Energy Performance of a Solar Trigeneration System Based on a Novel Hybrid PVT Panel for Residential Applications

María Herrando[1], Alba Ramos[1], Ignacio Zabalza[2] and Christos N. Markides[1]

[1] Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London (United Kingdom)

[2] School of Engineering and Architecture, University of Zaragoza, Zaragoza (Spain)

Abstract

The overall aim of this work is to assess the performance of high-efficiency solar trigeneration systems based on a novel hybrid photovoltaic-thermal (PVT) collector for the provision of domestic hot water (DHW), space heating (SH), cooling and electricity to residential single-family households. To this end, a TRNSYS model is developed featuring a novel hybrid PVT panel based on a new absorber-exchanger configuration coupled via a thermal store to two alternative small-scale solar heating and cooling configurations, one based on an electrically-driven vapour-compression heat pump (PVT+HP) and one on a thermally-driven absorption refrigeration unit (PVT+AR). The energy demands of a single-family house located in three different climates, namely Seville (Spain), Rome (Italy) and Paris (France), are estimated using EnergyPlus. Hourly transient simulations of the complete systems considering real weather data and reasonable areas for collector installation (< 30 m^2) are conducted over a year. The household energy demands covered by the two systems indicate that the PVT+HP configuration is the most promising for the locations of Rome and Paris, covering more than 74% the DHW demand, 100% of the space heating and cooling demands, as well as an important share of the electricity demand. Meanwhile, for Seville, the PVT+AR configuration appears as a promising alternative, covering more than 80% of the DHW, around 70% of the cooling and electricity, and 54% of the space heating demands.

Keywords: solar energy, hybrid PVT, heat pump, absorption cooling, residential energy, energy modelling

1. Introduction

The EU low-carbon economy roadmap (European Commission, 2011) concludes that it is possible to reduce the emissions in the build environment by around 90%, and that this would be a significant contribution towards achieving the 80% total emissions reductions relative to 1990 levels by 2050 without disrupting energy supplies. Meeting this commitment requires an increased generation of renewable energy in the built environment by clean and affordable technologies. Solar energy has the potential to play a leading role in delivering such a high-efficiency sustainable energy future, and is quickly approaching grid parity in high-irradiation regions. In addition, it is capable of satisfying both the electrical and thermal needs of buildings, by means of photovoltaic (PV) and solar thermal (ST) technologies, respectively. Especially where there are space constraints, hybrid photovoltaic-thermal (PVT) panels appear as highly suitable solutions, as these units combine the advantages of PV and ST systems while generating both electricity and a useful thermal output simultaneously from the same aperture area, and with a higher overall efficiency than separate stand-alone systems (Guarracino et al., 2016). Nevertheless, the wider use of PVT technology currently remains limited (Herrando et al., 2014), and it is of interest to consider and to improve aspects of this technology that would enable its further deployment.

Interestingly, PVT-water systems can have higher efficiencies by up to ~15% compared to PV while generating hot water suitable for domestic use (DHW) or for space heating (SH), and it is believed that this technology has an important potential in the residential sector (Affolter et al., 2005) that accounts for 25% of the total electricity and 30% of the total final energy consumption in the EU (Antonanzas et al., 2015), and where the heat demand accounts for 60-90% of the energy demand in buildings in cold climates, and 30-40% in warmer climates (Kempener et al., 2015). However, despite its potential, there are still very few companies worldwide commercialising this technology (Herrando and Markides, 2016), with most of the products available on the market not having optimised designs for PVT applications. In an attempt to overcome this barrier, previous work

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focused on the design and characterisation of novel absorber-exchanger configurations for flat-plate PVT collectors based on a flat-box structure (Herrando et al., 2016, 2017), which demonstrated promising results, specifically a ~4% higher optical efficiency and a ~16% lower heat-loss coefficient than an equivalent commercial sheet-and-tube PVT panel, also with a lower weight (close to 10%) and capital cost (about 20%). This novel PVT panel configuration is the one selected in the present work for further research.

One of the limitations of the integration of hybrid PVT systems in buildings for power and heating provision, especially in the residential sector, arises from the annual heat demand variations of these buildings, which in temperate climates such as in Mediterranean countries splits into an 75-80% demand for space heating and a remaining 20-25% for DHW, with the minimum demand being in summertime when the irradiation levels are high. To avoid oversizing/generation, an installation is typically sized to cover about 50% of the DHW load, such that the generated solar-thermal energy can only cover 10% of the total heating load of the building (del Amo, 2015). To avoid this limitation and use the surplus heat provided by the PVT panels for other building energy needs, the present work proposes integrating PVT panels with thermal storage and heat pumps (HPs) or absorption refrigeration (ARs) units, thereby allowing the generation of heating (SH and DHW), cooling and electricity from a single, affordable solar-energy system (IEA, 2012).

Solar cooling, in particular in domestic applications, is considered attractive because high solar irradiance levels are typically in phase with high building cooling demands, which have been and are projected to continue growing on a worldwide basis (Montagnino, 2017). Previous research has highlighted the fact that the relationship between the solar resource availability and the cooling demand is of key importance in obtaining accurate estimations of the potential of solar-cooling technologies (Mokhtar et al., 2010). At the same time, other recent studies have indicated that suitable solar-cooling technologies are currently associated with noteworthy challenges, including their limited performance and high cost (Bataineh and Taamneh, 2016). Ongoing research on a range of solar-cooling technologies has focussed on overcome these challenges.

