ENERGETIC AND EXERGETIC EXPERIMENTAL INVESTIGATION OF A HYBRID PHOTOVOLTAIC-THERMAL SOLAR COLLECTOR UNDER REAL WEATHER CONDITIONS

by

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Experimental results obtained using a photovoltaic thermal hybrid solar system are presented and discussed. This hybrid combination is an emerging technology that combines photovoltaic panels and solar thermal collectors in one bi-functional component providing both electrical and thermal energy. The main objective of this coupling is to improve the efficiency of the photovoltaic panels by reducing their operating temperatures and recovering the thermal energy they dissipate, using heat transfer fluids (water in the present study). A theoretical energy and exergy analysis of photovoltaic thermal hybrid solar system is presented. Both electrical and thermal performances of the proposed photovoltaic thermal prototype system are evaluated and analyzed under local weather conditions of Essaouira, Morocco (latitude: 31.51, longitude: –9.76). A comparative study in terms of overall energy efficiency of photovoltaic thermal and conventional photovoltaic systems is conducted and discussed. The obtained experimental findings show that, unlike the conventional photovoltaic panel for which the overall efficiency does not exceed 8.22%, the hybrid system makes it possible to achieve a maximum overall efficiency of about 42.72%. The extracted energy's quality and efficiency are evaluated through the exergy analysis of the proposed photovoltaic thermal system. The electrical and thermal exergy efficiencies recorded for the studied sytem are 9.78% and 3.07%, respectively.

Key words: *photovoltaic thermal hybrid solar system, experimental study, electrical and thermal energy, cell cooling, exergy analysis*

Introduction

Energy is at the basis of all human activities. Nowadays, a large part of the world's energy consumption is provided by fossil resources (oil, gas and coal). The fast growing energy demand, the inevitable depletion of these resources and the environmental deterioration caused by their irrational consumption [1], press humanity to diversify energy resources with the concern to preserve the environment that has been marginalized for the benefit of easy gain and already affected by various sources of contamination. The alternative lies in the development of renewable energies which are able to ensure a sustainable and ecological energy supply [2].

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The renewable energies are drawn directly from natural resources and qualified as clean compared to the fossil fuels which have a negative impact on the environment. In addition, they are primary, abundant, inexhaustible in human timescales and transformed in different forms depending on the applications [3]. Among the sustainable energies, solar energy is one of the most promising alternative energy sources. The oldest form of solar energy conversion consists of converting sunlight into heat, which is one of the most popular forms of energy exploited for different uses (domestic water heating, space heating, *etc.*). The second kind of conversion is based on solar panels, which are a collection of solar cells that can be used to generate electricity through photovoltaic effect. Photovoltaic systems are attracting more and more attention of researchers worldwide due to their implications in many fields including rural electrification [4], street lighting [5], thermoelectric air-conditioning [6], water pumping [7] and many others.

Presently, the efficient generation of PV energy is the main challenge for researchers involved in this research component. The studies conducted so far have shown that the improvement of the electrical performance of a PV generator requires the control of both internal and external parameters on which the overall efficiency of the PV conversion chain depends. In addition to the effect of illumination intensity [8] and crystalline nature of the used materials [9] on the performance of a photo-generator, the central question remains the operating temperature of the PV module. In fact, the PV module temperature analysis is of interest since the efficiency of the PV cells depends on it. Several studies have been devoted to examine the temperature effect on the power conversion efficiency of a solar PV module [10, 11]. They reported that the cell temperature has a significant effect on the PV parameters and controls the quality and the performance of the solar cell.

