14:30	663.1	69.6	19.9	89.5	16.6	72.9
15:00	223.1	41.4	18.5	59.9	15.3	44.6
15:30	228.0	54.0	16.8	70.8	16.7	54.1
16:00	356.3	60.5	17.9	78.4	16.4	62.1
16:30	344.0	44.8	19.8	64.5	14.8	49.8
17:00	226.5	0.0	17.0	17.0	11.4	5.6

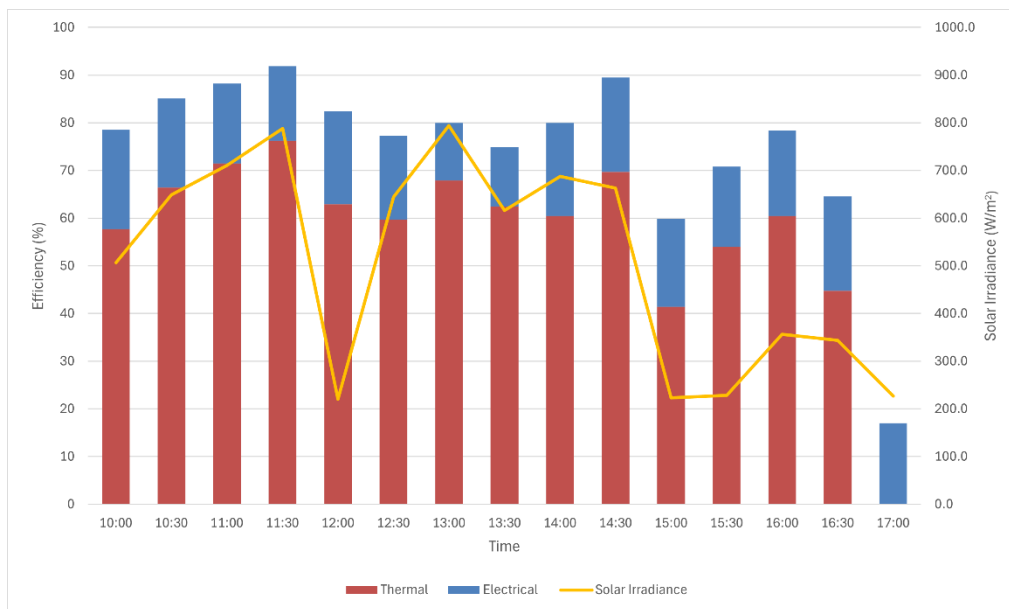


Figure 4-14: Graph of Efficiency against Time (Setup B)

For Setup B, it demonstrates a more stable overall energy harvest as compared to Setup A. Setup B achieved a peak efficiency at 11:30 while the standalone PV is only operating at 14.6%. This proves that Setup A is able to efficiently generate electricity while generating high yield thermal output. A notable trend is despite a dip of solar irradiance at 12:00, the thermal generation is still maintained. The sudden dip is caused by sudden cloud cover, as the PV module stored residual heat from previous hours of high irradiance, the panel

does not cool down to ambient temperature instantly even when the cloud cover blocks the sun.

By 17:00, the thermal efficiency in Setup B drops to 0%. This is because the panel's residual heat has been entirely depleted, and the low irradiance is not enough to generate new heat, causing the lack of temperature difference for heat transfer. However, Setup A is able to record a thermal efficiency of 26%. This evening spike in Setup A is influenced by its reduced mass flow rate. Setup A suffers from water loss in earlier period of the day due to evaporative cooling. By late afternoon, the reduced flow means a smaller volume of water maintains contact with the panel, causing the water to absorb panel's heat much faster.

While Setup A's thermal efficiency is higher in the evening, the electrical efficiency declines to 14.9% while Setup B is at 19.7% (16:30). This is because ambient and panel temperatures have dropped below the requirements for evaporative cooling. Setup A relies heavily on the latent heat of vaporization to strip massive amounts of heat as water turns to vapor. By late afternoon, the panel is no longer hot enough to trigger rapid evaporation and losing the main cooling advantage. Setup B direct contact cooling does not rely on evaporation, it continues to function as a steady conductive heat sink, making it superior for electrical performance even if environmental temperature drops.

Highest total efficiencies of both setups were recorded in the early to mid-morning period (10:30 to 11:30). The inlet water from the storage tank was coolest in the morning, while the dark surface of the panel rapidly absorbs heat from increasing solar irradiance when ambient temperature is lower compared to the afternoon. This increases the rate of heat transfer between the panel and water since the rate of heat transfer is directly proportional to the temperature difference. Hence, the system was able to extract heat at peak efficiency before the system begins reaching thermal equilibrium in the afternoon.