Most studies found in literature propose the integration of heating/cooling technologies with concentrated PVT (Mittelman et al., 2007), or PVT-air systems (Eicker and Dalibard, 2011; Kamel and Fung, 2014). Instead, in the few studies found to date on PVT-water panels integrated thermally with AR units, the hot water generated by flat-plate PVT-water collector designs (which can reach around 80-90 °C), can be utilized as a heat source for the generator of the absorption unit, thus providing cooling to the household. Recent studies have shown that coefficients of performance (COPs) of up to 0.8 can be achieved by solar-driven single-stage LiBr-water absorption chillers (Bellos et al., 2016). Some authors (e.g., Calise et al., 2012; del Amo, 2014; Ramos et al., 2017) considered the integration of PVT-water collectors with AR units, and concluded that this combination has an important potential for energy savings owing to the generated heating, cooling and electricity.

Alternatively, vapour-compression heat pumps (HP) driven by the electrical output of PVT-water collectors can also be integrated with the thermal output of the same collectors, increasing the COP of this configuration in winter “heating mode”, while in summer the electrical output generated by PVT units can be used to run the HP unit to provide cooling. Most of the approaches for the hybridisation of HPs with solar collectors involve a simple combination of ST and PV conventional systems. The ST+HP combination was the first the concept developed as a parallel source for minimising the HP operation or with more complex architectures in order to take advantage of higher source temperatures for enhancing the HP performance. Examples are solar air heaters coupled with air-air HP or ST collectors coupled with water-water HPs. The higher potential of heat source side solutions requires sophisticated, robust and well-tuned control systems to achieve high solar fraction for annual basis figures (Drosou et al., 2014). Further, Xu et al. (2009) developed a photovoltaic-thermal heat pump (PVT-HP) system model, from which they concluded that almost all of the required heating load in winter months in Nanjing and Hong Kong (China) can be covered by using a variable compressor for the HP. Similarly, Kamel and Fung (2014) studied an air-PVT collector integrated in a roof and coupled with air source HP, where the warm air generated in the air-PVT acted as the source for heat production. These authors concluded that an important reduction in electricity costs to run the HP can be achieved when it is connected with PVT systems. The economic performance of a solar photovoltaic/loop-heat-pipe (PV/LHP) and HP system for domestic heating applications has also been studied, e.g., by Zhang et al. (2014), who identified local utility prices and renewable incentives to be critical for the implementation of these systems.

The interest in the PV+HP combination is a more recent development, mainly driven by the cost reduction of PV modules in the last years; boosted also by the power-to-heat trends, the combination of these electricity-based technologies seems promising. A theoretical and experimental study of PV modules coupled with a solar assisted HP (SAHP) showed higher values of the HP COP as well as higher averaged PV efficiencies than separated units (Ji et al., 2008). However, the weakly coupled profiles of PV generation and HP consumption lead to an important distribution grid impact if they are not properly managed (i.e., through electrical storage), and thus in a high penetration scenario the ideal grid storage solution is not feasible (Protopapadaki and Saelens, 2017) due to grid operation and infrastructure oversizing needs.

This research aims to investigate the potential of domestic solar trigeneration systems based on hybrid PVT-water collectors for the provision of DHW, SH, cooling and electricity in residential single-family households.

2. Methodology

The most promising PVT panel identified in previous research (Herrando et al., 2016), based on a polycarbonate flat-box structure design, is connected to a HP or AR unit and a suitable thermal store, within a combined heating-cooling-electricity (trigeneration) system model in TRNSYS (Klein, 2016) (see Fig. 1). Two alternative system configurations are considered: 1) PVT integrated with a water-to-water reversible heat-pump/refrigeration unit fed by the electrical and/or thermal output of the PVT panel to provide heating/cooling; and 2) PVT integrated with a thermal absorption refrigeration unit (single-stage LiBr-water) fed by the thermal output of the PVT panel to satisfy the cooling demand in summer, plus a suitable thermal store. Innovative approaches in the PVT+HP configuration are studied such as the integration of the PVT thermal output with a water-to-water HP unit to increase its COP (see Fig. 1 left), and the optimisation of the tank size.

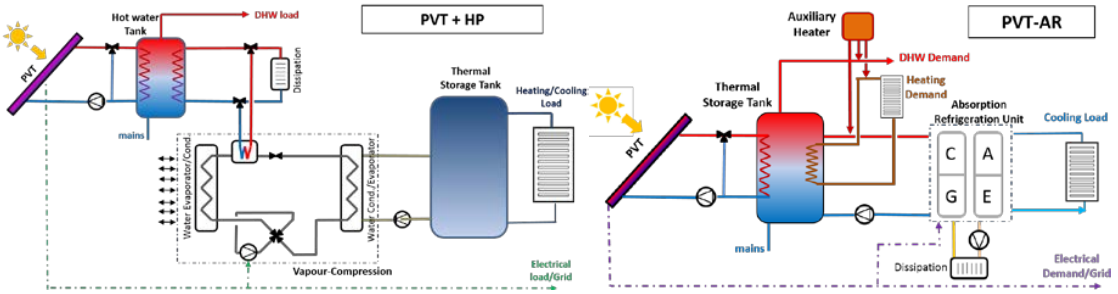

Fig. 1: Schematic diagrams of solar PVT panels integrated with (left) heat pumps, Configuration 1, and (right) absorption refrigeration units, Configuration 2.

2.1. Solar trigeneration system models

The core components of the solar trigeneration systems studied and modelled in this work are: i) the PVT collector, ii) a stratified water storage tank, iii) a closed loop with a water circulator pump that connects the PVT collector with the storage tank through an internal heat exchanger, iv) a HP unit (Configuration 1), v) an auxiliary heater, and vi) an AR unit (Configuration 2). The PVT collector, the stratified water storage tank, the HP and the AR unit models are described in detail below.

