Energy 107 (2016) 78–94

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energetic and exergetic performances analysis of a PV/T (photovoltaic thermal) solar system tested and simulated under to Tunisian (North Africa) climatic conditions

Majdi Hazami*, Ali Riahi, Farah Mehdaoui, Omeima Nouicer, Abdelhamid Farhat

Laboratoire des Procédés Thermiques, Centre de Recherches et des Technologies de l'Energie, Hammam Lif, B.P. 95, 2050, Tunis, Tunisia

A R T I C L E I N F O

Article history:
Received 21 July 2015
Received in revised form
28 March 2016
Accepted 29 March 2016
Available online 25 April 2016

Keywords:
PV/T solar system
Energy
Exergy
TRNSYS simulation

A B S T R A C T

The endeavor of this paper is to study the potential offered by the expenditure of a PV/T (photovoltaic thermal) solar system in Tunisian households. This investigation is performed according to two-folded approaches. Firstly, outdoor experiments were carried out during July 2014 for both passive and active mode. An exhaustive energy and exergy analysis was then performed to evaluate the instantaneous thermal and the electrical exergy outputs of the PV/T solar system. The results showed that the maximum instantaneous thermal and electric energy efficiency in active mode are about 50 and 15%, respectively. It was found also that the maximum thermal and electric exergy efficiencies were about 50 and 14.8%, respectively. The second approach is the evaluation of the monthly/annual performances of the PV/T solar system under typical climate area of Tunisia by using TRNSYS program. The results showed that the active mode enhances the electric efficiency and the exergy of the PV/T system by 3 and 2.5% points, respectively. The results showed that the optimized PV/T solar system covert the major part of the hot water and the electric needs of Tunisian household's with an expected annual average gain of about 14.60 and 5.33%, respectively. An economic appraisal was performed.

1. Introduction

By the virtue of its position Tunisia has an important potential of solar energy with an average annual solar radiation of about 26.13 MJ/m^2. This favorable circumstance allows Tunisia to be a pioneer in the exploitation of solar energy as a part of energy conservation strategy and government management programs. Henceforth, the utilization of solar energy through solar collectors presents a great prospect and opportunity for reducing the amount of conventional energy required with a significant potential to reduce environmental pollution arising from the use of fossil fuels. Under this program several solar collectors used for domestic hot water purposes were installed and investigated. Nowadays new generations of PV (Photovoltaic) panels used for electric supply were promoted in Tunisian marked. However, in PV panels, when the solar cells temperature increases, electrical voltage and efficiency decreases. Therefore, in order to achieve higher electrical efficiency, the PV panel should be regularly cooled by moving water/air through the panel. Hence for a new technology of solar collector is proposed. It consists in combining in the same hybrid (photovoltaic/thermal) solar collector, the electric generation with thermal supply. The advantage of combining these two systems lies in the reduction of the demands on physical space and the equipment cost through the use of common frames and brackets as compared to the separated PV panels and solar collectors placed side-by-side. Although the initiative of joining PV electricity generation with thermal collectors seemed promising, research on the field has been very slow compared to the significant technological advancements concerning all PV/T collectors' types. In 2013, Dubey S and Tay AAO [1] tested two types of hybrid PV/T solar systems. They found that the average thermal efficiency and electric efficiency for Type (A) PV/T module are 40.7 and 11.8%, respectively, and for Type (B) are 39.4 and 11.5%, respectively. The electrical efficiency of the PV modules was also compared with and without water mass flow. It was found that the average electric efficiency of the PV modules with water mass flow is about 0.4% higher than the normal PV module. In his work, Kalogirou S [2] presented an

* Corresponding author. Tel.: +216 71430044, +216 71430215; fax: +216 71430934.
E-mail address: hazamdi321@yahoo.fr (M. Hazami).

http://dx.doi.org/10.1016/j.energy.2016.03.134
0360-5442/

analytic study which aims to evaluate the thermal efficiency of a conventional PV/T water solar collector. He showed that the hybrid system increases the annual efficiency of the PV solar system from 2.8 to 7.7% and covers 49% of the hot water needs of a typical house. In 2015, Dupeyrat P et al. [3], investigated the efficiency of a single glazed flat plate PV/T collectors used in domestic hot water application. The thermal and electrical performances of several single glazed flat plate PV/T collectors based on water circulation were evaluated under steady state conditions using a simple 2D thermal model. In order to simulate the thermal and the electric behavior of the PV/T solar collector, Haurant P et al. [4] proposed in 2015 a simulation study based on a comparison investigation according to various evaluation criteria. The comparison was made assuming the same surface area and under the same climatic conditions. The results showed that in configuration of limited available space for solar collector area, the use of efficient PV/T collectors in the building envelop can be more advantageous than standard PV and solar thermal components. In the same context, Tomas M [5] (2014) has analyzed the performance of different concepts of solar hybrid PV/T solar collectors used in domestic hot water applications. A comparison with conventional installation of photovoltaic and thermal solar collectors with the same total collector area 100 m^2 has been done for identical load conditions. Economic analysis based on the performance results and energy prices have also been accomplished. In their study, Sujala B et al. [6] analyzed the performance of a photovoltaic thermal system, conventional collector, and PV (Photovoltaic) plate at different water storage capacities (25, 50, 75, 100, and 125 kg/m^2). Sujala Bhattarai et al. showed that the thermal efficiency of the PV/T system and the conventional collector increased sharply with increasing storage capacity. An economic study was also presented. It showed that the cost payback period of PV/T system and PV plate are remarkably reduced when the electricity price increased from 0.049 to 0.364 US$/kWh. Besides, Mohd NAB et al. [7] presented in their work an improved design of a (PV/T) solar collector integrating a PV panel with a serpentine-shaped copper tube as the water heating component and a single pass air channel as the air heating component. The results indicated that when both fluids are operated independently the overall thermal and electrical performances of the solar collector are considered as satisfactory. It is also seen that and once operated simultaneously the overall performance of the PV/T solar collector is higher. In the same context, Pei G et al. [8] presented a novel heat pipe PV/T (photovoltaic/thermal) system that could simultaneously supply electrical and thermal energy was proposed. A dynamic model of the heat pipe PV/T system was presented, and a test rig was constructed. They showed that the average total first- and second law efficiencies of the PV/T system are about 51.5 and 7.1%, respectively.

The PV/T solar collectors were also investigated on exergetic bases to compare the two kinds of energies, which are different in their quality. In 2010, Skin K et al. [9] presented a study dealing with the optimization of the number of collectors for PV/T hybrid active solar still for different water flow rates. It has been observed that the exergy efficiency of the PV/T hybrid active solar decreases linearly and nonlinearly with increase of water mass rates. In 2014, Sobhnamayan F et al. [10] presented an optimization analysis of a solar PV/T (photovoltaic thermal) water solar collector based on exergy concept. GA (Genetic algorithm) has been used to optimize the exergy efficiency of PV/T water collector. They showed that the maximum exergy efficiency is about 11.36%.

The primary objective of this paper is to study the potential offered by the use of a PV/T solar collector (Fig. 1) in Tunisian households to supply electricity and domestic hot water simultaneously. The methodology in this work consists in: (i) the evaluation of the instantaneous thermal and electric performances by the achieving of a series of experimentations under various Tunisian climatic conditions during selected days of July 2014. The experimentation consists in following the temperature changes at different elements of the PV/T system during selected days (inside the storage cylinder, at the inlet and outlet of the PV/T collector, PV cells, output voltage and current). (ii) The elaboration of TRNSYS model to simulate the annual thermal and electric performances of the PV/T system. The annual performances investigation includes: energy extracted and delivered to the user from the PV/T system, heat loss, auxiliary energy, solar fraction and electric and thermal efficiencies. The originality in this work lies in the facts that: (i) it covers an energetic and exergetic study performed to obtain thermal and electrical outputs of the PV/T solar collector, (ii) it presents a TRNSYS simulation of the annual thermal and electric energetic and exergetic performances of the PV/T system, (iii) it presents a comparison between obtained results and literature (iv) it presents also a comparison between the PV/T solar collector and the most popular water heating solar collectors (flat plate solar collector, FPC and evacuated solar collector, ETC (Evacuated tube collector)) and PV panel to confirm the improvement of the PV/T solar collector. The comparison was made on economic and availability bases.

Fig. 1. The PV/T solar collector used in our study.

2. Experimental study

2.1. Description of the PV/T solar collector

In order to determine the instantaneous thermal and electric performances of the PV/T solar system an experimental device was conceived. In Fig. 2 is displayed the schematic illustration of PV/T solar system experimental set-up which consists mainly of:

- A commercially available flat-plate PV/T solar collector having 72 monocrystalline solar cells and an aperture area of 1.42 m^2. It is mounted on a stand, oriented N-S, and tilted 45° N towards the south. The technical specifications of the PV/T solar collector are shown in Table 1.

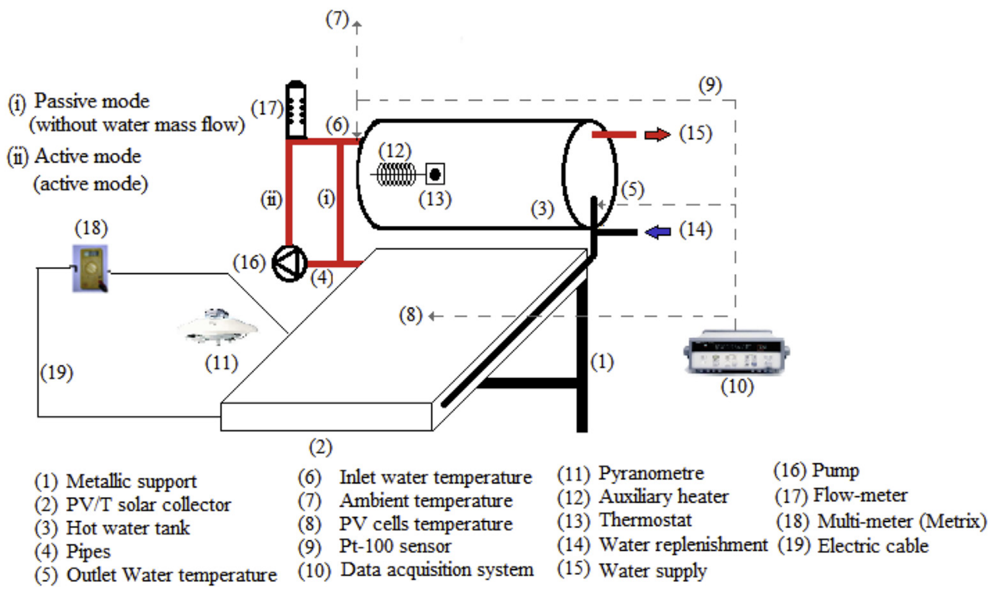

Fig. 2. Descriptive diagram of the experimental set-up of the PV/T solar system.

Table 1
Technical specifications of the PV/T solar collector.

Specifications	Value
PV module type	Mono-crystalline silicon
Dimensions (mm)	870 × 1640 × 105
Weight (kg)	34,4
Sealing	Epdm & silicone
Thermal insolation coefficient, λ_i	0.035 W/mK
Cells number	72
Cells dimension	125 × 125 mm
Cells emissivity, ε_{cell}	0.95
Cells absorption coefficient, α_{cell}	0.85
Cells filling coefficient, β_{cell}	0.83
Power generation efficiency, $\eta_{Ther\ Elec}$	0,38
Cells temperature coefficient, β	0.0045 °C^{-1}
Absorber panel	Copper

- A hot water storage tank with a capacity of 200 L. Inside the hot water storage tank is immersed an electric auxiliary heating equipments.
- Pump, a sliding valve and a flow-meter were used to control the water mass flow rates during the experimental tests.
- PT100 sensors were used to measure the ambient temperature and the water temperature at the inlet and the outlet of the PV/T solar collector.
- A Kipp & Zonen pyranometer was mounted close to the PV/T solar collector to evaluate the global solar irradiance.
- All instruments and sensors were connected to a multi-channel digital HP data-logger used for measuring all experimental parameters.
- A Muli-meter type Matrix was also used to evaluate the instantaneous current and voltage outputs of the PV/T solar collector.

