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SIZING OF AN AUTONOMOUS INDIVIDUAL SOLAR WATER HEATER BASED IN ORAN, ALGERIA

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Abstract

The study concerns an autonomous individual solar water heater installed in the Oran region in Algeria. Supplied by two sources of solar thermal and photovoltaic energy, this solar water heater provides domestic hot water for the needs of an average family of 6 people. A comparative approach was made to find the most adequate solution between increasing the surface area of the thermal solar panel or those of the photovoltaic panels, by analyzing the solar fraction and the efficiency of the thermal panels. The choice was make for a thermal panel with a surface area of 4 m² and complete with 16 photovoltaic panels, thus resulting in a total surface area of 14 m² to obtain an autonomous solar water heater powered only by solar energy. Another option was considered by incorporating a photovoltaic thermal panel, and substantial savings were found.

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Key words

- Solar energy,
- PT,
- PV,
- Solar water heater,
- Autonomous.

1 INTRODUCTION

The transition to renewable energy has been accentuated by the harmful effects of the consumption of fossil fuels; researchers and policymakers are looking for solutions from renewable energy systems. Solar energy is the most promising source due to its availability and abundance around the world; it can be easily converted into electricity and heat. Algeria, due to its geographical location, has significant potential in solar energy, it has a duration of sunshine varying from 2650 to 3500 hours per year and an average of received energy varying from 1700 to 2650 kWh / m² per year (Zidane et al., 2020).

Two distinct applications arise from solar energy, i.e., photovoltaic panels (PV) producing electricity and thermal panels (PT) producing heat. These two modules can be grouped together in the same box to produce electricity and heat in photovoltaic and thermal panels (PV/T) (Sultan and Ezfan, 2018). The energy consumption of buildings consumes one-third of the world's energy consumption (Good et al., 2015); this energy is supplied for the needs of electricity for air conditioning and the production of domestic hot water, which can be provided by thermal or photovoltaic panels or a combination of both.

Baki (2021) compared the performance of a domestic solar water heater with thermal panels in three regions in Algeria. Using the TRNSYS code (Rawat and Kesari, 2018) simulated the performance of a solar water heating system operating with solar energies of the PV, PT, and PV / T types. (Matuska and Sourek, 2017) studied the performance of solar water heaters coupled to resistance and photovoltaic panels and compared them with a solar water heater coupled to a thermal panel. (Chen et al., 2019) evaluated the performance of a solar water heater system and developed a model to simulate the power and heat output. (Huide et al., 2017) developed solar thermal, photovoltaic and hybrid simulation models, and experiments were carried out to validate the simulation. The performances of the three solar systems for residential applications were analyzed. (Khordehgah et al., 2020) simulated a PV / T to produce electricity and hot water for a house and studied the performance of the system. (Lazreg et al., 2020) simulated the performance of a solar water heater powered by a solar thermal panel and investigated the stratification of the temperature at the tank level. (Baki et al., 2021) have analytically studied a solar water heater installation for the domestic hot water needs of a family; the approach used compares the incoming and outgoing energies at the level of the tank. Formulations have been established, and the temperatures and energies were evaluated.

we have studied the performance of a solar water heater by making a dynamic simulation with the TRNSYS software; the parameters have been varied to find a compromise between a solar energy supply with PT thermal collectors and PV photovoltaic modules. The PT thermal collector was then replaced by a PV / T thermal and photovoltaic panel.

2 DESCRIPTION OF THE INSTALLATION

Domestic hot water is used for the needs of an individual dwelling housing an average family of 6 people. The total consumption is on average 40 liters per person per day, which is equivalent to 240 liters per day at a temperature of 60°C.

2.1 Details of the water heater

The water heater is powered by two energy sources, i.e., one thermal and the other photovoltaic. The thermal panel transfers energy to the heat exchanger located inside the tank by the circulation of the heat transfer fluid, while the pump only operates when the temperature at the outlet of the thermal panel is higher than the temperature of the water in the lower part of the balloon. The PV panel produces electricity, and the regulator dispatches it. If the hot water outlet temperature is sufficient, the energy captured is transmitted to the batteries for storage, but if the temperature is lower than the set temperature, the regulator provides electricity to the inverter to power the resistance. The electricity comes to the inverter from the panel during the day and as needed from the battery when the PV panel does not provide enough electricity or during the absence of sunlight. The operation of the installation is detailed in Figure 1.

