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Research Paper

Energy and environmental benefits of an integrated solar photovoltaic and thermal hybrid, seasonal storage and heat pump system for social housing

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A R T I C L E I N F O

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A B S T R A C T

A facility based on a photovoltaic and thermal hybrid solar field with a seasonal storage tank coupled to a water-to-water heat pump is presented in this paper as an adequate energy supply system for a building of social homes in Zaragoza (Spain), currently under construction. Two types of complementary software have been used for the complete design, sizing, and simulation of the system. DesignBuilder was used to determine the hourly demands from the construction drawings, and TRNSYS was then implemented to dynamically simulate the whole energy system. System performance has been tested in terms of 3E aspects (energy, environmental and economic) with a few well-known key performance indicators. Results obtained by the combined use of the demand simulation software and quantification with different indicators (KPI) show that the proposed solution is suitable for this building: the calculated coverage of the domestic hot water demand is about 80%, the payback period is 8.5 years, and the installation could avoid 44,200 $kgCO_2/year$ of global warming potential. To sum up, this paper shows how this novel, high-efficiency heating system is a good solution for social housing, owing to its low energy costs and a possible subsidization of a fraction of the high initial investment.

1. Introduction

Energy poverty is currently a severe problem that affects global society. Spain performs worse than the EU average [1]: 7.2% of the population could not pay their utility bills in 2019. Additionally, the population living in social housing struggles more with the energy poverty compared to the population living in other types of dwellings (owners, private tenants): in 2017, 17.4% could not keep their homes sufficiently warm [2] compared to a mere 9.1% in the average population.

There are different ways to deal with energy poverty. Energy poverty can be partly solved by subsidies like a social bonus for electricity [3] and heating [4]. Nevertheless, some experts claim that these immediate actions are not sustainable in the long-term [5]. For this reason, regional energy efficiency programs [6] and housing renovation programs for vulnerable households [7] have been alternatively implemented in Spain. These programs try to solve energy poverty from the root of the problem, promoting the decrement of energy consumption and demand in households. Social housing offers a unique opportunity to address both energy efficiency and social inclusion through potential economies of scale and the reduction of social and financial costs for residents [8].

The increase in energy use from renewable sources also reduces the national inequality and emissions (McGee and Greiner [9]). Bahaj and James [10] showed the benefits of urban energy generation by adding photovoltaic (PV) modules to social housing. Lee and Shepley [11] researched the economic benefits of installing PV panels in low-cost, government-aided apartments in Korea.

Social housing in Spain is quite obsolete in terms of energy, due to different economic and technical factors. Most of the constructions were built from the 1940s to the 1980s with poorly insulated enclosures. In addition, most social homes lack district heating and employ systems with high carbon emissions to heat the spaces [12].

Different programs for refurbishment of social housing have been implemented in Spain. Nevertheless, these strategies tend to favor retrofitting the envelopes of the buildings and resist installing renewable energy equipment, whose cost recoupment is nearly unachievable [13,14].

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Nomenclature

Abbreviations

COP	Coefficient of Performance of the HP
CTE	Technical Building Code
BHST	Backup Hot Storage Tank
DHW	Domestic Hot Water
FPC	Flat Plate Collector
HEP	Hidden Energy Poverty
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LCoE	Levelized Cost of Electricity
LCoH	Levelized Cost of Heat
NPV	Net Present Value
NZEB	Nearly Zero-Energy Building
PB	Payback
PCM	Phase Change Material
PV	Photovoltaic
PVT	Photovoltaic and Thermal hybrid panel
SAHP	Solar Assisted Heat Pump
SH	Space Heating
SHC	Solar Heating and Cooling
SMZV	Municipally Owned Corporation for Housing in Zaragoza
SSWT	Seasonal Storage Water Tank

Symbols

A_{PVT}^{gross}	gross area of the PVT panels
$C_{fuel,avoided}$	cost of the avoided fuel by the implementation of the heating installation [€]
C_{fuel}	fuel cost [€/kWh]
$e_{PVT}^{DC,gross}$	area-specific solar electricity yield $[kWh/m^2\ year]$
E_{from_grid}	electricity from the conventional electricity grid $[kWh/year]$
E_{HP}	electrical consumption of the HP $[kWh/year]$
E_{other_comp}	other electrical needs of the heating installation $[kWh/year]$
E_{PVT}^{ac}	Electrical energy production of the solar field (after being transformed into alternating current)$[kWh/year]$
E_{PVT}^{dc}	Electrical energy production of the solar field (direct current)$[kWh/year]$
$E_{PVT_{toSYS}}$	Electrical production of the PVT panels that feed electrical consumption of the heating installation $[kWh/year]$
E_{SYS}	demand of the installation $[kWh/year]$
$E_{to_{grid}}$	excess of electricity $[kWh/year]$
$E_{building}$	electrical demand of the building $[kWh/year]$
$f_{sol,el}$	solar electrical fraction
$f_{sol,en}$	solar combined energy fraction
$f_{sol,th}$	solar thermal fraction
F_{sc}	electrical self-consumption fraction
F_t	yearly cash flow [€]
G_{col}	solar irradiation per area in the collector plane $[kW/m^2year]$
$GWP_{avoided}$	avoided global-warming potential $[kgCO_2/year]$
GWP_{elgrid}	global-warming potential factor of electricity from grid $[kgCO_2/kWh]$
GWP_{fuel}	global-warming potential factor of fuel $[kgCO_2/kWh]$
I_0	initial investment [€]
η_{burner}	performance of the auxiliary heater
$\eta_{PVT,el}^{dc,gross,STC}$	the electrical efficiency of the PVT collectors under standard testing conditions
OM_t	peration and maintenance cost of the installation [€/year]
PR_{PVT}	electrical performance ratio of the PVT yield
q_{PVT}^{gross}	area-specific solar heat yield $[kWh/m^2\ year]$
Q_{DHW_aux}	heat flow provided by the auxiliary heater to feed DHW demand $[kWh/year]$
Q_{SH_aux}	heat flow provided by the auxiliary heater to feed space heating demand $[kWh/year]$
$Q_{building}$	heat demand of the building $[kWh/year]$
Q_{HP}	heat flow provided by the HP $[kWh/year]$
Q_{loss}	thermal losses in the PVT yield $[kWh/year]$
Q_{PVT}	thermal production of the PVT panels $[kWh/year]$
$\dot{Q}_{PVT}$	thermal capacity provided by the PVT yield at each time step $[kW]$
Q_{PVT}^{direct}	useful thermal energy production of the PVT yield $[kWh/year]$
r	discount rate
SPF_{SHP}	seasonal performance factor of the HP
t	period of analysis [year]
$\vartheta_{char,power}^{m}$	characteristic operating temperature
ϑ_m	operative temperature of the PVT panels at each time step
$\omega_{PVT,el}^{gross}$	solar electrical utilization ratio
$\omega_{PVT,en}^{gross}$	solar combined energy utilization ratio
$\omega_{PVT,th}^{gross}$	solar thermal utilization ratio

This paper studies a building of social homes in Zaragoza (Spain), currently under construction, featuring a novel system for social housing based on a photovoltaic and thermal hybrid solar field (PVT) with a seasonal storage tank coupled to a water-to-water heat pump. The system performance has been tested in the terms of 3E aspects (energy, environmental and economic) with a few well-known key performance indicators. The results show that the proposed solution is suitable for this building.

Literature contains very few examples of the innovative combination of SAHP based on PVT and seasonal storage with a buried tank, which allows the production of hot water and electricity according to the demand of the building. Three case studies were implemented in an EU project [15], but none of them refer to social housing (a municipal sports center, a high-end housing block, and an office building). Regardless, all of them reported significant energy and environmental savings. Del Amo et al. [16] optimized this system but applied it to an educational building and showed that it brought considerable economic savings.