The harmful effect of temperature increase on the electrical performance of PV modules has challenged researchers to use the accumulated heat behind the PV modules to control the cell temperature and improve its efficiency. The inclusion of the thermal aspect in the process has led to the development of the hybrid photovoltaic thermal (PVT) system device to generate electricity and collect thermal energy, usually lost as heat. The collected excess heat from the PV module can be useful for different services. For instance, it can be used for domestic water heating (PVT liquid based) and space heating (PVT air based). The PVT collectors combine the generation of solar electricity and heat in a single component, and thus achieve a higher overall efficiency and better utilization of the solar spectrum than the separate conventional PV modules and solar thermal collectors. Many theoretical and experimental works have been conducted to improve the performance of the hybrid PVT solar systems. The performance of 1.44 kW unglazed PVT system was investigated by Huang and Huang [12] in different locations in Taiwan. In this study, TRNSYS software was used as a simulation tool. The results obtained show electrical and thermal efficiencies varying, respectively in the ranges 11.7%-12.4% and 26.78%-28.41%. Using CFD software, Pauly *et al.* [13] evaluated the performance of a hybrid PVT air collector. A novel design was proposed and investigated and the results obtained were validated against experimental results from the literature. The overall performance of the proposed hybrid PVT system recorded a 20% increase compared to the conventional solar hybrid PVT air collector. The effect of absorber plate shape factor and mass-flow rate on the performance of the PVT system was investigated by Singh *et al*. [14]. Simulation process based on iterative method was applied to different types of absorber plate shapes. The results found indicated fall in temperature both for PV and outlet temperature and rise in energy and exergy values and pressure drop with mass-flow rate. Recently, Singh [15] considered a PVT system using water as the heat extraction fluid and providing electricity and hot water. The suggested system was analyzed in terms of electrical and thermal efficiencies, temperature variations over time and effect of system cooling with water on electricity generation. The experimental results of the tests clearly show that PVT systems can provide electricity and hot water for domestic purpose. From a performance point of view, this study shows that PVT water system is nearly 40% more efficient compared to the conventional system and could be an appropriate alternative choice for the generation of electricity and hot water simultaneously in low latitude areas. Likewise, a novel hybrid PVT bi-fluid system using active cooling and self-cleaning was proposed and experimentally tested by Lebbi *et al*. [16]. An improvement of about 5.7% in electrical efficiency of the PVT system compared to the PV reference panel was obtained in this study. A year later, a new dual-cooling active PVT system based on a thermoelectric device was developed by Eid *et al*. [17]. The experimental and numerical results of this study show that this innovation led to a decrease in the module temperature to 21 °C, resulting in an improvement in efficiency of 11.23% and an increase in daily output energy of 8.3%. For their part, Yildirim *et al*. [18] proposed a distinctive design with higher electrical conversion and thermal efficiency for the PVT systems. Different inlet mass-flow rates and temperatures were simulated under normal operating cell temperature conditions. The results of this study show that when the mass-flow rate is 0.014 kg/s, and the inlet flow temperature is 15 °C, the PV module achieves an electrical conversion efficiency of 17.79% with 76.13% thermal efficiency. The conclusions of this article highlight the usefulness of PVT systems and their enormous potential to popularize the field of solar energy and simultaneously harvest thermal and electrical energy. More recently, a PVT collector system in a solar cell cooling system was modeled by Prasetyo *et al.* [19]. Simulations were performed using ANSYS software with steady-state thermal modelling for the PV solar cells and fluent modelling for fluids in the collector. The authors modeled various riser configurations on PVT collectors to cool PV solar cells using as coolants water and nanofluids with different mass-flow rates. The semi-circular collector configuration with water at a mass-flow rate of 0.5 kg/s demonstrated the highest electrical efficiency, reaching 11.98%. A comparative numerical study on the performance analysis of flat plate PVT for different flow regimes was carried out by Azad and Parvin [20]. A water based nine layered flat plate PVT collector was considered in this study. The analysis's results indicated that electrical efficiency decreases from 11.34 to 8.09% for creeping flow, 12.16% to 11.77% for laminar flow, and 12.24% to 12.07% for transitional flow when solar intensity rises from 200-1000 W/m^2. Comprehensive literature reviews offering an overview of the state-of-the-art in hybrid PVT collectors and the wider systems within which they can be implemented were lately conducted by Herrando *et al*. [21] and Bilen and Erdogan [22]. The various cooling techniques used was described and widely explained in these reviews and their effects on decrease in operating temperature and increase in electrical efficiency was separately analyzed. In their reviews, the authors classified and reviewed the main types of PVT collectors, including air-based, water-based, dual air-water, nanofluid-based, heat-pipe, building integrated and concentrated PVT collectors.

The present work deals with an experimental study of a water-based PVT hybrid solar collector producing electricity and heat from a single device. Both electrical and thermal performances of the proposed prototype system are evaluated and analyzed under real local weather conditions. A comparative study of energy efficiency between PVT and conventional PV systems is presented and widely discussed in this paper. To have a more representative performance rating, an exergy analysis of the studied PVT system is also carried out. The optimum electrical, thermal and overall exergy efficiencies of the system are determined.

Theoretical study of a PVT hybrid system

Energy balance

The characterization of a PVT solar collector performance requires an energy balance taking into account all the energy fluxes entering and leaving the collector. Thus, for a flat-plate PVT collector, the energy balance can be expressed as [20]:

$$Q_s = Q_e + Q_{th} + Q_l \quad (1)$$

where Q_s, Q_e, Q_{th}, and Q_l are respectively the solar energy reaching the collector, the electrical energy produced by the collector, the thermal energy carried by the heat transfer fluid, and the energy lost by the three modes of heat transfer.

