Performance and Energy Assessment of a PV/T Air Collector in Tropical Climates

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Abstract. A Photovoltaic/Thermal (PV/T) collector system utilizes solar energy by generating both electricity and thermal energy. However, elevated PV module temperature typically reduces electrical efficiency by approximately 0.3-0.5% per °C. To enhance the system performance, ambient air was used as the cooling medium at airflow rates of 1.2, 2.2, and 4.5 m/s. Results showed that 1.2 m/s produced the highest thermal efficiency of 64% with an outlet air temperature of 45.8°C. 2.2 m/s provided the balance of thermal and electrical efficiency of 62% and 11.5% with stable convective cooling, while 4.5 m/s yielded lower gains due to excessive cooling. The system attained a maximum heat gain of 411 kJ and an annual energy yield of 410 MJ m^{-2} yr^{-1}, offsetting 1.4 kg CO_2 m^{-2} yr^{-1} with a payback period of 8–10 years. This confirms the PV/T air collector as an efficient and low-cost solution for low-grade heat recovery in solar drying and space heating applications under a hot and humid climate.

1 Introduction

Photovoltaic/Thermal (PV/T) systems have emerged as a promising technology for generating both electrical and thermal energy simultaneously within one system. The high solar irradiance throughout the year, as in Malaysia, makes PV/T systems attractive for sustainable energy applications. However, in countries with high humidity and hot weather, where temperatures can rise to 35°C, a rise in PV cell temperature typically reduces module efficiency by 0.3% to 0.5% per °C [1, 2]. To minimize efficiency losses, air cooling is one of the simplest and most economical methods to address this issue. The heat gained from the PV/T system can be collected and stored as thermal energy, a process known as the PV/T collector system. Note that this technology depends on airflow velocity, duct configuration, fin geometry, and turbulence generation within the collector [3-5], as in Figure 1. Several development works and research have been conducted on PV/T collector systems using water and air as cooling media. However, PV/T water systems are more efficient than PV/T air systems due to their higher thermo-physical efficiency. Although water is more efficient,

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PV/T air systems are more widely studied due to their lower cost, simple operation, and suitability for building-integrated applications [5].

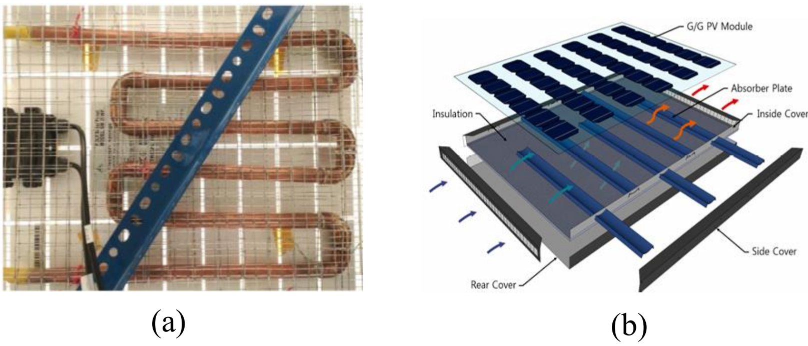


Fig. 1. (a) Water-cooling pipe design [1], (b) Air-type PVT collector [3] that focuses on design development.

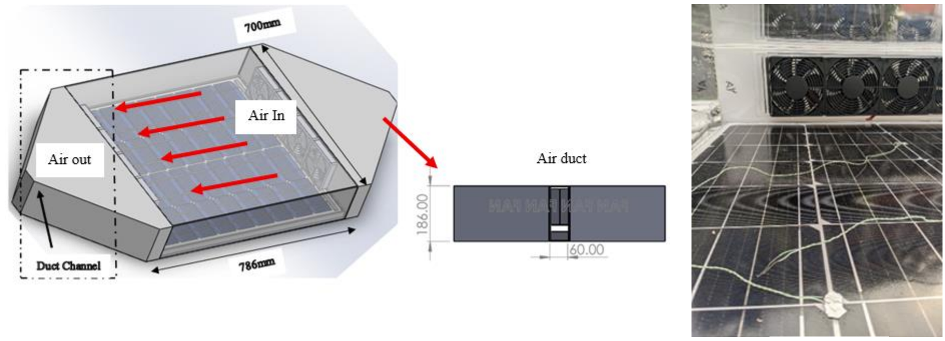
Previous research work by [3] demonstrated that interspaced baffle designs enhanced turbulence, thus reducing module temperature, while [6] used perforated baffles in a Building integrated photovoltaic-thermal (BIPVT) configuration. Likewise, [7] modified dual-inlet designs that improved cooling uniformity. Other research was done on the fin arrangements and geometric design [8-10] to enhance overall heat transfer and thermal efficiency. An exergy-based model for air-cooled PV/T collectors under tropical conditions [11, 12] provided comparative insights on PV/T hybrid configurations [13].