PVT collector

The novel PVT collector proposed and investigated in this work is based on a polycarbonate flat-box structure, which improves the heat transfer from the absorber to the fluid by means of 2×3 mm channels (Herrando et al., 2016). This main design features of this PVT collector are presented in Fig. 2.

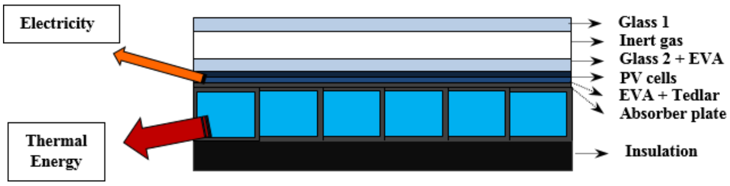

Fig. 2: Schematic diagram of the novel PVT collector proposed in this work, based on a polycarbonate flat-box structure.

In order to model the proposed PVT collector, an existing PVT unit in TRNSYS (Type 560) is modified accordingly and the adjusted PVT model is validated against experimental data (Herrando, 2017). The PVT collector has a nominal electrical power of 240 W_p and an aperture area of 1.55 m^2. The nominal electrical efficiency (η_{el}) of the PVT collector is 14.7%, and the temperature coefficient of the PV cells is 0.45 %/K. The thermal performance (η_{th}) of the collector is described by Eqs. 1 and 2 as follows,

$$\eta_{\mathrm{th}} = 0.726 - 3.325 \cdot T_{\mathrm{r}} - 0.0176 \cdot G \cdot {T_{\mathrm{r}}}^2 \qquad \text{(eq. 1)}$$

$$T_{\mathrm{r}} = \frac{(T_{\mathrm{fm}} - T_{\mathrm{a}})}{G} \qquad \text{(eq. 2)}$$

where G is the total global solar irradiance on the surface at tilted angle (in W/m^2), T_{fm} is the mean fluid temperature and T_a is the ambient temperature.

Stratified water storage tank

A one-dimensional (1-D) model is used for the hot water storage tank (Type 534). The tank is assumed to consist of 6 fully mixed equal-volume segments that divide the cylinder along its vertical axis. The total mass of fluid in the tank is assumed constant, therefore the total mass flow-rate entering the tank through the inlet port must equal the total mass exiting the tank from the outlet port. For the stratification, a temperature gradient is preserved in the tank by ensuring that the hot water for DHW demand is supplied via a port at the top of the tank (at node $n = 1$), while replacement cold water from mains is introduced at the bottom ($n = 6$). The tank also has two immersed heat exchangers (HX): one connected to the PVT collector and another one to provide hot water to satisfy the SH demand (via radiant underfloor heating, UFH) to the household. In this second HX, water flowing in a separate closed loop circuit enters the heat exchanger coil (at node $n = 4$) at the UFH return temperature of 35 °C and is heated to a target supply temperature of 45 °C. This closed loop exits the tank at node $n = 2$. A bypass is included, to avoid sending fluid to the heat exchanger when the tank temperature is lower than 35 °C. In Configuration 1, the outlet of this second HX is connected to the HP to provide the target supply temperature when it is not reached within the tank, while in Configuration 2, a (gas-fired) auxiliary heater (nominal efficiency of 90.1% (BRE, 2014) is used. To satisfy the cooling demand, the reversible HP is used in Configuration 1, whereas in Configuration 2 the AR unit generator is connected to a second port leaving the tank at the top ($n = 1$) and entering at the bottom node ($n = 6$).

The storage tank volume is varied through the variation of the V_t/A_{cT} ratio, where V_t is the tank volume in litres and A_{cT} is the total PVT collector area in square meters. According to the Ministry of Housing of the Spanish Government (Gobierno de España, 2013), for solar thermal installations in households this range should be kept between $50 < V_t/A_{cT} < 180$. In this work, this recommendation has been considered for the 3 different locations under study. The size of the solar immersed heat exchanger coil also varies with the tank size, through the variation of the tank height, such that the ratio between the coil heat transfer area, and the total PVT collector area, is not lower than 0.15 (IDAE and CENSOLAR, 2009) to ensure adequate heat transfer. This HX enters the tank at the top ($n = 1$) and exits it at the bottom ($n = 6$).

Heat pump unit

In Configuration 1 (PVT-HP system), the PVT collector and the water storage tank are coupled with a single-stage water-to-water heat pump (HP) unit (Type 927). The heat pump conditions a liquid stream by rejecting energy to (cooling mode) or absorbing energy from a second liquid stream (heating mode). In heating mode, as detailed above, the inlet of the hot side of the HP is connected to the HX outlet of the water storage tank to raise the water temperature up to 45 ºC when required, while the inlet of the cold side of the HP is fed with water from mains, which is cooled down to absorb the energy required and transfer it to the hot side. In cooling mode, the cold side is cooling water from the mains to serve the cooling demand, while the hot side heats up the water from the bottom part of the tank to compensate the heat rejection on the cooling side; then the warm water is returned to the tank. Performance modelling of this HP unit is based on user-supplied data files containing catalogue-data for the normalised capacity and power draw, based on the entering load and source temperatures and the normalized source and load flow-rates (Klein, 2016).

