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COB-2023-0692 - PERFORMANCE ANALYSIS OF A THERMAL PHOTOVOLTAIC SYSTEM USING WATER COOLING AND THERMAL STORAGE

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Abstract. *This work aims to evaluate the performance of a thermal photovoltaic system (PVT), comparing it with a conventional photovoltaic system (PV) to increase its photovoltaic conversion efficiency, mitigating the effect of increasing operating temperature. Water is used for cooling and thermal storage. Experimental tests are carried out in a climate-controlled chamber consisting of a solar simulator with a maximum irradiance of 1000 W/m², ventilation of 1 m/s, water mass flow of 0.0209 kg/s, and ambient temperature and water stabilized at 25 °C. The variables measured in the tests are temperature, potential difference, electric current, and irradiance. The results show that the PVT system corresponds to the lowest operating temperature and the highest open circuit electrical voltage, with a reduction in operating temperature of 34.4 % compared to the conventional system and a 2.1 % increase in open circuit voltage. The electrical efficiency is higher in the PVT system, 5.3 % against 5.1 % in the conventional one. The main advantage of a PVT system over the conventional one is the thermal use for heating water. This work's thermal efficiency is 75.3 % for the configuration without ventilation. The overall efficiency of the PVT system is 80.5 %. Thus, this work obtained an overall efficiency 16 times greater than the conventional system.*

Keywords: *electrical efficiency, thermal efficiency, overall efficiency, thermal photovoltaic system, experimental tests.*

1. INTRODUCTION

According to the International Energy Agency (IEA), the worldwide expansion of renewable energy capacity between 2023 and 2027 is expected to grow by approximately 2400 GW, representing an increase of 85 % compared to the period between 2018 and 2022. Photovoltaic solar energy is currently the world's fastest-growing renewable energy, forecast to account for one-third of the world's global additions by 2030.

According to Intersolar Europe 2022, the world reached the milestone of 1 TW of installed power in photovoltaic sources in 2022, with Brazil expected to become one of the leading global markets in the coming years, with the possibility of reaching the milestone of 50 GW of generated photovoltaic energy.

According to the National Electric Energy Agency, the leading electricity matrix in Brazil is generated from hydroelectric plants. However, the country has frequently experienced low levels in the hydroelectric reservoirs, leading to the risk of rationing and severe social impacts.

The use of renewable sources of electricity, such as photovoltaics, has been increasing in Brazil. Currently, photovoltaic generation represents the second largest source of electricity generation, and it is expected to occupy the first position by 2050 (ANEEL, 2022).

However, there are two main limitations for further growth in the sector, namely the cost of acquiring and installing the system and the low efficiency in converting photovoltaic energy into electrical energy due to the increase in its operating temperature, especially since Brazil has a large share of its territory located in the tropical zone (Vian *et al*., 2021).

Several works deal with energy efficiency in hybrid photovoltaic systems, using water as a cooling technique to reduce the operating temperature.

Thus, Bergene and Lovvik (1995) proposed a detailed physical model of a hybrid thermal photovoltaic (PVT) system, in which they presented an algorithm for quantitative predictions of the system's performance, considering that solar cells act as good collectors of heat and selective absorbers, in addition to the fact that most solar cells increase their efficiency when heat is extracted from the cells. The model was based on analyzing energy transfers due to conduction, convection, and radiation, predicting the amount of heat removed from the system and its output energy.

For Morita *et al*. (1999), a hybrid PVT module is a high-efficiency energy converter that provides electrical and thermal energy from solar energy. Through numerical analysis, considering two PVT systems with different environmental conditions and fluid mass flow rates, they found photovoltaic efficiencies of 9.61 % and 10.56 % for the systems at an ambient temperature of T = 25 °C; the thermal efficiencies were 52.11 % and 40.14 % at an average temperature of T = 40 °C, and the intensity of solar radiation found was 800 W/m^2. Based on these results, the authors compared energy efficiencies under ideal operating conditions and various environmental conditions. They concluded that the increase in the intensity of solar radiation leads to an increase in the energy absorbed in the receiving surface and, consequently, an increase in the temperature in the photovoltaic cell.

