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Performance Comparison of Photovoltaic (PV), Heat Pipe Photovoltaic/Thermal (HP-PV/T), and Heat Pipe Solar Thermal Collectors (HP-STC): Energy Analysis

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ABSTRACT

A hybrid system called photovoltaic/thermal (PV/T) is the combination of photovoltaic (PV) and solar thermal collector (STC) to simultaneously produce heat and electricity. The combination optimizes the use of solar energy, functioning as a heat source for water heating and mitigating the low PV efficiency issue caused by module high temperature. Therefore, this research aimed to investigate and compare the efficiency of PV, PV/T, and STC, with heat pipe (HP) as heat-absorbing media to warm water. The systems were experimented with the same conditions at ambient temperatures of 27-40°C and solar intensity of 122-967 W/m^2, at intervals between 08.00 AM to 04.00 PM during 8 days of testing. The experiment was conducted by directly measuring the intensity of the sun, water temperature, as well as thermal and electrical energy generated by the systems. The results showed that PV and HP-PV/T had average electrical energy efficiency of 16.92% and 17.68%, respectively, indicating a 0.76% increase. Furthermore, there was a difference in average thermal efficiency of 1.72% between HP-PV/T and HP-STC, with values of 22.93% and 24.65%, respectively. These results offered a promising implication for the development of PV/T for residential applications.

1. INTRODUCTION

An estimated 46% of total energy consumption is used for heating and cooling in the industrial and residential sectors. The majority of this energy usage is sourced from fossil fuels, with renewable comprising 15% [1, 2]. Therefore, the development of a sustainable and clean energy sector is essential as a replacement of fossil fuels with renewable energy [3-5]. In this context, solar energy offers promising potential due to the abundance, affordability, and cleanliness, as the most significant renewable energy source [6, 7].

The difficulties in obtaining and preserving this unpolluted energy substantially limit the potential for industry. Due to the limited availability of solar radiation at night, there is a need for efficient absorption, transmission, and storage [8]. To overcome these challenges, solar radiation can be converted into useable energy using a variety of solar absorption processes [7, 9-11].

Photovoltaic (PV) is the most rapidly growing solar energy conversion method with significant potential application [12]. PV panels capture solar radiation and transform into electrical power with an efficiency of 6- 20%, while the rest of the energy is retained as heat. This retained energy contributes to a significant increase in temperature, which negatively impacts the efficiency of the systems [13-15]. Previous research showed that every increase of 1℃ PV cell temperature could reduce efficiency by ± 0.4-0.5% [16]. The reduced performance of PV module can be overcome through the additional cooling systems, which function as a heat exchanger and flow beneath PV module. This hybrid system, namely photovoltaic/thermal (PV/T), improves thermal and electrical energy [17, 18].

PV/T, which combines the production of electrical and thermal energy, is a viable method to improve the use of solar energy [19]. A hybrid solar thermal and PV collector can facilitate the energy production per unit area compared to using only solar PV or thermal system [20]. This method is predicted to solve the problems of low electricity efficiency and heat dissipation caused by the high temperature of PV cells [21].

Heat pipe (HP) plays a significant role in PV/T due to the rapid heat transfer through evaporation and condensation without external electricity. The working fluid in the evaporator section absorbs heat from the surrounding system, transforming into vapor, and flows to the condenser to release heat through condensation before returning as a liquid [22]. The pressure difference and capillary force inside HP ensure continuous operation [23, 24]. Wickless HP, often referred to as closed thermosyphon or gravity-assisted, offers the benefits of a simple design, cheap power costs, lightweight designs, high dependability, and extended service lives [25, 26]. Additionally, the use of phase change heat transfer by the working medium reduces temperature differential across the system, resulting in consistent temperature in the solar panel

[26].