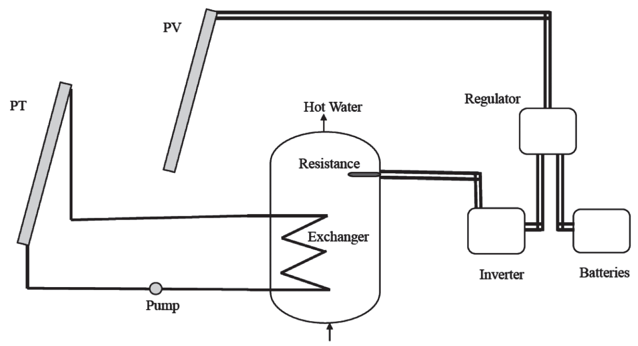

Fig. 1 *Installation diagram*

2.2 Weather data

The city of Oran is located on the southern coast of the Mediterranean Sea. Its climate is classified as Csa (Koppen-Geiger), which is of the warm temperate type with hot and dry summers and rainy and mild winters. The rainfall is low and varies between 330 and 400 mm per year. Figure 2 shows the variations in the average monthly temperature. It is around 12°C in the winter and 26° during the months of July and August. The average annual temperature is 18.1°C. The maximum solar radiation on a horizontal surface during the months of the year are shown in Figure 3; they vary from 560 W/m² in December to over 900 W/m² from April to September.

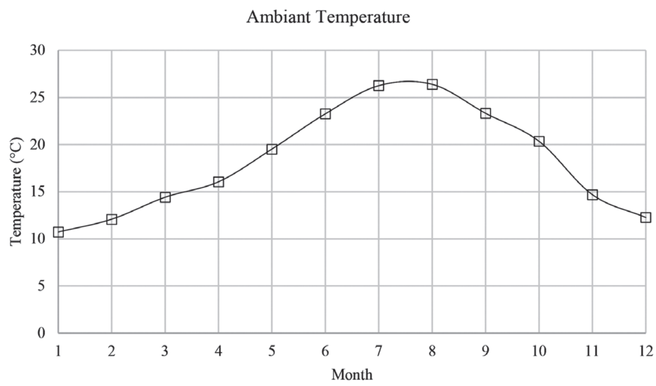

Fig. 2 *Average monthly temperature in Oran*

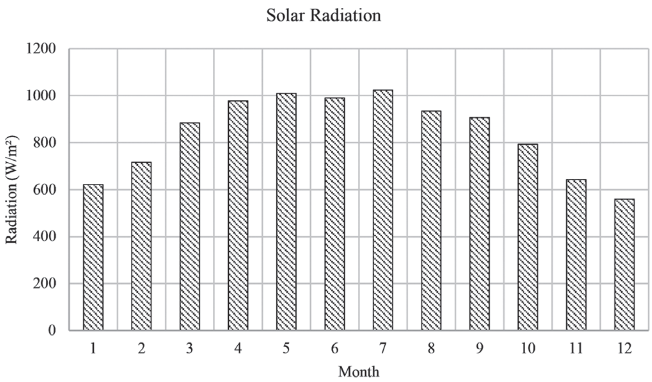

Fig. 3 *Monthly solar radiation in Oran*

2.3 Hot water demand load

Hot water needs are estimated at 240 liters of hot water per day at a temperature of 60°. The tank is supplied by city water at an average annual temperature of 18°; the heating is provided by the exchanger supplied by the thermal panel and the resistance supplied by the photovoltaic panel. The hourly distribution follows the profile in Figure 4. There are two consumption peaks on the order of 10% of the load between 8 and 11 a.m. in the morning and between 8 and 10 p.m. in the evening. The consumption is zero between 2 and 5 a.m. and fluctuates during the rest of the day between 2 and 4%.

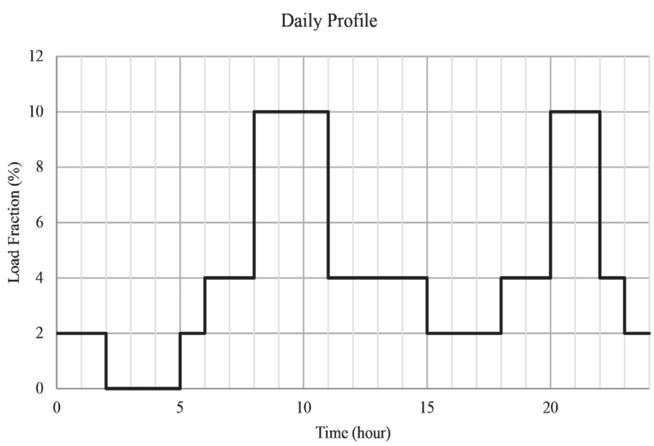

Fig. 4 *Load profile per day*

2.4 PV Module

For the simulation of the photovoltaic panels, a module composed of 36 monocrystalline cells in a series with an area of 0.89 m^2 were used. Their specifications are shown in Table 1. The peak power can reach 100 Wp; the energy supplied is either consumed by the resistance or stored in the batteries. The characteristics of the module indicated in Table 1 are taken from the default parameters of the TRNSYS code; the panel faces south and has an inclination angle of 35°.

