Experimental Study of a Heating and Cooling Pilot Installation Driven by a Hybrid PV-Thermal Solar Field

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Abstract

This paper studies the energy performance of a pilot plant of a trigeneration system, that provides heating, cooling and electricity in an office area of an industrial building, using an air-to-water heat pump, driven mainly by the electricity produced by a liquid-based photovoltaic-thermal (PVT) solar field. The heat pump has a nominal capacity of 16 kW in heating, and 10.5 kW in cooling; and the PVT solar field has a total gross area of 13.6 m^2, with a nominal electrical power of 2.56 kWp. The pilot installation was monitored and analyzed for eight weeks during the winter and summer seasons. The results show that under real operation conditions, the PVT solar field has average thermal efficiency between 19.3 and 22.4% during the winter weeks, and between 25.4 and 28.3% during the summer weeks. The electrical efficiency varies between 15.7 and 16.2%, with no relevant difference between the winter and summer weeks. Thanks to the PVT electrical generation and the heat pump performance,e, the system achieves high electrical solar cover factors during both: summer and winter weeks..

Keywords: Hybrid solar photovoltaic-thermal (PVT) collectors, heating and cooling, trigeneration system, energy performance, experimental performance.

Introduction

According to the latest IEA report, 32% of final energy consumed globally is concentrated in the industrial sector, 31% in the transport sector, 22% in households and 14% in other sectors (United Nations - Department of Economic and Social Affairs, 2021). The distribution by use indicates that 51% of total final energy is dedicated to thermal uses (heating and cooling), 32% to transport uses and 17% is dedicated to electricity production (REN21, 2021).

The energy intensity in the building sector has been decreasing slowly during the last two decades, especially in developed countries. However, the energy demand from buildings and building construction is rising in absolute values, due to the population growth, the better electricity access in the developing countries and the increase of space cooling demand in developed countries (IEA, 2021). In this context, the need for reduction of CO2 emissions requires the acceleration change in the energy model, including several technological lines such as the improvement of the building envelope, the use of more efficient systems for space heating and cooling, the increase of the share of renewable production in buildings as well as the implementation of smart controls in these different systems (Delmastro et al., 2021; IEA, 2021).

Solar energy technologies (thermal and photovoltaic) are options easier to implement in buildings. Until now, solar thermal technology is mainly dedicated to domestic hot water production while photovoltaic (PV) technology is focused on producing electricity for several uses in buildings. photovoltaic-thermal (PVT) technology combines in one unit both solar technologies with better overall efficiency, in comparison to separated photovoltaic and solar thermal technologies (Al-Waeli et al., 2019; Zondag, 2008). The progressive decrease of PV laminate prices since the beginning of the XXI century has improved the competitiveness of PV technology as well as the hybrid PVT technology; in fact, by 2019 there were 24 manufacturer companies of PVT technology located in the European countries (Baggenstos et al., 2019).

The use of solar energy for cooling generation is an option of great interest, since the solar resource reaches its highest values during the summer, coinciding with the peak demand for space cooling. Trigeneration systems for the production of heat, cold and electricity, driven by solar energy, usually solar thermal energy, have been analyzed and implemented within the framework of various research and development programs (Henning et al., 2013). The implemented solutions use mainly two options: thermally driven absorption/adsorption machines in combination with solar thermal technology, and electrically driven mechanical compression heat pumps in

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combination with PV technologies. There is also more recent work that combines PVT technology in trigeneration systems (Calise et al., 2016; Herrando et al., 2021, 2019; Lazzarin, 2020; Ramos et al., 2017). In this case, almost all studies are focused on the experimental, simulation, and economically analysis in the early stages; however, there are still few implementations that show performance results in a real environment (Baggenstos et al., 2020).

This paper presents the performance results of a solar trigeneration system, that integrates an air-to-water reversible heat pump with a PVT solar field by using thermal storage tanks, that provide heating at low temperature, domestic hot water and cooling in the office space in an industrial building located in Zaragoza (Spain). The plant was operated from January to September 2021 under different operation modes (winter and summer). Different operating conditions were tested for both operation modes, such as various mass flow rates in the solar circuit, different temperature setpoints for heating and cooling, and different thermal storage volumes.

Several performance indicators were calculated, including the PVT solar field efficiency (electrical and thermal), the weekly and daily heat pump (HP) performance factor, the PVT solar thermal fraction, as well the HP electrical self-sufficient ratio. The paper shows the main results for 4 weeks during winter and 4 weeks during summer. These indicators show that the system achieves very high solar contribution factors (electrical and thermal), and is a feasible technical option to be applied in the net-zero building context and can contribute to the energy transition.