Souliotis et al. [17] presented two real case studies of solar water heating systems in social housing. One of the systems combined solar collectors with water tanks; the other comprised a photovoltaic and thermal hybrid (PVT) panel. PVT panels have a higher overall efficiency than PV panels and independent solar thermal collectors (STC) [18]. Moreover, limitations of the roof space on the buildings make this technology a great option for the residential sector. Thermal recovery of the PVT panels extracts the excess heat from the PV cells of the collector [19], as different authors have shown mathematically [20]. Water-cooled PVTs are the most common due to their high efficiency [21]. Task 60 of the International Energy Agency (IEA) [22] focuses on applying PVT collectors to substitute the classical side-by-side installations of STC and PV modules. Energy production, competitive costs, safety, and reliability of PVT systems have been confirmed by numerous studies [23]. In this sense, the adequacy of PVT for dwellings has already been shown and its performance experimentally validated [24].

In the last years, the combination of solar thermal collectors and a heat pump (HP) has been thoroughly researched. This technology is called Solar Assisted Heat Pump (SAHP). In Task 44 of the SHC Program, SAHP facilities have been investigated to optimize installations in the domestic sector [25] which provide heating and DHW. In essence, the electrical consumption of the HP can be lower when coupled to a solar installation than if it works independently, since the cold side of the HP is raised. Exciting and detailed reviews can be found in [26,27]. The critical point defining the opportunity for SAHP energy systems is that experimental studies are being published with fascinating results in a large number of applications [28–30], giving attractive figures from both technical and economic perspective [31,32] by using flat plate collectors (FPC). Dannemand et al. [33] researched the coupling with both cold buffer storage and hot water storage tanks, and they showed the feasibility of this combination for a small lab facility. Moreover, Del Amo et al. [34] presented an installation for space heating in an industrial building.

Lazzarin and Noro [35] studied a refurbished building located in Northern Italy, equipped with a PVT dual-source heat pump, demonstrating that the installation has very high efficiency and low primary energy consumption. In addition, they presented a complete work on a solar cogeneration installation. In this paper, a study was conducted on the relation between the size of water tanks and the solar field for electricity production, concluding that the correct dimensioning led to energy and operating cost savings [36].

The reviewed literature indicates that energy storage is required to match the energy demand and solar supply in the housing sector. Storage mechanisms were researched in the frame of Task 32 of the Solar Heating and Cooling (SHC) program of the IEA [37]. Pinel et al. [38] found sensible thermal energy storage as the most common and the cheapest way to match thermal production and demand in this sector. Yang et al. [39] reviewed that water is the most used medium in low-temperature applications because of its properties (high thermal capacity, thermal diffusivity, cost, availability) [40]. Buried water tanks allow energy storage almost anywhere [41], regardless of the climatic conditions or space limitations.

Seasonal storage (SS) is usually justified when the queued technology requires stable temperatures for optimal operation. Traditionally, it has been installed in high latitude areas where seasonal temperature variation is high [42,43]. Numerous operative heating district installations in Northern Europe store thermal energy in buried water tanks. A solar thermal storage is an optimal solution in locations where the solar radiation is high and the number of solar hours per day is stable [44–46]. Buildings in which the heating demand is higher than the domestic hot water (DHW) demand are also suitable for storage technology. Some authors have shown detailed dynamic studies with those profiles [47].

The use of boreholes to install the seasonal storage coupled with the SAHP can be found in [48] for a single-family home. The combination of FPC, SS (buried tanks), and SAHP has been studied for individual housing [49–51], but also for district heating [52–54] and even for drying [41].

All of the above indicates that, to the best of the authors' knowledge, this is the first time the design analysis of an innovative SAHP based on PVT and coupled with a seasonal storage has been applied to social housing for provision of electricity, heating, and, partially, DHW. This integration is proposed as a low-energy-cost solution for its tenants, given the high COP obtained. Moreover, it is considered that the administration may subsidize part of the investment cost required for the seasonal storage. In addition to the proposed installation, an efficient construction design and actions towards the increase in energy savings are foreseen. The second innovation presented in this paper is the successful combination of two types of software for scheme optimization. One was explicitly used to estimate the heating and cooling demands of the building, whereas the second one was a dynamic process simulator for the proposed installation. The third novelty includes an in-depth energy, economic and environmental (3E) analysis through Key Performance Indicators (KPI), designed explicitly for PVT installations. The KPI sets will permit further comprehensive comparisons with similar proposals in the sector for coverage of the heating and DHW demands.

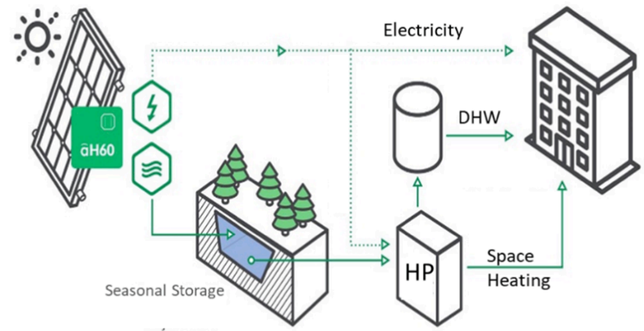

Fig. 1. Schematic visualization of the system [69].

2. Methodology

Three sequential stages have been carried out in this work. Firstly, the thermal (DHW and heating) and electricity demands of the building were calculated, in accordance with the final purpose of the project. Secondly, the energy system was modeled and parametrized with the aid of a dynamic simulator. Finally, a socio-economic and environmental global analysis was performed together with the calculation of energy efficiency ratios. Both types of software allow an hourly analysis of their calculations, thereby permitting a detailed hourly analysis for every day of the year.

A schematic diagram of the described SAHP with seasonal storage installation is shown in Fig. 1. Key components of the heating installation are the collector area, the volume of the seasonal storage tank, the thermal capacity of the water-to-water heat pump, and the water tank size that supports the load and constitutes the hot side of the HP.

2.1. Energy demands of the building

The building was designed in compliance with the legal and technical requirements from the Spanish Technical Building Code (*Código Técnico de la Edificación*, CTE) [55]. In essence, the requirement for this type of buildings is that a minimum of 60% of the annual domestic hot water demand and 15% of the electricity demand are covered with renewable energies. The thermal energy demand was calculated with the software DesignBuilder [56] which includes a powerful calculation engine and enables a graphical representation of the thermal enclosure of constructions and a partition into multiple zones. Climatic data for Zaragoza (Spain) belongs to the SWEC database (Spanish Weather for Energy Calculations)[57], generated from actual climatic data provided by the State Meteorological Agency (AEMET) [58].

The main physical layout of the building can be obtained from the floor plans provided by the real estate promoter (*Sociedad Municipal Zaragoza Vivienda*, SMZV). Each zone has specific heating and DHW demands, schedules, occupancy, and ventilation requirements according to their specified purposes. Thermal transmittance of the different enclosure elements (façades, roofs, windows, doors…) was carefully calculated by setting up materials and characteristics of each layer. Highly detailed hourly thermal demands were then obtained. Annual results were validated in accordance with the demand ratios as stated in the approved project provided by SMZV.

Forecasted electricity demand of the building was obtained from the ESIOS database [59], provided by the technical manager of the Spanish Power Grid (*Red Eléctrica de España*, REE).

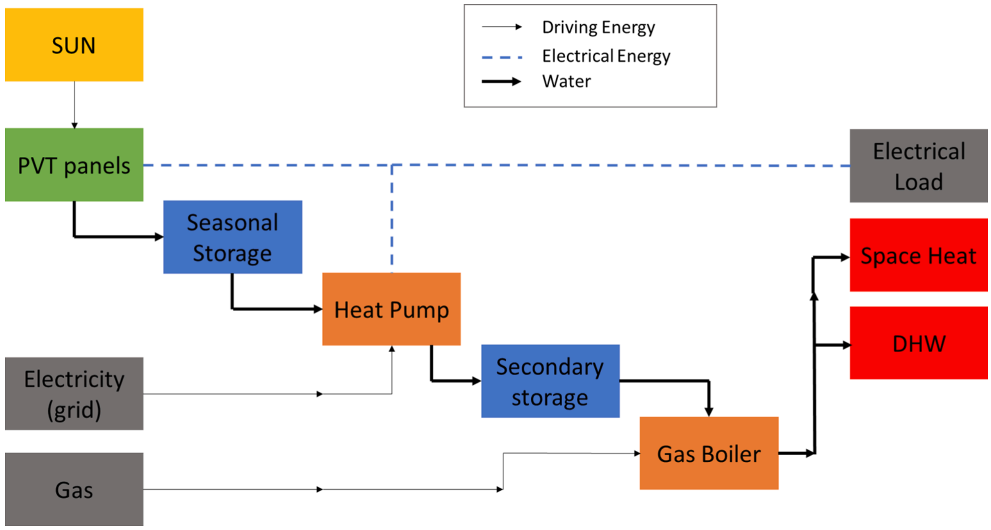

Fig. 2. Visualization of the PVT system.

