Comparative Study of the performance of a hybrid PVT panel with water as coolant under two different weather conditions

Estudio comparativo del rendimiento de un panel PVT con agua como refrigerante bajo dos diferentes condiciones climáticas.

Hugo Arias[1], Javier Cabrera[2], Johann Hernández[3]

ABSTRACT

This paper describes the performance comparison of a Photovoltaic-Thermal (PVT) solar collector in thermosyphon closed loop mode under two different weather conditions, fully cloudy and partially cloudy scenarios. The PVT electrical and thermal performance were evaluated and compared with a same unmodified factory Photovoltaic (PV) panel for both scenarios. The PVT performance was evaluated by electrical, thermal and primary energy savings efficiencies. It was found that the PVT total efficiency increased 7.28 % under the partially cloudy scenario, due mainly to the thermal energy gain. At the fully cloudy scenario this improvement was 2.12 %, which indicates that for places where present mostly cloudy conditions, the PVT enhancement will not be so significant.

Keywords: Hybrid photovoltaic thermal solar collector PVT, thermosyphon, electrical yield, thermal energy, primary energy savings.

RESUMEN

Este documento describe la comparación del rendimiento de un colector solar Fotovoltaico-Térmico (FVT) en modo termosifón de lazo cerrado bajo dos diferentes condiciones climáticas, totalmente nublado y parcialmente nublado. El rendimiento eléctrico y térmico del panel FVT fue evaluado y comparado con un mismo panel Fotovoltaico (FV) sin modificaciones de fábrica para los dos escenarios. El rendimiento del panel FVT fue evaluado por su eficiencia eléctrica, térmica y el ahorro de energía primaria. Se encontró que la eficiencia total del panel FVT incrementó 7.28 % para el escenario parcialmente nublado, debido principalmente a la ganancia en energía térmica. En el escenario totalmente nublado la mejora fue de 2.12 %, lo cual indica que para lugares que presenten condiciones climáticas mayormente nubladas, la mejora en el rendimiento del sistema FVT no es tan significativa.

Palabras clave: Colector solar fotovoltaico-térmico PVT hibrido, termosifón, eficiencia eléctrica, energía térmica, ahorro de energía primaria.

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Introduction

In the recent decades the development of renewable nature electricity sources has been one of the world main priorities. The development and deployment of non-conventional energy sources (NCES) has as main objectives the reduction of environmental pollution and diversify the energy matrix to reduce the climate change vulnerability. Even though the conventional sources (fossil fuels) continues providing more than 70 % of the global electricity production [1] and will keep most of this percentage, it is necessary to raise the NCES participation given that the increase of electrical energy demand caused by the industrial and population growth makes the world current energetic model unsustainable.

Photovoltaics are the source of energy that has the biggest growth in the last lustrum, around 55 %; reaching an installed capacity of 139 GW until 2013 according to the global status report (GSR) of REN21. Also solar thermal energy has added 55.4 GWth in solar heating, which sum a total of 326 GWth of world installed capacity. Photovoltaic thermal (PVT) systems which integrate these two renewable sources have been developed since 1970´s focused on PVT collectors with the primary aim of increasing PV efficiency [2]. Solar PV and solar thermal applications are regarded as potential solutions for the current energetic model.

The R&D in solar cells has encouraged innovative cell manufacturing techniques, in [3] - [4] a review of them is described. The efficiency of average commercial wafer-based silicon modules increased from about 12 % to 16 % in the last decade [5]. The relation between solar PV and solar thermal system is evident, because the non-harvestable energy by the PV system could be used as thermal potential by the solar collector, which is considered as energy cogeneration [6]. Furthermore the PV and solar thermal integration allows exploit more efficiently the energetic potential by the heat evacuation to a thermal system which can

[1] Hugo Arias: Electrical engineering student, Universidad distrital Francisco José de Caldas, Colombia. LIFAE. E-mail: hugo.arias.forero@gmail.com.
[2] Javier Cabrera: Electrical engineering student, Universidad distrital Francisco José de Caldas, Colombia. LIFAE. E-mail: javierhcabrera88@gmail.com.
[3] Johann Hernandez: Phd, Engineering, Universidad Nacional, Colombia. Director LIFAE. E-mail: johann.hernandez@gmail.com.

be subsequently used, and enable higher energy density per unit area.