Methodology

2.1. Pilot installation description

The trigeneration pilot installation evaluated in this paper is used in an industrial building, located in Zaragoza (Spain). The building has domestic hot water (DHW) demand throughout the year, and heating and cooling demand during the winter and summer periods respectively. The DHW demand varies depending on the productive activity of the industry. The demand for heating and cooling services are dedicated to an office zone, that has a total area of 53 m^2, an occupation of 4-5 people, who normally work from Monday to Friday and some Saturdays from 8:00 a.m. to 6:00 p.m

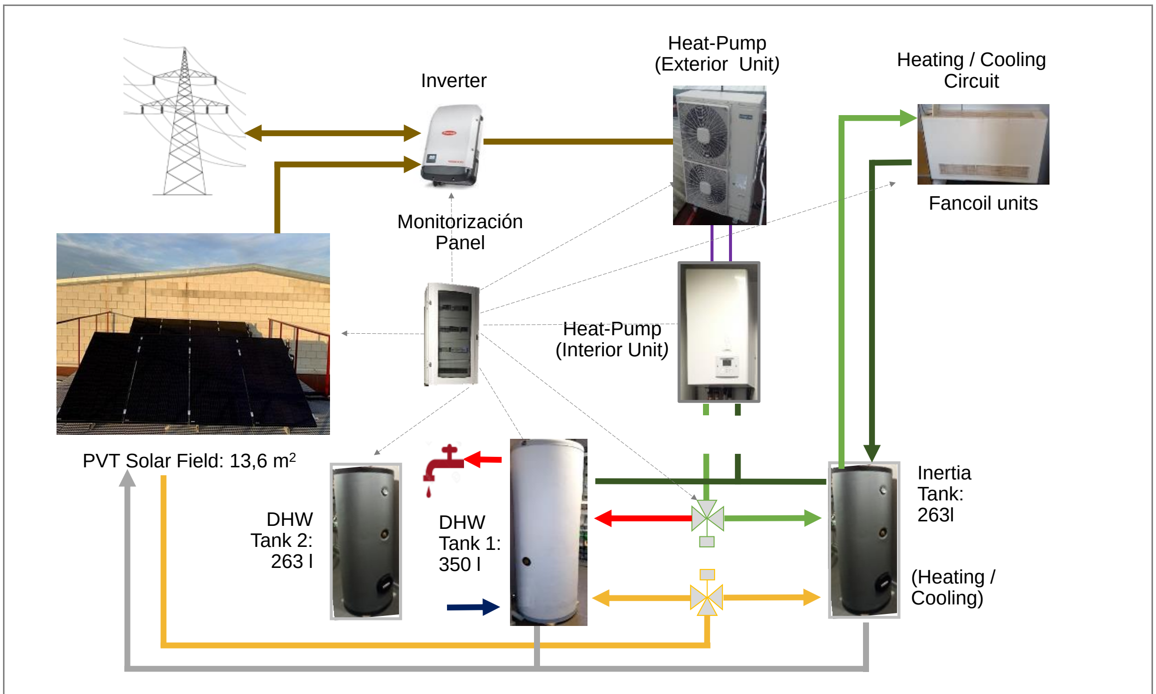


Fig. 1: Basic scheme of the heating and cooling solar pilot plant with the main components

The pilot plant consists of a solar PVT field of 13.6 m^2 with a peak electrical power of 2.56 kW, a high-efficiency air-to-water HP with a capacity of 16.0 kW in heating and 10.5 kW in cooling. In total, there are two water storage tanks of 350 l and 263 l, for domestic hot water (DHW) production and a third inertia tank, of 263 l, is used in the heating/cooling distribution circuit. The heating/cooling distribution circuit uses fan coils as thermal emitters, allowing a minimum supply temperature of 40 °C in winter and 7 °C in summer. To increase the use of low-temperature heat, DHW is supplied at 50 °C, performing periodic sanitary heat treatments at 60 °C to avoid legionellosis. Fig. 1 presents a simplified diagram of the pilot plant, built-in 2020.

The PVT solar field consists of 8 solar hybrid PVT collectors, manufactured by EndeF, arranged in two arrays (Fig 1). The PVT collectors are unglazed, with a nominal electrical power of 320 Wp each, and a sheet-and-tube heat exchanger. The gross and absorption areas of the PVT collector are 1.70 m^2 and 1.35 m^2 respectively. The reversible air-to-water HP, manufactured by Hitachi, the Yutaki S6, has a nominal capacity and coefficient of performance (COP) of 16.0 kW and 4.57 in heating mode, and 10.5 kW and 3.31 in cooling mode. The seasonal COP (SCOP) values indicated by the manufacturer are 3.90 for heating production at 55 °C, and 2.84 for cooling production.