2.2. *Simulation of the installation*

The project specifications comply with the Regulation of Thermal Installations in Buildings (*Reglamento de Instalaciones Térmicas en los Edificios*, RITE) [60]. The layout was elaborated in TRNSYS v.18 [61]. It is the leader in the simulation of transient systems with a modular structure which uses libraries with standard components (called "types") found in thermal and electrical installations. Each type has its inputs and associated parameter values, as well as some outputs obtained from internal physical equations. Auxiliary types were also required to complete the installation (pumps, valves, piping, controllers, counters, etc.). It also includes routines and/or new types which handle data on the weather and the demand and which represent and aggregate the outputs of the simulation for a further 3E analysis. The weather data were obtained from an external software, Meteonorm [62], which uses data from the National Database [63]. The demands were obtained as described in Section 2.1. A comparison was performed between the climate data employed in the simulation of the heat load in the DesignBuilder and those used in TRNSYS, and the results showed a minor deviation.

Fig. 2 shows the main building blocks of the installation. The demand for the installation components (E_{SYS}) is composed by the HP energy consumption (E_{HP}) as well as by other electrical needs (E_{other_comp}) of the heating installation (Equation (1)). Electrical energy production of the PVTs (E^{ac}_{PVT}) after the transformation of the direct current (E^{dc}_{PVT}) into the alternating current is then compared with the demand: if it is higher, the excess of electricity (E_{to_grid}) goes to cover other needs of the building (Equation (2)); if it is lower, additional electricity is provided by the conventional electrical grid (E_{from_grid}) (Equation (3)).

$$E_{SYS} = E_{HP} + E_{other\_comp} \tag{1}$$

$$E^{ac}_{PVT} = E_{PVT\_to\_SYS} + E_{to\_grid} \tag{2}$$

$$E_{SYS} = E_{PVT\_to\_SYS} + E_{from\_grid} \tag{3}$$

Note that the HP operates in heating mode by providing a heat source at high temperature to produce DHW and heat for the space heating installation.

2.3. *Key performance indicators*

A Key Performance Indicator (KPI) measures the performance level of a process. Definition and evaluation of the appropriate KPIs provides helpful and valuable data extraction for further comparison between different installations and decision-making. A recent publication [64] in Task 60 of the IEA [22] defined energy, economic and environmental KPIs for PVT systems. They are summarized in the following subsections.

2.3.1. *Energy-based KPIs*

Six energy KPIs were selected to cover different facets of the analysis. The area-specific indicators represent the normalization of thermal (q^{gross}_{PVT}) and electricity ($e^{DC,gross}_{PVT}$) production of the PVT panels in accordance with their gross area (A^{gross}_{PVT}). This way, different PVT models and installations may easily be compared among them.

The solar utilization ratio (ω) describes the efficiency of a collector field (production) over a specified period (in general, one year). Within the framework of this project, it can be applied to the thermal, electrical, or combined performances. These ratios are defined as:

$$\omega^{gross}_{PVT,th} = \frac{Q_{PVT}}{\int G_{col}dt^{*}A^{gross}_{PVT}} \tag{4}$$

$$\omega^{gross}_{PVT,el} = \frac{E^{dc}_{PVT}}{\int G_{col}dt^{*}A^{gross}_{PVT}} \tag{5}$$

$$\omega^{gross}_{PVT,en} = \frac{Q_{PVT} + E^{dc}_{PVT}}{\int G_{col}dt^{*}A^{gross}_{PVT}} \tag{6}$$

where G_{col} is the solar irradiation per area in the collector plane.

The Performance Ratio (PR) is the ratio of effectively produced energy (used) with respect to the energy which would be produced if the system was continuously working at its nominal efficiency at Standard Testing Conditions (STC). It has been widely employed in photovoltaic installations because of the valuable information it provides [65]. This concept has also been applied to a PVT installation.

$$PR_{PVT} = \frac{E^{ac}_{PVT}}{\int G_{col}dt^{*}A^{gross}_{PVT}\,\eta^{dc,gross,STC}_{PVT,el}} \tag{7}$$

where E^{ac}_{PVT} is the electrical production of the PVT panels after the inverter (useful energy) and $\eta^{dc,gross,STC}_{PVT,el}$ is the electrical efficiency of the PVT collectors (under STC).

The operative temperature of the thermal collector has an essential influence on its thermal and electrical performance. The characteristic operative temperature is then a new KPI defined as:

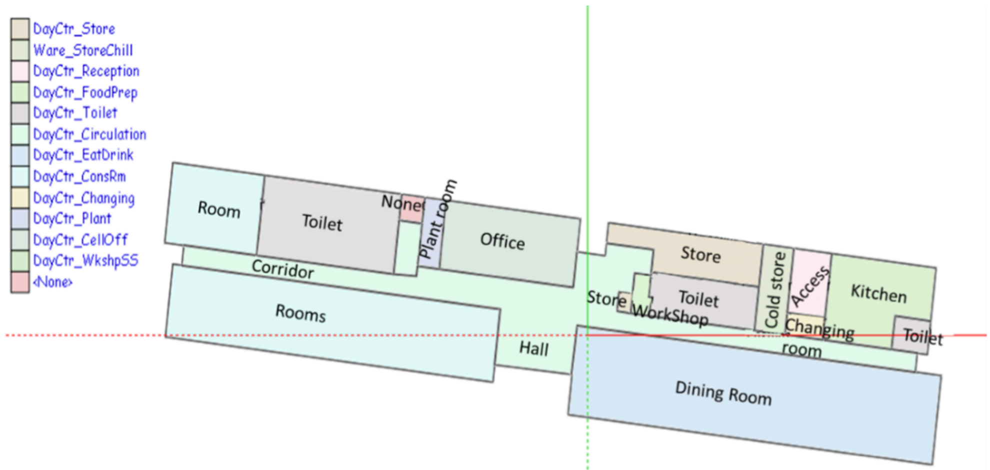

Fig. 3. Distribution plan of the ground floor of the building.

$$\vartheta^{m}_{char,power} = \frac{\int\left(\vartheta_m \cdot \dot{Q}_{PVT}\right)dt}{\int \dot{Q}_{PVT}dt} \tag{8}$$

where ϑ_m is the operative temperature of the PVT panel at each time step (the average between the inlet and outlet fluid temperature flows) and $\dot{Q}_{PVT}$ is the thermal energy provided by the solar yield at each time step.

The solar fraction is a well-known indicator representing the relation between the produced energy and the final energy consumption of the building. It includes energy losses and can be stated for thermal, electrical, or total energy demand.

Finally, the seasonal performance factor of the HP system represents the ratio between the useful energy production of the HP (Q_{HP}) and the electrical consumption of the entire heating installation (E_{SYS}).

2.3.2. Economic-based KPIs

In addition to being energy-efficient and sustainable, all projects must be economically viable. The financial indicators used for the analyzed project are the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Payback Period (PB). In Spain, an investment is recommended when IRR in RES-based installations is higher than 7.09% [66].

The Levelized Cost of Energy concept was developed in Task 60 of the IEA [22] to account for the installation and O&M costs per kWh of energy produced in the facility along its life cycle. This paper considers the Levelized Cost of Heat (LCoH) and the Levelized Cost of Electricity (LCoE).

$$LCOH = \frac{\left[I_0 + \sum_{t=1}^{T=25} OM_t \cdot (1+r)^{-t}\right]_{HS}}{\sum_{t=1}^{T=25} Q_{HP} \cdot (1+r)^{-t}} \tag{9}$$

$$LCOE = \frac{\left[I_0 + \sum_{t=1}^{T=25} (OM_t) \cdot (1+r)^{-t}\right]_{ES}}{\sum_{t=1}^{T=25} E_{PVT} \cdot (1+r)^{-t}} \tag{10}$$

where I_0 is the investment, OM_t is the operation and maintenance cost of the installation, r is the discount rate, Q_{PVT} is the thermal production and E_{PVT} is the electrical production of the PVT field.