To improve the PV performance, much research effort has been spent on the development of hybrid photovoltaic-thermal (PVT) collector technology using water as the coolant [2], [7] mostly flat plate solar collector (FPSC) have been used in PVT. Many types of FPSC have already been developed [2], [7], and [8]. They may be classified depending on the heat transfer fluid, the number of glass covers, the absorber design, etc.

Many researches have been made on PVT solar collector with forced circulation [2], [7] which needs an electrical supply for pumping. This electric energy is not considered in the primary energy savings and the energy balance. Natural circulation systems not require a power supply, meaning that the energy savings calculations are more accurate.

This paper focus on the performance comparison of single glaze FPSC under two different weather scenarios, which use water as coolant due to its higher heat capacity compared with air, allowing have a more effective cooling medium. A passive heat transfer system (thermosyphon) was designed and constructed with unexpensive materials without neglecting a good thermal performance.

Experimental Rig Description

In order to test electrical and thermal performance of the PVT solar collector, an open flow system operating in thermosyphon mode was constructed. The system consist of 3 major components, the PVT and PV module, the thermal circuit which includes the heat transfer system and the water tank, and finally the data acquisition and monitoring system.

The PVT collector was installed and tested under outdoor field conditions in Bogotá, Colombia (latitude 4°39' N, longitude 74°3' W). The PV and PVT collectors were mounted on an E-W oriented structure, and tilted 4° towards south. To compare the electrical and thermal performance between the PV and the PVT solar collector, the experimental test were carried out simultaneously. The experimental rig is shown in Figure 1.

PT100 thermistors were selected as temperature sensors due to its accuracy, repeatability and stability; also the relatively linear relation between temperature and resistance [9]. This relation was fitting by linear regression according to the load circuit electrical parameters.

The irradiance was measured by a Kipp & Zonen CMP3 pyranometer located in a weather monitoring station near the PVT structure and its output voltage was recorded with a Rigol DM3068 precision multimeter connected to the data acquisition system (DAS). In this study the output power, inlet fluid temperature, outlet fluid temperature, the PV and PVT backside temperature and mass flow rate were measured and recorded.

Data was collected and stored every minute using a data acquisition system (DAS) according to the IEC 61724/1998 standard [10]. It was implemented with low cost combination devices, an Arduino UNO as hardware and LabVIEW VI as data logger and monitoring software. These data was subsequently used to estimate the electrical and thermal efficiency and the primary energy savings.

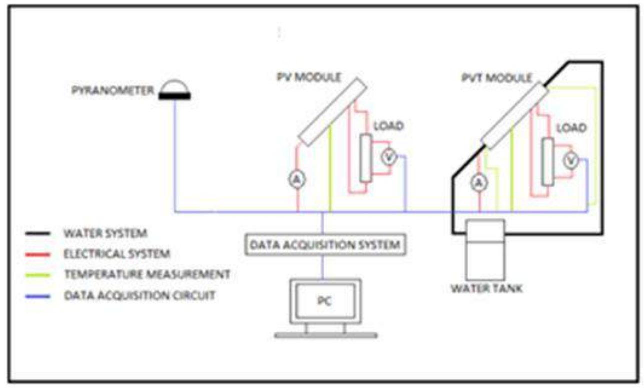

Figure1. Experimental rig diagram

Theoretical Basis

The PVT collector allows enhancing the PV performance through the PV module heat evacuation. The PVT performance could be evaluated by a combination of efficiency expressions [11], the PVT overall performance (ηT) and the primary energy savings (ηf) indicators defined in (1) and (2) respectively.