The system is controlled by two units. The first unit is linked to the solar thermal circuit; it consists of an off-on controller that measures the temperature difference between the PVT solar field outlet and the bottom zone of the tanks; when the temperature difference is above 5°C, the solar circulation pump is activated; when this difference is below 2°C the solar pump is turned-off. The Charging process of both tanks (DHW and Inertia) is carried out alternately, giving priority to the DHW tank. During summertime, the charging process in the inertia tank is deactivated, since there is no demand for heating.

The second unit control is linked to the heat-pump. It consists of a PDI temperature controller that measures the temperatures at the top zone of the tanks. This controller maintains the setpoint temperature in each tank, and prioritizes the charging process of the DHW tank. During summertime the heat pump alternates two operation modes: heating for DHW tank and cooling for the inertia tank.

To evaluate the thermal performance of the system, 28 temperature sensors and 4 flow meters were installed in the different hydraulic circuits: solar circuit, HP circuit, hot water circuit and heating/cooling distribution circuit (see Table 1). In addition, to evaluate the electrical performance, the HP electricity consumption was measured, and the PVT electrical production was monitored through a DC/AC inverter integrated into the monitoring system. Environmental variables were also measured and monitored, including ambient temperature (T_a), incident global solar radiation (G) and wind speed (u), through which the PVT performance solar field is evaluated.

Tab. 1: Summary of sensors in the monitoring system

Variable	Sensor type	Amount	Specifications
Temperature	1-wire sensor Arduino	28	-55 a 125°C, +/- 0.5°C
Solar Irradiance	Thermopile pyranometer	1	0-2000 $W.m^{-2}$, Class 2
Wind velocity	Hemispherical cup anemometer	1	0-50 $m.s^{-1}$, +/-3%
Electrical power PVT	Sensor integrated from Inverter by Modbus	1	0-10.000 W, +/-0.001%
Electrical powe HP	Sensor integrated from HP by Modbus	1	0-40 A, +/-5%
Flow rate	Sensor volumetric sensor by pulses	4	30-3000 $l.h^{-1}$, +/- 2%
3-way valves position	Voltage sensor in datalogger	2	0 -1

2.2. Data analysis procedure

System operation was analysed by calculating the power and energy production from the different sources (PVT solar field, and the HP, as well as the building energy demand. Based on these calculations, different performance indicators were obtained for both operation modes: winter and summer. The general procedure applied to obtain the power production (thermal and electrical), the demand and the performance indicators are described in the following paragraphs.

- ***Solar irradiance and solar irradiation***

Incident global solar irradiance (G), expressed in W.m-2, is measured directly from the monitoring system every 5 minutes. The incident solar irradiation (H) corresponding to the total incident solar energy H expressed in kWh.m-2, calculated for the analyzed period.

- ***Thermal and electrical production***

The thermal and electrical productions of the PVT subsystem were calculated. Thermal production calculation considered both arrays of the PVT collectors that integrate the overall solar PVT field. The corresponding instantaneous thermal power ($q_{PVT,i}$), for the array of PVT collectors i, was obtained through equation 1, where i indicates the number of the PVT array, C_{PVT} is the specific heat capacity of the heat transfer fluid (HTF), used in the solar thermal circuit, $\dot{m}_{PVT,i}$ is the mass flow rate, and $T_{in,i}$ and T_{out}Tout,i represent the inlet and the outlet temperatures for the corresponding PVT array.

$$q_{PVT,i} = C_{PVT}.\dot{m}_{PVT,i}.(T_{PVT,in,i} - T_{PVT,out,i}) \quad \text{(eq. 1)}$$

Because the PVT arrays are connected hydraulically in parallel, the total thermal power produced by the PVT solar field (q_{PVT}), is obtained by adding the individual thermal productions of the different PVT arrays, according to equation 2.

$$q_{PVT} = q_{PVT,1} + q_{PVT,2} \quad \text{(eq. 2)}$$

The instantaneous electrical power produced by the PVT solar field ($P_{PVT,DC}$), in Direct Current (DC), was obtained by applying equation 3, where $V_{PVT,DC}$ and $I_{PVT,DC}$ represent the DC voltage and current produced by the overall PVT solar field. In this case, the electrical power ($P_{PVT,DC}$) can be also read directly from the Inverter integrated into the monitoring system.

$$P_{PVT,DC} = V_{PVT,DC} * I_{PVT,DC} \quad \text{(eq. 3)}$$

Regarding the heat pump (HP), the instantaneous produced thermal power (q_{HP}) was calculated according to equation 4, where C_{HP} is the specific heat capacity of the heat transfer fluid used in the HP circuit, $\dot{m}_{HP}$ is the mass flow rate, and $T_{HP,in}$ and $T_{HP,out}$ are the inlet and the outlet temperatures of the HP.

$$q_{HP} = C_{HP}.\dot{m}_{HP}.(T_{HP,in} - T_{HP,out}) \quad \text{(eq. 4)}$$

In general, qHP is positive when the operation mode of HP is heating and is negative in cooling mode. The values assigned for heating or cooling were also validated according to the operation mode of HP, which is read directly from the HP regulation unit, integrated also into the monitoring system.

