Technoeconomic modelling and optimisation of solar combined heat and power systems based on flat-box PVT collectors for domestic applications

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**A B S T R A C T**

We investigate solar combined heat and power (S-CHP) systems based on hybrid photovoltaic-thermal (PVT) collectors for the simultaneous provision of domestic hot water (DHW), space heating (SH) and power to single-family homes. The systems include PVT collectors with a polycarbonate flat-box structure design, a water storage tank, an auxiliary heater and a battery storage subsystem. A methodology is developed for modelling the energetic and economic performance of such PVT-based S-CHP systems, which is used to optimally size and operate systems for covering the energy demands of single-family reference households at three selected locations: Athens (Greece), London (UK) and Zaragoza (Spain). The results show that optimised systems are capable of covering \(~65%\) of the annual household electricity demands in Athens, London and Zaragoza when employing 14.0, 17.0 and 12.4 m\textsuperscript{2} collector array areas respectively, while also covering a significant fraction of the thermal energy demands in Athens (\(~60\%\)) and Zaragoza (\(~45\%\)); even in London, almost 30% of the reference household’s thermal demand is covered by such a system. A corresponding economic analysis reveals that, despite the suitable weather conditions for implementing such solar-energy systems, the payback time (PBT) of the optimised S-CHP system in Athens is 15.6 years in contrast to the 11.6 years predicted for Zaragoza, due to the lower electricity prices in Greece. On the other hand, the high carbon emission factor of the electricity grid in Greece makes these systems particularly promising at this location. Specifically, the investigated systems have the potential to displace 3.87, 1.65 and 1.54 tons of CO\textsubscript{2} per year in Athens, London and Zaragoza, when substituting the conventional means for household energy provision (i.e. grid electricity and gas-fired boilers). Furthermore, it is demonstrated that the optimised systems outperform benchmark equivalent systems comprising conventional sheet-and-tube PVT collectors in all studied cases, by covering similar or slightly (up to 3%) higher fractions of the household electrical and thermal demands with 9–11% lower PBTs, and that PV-only solutions displace 3.56, 1.21, 1.22 tCO\textsubscript{2}/year (up to \(\sim 20–25\%\) lower) for the same area. Overall, the results suggest that the newly proposed polymeric flat-box PVT collector designs are an improved economic proposition over their conventional equivalents, but that the cost of this technology still remains high relative to PV and that if decarbonisation is a desirable goal, especially in high population-density regions with space restrictions, it is important to consider how to promote this technology.

**1. Introduction**

The utilisation of solar energy is a key enabler of the transition to a clean and sustainable energy future \cite{1,2}. Despite the widespread acceptance, significant market growth and deployment of photovoltaic (PV) systems, and the wide range of products available on the market, some challenges remain that hinder their potential. Of particular interest are the limited conversion efficiencies experienced at elevated operation temperatures and the greater thermal cycling experienced (passively) in response to external weather conditions, both of which also act to damage the PV cells. This has motivated important research into cooling techniques for the thermal regulation of PV modules \cite{3}, which has led to the proposal of hybrid photovoltaic-thermal (PVT) collectors, comprising a PV module typically laminated on top of a thermal absorber for heat removal, that are therefore capable of generating both electrical and thermal outputs from the same collector area \cite{4}. Similarly to conventional PV and solar-thermal (ST) systems, PVT systems are a means of moving energy generation closer to the point of

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Nomenclature

Abbreviations

BSD (monthly) battery self-discharge rate  
DHW domestic hot water  
FIT feed-in tariff  
FS fuel saving  
IEA International Energy Agency  
pc-Si poly-crystalline silicon  
PC polycarbonate  
PBT payback time  
PV photovoltaic  
PVT photovoltaic-thermal system  
PVT-w photovoltaic-thermal water system  
RHI renewable heat incentive  
SEER seasonal energy efficiency ratio  
SH space heating  
ST solar thermal  
TIC transparent insulating cover  
LCC life cycle cost  
PCE levelised production cost  
NPV net present value  
S-CHP solar combined heat and power  
SOC state of charge  
UFH (radiant) underfloor heating  