$$\eta T = \eta PV + \eta th \qquad (1)$$

$$\eta f = \eta PV / \eta P + \eta th \qquad (2)$$

Where (ηP) is the electric-power generation efficiency of a conventional power plant; its value can be taken as 38% [7]. The evaluation indicator of the primary energy saving efficiency also considers the quantity of the energy that the PVT system converts into usable energy [2]. The thermal and electrical performance of the PVT panel was evaluated based in the daily average widely-known efficiency equations. The electrical efficiency on the PV and PVT units was calculated from (3) where (Qe) is the output electric power, (Ac) is the collector area and (G) is the irradiance on the panel.

$$\eta PV = Qe \, / \, (Ac \; G) = (Im \; Vm) \, / \, (Ac \; G) \qquad (3)$$

The thermal efficiency of a conventional (FPSC) is the ratio between the useful thermal energy and the incident solar radiation (4). This thermal energy is expressed in terms of the inlet-outlet fluid temperature gradient (ΔT), the mass flow rate ($\dot{m}$) and the heat capacity of the heat transfer fluid (Cp). It is an effective method to evaluate the PVT thermal performance under several weather conditions.

$$\eta PV = {Q_{th}}/{A_c G} = {\dot{m} C_p (T_{out} - T_{in})}/{(AcG)} \qquad (4)$$

Results and Discussion

The PVT solar collector was tested under uncontrolled environmental conditions, to secure compliance on the measurement methodology both panels were tested under the same weather and electrical conditions during the same period. For the performance evaluation of both panels (PV and PVT) was determined evaluate two different weather conditions, the most common climate conditions in Bogotá. The first scenario was partially cloudy (January 2015), scenario under which the best weather condition was presented, i.e. high irradiance under long time periods, although cloudy periods was presented too. The second scenario was fully cloudy (may 2015), in this scenario low irradiance weather conditions were predominating – less than 400 W/m^2 – and high cloudiness.

In this paper, January 30 was used as example to analyze the PVT panel performance at the partially cloudy scenario, during which the solar irradiance on the panels had the longest period with highest irradiance intensity (greater than 600 W/m^2), and for the fully cloudy scenario, May 30 was used as evaluation period.

Partially cloudy scenario

In this scenario was presented the high irradiances - higher than 800 W/m^2 - longest time period, which last 40 minutes between 1:14 and 1:53 pm. The highest irradiance of all measurements was 1283.21 W/m^2 and occurred at 1:15 pm. Under this scenario the highest PV and PVT operation temperatures were achieved, 73.03 and 43.29 °C respectively. Should be noted that the panels maximum temperatures not presented simultaneously, because the thermal inertia of both panels is different due to their constructive characteristics. It is observe that PV panel temperature responds faster against the change of irradiance as it's shown in Figure 2, while the PVT temperature responds slowly due to its thermal inertia, but once the thermal energy of the storage tank has risen, this inertia allows the PVT panel temperature to be steadier than the PV temperature.

The PVT higher thermal inertia allowed the PVT temperature to be momentarily higher than the PV at the end of the higher irradiation period, between 1:44 and 1:49 pm, however, the posterior decrease of irradiance returned the PVT temperature to lower values of the PV operation temperature. This could indicate that the mass flow rate is not enough faster to evacuate the panel thermal energy to the storage tank, which means a temperature increase on the PVT panel.

