Assessment of Photovoltaic-Thermal (PV-T) system feasibility in Malaysia: A comprehensive study

Tang Jing Hui[1], *Rubina* Bahar[1,2*], *Jaslyn* Low[1,2], *and Hieng Kiat* Jun[1,2]

[1]Department of Mechanical and Materials Engineering, Lee Kong Chian Faculty of Engineering Science, Universiti Tunku Abdul Rahman, Sungai Long, Malaysia
[2]Centre for Sustainable Mobility Technologies, Universiti Tunku Abdul Rahman

Abstract. Malaysia's current renewable energy utilization for domestic usage is primarily limited to photovoltaic (PV) systems only, which leaves a gap in understanding the hybrid PV-Thermal (PV-T) performance within the Malaysian context, encompassing efficiency and economy. This study analyzes and compares three cases theoretically: i) PV only, ii) Solar Thermal (ST) only, and iii) PV-T combined hybrid systems in terms of energy load and economy for a Malaysian household. Return on Investment (ROI) analysis reveals that the PV-T combined hybrid system exhibits superior efficiency with a lower ROI. The study reveals that the theoretical PV-T combined hybrid system can reach up to an overall efficiency of 77.11% with a lowered mass flow rate of the cooling water. The PV-T system also has a favorable payback period of 6.54 years, and the ROI for the PV-T system is 15.30%, while the ROI for PV only is 4.81%. The ST system has an efficiency of 72.38%, a payback period of 7.39 years, and an ROI of 13.53%.

1 Introduction

Solar energy presents a sustainable solution for heating, electricity generation, and industrial processes, addressing the modern challenge of energy consumption and CO_2 emissions. The Malaysia Renewable Energy Roadmap (MyRER) aims to boost renewable energy adoption, cut greenhouse gases, attract investments, and spur job growth. By prioritizing sustainability, affordability, and economic gains, Malaysia seeks to lead in renewable energy transition. Solar hybrid systems, especially for combined cooling, heating, and power in residences, emerge as an efficient solution in solar energy utilization globally. Solar photovoltaic (PV) technology utilizes semiconductor materials to convert sunlight into electricity. When photons from sunlight strike a PN junction, electrons and holes are generated, creating an electric current [1]. This direct current (DC) is then transformed into alternating current (AC) for practical use, with key properties including efficiency, open circuit voltage, short circuit current, and Fill Factor [2].

* Corresponding author: rubina@utar.edu.my

Solar thermal (ST) collectors capture solar radiation's heat, converting it into thermal energy for applications like water heating and space heating. In residential energy consumption, thermal energy constitutes a significant portion, with space heating being the largest component [3]. Combining Cooling, Heating, and Power (CCHP) systems with solar enhancements can optimize energy efficiency [4]. PV/T hybrid systems combine PV cells and ST collectors to improve energy efficiency. Cooling PV cells increases their electrical efficiency, while the waste heat can be utilized for various purposes like water desalination [5]. Compared to standalone systems, PV/T hybrids generate more energy per unit area.

Despite the current prevalence of photovoltaic systems in Malaysia, there is a lack of research on the performance and viability of solar hybrid systems, specifically solar photovoltaic-thermal hybrids. Therefore, the primary objective of this study is to evaluate the efficiency and economic feasibility of solar hybrid systems in the context of Malaysia, with a focus on solar photovoltaic-thermal hybrids. By investigating and understanding the potential of these systems, this research aims to contribute valuable insights towards sustainable energy practices and environmental preservation in Malaysia. This study investigates into a thorough comparison of the efficiency, payback period, and return on investment (ROI) of photovoltaic (PV), solar thermal (ST), and photovoltaic-thermal (PV/T) hybrid systems intended for domestic water heating applications in Malaysia. While past research has mainly focused on experimentally examining the operational parameters of water-based PV/T hybrid systems for residential use, this study aims to assess the potential energy generation of solar hybrid systems and possible savings. By shedding light on the effectiveness of harnessing solar energy for combined heating, and power requirements, this analysis aims to optimize energy utilization and minimize environmental impact. Furthermore, the research sheds lights on the specific energy landscape of Malaysia and the feasibility of integrating renewable energy sources in the nation, with a particular emphasis on the viability of solar hybrid systems, especially the PV/T hybrid system. By adopting a localized approach, the study ensures that its findings are pertinent and actionable within the Malaysian energy context.