Moreover, the majority of previous studies focused on cooling strategies to improve electrical efficiency, while giving limited attention to harnessing thermal energy as a prime energy source. Module temperatures can exceed 45 to 60°C in humid and hot climates, particularly in Malaysia, where PV/T air collectors can simultaneously serve as low-grade heat sources suitable for drying applications in the agricultural sector. For example, [12] reviewed PV/T air technologies, [14] compared both air and water cooling strategies, and [15] improved the PVT air system to maximize convective heat extraction. However, the utilization of the heat gain from PV/T air collectors for drying processes remains underexplored.

Therefore, the objective of this experiment is to study the performance of PV/T air collector systems, to enhance the technology, and to serve as an effective renewable heat source for solar drying in hot and humid climates.

2 Methods and Experimental

The purpose of this experiment is to evaluate the thermal and electrical performance of a PV/T air collector system and to utilize a useful thermal energy source. The experiment was conducted at the Malaysia-France Institute, Universiti of Kuala Lumpur (2.9285° N, 101.7585° E). A prototype PV/T air collector, as illustrated in Figure 2, was developed by integrating a 100 W PV panel model, E-Ten (SF100-18V), with dimensions of 770 mm × 671 mm × 25 mm, into the collector box to enhance thermal performance. Meanwhile, the thermal system consists of a built-in air duct fan (JSDYFAN, 12V) with an acrylic body (0.78 m × 0.70 m × 0.18 m) mounted on the collector. This setup allows solar radiation to reach the PV surface while enhancing convective heat extraction by channeling airflow beneath the module.



(a) (b)

Fig. 2. (a) Illustration of PV/T air collector (b) Air duct fan

The PV/T system in Figure 3 depicts a single-pass air channel with airflow regulated by a KESTREL 2000 anemometer at 1.2, 2.2, and 4.5 m/s to simulate varying cooling conditions. Experiments (09:00–17:00) were conducted under clear-sky conditions for both PV and PV/T systems. Note that each airflow was stabilized for 30 minutes to reach a steady state before data collection. Measurement uncertainties were ±0.5°C for temperature and ±5 W/m² for irradiance, with data recorded at 1-minute intervals and averaged over steady state periods.

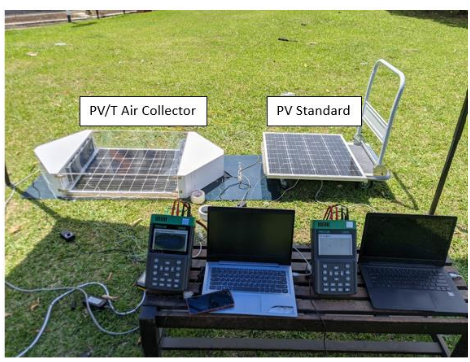


Fig. 3. Real Experiment Setup

Several type-K thermocouples were installed on the PV surface, inlet, outlet, and ambient points of the PV/T collector and connected to a data logger (OMRON ZR-RX25) for temperature measurement. Consequently, solar irradiance (600–1000 W/m²) was recorded using a pyranometer, while electrical parameters were obtained from a solar analyzer (MECO 9009-60V) for performance evaluation.

3 Results and discussion

The main objective of this study was to enhance overall performance and utilize the thermal energy. Correspondingly, all parameters included in the calculation of performance efficiency were measured. Thermal efficiency, η_{th}, was calculated using the general expression of the PV/T system:

$$\eta_{th} = \frac{mC_p\left(T_{out} - T_{in}\right)}{GA} \times 100\ \%, \tag{1}$$

where C_p is the specific heat of air (J/kg. K), T_{out} and T_{in} are the inlet and outlet air temperatures (°C), G is the solar irradiance (W/m^2) , A is the collector area (m^2), and $\dot{m}$ is the mass flow rate of air (kg/s). The flow rate was calculated using equation (2):

$$m = \rho A V_{av}. \tag{2}$$

Typically, the density of air at standard temperature (ρ=1.2 kg/m³ at 25°C) and standard temperature pressure (STP) is constant. The electrical efficiency is generally expressed in equation (3):

$$\eta_{el} = \frac{P_m}{A_{pv}G} \times 100\ \%. \tag{3}$$

Here, η_{el} represents electrical efficiency, A_{pv} denotes the surface area of the PV panel, and G stands for solar irradiance. The total efficiency performance (%) is calculated using equation (4).