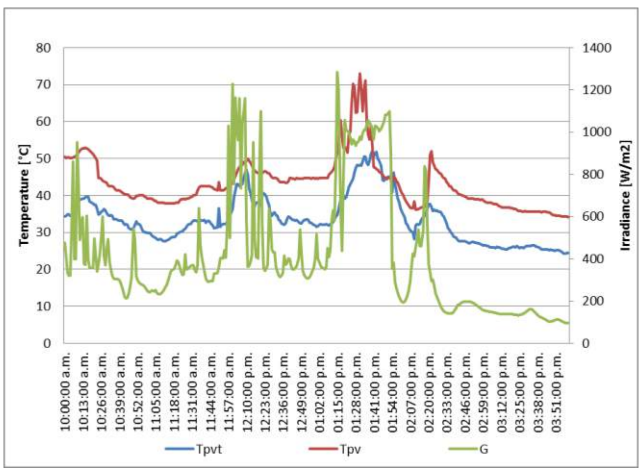

Figure2. PV and PVT temperature variations at the partially cloudy scenario

Regarding the heat transfer fluid temperatures (water), it was observed that the water inlet temperature always was smaller than the outlet water temperature, as it is shown in Figure 3, the mean gradient temperature was 9.75 °C; nevertheless at the end of the measurement period, between 3:28 to 4:00 pm, the inlet fluid temperature was slightly higher than the outlet fluid temperature, this may be due to the thermal energy stored in the thermal tank, which represents a considerable decrease in the thermal efficiency when there is a low irradiation and the storage tank has enough thermal energy stored during the day.

It was confirmed that the PV electrical efficiency is inversely proportional to the irradiance that impacts it. Both for the PV panel to the PVT panel the electrical efficiency behavior is in counter phase with the solar energy available. The PVT electrical efficiency was superior to the PV electrical efficiency at every time as Figure 4 shows. The higher PVT yield gain against the PV one was 0.56 % and the mean gain was 0.26 %, achieving a maximum value of 9.87 %. Although it was not a huge enhancement, it represents and improvement in the PV efficiency.

The PVT mean and maximum electric power were increased a 0.58 and 0.62 % respectively, in a power base of 50 W at standard technical conditions STC. For the daily mean irradiance (410 W/m^2) and a power base of 20 W, the PVT mean and maximum electric power were increased a 1.45 and 1.56 %.

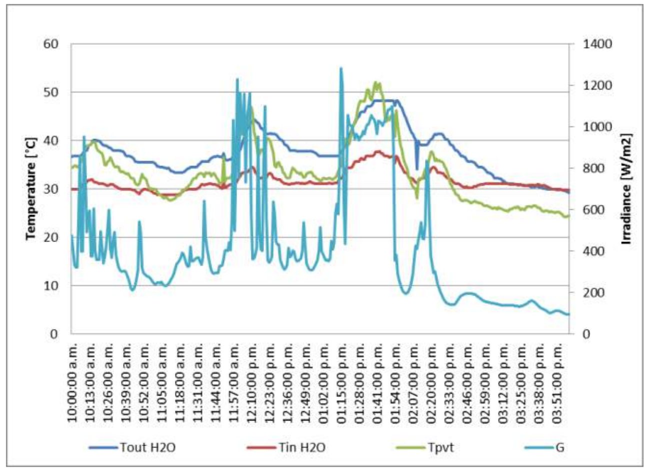

Figure3. Inlet and outlet HTF temperatures and rear surface PVT temperature under partially cloudy scenario