2 Methods

The study was planned for a geographical location in Kuala Lumpur, the capital of Malaysia. The data was used from the research location mostly as a case study that was conducted on a two-story terrace house situated at a landed area located at latitude 3°06'50"N, longitude 101°40'58"E, with an altitude of 33m above sea level. The front roof area of the terrace house measures 49.59m^2, while the rear roof area is 27.52m^2. The perimeters of the two sides are 27.27m and 21.08m, respectively. The tilt angle needs to be set so that the system produces its highest output. The angle between the north & south and the collector plane is known as the azimuth angle. The analysis conducted in the location of the study revealed that the collector plane achieves the highest yearly production of 1778 kWh/m2 when the tilt angle ranges from 2° to 5° and the azimuth angle ranges from -61° to 60°using PVSYST 7.4. The optimal output can be achieved with a transposition factor of 1.00 and a loss to an optimum of 0%. Therefore, the parameter was adjusted to a tilt angle of 4°, which corresponds to an azimuth angle of 0°, facing south. The selected geographical location experiences an average of 7.33 hours of daylight, resulting in a constant 7 hours of sunlight daily throughout the year. Sun irradiance ranges from 230 to 800 W/m^2, with a mean value of 500W/m^2 [6].

2.1 Electrical load requirements

In this study, a 600W PV system prototype was selected to power several small electric appliances to match with the available study conducted [6]. These include 10 LED tube lights

(20W each), 3 exhaust fans (80W each), a 32-inch LED TV (45W), and 3 phone chargers (30W each). The LED lights and exhaust fans are expected to run for 8 hours daily, while the TV and phone chargers for 2 hours each. The total daily electricity consumption of these appliances amounts to 3.81 kWh. With a 600 Wp PV system capable of generating 4.2 kWh of maximum electricity (after considering a 10% safety factor), it adequately covers the load requirements. The electric tariff rate was set to RM 0.276/kWh, which is the average of the first and second classification of Tariff A- domestic tariff, RM 0.218/kWh and RM 0.334/kWh respectively, based on Tenaga Nasional Berhad (TNB) which is the Malaysian multinational electricity company and is the only electric utility company in Peninsular Malaysia. It has been planned to make the system grid connected as no battery is used to store the energy for nocturnal use.

2.2 PV module/inverter/number of panels

Depending on factors such as panel material, panel quality, power output, and durability, various PV modules can be chosen depending on the load requirements. According to the electrical load requirements stated earlier, a total of 600W of electrical load is needed. Therefore, four 150W polycrystalline PV modules are selected in a series circuit to meet the needs. Selecting the right inverter ensures peak performance and reliability, often requiring slight oversizing for factors like inrush current. For a 600W load, a 1kW 12V solar all-in-1 pure sine wave inverter is selected to optimize system efficiency and performance. Determining solar panel quantity hinges on desired power output, space availability, and inverter electrical limits. It's crucial for performance and efficiency to stay within the inverter's voltage and current boundaries. For a 600W demand, four 150W PV modules in series meet requirements. This setup yields a total open circuit voltage (V_{oc}) of 86.4V, maximum power (V_{mp}) of 72V, short circuit current (Isc) of 9.02A, and maximum current (I_{mpp}) of 8.33A. Inverter specs include a max photovoltaic input power of 600W, voltage range of 20V to 150V DC, and maximum current of 80A, with 40A allocated to the PV system. It's crucial to match panel size to inverter limits, ensuring power output, V_{oc}, and I_{sc} stay within acceptable ranges. Figure 1 below shows the planned system diagram of the PV/T hybrid system under STC.

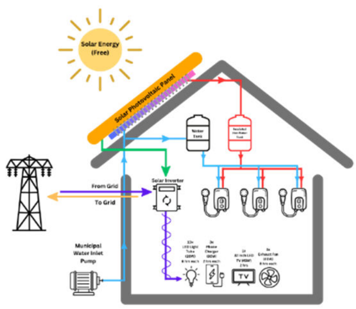

Fig.1. System diagram of the PV/T hybrid system under STC.