Symbols

\( A_{c} \) PVT collector aperture area (m²)  
\( A_{coil} \) coil heat transfer area (m²)  
\( A_{VT} \) total PVT collectors area (m²)  
\( A_{surf,T,n} \) surface area of the tank at node \( n \) (m²)  
\( c_{p} \) specific heat capacity (J/kg·K)  
\( C \) battery capacity (Ah)  
\( C_{conv} \) annual household running costs (€)  
\( c_{e} \) electricity price (€/kWh)  
\( c_{ng} \) natural gas price (€/kWh)  
\( C_{0} \) investment costs (€)  
\( C_{C/D} \) battery charge/discharge capacity (Ah)  
\( C_{O&M} \) operation and maintenance (O&M) costs (€/yr)  
\( C_{S-CHP} \) annual running costs of household with S-CHP system (€/yr)  
\( C_{T} \) battery energy capacity (Wh)  
\( d \) discount rate (%)  
\( D_{h} \) hydraulic diameter (m)  
\( D_{t} \) tank diameter (m)  
\( E \) energy (Wh)  
\( f \) friction factor (−)  
\( H \) height (m)  
\( i \) time step (−)  
\( i_{p} \) fuel inflation rate (%)  
\( I_{C/D} \) actual charge and discharge current (A)  
\( I_{C/D0} \) maximum allowed charge and discharge current (A)  
\( I_{T} \) total solar irradiance per meter square (W/m²)  
\( L_{c} \) levelised cost (€/yr)  
\( m_{b} \) storage tank water mass (kg)  
\( m \) mass flow-rate (kg/s)  
\( m_{c} \) mass flow-rate per PVT collector (kg/s)  
\( m_{CT} \) total mass flow-rate through the PVT collectors (kg/s)  
\( n \) node (−)  
\( n \) system lifetime (yr)  
\( N \) total number of PVT collectors (−)  
\( N_{t} \) total number of tank nodes (−)  

Greek

\( \beta \) PVT collector tilt angle (°)  
\( \lambda_{eff} \) effective vertical thermal conductivity in storage tank (W/m·K)  
\( \Delta C \) change in battery capacity (Ah)  
\( \Delta p \) total pressure drop through S-CHP system (Pa)  
\( \Delta t \) time step (s)  
\( \Delta T \) temperature difference (−)  
\( \epsilon \) heat exchanger effectiveness (−)  
\( \eta \) efficiency (%)  
\( \rho \) density (kg/m³)  

Subscripts

\( a \) ambient  
\( aux \) auxiliary heat  
\( bat \) batteries  
\( BC \) battery charge  
\( BD \) battery discharge  
\( c \) PVT collector  
\( cc \) charge controller  
\( cond \) conduction  
\( conv \) conventional means  
\( cov \) covered  
\( ct \) from PVT collector to storage tank  
\( D \) household demand  
\( DT \) total household demand  
\( dump \) heat rejected to the atmosphere  
\( e \) electrical  
\( exp \) surplus electricity exported to the grid  
\( gen \) generated  
\( grid \) electricity imported from the grid  
\( hh \) half-hourly  
\( in \) inlet  
\( int \) surroundings of the storage tank  
\( inv \) inverter  
\( loss \) losses  
\( net \) net energy/power in the household  
\( out \) outlet  
\( o \) optical  
\( PVT \) PVT collector outlet  
\( gen \) energy/power generated by the PVT collectors  
\( r \) reduced  
\( t \) water storage tank  
\( th \) thermal  
\( T \) total  
\( TDeq \) total household demand converted to “equivalent” electricity  
\( Teeq \) total “equivalent” electricity  
\( Tpe \) total primary energy  
\( w \) water  
\( win \) mains water entering the water storage tank
use, and thereby of reducing the demands on costly energy distribution infrastructure [5]. This makes these systems particularly promising for distributed deployment in domestic applications, which are at the focus of this work. Thus, a solar combined heat and power (S-CHP) system based on hybrid PVT collectors is hereby proposed, studied and optimised from both energetic and economic perspectives. This study extends earlier work that considered PV-only systems [6,7] and/or separate S-CHP systems based on ST collectors [8] for heat and power provision to buildings, including such systems based on low-temperature thermodynamic power cycles [9–12], as well as some limited attempts to consider PVT-based S-CHP systems [13].