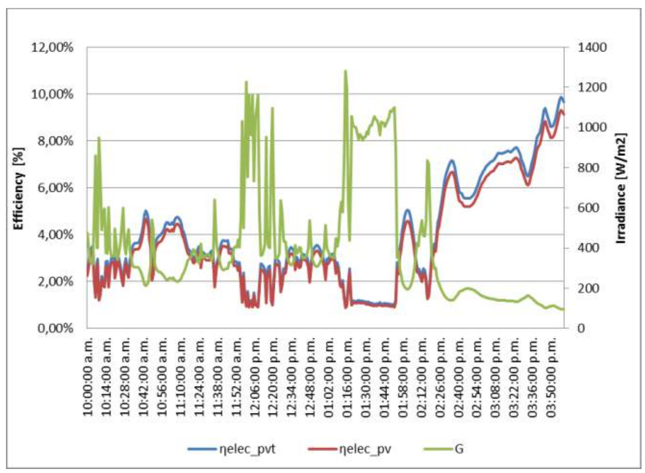

Figure4. PVT and PV electrical efficiencies at partially cloudy scenario

The PVT global performance was far superior that the PV performance, because not just the mean electrical efficiency was enhanced 0.26 %, but it also managed to have thermal energy available. The PVT total efficiency reached a maximum value of 16.58 %, which represents an improvement of 6.72 % regarding the maximum PV total efficiency.

The PVT panel achieved a maximum and mean thermal power of 22 and 10.7 Wth respectively, whereby was achieved to heat 20 liters of water at 31.6 °C. This fact shows a clear advantage of the PVT panel due this panel provides a higher energy density per unit area, i.e. a higher exploitation of the space available.

Regarding the primary energy savings indicator, the PVT panel showed an important enhancement of its total efficiency which achieved a maximum primary energy savings of 28.14 %, while the PV panel got a 9.30 %, i.e. the PVT panel took advantage of the solar resource an 18.83 % more than the PV panel, as Figure 5 shows.

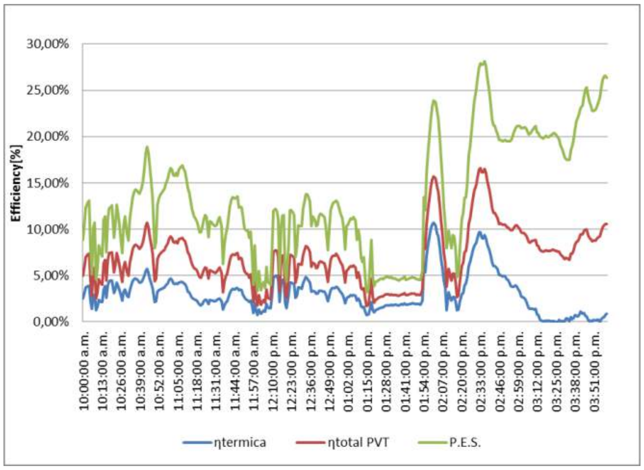

Figure5. Thermal, total and primary energy savings PVT efficiencies at partially cloudy scenario

Fully cloudy scenario

This scenario was predominantly cloudy, just few high irradiance peaks of short duration were presented, i.e. a time period greater than 20 minutes with higher irradiance than 600 W/m^2 never happened. The mean irradiance was 373.38 W/m^2. As in the partially cloudy scenario the highest PV and PVT temperatures (48.25 y 39.09 °C respectively) were in the highest irradiance time, which took place at 1:03 pm and was 1134.79 W/m^2. The panel's temperatures did not increase instantaneously due to their thermic inertia. It was observed that the PV temperature responds faster to irradiance change, and was higher than the PVT temperature every time as it is shown in Figure 6. The mean thermal gradient between both panels was 3.92 °C suggesting that for fully cloudy conditions the decrease in PV operation temperature, with flat plate cooler system in thermosyphon mode is not meaningful.