2.3.3. Environmental-based KPIs

Two environmental KPIs were considered. The saved fuel is calculated by the amount of heat which is supplied by solar thermal heat from the PVT and is therefore not provided by an auxiliary fuel heater. This can also be considered as an economic KPI.

Table 1
Floor areas for the different spaces on the ground floor.

Community areas	Useful surface [m^2]
Toilets	84.51
Cafeteria	52.92
Dining room	129.04
Plant room and storages	105.5
Administration area	85.90
TV room and living rooms	132.07
Study room	138.20
Workshop	20.81
Rehabilitation rooms	160.62
Changing rooms	77.42
Kitchen	48.91
Corridors	273.84
TOTAL SURFACE	1309.74

$$C_{fuel,avoided} = \frac{Q_{HP}}{\eta_{burner}} \cdot C_{fuel} \tag{11}$$

where Q_{HP} is the thermal production of the heating installation, η_{burner} is the performance of the auxiliary heater and C_{fuel} is the reference cost of the fuel consumed by the auxiliary heater. The seasonal performance of the auxiliary burner (η_{burner}=0.82) includes its consumption when starting up and stopping.

The avoided global warming potential (GWP) represents the reduction of CO_2 emissions, and it is calculated as follows:

$$GWP_{avoided} = \frac{Q_{HP}}{\eta_{burner}} \cdot GWP_{fuel} + E^{AC}_{PVT} \cdot F_{sc} \cdot GWP_{elgrid} \tag{12}$$

The electrical self-consumption fraction F_{sc} was set to 1 since it is expected that the heating system and the building would consume all the electrical production. Data for GWP of fuel (GWP_{fuel}) and electricity from the grid (GWP_{elgrid}) are taken from the Spanish Ministry of Environment [67] with values of 0.182 $kgCO_2/kWh$ and GWP_{elgrid} 0.233 $kgCO_2/kWh$, respectively.

3. Case study

The building of social homes under construction is located in Zaragoza (Spain). Its owner and real estate promoter is SMZV [68], who also operates the facility.

The gross floor area is about 7,317 m^2 and it is divided in five floors. The ground floor (Fig. 3) will be allocated for community activities and there will be different spaces for public use (i.e., catering, administration

Table 2
Areas of each residential floor.

Areas of each residential floor (1, 2, 3 and 4)	Units	Unitary dimensions [m^2/room]	Useful surface [m^2]
Apartment I	3	62.61	187.83
Apartment II	16	44.62	713.92
Apartment III	1	50.15	50.15
Maintenance room	3	–	9.41
Community rooms	2	–	98.06
Corridors	–	–	191.53

offices, education, and rehabilitation rooms; see Table 1).

The floor plans for the four upper floors contain 20 dwellings and common areas each (80 apartments in total). Three different typologies of apartments are projected according to their size (see Table 2 for details and Fig. 4 for the outside view). Finally, utility spaces for HVAC installation and other equipment are projected on the roof.

DesignBuilder allows to quickly enter the spatial distribution of the building with the help of the drawings. As already explained, space heating and DHW demand have been calculated in accordance with the defined purposes of the spaces in the building. The ground floor spaces and the common areas have been considered as a day care center. Thermal zones of the apartments have been defined according to the standard comfort in a dwelling (see Table 3). The community spaces have a daytime schedule during weekdays, and a partial occupation during the summer months has been considered. For homes, a partial use of the services (electricity, heating) during weekdays was contemplated.

The building has had two different well-insulated façade types, depending on the orientation. Both types have a ventilated system and are made of precast concrete. Thermal transmittance of façades has a value of 0.445 W/(m^2 K). Flat roofs with a similar composition present the enclosure with thermal transmittance of 0.320 W/(m^2 K). Thermal transmittance of the floor in contact with the ground is 0.270 W/(m^2 K). External joinery is composed of low-transmittance glass and aluminum joinery and has a global thermal transmittance of 1.6 W/(m^2 K). Internal compartmentalization uses gypsum wallboard with different qualities and thicknesses.

The installation aims to reduce the external energy employed for the demands for DHW and heating. A mechanical ventilation system was designed with a flow of 12.5 $L/(sperson)$ to maintain good air quality. Thus, the required thermal energy poses a relevant portion of the final consumption of the installation (34%). The Air Handling Unit (AHU) includes a heat exchanger section that contributes to the reduction of the energy demand. Hot water produced in the PVT panels is employed to feed the heat demand of the AHU posing as its water coil. Electricity production of the PVT panels will also contribute to a significant reduction of the electricity bills for the families.

The initial design sought the maximum coverage of heating and domestic hot water demands. The hybrid solar field comprises 90 PVT panels, model aH72sk, faced south and with a slope of 40°, which are manufactured by Abora Solar in Zaragoza [69]. Each panel has a total area of 1.96 m^2. The thermal specifications of the panels are: 0.7 for optical efficiency and 5.78 $W/(m^2K)$ and 0.00 $W/(m^2K^2)$ for thermal loss coefficients a_1 and a_2, respectively, as supplied by the manufacturer from their validation tests. The rated power of each panel is 350 W_p, and it is composed of 72 PV cells.

The seasonal storage tank (SSWT) has a volume of 100 m^3 and it will be buried in the vicinity of the projected building. It is made of polyester fiberglass (0.35 $W/(mK)$) with 200 mm of high-density polyurethane (0.028 $W/(mK)$) and an external jacketing. Thermal transmittance of the SSWT is around 0.128 $W/(m^2K)$. It constitutes the cold side in the 50 kW_t water-to-water HP included in the project. The selected ON/OFF HP is brand Carrier, model 61WG-020–090 [70], with nominal energy performance of 4.32, which only operates in heating mode. According to the manufacturer, the inlet flow to the HP cold side must be in the range of 5 to 27 °C, and the temperatures of the inlet flow to the hot side between 20 and 65 °C [71]. If the temperatures are not in the specified ranges, the HP switches off automatically to prevent its malfunction. This HP regulation has also been introduced in TRNSYS.

A backup hot storage tank (BHST) of 13 m^3 constitutes the hot side of the HP. As it is directly connected to the users, its preliminary size has been estimated according to the daily demand of DHW and the water demand peaks for space heating consumption.

The summary of the main types employed in TRNSYS for the physical devices in the simulation of the installation is listed in Table 4. The simplified scheme is depicted in Fig. 5.

Control functions have been modeled with type 2 by introducing the controlled variable ranges. The hydraulic system considers pipe losses (type 31), and types 11 and 115 simulate the valves. A unit conversion routine (type 57), integrators (type 24), and calculators have also been

Table 3
Comfort temperatures for the different areas of the building.[68].

Area	Heating temperature [°C]
Storages and maintenance	20
Toilets, bathrooms, and changing rooms	20
Kitchen (Ground floor)	17
Office	20
Rooms of the community center	23
Dwelling	21
Corridors of the residential floors	18
Corridors of the ground floor	20

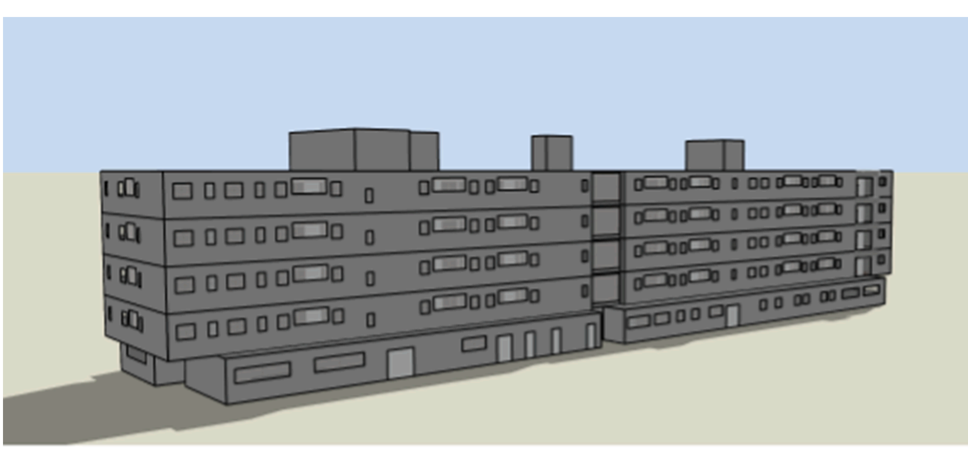

Fig. 4. Outside view of the studied social housing. (Renders from DesignBuilder simulation).