Several investigations have been carried out to explore the performance of heat pipe photovoltaic/thermal (HP-PV/T). Pei et al. [27] conducted a parametric analysis, exploring the performance of HP-PV/T that simultaneously supplied thermal and electrical energy. A significant advantage of the system over traditional water-type PV/T is the ability to operate without freezing in cold climates. The impact of tilt angle on thermal performance of wire-meshed and wickless HP-PV/T systems was investigated experimentally by Hu et al. [28]. The result showed that wire-meshed HP thermal performance was less susceptible to tilt angle compared to wickless. A performance comparison between HP-PV/T and heat pipe solar water heating (HP-SWH) systems was carried out by Zhao et al. [29]. In three distinct places, HP-PV/T produced an extra 73.019 kWh, 129.472 kWh, and 90.309 kWh of electricity per unit area (m^2), respectively. A micro-channel HP-PV/T was explored numerically and experimentally by Modjinou et al. [30], where the electricity generated increased from 17 W to 74 W under radiation intensity conditions of 367-787 W/m²

The majority of earlier investigations only addressed the impact of tilt angle, energy evaluation, and other HP designs in PV/T. The improvements in PV efficiency with wickless HP need to be explored intensively to determine the effectiveness of the technology application. The potential of heat that can be transferred from PV by HP for water heating compared to using heat pipe solar thermal collector (HP-STC) also requires appropriate measurement. Therefore, this research was carried out to compare the energy efficiency (electrical and thermal) of PV, HP-PV/T, and HP-STC. The results are expected to be beneficial in obtaining optimum energy from HP-PVT and provide guidelines for future investigations. Knowledge of improving PV efficiency using HP can also be applied to enhance solar power generating system and water heating in residential buildings.

2. EXPERIMENTAL SETUP

The installation of this research, as shown in Figure 1 [31], is located on the roof of thermal engineering laboratory at the Department of Mechanical Engineering, Universitas Riau, Pekanbaru, Indonesia (0°35' North Latitude and 101°24' East Longitude). To evaluate the energy efficiency of PV, HP-PV/T, and HP-STC, the daily electrical performance of PV and HP-PV/T and thermal performance of HP-PV/T and HP-STC was tested and analyzed.

Figure 1. PV/T, STC, and PV systems

PV, PV/T, and STC were tested with parameters such as open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), wind speed (v), solar radiation (G_T), ambient temperature (T_a), temperature of PV cell (T_{pv}), temperature of absorber plate (T_{ab}), temperature of water tank (T_w), temperature of HP evaporator (T_{hpe}), and temperature of HP condenser (T_{hpc}). These parameters were required for system evaluation measured at intervals between 08.00 AM to 04.00 PM. Wind speed and ambient temperature were measured using an anemometer and temperature gauge, while the intensity of solar radiation was measured using a portable solar power meter. A detailed schematic diagram of the test facility with the various components is shown in Figure 2.

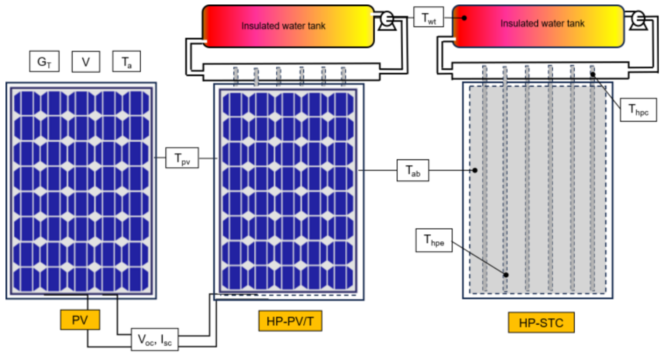


Figure 2. Schematics of experimental apparatus

The main features of the data collection devices used are listed in Table 1. Solar irradiance was measured using a Tenmars solar power meter (TM 208), with a measuring range of approximately 1999 W/m^2 and an accuracy of ± 3%. The temperature of PV cells, heat absorber, HP, water, and ambient air were recorded using a digital thermometer Lutron TM 946, PT 100 ohm, with measuring capacity ranging from -199.9° to 850°C. A digital multimeter Hioki DT 4211 was used to measure current and voltage with an accuracy of ±0.5% rdg. ±3 dgts. The wind speed and ambient temperature were measured using an anemometer Benetech GM 802, with a measuring range of 0.3-45 m/s, as shown in Table 2.