In this study, two configurations of PV/T solar system were considered:

(i) A PV/T solar system functioning in passive mode (without water mass flow)

(ii) A PV/T solar system functioning in active mode (with water mass flow). In active mode the PV/T solar water heating system needs a pump to circulate the water from the PV/T solar collector to hot water storage tank with a fixed water mass-flow equal to 0.083 kg/s.

The experiments were carried out under outdoor field conditions of Borj cedria (North of Tunisia, Latitude 36°50′ N and Longitude 10°44′E) in July 2014 during which the solar irradiance intensity satisfies the experimental requirement.

To enhance the quality and the consistency of the measurements of the following conditions have been taken into account: (i) a total solar energy higher than 16 MJ/m^2; (ii) the average wind speed should be lower than 1.5 m s^{-1}; (iii) the water inlet temperature in the system will be at 20 ± 2 °C and (iv) average ambient temperature superior than 25 °C. Several days (12th, 13th, 14th and 15th of July 2014) are selected to present the experimental results. In Table 2 are illustrated the solar irradiation intensity and the ambient temperature arrays through the selected days of July 2014. It is seen that during the selected days of July the PV/T solar collector was exposed to solar radiation ranging from 380 to 1070 W/m^2 and an ambient temperature in the array of 35–43 °C.

During the experimental study the rate of the incident solar radiation falling on to the PV/T solar system as well as the temperature changes at: the inlet and the outlet of the PV/T solar collector, the PV cells, the output-current and the output-voltage delivered in open circuit mode were measured. The tests begins at 9:00 h (Local solar time) when the data acquisition system are switched on. At the end of the solar journey at 18:00 h, the valves of the solar loop are closed after that the day test is finished. The experiments were achieved in order to determine the daily thermal and the electric performances of the PV/T solar system.

The TRNSYS program inputs (i.e. solar collector efficiency and storage tank heat loss coefficient) of the PV/T solar system were determined by another investigation based on an experimental protocol developed as a draft of test standard [11,12]. The mainly result of the experimental test is the evaluation of the instantaneous efficiency η_{th} changes (Eq. (2)). The instantaneous efficiency η_{th} changes allows the evaluation of the PV/T solar system

Table 2
Solar irradiation intensity and ambient temperature arrays during the selected days of July 2014.

Days	Characteristics	Solar irradiation intensity arrays (W/m^2)	Ambient temperature arrays (°C)
12th	Clear sky day	400–1000	35.5–42
13th	Clear sky day	390–1020	36.5–42.5
14th	Clear sky day	420–1050	33.5–41.6
15th	Clear sky day	380–1070	35–42.9

parameters $F^{'}(\tau\alpha)_{PV}K_{\theta}$, a (W/m^2 K) and b (W/m^2 K^2) and the hot water tank thermal loss coefficient, U_L [12]. All these parameters are mentioned in Table 3. The incidence angle modifier (K_{θ}) for different angles of incidence (θ) are shown in Table 4 [13].

2.2. Uncertainly analyses

An uncertainty analysis was achieved to appraise the precision of the experimental study. In the experimental study, errors came from the sensitiveness of equipment and measurements explained previously. The errors are rearranged into three groups:

- Errors due to measurement of temperature are: (i) sensitiveness of data acquisition system and Pt-100 sensor which are about ±0.1% °C, (ii) measurement error is ±0.2% and (iii) sensitiveness of the is ±0.1% °C.
- Errors due to measurement of the voltage and current of PV module are about ±1.0%.
- Errors came from the measurement of the flow rate: (i) the sensitiveness of the flow meter is about ±0.1% and (ii) errors due to measurement are about ±0.1%.

In total, errors of measurement of the flow rate are about ±0.2%. The total uncertainties associated with the calculated values were found as follows: (i) ±2% for the PV/T solar collector's instantaneous thermal efficiency and (ii) ±2% for its exergy efficiencies.

3. Energetic and exergetic analysis

3.1. Energy analysis

- The useful heat gain, $\dot{Q}_{th}$, is evaluated by means of the Eq. (1):

$$\dot{Q}_{th} = \dot{m}C_p(T_o - T_i) \tag{1}$$

- In order to specify the sharing of the incident solar radiation into the useful energy gain and to describes the optical losses effect on the thermal performance of the PV/T solar collector it is more appropriate to evaluate the instantaneous thermal efficiency, η_{th}, of PV/T solar collector by means of the equation [14,15]:

$$\eta_{th} = F'(\tau\alpha)_{PV}K_{\theta} - a\frac{(T_{av} - T_a)}{G} - b\frac{(T_{av} - T_a)^2}{G} \tag{2}$$

Table 3
PV/T solar system and hot water tank thermal performances.

Parameters	Value	Unit
Tested flow rates	0.027	kg/s
Intercept efficiency, ($F^{'}(\tau\alpha)_{PV}K_{\theta}$)	0.486	%
First order efficiency coefficient, a	4.028	W/m^2 K
Second order efficiency coefficient, b	0.067	W/m^2 K^2
Hot water tank loss coefficient, U_L	1.6	W/m^2 K

Table 4
Experimental values of the incidence angle modifier for different angles of incidence.

θ	0	30	45	60	65	80
K_{θ}	1	0.98	0.94	0.80	0.73	0.40

3.2. Electrical analysis

- The electric energy supplied by the PV/T system is evaluated by the Eq. (3):

$$\dot{E}_{elect} = \eta_0\left[1 - \beta\left(T_{cell} - T_{a,ref}\right)\right]\cdot A.G \tag{3}$$

where $T_{a,ref}$ (25 °C) is the reference temperature and β is the cells temperature coefficient. η_O evaluated at standards conditions ($T_{a,ref} = 25$ °C and $G_{max} = 1000$ W/m^2) is given by:

$$\eta_O = \frac{P_{elec}}{A.G} = \frac{U_m\cdot I_m}{A.G} \tag{4}$$

- The electrical efficiency of PV/T solar collector, η_{elect}, is defined as the ratio of actual electrical output power to input the rate of solar energy incident on the PV/T surface. η_{elect} is given by the Eq. (5) [16,17]:

$$\eta_{elect} = \frac{U_m\cdot I_m - \dot{E}_p}{G.A} \tag{5}$$

- The consumed electrical power by the pump is calculated from:

$$\dot{E}_p = \frac{\dot{m}\cdot\Delta p}{\rho\cdot\eta_p} \tag{6}$$

In the previous equations, Δp, ρ and η_p are the pressure drop in PV/T collector, the density of water and the pump efficiency, respectively.

- The energy utilization factor is given by the Eq. (7):

$$F = \frac{\dot{Q}_{th} + \dot{E}_{Elec}}{A.G} \tag{7}$$

3.3. Exergy analysis

The exergy analysis (based on the second law analysis) is the most suitable method to get a clear vision on the PV/T solar collector efficiencies and on the degradation of energy during the thermal and the electrical conversion processes.

- The exergy inflow coming from the solar radiation falling on the collector surface is given by the Eq. (8) [17–21]:

$$\dot{E}x_{Q,sun} = \dot{S}\left[1 - \frac{T_0}{T^*}\right] \quad (8)$$

where T* is the apparent sun temperature as an exergy source and $\dot{S}$ is the net solar heat transfer. $\dot{S}$ is proportional to the collector area A and the proportionality factor is G (W/m^2).

In this analysis the value suggested by Petela [21] is adopted, i.e. T* is approximately equal to 3/4. T_{sun}; where T_{sun} is the apparent black body temperature of the sun, which is about 6000 K. Therefore, T* considered here is 4500 K.

- The thermal exergy, $\dot{E}x_{th}$, is given by the Eq. (9):

$$\dot{E}x_{th} = \left(1 - \frac{T_a}{T_{s,w}}\right)\cdot\dot{Q}_{th} \quad (9)$$

- The electrical exergy, $\dot{E}x_{elec}$, includes the difference between the outlet electrical power of PV module and the consumed electrical power by pump. $\dot{E}x_{elec}$ is calculated by using the Eq. (10) [18,19,21]:

$$\dot{E}x_{elect} = \dot{E}_{elect} - \dot{E}_p \quad (10)$$

- The net electrical energy yield is defined as [22]:

$$\dot{Q}_{net\ elect} = \eta_{elec}\cdot\dot{S} - P_{cons\ pump} \quad (11)$$

Where $P_{cons\ pump}$ is estimated to 40 W

- The exergy losses $\dot{E}x_{loss}$, caused by heat leakage rate is calculated by Refs. [17–19]:

$$\dot{E}x_{loss} = U_L\cdot A\cdot\left[1 - \frac{T_a}{T_{cell}}\right] \quad (12)$$

- The exergy destroyed rate due to pressure drop in flow pipes (Kotas, 1995; Wong, 2000):

$$\dot{E}x_{des,\Delta P} = \frac{T_a\cdot\dot{m}\cdot\Delta p}{\rho\cdot\overline{T_f}} \quad (13)$$

- The electrical exergy destroyed rate [22,23]:

$$\dot{E}x_{des,\Delta P} = I_{SC}\cdot U_{0C} - \left(I_m\cdot U_m - \dot{E}_P\right) \quad (14)$$

- The exergy destroyed rate of PV/T water collector caused by optical losses in PV/T collector surface (Sarhaddi et al., 2009, 2010b):

$$\dot{E}x_{loss,opt} = \dot{E}x_{Q,sun}\cdot\left(1 - (\alpha\tau)_{eff}\right) \quad (15)$$

- The exergy destroyed rate due to the temperature difference between the sun and PV/T collector surface [22,23]:

$$\dot{E}x_{loss,Sun-PV/T} = (\alpha\tau)_{eff}\cdot\dot{E}x_{Q,sun} - \left((\alpha\tau)_{eff}\cdot\dot{S}\left[1 - \frac{T_a}{T_{cell}}\right]\right) \quad (16)$$

- The exergy destroyed rate due to heat transfer from the PV/T surface to the working water at finite temperature difference:

$$\dot{E}x_{loss,PV/T} = \left((\alpha\tau)_{eff}\cdot\dot{S}\left[1 - \frac{T_a}{T_{cell}}\right]\right) - \left[\dot{Q}_{loss}\left(1 - \frac{T_a}{T_{cell}}\right) + \dot{Q}_{th}\left(1 - \frac{T_a}{T_{s,w}}\right) + U_{oc}\cdot I_{sc}\right] \quad (17)$$

where $\dot{Q}_{loss}$ is heat loss rate from PV/T system to surrounding [22,23]:

$$\dot{Q}_{loss} = U_L\cdot A\cdot(T_{cell} - T_a) \quad (18)$$

- The global exergy destruction $\dot{E}x_{des}$ are equal to the product of reference environmental temperature to the entropy generation rate, $\dot{S}_{gen}$, in control volume [18,19,23]:

$$\dot{E}x_{des} = T_{a,ref}\cdot\dot{S}_{gen} \quad (19)$$

- The thermal and the electric exergy efficiency of the PV/T solar collector are defined by the relations (20) and (21) respectively [24]:

$$\Psi_{Th} = \frac{\dot{E}x_{th}}{\dot{E}_{x,sun}} \quad (20)$$

$$\Psi_{Elec} = \frac{\dot{E}x_{elec}}{\dot{E}_{x,sun}} \quad (21)$$

- The exergy efficiency of the PV/T solar system in general could be represented as:

$$\Psi_{PV/T} = \frac{\dot{Q}_{th}\left(1 - \frac{T_a}{T_{s,w}}\right) + \eta_0\left[1 - \beta\left(T_{cell} - T_{a,ref}\right)\right]\cdot\dot{S} - \dot{E}_p}{\left(1 - \frac{T_a}{T_{cell}}\right)\cdot\dot{S}} \quad (22)$$

4. Instantaneous thermal and electric performances of the PV/T solar system

The evaluation of the PV/T solar system performances is complex due to the interaction of the thermal and the electrical outputs. Thus performances estimation taking in to account the amount of the thermal and the electric energy produced through thermodynamic considerations were recommended.