The most widely studied absorber-exchanger design in PVT collectors is that of parallel copper tubes (sheet-and-tube) with water or water-glycol mixtures as the heat transfer fluid [14–18], which is also the one used most commonly in commercially-available collectors [19]. In this design, the amount of heat that can be extracted, and thus the overall efficiency that can be achieved, depend on the collector fin efficiency and the tube bonding quality [20]. Consequently, several investigators have made significant efforts to optimise the design of these collectors by paying attention to these design aspects [16,17], while others have proposed an alternative flat-box structure with square or rectangular channels in order to significantly increase the heat transfer area between the absorber plate and the cooling fluid [14–20,25]. Some of these studies [14,20,25] have considered extruded aluminium alloy as the absorber-exchanger material, while others [21,23,24] have proposed polycarbonate (PC) as the material of choice in order to lower the cost and weight of the collector. The work presented here focuses on a novel PVT water collector designed and modelled in previous research [26], based on a PC 3 × 2 mm flat-box structure. Previous research undertaken by the authors [26] concluded that this absorber-exchanger design can achieve a 4% higher optical efficiency and a 15% lower heat loss coefficient, leading also to a 9% reduction in weight and a 21% reduction in investment cost compared to a commercial PVT collector based on a copper sheet-and-tube arrangement.

A number of approaches have been used to estimate the operational characteristics, performance and economics of PVT systems [18,27–30]. Almost all previous studies were based in relatively low-latitude regions with a substantial solar resource, while previous R&D reviews [31] concluded that further work should focus on long term (seasonal, annual) analyses of system performance considering the influence of weather conditions. In this respect, the present research explores the potential of PVT-based S-CHP systems in three different European climates for comparison purposes, including the United Kingdom (UK), which is representative of cooler northern climates with lower levels of solar irradiation. Significantly different results are expected at different locations, not only due to the different environmental conditions, but also due to the different household energy demands, electricity and gas prices, policies and incentives, etc.

The electricity and heat consumed by a household are both strongly dependent on occupant behaviour. Therefore, in order to design and size appropriately an S-CHP system for domestic heating, including space heating (SH) and domestic hot water (DHW), as well as power provision, it is necessary to know these energy profiles [32]. Research in this field has typically considered monthly household energy demand profiles based on degree-days [33], or estimated daily profiles [18,27]. Other studies that did model the building energy-demand profiles, did not include full user profiles and internal gains [34]. More recently, some authors have begun to consider the building energy demands in detail, in particular for the analysis of solar polygeneration systems installed in university buildings [35] and offices [36]. Such efforts include detailed household energy models that can account not only for the specific weather conditions, but also for the transient occupancy profiles and operation schedules of the various household energy consuming devices (i.e. HVAC systems, electric appliances, etc.), thereby providing useful estimates of the household energy demand profiles. In this present research, reference homes have been modelled in EnergyPlus [37], including occupancy profiles and operation schedules, leading to household energy demand estimates at half-hourly time-steps over a whole year. Previous studies [38,39] that considered DHW provision concluded that the use of a stratified storage tank enhances the thermal performance of the PVT systems. However, the provision of space heating by radiant underfloor heating (UFH) with the thermal output of PVT water collectors has not been investigated.

The two main options for increasing the electrical self-consumption of residential S-CHP installations are energy storage and demand-side management (DSM), which can be implemented either as part of separate or combined strategies [40,42]. This research considers energy storage, both thermally which is standard in such systems, and also electrically in an attempt to reduce the interaction of the investigated systems with the electrical grid, whose availability/reliability comes at an external cost that is rarely accounted for in similar studies. One of the most common types of battery technology used in PV systems is the lead-acid battery due to its maturity and low-cost, with lithium-ion batteries recently gaining market share although their costs still remain higher [7,43,44]. In this work we focus on the former.