4.5.2 Normalized Yield

To assess the performance of the hybrid PV-T configurations under fluctuating weather conditions more accurately, the raw thermal and electrical outputs are standardized against the solar irradiance. Normalized yield was calculated by dividing the thermal power and electrical power by the solar irradiance recorded

at the exact timestamp. This calculation gives us a standardised ratio of yield per solar irradiance in W per W/m^2 , removing the variable of solar irradiance and allows for a direct comparison of system efficiency throughout the logging period. Figure 4-15 below shows the comparison under normalized yield.

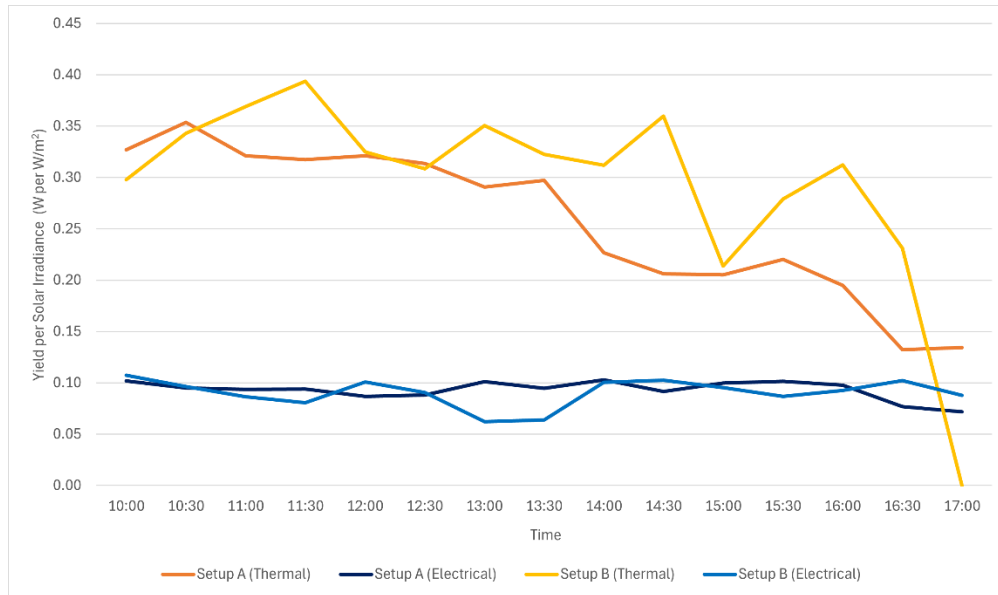


Figure 4-15: Graph of Normalized Thermal and Electrical Yields of Setup A and Setup B

Based on the graph, there is a gap between thermal lines at the top and the electrical lines at the bottom when compared between both setups. For electrical efficiency, Setup A stayed relatively consistent all day while Setup B had a slight drop around 13:00 to 13:30. The dip occurred because the panel got hotter during peak sunlight, causing a slight drop in voltage output.

The thermal performance shows a downward trend as it is more efficient in the morning, but the normalized yield drops as it got later into the afternoon. As the days goes by, the solar irradiation decreases and causing the panel to become less hot, reducing the heat transfer between the water and panel which lowers the overall thermal efficiency later in the day for both Setups.

Comparing the two cooling methods, Setup B had a higher thermal yield during peak hours, indicating that it removes heat from the panel to the water quicker. Despite Setup A extracting slightly less heat overall, Setup A has a more consistent electrical efficiency due to sprinkler system cooling down the panel more efficiently.

4.6 Economic Analysis

The hybrid PV-T system must be economically viable to be fitted for real world application. While the system effectively reduces thermal degradation and provides hot water, this section evaluates whether energy harvested translate into meaningful financial returns. To calculate these savings, this economic evaluation relies on several standardized parameters and assumptions specific to Malaysian residential context:

- Thermal energy, Q calculated is based on Equation 3.6 mentioned in previous chapter.
- Financial savings are calculated using the domestic Tenaga Nasional Berhad (TNB) rate of RM0.334 per kWh.
- The calculations assume an average of 4.5 Peak Sun Hours (PSH) per day, which is the standard baseline for solar yield estimations in Malaysian, operating over a standard 30-day month.
- 100 W solar panel is used as the baseline prototype for economic analysis as it is consistent with current project and utilizes previously recorded data to ensure higher accuracy and reliability in the estimations.
- Assume a 4-person family taking an average of 8 showers per day (2 per person), with each shower lasting approximately 10 minutes, utilizing a standard 4.0 kW instantaneous electric water heater.