4.1. Thermal performances

In Fig. 3 is represented the amount (V) and the temperature of the water supplied by the PV/T solar system ($T_{s,w}$) in both passive and active modes. It is seen that the active mode improve considerably the amount of the supplied hot water. Indeed in passive mode the amount of the extracted water (V) was about 200 L at an average temperature about 45.5 °C. In active mode (0.083 kg/s) the supplied hot water enhances to about 250 L at an average temperature of 46.4 °C.

In Fig. 4 is plotted the instantaneous changes of the thermal energy collected by the PV/T solar system during the 12th of July 2014 in both passive and active modes. We found that in passive

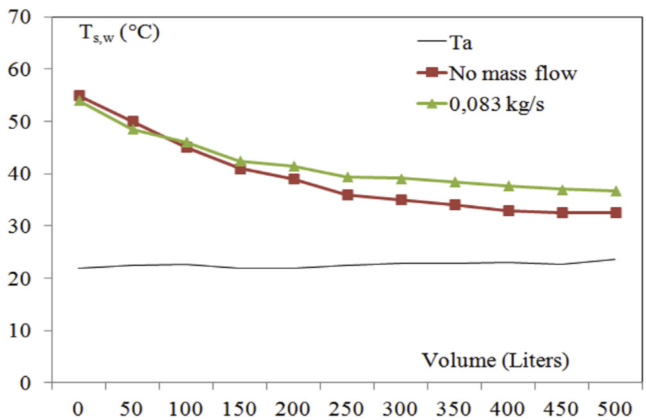

Fig. 3. The amount (V) and the temperature of the water supplied by the PV/T solar system ($T_{s,w}$) in both passive and active modes (0.083 kg/s) during the selected days of July 2014.

mode the energy collected by the PV/T solar system ranged between 0.04 and 0.39 kWh/m^2 with an overall total daily amount equal to 2.36 kWh/m^2. It is also seen that in active mode (0.083 kg/s) the energy supplied by the PV/T solar system is more important. It varies between 0.056 and 0.52 kWh/m^2 suppling a daily energy rates of about 3.18 kWh/m^2.

In Fig. 5 is illustrated the instantaneous thermal energy and exergy efficiencies changes of the PV/T solar collector during the 13th of July 2014 in both passive and active modes. It is seen that in passive mode the instantaneous energy efficiency vary between 12 and 36% from 07:00 to 12:00 and then decrease to 18%. Nevertheless in active mode the instantaneous energy efficiencies scrambled to range between 18 and 50%. Simultaneous it was found that in passive mode the thermal exergy efficiencies were in the array of 12–30% whilst in active mode we establish that the thermal exergy efficiency become more significant. It ranges from 12 to 41%. Compared to the exergy efficiency, we established that the thermal energy efficiency was always higher than exergy efficiency. This was expected because in the calculation of the net energy efficiency one just take into account, the amount of the useful energy supplied by the PV/T solar collector whereas the quality of this energy was neglected [20,21].

4.2. Electric performances

In Fig. 6 are illustrated the solar cell T_{cell} temperature same as the electric efficiency changes in both passive and active modes during the selected days of July 2014 (12th, 13th, 14th and 15th). In passive mode it is seen that while T_{cell}, growth from 78.9 to 124.8 °C, the electric efficiency decline from 12.7 to 10%. It is also noted that the active mode (0.083 kg/s) reduces clearly the solar cells temperature T_{cell}, which ranges is in the array of 36.7–82.6 °C. Besides the active mode ameliorate the electric efficiency which stabilized to about 14.8%. These results showed also that the use of the PV/T solar collector in active mode ameliorates distinctly the significance of the instantaneous electric efficiency. The active mode resulted also in T_{cell} drops by 33.7% for a mass flow rate equal to 0.083 kg/s. The decrease of the solar cell temperature ameliorates the electric efficiency of the PV/T solar collector.

In Fig. 7 is plotted the output current–voltage characteristics of the PV/T solar system in passive mode under different solar irradiance intensities. It is noted that the electric output of the PV/T solar system is affected by the availability of solar irradiance intensities. It is showed that the short-circuit current (*Icc*) increases from 2.2 to 4.5 A once solar irradiance intensities growth from 500 to 1000 W/m^2. However the short-circuit voltage (*Ucc*) is conversely proportional to solar irradiance intensities. Indeed, for the solar irradiance equal to 500, 700 and 1000 W/m^2, *Ucc* is respectively equal to 36, 34 and 32 V. In Fig. 8 is represented the output current vs output voltage in active mode for a solar irradiance intensity is equal to 1000 W/m^2. It is seen that the generated electricity is affected by the water mass flow moving inside the cooper heat exchanger underneath the PV cells. Results show that *Icc* increase even as *Ucc* decrease with mass flow. Actually, the active mode leads to the recovery of more heat from PV cells, consequently, the production of electricity goes up.

In Fig. 9 is represented the instantaneous electric energy and exergy efficiencies of the PV/T hybrid solar system. It is noted that the electrical and the exergy efficiencies of the PV/T solar system are improved in active mode. In passive mode the electric energy efficiency vary from 9.5 to 12% whereas in active mode it is approximately constant, about 15%. Fig. 9 showed also that in passive mode the exergy electric efficiency ranges from 8.5 to 10.6% against an array of 12.5 and 14.8% obtained in active mode.

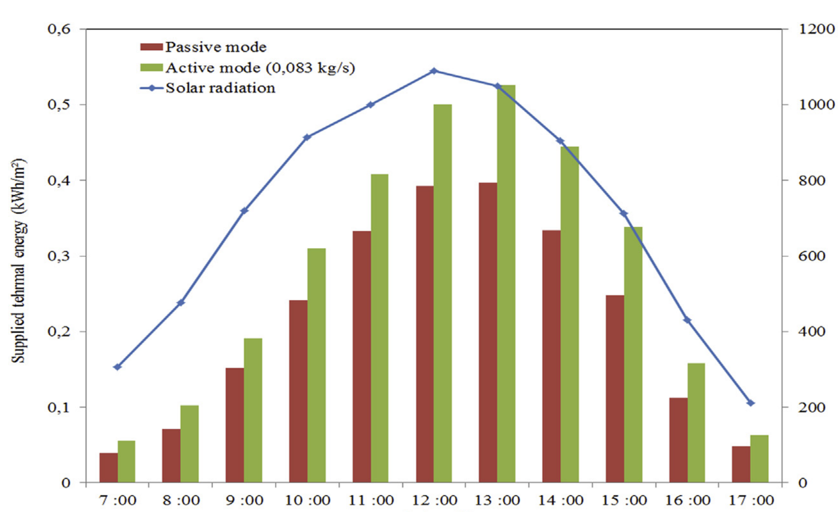

Fig. 4. Changes vs local time of the thermal energy supplied by the PV/T solar system in both passive and active modes and the solar irradiation during the 12th of July 2014.

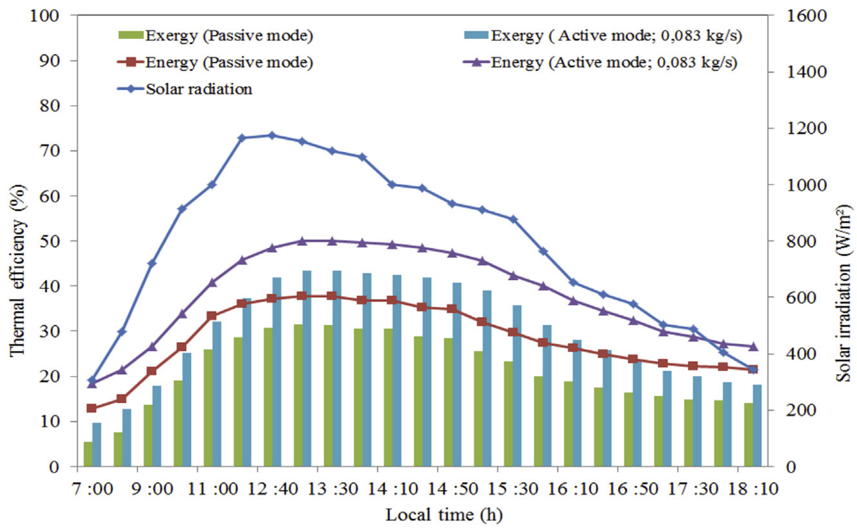

Fig. 5. Changes vs local time of the thermal energy and exergy efficiency of the PV/T solar system and the solar irradiation during the 13th of July 2014.

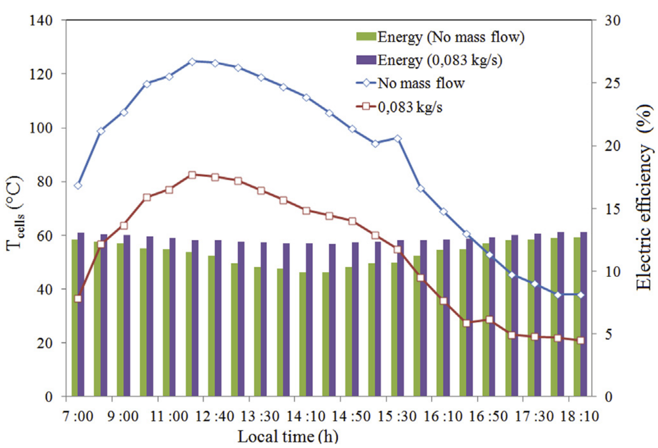

Fig. 6. PV cells temperature and electric efficiency changes vs local time in passive and active modes during the selected days of July 2014.

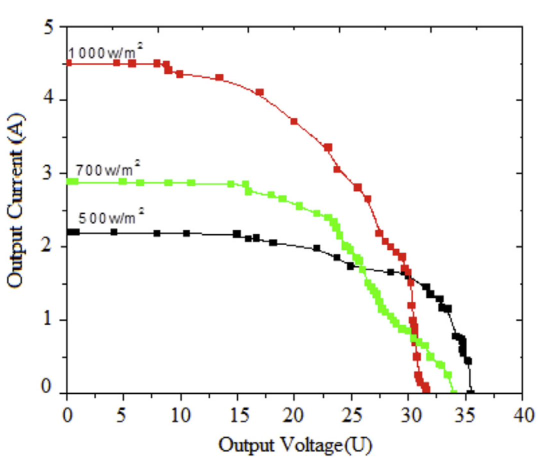

Fig. 7. Output current vs output voltage in passive mode for different solar radiation intensity during the 14th of July 2014.

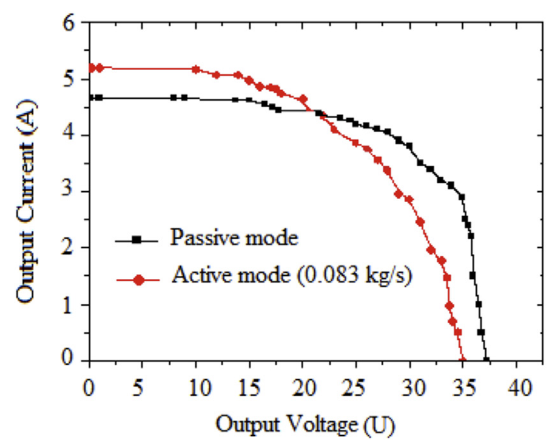

Fig. 8. Output current vs output voltage in active mode during 15th of July 2014 for solar radiation intensity equal to 1000 W/m^2.