Tripanagnostopoulos *et al*. (2002) presented the results of tests on hybrid solar PVT systems consisting of photovoltaic modules and thermal collectors. As solar radiation increases the temperature of the photovoltaics modules, resulting in a drop in their electrical efficiency, the authors transfer the heat from the photovoltaics modules through the circulation of a fluid with a low inlet temperature, thus maintaining the electrical efficiency at fair values, since the extracted thermal energy increases the total energy production of the system.

Radziemska (2003) researched the performance of Si and GaAs solar cells, presenting the main parameters and phenomena that affect their production, focusing on photovoltaic and thermal specifications and the integrated construction of photovoltaic systems. The author concluded that the increase in the operating temperature of photovoltaic modules means that more absorbed solar radiation is not converted into electrical energy, reducing the electrical efficiency of the module.

Thus, this work aims to analyze the performance of a photovoltaic system with thermal utilization, aiming to reduce its operating temperature and improve its energy efficiency, comparing it with a conventional photovoltaic system.

This work is organized into four sections, the first of which contextualizes the research theme, presenting the work's justifications, motivations, and objectives. In the second, the methodological procedures adopted in the experimental tests are described, supporting the equations that govern the functioning of the systems. In the third, the results and analysis of the data obtained from the experimental tests are presented, and in the fourth, the conclusions of the work are presented.

2. METHODOLOGY

To carry out this work, experimental tests are used in a controlled climatized chamber with dimensions of 3.0 x 3.0 x 3.0 m, with a temperature range from -10 to +65 °C. The solar simulator is 2.1 m high, 1.85 m wide and 1.25 m deep. For the generation of light irradiation, continuously for 3 hours, nine (9) halogen lamps of 500 W each coupled to directional reflectors are used, sufficient for the generation of 1000 W/m^2.

Irradiance reading is performed by a pyranometer model CMP11-Kipp & Zonem, with a sensitivity of 9.03 μVm^{2}W^{-1} and uncertainty of 0.1 %. The adjusted value in the tests is 1000 W/m^2.

Ventilation is measured using a Testo 445 portable digital anemometer sensor, with a range of 0 to 20 m/s, resolution of 0.01 m/s, and uncertainty of 0.1%. In this work, a speed of 1 m/s is used in tests with ventilation.

The circulation of the water mass flow is carried out using a digital thermostatic bath, model Haake F6-C25, control precision of ±0.01 K, 1450 VA, with the water temperature set at 25 °C, mass flow at 0.0209 ± 0.0008 kg/s, with an uncertainty of 4 %.

The water circulates between the thermostatic bath and a solar collector, allowing heat transfer between the water and a finned heat sink, machined from a steel plate, with dimensions like that of the photovoltaic module, as shown in Figure 1. To measure temperatures, T-type thermocouples are used (± 1.0 K) positioned on the surfaces to be monitored.

Figure 1. Solar collector (left). Heat sink (right).

The heat sink transfers excess heat from the photovoltaic module to the solar collector, through which water circulates, which is used for cooling and thermal storage.

The temperature difference (ΔT) of the water entering and leaving the solar collector is measured using the potential difference (ΔV) between two T-type thermocouples interconnected using calibrated compensation wires. The highest mass flow rate available in the equipment will be used.

Data acquisition takes place using the Agilent 34970A Signal Acquisition System (SAS), configured for a 10 s interval, with the data treated and presented based on descriptive statistics through Excel 365 Family software.

The photovoltaic modules used in this work are of model Yingli YL010P-17b 1/13 with 245 x 375 x 25 mm dimensions, containing 36 polycrystalline Si cells. The electrical and thermal parameters of the photovoltaics modules are presented in Tables 1 and 2 (YINGLISOLAR, 2022).

Table 1. Electrical parameters of the photovoltaic module YL010P-17b 1/13.