Absorption refrigeration unit

In Configuration 2 (PVT-AR system), the PVT collector and the water storage tank are coupled with a single-effect absorption refrigeration (AR) unit (Type 107). The refrigeration cycle starts with LiBr-water pumped to the generator to be heated (using hot water from the top of the storage tank), as a result water is desorbed from this solution to vapour form as it is heated. Water vapour then flows to the condenser (cooling tower) where it is condensed and rejects heat to the ambient. Condensed fluid then flows through an expansion device where the pressure is reduced and evaporated for the cooling effect (refrigeration or space cooling). The evaporated water is then absorbed into a strong LiBr solution in the absorber and the cycle is repeated. When the water exiting the top of the storage tank is lower than 65 ºC, an auxiliary (gas-fired) heater heats it up to ensure that it enters the AR unit at a temperature above 60 ºC (minimum temperature to start the cycle). Performance data of a commercial AR unit, Sonnen Klima-10 kW, is considered for the modelling of this unit (Mugnier and Sire, 2009). In addition, the data files are normalised so different AR unit sizes can be modelled.

2.2. Reference family house

To simulate the performance of the solar trigeneration system for domestic applications, a reference house is modelled in EnergyPlus (EnergyPlus, 2017) using real hourly weather data to estimate the energy demand in different months, including the thermal energy for space heating and DHW, the cooling demand, and electricity for lighting and other household appliances. The reference house is a semi-detached household with 2 floors with an area of ~58 m^2 each, a façade U-value of 0.26 W/(m^2·K), a roof U-value of 0.18 W/(m^2·K), and double-glazed windows. Typical occupancy profiles of a 4-inhabitant house (2 adults, 2 children) are considered, following the guidelines provided in the Spanish Building Code (Código Técnico de la Edificación) (Gobierno de España, 2013), which differentiates between working and non-working day, and provides loads and schedules for lighting and home appliances, as well as for occupancy, and the air renovations in the different months. Based on the aforementioned normative, the following temperature set-points are set: 20 °C primary and 17 °C secondary for space heating (January to May and October to December) and 25 °C primary and 27 °C secondary for air conditioning (June to September). As shown in Table 1, even though the same set-points and occupancy profiles are considered, due to the different weather conditions of the locations under analysis, considerably different space heating and cooling demands are estimated. The electricity demand (lighting and other household appliances) is relative similar between these three locations, and the small differences found are due to the lower lighting necessities while moving towards southern latitudes.

Tab. 1: Annual energy demand breakdown of the reference single-family house in the three different locations under analysis.

Location	DHW		Space Heating		Cooling		Electricity	
	kWh/year	kWh/m^2-year	kWh/year	kWh/m^2-year	kWh/year	kWh/m^2-year	kWh/year	kWh/m^2-year
Seville	942	8.19	668	5.81	2762	24.02	2603	22.63
Rome	942	8.19	2527	21.97	1327	11.54	2669	23.21
Paris	942	8.19	5373	46.72	529	4.60	2659	23.12

2.3. Methodology approach

The objective of the work presented in this paper is to analyse the performance of a solar trigeneration system based on the novel hybrid PVT panel described above. Two different configurations (PVT-HP and PVT-AR) are studied in three different climates: Seville (Spain), Rome (Italy) and Paris (France). For each of the former locations and for each different configuration, the sizing of the systems is undertaken as follows: i) the number of PVT collectors is selected after a parametric analysis to cover as much energy demand as possible (including DHW, SH, cooling and electricity), while minimising the excess of thermal energy and using reasonable areas (up to 29 m^2 area is considered available for the PVT collectors, which is half of the floor area of the reference house); ii) the tank size is selected as a trade-off to minimise the thermal energy excess while maintaining appropriate temperatures through the different nodes to satisfy the demand; iii) the PVT collector flow-rate selected for each location is that resulting in the highest percentage of the domestic energy demand covered from a previous parametric analysis, and in this analysis is kept constant over the year following previous conclusions (Herrando, 2017); iv) for the PVT-HP configuration, the size (nominal power) of the HP unit corresponds to maximum peak power required over the year (for both heating and cooling modes); this varies for each studied location; and v) and for the PVT-AR system the size of the AR unit corresponds to the peak cooling power required instantaneously, which also varies depending on the location.

The model for the PVT+AR configuration built in TRNSYS environment is presented in Fig. 3, with the element types indicated. The diagram presented in this figure has been simplified for clarity purposes. The main elements are the PVT panel, the water tank (thermal storage), the pumping system, the controller, the auxiliary heater and the AR unit. As it can be observed, DHW, SH, cooling and electricity demands are inputs to the model, as well as the weather data. The main outputs are the electricity and thermal energy generated by the PVT panels, and the percentages of the household energy demands covered. The equivalent model built for the PVT+HP configuration is not presented here due to space constraints. Briefly, the PVT+HP model is built removing the AR unit, and its corresponding connections from the TRNSYS model presented in Fig. 3, and connecting the outlets of the two tee piece units in Fig. 3 with a new element, the HP unit (Type 927), which also needs a second controller unit (Type 2b) and second water tank (Type 4b), as indicated in Fig. 1.