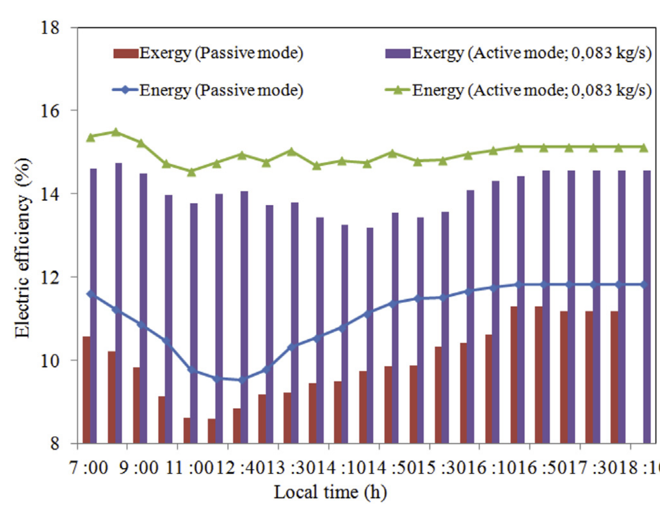

Fig. 9. Electric energy and exergy efficiency changes vs local time in passive and active modes during the days of July 2014.

5. Annual thermal and electric performances of the PV/T solar system

The annual thermal and electric performances are predicted by a TRNSYS simulation. It permits the evaluation of the global behavior of the PV/T hybrid solar system. The simulation of the thermal and electric performances of the PV/T hybrid solar system consists in: (i) the simulation of the performances of the PV/T solar system during selected days of July 2014 by using TRNSYS model, (ii) the verification that the elaborated TRNSYS model presents suitable results by comparing the simulated with the experimental results and (iii) the evaluation of the monthly/annual performances of the PV/T hybrid solar system by introduction the meteorological year data for Borj Cédria, Tunis, Tunisia.

The results of the TRNSYS model were used to evaluate the energy and exergy collected and delivered to the user, the auxiliary energy, the solar fraction relative to the PV/T solar system. The results of the TRNSYS model were also used to evaluate the energy and exergy efficiency of the PV/T solar system.

5.1. TRNSYS model development

In Fig. 10 is represented the descriptive diagram of the TRNSYS model. It consisted mainly of Type 50a PV/T hybrid solar collector, Type 3b circulating pump, Type 4c stratified hot water storage tank, Type 2b differential temperature controller, Type 14b water consumption load profile and Type 109 (TMY of Borj cedria, Tunis, Tunisia). A mixing valve is being simulated with a type 11 used as a tee-piece in the storage outlet fluid. Another type 11 is being used as a liquid flow diverter in the mains cold water line. The hourly distribution of hot water consumption in a day can be affected by several factors. It can vary from day to day, from season to season and from family to family. For the present simulation, the hot water consumption and energy needs of medium size families living in Tunisia is about 200 l/day at 50 °C distributed during a day according to the profile illustrated in Fig. 11 [13]. The hot water consumption profile is integrated in load unit (Type 14b) to manage the hot water supplied by the PV/T system.

The system input parameters of the simulation program defined from experimental test results are shown in Table 3. For the PV/T hybrid solar collector, the experimental values of the incidence angle modifier (IAM, K_θ) for different angles of incidence (θ) are acquired from an external data file interpolated by the generic DYNAMIC DATA routine existing in the TRNSYS program (Table 4).

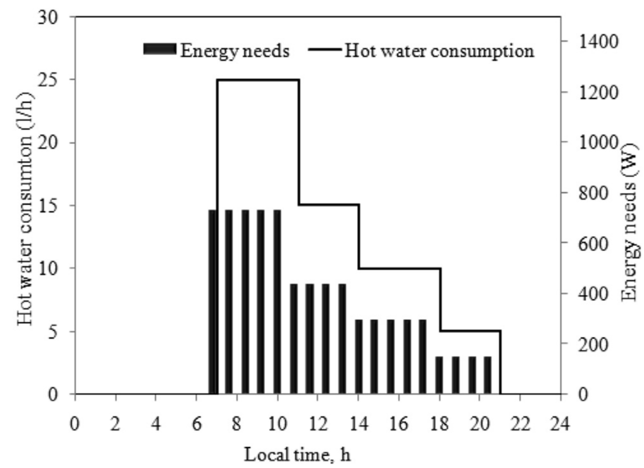

Fig. 11. Hot water consumption and energy needs at different times of the day (200 l/Day).

In Table 5 is presented the general specifications of the typical Tunisian households.

5.2. Validation of the model

To test the consistency of the TRNSYS simulation program we confronted the simulated results of the model with the experimental tests conducted during 14th of July 2014. The validation presented in this section appraises the capacity of the TRNSYS model to represent qualitatively the observed physical phenomena evaluated experimentally, in particular the variation of the PV/T cells temperature (T_{cell}) and the delivered electric power (E_{power}) (Fig. 12). It is perceived that both experimental and simulated plots of T_{cell} and E_{power}changes vs local time presents similar tendency, respectively. For the model validation process the predicted values closely match the measured data with acceptable disagreement of

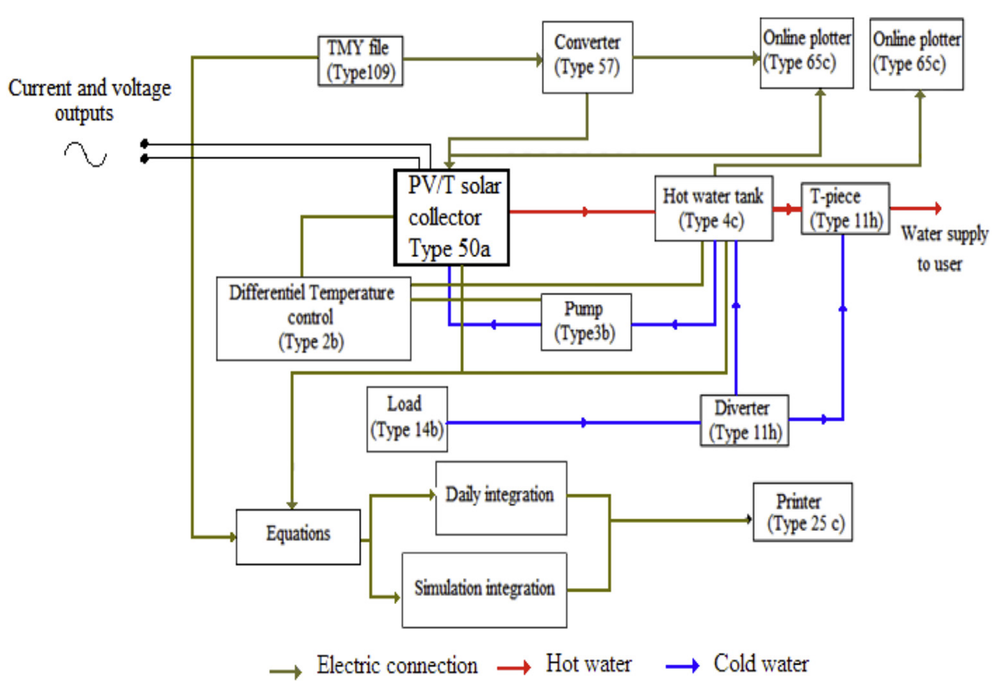

Fig. 10. The flow diagram of the TRNSYS simulation of the PV/T solar system.

Table 5
Specific Parameters of the Tunisian households.

Parameters	Value
Average number of peaple/house	4–5
Occupancy rate (%)	90
Daily hot water usage estimation (l/day)	200
Hot water temperature (°C)	45
Operating days per week	7
Conventional fuel type	Electricity, gas, town/gas

about 4–5% points. Even when the solar radiation intensity was gradually increased the model gives reasonably good results; thus, allows a flexibility which is a great advantage. The mismatch between the simulated and experimental results is mainly attributed to the experimental errors. The good behavior of the model is clearly stated in the calculation of the standard error value in terms of the prediction between simulated and measured cells temperature (T_{cell}) and the electric power (E_{power}). Hence we deduced that the simulation by TRNSYS of the PV/T solar system permits the evaluation of the annual electric and thermal performances, with a bearable error.

5.3. Annual thermal and electric performances

The annual performances of the PV/T solar system were effectuated by TRNSYS simulation model according to outdoor field conditions of Borj cedria (Tunis, Tunisia) during the whole year of 2014 to cover different environment conditions (Sunny, and cloudy and rainy conditions). The annual investigation treats the energy and exergy collected, the auxiliary energy, the thermal and electric energy and exergy delivered the solar fraction and finally the thermal and the electric energy and exergy efficiencies of the PV/T hybrid solar system evaluated in both passive and active modes.

Fig. 13 shows the plot of the collected, the auxiliary and the delivered energy by the PV/T hybrid solar system during 2014 simulated by TRNSYS program. We noted that in passive mode the monthly energy collected ranged between 63.9 and 212.4 MJ/m^2 in January and July respectively with a yearly total of about 1661.5 MJ/m^2. In active mode the monthly energy collected are more important, ranging between 269.8 and 81.14 MJ/m^2 with a yearly total energy collected of about 2110 MJ/m^2. We found that the active mode improves the amount of the energy collected by 12% points compared to the passive mode. Fig. 13 illustrates also that the monthly average quantity of auxiliary energy varied between 214.15 and 3 MJ/m^2 and between 190.6 and 2.7 MJ/m^2 in passive

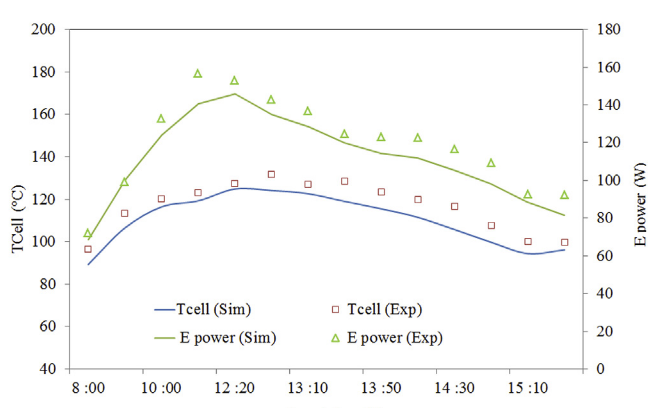

Fig. 12. Experimental and simulated cells temperature and electric power changes vs local time during 14th of July 2014.

and active modes, respectively. It is obvious that in active mode the auxiliary energy is reduced by 11% compared to the passive mode. We noted also that for both passive and active modes the maximum of auxiliary energy consumption is maximized in cold months chiefly in December, January and February. During the summer months (Jun, July and August) the heat requirements are wholly met by solar, hence no auxiliary is needed. We establish that there is an important increase of delivered energy once the PV/T solar system works in active mode. Indeed the growth in delivered energy is enhanced of about 20% compared to the passive mode.

In Fig. 14 is plotted the thermal efficiency and solar fraction of the PV/T solar system in passive and active modes simulated by TRNSYS program during 2014. It is seen that the efficiency of the PV/T solar system ranged between 19 and 38% and between 22.7 and 45% in passive and active modes, respectively. We established that the active mode increase the efficiency of the PV/T solar system by 5% points compared to the passive mode.

In Fig. 15 is represented the plot of the exergy collected by the PV/T solar collector simulated during 2014 in both passive and active modes. We noted that in passive mode the monthly thermal exergy collected ranged between 43.5 and 144.5 MJ/m^2 with an annual total of about 1129.8 MJ/m^2. Conversely in active mode, the amount of the monthly thermal exergy collected is more significant. It ranges between 52.6 and 174.8 MJ/m^2 with an annual total exergy collected of about 1367.13 MJ/m^2. It is also noted that the amount of the exergy delivered by the PV/T solar system in active mode raises by 20% points compared to the passive mode.