When modelling PVT systems, the temporal resolution chosen for the simulations has been shown to significantly affect system performance predictions [40,41]. A low resolution can lead to an over-estimation of self-consumption, because any mismatch between the instantaneous generation and the load can be smoothed out, depending on how the data is aggregated or downsampled. In Ref. [40], it was concluded that half-hourly data is sufficient for the modelling of an individual building especially in order to capture the behaviour of load profiles during peak power consumption. Therefore, this research considers half-hourly time-steps for the S-CHP system simulations.

In Section 2, we present the modelling methodology and related assumptions that were used in its development, including details of the PVT-based S-CHP system model and parameters, the reference single-family houses modelled in EnergyPlus, the economic analysis undertaken and the economic and environmental parameters. Section 3 contains the main results and an associated discussion, including the selection of the key performance indicators for system sizing, the technoeconomic optimisation of the S-CHP system, the PVT collector operation optimisation, daily analysis and comparison of the optimised S-CHP systems in the different locations. Finally, the main conclusions from this work are summarised in Section 4.

2. Methodology and model definition

A quasi-steady state model of S-CHP systems has been developed in software Engineering Equation Solver (EES) [45], as an extension to a model developed in previous research [46], with the aim of assessing the technoeconomic performance of such systems, in particular when featuring polycarbonate flat-box PVT collector designs and electrical energy storage. System operation and performance are also compared to those of equivalent benchmark systems comprising commercial sheet-and-tube PVT collector. Reference households in different regions are modelled through transient simulations in EnergyPlus [37] to estimate their energy demands in half-hourly steps throughout the year. Together with the weather conditions that are representative of the corresponding geographical locations of these households, the energy demands are used as inputs to the S-CHP system model in EES that simulates system performance in half-hourly time-steps. Key economic characteristics of S-CHP systems, including their capital (investment), running (electricity and natural gas) and operation/maintenance (O&M) costs, are also included in the model. The outputs returned by the model at each half-hourly time-step include the temperatures of the different layers of the PVT collector, the collector water outlet temperature, the water temperatures at each node in the storage tank, the state of charge (SOC) of the batteries, the electrical and thermal energy generated by the complete S-CHP system, the electrical and thermal energy demands of the household covered by the system, the energy,
cost and CO₂ emissions savings, the levelised production cost (LPC) and the payback time (PBT) of the system. The methodological approach is summarised with the help of a block diagram in Fig. 1.

2.1. S-CHP system model

The complete S-CHP model developed this work for the provision of heating (DHW and SH) and power to domestic users is shown in Fig. 2. The core components of this system are: the PVT collector array (Component 1), a pumped water closed-loop circulation loop that connects the PVT collector with the storage tank through an internal heat exchanger (Components 2 and 3), a stratified hot water storage tank (Component 4), an auxiliary heater (Component 6), and electrical storage provided by a number of lead-acid battery units connected to the PVT collectors and to the grid (Component 8). The energy demand breakdown of a reference house modelled in EnergyPlus is integrated as an input to the model together with the weather conditions (ambient temperature and solar irradiance) also taken from EnergyPlus (see Section 2.2). Most of the S-CHP system component parameters can be varied in the model, including: the PVT design (geometry, materials), the PVT collector flow-rate, the number of PVT collectors, the water storage tank volume, and the size and key features of the batteries.

The S-CHP system model was developed under the following assumptions: (i) the incident solar irradiance is absorbed only by the collector [47], and the light absorption by the cover glass and the frame are negligible, (ii) the ambient temperature is uniform around the PVT collector [38, 48], (iii) solar irradiance is uniform on the collector surface, (iv) the temperature dependence of all relevant solid-component material properties can be neglected [49], (v) the water mass flow-rate is distributed uniformly between all riser tubes [38, 50], (vi) free convection in the riser tubes is negligible, (vii) all radiative heat exchanges between the sides of the solar collectors’ channels can be neglected [17, 38, 51, 52], and (viii) the pipes connecting the PVT collectors to the water storage tank are well insulated, such that there are no heat losses to the environment [38].