Table 1. Detail of instrumentation

Variable	Instrumentation	Measurement Accuracy	Resolution
Solar irradiance (W/m^2)	Tenmars Solar Power Meter (TM-208)	± 3%	0.1
Temperature (°C)	Lutron TM 946	-199.9° to 850°C	0.1°C
Wind Speed (m/s)	Benetech GM 802	± 3% ± 0.1dgts	0.1m/s, 0.2°C
Current (A)	Hioki DT 4211	±0.5% rdg. ±3 dgts	0.1
Voltage (V)	Hioki DT 4211	±0.5% rdg. ±3 dgts	0.1

Table 2. Measured parameters

Output Parameter	Notation
PV cell temperature	T_{sel}
Water temperature	T_w
Ambient temperature	T_{amb}
Absorber temperature (plate)	T_{pm}
Solar radiation Intensity	G_T
Open-circuit voltage	V_{oc}
Short-circuit current	I_{sc}
Wind velocity	v

2.1 PV system

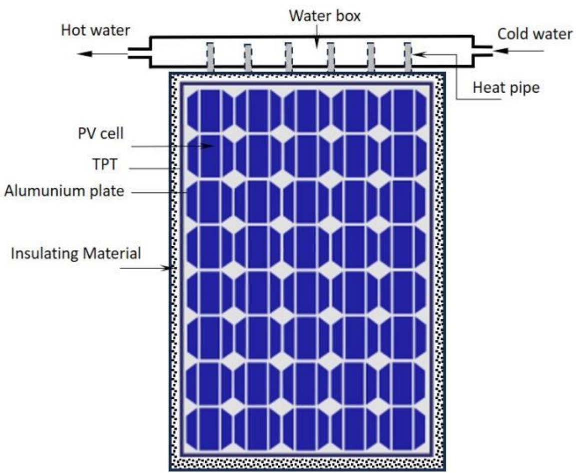
PV system consists of only PV module exposed to solar radiation with a 60℃ angle of tilt. In this research, PV used was monocrystalline type with a maximum power of 120 WP, with the module primary specifications shown in Table 3.

Table 3. Specification of PV module

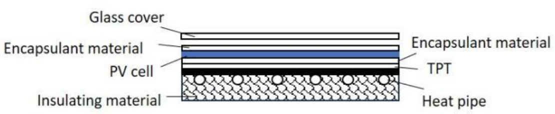
PV Specifications	Value
Power output	120 WP
Open-circuit voltage	22.7 V
Normal operating cell temperature	47±2℃
Number of cells	36
Dimensions	900 × 670 × 30 mm
Cell technology	Mono-Si

2.2 HP-PVT system

Figures 3(a) and (b) show the detailed structure of HP-PV/T and parts of the collector. At the base of the single-crystalline silicon PV module, the aluminum plate is attached to optimize heat absorption. Between PV cells and aluminum plate, the tedlar-polyester-tedlar (TPT) serves as the electrical insulation and the enhancement of solar radiation absorption. The evaporator of wickless gravity-assisted HP is connected to the rear of aluminum plate, transporting heat from the collector (aluminum) to the condenser. Heat in the condenser is rejected by placing in water box and a tempered glass plate is used as the upper glaze for the collector before PV cells. This allows sunlight access while minimizing thermal loss, and the introduction of rain, and dust particles. Glass wool is put into PV module's back and side edges to prevent heat loss and ensure thermal performance of the system.



(a) front view of HP-PV/T



(b) side view of HP-PV/T

Figure 3. Detail structure of HP-PV/T

Figure 2 shows HP-PV/T schematics, comprising solar collector (HP, aluminum plate, and PV module), a storage tank, and a circulation pump. Most solar energy is absorbed by PV cells after entering HP-PV/T through the glass cover. A portion of the radiation is converted to electricity, while the rest is transformed into heat energy. The evaporator portion of HP receives heat by conduction along the aluminum plate. Furthermore, this energy is exchanged for water flowing through the condenser, which is accumulated in the tank.