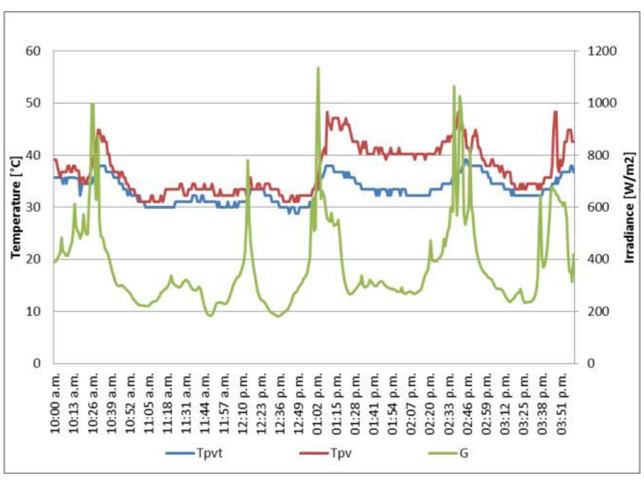

Figure6. PV and PVT temperature variations at fully cloudy scenario

As Figure 7 shows, the inlet and outlet fluid temperatures present a lot of fluctuations for this scenario; in the first measurement hour the outlet fluid temperature was higher than the inlet temperature, and thereafter the inlet temperature was greater than the outlet until an irradiance peak increased again the outlet temperature over the inlet temperature values. From this behavior could be seen that for a fully cloudy condition the thermal efficiency is too low due to the temperature fluctuation and the low thermal gradient (0.39 °C). This also indicates that the mass flow rate is much lower than the partially cloudy scenario and scenarios with higher irradiance levels, i.e. there is not an appropriate evacuation of the residual heat in the PVT panel.

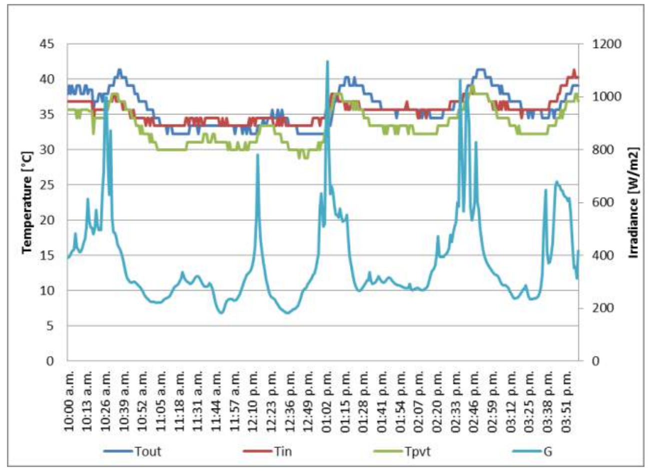

Figure7. Inlet fluid, outlet fluid and back surface PVT temperatures at fully cloudy scenario

Just like the partially cloudy scenario, it was confirmed that the PV electrical efficiency is higher for low irradiance levels, no matters the time of the year as Figure 8 shows; however for this fully cloudy scenario, the electrical efficiency of both panels was much lower than the partially cloudy condition, the PV and PVT was 4.15 and 4.37 % smaller than the partially cloudy efficiencies. So under high cloudiness conditions the PVT electrical efficiency was 0.35 % greater than the PV panel, in contrast with the larger irradiance condition, where the maximum difference was 0.56 %, i.e. it diminished a 0.21 % the mean PVT electrical performance.

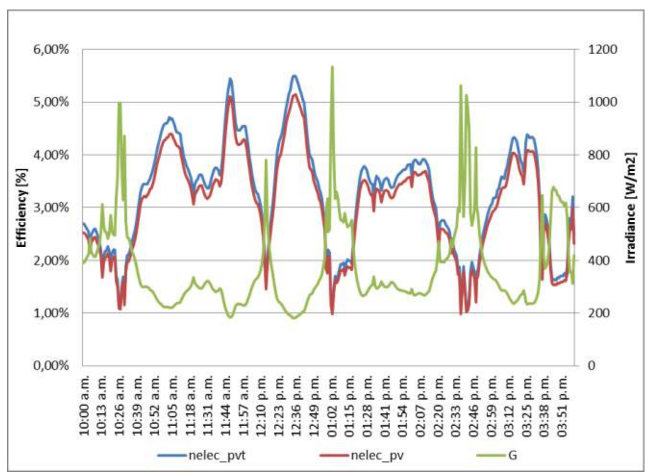

Figure8. PV and PVT electrical efficiencies at fully cloudy scenario

As Figure 9 shows, the PVT panel global efficiency was superior to the PV panel efficiency, quantitatively the PVT panel had a maximum total yield of 7.27 %, while the PV panel got a 5.15 %, and namely the last one was 2.12 % less efficient. Besides the PVT panel generated a maximum thermal power of 8.22 Wth and a mean thermal power of 0.71 Wth, i.e. a daily thermal energy of 4.22 WthH-day. In contrast with the partially cloudy scenario, the thermal efficiency was 7.97 % lower, indicating that under high cloudiness conditions there are not large energy benefits in the PVT system.