2.3 Efficiency analysis of PV system

The efficiency study of a PV system analyses its ability to convert sunlight into electricity. This step analyses the system's energy production and efficiency, providing knowledge about its performance in practical use. η_{el} is the electrical efficiency of a PV system that can convert light energy into electricity, expressed in Equation 1.

$$\eta_{el} = \frac{V_{mpp}\times I_{mpp}}{G\times A_c\times \tau_g} \quad (1)$$

V_{mpp} *and* I_{mpp} are the maximum power point voltage and electric current, G is the solar irradiance, Ac is the total cell area; τg is the transmissivity of glass. $Pmax$ is the maximum electrical power as in Equation 2.

$$P_{max}=V_{mpp} \times I_{mpp} \quad (2)$$

2.4 Solar thermal (ST) system

Designing a solar water heater involves meticulous calculations based on heat and mass transfer principles to meet performance needs. Considerations include solar radiation, collector efficiency, and thermal storage capacity. By ensuring optimal design, an efficient and effective system can be engineered to meet desired requirements.

The daily hot water consumption (W_{rsite}) of a household is influenced by its needs and habits. According to [7], a Malaysian household with 3 to 5 occupants requires 100L to 150L of hot water daily. The average shower duration is 12 minutes, using 60 to 120 litres of water [8], with desirable temperatures ranging from 36 to 41°C [9]. This study examines a four-person household, each showering twice daily, using 70 litres per shower at 39.3°C. The flow rate of heat transfer fluid through the collector can be calculated using the energy balance equation (3) as below:

$$\dot{m} = \frac{Q_{daily}+Q_{losses}}{C_p\Delta T} \quad (3)$$

Here $\dot{m}$ is the fluid mass flow rate (kg/s), C_p is the specific heat capacity (J/kg·K) and ΔT is the desired temperature rise (K). Q_{daily} and Q_{losses} represent the daily heat requirements and losses occurred, respectively.

2.5 Efficiency analysis of solar thermal (ST) system

The efficiency of the solar water heater depends on the thermal efficiency of the system; hence it can be determined by Equation (4).

$$\eta_{th} \frac{\dot{m}C_p\Delta T}{GA_c} \quad (4)$$

2.6 Combined efficiency and economic analysis of PV-T system

When evaluating the efficiency of PV/T hybrid systems, it is important to consider both electrical and thermal energy outputs. The sum results of electrical and thermal efficiency are the overall efficiency of PV/T hybrid systems, as demonstrated in Equation (5). Where η_{th} is thermal efficiency, η_{el} is electrical efficiency.

$$\eta_{tot}=\eta_{th}+\eta_{el} \quad (5)$$

The economic analysis provides information on the economic sustainability and operational effectiveness of the PV-T system. The investigation specifically concentrated on the simple payback period and ROI. The mathematical expressions for calculating the payback period and ROI can be expressed as:

$$Payback\ Period = Initial\ Investment\ of\ System / Annual\ Cash\ Flow \quad (6)$$
$$ROI = Amount\ saved / Initial\ Investment\ of\ System \times 100\% \quad (7)$$

3 Results

3.1 Performance of PV only system

The proposed 1 string - 4 module PV only system is projected to achieve an efficiency of 17.18%. Under standard test conditions (STC), the system is projected to produce 4.2kWh of electricity and provide 3.82kWh after factoring in a 10% safety margin during 7 hours of solar exposure to meet household energy needs. However, [6] conducted experiments and discovered that the practical efficiency in real-life situations is only 13.1% under 500W/m2, which is lower than the STC. Therefore, the actual power generated in practical scenarios is projected to be 208.88 W, resulting in a simply 1.46 kWh of energy production. With a 10% safety margin, it yields 1.329 kWh. The STC assumes perfect conditions, including a consistent irradiance of solar at 1000 W/m², and with a cell temperature of 25°C, and a spectral distribution that closely mimics noon sunlight. Nevertheless, in practical situations, the levels of solar irradiance fluctuate throughout the day and are impacted by various factors like weather conditions, and seasonal changes.

3.2 Performance of the water heating system

According to the household requirement, it was determined that to meet the daily demand of 672 litres of hot water at a temperature of 39.3°C, 510.65 litres of cold water at 29.3°C needed to be mixed with 161.35 litres of hot water at 70°C. To provide a daily supply of 161.35 litres of hot water heated to 70°C, the regular mass flow rate has been adjusted to 0.0064 kg/s, under 7 hours of sun hours daily. After calculating the mass flow rate, a solar water heater was chosen from the market - the Aquasolar L35 (160 litres) Solar Water. The Aquasolar L35 (160 litres) Solar Water heater can consistently produce hot water at an average temperature of 70°C. Additionally, it offers an impressive overnight heat loss rate of only 8%, making it an efficient choice for heating water. With a total requirement of 1.09 kW energy, the water heating system can perform with an efficiency of 72.3%.