The monthly electrical energy production of the PV/T solar system is represented in Fig. 16. It was found that the annual electricity production from the PV/T solar system was 540 MJ/m^2 in passive mode and about 712.7 MJ/m^2 in active mode. The monthly yield in electrical efficiency is also simulated and presented in Fig. 16. We establish that the active mode enhance the efficiency of the PV/T solar system by 3% points compared to the passive mode. Indeed, the water flow rate enhance the rates of heat transfer from the back of the PV panel to the flowing water inside the heat exchanger, reducing the operating temperature of the cells and increasing the electrical power output.

Fig. 17 shows the monthly electric exergy and electric exergy efficiency changes during the whole year of 2014 in both passive and active modes. It is seen that the yielded electric exergy varies between 20.55 and 54.52 MJ/m^2 and between 25.5 and 67.7 MJ/m^2 in passive and active modes, respectively. It was found that the active mode enhance the amount of the annual yielded electric exergy by 19.35% points compared to the passive mode. Fig. 17 showed also that the electric exergy efficiency of the PV/T solar system is more important in active mode. It varies respectively in the ranges of 7.62 and 12.42% and 9.27 and 15% in passive and active modes. It is noted that the improvement in the exergetic efficiency agreed by the active mode compared to the passive mode is of about 2.5%.

6. Optimization of the PV/T solar system for a typical Tunisian household

To achieve maximum performances from the PV/T hybrid solar system it is essential to optimize all PV/T solar system design parameters. Hence another TRNSYS simulation was achieved. It aims to determine the appropriate collector area (A), the hot water cylinder volume (V) and the water mass flow rate ($\dot{m}$). The solar fraction, *SF* is the most suitable indicator of the system performance compared to the other parameters such as collector efficiency or heat removal factor, since it manifests the overall performance of the entire system. However, it is necessary to consider that the simultaneous production of a large scale of thermal and electric

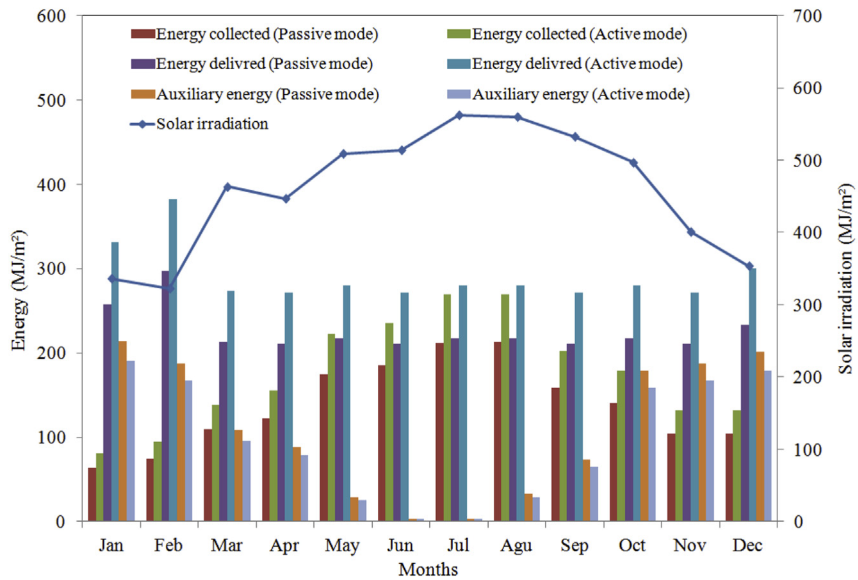

Fig. 13. Simulated monthly and yearly solar exergy irradiance and energy flow changes of the PV/T solar system in passive and active mode.

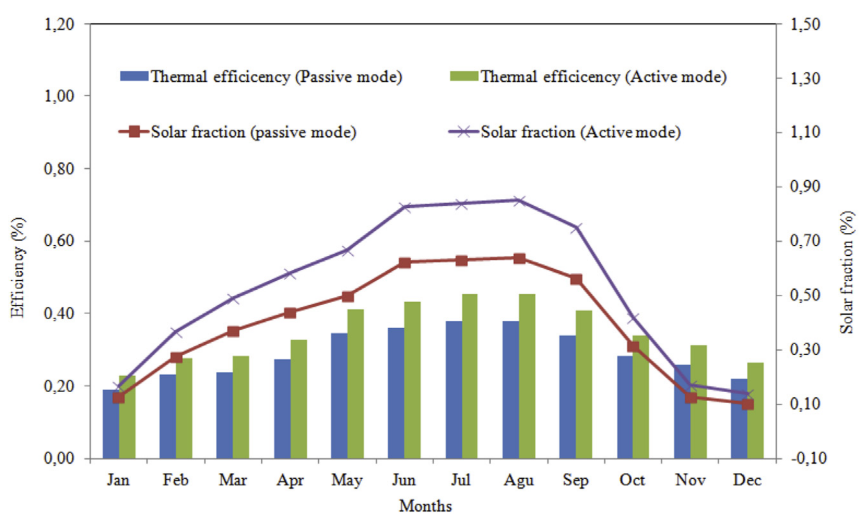

Fig. 14. Monthly and yearly simulated thermal efficiency and solar fraction changes of the PV/T solar system.

energy and the using of water pumps to circulate hot water modify the performances of the PV/T hybrid solar system. In this context, Gilles Notton et al. [25] suggest using an energy-saving efficiency identified also as a global efficiency. In the global efficiency the thermal energy is converted into electrical energy via an electric power generation efficiency $\eta_{Ther\ Elec}$ considering a conventional power plant [26]. The power generation efficiency $\eta_{Ther\ Elec}$ relative to the PV/T solar collector is equal to 0.38 (Table 1). This formulation suggests energy equivalence between electricity and thermal energy with an electrical-to-thermal ratio equal to 2.63 (1/0.38). Thus another form the solar fraction equation taking into account this difference of quality of energy is obtained:

$$SF = \frac{1}{1 + \frac{Q_{Elec,Aux} + Q_{Elec,pump}}{Q_{Ther,sol} \cdot \eta_{Ther-Elec}}} \tag{23}$$

In Fig. 18 is represented the result of the monthly/annually *SF* changes vs collector area. The investigation consist in the variation of the PV/T solar collector areas (A) (1.42, 2.84, 4.26, 5.68, 7.1 and 8.52 m^2) and then we estimate the monthly/annual solar fraction, *SF*, changes. During the simulation the initial value of the hot water tank volume-to-collector area ratio (V/A) is set equal to 75 l/m^2, which is the base value for the f-chart method (Klein et al., 1976) [27]. The collector mass flow rate-to-collector area ratio ($\dot{m}/A$) is also initially set equal to 40 kg/h.m^2, which is within the recommended range in the literature [11,13,27]. Results indicate that for 1.42 and 2.84 m^2 collector's area, *SF* ranges in the array of 20–60% and 33–64% respectively. It is also seen that for 4.26 and 5.68 m^2 collector's area, *SF* ranges in the array of 46.8–81.5% and 50–88.7%, respectively. For more significant collector area of PV/T solar collector (7.2 m^2) the *SF* ranges throughout the same period of the year among 60 and 88.7%. It is also obvious that enhancing the PV/T hybrid solar collector area from 7.2 to 8.52 m^2, does not significantly ameliorate the *SF* amount. It is in the range of 3.7–4%. Moreover, considering the cost and the space requirements of a large collector's area (8.52 m^2) that supplies between 64 and 90% of the required hot water, a collector with 7.2 m^2 of area that provides 60–88% of the demand in summer can be considered as the

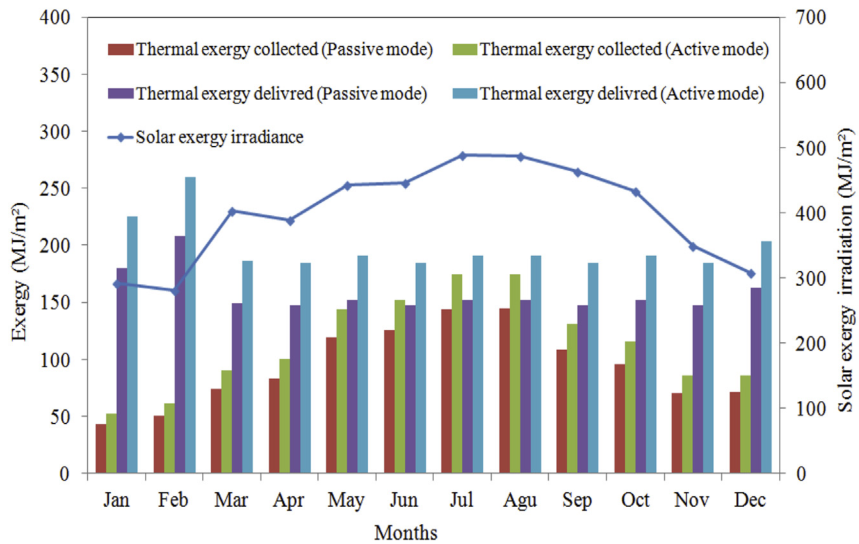

Fig. 15. Simulated monthly and yearly solar exergy irradiance and exergy flow changes of the PV/T solar system in passive in and in active mode.

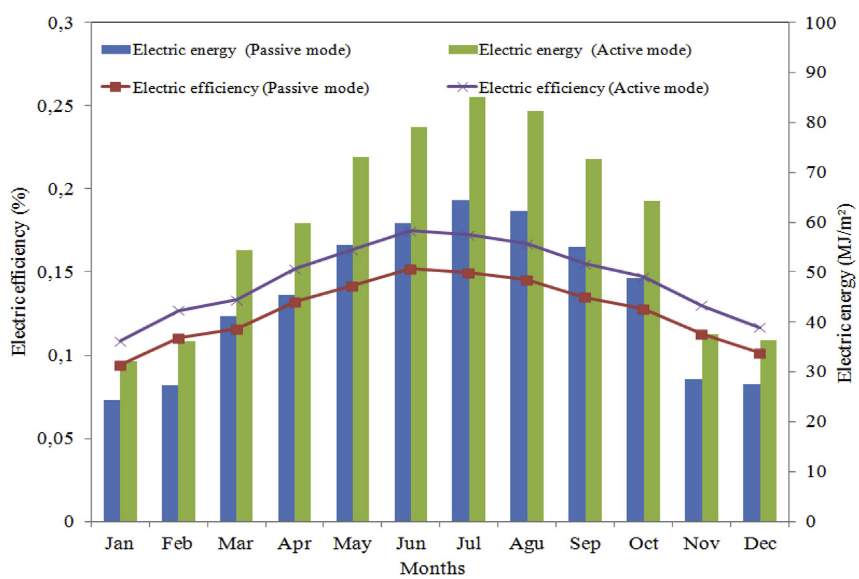

Fig. 16. Monthly distribution of the electric efficiency and electric energy production of the PV/T solar system.

adequate size for the present application. Indeed we noted that 7.2 m^2 of PV/T solar collector area is more benefic than 5.68 m^2 and is nearly equivalent to the use of 8.52 m^2 of PV/T collector area. Thus we conclude that 7.2 m^2 is the optimal PV/T solar collector area.