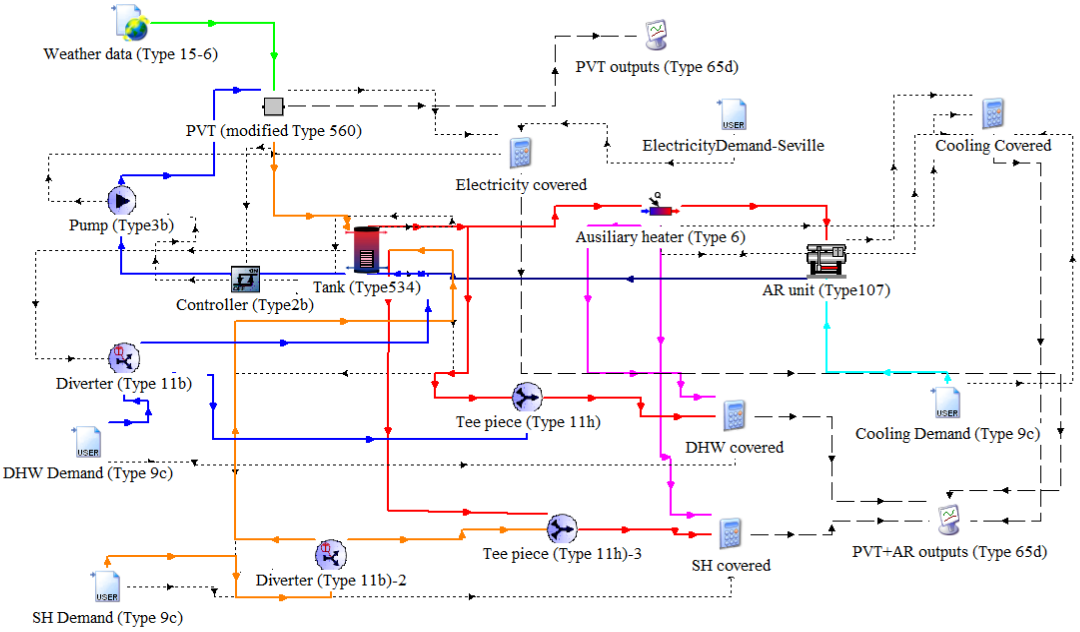

Fig. 3: Simplified model of the PVT+AR configuration built in TRNSYS environment.

Once each solar trigeneration system is sized for each of the aforementioned locations, an hourly transient simulation considering real weather data (Meteonorm Data Base, 2017) is conducted over a year, and the percentages of DHW, space heating, cooling and electricity demands covered are estimated. The modelled system, in all the locations and for both configurations, prioritises first of all DHW and SH demand, then cooling demand, and finally the electricity demand (corresponding to lighting and home appliances). For the results presented below, the family house is assumed to be connected to the electricity grid allowing the continuous exchange of electricity: i.e., electricity generation surplus is fed to the grid and when the PVT electricity generation is not enough to cover the instantaneous demand (deficit), this can be taken from the grid. However, this electricity exchange is only allowed until the electricity balance over a year is reached, that is, when the total annual electricity exported equals the total annual electricity imported to/from the grid.

3. Results and discussion

3.1 Solar trigeneration system configurations

For each of the selected locations and the two different configurations considered (PVT+HP and PVT+AR) a preliminary analysis is conducted, as indicated in the Methodology section, to size each system. In Table 2, the selected size of the storage tank together with the corresponding number of PVT collectors for each solar trigeneration system, based on an innovative polycarbonate flat-box PVT panel, are presented for Seville (Spain), Rome (Italy) and Paris (France). In addition, within the ranges of inlet and outlet temperatures considered for the HP and AR units, in the PVT+HP configuration an annual averaged COP of 4/5 is obtained in heating/cooling modes respectively; while for the PVT+AR configuration the annual averaged COP is 0.78.

On the basis of the solar trigeneration systems size presented in Tab. 2, hourly transient simulations over a year are conducted in TRNSYS software, and results and percentages of the energy demand (DHW, space heating, cooling and electricity) covered are discussed in the following subsections.

Tab. 2: Solar trigeneration systems size based on an innovative PVT collector for each particular location under analysis.

Location	Total PVT collector number / area	PVT collector flow-rate	Water storage tank volume	Peak heating/cooling power
Seville	6 / 9.3 m^2	50 L/h	0.54 m^3	3.9 kW/ 11.9 kW
Rome	12 / 18.6 m^2	50 L/h	1.08 m^3	4.6 kW/ 7.3 kW
Paris	18 / 27.9 m^2	30 L/h	1.08 m^3	5.2 kW/ 5.8 kW

3.2 Annually-integrated results in the selected locations

Annual results for the two solar trigeneration configurations, including the single-family house DHW, space heating (SH), cooling and electricity demand fractions covered in Seville, Rome and Paris are presented in Table 3. It is worth mentioning that the breakdown of the energy demand varies significantly from one location to another, as previously shown in Table 1; i.e., while the DHW demand is virtually the same in all the selected locations, it represents 1.4, 0.37 and 0.17 of the annual SH demand in Seville, Rome and Paris, respectively. Significant differences can also be found in the annual cooling/SH demand ratios between the mentioned locations, which take values of 4.13, 0.53 and 0.10, for Seville, Rome and Paris, respectively.

Tab. 3: Annual results for the two different solar trigeneration configurations, including percentages of DHW, space heating (SH), cooling and electricity demands covered of a reference single family house in three different locations.

Location	Configurations	DHW covered	SH covered		Cooling covered	Electricity Covered	
			PVT	HP+		Inst.*	with excess+
Seville	PVT+HP	90.0%	53.7%	100%	100%+	24.5%	35%
	PVT+AR	81.9%	53.7%	-	71.4%	29.8%	70%
Rome	PVT+HP	87.7%	44.1%	100%	100%+	27.2%	81%
	PVT+AR	86.9%	44.1%	-	96.9%	30.9%	126%
Paris	PVT+HP	74.3%	18.7%	100%	100%+	25.1%	37%
	PVT+AR	73.4%	18.7%	-	85.8%	31.6%	124%

**Percentage of demand covered instantaneously at each time step, without grid interaction.*

+Percentage of demand covered considering that instantaneous surpluses of electricity exported to the grid can be used at other time step to cover a deficit of electricity.