2.1.1. PVT collector

This study considers a new flat-box PVT collector design and compares this to an equivalent commercially available sheet-and-tube collector, namely the ECOMESH PVT collector by company Endef Engineering [53]. The two main components of the flat-box PVT collector are the PV module and thermal absorber. As in previous work by the same authors [19] and similar modelling attempts [16, 48], a set of energy conservation equations are written that describe the heat fluxes and temperatures through all layers of the collector. The equations are applied separately to each layer of the collector in order to identify the average absorber plate temperature, and to uncover the distribution of the average temperatures and energy flows through all separate component layers that comprise the collector [52, 54]. The main heat transfer mechanisms that have been considered in this work for the different collector layers are shown in Fig. 3. Full details of the collector model can be found in Ref. [26].

The model contains the governing equations of the PVT collector detailed in previous work [26], based on the ASHRAE method [55], which includes parameters describing the PVT geometry (such as fin efficiency, $F$, heat removal factor, $F_h$, overall heat loss coefficient, $U$, etc.), adapted to the flat-box structure.

The aperture area and electrical characteristics of the polymeric flat-box PVT collector have been defined to be equal to those of the equivalent benchmark commercial sheet-and-tube PVT collector [53], i.e. 1.55 m² aperture area, 240 Wp electrical power, 14.7% nominal PV module efficiency and $-0.45\%/K$ PV temperature coefficient. Thus, the two collectors vary only in terms of their thermal performance, as follows (see Fig. 4):

| Collector Type | Performance Equation |
|---------------|----------------------|
| Sheet-and-tube (S&T) PVT collector (benchmark): | $\eta_{th} = 0.700 - 3.937 \cdot \frac{T_i - 0.0155 \cdot I}{T_i}$ |
| Polycarbonate (PC) 3 × 2 flat-box PVT collector: | $\eta_{th} = 0.726 - 3.325 \cdot \frac{T_i - 0.0176 \cdot I}{T_i}$ |

As mentioned above, detailed technical specifications of the modelled PVT collectors can be found in Ref. [26].

2.1.2. Stratified water storage tank

A one-dimensional (1-D) model is used for the hot water storage tank. The tank is assumed to consist of $N_w$ fully mixed equal volume segments that divide the cylinder along its vertical axis. Each segment is represented by a node $n$, where $n = 1$ is the bottom segment and $n = N_w$ is the top one. In this study, based on the results obtained in previous research where an adequate stratification was achieved [39], $n = 6$ nodes are considered ($N_w = 6$). The total mass of fluid in the tank is assumed constant. 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 ($n = N_w$), while replacement cold water from mains (at $T_{win}$) is introduced at the bottom ($n = 1$). A (gas-fired) auxiliary heater of sufficient power is installed at the outlet port at the top of the tank ($n = N_w$), to raise the temperature up to a fixed supply temperature of 60 °C when required.

In the sizing calculation, the storage tank volume is varied through the variation of the ratio $V_t/A_{CT}$, where $V_t$ is the tank volume in litres and $A_{CT}$ is the total PVT collector area. According to the Ministry of Housing of the Spanish Government [56], for SH installations in households this range should be kept between 50 < $V_t/A_{CT} < 180$ (in L/m²). The size of the solar heat exchanger coil (Component 5 in Fig. 2) also varies with the tank size, through the variation of the tank height, $H_t$, such $A_{coil}/A_{CT} \approx 0.15$ [57] to ensure adequate heat transfer. This coil runs the full length of the tank, with the coil inlet port positioned at the top ($n = 6$) and the coil outlet port positioned at the bottom of the tank ($n = 1$).

To provide SH (via radiant underfloor heating, UFH), a second heat exchanger coil is located in the tank (Component 7 in Fig. 2), which
also varies with the tank size. Water flowing in a separate closed-loop circuit enters the heat exchanger coil at node \( n = n_{SH,\text{in}} \) at the UFH return temperature of 35 °C, it is heated to a target supply temperature of 45 °C, and exits the tank at node \( n = n_{SH,\text{out}} \). Again, a bypass is included to avoid sending fluid to the heat exchanger when the tank temperature is lower than 35 °C.