Tab. 1 *PV module specification*

Module short-circuit current at reference conditions	6.5	amperes
Module open-circuit voltage at reference conditions	21.6	V
Reference temperature	298	K
Reference insulation	1000	W/m^2
Module voltage at max power point and reference conditions	17	V
Module current at max power point and reference conditions	5.9	amperes
Temperature coefficient of Isc at (ref. cond)	0.02	-
Temperature coefficient of Voc (ref. cond.)	-0.079	-
Number of cells wired in series	36	-
Module temperature at NOCT	313	K
Ambient temperature at NOCT	293	K
Insulation at NOCT	800	W/m^2
Module area	0.89	m^2

2.5 PT Module

The thermal solar flat panels used in the simulation with characteristics taken from the TRNSYS code are presented in Table 2. The thermal panels transfer the heat captured from the solar rays to the hot fluid conveyed to the exchanger; the thermal panel is also oriented towards the south and inclined at 35°.

Tab. 2 *PT module specifications*

Fluid specific heat	4.190	kJ/kg.K
Efficiency mode	1	-
Tested flow rate	40.0	kg/hr.m^2
Intercept efficiency	0.80	-
Efficiency slope	13.0	kJ/hr.m^2.K
Efficiency curvature	0.05	kJ/hr.m^2.K^2
Optical mode 2	2	-
1st-order IAM	0.2	-
2nd-order IAM	0.0	-
Module area	1	m^2

2.6 Hot water storage tank

The characteristics of the storage tank are listed in Table 3; this tank is a buffer stock for water to heat it. It is cylindrical in shape with a shell and two domed ends and contains a volume of 300 liters. The balloon is installed vertically and is equipped with several nozzles for the entry and exit of fluids and the mounting of regulation and control accessories. Inside the tank a helical-shaped copper exchanger with an internal diameter of 10 mm, an external diameter of 12 mm, and a length of 26 meters is mounted.

Tab. 3 *Characteristics of the storage tank*

Tank volume	0.3	m^3
Tank height	1.25	m
Height of flow inlet	1.25	m
Height of flow outlet	0.0	m
Fluid specific heat	4.190	kJ/kg.K
Fluid density	1000.0	kg/ m^3
Tank loss coefficient	3.0	kJ/hr.m^2.K
Fluid thermal conductivity	1.40	kJ/hr.m.K
Height of 1st aux. heater	1.0	m
Height of 1st thermostat	1.25	m
Set point temperature for element 1	60	C
Deadband for heating element 1	5.0	deltaC
Maximum heating rate of element 1	1800	kJ/hr
Number of internal heat exchangers	1	-
Heat exchanger inside diameter	0.01	m
Heat exchanger outside diameter	0.012	m
Total surface area of heat exchanger	1	m^2
Heat exchanger length	26.0	m
Heat exchanger conductivity	1.40	kJ/hr.m.K

2.7 TRNSYS Diagram

The simulation is performed with TRNSYS software. The parameters are taken by default except for those indicated; the calculations are done by a time step of one hour over the entire length of the year. The assembly of the installation is shown schematically in Figure 5. The 60d type tank is connected to the 1b type thermal panel and to the 94a type electrical panel. The water is heated by the heat exchanger located inside the tank. If the temperature does not reach 60°C, the resistance is triggered.

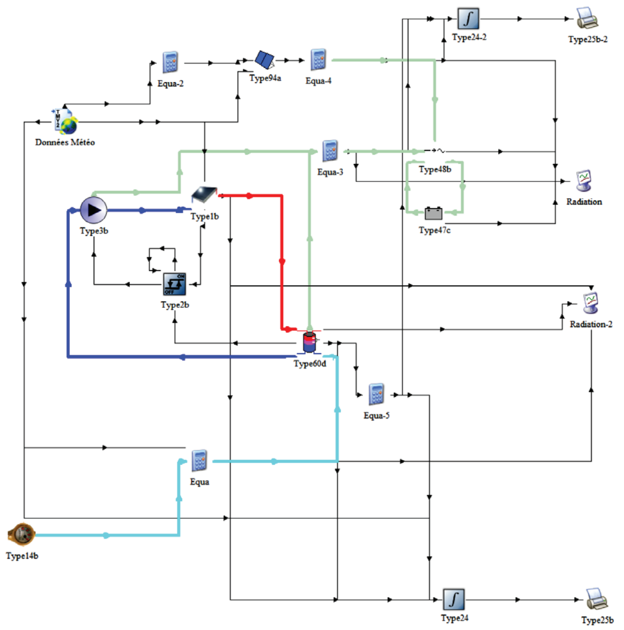

Fig. 5 *TRNSYS diagram*

2.8 Mathematical formulation

In order to compare the variables with each other, the following formulations of the energy and ratios were selected and are presented below.