$$\eta_{total} = \eta_{th} + \eta_{el} \tag{4}$$

where η_{th} is the thermal efficiency and η_{el} is the electrical efficiency of the system. The useful thermal energy Q_{th} gained from the PV/T air collector was calculated using equation (5):

$$Q_{th} = mC_p\left(T_{out} - T_{in}\right), \tag{5}$$

where m is the mass flow rate of air (kg/s), C_p is the specific heat of air (J/kg·K), T_{out}, and T_{in} are the outlet and inlet air temperatures (°C). This parameter represents the total useful heat energy.

3.1 Energy and Exergy Analysis

The energy and exergy analyses were performed to evaluate the overall performance of the PV/T air collector. The energy efficiency η_{th} was calculated using equation (1), while the exergy efficiency (η_{ex}) is expressed by equation (6):

$$\eta_{ex} = \frac{Q_{th}\left(1 - \frac{T_{am}}{T_{out}}\right)t}{l \times A}, \tag{6}$$

where Q_{th} is the useful thermal energy (W), T_{amb} and T_{out} are the ambient and outlet air temperatures (K), I is the solar irradiance (W/m²), and A is the collector surface area (m²).

3.2 Auxiliary Power and Net Efficiency Evaluation

The effect of auxiliary power consumption, P_{aux}, on overall PV/T system performance was considered. The auxiliary power was calculated using the following equation (7):

$$P_{aux} = \frac{Q_{air} \times \Delta P}{\eta_m}, \tag{7}$$

where Q_{air} is the volumetric airflow rate (m³/s), ΔP is the static pressure drop across the collector duct (Pa), and η_m is the motor efficiency. The net efficiency, η_{net}, of the PV/T air collector was determined by the gross output power as expressed in equation (8):

$$\eta_{net} = \frac{\left(P_{el} + Q_{th} - P_{aux}\right)}{GA}, \tag{8}$$

where P_{el} and Q_{th} are the electrical and useful thermal powers (W), G is solar irradiance (W/m²), and A is the collector area (m²). These equations ensure that auxiliary loads are reflected in the overall system performance.

3.3 Performance Evaluation

The results in Figure 4 demonstrate the temperature difference (ΔT), outlet temperature (T_{out}), and PV surface temperatures T_{PV} with mass flow rate (m). When the mass flow rate increased from 0.02 to 0.09 kg/s (1.2–4.5 m/s), the temperature difference decreased from 10.2°C to 2.2°C due to high convective cooling. The highest outlet temperature (46°C) occurred at 1.2 m/s, while 2.2 m/s achieved a balanced performance with ($\Delta T \approx 6$°C) and a stable outlet temperature (41°C). 4.5 m/s indicates a lower temperature, 37.4°C, when excessive airflow reduces air residence time. Hence, 2.2 m/s represents the optimal rate for heat extraction and surface panel cooling under high irradiance.

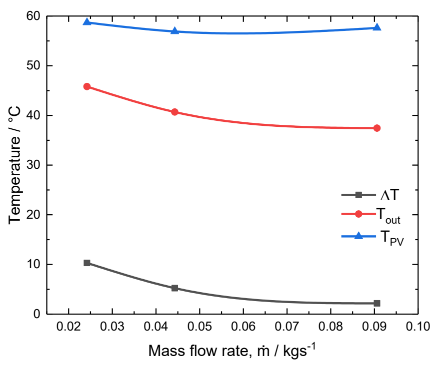


Fig. 4. Temperature difference and outlet temperature with mass flow rate for the PV/T air collector.

Figure 5 illustrates the electrical efficiency (η_{el}) of the PV/T air collector with time for different airflow rates. The electrical efficiency slightly reduces at noon (1000-1200) and improves in the afternoon (1200-0200) as irradiance decreases. Across all conditions, the PV/T air collector maintained higher efficiency (11-11.7%) compared to the standard PV (10.4%). 4.5 m/s had the highest performance (11.7%), while the 2.2 m/s provided the most stable performance. This confirms that air cooling effectively mitigates thermal losses, sustaining electrical conversion efficiency even under high irradiance levels.

