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A simulation-based analysis of photovoltaic thermal hybrid solar collectors with a new TRNSYS type model

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Abstract. Nowadays buildings are responsible of 36% of CO_2 emissions and space heating and cooling alone accounts for 40% of the final energy consumption at European level. In this context, solar-assisted systems represent an important solution to support the decarbonisation pathways in residential sector. In this work, a novel lumped parameter simulation model for photovoltaic thermal hybrid solar collectors developed by Authors as a type of Transient System Simulation (TRNSYS) software is used to carry out computer simulations in different climatic conditions. The model is based on the electrical analogy method to solve the transient heat transfer problem and considers the effect of the thermal capacitances of the elements composing the photovoltaic thermal collector. The simulation tool was also validated with the experimental data in terms of both electrical and thermal power. In this work, a simulation-based analysis is carried out considering three climatic zones in order to evaluate the thermal performance of photovoltaic thermal hybrid solar collectors under different operating conditions.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) [1] has estimated in 2018 that human activities, which have led to increased volumes of greenhouse gases, have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Moreover, the last report of the IPCC states that global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. With the aim of decreasing the greenhouse gas emissions, during the last decades, the exploitation of the renewable energy sources was pushed, together with the development and investigation of innovative, more efficient and environmentally sustainable systems. The issue regarding the energy consumption in the building sector, which has been widely discussed in the literature, represents a field of application with a large energy savings potential. Data published by Eurostat revealed that, in 2016, the residential sector represented about 27% of final energy consumption in Italy [2]. Therefore, the transition to a more energy efficient households sector represents a fundamental measure to take towards sustainability. In particular, it becomes interesting to focus on how the energy used for space heating, space cooling, and domestic hot water production is derived and used, as, in Italy, it accounts alone for nearly 80% of the final energy consumption in the whole residential sector [2]. In this context, the heat pump technology plays a key role in increasing the renewable ratio of the total thermal energy use. Moreover, heat pump systems make it possible to economically and efficiently extract and utilise the heat content of low-temperature sources, such as ground, water and air, which can be used for space heating and domestic hot water production.

To minimize the use of fossil fuels, it is possible to integrate renewable technologies to the heating system and, more in general, to the air-conditioning plant. This contribution, in residential applications, usually partly covers the electrical and thermal loads of the building. For this purpose, solar-energy systems are already widely used: Solar Thermal Collectors can lighten the heat demand for the DHW production, while a photovoltaic field (PV) supplies the electrical demand of the heat pump.

A solar thermal collector converts the incident solar radiation into heat. In domestic applications, the solar field might assist the heat pump in heating and DHW production. In literature these systems are named Solar Assisted Heat Pump (SAHP) [3]. The layout of a SAHP system can be different and synthesized into “parallel” and “serial” systems [4]. According to this classification, in the parallel SAHP system, the solar thermal field directly supplies thermal energy to a storage tank for the DHW production and the heat pump feeds independently the same thermal storage whenever the solar energy level is insufficient. On the other hand, in the serial SAHP system the solar thermal collectors represent the heat source of the Heat Pump, and, therefore, contribute only indirectly to the DHW production [3].

As mentioned above, photovoltaic panels could be a noteworthy integration to the SAHP system. Indeed, the electrical energy obtained from the conversion of solar radiation through this technology might contribute to meet the electrical demand of the heat pump, increasing the overall renewable share of the system. The energy efficiency of PV modules is affected by different factors, such as solar radiation, humidity, dust, and temperature [5]. In particular, several studies have been carried out to enhance the energy efficiency by decreasing the temperature of the PV panels [6], [7]. Furthermore, only 15–20% of incident solar irradiation is converted into electricity, while the exceeding part is converted into heat [5] [8].

From the previous considerations, it could be interesting to take advantage of the heat recovery deriving from the PV panels installation, co-generating heat and electricity by means of the so-called photovoltaic-thermal collectors (PVT) [9].

PVT collectors represent an advantageous technology in comparison to the installation of a solar thermal field and a photovoltaic system separately. Indeed, one of the main benefits is the saving of roof space, as the area covered with PVT collectors can usually provide more electricity and heat than an area covered with the two conventional PV and thermal collectors systems. In addition to this, the PVT field can keep the architectural uniformity on roofs and reduce installation cost. Eventually, the total energy efficiency of the PVT collector (thermal and electrical) is higher than that of the two conventional systems [10].