Parameters	**Values**
Power output	10 W ± 5 %
Module efficiency	10.8 %
Maximum power voltage	17.1 V
Maximum power current	590 mA
Open-circuit voltage	21.8 V
Short-circuit current	650 mA
Maximum system voltage	50 V

Table 2. Thermal parameters of the photovoltaic module YL010P-17b 1/13.

Parameters	**Values**
Maximum power temperature coefficient	-0.45 %/K
Open-circuit voltage temperature coefficient	-0.37 %/K
Short-circuit current temperature coefficient	0.06 %/K

For the tests, a conventional photovoltaic module is used as a reference. A second one is for the hybrid system, where temperature measurements are carried out on the upper and lower face of the modules, voltage, and electric current. For the hybrid PVT system, a heat sink, a solar collector, and a thermostatic bath are coupled to the photovoltaic module, as shown in Figure 2.

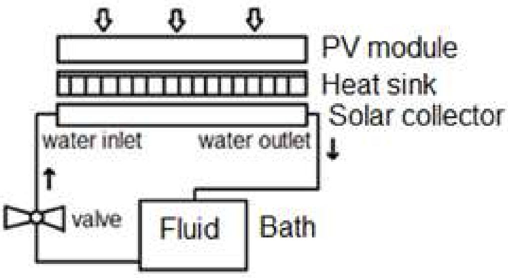

Figure 2. Diagram of experimental tests.

To obtain the electrical efficiency of the photovoltaics modules, a rheostat is used with a variable load of 150 Ω to get the maximum electrical power, as shown in Figure 3.

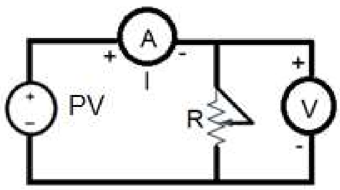

Figure 3. Electrical circuit to obtain the maximum current, voltage, and power values.

When turning on the solar simulator lighting system, the electrical circuit is powered by the potential difference generated in the photovoltaic module. When the load R is at the minimum value, the circuit behaves like a short circuit, presenting a maximum current value called short circuit current (I_{SC}).

By varying the load to its maximum value, the circuit behaves like an open circuit, presenting a maximum voltage value called the open circuit voltage (V_{OC}).

The curve formed from the charge variation, relating the current and the electrical voltage, is denoted the IV characteristic curve. In the same way, the PV curve is obtained, from which the maximum power point (P_{MP}) is acquired, thus getting the values of maximum power current (I_{MP}) and maximum power voltage (V_{MP}).

Thus, the experimental tests consist of adjusting the wind speed to 0 m/s or 1 m/s; the luminous irradiance in 1000 W/m^2 ± 5 %, the mass flow rate of the water in 0.0209 kg/s; the water temperature of the thermostatic bath and the ambient temperature at 25 °C. For each test, an average of five hours of measurement is required, three hours with the lighting system on and another two hours for cooling all components.

2.1 Power and efficiency of the photovoltaics modules

The power and thermal efficiency of the PVT system are calculated by equations 1 and 2 (Radziemska, 2003).

$$P_T = \dot{m}.c.\Delta T_w \quad (1)$$

$$\eta_T = \frac{P_T}{G.A} \quad (2)$$

where P_T and η_T mean the thermal power [W] and the thermal efficiency, $\dot{m}$ is the mass flow rate of the water [kg/s], c is the specific heat of the water [J/(kg K)], ΔT_w is the temperature difference of the water output and input [K] of the solar collector, G is the solar irradiance [W/m^2], and A is the area of the photovoltaic module [m^2].