From the results summarised in Table 3, Configuration 1 (PVT+HP) appears as the most promising alternative in two of the locations (Rome and Paris), since percentages above 74% of DHW and 100% of the SH and cooling demand are covered; while with Configuration 2 (PVT+AR), similar percentages for DHW and slightly lower for cooling demand are covered, but instead less than 45% and 20% of the SH demand are covered in Rome and Paris, respectively. The case of Seville is significantly different, mainly due to the higher solar irradiance levels, thus the household has very small SH demand and quite high cooling demand. Therefore, in this location, the integration of the PVT collectors with an AR unit appears as a promising alternative because, although only around 54% of the SH demand is covered, the remaining percentage corresponds to a small amount of energy in absolute numbers (332 kWh/year), while the electricity covered with the PVT+AR is twice than the one covered with the PVT+HP configuration (1826 kWh/year *vs*. 915 kWh/year respectively).

3.2 Time-resolved weekly analysis of the systems in the selected locations

In this section, detailed results (weekly results on an hourly basis) are presented with the aim of understanding of the annual data presented in Table 3. A more detailed description of the energy performance of the most promising solar configuration at each of the selected locations is also included.

Solar trigeneration (PVT+AR) system integrated in the household located in Seville (Spain)

As shown in Table 3, the integration of the PVT collectors with an AR unit appears to be a promising alternative in Seville (Spain), as the AR unit uses the hot water generated by the PVT collectors in the summer months to satisfy the cooling demand, leaving a significant amount of electricity generated by the PVT collectors to satisfy the rest of the household's electricity demand. The later observation may seem not clear from the annual results presented in Table 3, where higher percentages of space heating and cooling are covered with the PVT+HP configuration. However, the PVT+AR configuration presents the additional advantage of covering double of the electricity domestic demand, since most of the cooling demand is covered by means of the PVT thermal output, thus avoiding excess of thermal energy that would be otherwise dumped to the ambient.

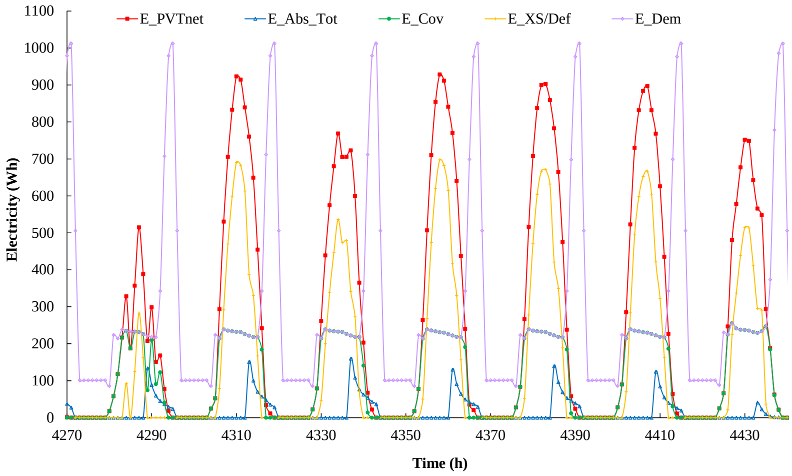

Fig. 4: Electricity generated by the PVT collectors (E_{PVTnet}), electricity consumed by the AR unit ($E_{Abs,Tot}$), electricity demand covered (E_{Cov}), electricity demand (E_{Dem}) and electricity excess/deficit ($E_{XS/Def}$) for the PVT+AR system located in Seville (Spain) during a summer week (28th June - 4th July).

Figures 4 and 5 show the hourly results of the PVT+AR system located in Seville detailed in Table 3 during a representative summer week (28th June - 4th July). It is observed that there is a clear mismatch between the profile of electricity generation (E_{PVTnet}) and that of the electricity demand (E_{Dem}), which implies that during the day all or most of the electricity demand is covered by the PVT+AR system (green circles in Fig. 4), with also an important excess of electricity (yellow pluses) that is exported to the grid. Meanwhile, at night the peak electricity demand (purple diamonds) is not covered. This gives rise to the difference in the percentage of electricity covered in Table 3, depending on whether only the electricity generated at each time step is considered ('Inst.' Column in Table 3) or whether it is assumed that the electricity exported to the grid at any time step can be used at other time step to satisfy the demand ('with excess' Column in Table 3).

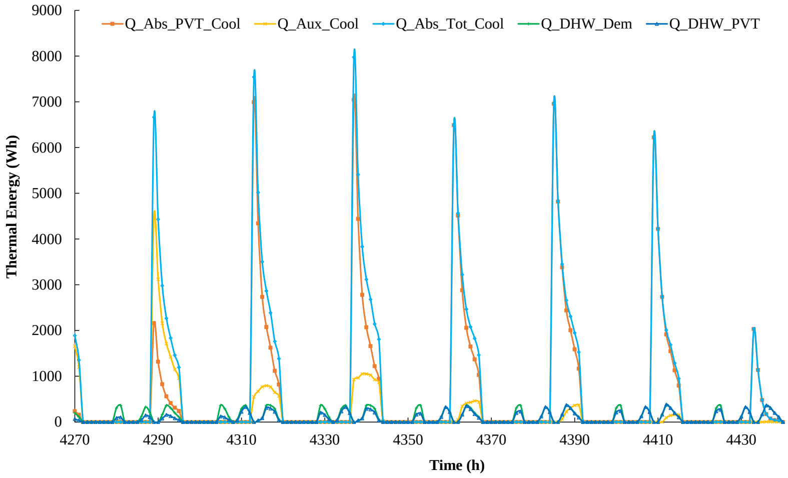

Fig. 5: DHW demand ($Q_{DHW,Dem}$), DHW demand covered by the proposed PVT+AR system ($Q_{DHW,PVT}$), thermal energy required by the AR unit to satisfy the cooling demand ($Q_{Abs,Tot,Cool}$), thermal energy provided by the proposed PVT+AR system to satisfy the cooling demand ($Q_{Abs,PVT,Cool}$) and auxiliary energy required to satisfy the cooling demand ($Q_{Aux,Cool}$) for the PVT+AR system located in Seville (Spain) over a summer week (28th June - 4th July).