The thermal production from the PVT system can be sent either to the DHW tank or to the inertia tank. To do this, the installation used the 3-way-valve 1 (3WV-1), whose position (open/closed) is monitored every minute. Similarly, the HP thermal production can be sent either to the DHW tank or to the inertia tank, by using another 3-way-valve (3WV-2), also monitored every minute.

- ***Thermal and electrical demand***

The power demand calculation includes the thermal demand for domestic hot water (DHW), heating and cooling in the building, as well as the electrical consumption for the HP.

Similarly, as before, the thermal and electrical demands were obtained from the mass flow rate and temperatures measured in the two energy demand circuits. The thermal for DHW (q_{DHW}) was obtained through equation 5, where C_W correspond to the cold-water specific heat capacity, $\dot{m}_{DHW}$ is the mass flow rate in this circuit, and T_W and T_{DHW} indicates the inlet cold water and the outlet hot water temperatures, respectively,

$$q_{DHW} = C_W.\dot{m}_{DHW}.(T_W - T_{DHW}) \quad \text{(eq. 5)}$$

Likewise, for the heating/cooling distribution circuit (with fan coils (FC) emitters), the instantaneous thermal demand was calculated using equation 6, where C_{FC} is the specific heat capacity of the HTF used in this circuit, $\dot{m}_{FC}$ is the corresponding mass flow rate, and $T_{FC,sup}$ and $T_{FC,ret}$ are the supply and return temperatures in the circuit, respectively,

$$q_{FC} = C_{FC}.\dot{m}_{FC}.(T_{FC,sup} - T_{FC,ret}) \quad \text{(eq. 6)}$$

Because one of the purposes of this trigeneration system is to cover the electrical consumption of the HP, the electrical demand of this equipment was calculated for the heating and cooling operation modes, according to equation 7, where $V_{LL}$is the Voltage line-line in the AC electrical grid, and I_{HP} is the three-phase AC electrical current demanded by the HP. These variables were read directly from the HP regulation unit, integrated into the monitoring system.

$$P_{HP} = \sqrt{3} * V_{LL} * I_{HP} \quad \text{(eq. 7)}$$

- ***Performance indicators***

To evaluate the energy performance of the PVT solar field, two main indicators were considered: the PVT thermal efficiency ($\eta_{PVT,th}$) and the PVT electrical efficiency ($\eta_{PVT,el}$). The PVT thermal efficiency was calculated according to equation 8, where q_{PVT} is the thermal production of PVT solar field, calculated with equation 2, G is the total incident global solar irradiance, expressed in W.m^{-2}, and A_{PVT} is the gross area of the PVT solar field.

$$\eta_{PVT,th} = {q_{PVT}}/{G.A_{PVT}} \quad \text{(eq. 8)}$$

Similarly, the electrical efficiency ($\eta_{PVT,el}$) of the PVT solar field was calculated according to equation 9, in which the P_{PVT-DC}, corresponds to DC power production, and G is the total incident global solar irradiance. Daily and monthly efficiency values were also calculated taking into account the overall incident solar irradiation and thermal/electrical production throughout the day and week.

$$\eta_{PVT,el} = {P_{PVT-DC}}/{G.A_{PVT}} \quad \text{(eq. 9)}$$

Inverter efficiency, η_{INV} is calculated as the ratio between the PVT electrical production in direct current P_{PVT-AC}, and the PVT electrical efficiency in alternating current P_{PVT-DC}., according to equation 10.

$$\eta_{INV} = {P_{PVT-AC}}/{P_{PVT-DC}} \quad \text{(eq. 10)}$$

The HP coefficient of operation (COP_{HP}) was calculated as instant values, every 5 minutes, according to equation 11.a, where q_{HP} and P_{HP} correspond to the instantaneous thermal power production and electrical power consumption of the HP. In addition, the HP performance factor (PF_{HP}) was also calculated for the daily and weekly thermal energy production Q_{HP} and electrical consumption E_{HP}, according to equation 11.b,

$$COP_{HP} = {q_{HP}}/{P_{HP}} \quad \text{(eq. 11.a)}$$

$$PF_{HP} = {Q_{HP}}/{E_{HP}} \quad \text{(eq. 11.b)}$$

The solar thermal fraction of the PVT subsystem ($SF_{PVT,th}$), is calculated according to the equation 12.a, where, Q_{PVT} corresponds to the thermal production of the PVT solar field, and Q_{HP} is the thermal production of the HP. Finally, the electrical ratio PVT production - HP consumption (ER_{PC}) is calculated, as the ratio between the AC electricity production of the PVT solar field ($E_{PVT,AC}$) and the HP electricity consumption (E_{HP}), as equation 12.b indicates.