A limitation of this experimental study is that the physical prototype is restricted to a specific dimensional scale (a single panel). Hence, a bigger panel is not used for economic analysis as scaling up physical dimensions will lead to inaccurate data since it's not directly proportional to the size or rating of the panel. Therefore, to project the system's performance for a whole house, the economic scale-up is calculated by arraying multiple identical prototypes rather than increasing the surface area of one unit or using standardized solar panel for household use.

To determine how much energy the household uses strictly for water heating, the daily load is calculated as follows:

- Total daily shower time: $8 \text{ showers} \times 10 \text{ minutes} = 80 \text{ minutes per day}$ (1.33 hours)
- Daily Energy Load: $1.33 \text{ hours} \times 4 \text{ kW} = 5.33 \text{ kWh/day}$

The monthly thermal yield and the corresponding financial savings were evaluated for both experimental setups as such:

- Setup A: The total thermal energy yield from 10:00 to 17:00 averages 162.42 W (0.1624 kW). The total electrical power yield over the same period averages 54.4 W (0.0544 kW).
- Setup B: The total thermal energy yield from 10:00 to 17:00 averages 163.22 W (0.1632 kW). The total electrical power yield from 10:00 to 17:00 averages 45.2 W (0.0452 kW).

Using the assumed 4.5 PSH, the average thermal power is converted into daily, monthly and yearly, thermal yield:

a) Setup A

- i. Daily Yield: $0.1624 \text{ kW} \times 4.5 \text{ PSH} = 0.7308 \text{ kWh/day}$
- ii. Monthly Yield: $0.7308 \text{ kWh/day} \times 30 \text{ days} = 21.92 \text{ kWh/month}$
- iii. Yearly Yield: $21.92 \text{ kWh/month} \times 12 \text{ months} = 263.04 \text{ kWh/year}$

b) Setup B

- i. Daily Yield: $0.1632 \text{ kW} \times 4.5 \text{ PSH} = 0.7344 \text{ kWh/day}$
- ii. Monthly Yield: $0.7344 \text{ kWh/day} \times 30 \text{ days} = 22.03 \text{ kWh/month}$
- iii. Yearly Yield: $22.03 \text{ kWh/month} \times 12 \text{ months} = 264.36 \text{ kWh/year}$

Using the same method of calculations, the electrical power yield:

a) Setup A

- i. Daily Yield: $0.0544 \text{ kW} \times 4.5 \text{ PSH} = 0.2448 \text{ kWh/day}$
- ii. Monthly Yield: $0.2448 \text{ kWh/day} \times 30 \text{ days} = 7.34 \text{ kWh/month}$
- iii. Yearly Yield: $7.34 \text{ kWh/month} \times 12 \text{ months} = 88.08 \text{ kWh/year}$

b) Setup B

- i. Daily Yield: $0.0452 \text{ kW} \times 4.5 \text{ PSH} = 0.2034 \text{ kWh/day}$

- ii. Monthly Yield: $0.2034 \text{ kWh/day} \times 30 \text{ days} = 6.10 \text{ kWh/month}$
- iii. Yearly Yield: $6.10 \text{ kWh/month} \times 12 \text{ months} = 73.2 \text{ kWh/year}$

The total economic value of the prototype includes savings from displacing grid from water heating, combined with electrical savings gained from cooling the panel.

a) Setup A

- i. Thermal Savings: $263.04 \text{ kWh} \times \text{RM}0.334 = \text{RM } 87.86$
- ii. Electrical Savings: $88.08 \text{ kWh} \times \text{RM}0.334 = \text{RM } 29.42$
- iii. Total Annual Savings: $\text{RM } 87.86 + \text{RM } 29.42 = \text{RM } 117.28$

b) Setup B

- i. Thermal Savings: $264.36 \text{ kWh} \times \text{RM}0.334 = \text{RM } 88.30$
- ii. Electrical Savings: $73.2 \text{ kWh} \times \text{RM}0.334 = \text{RM } 24.45$
- iii. Total Annual Savings: $\text{RM } 88.30 + \text{RM } 24.45 = \text{RM } 112.75$

To determine the effectiveness of offsetting the household's water heating load, the daily thermal yield is divided by the household load:

- Setup A Offset Percentage: $\frac{0.7308}{5.33} \times 100\% = 13.71\%$
- Setup B Offset Percentage: $\frac{0.7344}{5.33} \times 100\% = 13.78\%$

Table 4-15 compares the economic viability for both setups.