In Fig. 5 we consider the thermal energy generation/consumption. From this figure, it can be seen that in the selected summer week most of the DHW demand can be covered by the proposed PVT+AR system (dark blue triangles and green pluses), as well as a significant part of the cooling demand (light blue diamonds and orange squares). It is observed that on the first day, due to the lower solar irradiance (which can be inferred from the electricity generated by the PVT panels in Fig. 4), the temperature reached at the top of the tank is not enough to feed the AR unit and to satisfy the cooling demand, so an important amount of auxiliary heat is need (yellow crosses). Conversely, later in the week, thanks to the increase in solar irradiance, more thermal energy is collected by the PVT collector array, leading to an increase in the storage tank temperature and thus a reduction in the auxiliary energy required to heat the water that feeds the AR unit.

Solar trigeneration (PVT+HP) system integrated in the household located in Rome (Italy)

In the case of the household located in Rome (Italy), the results indicate that it is more appropriate to integrate the PVT collectors with a HP instead of with an AR unit, as this allows the system to cover all the space heating and cooling demands while also covering most of the DHW and an important fraction of the electricity demands, when the electricity excess at different time steps is considered ('with excess' Column in Table 3).

To compare the energy performance of the PVT+HP system with the PVT+AR system, the same summer week as in the case of Seville is shown in Fig. 6 below. In this case, only the electrical results are shown as the thermal outputs are the ones corresponding to the DHW demand and are very similar to those shown in Fig. 5. As before (in Seville, Fig. 5), a mismatch is observed between the electricity generated by the PVT panels and the household electricity demand. However, here, the cooling demand is satisfied by the HP, consuming electricity (see dark blue triangles), so there is less excess of electricity during the main cooling hours (early afternoon), while when the electricity generation decreases later in the day (red squares), there is a deficit of electricity (yellow crosses) that should be bought from the grid to cover the HP electricity consumption.

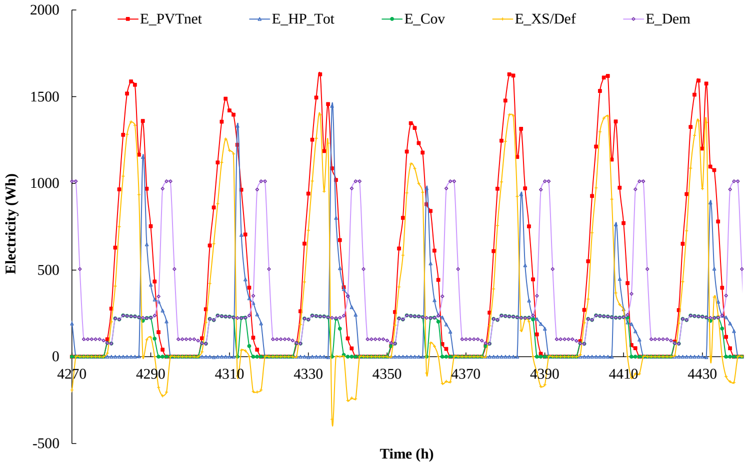

Fig. 6: Electricity generated by the PVT collectors (E_{PVTnet}), electricity consumed by the HP unit ($E_{HP,Tot}$), electricity demand covered (E_{Cov}), electricity demand (E_{Dem}) and electricity excess/deficit ($E_{XS/Def}$) for the PVT+HP system located in Rome (Italy) over a summer week (28 June - 4 July).

Solar trigeneration (PVT+HP) system integrated in the household located in Paris (France)

For the case of the household located in Paris (France), the results show once again that the most appropriate system configuration is the one that integrates the PVT collectors with a HP instead of an AR unit, which in this case allows the system to cover up to 100% of the space heating and cooling demands, while also covering most of the DHW demand; on the other hand, only 37% of the electricity demand is covered (see Table 3).

In this case, it is considered more relevant to show a representative winter week (27th January to 2nd February) since the cooling demand in Paris is small compared to that for space heating. In Fig. 7 one can clearly observe the mismatch between the profiles of the electricity generated by the PVT panels and that of the household electricity demand, while it can also be seen that the electricity demand (purple diamonds) is lower than the electricity needed by the HP to cover the SH demand (blue triangles) from morning to evening. In addition, despite the fact that the amount of electricity covered seems quite small (green circles), on an annual basis the instantaneous energy covered is around 668 kWh/year which, together with the annual excess of electricity (310 kWh/year), allows the system to cover 37% of the total domestic electricity need (assuming that the electricity exported to the grid at any time step can be used at other time step to satisfy the electricity demand).