$$SF_{PVT,th} = {Q_{PVT}}/{(Q_{PVT} + Q_{HP})} \quad \text{(eq. 12.a)}$$

$$ER_{PC} = {E_{PVT,AC}}/{E_{HP}} \quad \text{(eq. 12.b)}$$

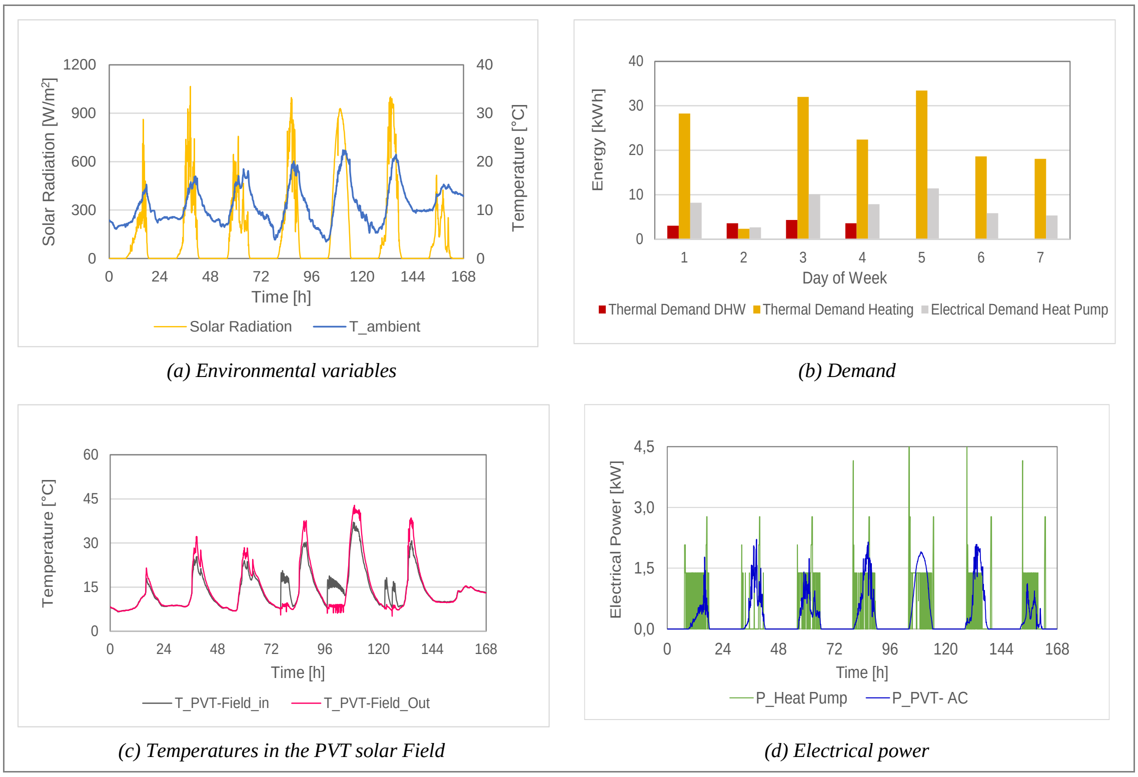
Main results and discussion

3.1. Winter operation mode

Under the winter operation mode, the HP is configured to provided domestic hot water (DHW) and heating (at low temperature), and the PVT system can provide DHW, heating and electricity, whose main purpose is to cover the HP electricity consumption.

The HP was set at 50°C for DHW preparation, instead of the typical value of 60°C, to enhance the solar thermal contribution of the PVT solar field. As it is well known, the heating circuit, that uses fan-coils as thermal emitters, usually operates in a close loop with an internal ΔT close to 5°C. In this case, the tests were performed with two values of supply/return temperature, at 45/40 °C and 40/35 °C.

The monitoring system allows to measure and follow the evolution of the temperatures and flow rates of the different circuits. Fig. 2 illustrates some data monitored during one winter week (Feb 15 to Feb 21), in which the average global incident radiation was 3.77 kWh.m-2.day^{-1}, and the ambient temperature ranged from 5 to 20°C (Fig.2.a). The thermal energy demand reached weekly values of 14.5 kWh for DHW and 155.1 kWh for heating, which implies that the heating demand represented 91% of overall thermal demand (Fig.2.b). During this week, the output temperature of the PVT solar field rarely reached values above 40°C (Fig.2.c), which limits the solar thermal contribution to the heating circuit. PVT electrical production, however, allowed to cover almost all the HP electricity consumption (Fig.2.d)



(a) Environmental variables *(b) Demand*

(c) Temperatures in the PVT solar Field *(d) Electrical power*

Fig. 2: Monitoring temperatures and relevant variables in the pilot plant from Feb 15 to Feb 21 in 2021

Table 2 summarizes the main results for the different weeks tested under winter operation mode, between February and March of 2021. The PVT thermal efficiency, calculated on a weekly basis has an average value of 19.2 %; and the average PVT electrical efficiency was 15.9%. The DC/AC inverter efficiency had an average weekly value of 92.1%.