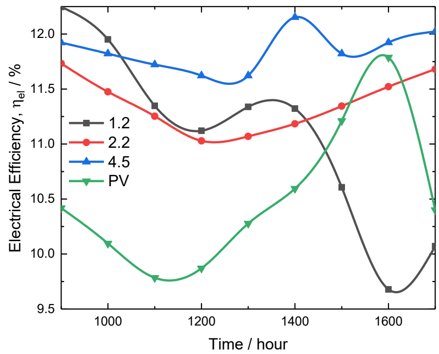


Fig.5. Electrical efficiency of PV and PV/T for different airflow rates with time

The results in Figure 6 indicate the thermal efficiency (η_{th}) for the PV/T air collector at different mass flow rates. Note that the efficiency profile integrated around noon (1100-1200) and decreased (64%-53%) toward late afternoon (1300-1400). The system achieved the highest thermal efficiency,64% at a mass flow rate of 0.024 kg/s, followed by 0.044 kg/s. However, 0.090 kg/s yielded only 53% due to excessive airflow reducing heat retention. It was confirmed that 2.2 m/s delivers the most sustainable heat extraction and stability under tropical irradiance [12].

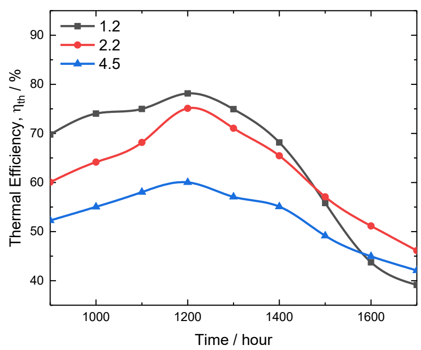


Fig.6. Thermal efficiency of the PV/T air collector with time at different mass flow rates

The graph in Figure 7 illustrates the total efficiency (η_{total}) of the PV/T air collector as it relates to mass flow rate and irradiance. The result demonstrates that at 1.2 m/s ($\dot{m}$ = 0.024 kg/s), the system achieved the highest total efficiency (75.4%) under 715 W/m², but with limited PV cooling. Here, 2.2 m/s ($\dot{m}$ = 0.044 kg/s) proved balanced performance (73.4%, 694 W/m²), representing the best performance. At 4.5 m/s ($\dot{m}$ = 0.091 kg/s), total efficiency decreased to 64.5% due to excessive convective cooling, and air temperature reduced.

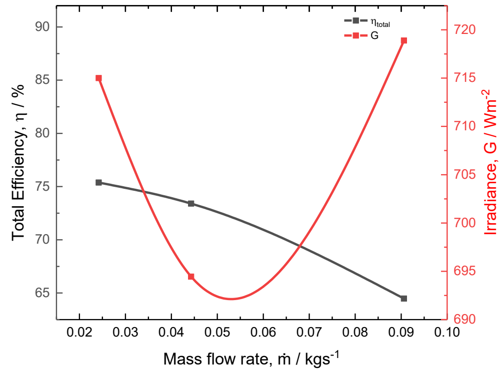


Fig. 7. Total efficiency and irradiance with different mass flow rates

3.4 Heat Gain and Energy Utilization

Figure 8 depicts the useful thermal energy (Q_{th}) with time for airflow rates (1.2, 2.2, and 4.5 m/s). 1.2 m/s airflow produced the highest thermal energy,411 kJ at noon (1200) due to a higher temperature difference, followed by 379 kJ at 2.2 m/s, and 316 kJ at 4.5 m/s, corresponding to the irradiance peak of ≈1000 W/m². Overall, thermal energy increased proportionally with irradiance and decreased with higher mass flow rates, confirming that 2.2 m/s provides optimal heat extraction for solar drying under tropical conditions [11].