2.3 HP-STC

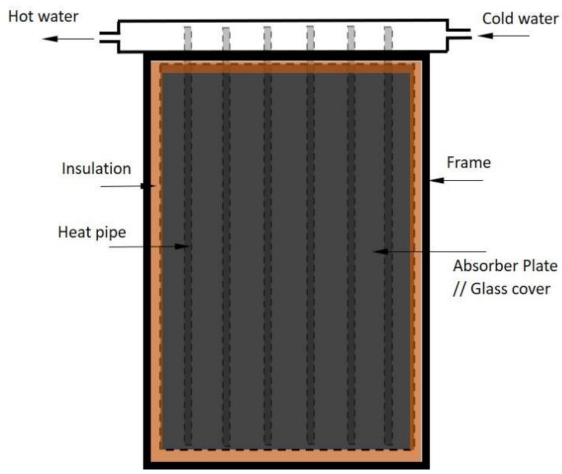


Figure 4. HP-STC design

Table 4. Design characteristics of HP-PV/T and HP-STC

Parameter	HP-PV/T	HP-STC
PV technology	mc.-Si*	n.a**
Power output	120 W	n.a
Thermal absorber area	0.67 m^2	0.67 m^2
Absorber material	Aluminum (thickness of 1 mm)	Aluminum (thickness of 1 mm)
HP Specifications	Wickless	Wickless
Number of HP	6	6
Length of HP	1250 mm (evaporator length 1000 mm, condenser length (250 mm)	1250 mm (evaporator length 1000 mm, condenser length (250 mm)
Inner diameter of HP	10 mm	10 mm
Glass cover thickness	5 mm	5 mm
Diameter of heat exchanger (water box)	250 mm	250 mm
Working fluid	Water (10% filling ratio)	Water (10% filling ratio)
Insulation	Styrofoam = 20 mm Rockwall = 50 mm	Styrofoam = 20 mm Rockwall = 50 mm
Capacity of water-heated	20 Liter	20 Liter

*Mono-Crystalline Silicon; *** Not applicable

Figure 4 shows the structure of HP-STC, where HP evaporator portion is attached to an absorber plate, and the condenser sections are placed into water box. The solar radiation heat on the absorber plate is transferred through the evaporation of water inside the evaporator to the condenser. Water with a constant flow rate passing through water box absorbs heat. This process is continuously carried out, facilitating the condensation of water vapor in the condenser into a liquid, which returns to the evaporator. Subsequently, the heat carried by water accumulates in water tank. A piece of glass wool as thermal insulation is positioned behind the absorber plate to prevent thermal loss. Similar to HP-PV/T, a tempered glass plate is used as the upper glaze for the collector before PV cells, enabling solar access while preventing thermal loss, the entry of dust particles, and rain. In comparison, HP-STC solely converts solar radiation into heat energy and warms water. Table 4 shows the detailed parameters of HP-PV/T and HP-STC.

3. DATA REDUCTIONS

PV energy efficiency, as expressed in Eq. (1), is the ratio between the electrical and solar energy that reaches PV surface.

$$\eta_{e,pv} = \frac{V_{oc} \times I_{sc}}{A_{pv} \times G_T} \times 100\% \quad (1)$$

where, V_{OC} is the open circuit voltage, I_{SC} represents short circuit current, G_T is the intensity of solar radiation, and A_{pv} denotes the area of PV panel.

The proportion of the heat energy absorbed by fluid to that of PV/T as solar radiation is defined as thermal efficiency. It is also defined as the ratio of usable energy to thermal energy entering the solar collector surface, as shown in Eq. (2) [32]:

$$\eta_{e,th} = \frac{\dot{E}_{th}}{A_c G_T} = \times 100\% \quad (2)$$

where, $\dot{E}_{th}$ is the useful thermal energy recovered by PV/T or STC, A_c is the collector area, with $\dot{E}_{th}$ defined as:

$$\dot{E}_{th} = \dot{m}_w C_{p,w} (T_{wo} - T_{wi}) \quad (3)$$

where, $\dot{m}_w$ is the mass flow rate of water passing through water box, $C_{p,w}$ represents the specific heat of water, T_{wi} and T_{wo} are the input and output temperature of water, respectively.