Performance evaluation of a PVT hybrid collector

The overall efficiency η_o of the PVT hybrid collector is the sum of the electrical, η_e, and thermal, η_{th}, efficiencies of the system [19] :

$$\eta_o = \eta_e + \eta_{th} \quad (2)$$

In eq. (2), the expressions of η_e and η_{th} are obtained as [23]:

$$\eta_e = \frac{P_e}{E \times A_e} \quad \text{and} \quad \eta_{th} = \frac{P_{th}}{E \times A_{th}} \quad (3)$$

where P_e and P_{th} are, respectively, the maximum electrical and thermal powers generated by the hybrid system, E [Wm^{-2}] – the incident solar illuminance, A_e – the PV panel surface area, and A_{th} – the solar thermal collector surface area.

The thermal power can be evaluated using [20]:

$$P_{th} = \dot{m} C_p \left(T_{out} - T_{in} \right) \quad (4)$$

where $\dot{m}$ [kgs^{-1}] is the heat transfer fluid mass-flow rate, C_p [Jkg^{-1}K^{-1}] – the specific heat capacity, and T_{in} [K] and T_{out} [K] are the heat transfer fluid temperatures at the collector inlet and outlet, respectively.

Exergy efficiency and analysis

Exergy analysis is a tool for overcoming many of the shortcomings of energy analysis, which only provides a quantitative analysis of the energy obtained from the system. Its advantage over energy analysis lies in the fact that it allows identifying both the quantity and the quality of the useful electrical and thermal energies output as well as the internal irreversibilities.

Based on the Second law of thermodynamics, the exergy balance of a flat-plate water based PVT system can be written at steady-state conditions as [24]:

$$Ex_{in} = Ex_{out} + Ex_{loss} \quad (5)$$

where Ex_{in} and Ex_{out} are, respectively inlet and outlet exergies and Ex_{loss} is the exergy loss or destruction due to the irreversibility.

The inlet energy is the incident solar irradiation. Therefore, the inlet exergy is equal to the exergy of solar radiation that reaches the system, Ex_{Sun} [25]:

$$Ex_{in} = Ex_{Sun} \quad (6)$$

To evaluate Ex_{Sun}, various models have been proposed in previous studies. The most popular expression of Ex_{Sun} in the literature is adopted here, it is given [24]:

$$Ex_{Sun} = EA_e \left(1 - \frac{T_a + 273}{T_{Sun}} \right) \quad (7)$$

where E [Wm^{-2}] is the incident solar irradiation, A_e [m^2] – the surface area of the PV module, T_a [°C] is the ambient temperature, and T_{Sun} [K] – the surface temperature of the Sun, $T_{\text{Sun}} \cong 5777$ K.

The overall output exergy, Ex_{out}, of the PVT collector is evaluated by the following sum [26]:

$$Ex_{\text{out}} = Ex_{\text{el}} + Ex_{\text{th}} \tag{8}$$

where Ex_{el} and Ex_{th} are the electrical and thermal exergies, respectively.

The electrical energy output is equivalent to the electrical exergy assuming negligible the pumping power given the low mass-flow rate of the working fluid. Thus, the electrical exergy for an active PVT system can thus be expressed [26, 27]:

$$Ex_{\text{el}} = E_{\text{el}} \tag{9}$$

The thermal exergy rate of the PVT system can be evaluated by using [26]:

$$Ex_{\text{th}} = \dot{m}C_p\left(T_{\text{out}} - T_{\text{in}}\right)\left(1 - \frac{T_{\text{a,min}} + 273}{T_{\text{out}} + 273}\right) \tag{10}$$

According to eq. (2), the overall exergy efficiency of the system is the sum of both electrical, $\eta_{Ex\text{el}}$, and thermal, $\eta_{Ex\text{th}}$, efficiencies [28]:

$$\eta_{Ex_{\text{out}}} = \eta_{Ex_{\text{el}}} + \eta_{Ex_{\text{th}}} \tag{11}$$

where $\eta_{Ex\text{el}}$ and $\eta_{Ex\text{th}}$ are defined by the ratios [28]:

$$\eta_{Ex_{\text{el}}} = \frac{Ex_{\text{el}}}{Ex_{\text{Sun}}} \quad \text{and} \quad \eta_{Ex_{\text{th}}} = \frac{Ex_{\text{th}}}{Ex_{\text{Sun}}} \tag{12}$$

The PVT hybrid system conception

This part of the study focuses on the conception of a PVT hybrid system that consists of combining electrical and thermal energy components. The experimental equipment used is shown in fig. 1. In this system, the PV solar module is integrated with the thermal collector, either by pasting the PV solar module on the absorber plate of the collector or by separating them with an air gap. This configuration allows the heat released by the PV cells to warm up the heat carrier fluid through the thermal collector.