Table 4
Description of the employed types in the simulation of the installation in TRNSYS.

Element	Type in TRNSYS	Input data	Outputs
PVT panels	–	- Solar radiation. - Ambient temperature. - Inlet flow mass and its temperature. - Number of PVT panels, dimensions, and their technical characteristics.	- Outflow and its temperature. - Electrical production.
SSWT and BHST	156	- Ground temperature (SSWT) and ambient temperature (BHST).- Inlet flow mass and its temperature (cold and hot side) . - Dimensions, fluid properties, and loss coefficients.	- Outflow and its temperature (cold and hot side).- Temperatures of the fluid inside the tank (stratification) .
Water-to-water heat pump	927	- Inlet flow mass and its temperature (cold and hot side). - Heat capacity and electrical consumption.- Control function (ON/OFF) is dependent on the needs of the installation and the temperature range of the working flow.	- Outflow and its temperature (cold and hot side). - Electrical consumption.
Impulsion pumps	114	- Inlet flow mass and its temperature.- Control function (ON/OFF) .	- Outflow and its temperature. - Electrical consumption.
Inverter	48	- DC electrical production. - Efficiency. - Electrical demand.	- AC electrical production. - Excess electricity. - Self-consumption.
Auxiliary heater	138	- Inlet flow mass and its temperature. - Efficiency. - Heating capacity. - Setpoint Temperature.	- Outflow and its temperature. - Energy consumption.
Aerotherm	5 g	- Inlet flow mass and its temperature (cold and hot side).- Control function (ON/OFF) is dependent on the range temperature of the working flow.	- Outflow and its temperature.
Space heating demand	9 + Calculator Assembly	- Hourly space heating demand in kWh calculated with the help of DesignBuilder.	- A mass flow that supplies heat to the space heating installation.
DHW demand	14	- Hourly DHW demand in kg/h calculated with the help of DesignBuilder.	- DHW needs.

linked in the model.

The model considers variable tap water temperatures throughout the year. The DHW and heating demands are imported from DesignBuilder. For DHW, the required mass flow profiles have been modeled with type 14. The input flows to supply the space heating demands to the HP uses type 9. The weather data are also imported to TRNSYS by selecting the type 15 applied to conditions in Zaragoza. Types 25 and 65 export the results from the TRNSYS model to editable files.

The cost of the investment has been estimated from data provided by the suppliers and their installers. The installation cost for SAHP is estimated at €120,365, and the seasonal storage tank will have a value of 350 €/m^3 leading to a total cost of the investment at €155,355. The life span of the facility is 25 years. Annual maintenance costs are 1% of the investment cost, and the discount rate was set to 4%. Current electricity and gas prices for a home in Spain average 0.1458 €/kWh and 0.06 €/kWh, respectively [72].

4. Results and discussion

4.1. Energy results

Yearly energy results of the energy system are summarized in Table 5. The building's space heating demand is 243,252 $kWh/year$ and its DHW demand is 47,406 $kWh/year$. That is to say, the demand for heating purposes accounts for 82.6% of the total thermal demand. The DHW demand profile varies depending on whether it is a weekday or a weekend day. Also, a partial occupation was initially scheduled for the summer period. Fig. 6 shows the hourly DHW demand on a regular day. Average daily DHW demand of the building is 5,040 L/day.

Despite this, a nearly constant demand of DHW is observed compared to the space heating demand, which has a marked seasonal profile (Fig. 7). Therefore, it is clear that a seasonal storage is the suitable solution for the heating installation, since the HP requires higher temperatures in winter to increase its COP based on solar energy.

Annual electricity demand is 225,240 $kWh/year$. The demand is higher in the cold months because the HP power is consumed for heating. In summer, there may be other demands for electricity in the future, due to air conditioning. However, a centralized cooling system has not been considered in the initial design of the building. To sum up in specific terms, the studied building has a space heating demand of 33.6 kWh/m^2year, from which about 7.1 kWh/m^2year are dedicated to DHW. Further, the electricity demand ratio is 29.7 $kWh/m^2\ year$.

Solar irradiance on the PVT panel at the studied location is 1,796 kWh/(m^{2}year). Consequently, the total raw solar energy that falls in the solar field is 355,608 kWh/year. Solar thermal production of the PVT panels is 80,869 kWh/year, leading to a solar thermal utilization ratio of 0.255. On the other hand, raw electricity production is 56,189 kWh/year, which means that the electrical utilization ratio constitutes 15.8%. Fig. 8 shows the annual solar energy production of the 90 PVT collectors. Electricity production remains approximately constant during the studied period. However, hot water production is highly influenced by climatic conditions and the seasonal storage tank size. More heat output from the PVT panels during the summer months was expected, but the installation is really charging the SSWT due to the unique DHW demand. Thus, the main advantage of seasonal storage, to delay the heat supply up to the periods when it is highly demanded, is herewith easily obtained.

Fig. 9 and Fig. 10 show the evolution of the electrical distribution of the produced energy by the PVT and the energy balance of the HP. The proper electricity production is 53,386 $kWh/year$. The electricity destined to feed the electrical consumption of the HP is 31.5%. This means that 36,568 $kWh/year$ are used to supply other needs of the social housing. The annual electricity consumption of the HP is 38,975 $kWh/year$. Therefore, the self-consumption reaches 43.2% of the HP annual consumption. The thermal energy input in the HP (coming from the seasonal storage) accounts for 103,043 $kWh/year$, and the thermal energy of the hot side of the heat pump is 142,018 $kWh/year$. The seasonal performance ratio of the HP is 3.6.

On the other hand, the demand-side analysis allows the calculation of the coverage ratios of the facility. Fig. 11 shows the space heating and DHW demands of the building and the heating provided by the installation. Both thermal loads are unmet, since the available roof space is insufficient to cover the needs of the whole building. An auxiliary heating system is then required (a gas boiler), which supplies 178,245 $kWh/year$ to the space heating installation and 9,554 $kWh/year$ to DHW.

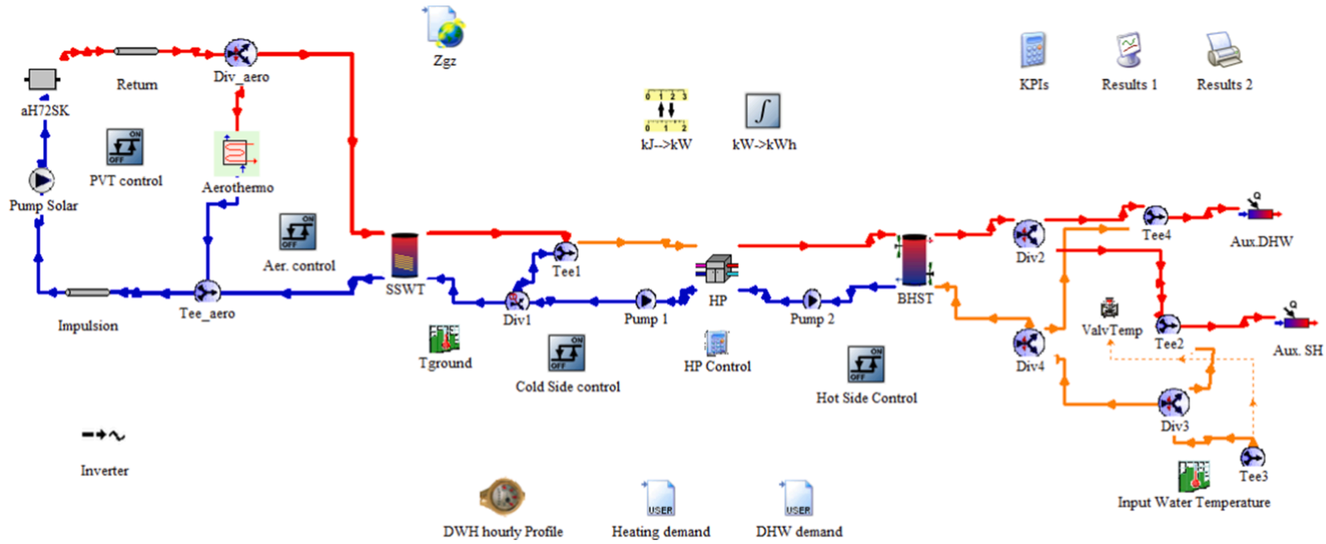

Fig. 5. Scheme of the installation model in TRNSYS.