The energy consumed, Q_c, is the quantity of energy that takes into account the water temperature at the inlet to the tank and which leaves it with the flowing of the hot water consumed; this quantity varies every hour. The total quantity will be the integration over a period of one day or one month.

$$Q_c = \int f \dot{m} c_p (T_{o\_b} - T_{i\_b}) . dt \tag{1}$$

The instantaneous efficiency of a photovoltaic panel is calculated by the relationship:

$$\eta_{el} = \frac{UI}{A_{PV} G} \tag{2}$$

The efficiency of a thermal collector at any time is determined by the following relationship:

$$\eta_t = \eta_0 - a_1 \frac{\Delta T}{G} - a_2 \left(\frac{\Delta T}{G}\right)^2 \tag{3}$$

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Likewise, we can determine the electrical energy collected over a period of a day or a month.

$$E_{el} = \int \eta_{el} A_{PV} G . dt \tag{4}$$

The useful thermal energy supplied by the thermal collector over a given period:

$$Q_u = \int \eta_t \, A_{PT} G . dt \tag{5}$$

represents the energy lost by the walls of the balloon, this value is determined by:

$$Q_p = \int U_t . S_t (T_i - T_L) . dt \tag{6}$$

The necessary auxiliary energy supplied by the electrical resistance to bring the hot water to the temperature of 60 ° C is deduced from the following relation:

$$Q_{aux} = Q_p + Q_c - Q_u \tag{7}$$

We also define the total solar energy irradiated on a given surface by:

$$Q_s = \int A \, G . dt \tag{8}$$

The solar fraction is thus equal to:

$$SF = \frac{Q_c - Q_{aux}}{Q_c} \tag{9}$$

The efficiency of the overall thermal collector is:

$$\eta_{t\_g} = \frac{Q_u}{Q_s} \tag{10}$$

The efficiency of the overall photovoltaic panel is:

$$\eta_{el\_g} = \frac{E_{el}}{Q_s} \tag{11}$$

3 RESULTS AND DISCUSSION

3.1 Energy consumed

Figure 6 shows the monthly energy required for the supply of domestic hot water leaving the tank at 60°C over a period of one year. This energy remains relatively constant with slight variations from one month to another. The differences are due to variations in the temperature during the seasons. In the cold months the demand is high, i.e., around 340 kWh, unlike the hot months, where it decreases to 294 kWh. In February the demand is 310 kWh since there are fewer days than the other cool months. The annual demand is 38.8 GWh.

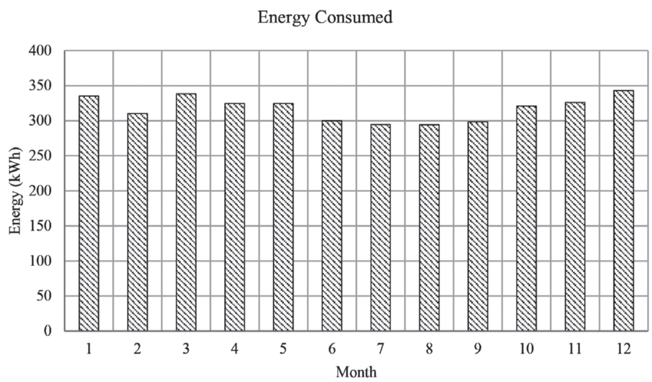

Fig. 6 *Energy consumed*

3.2 Solar thermal panel surface

Figure 7 shows the effect of the surface of the thermal solar panel on the solar fraction. By varying the surface of the solar panel from 1 to 10 m², we can notice an increase in the solar fraction, which starts from 0.11 and goes to 0.91. At the beginning the increase is significant; then it decreases and tends towards a given value. Table 4 shows a strong increase in the solar fraction going from 230 % to 24 %; then it decreases until it reaches 1% for an area going from 9 to 10 m².

Tab. 4 *Progression of the solar fraction*

PT	SF	Progression (%)
1	0.11	-
2	0.35	230
3	0.55	55
4	0.68	24
5	0.77	13
6	0.82	7
7	0.86	4
8	0.88	3
9	0.90	2
10	0.91	1