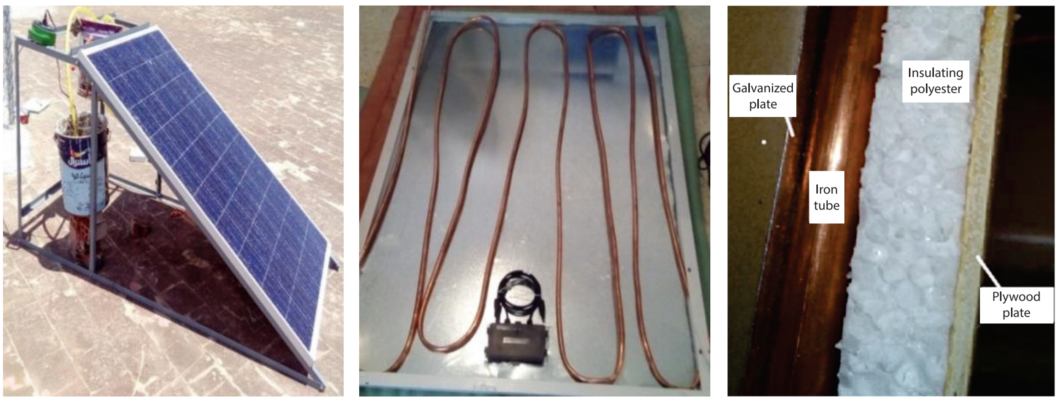

Figure 1. Experimental material of the proposed PVT hybrid system

To allow incident solar radiation reach the absorber plate, a mono-crystalline semi-transparent PV solar module (TS250P-60) having a transparency of about 10% and a size of 95 cm × 157 cm was used. The electrical characteristics of this module under standard test conditions are indicated in tab. 1.

Table 1. Electrical characteristics of the PV panel

Rated maximum power P_{max}	Current at P_{max}	Voltage at P_{max}	Short-circuit current	Open-circuit voltage	Operating temperature
250 W_P	8.26 A	30.3 V	8.65 A	37.4 V	–40 °C to +85 °C

The thermal collector used in this experimental unit is an active system with a pump (3W, DC) ensuring the circulation of water, used as heat carrier fluid, between the collector and the storage tank. On the absorbent plate, which is a 0.2 mm thick galvanized plate shown in fig. 1, there are eight quasi parallel *U*-shape copper tubes of 14 mm diameter spaced an average of 10 cm.

More details regarding the thermal solar collector are given in fig. 1 that shows that the collector has been fitted with a 20 mm thick polyester insulating plate to limit the heat loss through the walls. In addition, to reinforce the protection of the collector, a 4 mm plywood plate was included. The designed metal support for the collector is made of iron and inclined at 30° with respect to the horizontal plane.

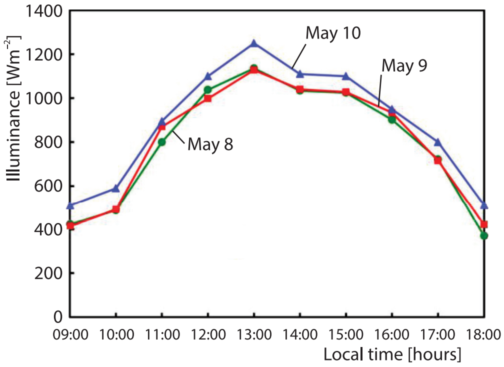

Figure 2. Hourly variations of the solar illuminance for three consecutive days of May 2021

Results and discussion

The content of this section focuses on the experimental evaluation of the electrical and thermal performances of the proposed PVT hybrid system. These performances are compared to those of the PV system operating under similar weather conditions. To this end, we proceeded to series of meteorological, thermal and electrical measurements during the period from May 8-10, 2021. It is to be specified that the measured values have been daily averaged and the analysis and interpretation relate to the averaged results.

Regarding the meteorological aspect, the daily changes of the incident solar illumination was tracked during the test period by the weather station (Campbell Scientific's CR3000 data logger with CMP3-type pyranometer) installed on the roof of our school. The evolutions *vs*. time of the collected pyranometer data, collected during three consecutive days of May 2021, are illustrated in fig. 2.

From sunrise to sunset, a similar behavior in the evolution of the irradiance is observed for the three curves, resulting from the relative stability of the weather conditions in the city of Essaouira. The distribution of the daily radiation approaches the sinusoidal shape. The limited deviation from the sinusoidal form lies in the frequency of the measurements and local unpredictable limited disturbances resulting from several factors. Thus, the illumination undergoes a gradual increase from sunrise until 13:00 p. m. local time in Essaouira city (zenith hour) where it reaches its maximum. Afterwards, the radiative flux decreases monotonously for the rest of the day. The evolutions on either side of the maximum are almost symmetrical. Quantitatively, it can be noticed that the period of experience was characterized by fairly high daily sunshine rates. This favorable climatic situation has helped a lot to assess both the thermal and electrical performances of the experimented PVT hybrid system.