Table 5
Overview table of energy production and consumption of the installation.

Energy	*kWh/year*	Energy	*kWh/year*
Q_{PVT}	80,869	E_{HP}	38,975
E_{PVT}^{dc}	56,189	Q_{HP}	142,018
E_{PVT}^{ac}	53,386	Q_{DHW_aux}	9,554
$E_{PVT_{toSYS}}$	16,818	Q_{SH_aux}	178,245
E_{other_comp}	36,568		

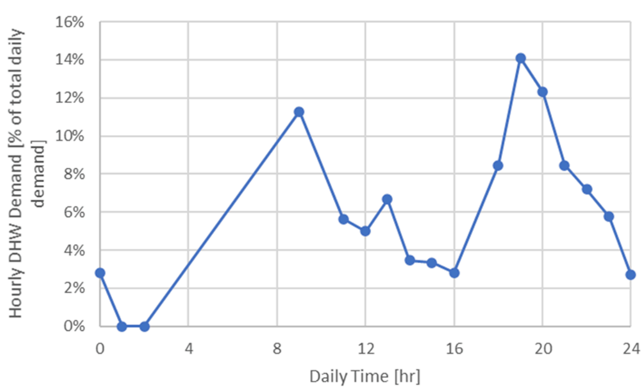

Fig. 6. DHW hourly demand.

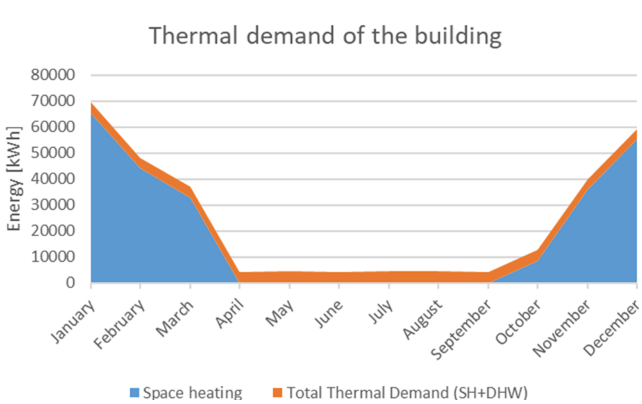

Fig. 7. Thermal demand of the building.

The DHW coverage is 79.8%, thereby fulfilling the Spanish legal requirements [55,60]. The auxiliary heater is only (and partly) used for DHW in winter. Unfortunately, the space heating coverage is only 26.7%.

4.2. *Economic results*

The internal rate of return of 10.9% shows that the investment is highly recommended. The LCoH and LCoE achieved with the implementation of the studied installation are 0.0137 €/*kWh* and 0.0365 €/*kWh*, respectively, and both are below the supplier prices in Spain. The avoided global warming potential is 44,180 $kgCO_2/year$. Table 6 includes these and other energy, economic, and environmental indicators (selected KPIs).

4.3. *Sensitivity analysis*

Three key-design parameters of the base-case heating installation have been increased up to the physical space limitations of the new building: the number of PVT panels (case 1), the seasonal storage water tank (SSWT) volume (case 2), and the HP heat capacity (case 3). The ultimate aim is to obtain a higher coverage of solar energy for the heating demands. Results of the three studied cases can be seen in Table 7 (economic and environmental KPIs) and Fig. 12 (most of the energy KPIs).

With the addition of 10 PVT panels in case 1, this increment in the solar field is translated into an increment in solar coverage of the space heating demand up to 53%. Thus, this measure induces better financial results than the base case installation. Despite having higher investment costs, the payback period would be lower. Additionally, the LCoE and LCoH are also reduced.

In case 2, the volume of the seasonal storage tank is tripled. Thus, an increment in the thermal capacity production of the PVT panels is observed. Nevertheless, the additional investment cost of the SSWT worsens economic KPIs.

Finally, in case 3, the produced energy shows the worst adaptation to the building demands. When the HP capacity is raised up to 69 kWt, it has a discontinuous operation because of the high-temperature limit found in the BHST, which should be re-grown accordingly. In any case, the higher HP capacity encourages the evacuation of the seasonal storage tank, and the thermal production of the PVT panels is higher than in the Base Case. Given the above, it is concluded that Case 1 is the optimal design for this building.

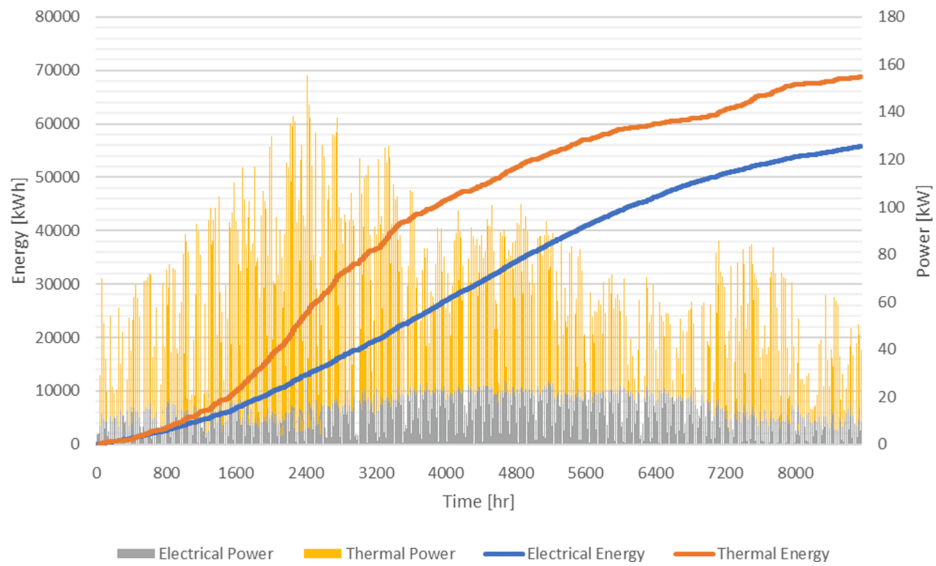

Fig. 8. Thermal and electrical production of the PVT panels.

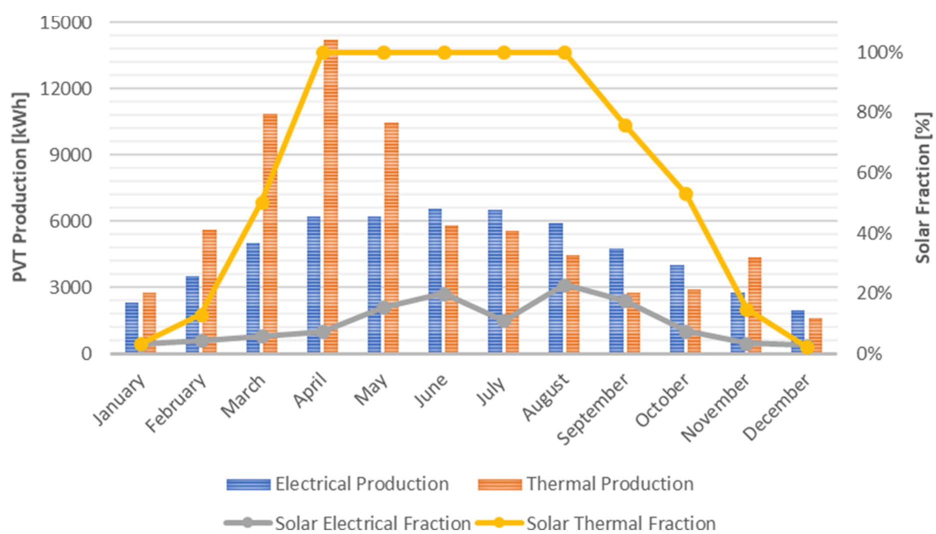

Fig. 9. Monthly production and solar coverage results.