Therefore, in the context of this research, PVT collectors can replace the separate thermal collectors and photovoltaic fields, for providing DHW to a residential building.

The prediction of the energy efficiency of these systems is usually done using dynamic energy simulations tools. The thermal and electric behaviours of the PVT collectors are assessed using analytical and numerical models. The models of the PVT collectors are then implemented in wider systems’ models including other components such as storage tanks and heat pump. Several case studies have been analysed in literature in order to simulate the operating conditions of PVT collectors. Herrando et al. [11] focused on the maximisation of the performance of PVT water systems in the residential sector, examining the suitability of this technology for the distributed generation of electricity and the simultaneous provision of DHW. Dupeyrat et al. [8] described the test results of an experimental flat plate PVT collector, evaluated the performance of this hybrid collector in a solar thermal system, comparing it to that of systems operating with standard solar devices and discussed the advantages of the hybrid technology from the energetic, exergetic and primary energy saving point of view. Emmi et al. [12] examined a multi-source energy system equipped with photovoltaic thermal hybrid solar collectors assisting a heat pump for the provision of space heating and DHW production to a single-family dwelling located in North East Italy and found that the investigated multi-energy source systems were responsible for increasing the energy efficiency by 16–25% with respect to an ordinary air to water heat pump system.

In the current work a model of a system for the production of DHW by means of a heat pump and PVT collectors, simulated in (Transient System Simulation) TRNSYS environment, is described. The model used for the PVT collector refers to the research carried out by Zarrella at al. [13] and is implemented by the same research group as a TYPE of TRNSYS software. The modelling approach considers the effect of the thermal capacitances of the layers composing the photovoltaic thermal collector, using an electrical analogy method to solve the transient heat transfer problem [13]. The results of the study can be useful to understand the effects of using the PVT technology in DHW applications for different layouts of the plant. In particular, the use of electric storage significantly decreases the electrical energy that have to be withdrawn from the grid. The analysis has been carried out considering different climates, highlighting the difference thermal and electrical behaviour of the system in the Italian context.

2. Method

The analysis of energy systems can be carried out by the use of two different approaches. The first possibility is the use of simplified methods, which usually evaluate the energy inputs and outputs, and the energy balances considering the mean operating conditions during medium- and long-term periods. These approaches are based on analytical equations either developed through the practical experiences on that field of operation or derived from detailed and parametric analysis of such systems. In these cases, the validity of the models cannot be extended to a wide range of applications, and the boundary conditions are affected by limitations. On the other hand, the second approach comprises models requiring a more detailed description of the characteristics of the system, and therefore a greater computational effort. For this aim, dynamic simulation tools are used in the research field. These software and their extensions can provide a detailed simulation of the devices and components' behaviour, to deeply describe the whole energy system.

In this study, the second approach has been used and hourly dynamic simulations have been carried out. Moreover, the effects of climate conditions on a hybrid solar system for DHW production have been investigated.

3. The case study

The main purpose of the study is the analysis of the energy performances and behaviour of a PVT system for the provision of domestic hot water to a residential building. The climate conditions of Venice, Rome and Palermo were considered in the simulations and the TRY data gathered from Energyplus database were used. For this aim, the profile of the DHW use throughout one day was evaluated and repeated uniformly along the year. In detail, the daily consumption of 220 L of DHW was considered, with three main picks during the day, the first one around 7 a.m. (75 L), the second at 1 p.m. (80 L) and the last one at 8 p.m. (65 L). The TRNSYS model needs several input data, from the climate conditions to the technical properties of devices and components, to describe the operation of the system. The details of the PVT collector and the input data to the PVT TRNSYS Type used in this study are summarized in Zarrella et al. [13], while the main properties of the PVT field are summarized in Table 1.

Table 1. Main properties of the PVT field

Name	Value	Unit
Orientation	South	[-]
Slope	45	[°]
Number of collectors	10	[-]
Connections	Parallel	[-]
Pick Power PV field	2500	[W_p]
Cell type technology	Polycristalline Silicon	[-]
PV field reference area	14.4	[m^2]
Module area	16.6	[m^2]
η_0	0.6	[-]
a_1	12	[$W/(m^2K)$]
a_2	0	[$W/(m^2K^2)$]
η_{ref-PV}	0.15	[-]
$\eta_{el.\ sys}$	0.9	[-]

The system was basically constituted of two loops: the *heat pump loop* and the *solar loop* as shown in Figure 1. The first set the thermal power of the heat pump and, on the basis of the heat carrier fluid flow rate circulating in the loop, calculated the temperature difference between the inlet and the outlet. The second simulated the operating condition of the PVT field.