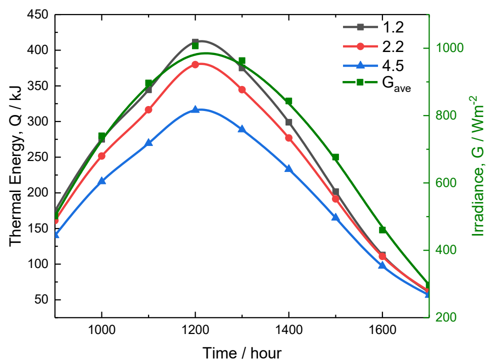


Fig. 8. Thermal energy and irradiance with time for different airflow rates

3.5 Environmental and Economic Assessment

The effectiveness and sustainability of the PV/T air collector for environmental and energy contributions at the optimum airflow rate of 2.2 m/s. The PV/T air collector achieved a maximum thermal energy of 380 kJ at noon and a total efficiency of 73%. The PV/T total performance is 21 kJ/100 W panel, equivalent to an annual energy output of 410 MJ m^{-2} yr^{-1}. Based on SEDA Malaysia's emission factor (0.69 kg CO_2 kWh^{-1}), the PV/T system can offset ≈ approximately 1.4 kg CO_2 m^{-2} yr^{-1}. Hence, with an installation cost of USD 150 m^{-2} and annual savings of (USD 15–18 m^{-2}) [11], the projected payback period of 8–10 years for the present work (2025) as in Table 1, demonstrates both economic and environmental feasibility for solar drying and space heating applications which are comparable to recent studies by [12] and [15], confirming its suitability for solar drying.

Table 1. Environmental and Economic Performance Comparison of PV/T air Systems

Study	Airflow (m/s)	η_{th} (%)	CO_2 Reduction (kg/m²·yr)	Payback (yrs)
Present work (2025)	2.2	73	1.4	8–10
Kim (2024)	2.0	70-75	1.5	9–11
An et al. (2024)	2.5	78-82	1.7	7–9

3.6 Auxiliary Power Evaluation

The evaluated auxiliary power consumption of the PV/T air collector at airflow rates (1.2, 2.2, 4.5 m/s). Fan input ranged from 2–24 W (0.9–10.9% of gross output). At the optimal 2.2 m/s, the auxiliary demand was 5.5%, reducing total efficiency from 73% to 69%. 1.2 m/s showed negligible loss (< 1%), while 4.5 m/s decreased to 57%. These results in Table 2 confirmed that 2.2 m/s ensures effective cooling with minimal auxiliary demand, ensuring positive net energy performance across all tests.

Table 2. Comparative performance and auxiliary power evaluation of PV/T air collector at various airflow rates

Airflow (m/s)	ΔT (°C)	T_{outlet} (°C)	η_{th} (%)	η_{el} (%)	η_{total} (%)
1.2	4.5–10.0	38–51	65	11.4	75
2.2	2.9–8.0	34–49	62	11.5	73
4.5	1.4–3.1	31–42	53	11.9	64

3.7 Comparative Analysis with Literature

The present PV/T air collector system achieved an average thermal efficiency of 60% and an 11.5% improvement in electrical efficiency (compared to standard PV). This aligns well with reported studies by [12] and [15], which show thermal efficiencies of 48–52% and electrical efficiencies of 4.5–4.8%, respectively. Table 3 summarizes the thermal and electrical performance of the PV/T air comparison.

Table 3. Comparative Performance of Air-Type PV/T Systems

Study	Collector Type	Thermal Efficiency (%)	Electrical Efficiency (%)
Present work (2025)	Single-pass duct	60	11.5 (~5% vs PV)
Kim (2024)	Dual-channel PV/T	48	4.8
An et al. (2024)	Turbulator-assisted PVT	52	4.5
Chaichan et al. (2023)	Flat-plate PV/T	47	4.0

The results confirm that the present work enhanced convective heat transfer at maximum thermal energy of 366 kJ (2.2 m/s). The air-cooling maintains outlet air temperatures (48°C) with auxiliary demand, low cost, and a maintenance-friendly design compared to other cooling methods. These outcomes confirm that air-type PV/T collectors are practical for solar drying in Malaysia's tropical climate.

4 Conclusions

This experimental study investigates the performance of a PV/T collector under Malaysian climate conditions by utilizing airflow rates (1.2, 2.2, and 4.5 m/s). The results showed that 1.2 m/s achieved the highest thermal efficiency of 64% and an outlet air temperature of 46°C, while 2.2 m/s provided a total efficiency of 62% and an electrical efficiency of 11.5%, 5% increase compared to standard PV with stable cooling.

The novelty of this work confirmed that a PV/T air collector achieves effective heat extraction without auxiliary energy at a 2.2 m/s flow rate, providing optimal heat transfer and balanced performance.

Flow non-uniformity, and thermal stratification may affect long-term performance. Future improvements should focus on absorber design and better insulation, supported by Computational Fluid Dynamics (CFD) simulations and bi-fluid cooling designs to improve efficiency and durability.

The environmental and economic analyses indicated an annual energy yield of 410 MJ m^{-2} yr^{-1}, a CO_2 offset of 1.4 kg m^{-2} yr^{-1}, and a payback period of 8–10 years, validating the practicality and sustainability of PV/T air collector for low-cost solar-drying applications in Malaysia's hot and humid climate.

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