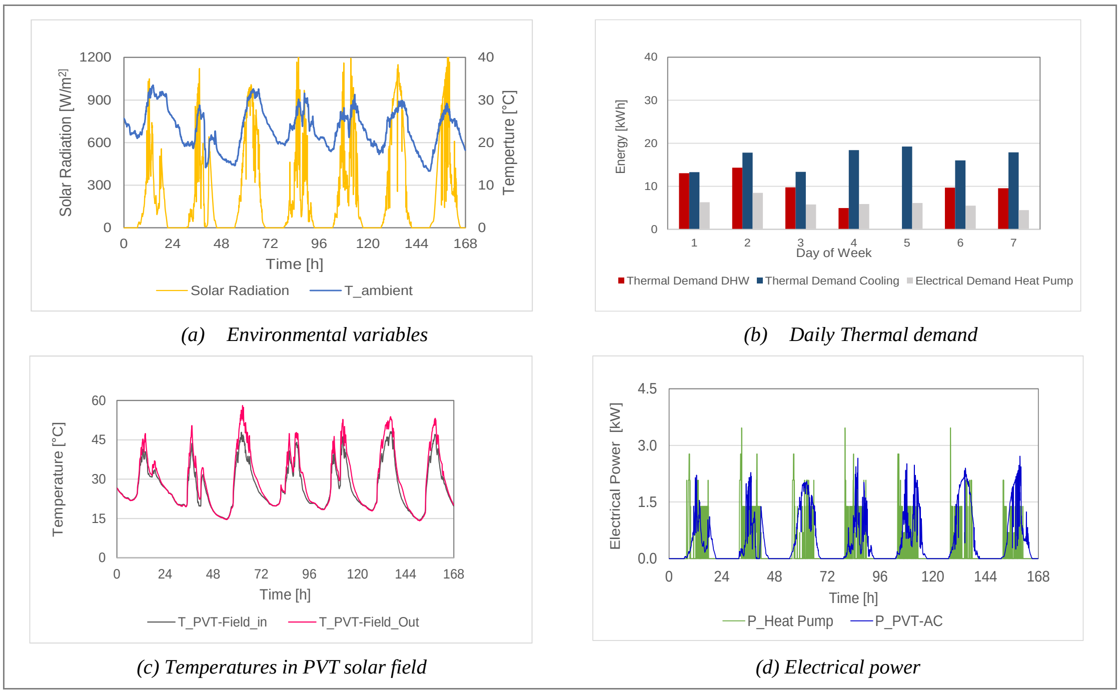
As underlined before, the solar thermal fraction ($SF_{PVT,th}$) is relatively low under this operation mode, with average weekly values between 0.07 and 0.11; however, the electrical ratio PVT production - HP consumption (ER_{PC}) reached very high values, between 0.95 and 1.16, which implies a high global solar contribution factor of the PVT system to the thermal demand. The HP performance factor (PF_{HP}), ranged between 3.6 and 4.0, during the evaluated weeks, with an average value of 3.8, very close to the nominal SCOP for heating stated by the HP manufacturer (3.9). As expected, the PF had better values during the week with less severe environmental conditions (Feb 22-28).

Tab. 2: Main performance results during winter operation mode: DHW+heating+electricity

Week:	**Units**	**I** Feb 8-14	**II** Feb 15-21	**III** Mar 1-7	**IV** Feb 22-28
Based operation conditions					
HP: Setpoint DHW temperature	[°C]	50	50	50	50
HP: Setpoint supply /return temperature	[°C]	40 /35	40 / 35	45/ 40	45/ 40
Solar system: setpoint temperature DHW tank	[°C]	50	50	50	50
Solar system: setpoint temperature inertia tank	[°C]	40	40	40	40
Mass flow rate in the PVT solar field	[l.h^{-1}m^{-2}]	50	30	50	30
Global incident solar irradiation (*H*)					
H per day per unit of area	[kWh.m^{-2}]	3.77	3.50	3.01	4.18
H per week	[kWh]	359	333	286	398
H per week during the operation period	[kWh]	208	142	132	200
Main performance indicators					
Thermal efficiency PVT ($\eta_{PVT,th}$)	[%]	19.5.0%	18.1%	21.2%	18.1%
Electrical efficiency PVT ($\eta_{PVT,el}$)	[%]	15.8%	15.9%	16.2%	15.7%
Inverter efficiency (η_{INV})	[%]	92.5%	92.1%	91.1%	92.9%
HP Performance factor for heating (PF_{HP-H})	[-]	3.7	3.6	3.8	4.0
Solar thermal fraction PVT ($SF_{PVT, th,}$)	[-]	0.11	0.08	0.08	0.07
Electrical ratio PVT production- HP consumption (ER_{PC})	[-]	1.16	0.95	0.97	0.97