3.3 Efficiency evaluation of PV/T hybrid systems

For this study, the value increased from 228.76W to 240.11W. The flow of water helps to cool down the PV module, which in turn prevents efficiency losses due to overheating. The heated water may then be used to take showers. This results in an overall enhancement in efficiency. Table 1 shows the value for a single module and 4 modules arrangement of estimate the power.

Table 1. Electrical Performance in PV/T Hybrid System under 500 W/m^2.

No.	No of Modules	Solar Irradiance (W/m^2)	Estimated Power Output (W)	Electrical Efficiency (%) [6]	Hours to Power (Hr)	Total kWh	10% Safety Factor
1	1	500	60.02829	13.75	7	0.42	0.382
2	4		240.11316			1.68	1.528

Regarding the thermal performance of PV/T hybrid [6] presented that the energy gained per PV/T hybrid module is 8035.02 kJ. To meet the requirements of this study, certain modifications were implemented. The concept involves creating a system like a solar water heater, where water can be delivered at a higher temperature. The necessary mixing ratio to raise the temperature above the desired level can be determined. It was found that only 178.88 liters of water at a temperature of 66.04 °C are needed. However, the PV/T hybrid system can provide 210 liters of water at the same temperature with a lower mass flow rate, which is more than enough to meet the need.

3.4 Economic evaluation of PV/T hybrid systems

The economic analysis of the PV/T hybrid system involves two approaches: analyzing under Standard Test Conditions (STC) and real-life solar irradiance conditions (500 W/m^2). Converting PV to PV/T incurs extra costs, mainly for copper conduit, insulation, and a water tank, as no ready-made products are available. Despite this, PV/T yields annual savings in electricity and thermal aspects compared to PV and ST systems. STC analysis shows a shorter payback period of 5.18 years with an ROI of 19.31%, contrasting with real-life scenarios taking 6.54 years with an ROI of 15.30%. Despite this, PV/T offsets RM715.39 on electric bills by meeting bathroom hot water load, contributing to overall savings.

3.5 Comparative analysis

The PV/T hybrid system outperforms both PV and experimental ST systems in efficiency, payback period, and ROI. As per Eq. 5, the total efficiency of the PV-T system is represented as the addition of electric efficiency from PV and thermal efficiency from T. Although it requires the highest initial investment due to combining PV and ST, it proves a practical choice for power and water heating. Figures 2 illustrates the overall comparison and cost breakdown for the three cases, highlighting the PV/T hybrid system's favourable outcomes in efficiency, cost, payback period, and ROI. The efficiency level may reach up to 77% for PV-T system and it is slightly higher than the experimentally obtained thermal efficiency (69.91%) for 0.5 Liter per minute flowrate as obtained by Basuhaib et al.[6].

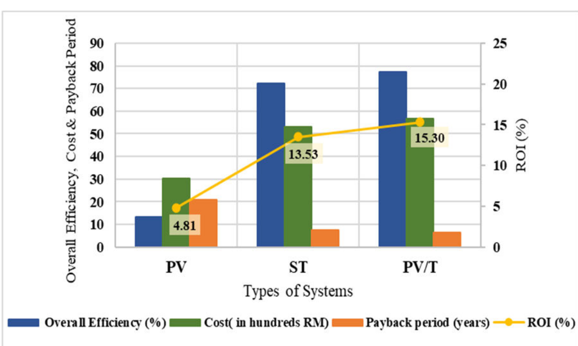

Fig. 2. Comparison of overall efficiency, cost, payback period, and ROI of each system.

For the work presented here the ideal steady state operating conditions were considered, ignoring the heat losses to the surrounding. The household's monthly electricity bill is estimated to be RM300. The analysis show that grid dependence is 76%, while PV and ST systems require 96% and 80% grid electricity coverage, respectively. PV-T system's standard payback period is 5.18 years with an ROI of 19.31%; real-life recovery is 6.54 years with

ROI of 15.30%. Despite this, PV-T covers bathroom hot water load, offsetting RM715.39 on bills and contributing to savings.

4 Conclusion

The PV/T hybrid system, operating in a solar irradiance environment of 500 W/m² with an area of 4.0256 m², can generate 240.11 W of electrical energy and 1.2754 kW of heat energy. Economic assessments revealed different costs, payback periods, and ROI under various conditions. Under standard test conditions (STC), the system achieved a payback period of 5.18 years and a 19.31% ROI for a 4-module setup. At 500 W/m², the payback period extended to 6.54 years, with an ROI of 15.30% for the same configuration.

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