The power and electrical efficiency of photovoltaic (PV) and PVT systems are calculated using equations 3, 4, and 5 (Tripanagnostopoulos *et al.*, 2002).

$$P_{MP} = V_{OC}.I_{SC}.FF \quad (3)$$

$$FF = \frac{V_{MP}.I_{MP}}{V_{OC}.I_{SC}} \quad (4)$$

$$\eta_E = \frac{P_{MP}}{G.A} = \frac{V_{MP}.I_{MP}}{G.A} \quad (5)$$

where FF is the form factor, meaning that the closer the result is to 1, the more efficient the system is, and η_E is the system's electrical efficiency. Therefore, for the conventional photovoltaic system, the total power equals P_{MP}, and the total efficiency is η_E. For the PVT system, the total power and efficiency are given by equations 6 and 7 (Tripanagnostopoulos *et al.,* 2002).

$$P_{PVT} = P_{MP} + P_T \quad (6)$$

$$\eta_{PVT} = \eta_E + \eta_T = \frac{P_{PVT}}{G.A} \quad (7)$$

where P_{PVT} and η_{PVT} mean, respectively, the total power [W] and the total efficiency of the PVT system.

3. RESULTS AND DISCUSSION

Initially, experimental tests were carried out to verify the influence of ventilation at 1 m/s and the use of water on the operating temperature of the photovoltaics modules, considering the ambient and bath temperatures stabilized at 25 °C, the irradiance set at 1000 W/m^2 ± 5 % and with the presence of heatsink and mass flow of water at 0.0209 kg/s. Thus, the operating temperatures of the photovoltaic (PV) and PVT systems as a function of ventilation are shown in Figure 4.

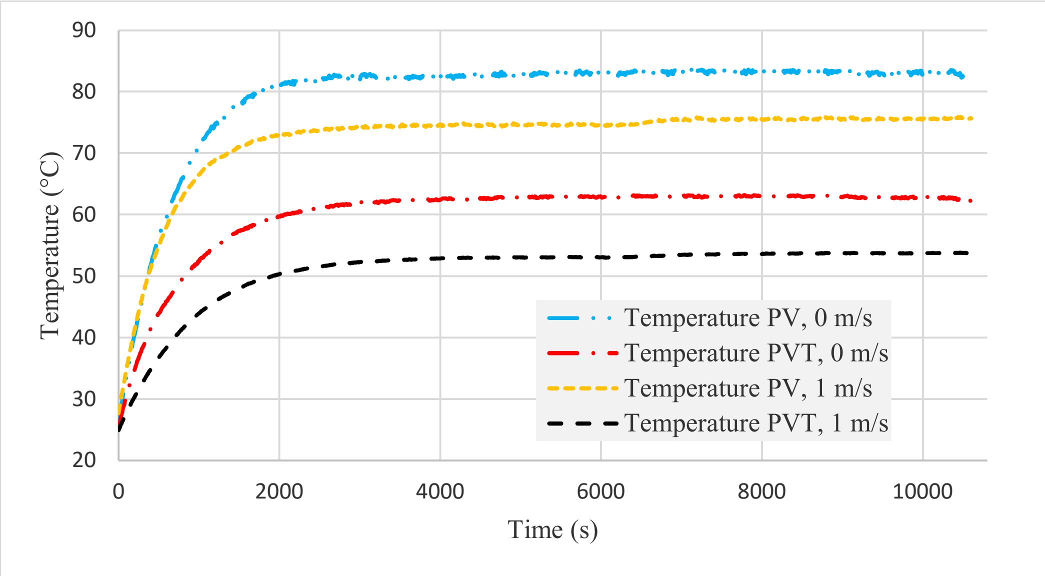

Figure 4. Operating temperature of the PV and PVT systems as a function of ventilation.

It is observed that the use of the hybrid PVT system causes a reduction in the operating temperature of the photovoltaic system. Since most of the incident energy is converted into heat, the operating temperature in the conventional system is high. In the PVT system, this heat is transferred to the solar collector, is stored, and reduces the operating temperature of the hybrid module.

Thus, ventilation reduces the operating temperature in the conventional photovoltaic system to 8.8 K, representing a 10.7 % difference from the test without ventilation. In the hybrid system, the reduction is up to 10.1 K compared to the system without ventilation, representing a 16 % difference. Likewise, the decrement is 23.2 K or 34.4 % from the conventional system to the hybrid. The open circuit electrical voltages are shown in Figure 5.