Electricity and thermal efficiency is known as the total efficiency of PV/T. Eq. (4) can be used to assess thermal efficiency of PV/T:

$$\eta_0 = \eta_{e,pv} + \eta_{e,th} \quad (4)$$

4. RESULTS AND DISCUSSION

Thermal and electrical properties were used to evaluate the performance of PV, HP-PV/T, and HP-STC. The efficiency of the systems was evaluated based on exposure to solar radiation. The reference incident solar radiation intensity was determined by measuring the radiation intensity minute-by-minute for 8 days in clear weather, as shown in Table 5.

During the 8 days of testing, the ambient temperature varied between 27 and 40℃, with the highest recorded irradiance at an average of 614 W/m^2. However, the analysis did not consider the impact of surrounding temperature and humidity on the three systems' performance. This was attributed to the assessment of all systems under the same conditions, ensuring uniformity across the evaluated process.

4.1 Evaluation of PV, PV/T, and STC performance in one day experiment

This section evaluates the energy-related functionality of PV, PV/T, and STC. Figure 5 shows the measurements taken on a single testing day for both ambient temperature and solar radiation intensity. The results show that solar radiation achieves the maximum value at 12:00 PM (997 W/m²) and gradually decreases. Meanwhile, the ambient temperature increases significantly from 8:00 AM to 13:00 AM, followed by a significant decrease.

Table 5. Intensity of solar radiation

Time	Solar Radiation Intensity (W/m^2)							
	1st	**2nd**	**3th**	**4th**	**5th**	**6th**	**7th**	**8th**
08:00	122	130	163	214	102	106	110	203
08:30	180	302	201	285	242	303	248	202
09:00	253	340	290	312	329	305	453	564
09:30	367	387	324	309	616	357	478	457
10:00	431	450	361	432	650	382	645	748
10:30	501	502	498	487	610	487	692	476
11:00	554	560	538	562	734	538	769	891
11:30	838	890	675	650	853	603	820	940
12:00	992	947	740	787	884	739	768	957
12:30	995	929	790	823	857	856	887	967
13:00	923	811	636	785	765	890	743	856
13:30	773	793	674	704	602	730	754	745
14:00	719	704	700	634	241	619	682	683
14:30	438	430	629	602	185	590	556	575
15:00	357	360	534	575	437	462	477	460
15:30	332	304	379	476	599	301	467	403
16:00	354	302	255	367	453	113	273	312
Average	**516**	**538**	**493**	**530**	**539**	**493**	**578**	**614**

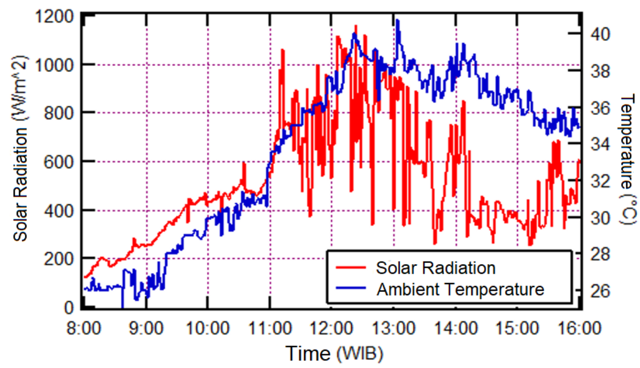


Figure 5. Intensity of radiation and ambient temperature during one day of testing

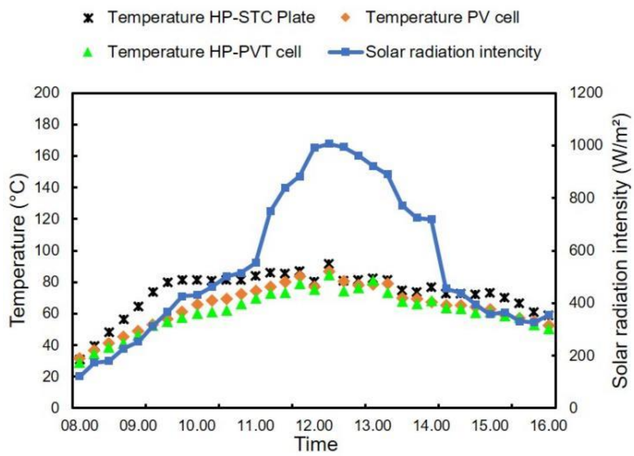


Figure 6. Comparison of PV, HP-PV/T, HP-STC surface temperature

Figure 6 shows the temperature elevates in both PV and HP-PV/T, as solar radiation exposure increases. HP-STC plate has the highest temperature due to the use of high thermal conductivity material as a heat absorber (aluminum). The heat dissipation system (HP) built behind PV model reduces PV cells' temperature by approximately 32℃.