The effect of the variation of the hot water cylinder volume on *SF* is studied for various tank volume–to–collector area ratios (*V/A*). During the simulation the PV/T solar collector area is fixed to the value of 7.2 m^2 and the flow rate inside the PV/T solar system is set to 100 kg/h.m^2. The results of the *V/A* variation impact on the *SF* changes are presented in Fig. 19. The results of the simulation showed that the annual *SF* increases rapidly as *V/A* increases from 20 to 75 l/m^2. It is seen that in the array of 75 and 120 l/.m^2 the value of *SF* does not change seriously. Besides beyond the value 120 l/m^2 the *SF* decreases. This decrease is attributed to the increase in heat losses from the storage tank, as the tank become greater. It is observed that with the increase of tank volume, the rate of the removed energy from the tank to supply the load increases, and the required auxiliary energy decreases. We noted that the suitable values of *V/A* are around 75–120 l/$m^2$with an annual *SF* about 88%. It is found that the recommended range for *V/A* is in agreement with the other types of solar water heating systems [13]. We concluded that according to the area of 7.2 m^2 the value of 75 l/m^2 represents the optimal value of the hot water cylinder volume-to-collector area ratio (*V/A*) which correspond to a storage capacity of about 540 L.

The results indicate that the optimal water mass flow rate, $\dot{m}$, growth increases the PV/T hybrid solar system useful energy (Q_{th}). The results indicate also that as long as the $\dot{m}$/A ratio is around 16–25 kg/h.m^2, the *SF* increase seriously (Fig. 20). Once the $\dot{m}$/A ratio is equal to 25 kg/h.m^2 which corresponds to a water mass flow rate, $\dot{m}$, equal to 180 kg/h the *SF* reaches its maximal value (about 85%). Accordingly, we presume that correspond to a solar collector area and a hot water storage capacity equal to 7.2 m^2 and 540 L, the value of 180 kg/h represents the optimum water mass flow rate, $\dot{m}$. The optimum values of the ratio $\dot{m}$/A are found to be in good agreement with the previous results for the DSWH systems, e.g. 50 kg/hm^2 [11,13] and 18–48 kg/hm^2 [28].

To evaluate the performance of the optimized system, the simulations were conducted using the optimized parameters (7.2 m^2,

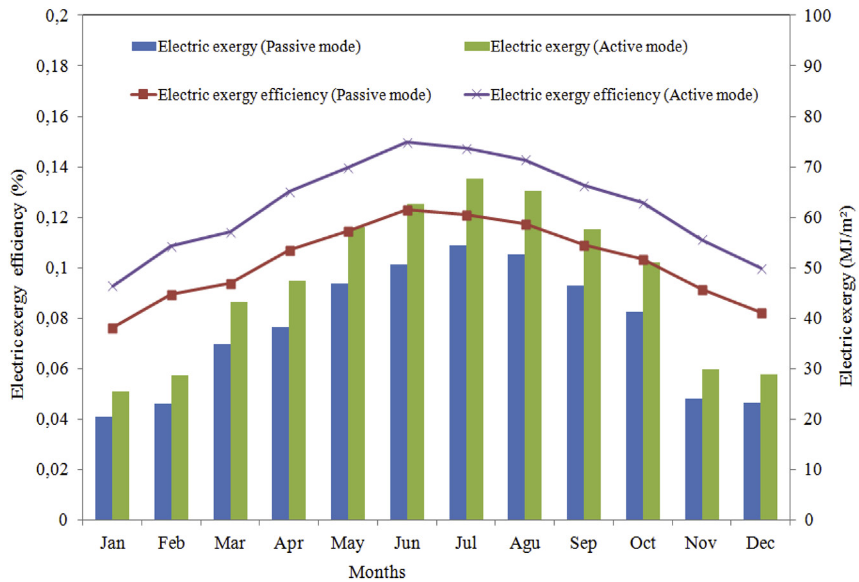

Fig. 17. Monthly distribution of the electric exergy efficiency and electric exergy production of the PV/T solar system.

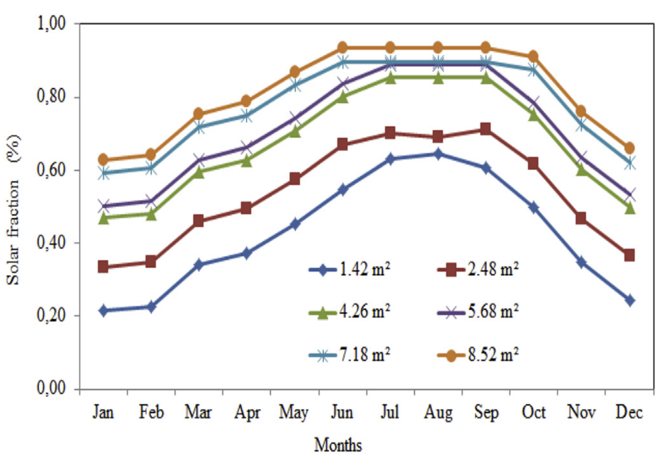

Fig. 18. Variation of monthly *SF* for different collector areas.

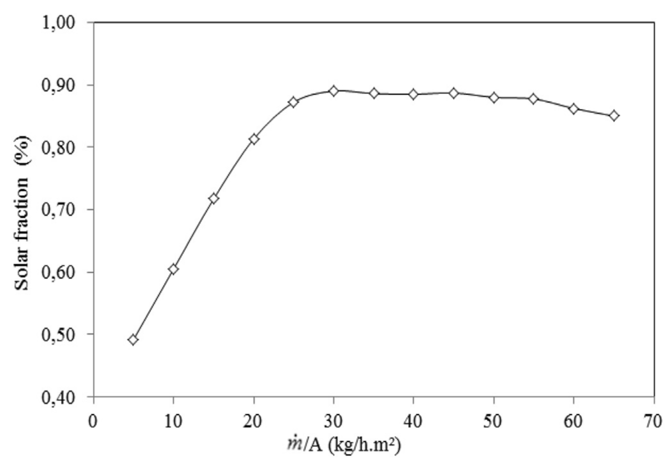

Fig. 20. Variation of the annual *SF*versus the collector flow rate to area ratio (m/A).

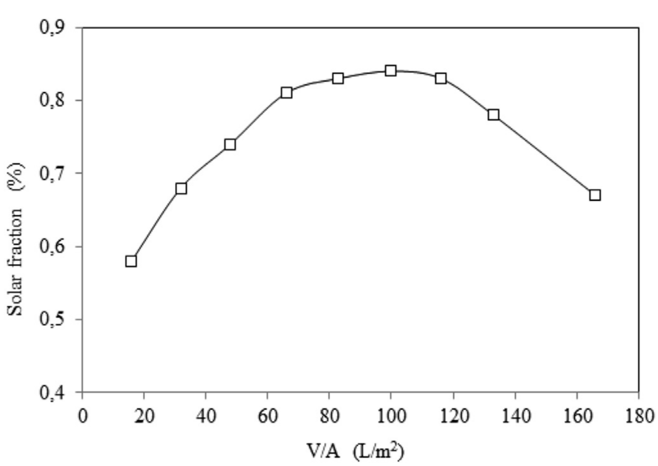

Fig. 19. Variation of the annual *SF* of the value of the hot water tank volume to collector area ratio (V/A).

540 L and 100 kg/h). In Table 6 is mentioned the monthly/annual thermal and electric energy gain acquired by the using of the PV/T hybrid solar system compared to a typical Tunisian family needs predicted by TRNSYS program. The simulation was achieved by considering all optimal PV/T solar system design parameters. It is seen that in summer months the thermal energy needs of the Tunisian family dwindled whilst the electric energy needs growth. This result is explained by the fact that there are no crucial needs to heat water once the weather is hot. However in summer months there is an important request to use frigorific machines to cool the households. A great part of the electric energy is also claimed in the lighting and the machines of current usage. Considering these needs the gain in thermal energy vary in the range of −18 and 57% in January and August or July, respectively. Indeed in summer months the PV/T solar system produces an excess of thermal energy compared to the needs while in cold months it supplies less energy than the requests.

We concluded that throughout the cold period of the year (from November to Mars) the PV/T hybrid solar system cannot satisfy the whole thermal energy needs of the Tunisian family. Conversely the PV/T solar system supplies an excess of electric energy in cold months (especially January) with 24% of gain whilst in hot months the system produce less electric energy that the requests (especially in August) with −16% of gain. Results show that during the

Table 6
Monthly and annual energy flows and thermal and electric gain predicted by TRNSYS program.

Months	Solar irradiation (MJ/month)	Thermal energy needs (MJ/month)	Thermal energy supplied (MJ/month)	Thermal gain (%)	Electric energy needs (MJ/month)	Electric energy supplied (MJ/month)	Electric gain (%)	Energy utilization factor (%)	Exergy efficiency (%)
Jan	336.36	163.14	56.8	−0.18	69.8	8622	0.24	25.51	22.51
Feb	322.64	153	67.8	−0.14	79.9	98.06	0.23	31.40	29.40
Mar	463.40	123.7	75.3	−0.06	119.1	116.81	−0.02	38.45	32.71
Apr	446.66	102.72	87.9	0.06	162.7	145.1	−0.11	42.16	35.16
May	508.34	87.7	99.98	0.28	172.8	156.03	−0.10	45.36	38.36
Jun	513.24	80.72	112.32	0.45	178.9	155.85	−0.13	51.25	39.15
Jul	562.10	76	118.5	0.57	176.1	161.58	−0.12	52.82	39.42
Agu	560.20	77	121.76	0.57	168.76	141.28	−0.16	51.95	38.85
Sep	532.00	80.72	115.76	0.43	119.8	123.94	0.03	45.05	32.81
Oct	497.00	103.7	98.8	0.09	98.9	104.01	0.05	43.80	28.80
Nov	400.73	121	84.21	−0.14	62.1	82.52	0.33	40.60	24.60
Dec	353.70	134	77.23	−0.18	52.8	73.74	0.40	36.68	18.52
Annual total	5496.37	1303.4	1116.36		1461.66	1445.14			
Annual average	458.03	108.6	93.03	14.6	121.80	120.42	5.33	42.08	31.70

summer period of the year (from May to September) the PV/T solar system cannot satisfy the whole electric energy needs of the Tunisian family. Indeed results of the TRNSYS simulation shows that in summer months the energy utilization factor ranges in the array of 45.36–52.82% with an average annual value about 42% (Table 6). On the other hand, the energy utilization factor of the PV/T solar system decreases seriously in cold months (especially January with a value of 25.51%). We found also that the PV/T hybrid solar system's overall exergy efficiency ranges in summer months between 52.36 and 55.42%. The annual overall exergy efficiency of the PV/T solar system is estimated to 31.7%. Compared to previous study (Fujisawa T and Tani T [24], Bosanac M et al. [26] and Saitoh H et al. [28]) the PV/T solar system simulated according to Tunisian climatic conditions presents significant annual average overall exergy efficiency.

We concluded that the PV/T solar system presents an important solution to produce the hot water and the electric needs of Tunisian household's with an annual average of about 14.60 and 5.33%, respectively. However it is necessary to compare PV/T solar system performances and economic costs with commercialized conventional solar collector and PV panels. The thermal performances of the PV/T hybrid solar collector were compared with two high quality commercial domestic water heaters (Evacuated tube collector (ETC) and flat-plate solar collector (FPC) intended to produce 200 L of hot water daily. The electric outputs of the PV/T hybrid solar collector are compared to the electric outputs of a PV panel available in Tunisian market destined to produce electric energy.

7. Comparison between PV/T hybrid solar collector and conventional solar systems

The thermal efficiency, η_{th} (ETC and FPC), electric efficiency, η_{elect} (PV panel), and economic profitability were analyzed and compared for each system on the base of experiments achieved during comparable climatic conditions. The PV/T electric exergy efficiency was compared to other kind of PV/T solar collector that have been published (Table 7). It is seen that the PV/T solar collector exergy efficiency in active mode is affiliated to results obtained in literature.