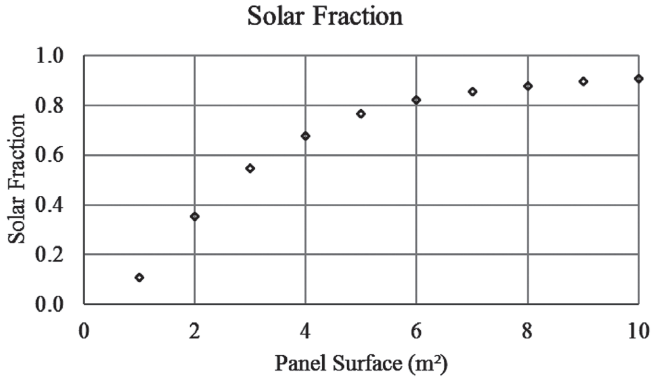

Fig. 7 *Effect of the area on the solar fraction*

3.3 Auxiliary energy requirements

Figure 8 shows the auxiliary energy requirements necessary to make up the difference in energy supplied by the thermal solar panels for a month. January is considered to be the most unfavorable month for solar radiation; with 1 m² of the surface area of the solar panel, the needs are on the order of 350 kWh. The more the surface increases, the solar energy needs to decrease to reach 115 kWh. The auxiliary energy must compensate for the need to bring the water to 60°C to compensate for thermal losses through the walls of the tank and provide the energy necessary for the operation of the solar loop circulation pump.

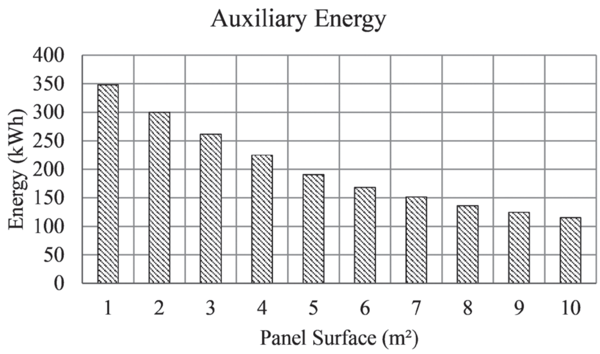

Fig. 8 *Auxiliary energy requirements*

3.4 Photovoltaic panel requirements

Table 5 shows the results of the simulation of the energy needs provided by the photovoltaic panels to meet the needs of the installation; 25 photovoltaic panels with an area of 0.89 m² will be needed to provide the necessary energy of 367 kWh for the month of January with 105% coverage. The more the surface of the thermal solar panels increases, the more the needs for the number of photovoltaic panels sharply decreases, i.e., between 4 m² and 7 m² of the surface of the thermal panels. The surface decreases by 2 photovoltaic panels.

Tab. 5 *Effect of the PT number*

PT	PT	PV	PV			Cover
Number	Efficiency	Number	Efficiency	kWh	kWh	%
1	0.46	25	0.11	367	348	105
2	0.43	20	0.11	293	300	98
3	0.41	18	0.11	264	261	101
4	0.38	16	0.11	235	225	104
5	0.35	14	0.11	205	191	108
6	0.33	12	0.11	176	168	104
7	0.30	10	0.11	147	151	97
8	0.29	9	0.11	132	136	97
9	0.27	9	0.11	132	124	106
10	0.26	8	0.11	117	115	102

3.5 Panel performance

Figure 9 shows the efficiency of the thermal and photovoltaic panels. When the surface of the collector is increased, the efficiency of the thermal panels decreases. It goes from 0.46 for a surface of 1 m² to 0.26 for 10 m²; on the other hand, the yield of the photovoltaic panels remains constant and carries a value of 0.11.

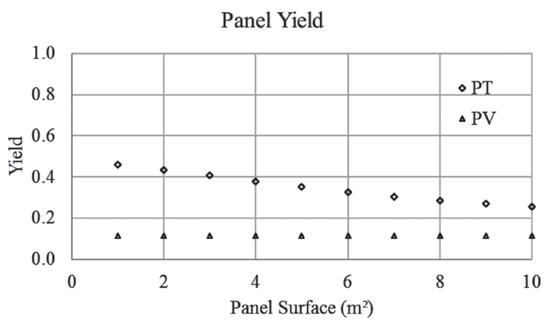

Fig. 9 *PT and PV performances*

3.6 Battery and regulator requirements

In order to allow for continuous operation, the electrical installation was connected to batteries. The connection of the inverter regulator manages the flows for the various components. The number of batteries required for total coverage is shown in Table 11; this number varies from 13 for a thermal collector area of 1 m² to 4 batteries for a thermal collector area of 10 m².