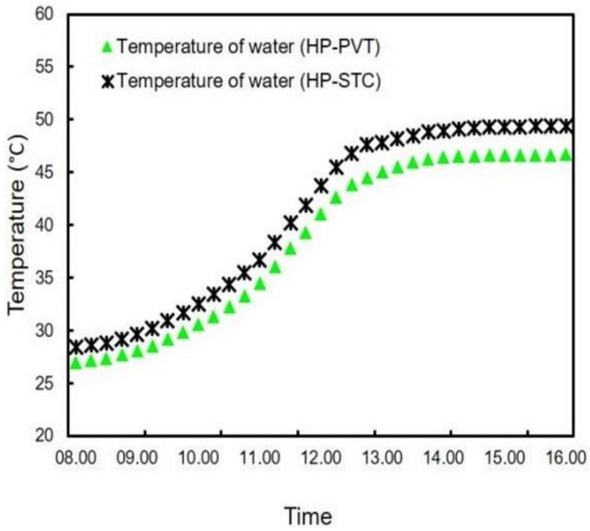


Figure 7. Comparison of water temperature at HP-PV/T and HP-STC

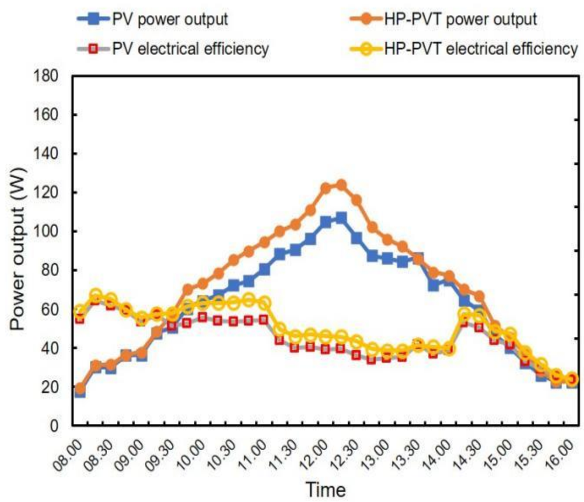


Figure 8. Comparison of electrical energy and energy efficiency of PV and PV/T electricity

Figure 7 shows water temperature variations in HP-PV/T and HP-STC. Based on the results, PV/T water temperature increased from 27.1℃ to 46.7℃ while STC rose from 28.1℃ to 49.3℃. Due to the absence of PV module on absorber plate surface for STC, all solar radiation was converted into thermal energy, which increased the temperature.

The use of a cooling system in PV by developing HP-PV/T to absorb heat in solar cells was expected to increase electricity efficiency. Moreover, the amount of electrical energy produced by HP-PV/T and PV was obtained through performance testing. Figure 8 shows the comparison of the electrical efficiency and power generation for a single testing day.

The electrical energy obtained from PV and HP-PV/T increased from 8:00 AM to 12:30 PM due to increasing solar radiation exposure. However, the energy generated decreased in the identical trend as solar radiation. By comparing the electrical performance of PV with PV/T, HP was found to increase the efficiency of PV cells which modified the temperature.

HP used in PV/T and STC wickless systems was gravity-operated, with the condenser placed above the evaporator. This design facilitated the return of liquid to the evaporator without requiring capillary structures or external electricity. In water box, water flow absorbed the heat transferred by vapor, which condensed inside the condenser and returned to the evaporator. Furthermore, thermal energy would be quantified due to the rising temperature in water reservoir (HP-PV/T and HP-STC water container). A comparison of thermal energy and efficiency of PV/T and STC during a single testing day is shown in Figure 9.