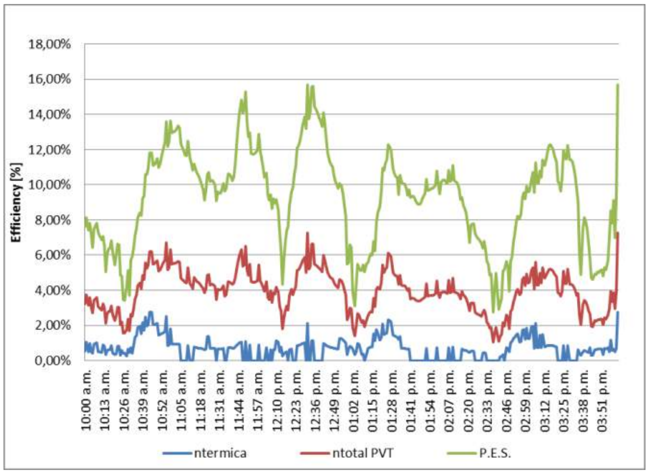

Figure9. PVT thermal, total and primary energy savings efficiencies at fully cloudy scenario

According to the results of the test carried out on both panels under fully cloudy and partially cloudy scenarios, a comparative chart was created (see Table1), where the main characteristics and energy benefits provided by two devices (PV and PVT) are shown.

Table1. PV and PVT energy benefits comparative chart

FULLY CLOUDY SCENARIO			PARTIALLY CLOUDY SCENARIO		
PARAMETERS	PV	PVT	PARAMETERS	PV	PVT
Pmax [W]	4.468	4.716	Pmax [W]	4.545	4.858
Pmean [W]	3.893	4.149	Pprom [W]	3.978	4.269
Pthermal [Wth]	-	8.228	Pthermal [Wth]	-	22.047
u_electrical [WH-día]	26.80	28.296	u_electrical [WH-día]	27.27	29.147
u_thermal [WthH-día]	-	4.221	u_thermal [WthH-día]	-	64.380
Tpanel [°C]	48.25	39.097	Tpanel [°C]	73.03	52.069
Tinlet [°C]	-	35.508	Tinlet [°C]	-	37.742
Toutlet [°C]	-	41.386	Toutlet [°C]	-	48.330
ηelect %	5.15	5.50	ηelect %	9.30	9.87
ηtérmica %	-	2.76	ηtérmica %	-	10.73
ηtotal %	5.15	7.27	ηtotal %	9.30	16.58
P.E.S.%	5.15	15.68	P.E.S.%	9.30	28.14

Conclusions

The PVT panel offers greater energy benefits than the PV panel, not just improving the electric power available and the electrical efficiency, but also generating thermal energy which were not preciously available.

The natural circulation water (thermosyphon) cooling system reduces significantly the panel operation temperature, which allows the panel to supply higher electrical outlet power and this way enhance its performance.

The PVT total efficiency increased 7.28 % under the partially cloudy scenario, due mainly to the thermal energy gain. At the fully cloudy scenario this improvement was 2.12 %, which indicates that for places where presents mostly cloudy conditions, the PVT enhancement will not be so significant.

The results reveal an enhance in the solar resource exploitation, important argument for possible expansions in solar parks and residential facilities, taking advantage of the PVT thermal potential in water preheaters, domestic hot water systems or an endless number of applications where heat is used.

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