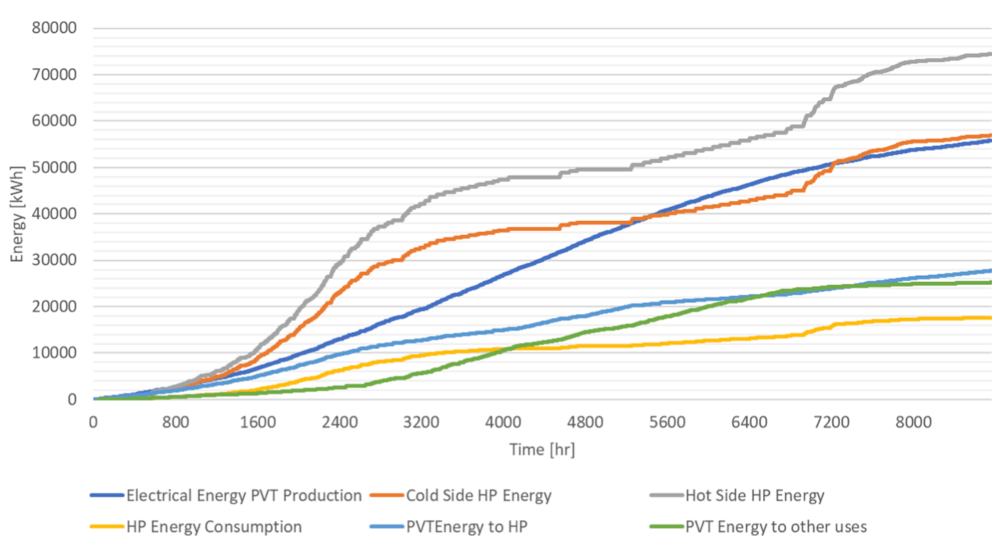

Fig. 10. Production and consumption of energy in the heating installation.

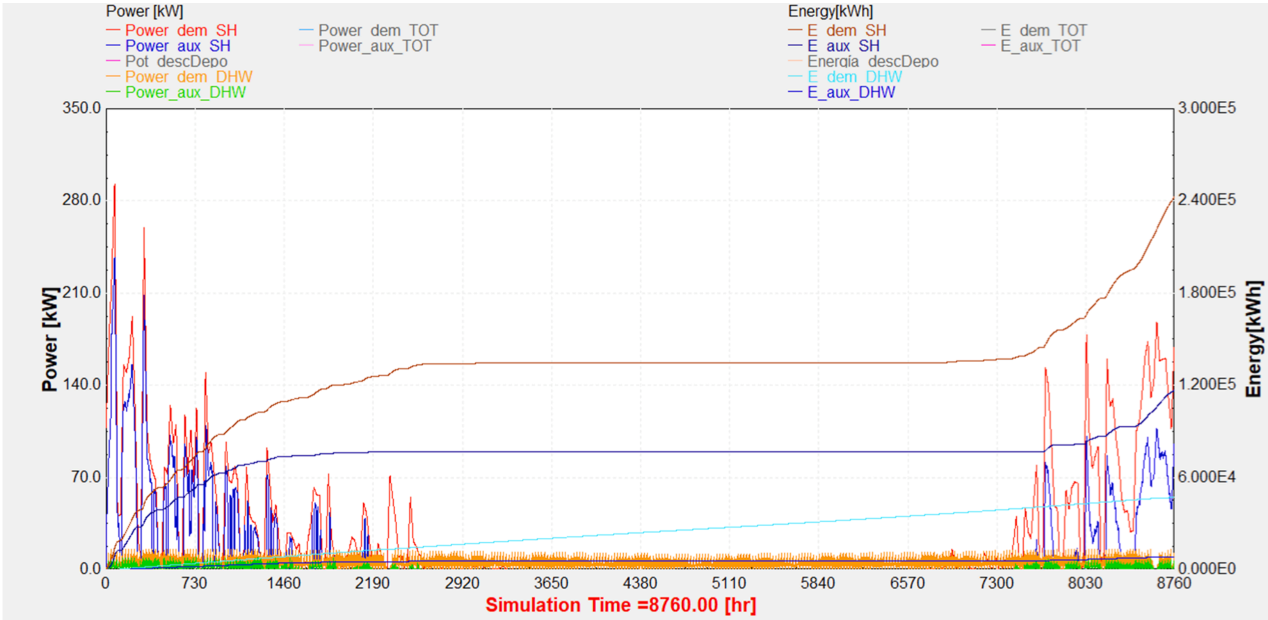

Fig. 11. Thermal demand of the building.

Table 6
Key Performance Indicators analyzed in the project. Base Case.

Energy	Area-specific solar heat yield	$q_{PVT}^{gross}[kWh/m^2]$	408.429
	Area-specific solar electricity yield	$e_{PVT}^{DC,gross}[kWh/m^2]$	283.781
	Solar thermal utilization ratio	$\omega_{PVT,th}^{gross}$	0.227
	Solar electrical utilization ratio	$\omega_{PVT,el}^{gross}$	0.158
	Solar combined energy utilization ratio	$\omega_{PVT,en}^{gross}$	0.385
	Electrical performance ratio	PR_{PVT}	0.822
	Characteristic operating temperature	$\vartheta_{char,power}^{m}$	44.52
	Solar thermal fraction	$f_{sol,th}$	0.263
	Solar electrical fraction	$f_{sol,el}$	0.075
	Solar combined energy fraction	$f_{sol,en}$	0.181
	Seasonal performance fraction of the HP	SPF_{SHP}	3.6
Economics	Net present value	*NPV [€]*	129,714.16
	Internal rate of return	*IRR [%]*	10.85
	Payback	*PB [year]*	8.5
	Levelized cost of heat	LCoH [€/kWh]	0.014
	Levelized cost of electricity	LCoE [€/kWh]	0.037
Environment	Saved fuel cost	$C_{fuel,avoided}$ [€/$year$]	10,464.26
	Avoided global warming potential	$GWP_{avoided}[kgCO_2/year]$	44,180.36

5. Discussion

From what the authors know so far, there is no similar facility in terms of end-users, which can be compared with the one proposed here. An equivalent example in terms of configuration based on a SSWT and SAHP is located precisely in Zaragoza [16]. Note that the dimensions of that project are much more prominent since it is an academic building under construction at the University, and PV was also mounted to increase the power coverage for the educational purposes. Thus, different KPIs were found for that project: the value of one of them is worse (PB is 15.4 years), whereas the value of another one is better (60% of solar coverage for the thermal demands). In any case, reference values given by the guide report defining the KPIs [64] show that all the values are within the acceptable ranges for a profitable installation, as is summarized below.

In regard to the area-specific solar thermal energy yield, the installation value is 408.5 $kWh/m^2 year$, whereas the minimum recommended for a profitable DHW and SH installation in Europe is 360 $kWh/m^2\ year$ [73]. The electrical area-specific ratio is more significant than the one shown in the KPI reference document. The solar thermal utilization ratio is higher than the average of the studied installations. Moreover, the electrical utilization ratio of the projected installation is the best when compared with similar facilities with PVT collectors. The seasonal performance factor of the HP has been compared with that of four structures assisted with the solar energy, and this study shows that our proposal can achieve the highest value.

Regarding the technical novelty exposed here, the implementation of a PVT panel field with a seasonal storage tank allows a better adaptation between the heat production and the energy needs of the building and even provides some excess electricity for other types of consumption. This is because the excess heat produced by the PVT collectors is collected in the buried tank in the summer months and delivered when the demand for heating becomes most crucial in winter. The increase of the demand coverage is obtained by the high COP found for the SAHP coupled to this SSWT as the cold side. In any case, it should be examined whether this increase in the COP outweighs the direct use of the tank for conventional heating with fan coils or radiators in the winter period, in favor of using a ASHP which is directly connected to the solar field, as proposed in [74]. Fig. 13 shows the average temperature of hybrid solar panels, and it proves that this source of heat is insufficient to provide space heating for the building.