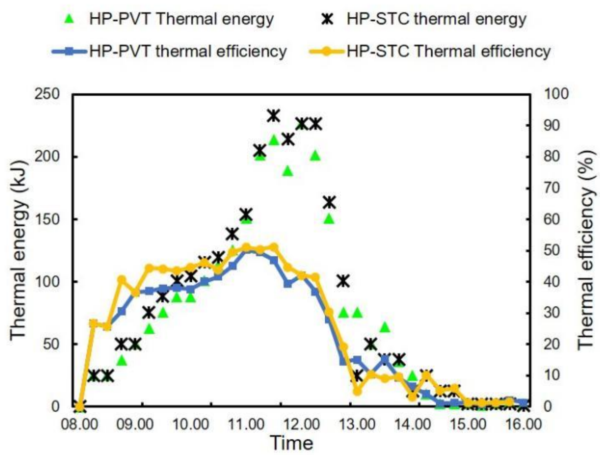


Figure 9. Comparison of thermal energy and efficiency of HP- PV/T and HP-STC

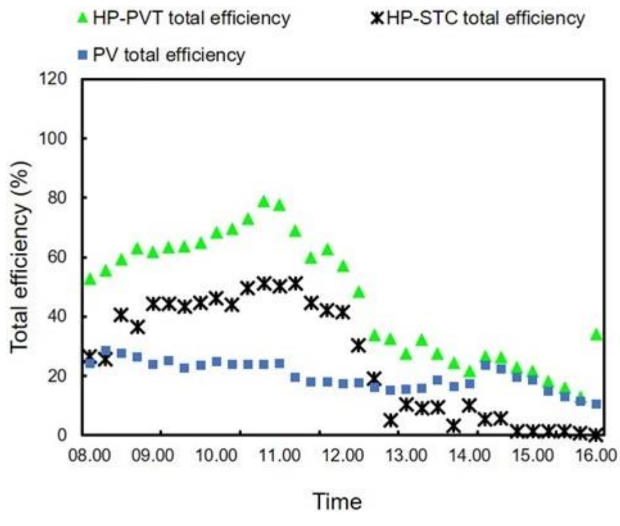


Figure 10. Comparison of the system's overall energy efficiency for a single testing day

Thermal energy absorbed by HP-STC was greater compared to HP-PV/T value. This phenomenon occurred because the solar radiation directly exposed HP-STC absorber plate, and the surface heat collector was covered by PV panel in HP-PV/T. Thermal energy increased from 8:00 AM to 12:30 PM and gradually decreased as the temperature of water circulation increased. The results also showed that water flow temperature had an impact on the systems' thermal efficiency.

A comparison of the overall efficiency of PV, HP-PV/T, and HP-STC is shown in Figure 10. Based on the results, HP-PV/T had the best efficiency compared to other systems, showing the capacity to enhance PV performance by absorbing heat from the panels and converting into useful thermal heat (water heater).

4.2 Electrical energy comparison between PV and HP-PV/T

Figure 11 shows the electrical energy produced for 8 days, with, PV panels generating 57 to 80 W of electricity. The use of HP as absorber could enhance electricity production by approximately 86.42 W, showing an increase in electrical performance from 0.36 to 1.17% (0.77% on average). Based on the results, PV and HP-PV/T electrical efficiency were 16.92% and 17.69%, respectively. The electrical efficiency of HP-PVT in this research was acceptable and superior compared to conventional PV/T, which ranged from 4% to 13% [20, 27, 33, 34].

Despite the appropriate improvement in electrical energy generation, PV/T still offers the benefits of using other sources, including thermal energy for heating water. The graph in Figure 12 shows the daily total thermal energy absorbed and effectiveness for 8 testing days. To assess PV/T thermal performance, there is a need to compare thermal energy absorption at STC.