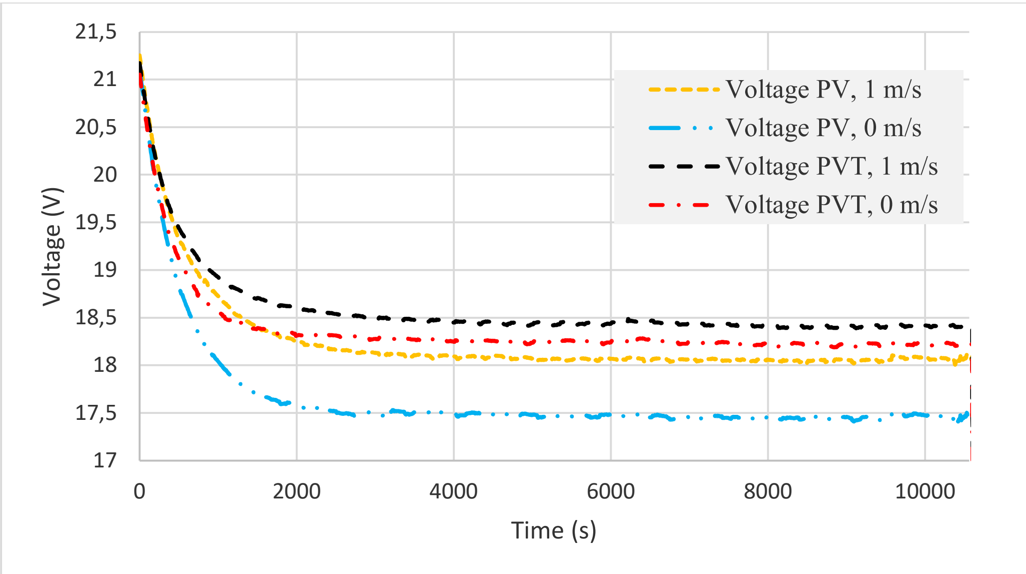

Figure 5. Open circuit voltage of the PV and PVT systems without ventilation.

Due to the lower operating temperature in the PVT system, its open circuit voltage is higher. Ventilation also reduces the operating temperature, which, associated with water use, increases the hybrid system's open circuit voltage.

Thus, ventilation increases the potential difference in the photovoltaic system by up to 0.8V, representing a 4.8% increase compared to the test without ventilation. The hybrid module's increment is up to 0.4V compared to the system without ventilation, meaning a 2.4% difference.

However, to survey the electrical efficiency of the systems, it is necessary to identify the maximum power points from which the maximum power voltage and current values are obtained, responsible for providing the highest efficiency in the electrical conversion of the photovoltaic module.

Thus, from the electric power: current x voltage (IxV) and power x voltage (PxV) sweeps, the maximum power values are obtained for each configuration, making it possible to get the maximum electrical efficiency of the systems. Based on equations 3 to 5, presented above, Table 3 is obtained, where η_E represents electrical efficiency in PV and PVT systems as a ventilation function.

Table 3. Electrical efficiency of the PV and PVT systems.

	PV	PVT
	η_E (%)	η_E (%)
v = 1 m/s	5,1	5,3
v = 0 m/s	5,0	5,2

It is observed that for both systems, the electrical efficiency is more significant for the configuration with ventilation since there is a greater reduction in the operating temperature of the photovoltaic modules. Based on the experimental tests conducted indoors, the electrical efficiency is higher for the PVT system (5.3%) than 5.1% for the conventional photovoltaic system.

To calculate the powers and thermal efficiencies of the systems, it is necessary to analyze the temperature gradient of the outgoing and incoming water in the solar collector of the PVT system, as shown in Figure 6, where ΔT represents the temperature difference.