The hot water tank equations are based the Multiport Store model developed for TRNSYS, Type 340 [58]. The temperatures in each node of the tank are solved using the following explicit method, in which the temperature of the tank in each time-step \( (i) \) is used to evaluate the temperature of the tank in the subsequent time-step \( (i + 1) \). The energy balance for each node of the hot water cylinder is as follows:

\[
T_{tn}(i + 1) = T_{tn}(i) + \frac{Q_{\text{DHW},n}(i) + Q_{\text{SH},n}(i) + Q_{\text{cond},n}(i) + Q_{\text{loss},n}(i) + Q_{\text{dump},n}(i)}{m_{tn}c_p} \Delta t,
\]

where \( T_{tn}(i) \) and \( T_{tn}(i + 1) \) are the tank temperatures at node \( n \) at time-steps \( i \) and \( i + 1 \) respectively, \( m_{tn} \) is the amount of water (in kg) in each tank node, \( c_p \) is the specific heat capacity of water, \( \Delta t \) is the time-step duration (0.5 h in this case), and \( Q(i) \) are the heat flows that might take place in each node.

As mentioned above, the supply of DHW involves extracting water from the top of the tank and replacing this with mains water at the bottom. Therefore, at each node, the following heat transfer takes place:

\[
Q_{\text{DHW},n}(i) = m_{\text{DHW}}(i)c_p(T_{tn-1}(i) - T_{tn}(i)),
\]

where \( m_{\text{DHW}}(i) \) is the mass flow-rate of DHW demand which is a model input for each time-step. For the bottom node \( (n = 1) \), \( T_{C0} = T_{\text{win}} \).

According to Ref. [59], the most practical approach towards heat exchanger design for solar systems is based on the NTU-effectiveness \( \varepsilon \) method, so for each node containing a segment of the SH heat exchanger coil, the heat transferred from the coil fluid to the hot water in the tank is:

\[
Q_{\text{SH},n}(i) = m_{\text{SH}}(i)c_p\varepsilon_{\text{SH}}(T_{\text{coil, in},n}(i) - T_{tn}(i)),
\]

and the temperature of the fluid exiting the coil segment in one node, which becomes the temperature entering the next coil segment in the adjacent node, is:

\[
T_{\text{coil, out},n}(i) = T_{\text{coil, in},n}(i) - \varepsilon_{\text{SH}}(T_{\text{coil, in},n}(i) - T_{tn}(i)).
\]

The mass flow-rate of SH, \( m_{\text{SH}}(i) \), is provided to the model at each time-step. The heat exchanger effectiveness \( \varepsilon_{\text{SH}} \) can be predicted directly from the characteristics of the heat exchanger and the relevant flows [60].

Similarly, for each node containing a segment of the solar heat exchanger coil, the heat transferred from the fluid coming from the PVT collectors circulating to the hot water in the tank is:

\[
Q_{\text{SH},n}(i) = m_{\text{SH}}(i)c_p\varepsilon_{\text{SH}}(T_{\text{coil, in},n}(i) - T_{tn}(i)),
\]

and the temperature of the fluid exiting the coil segment in one node, which becomes the temperature entering the next coil segment in the adjacent node, is:

\[
T_{\text{coil, out},n}(i) = T_{\text{coil, in},n}(i) - \varepsilon_{\text{SH}}(T_{\text{coil, in},n}(i) - T_{tn}(i)).
\]

The mass flow-rate of SH, \( m_{\text{SH}}(i) \), is provided to the model at each time-step. The heat exchanger effectiveness \( \varepsilon_{\text{SH}} \) can be predicted directly from the characteristics of the heat exchanger and the relevant flows [60].