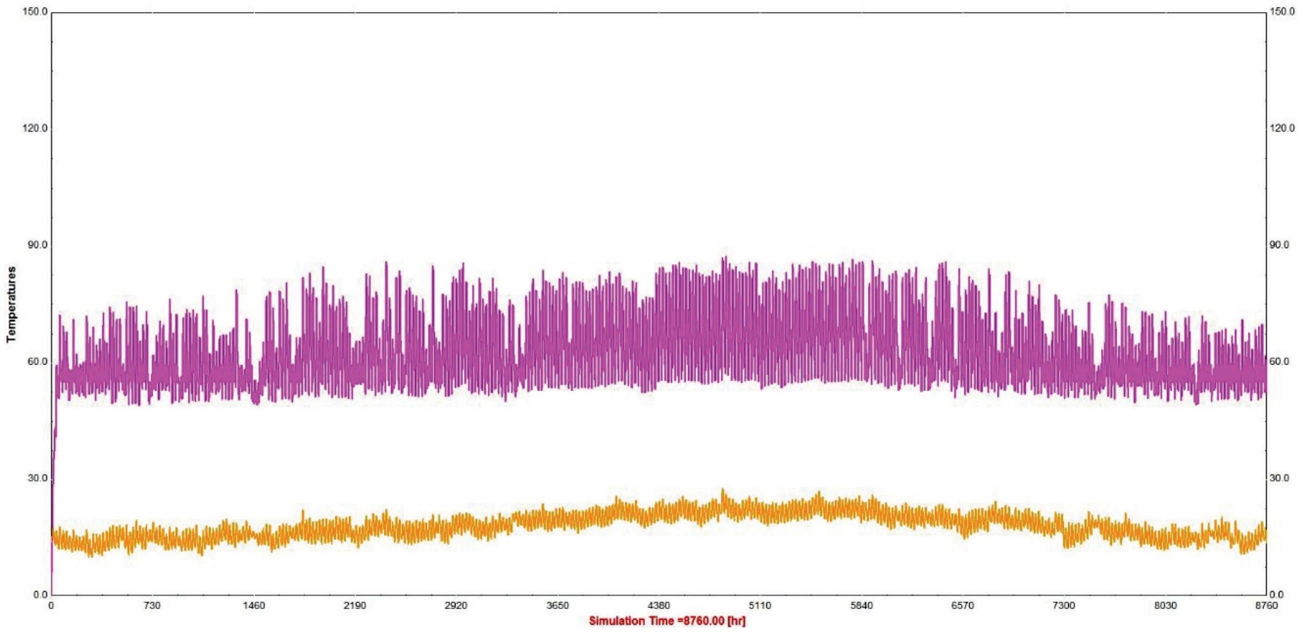

Fig. 10 *Inlet and outlet temperatures of the tank (inlet: yellow, outlet: purple)*

Tab. 6 *Number of batteries*

PT	PV		Battery
Number	Number	kWh	Number
1	25	367	13
2	20	293	10
3	18	264	9
4	16	235	8
5	14	205	7
6	12	176	6
7	10	147	5
8	9	132	5
9	9	132	5
10	8	117	4

3.7 Choice of the most adequate option

The most suitable option is to install a solar water heater equipped with thermal panels with a surface area of 4 m² and 16 photovoltaic panels; this choice is motivated by the fraction reached, which is 0.68, and the fact that the efficiency of the thermal panels is 0.38. It is in fact a compromise between these two criteria since when the surface of the thermal panel is increased, the fraction increases, and the thermal efficiency decreases. This choice of the appropriate option was also determined by the outlet temperature of the hot water tank, which must be under boiling. In the summer the temperature reaches values approaching 90°C, as shown in Figure 10, where we can observe the variations of the inlet and outlet temperatures inside the balloon.

4 STUDY OF THE SELECTED OPTION

4.1 Consumed and auxiliary energies

Figure 11 shows the energy necessary for the supply of hot water at 60°C; it remains relatively constant with slight variations from one month to another. This study was made for a the surface of a collector of 4 m² inclined at 35°. The energy is supplied by the solar panel to the tank, which if necessary, is filled by the electric resistance installed in the tank. In the same Figure we note that the auxiliary energy is at a maximum in January and December and a minimum during the summer period.

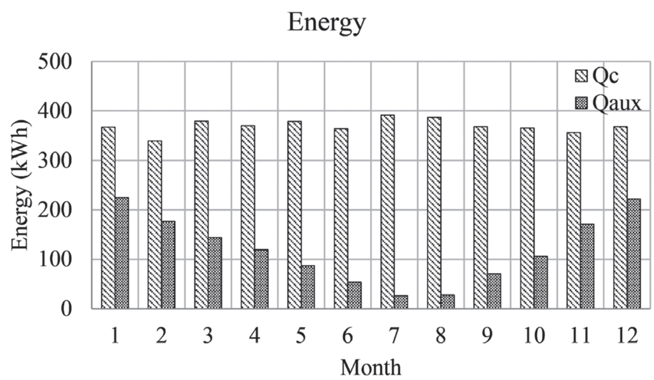

Fig. 11 *Consumed and auxiliary energies*

4.2 Energy supplied by the panels

Figure 12 shows histograms of the energy supplied by the thermal collector and the photovoltaic panels as well as the radiation of solar energy over an area of 1 m². The surface area allocated to the thermal collector is 4 m² and that of the photovoltaic panels is 16 panels of 0.89 m², resulting in a total surface area of 14.24 m². The sum of the captured energies is injected into the tank to heat the domestic hot water and meet consumption needs.