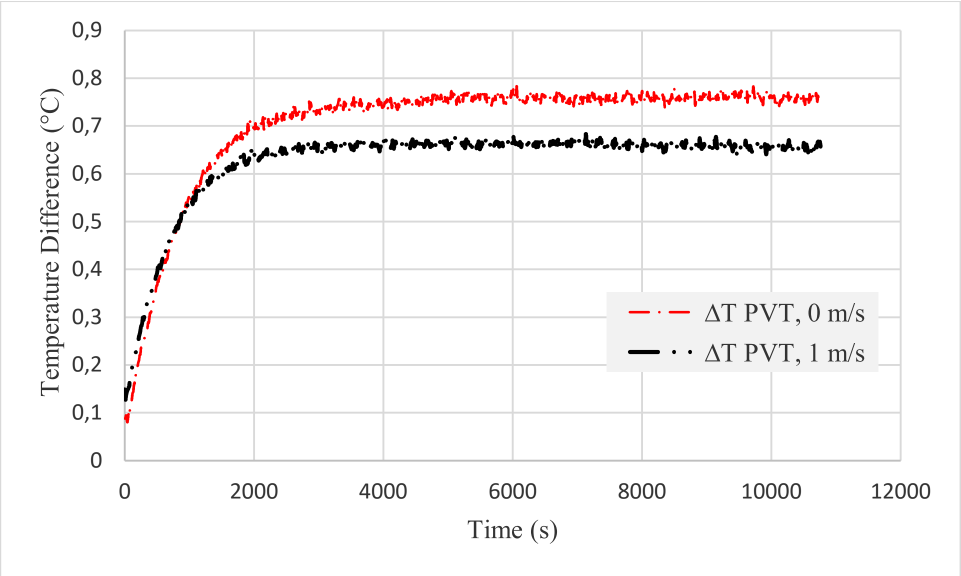

Figure 6. Difference between the temperature of the outlet and inlet water of the solar collector of the PVT system.

It is observed that at the beginning of the tests, the difference in temperature at the outlet and inlet of water in the solar collector is low and increases with time. This is due to the increased operating temperature, which leads to greater thermal storage in the water by heat transfer. This transfer tends to stabilize after 8000 seconds.

As previously presented in equations 1 and 2, from the difference between the inlet and outlet water temperatures in the solar collector, the thermal efficiency of the PVT system can be calculated, as shown in Figure 7.

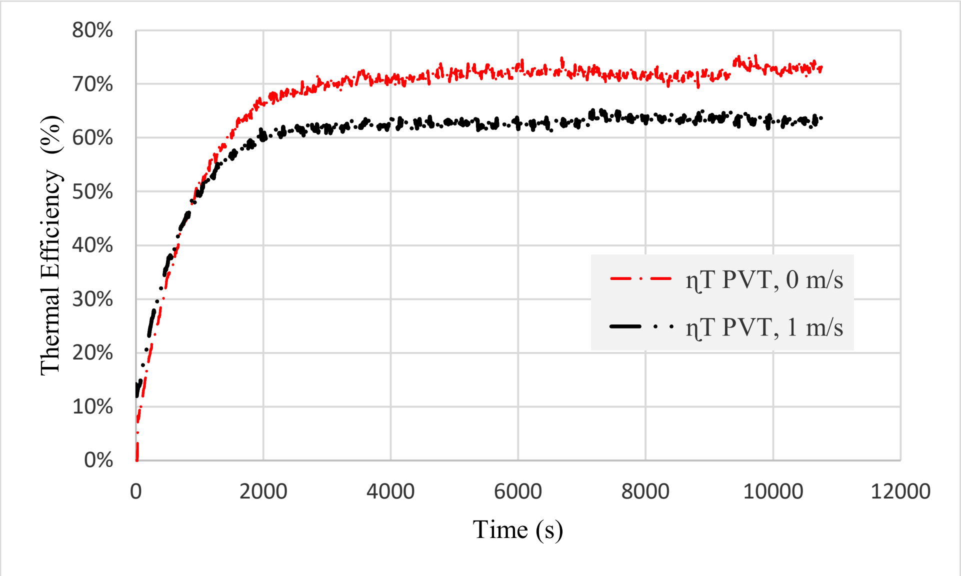

Figure 7. Thermal efficiency of the PVT system.