Similarly, for each node containing a segment of the solar heat exchanger coil, the heat transferred from the fluid coming from the PVT collectors circulating to the hot water in the tank is:

\[
Q_{\text{SH},n}(i) = m_{\text{SH}}(i)c_p\varepsilon_{\text{SH}}(T_{\text{coil, in},n}(i) - T_{tn}(i)),
\]

and the temperature of the fluid exiting the coil segment in one node, which becomes the temperature entering the next coil segment in the adjacent node, is:

\[
T_{\text{coil, out},n}(i) = T_{\text{coil, in},n}(i) - \varepsilon_{\text{SH}}(T_{\text{coil, in},n}(i) - T_{tn}(i)).
\]

The mass flow-rate of SH, \( m_{\text{SH}}(i) \), is provided to the model at each time-step. The heat exchanger effectiveness \( \varepsilon_{\text{SH}} \) can be predicted directly from the characteristics of the heat exchanger and the relevant flows [60].

Similarly, for each node containing a segment of the solar heat exchanger coil, the heat transferred from the fluid coming from the PVT collectors circulating to the hot water in the tank is:

\[
Q_{\text{SH},n}(i) = m_{\text{SH}}(i)c_p\varepsilon_{\text{SH}}(T_{\text{coil, in},n}(i) - T_{tn}(i)),
\]

and the temperature of the fluid exiting the coil segment in one node, which becomes the temperature entering the next coil segment in the adjacent node, is:

\[
T_{\text{coil, out},n}(i) = T_{\text{coil, in},n}(i) - \varepsilon_{\text{SH}}(T_{\text{coil, in},n}(i) - T_{tn}(i)).
\]
\[ Q_{\text{IT},n}(i) = h_{\text{IT}}(i) \cdot c_p \cdot \epsilon(i) \cdot (T_{\text{col},in,n}(i) - T_{\text{at}}(i)). \] (7)

Thus, the temperature of the fluid exiting the coil segment in one node (from Eq. (6)) becomes the temperature of the fluid entering the next coil segment in the adjacent node. In this coil, the flow direction is downward with respect to the tank as shown in Fig. 2, such that \( T_{\text{col},in,n} = T_{\text{col},out,n} + \Delta T. \) Furthermore, the total mass flow-rate circulating through the PVT collector array, \( \dot{m}_n(i) \), in which a number of N PVT collectors are connected in parallel, is given by \( \dot{m}_n(i) = N \cdot \dot{m}_c(i) \), where \( \dot{m}_c(i) \) is the mass flow-rate per PVT collector. As before, the heat exchanger effectiveness \( (\epsilon(i)) \) is calculated following Ref. [60], as part of the sizing exercise as it also varies with the tank volume \((V_i)\).

The heat transfer by conduction between the tank nodes is described by the term \( Q_{\text{cond},n} \) expressed as:
\[ Q_{\text{cond},n}(i) = \frac{\lambda_{\text{eff}} \cdot \pi \cdot D_i^2}{4 \cdot H_n} \cdot \left( T_{\text{at}}(i) + T_{\text{at}}(i-1) - 2 \cdot T_{\text{at}}(i) \right), \] (8)
where \( \lambda_{\text{eff}} \) is the effective vertical thermal conductivity, \( D_i \) is the tank diameter and \( H_n \) is the height of node \( n \) of the tank. A constant diameter (1 m) is considered such that the tank height varies accordingly to the tank volume. The effective vertical thermal conductivity is a lumped parameter that takes into account conduction in the water, the walls of the tank and the internal components such as the heat exchanger coils. A value of 1.85 W/(m K) is chosen, which is representative of a range of solar hot water cylinders [61].

The thermal energy loss to the internal environment through the tank walls is given by:
\[ Q_{\text{loss},n}(i) = U_i \cdot A_{\text{surf,at}} \cdot \left( T_{\text{at}}(i) - T_{\text{at}}(i) \right), \] (9)
where the indoor temperature surrounding the cylinder \( T_{\text{at}} \) is assumed constant at 20 °C, \( U_i \) is the overall tank heat loss coefficient taken to be 3 W/m² K [19,47,62], and \( A_{\text{surf,at}} \) is the tank surface area at node \( n \).