For experiments conducted under real conditions, it is necessary to specify all the operating conditions of a PV collector. In addition the radiation intensity, the wind speed and the ambient temperature are parameters that could also affect the efficiency of the collectors. In this regard, a monitoring of the hourly wind speed variation was carried out during the test days. The data collected from the local weather station and illustrated in fig. 3 provide and idea concerning the wind speed variations during the three test days with an average value varying in the short range [4.8 m/s, 5.06 m/s].

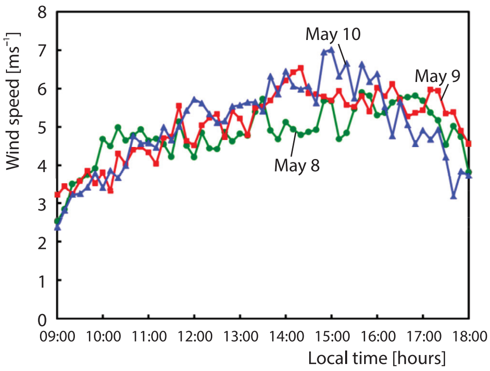

Figure 3. Average hourly variations of the wind speed during the test days

Concerning the thermal aspect of the study, the experimental evaluation of the PVT collector performance focused mainly on monitoring of daily variations between inlet and outlet heat transfer fluid (water) temperatures, T_{in} and T_{out}, measured at the inlet and outlet of the collector while imposing to the working fluid a constant mass-flow rate $\dot{m}$ = 0.008 kg/s. These data were used in eq. (4) to evaluate P_{th}. The daily monitoring also included the ambient temperature, T_a, and the surfaces temperatures of the PVT and PV collectors. Three series of measurements at 24 hours intervals were carried out for each of these temperatures. These measurement results have been subsequently averaged by combing the data of the three days. The resulting mean hourly variations from 9:00 a. m. to 6:00 p. m. of these results are exemplified in fig. 4 in terms of $\overline{T}_{in}$, $\overline{T}_{out}$, $\overline{T}_a$, and $\overline{E}$.

The examination of the results presented in fig. 4 shows that a maximum difference of about 18.4 °C is reached between the water temperatures at the inlet and outlet of the PVT collector. More specifically, the temperature of water at the exit of the PVT varies between 21.5 °C and 45.3 °C as maximum value reached at 1:00 p. m. local time. By this fact, the temperature at the exit remains higher than that at the inlet throughout the day since the latter varies between 19.4 °C and 30.7 °C. This gain of energy recuperated in PVT collectors to heat water is substantial insofar as that it is usually lost by PV systems under heat form. In addition, it can be noticed that the curve of the outlet water temperature has a tendency visibly influenced by that of the incident radiation. This tendency is characterized by a monotonous increase toward a maximum (reached at 1:00 p. m.) followed afterward by a decrease leading at the end of the day to a temperature close but slightly higher than that of the inlet temperature. The same behavior can be observed in fig. 5 for the variation along the day of the mean thermal power delivered

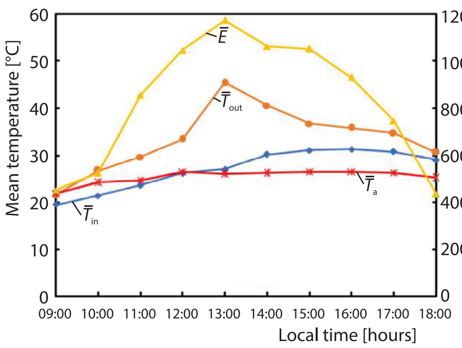

Figure 4. Hourly variation curves of both mean illuminance and inlet, outlet and ambient mean temperatures

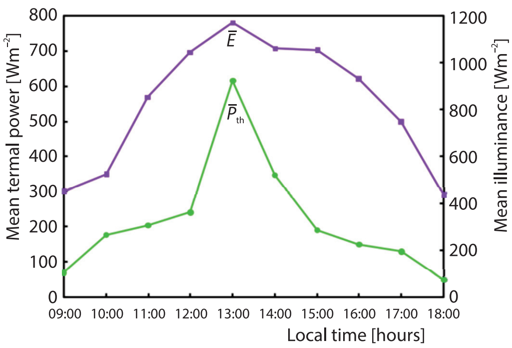

Figure 5. Variations during the day of mean thermal power and mean illuminance

by the PVT system. This behavior is in perfect compatibility with the variation of the intensity of sunshine throughout the day. It can also be expected from this figure that the daily thermal efficiency of the PVT hybrid collector will vary over the day and may be strongly dependent on the meteorological conditions, more importantly on the incident solar radiation.