The absence of ventilation generates the best result, whose maximum value is 75.3 %, while with ventilation, the maximum thermal efficiency is 65.2 %. It is observed that the use of ventilation generates losses by convection.

According to Vian *et al*. (2021), of all incoming energy in a photovoltaic module, about 75 % is lost in heat, and only 25 % is converted into electrical energy. In this way, the PVT system transforms the maximum heat generated into thermal power, and using other water mass flows would not significantly impact the results.

Thus, Table 4 presents the sum of each system's electrical and thermal efficiencies, representing the systems' global efficiency (η).

Table 4 – Overall efficiencies of the PV and PVT systems.

	PV	PVT
	η (%)	η (%)
1 m/s	5,1	70,5
0 m/s	5,0	80,5

Although the electrical efficiencies present a difference of only 2 % between the systems, the global efficiencies present differences of 65.4 % and 75.5 % because the thermal efficiency represents over 92 % of the overall efficiency obtained in this work, Figure 8 shows the overall energies of the PV and PVT systems for the no-ventilation configuration.

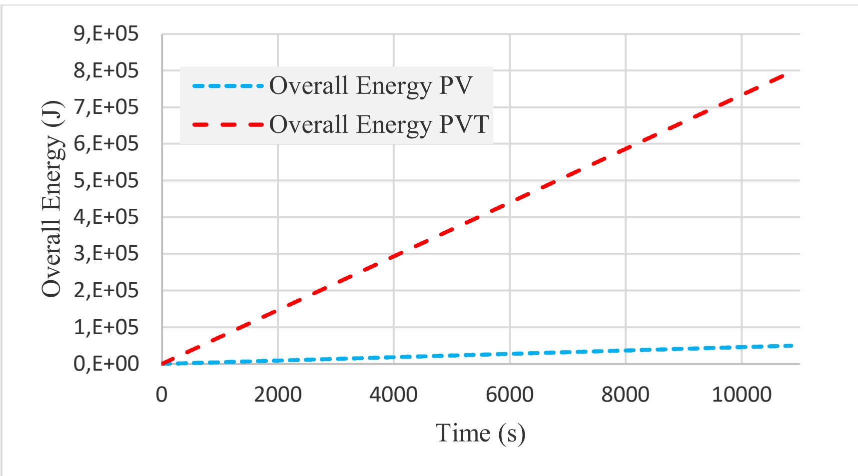

Figure 8. Overall energy of the PV and PVT systems.

Thus, this work presents greater electrical and overall efficiency for the PVT system. In this way, a global efficiency of about 16 times greater than that of the conventional system was obtained in this work. The operating temperature reduction and the thermal heating of the water caused this.

4. CONCLUSIONS

This work is based on reducing the operating temperature of photovoltaic modules, which suffer degradation and decrease their electrical efficiency from the thermal effect. This thermal effect is reused by heating water for domestic applications, improving hybrid systems' electrical and overall efficiency.

The ventilation reduces the operating temperature in the conventional photovoltaic system (PV) by 10.7 % from the test without ventilation. The reduction in the hybrid system (PVT) is 16% compared to the test without ventilation. The decrement is 34.4 % from the conventional system to the hybrid with ventilation. This difference in the temperature represents an increase in the hybrid system's open circuit voltage.

The electrical efficiency is more significant for the configuration with ventilation since there is a greater reduction in the operating temperature of the photovoltaic modules. Thus, the electrical efficiency is higher for the PVT system (5.3%) than for the PV system (5.1%).

With ventilation, the maximum thermal efficiency of the hybrid system is 65.2 %, and in the absence of ventilation, it is 75.3 % in the function of the losses by convection. Thus, the overall efficiency of the PVT system is 80.5% for the non-ventilated configuration and 70.5% for the non-ventilated one.

The results show an improvement in the electrical efficiency of the hybrid system due to the reduction of its operating temperature. This reduction is due to the heat transfer between the photovoltaic module and the solar collector. This transfer produces thermal power, resulting in 16 times increase in global efficiency compared to the photovoltaic (PV) system.

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