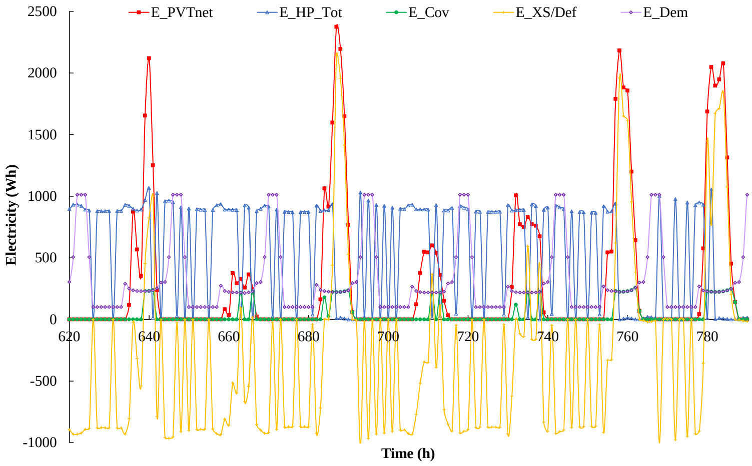

Fig. 7: Electricity generated by the PVT collectors (E_{PVTnet}), electricity consumed by the HP unit ($E_{HP,Tot}$), electricity demand covered (E_{Cov}), electricity demand (E_{Dem}) and electricity excess/deficit ($E_{XS/Def}$) for the PVT+HP system located in Paris (France) during a winter week (27 Jan. - 2 Feb.).

The total heating demand, including both DHW and SH, is presented in Fig. 8, together with the part of these demands covered directly by the PVT thermal-energy generation. From Fig. 7, the 4 days of the selected week that have relevant irradiance levels can be inferred (red squares), which allows the system to cover some percentage of the SH demand with the thermal PVT output on those days, especially in the evening (red squares on Fig 8). However, when the electricity generated by the PVT is used by the HP to cover the remaining SH needs (blue triangles in Fig. 7), 100% of the SH demand is covered (see Table 3).

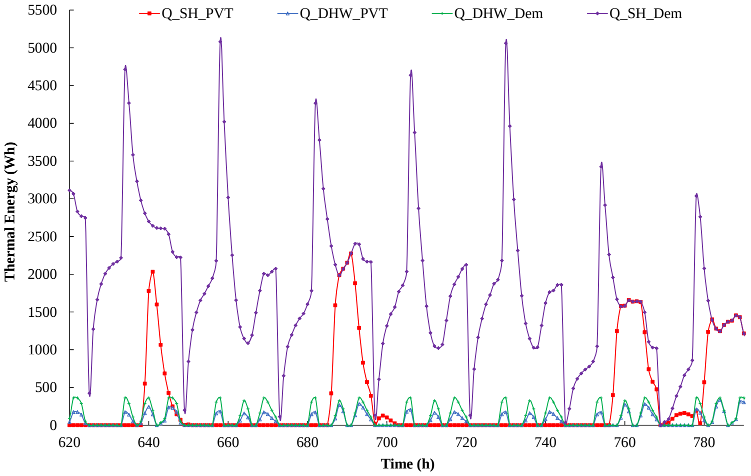

Fig. 8: Space heating demand ($Q_{SH,Dem}$), Space heating demand covered by the thermal output (hot water) of the proposed PVT+HP system ($Q_{SH,PVT}$), DHW demand ($Q_{DHW,Dem}$), DHW demand covered by the thermal output (hot water) of the proposed PVT+HP system ($Q_{H,PVT}$) for the PVT+HP system located in Paris (France) over a winter week (27 Jan. - 2 Feb.).

4. Conclusions

In this paper, the performance of high-efficiency solar trigeneration systems based on a novel hybrid photovoltaic-thermal (PVT) collector based on a flat-box structure for the provision of domestic how water (DHW), space heating (SH), cooling and electricity to residential single-family households is assessed. To this end, the energy demands of single-family houses located in three different climates, namely Seville (Spain), Rome (Italy) and Paris (France), are estimated using the engine tool EnergyPlus, and a TRNSYS model is developed featuring the hybrid PVT panel coupled via a thermal store in two alternative small-scale solar heating and cooling configurations to: 1) an electrically-driven vapour-compression heat pump (PVT+HP), or 2) a thermally-driven absorption refrigeration unit (PVT+AR).

Based on transient simulations over a full year on an hourly basis, it can be concluded that the proposed solar configurations, PVT+HP or PVT+AR depending on the location, appear as an interesting solutions for the provision of solar DHW, SH, cooling, and electricity in residential buildings. Significant fractions of domestic energy demands can be covered with reasonable PVT collector-array areas. It is also concluded that the most promising solar trigeneration configuration for each location depends on the weather conditions (in particular solar irradiance levels) and the household energy demand profiles. The percentages of the different energy demands covered indicate that the PVT+HP configuration is the most promising alternative for the locations of Rome and Paris, covering 87.7% and 74.3% of the DHW respectively, 100% of the space heating and cooling demands in both locations, as well as 81% and 37% of the electricity demand, respectively. This is achieved with a PVT panels installed area of 18.6 m^2 in Rome and 28.9 m^2 in Paris. For the case of Seville, due to the higher solar irradiance levels and the significant cooling demand, the PVT+AR configuration arises as a promising alternative, with which it is possible to cover 81.9% of the DHW, 53.8% of the space heating, 71.4% of the cooling and 70% of the electricity demands, with a PVT panels installed area of 9.3 m^2. In this case, the PVT+AR configuration presents the advantage of covering double of the domestic electricity demand compared to the PVT+HP system, since most of the cooling demand is covered by means of the PVT thermal output, thus making more electricity available for other purposes that would otherwise have been required to run the HP. Furthermore, the use of the PVT thermal output in summer helps reducing the high temperatures that would be otherwise reached in the storage tank and would lead to heat being dumped to the ambient.

This work suggests that PVT trigeneration systems have an important potential in domestic applications, in particular in urban areas where space is at a premium, since both electrical and thermal outputs are generated from the same area. Still, for the benefits of this technology to be realised and for it to contribute meaningfully towards the envisaged renewable energy generation in the built environment, additional research on solar heating and cooling technologies is required into enhancing efficiency, solar resource use, and reducing costs.

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