By combining the PV and thermal technologies, the proposed hybrid system allows recuperating the heat energy dissipated by the PV cells and makes it useful to produce domestic hot water for instance. Consequently, the hybrid system tolerates a better cooling of the PV cells, which leads to an improvement of their performances. Figure 6 shows clearly that the hourly average temperatures at the surface of the collectors are lower in the case of the PVT system compared to those of the PV one ($T_{PVT} < T_{PV}$). This substantial reduction of temperature in the case of the PVT prevents the overheating of the cells and allows them to work far from the limit critical conditions. The maximum difference of the surface temperatures between the two systems reaches a maximum value around 12 °C at 12:00 a. m. o'clock (local time). We will see thereafter how this cooling of cells impacts positively the electrical efficiency of the PV panel.

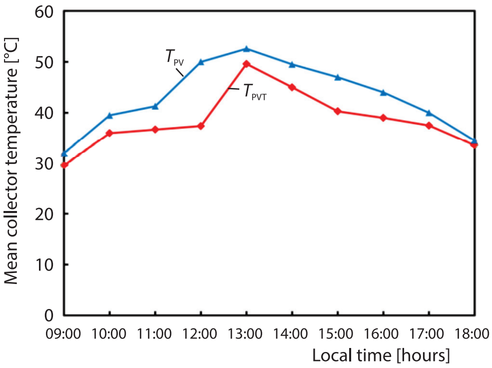

Figure 6. Daily variations of the average surface temperatures of the photovoltaic and photovoltaic thermal collectors

Now, when focusing on the electrical aspect of the PVT, the efficiency evaluation of the multi-energy system concerns its electrical performance compared to that of the classical PV collector. For this purpose, a comparative study of the PVT and PV systems was performed in terms of short-circuit current, open-circuit voltage, power and electrical efficiency. The corresponding results, illustrated in figs. 7(a)-7(c), show clearly that the PVT system does not improve the current intensity but the remaining electrical quantities corresponding to this hybrid system are higher than those of the classical PV prototype. This leads in consequence to an important improvement of the electrical efficiency in the case of the hybrid system, fig. 7(d), compared to the reference case. The presented results show that the electric power output for the PVT system, and therefore, its efficiency, increased up to 27% when compared to the PV panel. This yield improvement agrees well with what was previously reported in several research works [29, 30], with different rates depending on the experimental conditions. It was reported that increases in terms of electrical efficiency in favor of the PVT system ranging from 15%-20% (for the first study) and around 23.8% (for the second study) have been recorded. These important improvements are related to the fact that the PVT system ensures a better cooling of the cells since it operates at lower temperature, while the overheating of the cells in the case of the PV system is a disabling factor in terms of both performance and cells lifespan. In accordance with the predictions of the theory, these results confirm that, due to increased resistance, the PV cell's output drops sharply with the temperature increase, which leads to a decrease of its performance in terms of power and efficiency. In contrast, the study shows that, despite the temperature difference obtained for both PVT and PV systems, the generated short-circuit current intensity is the same for both systems.

Hereafter, the analysis focuses on comparison of the overall efficiencies of the PVT and PV systems. For the latter (the PV captor), the total energy production is restricted to the electrical energy, while for the PVT hybrid system, both thermal and electrical energies are si-