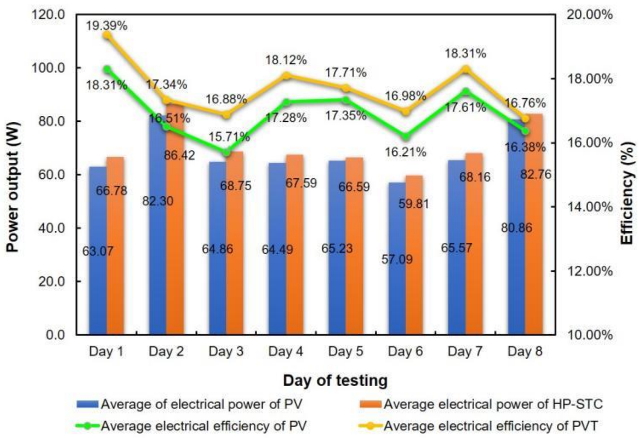


Figure 11. Average of electrical energy and efficiency generated by PV and HP-PV/T

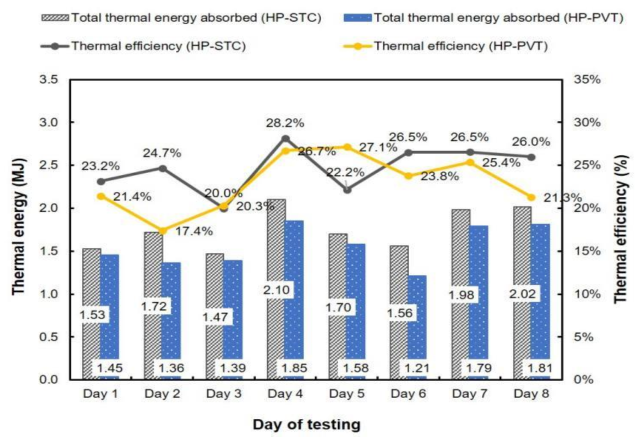


Figure 12. Total of thermal energy and average of thermal efficiency obtained by HP-PV/T and HP-STC

Total thermal energy absorbed was estimated by monitoring the increase in water temperature, multiplying by water mass and heat capacity, as well as conducting the experiment for one day. Figure 12 showed that STC usage was marginally superior to PV/T in terms of thermal energy. Compared to STC heat-absorbing plate, which absorbed thermal energy from direct sunlight, the heat-absorbing plate on PV/T only absorbed heat in PV cells.

The average amount of thermal energy absorbed by HP-PV/T and HP-STC was 1.55 MJ and 1.76 MJ, respectively, showing a difference of 1.72%. When compared to HP-PV/T (22.93%), HP-STC had an average thermal efficiency of 24.65%.

5. CONCLUSIONS

In conclusion, this research described the comparison of performance evaluation PV, HP-PV/T, and HP-STC. The systems were tested under the same conditions for 8 days to evaluate electrical energy generated from PV and HP-PV/T, as well as thermal energy used by HP-PV/T and HP-STC.

The results showed that the use of HP as a heat transfer medium enhanced PV efficiency by 0.77%, with PV of 16.92% and HP-PV/T of 17.69%. This increase showed that PV module in HP-PV/T could generate 0.77% more electricity compared to those without cooling. Additionally, HP-PV/T still benefited from the usage of thermal energy, which was a source of energy used to warm water. The average thermal energy efficiency for HP-PV/T and HP-STC was 22.93% and 24.65%, respectively.

This research showed that HP-PV/T had better efficiency than the other two systems due to the ability to simultaneously use both types of energy from the same area. The method was found to be beneficial in residential applications, where PV-based solar electricity generation and water heating systems used solar collectors. Additionally, the combination of PV and STC through PV/T technology offered cost benefits in terms of investment. These benefits showed the promising future of solar energy development, allowing more people to access clean, renewable energy sources, and reducing the impact of greenhouse gases on the environment.

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NOMENCLATURE

T_{sel}	Module temperature
T_w	Water temperature
T_{amb}	Ambient temperature
T_{pm}	Absorber temperature (plate)
G_T	Solar radiation Intensity
V_{oc}	Open-circuit voltage
I_{sc}	Short-circuit current
v	Wind velocity
$\eta_{e,pv}$	PV electrical efficiency
$\eta_{e,th}$	Thermal efficiency
$\dot{m}_w$	Water mass flow rate
$C_{p,w}$	Specific heat of water
T_{wi}	Temperature of water inlet
T_{wo}	Temperature of water outlet
η_0	Total efficiency