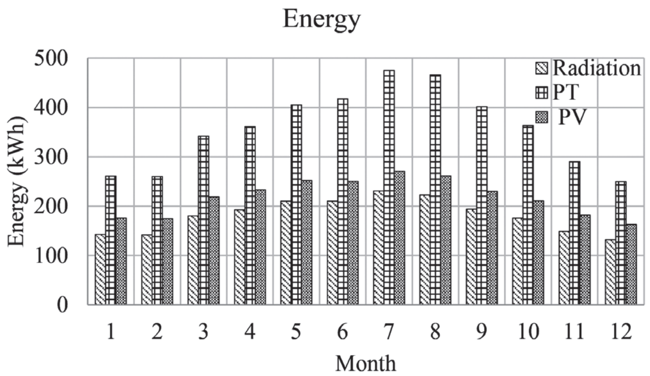

Fig. 12 *Energy supplied*

Over the months the energy captured is irregular and depends strongly on radiation; it is at a maximum in the summer and a minimum in the winter. The sizing of the photovoltaic panels is done on the basis of the least favorable month, which is the month of January. The auxiliary energy needs must be met during this month.

4.3 Efficiency

Figure 13 shows us the monthly variations in the efficiency of the thermal and photovoltaic panels. The efficiency of the thermal panel varies during the year between 0.35 and 0.42 with a maximum in August and minimum values during the rest of the year. For the months of January and December, the yield of the photovoltaic panel is, on the other hand, stable during the year and varies between 0.11 and 0.12. The minimum values are obtained during the summer; the average value of the annual yield is 0.38 for the thermal panel and 0.11 for the photovoltaic panel.

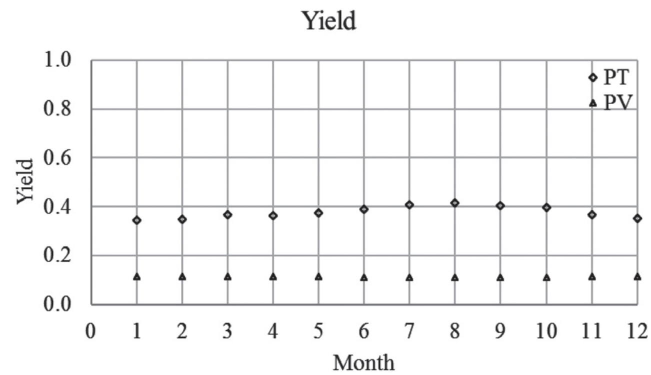

Fig. 13 *Performance of the panel*

4.4 Case study of a PV/T panel

In the diagram of the simulation in 5, the 1b type thermal solar panel is replaced by a 50b type thermal photovoltaic panel with all the connections, the characteristics of which are indicated in Table 7. The panel supplies heat through the solar loop and electricity to the regulator; additional electrical energy is provided by the photovoltaic panels.

The simulation results are presented in Table 8; they show the energy supplied by the PV/T panel and that supplied by the 12 PV panel modules during all the months of the year. The sum of these energies covers the months from January. The need for auxiliary energy or the saving of 4 photovoltaic panels was achieved by installing a PV/T instead of a PT.

Tab. 7 *PV/T characteristics*

Mode	2	-
Collector Area	4	m²
Collector Efficiency Factor	0.96	-
Fluid Thermal Capacitance	4.19	kJ/kg.K
Collector plate absorbance	0.92	-
Number of glass covers	1	-
Collector plate emittance	0.09	-
Loss coefficient for bottom and edge losses	1.1	kJ/hr.m².K
Collector slope	35	degrees
Transmittance absorbance product	0.9	-
Temperature coefficient of PV cell efficiency	0.0032	any
Temperature for cell reference efficiency	25	C
Packing factor	0.8	-
Cell efficiency at reference conditions	0.2	-

Tab. 8 *Simulation results of the installation with PV/T*

Month	(PV)	(PV/T)		Cover
	kWh	KWh	kWh	%
1	176	70	225	110
2	174	70	176	138
3	218	87	144	212
4	233	93	119	273
5	252	101	87	406
6	250	100	54	650
7	270	109	27	1420
8	261	105	28	1314
9	229	92	71	455
10	211	85	106	279
11	182	73	171	149
12	163	65	222	103