3.2. Summer operation mode

Under the summer operation mode, the HP was configured to provide DHW and cooling, while the PVT system produced electricity and hot water to contribute to the DHW production. The system performed under this operation mode from June to August of 2021 and the main results for four selected weeks are presented in this section.



(a) *Environmental variables*

(b) *Daily Thermal demand*

(c) Temperatures in PVT solar field

(d) Electrical power

Fig. 3: Monitoring temperatures and relevant variables in the pilot plant from June 16 to June 22 in 2021

Weekly tests were performed with and without a backup for DHW production, and under two setpoint temperatures for cooling production (15 °C and 7 °C); in this case, the corresponding supply/return temperatures in the distribution circuit were 7/12 °C and 15/20 °C respectively.

Following the same procedure applied for winter operation mode, several performance indicators were calculated to evaluate the pilot plant under summer operation mode. Table 3 presents the main results and indicators for the four selected weeks between June and July of 2021.

As expected, during summer the solar incident radiation is higher than during the winter period, with an average daily value between 5.53 and 7.52 $kWh.m^{-2}.day^{-1}$. The PVT thermal efficiency ($\eta_{PVT,th}$) had an average weekly value of 25.0%, which is higher than the average value obtained under winter operation mode (19.2%), mainly due to the higher solar irradiance and the less severe ambient conditions. Furthermore, this efficiency ($\eta_{PVT,th}$) has slightly better values when the pilot plant operates without a backup for DHW production, with average values with and without the backup of 24.3% and 25.7% respectively. The solar thermal PVT fraction ($SF_{PVT,th}$) had an average value of 0.65 when the HP was ON, and it increases up to 0.97 when the HP was OFF.

Tab. 3: Main performance results during summer operation mode: DHW+cooling+ electricity

Week:	**Units**	**I**	**II**	**III**	**IV**
		Jun 09-15	Jun 16-22	Jul 8-14	Jul 15-21
Based operation conditions					
HP: Setpoint DHW temperature	[°C]	OFF	50	50	OFF
HP: Setpoint supply /return temperature	[°C]	15/20	15/20	7/12	7/12
Solar system: setpoint temperature DHW tank	[°C]	60	60	60	60
Solar system: setpoint temperature inertia tank	[°C]	-	-	-	-
Mass flow rate in the PVT solar field	[$l.h^{-1}m^{-2}$]	30	30	30	30
Global incident solar irradiation (*H*)					
H per day per unit of area	[$kWh.m^{-2}$]	7.00	5.53	7.07	7.52
H per week	[kWh]	666	527	673	716
H per week during the operation period	[kWh]	498	354	487	615
Main performance indicators					
Thermal efficiency PVT ($\eta_{PVT,th}$)	[%]	26.4	25.0	23.6	25.0
Electrical efficiency PVT ($\eta_{PVT,el}$)	[%]	15.7	16.2	16.0	15.7
Inverter efficiency (η_{INV})	[%]	95.1	95.0	95.2	95.4
HP performance factor for heating ($PF_{HP\text{-}H}$)	[-]	-	3.8	3.8	-
HP performance factor for cooling ($PF_{HP\text{-}C}$)	[-]	-	3.7	2.7	-
Thermal solar fraction PVT ($SF_{PVT,TH}$)	[-]	0.97	0.6	0.7	0.99
Electrical ratio PVT production- HP consumption (ER_{PC})	[-]	2.8	1.9	3.2	1.5

The PVT electrical efficiency ($\eta_{PVT,el}$) reaches an average weekly value of 15.9%, without a relevant decrease compared to the winter operation mode, despite the higher ambient temperature registered under the summer operation mode. This positive behaviour is linked to the cooling effect on the PV laminate that normally occurs in the PVT solar collectors. Furthermore, the DC-AC inverter efficiency reaches an average value of 95.2% that is higher than the value obtained during the winter operation mode (92.2%), due to the larger solar incident radiation and the electrical production during summer operation mode.

Concerning the HP performance, the performance factor obtained for heating ($PF_{HP\text{-}H}$) and cooling ($PF_{HP\text{-}C}$) are 3.8 and 2.7 respectively, which are close to the seasonal performance values indicated by the manufacturer (3.90 for DHW and 2.84 for cooling production). The electrical ratio PVT production - HP consumption (ER_{PC}) of the HP varies between 1.9 and 3.2, when the backup is activated, which means that the PVT electrical production can cover the HP electricity consumption. Better values are obtained when the cooling demand is lower.