7.1. Analysis of the thermal efficiency η_{th}

In passive mode the PV/T solar collector carried out during hot months an average daily thermal performance, η_{th}, about 39%, against an average daily thermal efficiencies of about 45.6 and 58.8% for the ETC and FPC, respectively [13,29–31]. We noted also that the PV/T exergy efficiency vary between 12 and 35% whilst the thermal exergy efficiency of the ETC and the FPC varies between 13 and 40% and between 16 and 45%, respectively [13,29,32]. The comparison analysis shows that the PV/T solar collector exergy efficiency is quite good compared to the ETC and FPC solar collectors. We concluded that the PV/T solar collector has a satisfactory performance. Therefore it can partly cover the thermal needs of a typical Tunisian family.

7.2. Analysis of the electric efficiency, η_{elect}

We have also compared the electric efficiency, η_{elect}, of the PV/T solar collector to a PV panel with the same dimensions during comparable climatic conditions. Results showed that due to the water mass flow the PV/T solar collector has an important electric efficiency, η_{elect}, in the array of 11 and 13.8% while the η_{elect} of the PV panel ranges between 10.8 and 12% [33,34]. The PV/T exergy electric efficiency was also compared with PV panel exergy efficiency. Results showed that the PV/T exergy efficiency in active mode between 12 and 35% whilst the thermal exergy electric efficiency of the PV panel ranges between 13 and 40% [33,34]. We presume that the PV/T solar collector presents an important electric efficiency and exergy compared to PV panels.

7.3. Economic analysis

An economic analysis was also achieved in order to evaluate the PV/T solar system cost, energy price and payback period in comparison with the expected lifecycle [35]. The study was performed

Table 7
Comparison of the electric exergy efficiency values for some solar collector systems.

Solar collector type	Exergy efficiency (%)
The coverless PV/T water collector (Fujisawa T and Tani T [24])	11–12.87%
The glazed PV/T water collector (Bosanac M et al. [26])	8–13%
The glazed PV/T water collector (Saitoh H et al. [28])	13.3%

by comparing the cumulative energy invested with the annual energy saved, *AES*, by the PV/T hybrid solar system during its life-cycle. The period of economic analysis was taken as 20 years (average life of locally produced systems) with thermal performance degradation assumed to be 2% per year [13,35]. Electricity at a price of 0.41 $ per 1 kWh and gas at a price of 0.2482 $ per m^3 were assumed to be used for auxiliary energy resource [11,13,36]. The economic approach used in this analysis presume that the PV/T solar system costs is remunerated from the beginning (i.e., no credit payments are assumed). The annual energy saved, *AES*, and the energy payback, *Pb*, of the PV/T solar system was estimated by considering the number of years needed to save as much energy as its energy invested.

The cumulative energy invested, *CEI*, in the PV/T solar system's lifecycle represents the summation of the energy required for the fuel cycle and the energy requirements during the construction, transportation, operation and maintenance and decommissioning, refurbishment and recycling phases.

The majority of the components of the PV/T hybrid solar system (Pumps, storage tank, valves, collector, etc.) were imported from manufacturers in various countries, resulting in additional uncertainty over the *CEI* calculations [36]. Hence due to the numerous uncertainties, the evaluation of the provided energy during the PV/T solar collector life cycle is not simply achieved. The approach in this paper is to give a general estimation of the provided energy by considering bibliography [36,37] (Table 8).

The annual energy saved, *AES*, was calculated considering the efficiency of the auxiliary heating system to which the PV/T hybrid solar system is substituting, and applying a primary energy conversion factor depending of the nature of the fuel used. To determine the cumulative energy invested during the construction, the total energy obtained from electricity consumption must be transformed to primary energy conversion factor (*PEF*). The mean primary conversion factor is equal to 2.7 for the electric domestic use [11,13,38] and 1.1 for fuel use. Eq. (24) shows the formula used for the calculation of energy savings in primary energy units.

$$AES = \frac{Q_L \cdot PEF}{\eta} - \frac{Q_{Pump}}{PEF} \tag{24}$$

The payback duration (*Pb*) indicates the amount of time (in years) that the PV/T solar collector takes to generate an amount of energy equivalent to the energy provided during the lifecycle. *Pb* is defined as the energy provided during the PV/T solar collector lifecycle over the annual energy saved (*AES*) [13,38]:

$$Pb = \frac{CEI}{AES} \tag{25}$$

An economic comparison between PV/T, FPC, ETC and PV panel (300 W and 72 cells) was also performed by considering a typical Tunisian house composed of 4–5 people (Table 3). The investment profitability analysis of the FPC and ETC was presented by the authors in an earlier study [13,35]. The Results of the calculation of the *AES* and *Pb* for each installation are presented in Table 9. It was found that the costs per kWh of the FPC system and ETC system are respectively of about 940 $/kWh and 1100 $/kWh as against the cost of about 1370 $/kWh of the PV/T solar collector. We founded also that the cost per kWh of the PV panel is of about 838 $/kWh [39]. Although, an extra cost of 237.803 $/kWh is required for the PV panel installation and exploitation. The Results of the economic analysis shows that:

- The PV/T solar system's *AES* and *Pb* based on electric water heater were respectively equal to 2518 kWh/year and 10 years. Besides it was found that *AES* and *Pb* based on gas water heater were about 560 m^3 gas/town gas saving and 8 years, respectively.
- For the FPC system the *AES* and *Pb* were about1316 kW h/year and 8 years based on electric water heater and 306 m^3 gas saving and 6 years payback period based on gas water heater, respectively.
- For the ETC system the *AES* and *Pb* were estimated to 1459 kWh/year and 10 years based on electric water heater. Based on gas water heater *the* gas saving and *the payback period* were about 410 m^3 gas/town gas and 7.5 years, respectively.
- Regarding the PV panel of 72 *ce*lls *and* having the equivalent area of the FPC and ETC [11,35], the *AES* and *Pb* were estimated to about 1825 kW h/year and 8 years based on electric water heater as against 387 m^3 gas/town gas and 7 years based on gas water heater.

Another factor that reflects the significance *of* using each solar systems (PV/T, FPC, ETC and PV panel) is the life cycle savings which represents the mon^{e}y that the owner will save by installing whichever solar system instead of buying electricity/gas/town gas to satisfy his hot water needs [40]. The results show that:

- The PV/T and the PV panel life cycle savings, based electricity backup, were about $ 4508 and $ 3825, respectively. Once considering gas/town gas backup, the life cycle savings of the PV/T and the PV panel were about $ 2420 and $ 2140.2, respectively.
- Considering the FPC and ETC systems the life cycle savings based electricity backup, were about $ 3969 and $ 4400.3, respectively. On the bases of gas/town gas backup, the life cycle savings of the FPC and the ETC systems were about $ 1517.7 and $ 2035.2, respectively.

The Results of the economic analysis shows that AES and Pb based on the predicted performance of the installations fluctuate considerably depending of the type of installation and substituted conventional water heating system. Besides the relatively lengthy payback period is due to the expensive shipment/transportation cost of the each system.

It is seen (Table 9) that the adoption of the PV/T solar system in Tunisian buildings save about 47.7, 42.7 and 27% of electric energy kept back by FPC, ETC and PV panel, respectively. Based on gaz/gaz town systems, the PV/T solar system permits the saving of about

Table 8
Calculation of the cumulative energy invested (*CEI*) of the PV/T, PV, ETC and FPC in MJ.

Installation	Pump	Storage tank	Collectors	Pipes	Total system components	Total installation[a]
PV/T solar system	120	3200	6850	1240	11,410	13,692
PFC	0	1000	3160	1050	5210	6252
ETC	120	1000	6888	1400	9408	11289.6
PV panel	–	–	7015	–	10,542	12650.4

[a] 20% margin has been added to the total calculated CEI from the inventory analysis to account for transport, maintenance and disposal, as discussed in a sensitivity analysis by Ardente et al. [41].

Table 9
Life cycle savings and payback periods of the PV/T, PV, ETC and FPC according to the electric and gas energy.

		PV/T	FPC	ETC	PV panel
System cost, \$/kWh		1370	940	1100	1075
Installation cost, \$/kWh		30	20	20	30
Upholding cost, \$/kWh		60	40	60	30
Electricity saving, kWh/year		2518	1316	1459	1825
Gaz/gaz town saving, m^3/year		560	306	410	387
Life cycle based on electricity saving, \$		4508	3969	4400.3	3825
Life cycle savings based on gas saving, \$		2420	1517.7	2035.2	2140
Payback period, year	based on electric water heater	10	8	10	8
	based on gas water heater	8	6	7.5	7

45.3, 26.7 and 25.8% of gas/gaz town kept back by FPC, ETC and PV panel, respectively. We note also that the cost payback of the PV/T solar system (10 years) almost the same cost payback of the ETC system and more important than the FPC system and the PV panels (8 years). However the thermal energy gain in the PV/T hybrid solar system makes it economically more attractive compared to the PV panels.

8. Conclusions

This paper presents an experimental and a TRNSYS simulation studies achieved to reveal the potential offered by the integration of PV/T solar collector in Tunisian households. An energetic and exergetic analysis under Tunisian's climate conditions was also presented to appraise the impacts of climate conditions and operating parameters on the PV/T solar system electric and thermal efficiencies. The remarking points could be outlined as below.

- Overall results show that using PV/T hybrid solar collector in active mode (With water mass flow) presents obvious advantages. Indeed in active mode the amount of the supplied thermal energy is estimated to 3.18 kW/m^2 against 2.36 kW/m^2 in passive mode. We found that in active mode the thermal efficiency of the PV/T solar collector is significantly ameliorated compared to the passive mode. Definitely in active mode the instantaneous energy efficiencies scrambled to extent 50%. It was also found that the thermal exergy efficiency become more significant in active mode ranging from 12 to 41%.
- Other than the thermal efficiency, removing waste heat away from the PV/T collectors can enhance the electric efficiency of the PV cells. It is seen that in passive mode the electric energy vary from 9.5 to 12% against 15.5% in active mode.
- The TRNSYS simulation of the annual thermal performances of the PV/T solar collector shows that the active mode improves the amount of the energy collected by 12% points and the thermal efficiency by 5% compared to the passive mode. Accordingly, a growth by 20% in the delivered energy is acquired. Conversely, the amount of the yearly exergy delivered by the PV/T hybrid solar system in active mode is raised by 20% points compared to the passive mode. The TRNSYS simulation of the annual electric performances of the PV/T indicated that the annual electricity produced from the PV/T solar system was 540 MJ/m^2 in passive mode. It is also found that the yearly electrical efficiency and electric exergy in active mode are enhanced by 3 and by 19.35% points compared to the passive mode. Conversely an advance of about 2.5% of the exergetic efficiency is attained in active mode compared to the passive mode.

To achieve maximum performances from the PV/T hybrid solar system another TRNSYS simulation was achieved to optimize all PV/T solar system design parameters. The results of the simulation revel that the appropriate collector area (A), the hot water cylinder volume (V) and the water mass flow rate ($\dot{m}$) were respectively evaluated to 7.2 m^2, 540 L and 100 kg/h. We concluded that the PV/T hybrid solar system presents an important solution to produce the hot water and the electric needs of Tunisian household's with an annual average of about 14.60 and 5.33%, respectively.

A comparison between PV/T solar collector, FPC, ETC and PV panel based energetic and exergetic analysis was also achieved. It is established that in passive mode the exergy electric efficiency ranges from 8.5 to 10.6% against an array of 12.5 and 14.8% obtained in active mode. The PV/T solar collector energetic and exergetic thermal efficiencies are quite good compared to the ETC and FPC solar collectors. We founded also that the electric outputs of the PV/T solar collector are also prevalently enhanced compared to the electric outputs of a PV panel available in Tunisian market.