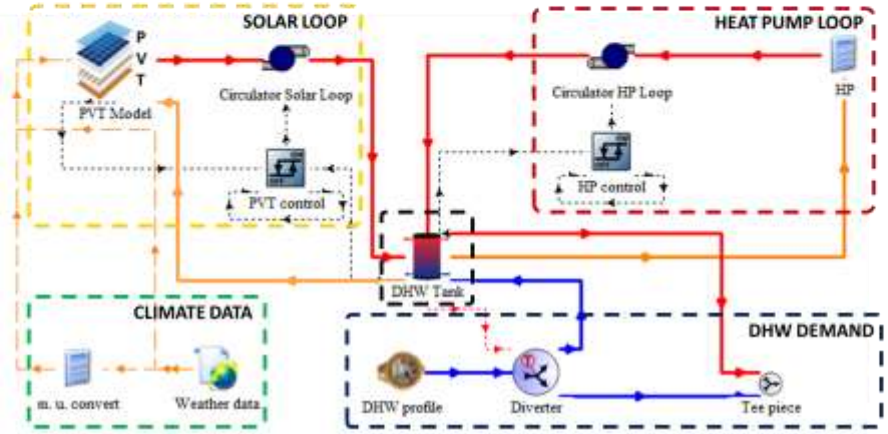

Figure 1. Scheme of the TRNSYS model

Since the main aim of the study was not the analysis of the heat pump performance, which was used to provide heat to the DHW tank, the electrical energy demand of the heat pump was simply calculated considering a constant COP value, set to 2.4.

The core of the system was the *DHW Storage Tank*, which was used to produce and store the domestic hot water used by the user. The thermal storage was modelled using Type 534 of TRNSYS and contained two immersed coiled heat exchangers, connected to the heat pump loop (top heat exchanger) and to the solar loop (bottom heat exchanger). The main data of the storage tank are summarized in Table 2.

Table 2. DHW Storage Tank data.

Name	Value	Unit
Effective tank volume	412	[L]
Top heat exchanger surface	4.6	[m^2]
Bottom heat exchanger surface	0.9	[m^2]
Heat exchanger fluid (Superior)	Pure water	[-]
Heat exchanger fluid (Inferior)	Propylene Glycol (30%), Water	[-]
Loss coefficient	0.308	[W/(m^{2}K)]

The number of nodes in which the boiler was divided was ten. The top heat exchanger occupied nodes from 1 to 5 and the bottom coiled tube is placed from nodes 6 to 9. The heat carrier fluid exiting the PVT collectors field exchanges heat with the water inside the tank on its bottom part. If the temperature from the solar loop was not enough to provide hot tap water, the heat pump supplied it.

When there was DHW demand, a part of the water coming from the municipality water (at a temperature that depended on the location of the simulated plant) was diverted to the DHW tank where it was warmed up. At that point, thanks to a tempering valve, simulated by means of Type 11b of TRNSYS, the ratio of stream that was needed to obtain the desired domestic hot water temperature (around 42°C), was mixed with the tank outlet flow rate.

The temperature of the DHW Tank was controlled through the use of two differential controllers (Type2b). One managed the circulator of the solar loop, monitoring the temperatures at the outlet of the PVT collectors and at node 9 of the tank, the other one controlled the heat pump loop and switched it on when the temperature of the storage tank (node 1) is under the set-point temperature of 47°C, with an upper and lower dead band of 5°C and 0°C respectively.

4. Results and discussion

In the present study, the thermal and electrical energy performances of the system previously described were evaluated. Annual energy simulations, with a time-step of 5 minutes, have been carried out using the TRY of the three locations, Venice, Rome and Palermo. The three case studies were analysed in order to investigate the response of the PVT system to the different climate conditions. Through this study, it was possible to estimate the ratio of thermal energy that was exchanged to the DHW tank by the heat pump and by the solar field.