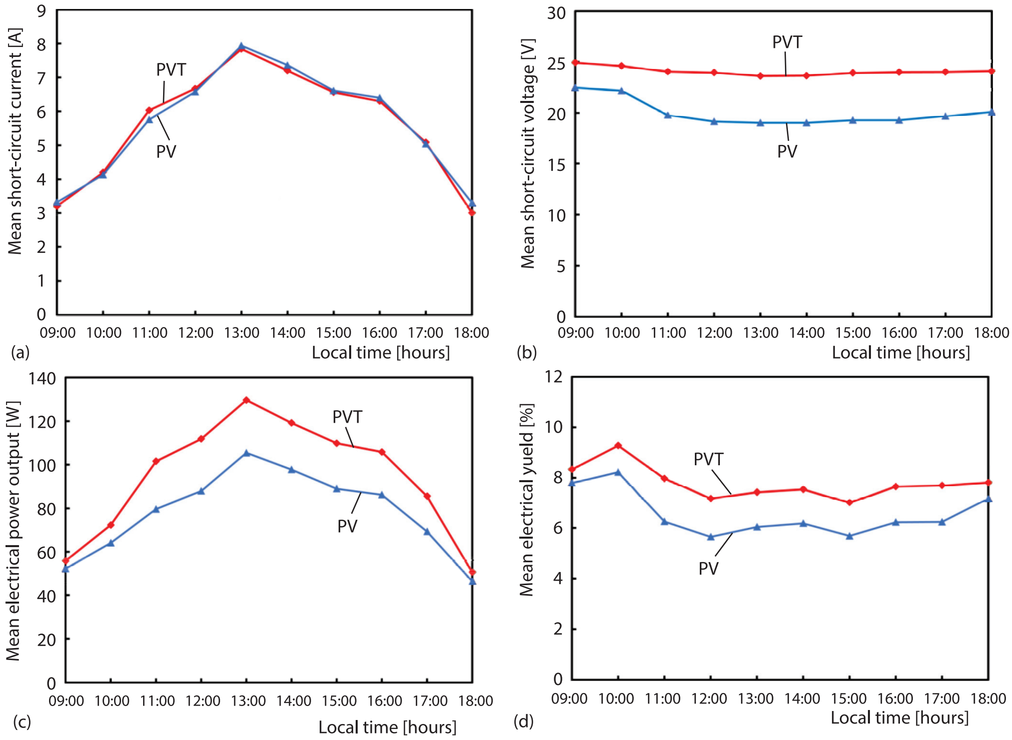

Figure 7. Daily variations of the mean short-circuit current intensities delivered by the PVT and PV collectors (a), daily variations of the mean open-circuit voltages generated by the PVT and PV collectors (b), daily variations of the mean electrical powers generated by the PVT (c), and PV collectors, and daily variations of the mean electrical efficiencies of PVT and PV collectors (d)

multaneously generated. Figure 8 exemplifies the daily variations of the hourly average values of the overall efficiencies for the PVT and PV systems. An important difference is observed between these efficiencies in favor of the PVT system. This advantage is attributed to the valorization of the thermal energy (waste heat) normally lost in the PV system but largely recovered in the case of the hybrid system which makes it useful. Unlike the PV collector for which the overall efficiency does not exceed 8.22%, the hybrid system allows to achieve an overall maximum efficiency of about 42.72%, reached at 1:00 p. m. local time. It can be concluded that, without an important difference in terms of costs, the hybrid technology provides a better energy efficiency compared to that of systems lying only on pure PV or thermal aspects. The rate of improvement in overall efficiency (electrical and thermal) obtained in this study is compatible with what has been reported in the literature. In fact, the performance of 1.44 kW PVT hybrid systems has been evaluated in different locations in Taiwan using TRNSYS software as simulation tool [12]. The results of this study showed that the system electrical efficiency was between 11.7% and 12.4%, its thermal efficiency was between 26.78% and 28.41% and therefore, its overall efficiency was between 38.48% and 40.81%. In a former study, He *et al.* [31] studied a hybrid PVT system using natural-convection circulate the cooling water. They reported a combined efficiency around 50%, with a contribution of the thermal efficiency neighboring 40%.

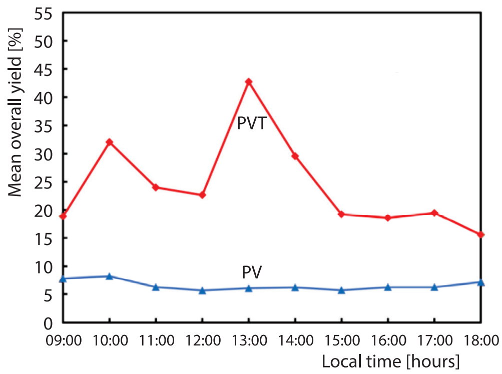

Figure 8. Comparison of the daily variations of the mean overall yields of PVT and PV systems

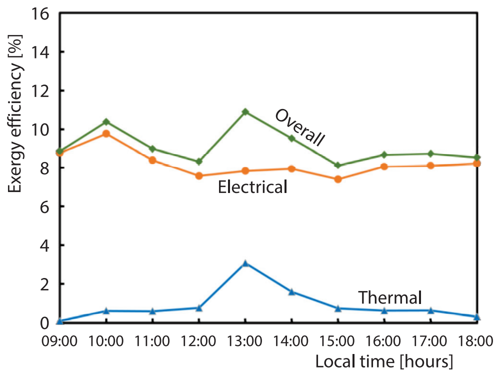

Figure 9. Average hourly variations of electrical, thermal and overall exergy efficiencies for the PVT system

The average hourly variations of electrical, thermal and overall exergy efficiencies are exemplified in fig. 9. The tendencies in this figure show some qualitative similarities compared to those exhibited by the energy aspect in figs. 7(d) and 8. In fact, both thermal and overall energetic and exergetic efficiencies reach their maximum values at 1:00 p. m. local time, which corresponds to solar noon (the solar radiation reaches its maximum). As for the electrical efficiency, the maximum value is reached at 10:00 a. m. local time for both energy and exergy.