Moreover a comparison between PV/T hybrid solar collector, FPC, ETC and PV panel based on techno-economic analysis was also carried out. It is found that the cost payback of the PV/T water heating system (10 years) almost the same cost payback of the ETC solar collector. However it is more important than the FPC and the PV panels (8 years). Although the thermal energy gain in the PV/T hybrid solar collector makes it economically more attractive compared to the PV panels. However, if there is a demand for heat only, having a solar thermal system would be more appropriate due to greater thermal performance and better economic feasibility of solar thermal systems. In case of electricity demand only, the PV/T hybrid solar collector is more suitable due to its electric performances. It is also to mention that incentives towards PV/T solar systems significantly affect their economic feasibility. Since PV/T systems do have an aspect strongly related to environmental and social responsibility, policies toward encouragement of implementations and extending use in Tunisian household's applications. We conclude that PV/T hybrid solar system confers a promises solution for Tunisian households compared to other conventional system. However the cost seems to be still higher compared to other system.

This paper has only reached the halfway phase consequently it will be supported by carrying out a number of studies, including a thermo economic study to show the feasibility and the profitability of the integration of the PV/T hybrid solar system in a collective installation used for producing heat and electricity.

Acknowledgments

The authors would like to thank the Laboratoire des Procédés Thermiques (LPT) and the Centre de Recherches et des Technologies de l'Energie (CRTEn), Tunis, Tunisia for financially supporting the project and for supplying useful data.

Nomenclature

A	collector area, m^2
a	first order efficiency coefficient, $W/m^2.K$
b	second order efficiency coefficient, $W/m^2.K^2$
C_p	water specific heat, kJ/kg·K
$\dot{E}_{elect}$	electrical power, W
$\dot{E}_p$	consumed electric power pump, W
$\dot{E}x_{des}$	internal exergy losses (exergy destructions), W
$\dot{E}x_{elec}$	electrical exergy, W
$\dot{E}x_{loss,\ opt}$	exergy losses rate caused by optical losses, W
$\dot{E}x_{loss,\ PV/T}$	exergy losses due to heat transfer from the PV/T surface to the working water, W
$\dot{E}x_{loss,\ Sun-PV/T}$	exergy destruction due to the temperature difference between the sun and PV/T collector, W
$\dot{E}x_{Q,\ sun}$	heat transfer exergy rate, W
$\dot{E}x_{th}$	thermal exergy, W
F	energy utilization factor, %
F'	PV/T solar collector efficiency factor,
F_R	heat removal efficiency factor,
G	total solar irradiance at collector's aperture, W/m^2
h_{ca}	convective & radiative heat transfer coefficient from solar cell to ambient air, W/m^2 K
K_θ	The incidence angle modifier
P_{elect}	electric power, W
$\dot{Q}_{loss}$	heat loss rate from PV/T system to surrounding, W
$\dot{Q}_{th}$	useful heat gain, W
I_m	output current, A
I_{SC}	short circuit current, A
$\dot{I}$	irreversibility rate, W
$\dot{m}$	mass flow rate in the PV/T solar collector, kg/s
K_θ	incidence angle modifier
$\dot{S} = G.A$	solar radiation intensity, W
T_a	ambient temperature, K
T_{av}	arithmetic average of the water inlet and outlet temperatures, K
$T_{a,ref}$	reference ambient temperature, K
T_{cell}	cell temperature, K
T_i	inlet of the PV/T solar collector, K
T_0	water temperature at the outlet, K
$T_{s,\ w}$	outlet working water flow, K
T_{sun}	sun's temperature, K
t_F	test end instants during the selected day, s
t_I	test start up during the selected day, s
U_L	heat loss coefficient of the storage tank, $W/m^2.K$
U_m	maximum output voltage, V
U_{OC}	open circuit voltage, V

Greek symbols

α	solar absorptance
β	temperature coefficient
Δp	pressure drop, Pa
τ	solar transmittance
$(\tau\alpha)_{PV}$	transmittance–absorptance product of the photovoltaic PV cells,
η_0	reference electric efficiency
$\eta_{\ elect}$	electric efficiency, %
$\eta_{\ th}$	thermal efficiency, %
η_p	pump efficiency; %
Θ	angles of incidence, °
ρ	water density, kg/m^3
Ψ_{Elec}	electric exergy efficiency of the PV/T solar collector, %
$\Psi_{PV/T}$	exergy efficiency of the PV/T solar system
Ψ_{Th}	thermal exergy efficiency of the PV/T solar collector, %

References

[1] Dubey S, Tay AAO. Testing of two different types of photovoltaic-thermal (PVT) modules with heat flow pattern under tropical climatic conditions. Energy Sustain Dev 2013;17:1–12.
[2] Kalogirou S. Use of TRNSYS for modeling and simulation of a hybrid PV thermal solar system for Cyprus. Renew Energy 2001;23:247–60.
[3] Patrick D, Christope M, Harry W, Mathias R. Improvement of PV module optical properties for PV-thermal hybrid collector application. Sol Energy Mater Sol Cells 2011;95:2028–36.
[4] Haurant P, Menezo C, Gaillard L, Dupeyrat P. Dynamic numerical model of a high efficiency PV–T collector integrated into a domestic hot water system. Sol Energy 2015;111:68–81.
[5] Tomas M. Performance and economic analysis of hybrid PVT collectors in solar DHW system. Energy Proced 2014;48:150–6.
[6] Sujala B, Gopi KK, Seung-Hee E, Jae-Heun O, Dae HK. Comparative study of photovoltaic and thermal solar systems with different storage capacities: performance evaluation and economic analysis. Energy 2013;61:272–82.
[7] Mohd NAB, Mahmod O, Mahadzir HD, Manaf Norain A, Hasila J. Design concept and mathematical model of a bi-fluid photovoltaic/thermal (PV/T) solar collector. Renew Energy 2014;67:153–64.
[8] Pei G, Fu H, Zhu H, Ji J. Performance study and parametric analysis of a novel heat pipe PV/T system. Energy 2012;37:384–95.
[9] Shiv K, Tiwari GN, Gaur MK. Development of empirical relation to evaluate the heat transfer coefficients and fractional energy in basin type hybrid (PV/T) active solar still. Desalination 2010;250:214–21.
[10] Sobhnamayan F, Sarhaddi F, Alavi MA, Farahat S, Yazdanpanahi J. Optimization of a solar photovoltaic thermal (PV/T) water collector based on exergy concept. Renew Energy 2014;68:356–65.
[11] Hazami M, Kooli S, Lazâar M, Farhat A, Belghith A. Energetic and exergetic performances of an economical and available integrated solar storage collector based on concrete matrix. Energy Convers Manag 2010;51:1210–8.
[12] Zerrouki A, Boumedien A, Said N, Tedjiza B. Input/output test results and long-term performance prediction of a domestic thermosiphon solar water heater in Algiers, Algeria. Renew Energy 2002;25:153–61.
[13] Hazami M, Kooli S, Naili N, Farhat A. Long-term performances prediction of an evacuated tube solar water heating system used for single-family households under typical Nord-African climate (Tunisia). Sol Energy 2013;94:283–98.
[14] Buckles WE, Klein SA. Analysis of solar domestic hot water heaters. Sol Energy 1980;25:417–24.
[15] Fischer S, Heidemann W, Muller-Steinhagen H, Perers B, Bergquist P, Hellstrom B. Collector test method under quasi-dynamic conditions according to the European Standard EN 12975-2. Sol Energy 2004;76:117–23.
[16] Anand S, Joshi ID, Bale VR. Performance analysis of photovoltaic systems: a review. Renew Sustain Energy Rev 2009;13:1884–97.
[17] Sarhaddi F, Farahat S, Ajam H, Behzadmehr A. Exergetic performance assessment of a solar photovoltaic thermal (PV/T) air collector. Energy Build 2010;42:2184–99.
[18] Joshi AS, Dincer I, Reddy BV. Energetic and exergetic analyses of a photovoltaic system. Proc Can Soc Mech Eng (CSME) Forum 2008;179:5–8.
[19] Hepbasli A. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew Sustain Energy Rev 2008;12:593–661.
[20] Bejan A, Keary DW, Kreith F. Second law analysis and synthesis of solar collector systems. J Sol Energy Eng 1981;103:23–8.
[21] Petela R. Exergy of heat radiation. ASME J Heat Transf 1964;86:187–92.
[22] Sarhaddi F, Farahat S, Ajam H, Behzadmehr A. Exergetic optimization of a solar photovoltaic array. J Thermodyn 2009. http://dx.doi.org/10.1155/2009/313561.
[23] Sarhaddi F, Farahat S, Ajam H, Behzadmehr A. Exergetic performance evaluation of a solar photovoltaic (PV) array. Aust J Basic Appl Sci 2010;3:502–19.
[24] Fujisawa T, Tani T. Annual exergy evaluation on photovoltaic-thermal hybrid collector. Sol Energy Mater Sol Cells 1997;47:135–48.
[25] Gilles N, Fabrice M,Christian C, Jean-Louis C. Performances and numerical optimization of a novel thermal solar collector for residential building. Renew Sustain Energy Rev 2014;33:60–73.
[26] Bosanac M, Sorensen B, Ivan K, Sorensen H, Bruno N, Jamal B. Photovoltaic/Thermal solar collectors and their potential in Denmark. Final Report, EFP Project. 2003. 1713/00–0014.
[27] Klein SA, Beckman WA, Duffie JA. A design procedure for solar heating systems. Sol Energy 1976;18:113–27.
[28] Saitoh H, Hamada Y, Kubota H, Nakamura M, Ochifuji K, Yokoyama S, et al. Field experiments and analyses on a hybrid solar collector. Appl Therm Eng 2003;23:2089–105.
[29] Huang BJ, Lin TH, Hung WC, Sun FS. Performance evaluation of solar photovoltaic/thermal systems. Sol Energy 2001;70:443–8.
[30] Baughn JW, Young MF. The calculated performance of a solar hot water system for a range of collector flow rates. Sol Energy 1984;32:303–5.

[31] Ayompe LM, Duffy A, Mc Keever M, Conlon M, McCormack SJ. Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate. Energy 2011;36:3370–8.
[32] Jahangiri S, Mamouri H, Gholami D, Ghiasi M, Shafii MB, Shiee Z. Experimental investigation of the effect of using thermosyphon heat pipes and vacuum glass on the performance of solar still. Energy 2014;75:501–7.
[33] Park KE, Kang GH, Kim HI, Yu GJ, Kim JT. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module. Energy 2010;35:2681–7.
[34] Joshi AS, Tiwari A, Tiwari GN, Dincer I, Reddy BV. Performance evaluation of a hybrid photovoltaic thermal (PV/T) (glass-to-glass) system. Int J Therm Sci 2009;48:154–64.
[35] Hazami M, Naili N, Attar I, Farhat A. Solar water heating systems feasibility for domestic requests in Tunisia: thermal potential and economic analysis. Energy Convers Manage 2013;76:599–608.
[36] Tripanagnostopoulos Y, Souliotis M, Battisti R, Corrado A. Energy, cost and LCA results of PV and hybrid PV/T solar systems. Prog Photovolt Res Appl 2005;13:234–50.
[37] Bahaidarah H, Subhan A, Gandhidasan P, Rehman S. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. Energy 2013;59:445–53.
[38] Al-Salaymeh A, Al-Rawabdeh I, Emran S. Economical investigation of an integrated boiler–solar energy saving system in Jordan. Energy Convers Manage 2010;51:1621–8.
[39] Christopher G. Le marché photovoltaïque en Tunisie: Situation actuelle et perspectives. Juillet. 2013.
[40] Valero A, Correas L, Zaleta A, Lazzaretto A, Verda V, Reini M, et al. On the thermoeconomic approach to the diagnosis of energy system malfunctions. Part 1: the tadeus problem. Energy 2004;29:1875–87.
[41] Ardente F, Beccali G, Cellura M, Lo Brano V. Life cycle assessment of a solar thermal collector. Renew Energy 2005;30:1031–54.