Levelized cost of energy is closely related to the gross area of installed PVT. On average, LCoH and LCoE are less than 0.1 €/kWh, a much lower cost than the current price of electricity in Europe. This installation will avoid more global warming potential than other studied and compared facilities. The average of avoided GWP is 130 $kgCO_2/m^2\ year$ and our installation will reach the goal of avoiding more than 250 $kgCO_2/m^2\ year$.

Note that the KPI definitions are not technology-specific. Therefore, their values can be seen together to decide on the best possible

Table 7
Key Performance Indicators of the different studied cases in the parametric analysis.

	Base Case	**Case 1**	**Case 2**	**Case 3**
Number of PVT panels	90	**100**	90	90
Volume of the SSWT $[m^3]$	100	100	**300**	100
Heat capacity of the HP [kW]	50	50	50	**69**
Volume of the BHST $[m^3]$	13	13	13	13
Investment [€]	155,355	166,833	225,355	161,215
NPV	€129,714	€153,887	€86,636	€95,980
IRR	10.85%	11.50%	7.36%	9.04%
PB [year]	8.5	8.1	11.3	9.8
LCoH $[€/kWh]$	0.0136	0.0128	0.0172	0.0175
LCoE $[€/kWh]$	0.0366	0.0356	0.0520	0.0369
$C_{fuel,avoided}$ $[€/year]$	10,464	11,955	12,029	8,454
$GWP_{avoided}$ $[kgCO_2/year]$	44,180	49,967	49,180	38,444

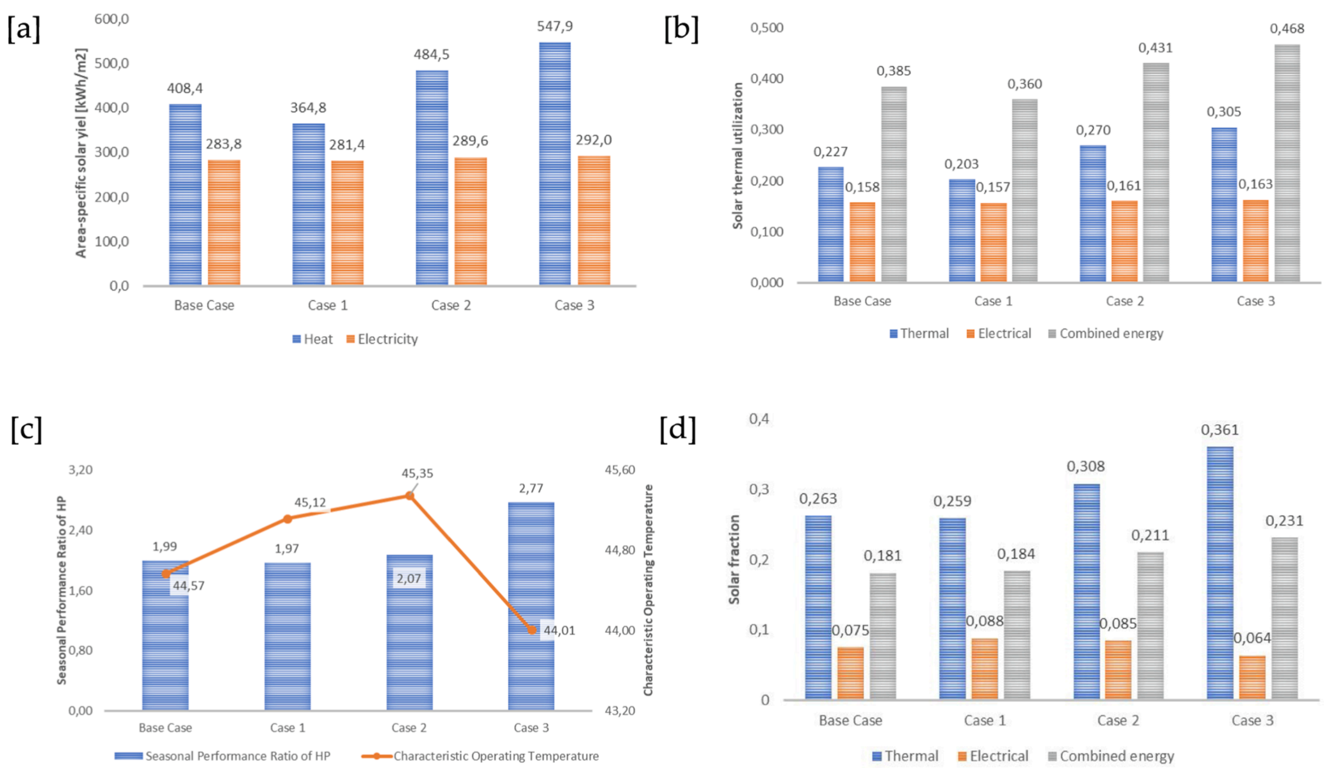

Fig. 12. Energy KPIs from the sensitivity analysis. [a] Area-specific solar yields. [b] Solar utilization ratios. [c] HP Seasonal performance ratio and Characteristic operating temperature. [d] Solar fractions.

installation for each end purpose. In short, they are the first step towards comparison of various identical object schemes.

6. Conclusions

This study has analyzed a facility based on PVT hybrid panels with a seasonal storage tank (SSWT) coupled to a high-efficiency SAHP as a partial solution to cover the heat demand of a building of social homes.

In the process of designing this scheme, the adequate combination of software devoted explicitly to estimating the climatization and power demands of a building (DesignBuilder) and the dynamic process simulator (TRNSYS) allowed a detailed yet flexible solution for the analysis of innovative proposals to reduce the external dependency of the conventional supplies. To achieve this, training time was required for a productive use of both types of software.

Furthermore, some KPIs have been defined and then used to allow a complete study of installation viability, as well as to enable comparison with other facilities found in the literature with similar aims but alternate configurations. Regarding the energy KPIs, the normalized thermal production of the PVT panels is around 550 kWh/m^2 $year$. This way, solar coverage of the entire thermal demand is 36.1%. On the other hand, the normalized electrical production and solar electrical coverage are up to 292 kWh/m^2 $year$ and 9%, respectively. The seasonal performance factor of the installed heat pump has a value of 1.9 in the optimized design. Concerning the economic KPIs, the calculated PB was 8.1 years, leading to LCoH and LCoE of 0.0128 and 0.0356 €/kWh, respectively. The environmental KPIs presented a saved fuel cost of almost 12,000 €/year and avoided GWP of about 50,000 kgCO_2/year.

As a result of the good values found within the KPIs, the studied facility will be implemented in the building of social homes. Its installation will reduce energy bills; the tenants who suffer from limited economic resources will be able to maintain reasonable comfort in their

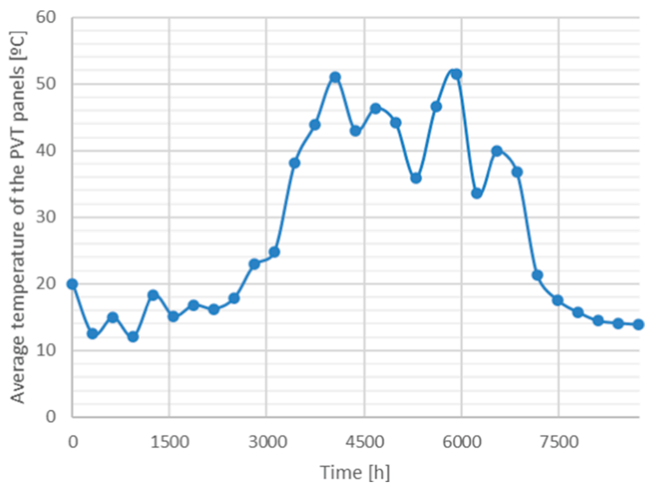

Fig. 13. The average temperature of solar PVT panels.

homes. Together with savings measures which are already implemented for new buildings, the authors consider that this innovative scheme could represent a suitable path for the development of the residential sector and specifically for the social housing. Additional investment required for the SSWT could be subsidized by the municipalities and/or other public authorities like the SMZV, thus taking steps towards social equity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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