From a quantitative point of view, contrary to the electrical efficiencies that are equivalent, the thermal exergy efficiency is significantly lower compared to the thermal energy one. The obtained results show that the highest thermal energetic efficiency is 35.30% while the exergetic efficiency does not exceed 3.07%. That means that the PVT collector is suitable to convert reasonably the available solar energy into useful heat, but this conversion occurs at a temperature close to the reference ambient temperature. Thus, the useful heat has a low quality in terms of its ability for generating mechanical work. These findings are in rational agreement with the results reported by Kallio and Siroux [28]. In their comparative study between two sites (Tempere in Finland and Strasbourg in France), these authors have shown that the highest thermal exergy efficiency of the PVT system recorded is around 2.47% in Tampere and 1.62% in Strasbourg, although the highest thermal efficiencies obtained in these sites are as high as 62% and 58.4%, respectively.

Conclusion

Hybrid PVT collector converting solar energy into heat and electricity has been investigated experimentally in this paper. The electrical and thermal characteristics of such a system have been presented and discussed. Both energetic and exergetic analysis have been performed in terms of electrical, thermal and overall efficiencies. The experimental results of this study revealed that the combination of PV and solar thermal technologies in a single panel enables an important increase of the efficiency of the total conversion of solar energy. The PVT system allows a substantial reduction of the PV cells temperature and prevents in consequence the problem of harmful heating up resulting from the traditional PV systems and affecting negatively their electrical performance. The comparative study of the results obtained by the PV and PVT systems, has shown that the electrical efficiency is by far the highest for the latter. This study has also shown that the overall energy efficiency of the integrated PVT system is significantly higher than that of the PV one, due to the valorization of heat losses by integrating the thermal component in the PVT system. The evaluation of the exergy performance carried out on the proposed hybrid system has shown that, contrary to the electrical efficiencies that are equivalent, the thermal exergy efficiency is significantly lower compared to the thermal energy one. The obtained results show that the highest thermal energetic efficiency is about 35.30% while the exergetic efficiency does not exceed 3.07%.

Nomenclature

A – amper
A_e – surface area of the PV module, [m^2]
A_{th} – surface area of the solar thermal collector, [m^2]
C_p – specific heat capacity, [Jkg^{-1}K^{-1}]
E – incident solar illuminance, [Wm^{-2}]
$\bar{E}$ – mean solar illuminance, [Wm^{-2}]
E_{el} – electrical energy output, [kWh]
Ex_{el} – electrical exergy, [kWh]
Ex_{in} – inlet exergy, [kWh]
Ex_{loss} – lost exergy, [kWh]
Ex_{out} – outlet exergy, [kWh]
Ex_{Sun} – solar radiation exergy, [kWh]
Ex_{th} – thermal exergy, [kWh]
$\dot{m}$ – heat transfer fluid mass-flow rate, [kgs^{-1}]
P_e – electrical power, [W]
P_{th} – thermal power, [W]
$\bar{P}_{th}$ – mean thermal power, [W]
P_{max} – maximum power output, [W]
Q_e – electrical energy produced by the collector, [kWh]
Q_l – lost energy, [kWh]
Q_s – solar energy reaching the collector, [kWh]
Q_{th} – thermal energy carried by the heat transfer fluid, [kWh]
T_a – ambient temperature, [°C]
$T_{a,min}$ – minimum ambient temperature, [°C]
$\bar{T}_a$ – mean ambient temperature, [°C]
T_{in} – inlet water temperature, [°C]
$\bar{T}_{in}$ – mean inlet water temperature, [°C]
T_{out} – outlet water temperature, [°C]
$\bar{T}_{out}$ – mean outlet water temperature, [°C]
T_{PV} – PV collector surface temperature, [°C]
T_{PVT} – PVT collector surface temperature, [°C]
T_{Sun} – surface temperature of the Sun, [K]

Acronyms

PVT – photovoltaic thermal
W_P – watt peak

Greek symbols

η_e – electrical energy efficiency of the cell, [%]
$\eta_{Ex_{el}}$ – electrical exergy efficiency, [%]
$\eta_{Ex_{out}}$ – overall exergy efficiency, [%]
$\eta_{Ex_{th}}$ – thermal exergy efficiency, [%]
η_o – overall yield of the PVT collector, [%]
η_{th} – thermal energy efficiency, [%]

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