Conclusions

This paper studies experimentally the energy performance of a pilot plant of a trigeneration system, that provides heating, cooling and electricity in an industrial building located in Zaragoza (Spain), using a reversible air-to-water heat pump (HP), and a liquid-based PVT solar field. The HP has a nominal capacity of 10.5 kW in heating, and 16.0 kW in cooling; and the PVT solar field, has a gross area of 13.6 m^2, with a nominal electrical power of 2.56 kWp. The pilot plant was operated under two operation modes (winter and summer), and several performance indicators were calculated and analyzed for several weeks. This work shows the results of four representative weeks under winter operation mode, and four weeks under summer operation mode.

The PVT thermal efficiency has average weekly values of 19.2% and 25.0% under the winter and summer operation modes respectively. When the DHW backup is activated, there is a slight decrease in the PVT thermal efficiency, and also an important increase in the solar thermal fraction during the summer operation mode. The PVT electrical efficiency has an average weekly value of 15.9% under both operation modes (winter and summer); thanks to the cooling effect on the PV laminate, this efficiency does not decrease during the summer period, despite the larger solar irradiance and ambient temperatures.

The HP performance factor achieves averages values of 3.8 and 2.7 in heating and cooling respectively; which are in agreement with the seasonal COP for heating and cooling indicated by the manufacturer of the reversible HP used in the pilot plant. The electrical ratio PVT production - HP consumption (ER_{PC}) reaches high values under two operation modes, with average weekly values of 1.0 and 2.6 under the winter and summer periods, respectively, when the backup for DHW is activated.

During the winter period, the solar thermal fraction has an average value of 0.09, which is relatively low due to main reasons: the high fraction of the heating demand (above 90%), and the minimum required temperature for heating (40°C) which is rarely reached by the PVT solar field during the wintertime. However, thanks to the high HP electrical self-sufficient ratio, it was possible to cover the thermal demand with the HP driven mainly by the PVT electrical production both in the summer and winter seasons.

On the other hand, during the summer period, the solar thermal fraction reaches values between 0.60 and 0.70, when the backup is activated. In this case, the Electrical Ratio PVT production -HP consumption is above 1.0, which also suggests that overall, the thermal demand for heating and cooling can be fully covered by the pilot plant, using the (thermal and electrical) energy produced by the PVT solar field and the reversible HP.

The overall system performance shows that this kind of trigeneration system, in which an unglazed PVT solar field is used, reaches very high solar contribution factors (electrical and thermal), and is a feasible technical option to be applied in buildings to accelerate the energy transition.

Further work in the project involves detailed daily analyses of pilot plant performance to optimize the system operation, including, among other works, the validation of a simulation model of the pilot plant, the comparison with a reference system based on a heat pump powered by a PV system and a detailed analysis of the electricity production and demand curves to determine the directly self-consumed electricity.

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Appendix: Unix and Symbols

Nomenclature

A	*Area*	m^2
G	*Solar irradiance*	$W\ m^{-2}$
G'	*Net solar irradiance*	$W\ m^{-2}$
H	*Solar irradiation*	$kWh\ m^{-2}$
m	*System mass*	kg
$\dot{m}$	*Mass flow rate*	$kg\ s^{-1}$
Q	*Thermal energy*	kWh
q	*Thermal power*	kW
E	*Electrical energy*	kWh
P	*Electrical power*	kW
T	*Temperature*	°C
u	*Wind speed*	$m.s^{-1}$
V	*Voltage*	V
I	Current	A
C	Specific heat capacity	$J\ kg^{-1}\ K^{-1}$
k	Thermal conductivity	W/K.m
ρ	Density	$kg.m^{-3}$
η	*Efficiency*	-

Subscripts

a	*ambient*
FC	*Fan coil*
H	*Heating*
HP	*Heat Pump*
i	*Number of PVT array*
in	*Inlet*
INV	*Inverter*
LL	*Line-Line*
out	*Outlet*
PVT	*Photovoltaic-Thermal*
ret	*Return*
sup	*Supply*
th	*thermal*
W	*Water, cold water*
PC	*Produccion-Consumption*

Acronyms

COP	*Coefficient Of Performance*
DHW	*Domestic Hot Water*
ER	*Electrical Ratio*
HTF	*Heat Transfer Fluid*
PF	*Performance Factor*

AC	Alternating Current	PV	*Photovoltaic*
av, m	*Average*	PVT	*Photovoltaic-Thermal*
C	*Cooling*	SCOP	*Seasonal COP*
DC	*Direct Current*	SF	*Solar fraction*
el	*electrical*	3WV	*3 Way Valve*