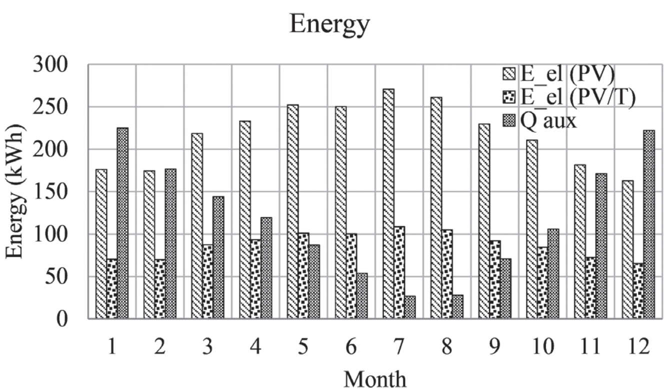

Fig. 14 *Electrical and auxiliary energies of PV/T*

Figure 14 shows the auxiliary energy needs during the months and the electrical energies supplied by the PV and PV/T panels; the auxiliary energy needs are at a maximum in the month of January and can be covered by the sum of the electric energies of the PV panels and PV/T.

5 CONCLUSION

The sizing of an autonomous solar water heater supplying a house housing 6 people under its roof has been studied. The energy coverage is based on the two types of solar energy, i.e., thermal and photovoltaic. A comparative study was made between a thermal panel surface area varying from 1 to 10 m² and the additional surface area of photovoltaic panels, resulting in an adequate option consisting of having a thermal panel surface area of 4 m² and additional auxiliary energy supplied by 16 photovoltaic panels. The heat collector was subsequently replaced by a PV/T panel; positive results have been achieved from the savings energy.

REFERENCES

Baki, T. (2021) *Comparison of the performance of a domestic solar water heater in different climates in Algeria*. Present Environment & Sustainable Development, Vol. 15. N° 1. pp. 143-151. DOI:10.15551/pesd2021151011

Baki, T. – Tebbal, M. – Berrebah, H. (2021) *Following the balloon temperature of a solar heater installed in Oran, Algeria.* Turkish Journal of Electromechanics & Energy, Vol. 6. N°2, pp. 74-80.

Chen, X. – Wang, W. – Luo, D. – Zhu, C. (2019) *Performance evaluation and optimization of a building-integrated photovoltaic/thermal solar water heating system for exterior shading: A case study in South China*. Applied Sciences, Vol. 9. N° 24, pp. 1-13. DOI:10.3390/app9245395

Good, C. – Andresen, I. – Hestnes, A. G. (2015) *Solar energy for net zero energy buildings–A comparison between solar thermal, PV and photovoltaic–thermal (PV/T) systems*. Solar Energy, Vol. 122, pp. 986-996. DOI: 10.1016/j.solener.2015. 10.013.

Huide, F. – Xuxin, Z. – Lei, M. – Tao, Z. – Qixing, W. – Hongyuan, S. (2017) *A comparative study on three types of solar utilization technologies for buildings: Photovoltaic, solar thermal and hybrid photovoltaic/thermal systems*. Energy Conversion and Management, Vol. 140. pp. 1-13. DOI: 10.1016/j.enconman.2017.02. 059

Khordehgah, N. – Żabnieńska-Góra, A. – Jouhara, H. (2020) *Energy performance analysis of a PV/T system coupled with domestic hot water system*. *Chem Engineering*, Vol. *4. N°* 2. Pp. 1-14. DOI: 10.3390/chemengineering 4020022.

Lazreg M. – Baki T. – Nehari D. (2020) *Effect of Parameters on the Stratification of a Solar Water Heater*. In: Belasri A., Beldjilali S. (eds) ICREEC 2019. Springer Proceedings in Energy. Springer, Singapore. DOI: 10.1007/978-981-15-5444-5_15

Matuska, T. – Sourek, B. (2017) *Performance analysis of photovoltaic water heating system*. International Journal of Photoenergy, Vol. 2017. pp. 1-10. DOI:10.1155/2017/7540250

Rawat, P. – Kesari, J. P. (2018) *Analysis of Three Types of Solar Systems: PV, Flat Plate Thermal, and Hybrid PV-T Using TRNSYS Model*. International Journal of Advanced Research in Science, Engineering and Technology, Vol. 5 N° 6. pp. 6257-6265.

Sultan, S.M. – Efzan, (2018) *M.N.E. Review on recent Photovoltaic/Thermal (PV/T) technology advances and applications*. Solar Energy, Vol. 173, pp. 939–954. DOI:10.1016/j.solener.2018.08.032

Zidane, T. E. K. – Adzman, M. R. – Tajuddin, M. F. N. – Zali, S. M. – Durusu, A. – Mekhilef, S. (2020) *Optimal design of photovoltaic power plant using hybrid optimisation: a case of south Algeria*. Energies, Vol. 13, N° 11, pp. 1-28. DOI: 10.3390/en13112776.