Table 4-15: Comparison of Setup A and Setup B Economic Analysis

Parameters	Setup A	Setup B
Yearly Thermal Power Yield	263.04 kWh/year	264.36 kWh/year
Yearly Electrical Power Yield	88.08 kWh/year	73.2 kWh/year
Thermal Savings	RM 87.86	RM 88.30
Electrical Savings	RM 29.42	RM 24.45
Total Annual Savings	RM 117.28	RM 112.75
Thermal Offset Percentage	13.71%	13.78%

While the raw economic calculations yields that Setup A has a higher annual savings due to the sharp electrical efficiency gains from evaporative cooling, Setup B remains economically viable recommendation for real world scaling.

When evaluating these theoretical yields, it is crucial to account for environmental conditions during testing phase. The experimental data for both configurations were recorded on 2 separate days. Setup A has a more consistent solar irradiance throughout its testing, while solar irradiance drops from cloud cover mid-day for Setup B, yet still managed to produce high energy yields.

Setup A is severely limiting commercial viability as it involves an open spray system that relies heavily on evaporative cooling, making it highly vulnerable to mass water loss and rooftop wind drift. In real-world residential application, the ongoing cost of replenishing water storage tank would negate its minor advantage. Conversely, Setup B utilizes direct contact, ensuring zero evaporation water loss to the atmosphere, reducing water loss. Setup B is deemed as the superior setup as it is the most practically and economically viable PV-T configuration for Malaysian climate.

4.7 Summary

The experimental evaluation of the hybrid PV-T configurations against a standalone PV has validated the advantage of active thermal management, while heat is extracted to boost electrical performance and repurpose for household use. Setup B, utilized a direct contact cooling, achieving system efficiency of 91.9% by maintaining stable heat extraction despite dip in solar irradiance. While Setup A evaporative cooling is able to decrease panel's temperature better and improves electrical efficiency, it is highly volatile due to mass water loss and highly dependent on environmental conditions. Economically, Setup B was proven to be the most viable solution for real-world scaling. Although Setup A saved RM 4.53 more per panel annually to its electrical efficiency, this advantage was recorded on a day with more consistent sun, it is still not practical due to the need of constantly replenishing water lost to evaporation. In contrast, Setup B mitigate the water loss along with consistent thermal extraction, successfully neutralizing nearly 13.78% of a four-person household's daily water heating load per 100 W prototype.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The study successfully evaluated the energy efficiency and practical viability of a hybrid photovoltaic thermal (PV-T) system for Malaysian household use. The primary research objectives were met through comparative analysis of 2 configurations, Setup A and Setup B.

The experimental results confirmed that active thermal management is essential to maintain PV stability in tropical climates. While standalone PV suffered from thermal degradation and reaches to a surface temperature up to 60.1 °C, PV-T system effectively maintained lower operating temperatures, even during peak solar irradiance. Setup A demonstrated a peak panel temperature reduction of 17.2 °C compared to the standalone unit, which recovers the lost electrical efficiency.

Furthermore, the system successfully demonstrated the purpose of harvesting solar energy by providing hot water alongside electricity. Setup B was proven to be highly effective in this regard, achieving a peak thermal power of 310.0 W and a maximum overall efficiency of 91.9%. This confirms that PV-T technology can significantly outperform standalone PV modules, which frequently waste most of the energy.

The first objective of designing a hybrid photovoltaic-thermal (PV-T) system optimized for front-surface water cooling was successfully accomplished through the fabrication of a functional prototype. The system utilized a 100W monocrystalline solar panel mounted on a structural steel frame, tilted at an optimal 10° angle to maximize solar capture. To extract waste heat effectively, two active cooling mechanisms were produced, an evaporative sprinkler system (Setup A) and a continuous, direct-contact water film (Setup B). This integration successfully combined standard electrical generation equip with thermal extraction, establishing a reliable prototype for outdoor testing.