The main thermal energy results of the simulations are summarized in Figure 2. The charts show the monthly balance of the heat rates on the DHW tank. The thermal energy required for the DHW production can be obtained by subtracting the thermal losses at the DHW storage tank from the sum of the thermal energy provided by the solar field and by the HP loop. In detail, it can be seen that the total thermal energy required for the DHW production decreases when considering, in this order, Venice, Rome and Palermo. This is due because of the heat needed to raise the municipality water temperature to the desired level of temperature for DHW use (42°C in this case) is lower for the last two cases. Indeed, the municipality water temperature has been considered of 13.2°C, 15.3°C and 18.4°C for Venice, Rome and Palermo respectively considering the average climatic conditions. Overall, during the simulation year, for Venice the total heat exchanged with the DHW tank was provided for 53% by the PVT collectors, while the remaining 47% was provided by the heat pump. The share provided by the PVT field increased for the case studies of Rome and Palermo, from 59% to 68% respectively. This can be explained considering the higher incident solar radiation to the same collector's area in the Southern part of Italy, in comparison to the Northern part, because of the smaller latitude. In addition, the thermal losses from the bottom, edge and top of the DHW Tank, correspond approximately to the 5%, 6% and 7% of the overall thermal energy provided for Venice, Rome and Palermo respectively.

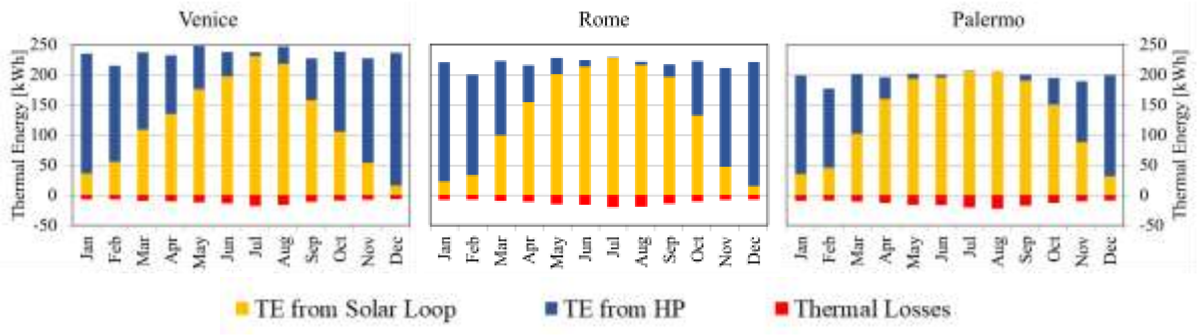

Figure 2. Thermal balance at the DHW storage tank.

Besides, it can be interesting to evaluate the electrical energy fluxes involved in the system. In particular, the electrical energy produced by the PVT field, together with the demand of the heat pump have been considered. As already pointed out, the behaviour of the heat pump is not deeply investigated in this model and, therefore, it has been chosen to keep a fixed COP value over the year. The coefficient of performance is hence used to estimate the electrical demand of the heat pump. In Figure 3 the just mentioned electrical demand and electrical energy produced by the PVT collectors' field are reported, divided by month and distinct for the three different case studies.

Furthermore, in Figure 3, the electrical energy that must be withdrawn from the electric grid and the exceeding electrical energy converted by the PVT field and to be given away to the grid, are shown.

It can be noticed that the overall electrical energy produced is higher for the case study of Palermo with 3248 kWh per year, followed by Rome (2829 kWh) and Venice (2622 kWh).

As a consequence of the previous considerations, together with the thermal energy, also the electrical energy demanded by the heat pump and the energy to be withdrawn from the grid are lower for the Southern cities.