For the second objective, the overall energy efficiency of the PV-T system was assessed under real, fluctuating Malaysian outdoor environmental conditions. The experimental data confirmed that front-surface cooling

significantly mitigates thermal degradation compared to a standalone PV module. The sprinkler system (Setup A) achieved a peak panel temperature reduction of 17.2 °C, though it is susceptible to environmental conditions and water loss. Conversely, the continuous water film mechanism (Setup B) demonstrated better overall stability and heat extraction, reaching a peak combined system efficiency of 91.9% and generating a maximum thermal power of 310.0 W. Throughout the testing period, the system showed consistent thermal reliability; Setup A's inlet water temperature ranged from 27.0 °C to 37.3 °C, resulting in an outlet range of 27.2 °C to 39.6 °C, while Setup B achieved even higher thermal gains with an inlet range of 30.5 °C to 42.0 °C heating to an outlet range of 32.4 °C to 44.5 °C.

Finally, the third objective was achieved by evaluating the practical and economic feasibility of integrating this PV-T system to meet the energy demands of a typical Malaysian household. By utilizing the recorded thermal and electrical performance into practical metrics, the system proved that it is highly capable of offsetting residential water loads. These temperature increases from PV-T system are sufficient to offset approximately 13.71% (Setup A) and 13.78% of the daily water heating load for a standard four-person household, leading to a projected savings of RM 117.28 (Setup A) and RM 112.75 (Setup). These results shows that integrated front surface cooled PV-T system is a suitable and economically viable technology for household use in Malaysia, offering dual-benefit solution that improves electrical power output while simultaneously meeting residential hot water demands.

5.2 Recommendation for Future Improvements

To further refine this prototype for future work of hybrid PV-T solar research, the following ideas are suggesting for future testing and development:

- a) Flow Rate Regulation: Future work should use a mechanical flow rate control using a flow meter (Figure 5-1) and manual valves instead of relying on a microcontroller for pump regulation. This would allow precise calibration and control of flowrate while maintaining a consistent water pressure. Such a setup is more robust for testing without the risk of electronic damages (Figure 5-2).



Figure 5-1: Flowmeter

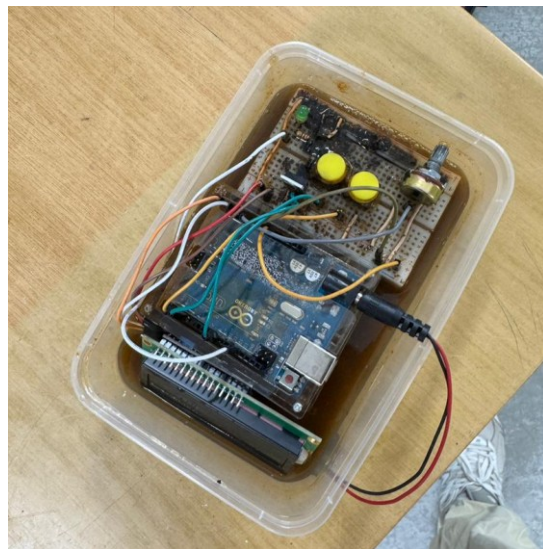


Figure 5-2: Water Damage of Electronics from Rain

- b) **Hydrophilic Surface Coating:** A recommendation for future testing is the application of hydrophilic coating on the glass surface of the PV module. While anti-fog sprays (Figure 5-3) were used in this research, a specialized hydrophilic layer would be more effectively prevent streaks of water and dry spots that occur when surface tension causes water to bead up or channel. Ensuring a perfectly uniform thin film of water, maximising heat exchange surface area and significantly improve both cooling consistency and thermal yield.



Figure 5-3: Anti-Fog Spray Coating

- c) Thermal Insulation and Rear-Surface Cooling: Future research should thermally insulate the cold-water tank to maintain highest possible temperature difference. Additionally, testing a rear-surface cooling by spraying at the bottom of the panel would allow the PV module to receive maximum, unobstructed irradiance while waste heat is extracted from the back, potentially providing a better overall system efficiency.
- d) Cloud Based Remote Data Acquisition: To improve the precision and convenience of future data collection, replacing the physical SD-card logging system with a wireless ESP32 microcontroller is recommended. This would enable real-time, remote monitoring of target parameters wireless, reducing the risk of data loss due to card corruption and allow for long-term performance tracking during various monsoon seasons.

5.3 Closing Summary

The integrated PV-T system provides an advancement in utilizing solar energy for Malaysian households, providing for electricity generation and thermal energy utilization into a single integrated unit. This creates a practical and sustainable solution for modern energy demands. This successful mitigation of thermal energy losses and production of useful hot water demonstrates that PV-T technologies is a suitable alternative to traditional solar irradiance in topical environments, particularly in Malaysia.

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