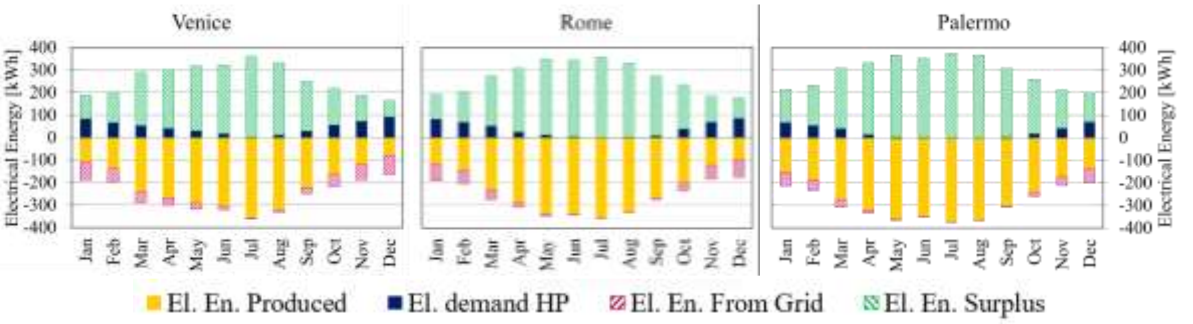

Figure 3. Electrical energy fluxes.

As usually happens in renewable energy exploitations there is no contemporaneity between the energy demand and the availability of renewable energy sources. In order to push up the self-use of the photovoltaic production, an electrical energy storage was added in the model. This device stores the excess of the electrical energy produced and make it available to the heat pump when necessary. In

detail, the self-use of the electrical energy has been calculated as the ratio of the electrical energy produced and used, and the electrical energy demanded. This calculation has been performed for each time-step of the simulation and the data has been summarised month by month. Though, two cases can be distinguished: when the battery is absent, to be considered self-used, the energy must be produced and used simultaneously at each time-step; when the battery is included in the system, also the electrical energy withdrawn from it after been stored for a certain time is considered self-used.
Table 3 summarises the results of the just described investigation considering a useful storage capacity of 2000 Wh. It can be noticed that the increase of the self-used share is relevant, and that, in general, this share is higher in Palermo compared to Rome and Venice.

Table 3. Electrical energy produced by the PVT field, demanded by the heat pump and self-used for the layout with and without energy storage, for the case studies of Venice, Rome and Palermo.

	Venice [kWh]				Rome [kWh]				Palermo [kWh]			
Month	EEP	EED	EESU		EEP	EED	EESU		EEP	EED	EESU	
			No ES	ES			No ES	ES			No ES	ES
Jan	111	83	6	56	116	83	7	73	152	68	7	66
Feb	139	66	6	51	143	70	7	65	186	55	7	54
Mar	242	54	6	53	229	52	6	51	274	41	6	41
Apr	266	41	5	40	287	26	4	26	321	15	2	15
May	292	30	3	30	338	11	2	11	363	3	1	3
Jun	306	17	2	17	342	4	1	4	351	2	0	2
Jul	358	3	0	3	357	1	0	1	374	1	0	1
Aug	321	12	1	12	330	2	0	2	367	0	0	0
Sept	223	29	3	29	267	9	1	9	304	4	0	4
Oct	166	55	4	51	202	38	5	38	244	18	2	18
Nov	120	72	4	47	121	68	6	66	174	42	4	42
Dec	78	92	5	51	96	86	5	73	137	70	6	69
Year	2622	553	46	438	2829	449	44	418	3248	319	36	315
			8%	79%			10%	93%			11%	99%

EEP: Electrical Energy Produced by the PVT field.
EED: Electrical Energy demanded by the Heat Pump.
EESU: Electrical Energy for Self-Use.
No ES: No Energy Storage included in the system.
ES: Energy Storage included in the system.

5. Conclusions

The present work analyses the renewable energy exploitation potential of the solar energy source. The energy performance of a PVT solar loop was investigated, from both the thermal and electrical point of view. The simulations carried out in TRNSYS environment allowed obtaining the thermal contribution of the PVT field to the DHW production for a residential building. For the three analysed case studies, referring to the weather conditions of Venice, Rome and Palermo, the heat transferred to the DHW tank by the solar loop in one simulation-year was of 1492 kWh, 1560 kWh and 1602 kWh respectively. On the other hand, the thermal energy provided by the HP for the same purpose was of 1327 kWh in Venice, 1078 kWh in Rome and 766 kWh in Palermo. Moreover, it was possible to obtain the electrical energy provided by the PVT field with the aim of partly supplying the electrical demand of a heat pump. The values of electrical energy produced ranged from 2622 kWh in Venice to 3248 kWh in Palermo.

In conclusion, the electrical self-use was evaluated for the system with and without the use of an energy storage. A set of simulations have been carried out modifying the size of the energy storage. The use of this component allows obtaining an increase of the self-use of about 9 times in comparison to the solution without the storage.

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