Finally, to avoid overheating in the tank, water is extracted from the top and replaced by cold mains water at the bottom when the temperature at the top of the tank is above 80 °C [63]. Then, the heat rejected, \( Q_{\text{dump},n} \), is calculated as if there was DHW demand, that is:
\[ Q_{\text{dump},n}(i) = m_{\text{dump}}(i) \cdot c_p \cdot \left( T_{\text{at}}(i-1) - T_{\text{at}}(i) \right). \] (10)

2.1.3. Rest of system

The model comprises an active closed loop system, composed by Components 1–3 and 5 in Fig. 2. In normal operation, the collector outlet flow enters the heat exchanger coil located inside the storage tank, heats the water in the tank, exits the tank and returns to the inlet of the solar collector to be heated again. A bypass valve is required to control the temperature of the cooling fluid leaving the collector and entering the tank, to ensure that this stream only heats (and does not cool) the water in the tank, as done in Refs. [19,77]. A differential temperature controller, widely used in ST systems, controls the valve position by comparing the temperature at the entrance of the heat exchanger coil at the top of the storage water tank \((T_{\text{at}}(n))\), with the temperature of the water exiting the PVT collector \((T_{\text{col}}(i))\); see Components 4–5 in Fig. 2.

In order to avoid the requirement for the circulator pump (Component 3 in Fig. 2) to be switched on and off frequently, it is activated only when solar irradiance is greater than zero, in order to cool the PV module. However, fluid from the PVT collector is only sent to the heat exchanger coil in the tank when the temperature difference between collector and tank, \( T_{\text{col}}(i) - T_{\text{at}}(n) \), increases above a minimum set-point value, \( \Delta T_{\text{ON}} \), at which point the tank bypass is deactivated by activating the valve position. Fluid is circulated to the tank (through the heat exchanger coil) until \( T_{\text{col}}(i) - T_{\text{at}}(n) \) drops below a minimum set-point value \( \Delta T_{\text{OFF}} \), at which instant the bypass is activated again. In most domestic installations, \( \Delta T_{\text{ON}} \), ranges between 3 K and 10 K and \( \Delta T_{\text{OFF}} \) is between 0.5 K and 1.5 K [64–66]. These values should be chosen carefully, as small changes in the settings might result in unexpected behaviour [67]. In this work, a symmetric band of allowed temperatures around the desired tank temperature is selected, \( \Delta T_{\text{ON}} \) is set to 5 K, and hence \( \Delta T_{\text{OFF}} = \Delta T_{\text{ON}}/2 = 2.5 \) K [65]; thus in agreement with the guidelines mentioned above.

The pressure drop through the PVT fluid-loop is estimated in order to calculate the power consumed by the circulator pump (\( P_i \)), which will be taken from the electrical power output of the PVT collectors. The pressure drop, \( \Delta p \), arises from losses in the closed hydraulic loop, and can be evaluated as the sum of major losses caused by friction and minor losses due to bends and fittings [19,25]. The pressure drop through the PVT collectors is estimated considering the friction losses in the collector tube and riser pipes (rectangular channels in the flat-box structure) and the minor losses due to the contraction and expansion from/to the collector tube to/from the riser pipes, using the expressions for sudden contraction and expansion provided in Ref. [68]. The flow within the PVT collector is laminar, such that \( f = 64/R \) for the S&T collectors [19,25], and \( f = 96/R \) for the flat-box structure [68]. Similarly, the pressure drop through the overall S-CHP system is evaluated by considering the total (volumetric) water flow-rate in the system and the estimated circuit length, tube diameters, number of elbows and fittings. The power consumed by the circulator pump is calculated by adding the pressure drop through the PVT collector and that through the rest of the fluid circuit, and multiplying this by the total (volumetric) flow-rate of water in the S-CHP system.

2.1.4. Electrical battery storage

The electrical output of the PVT collectors can be stored in batteries with an efficiency \( \eta_{\text{bat}} \) through a standard switched charge controller of efficiency \( \eta_{\text{cc}} \) that connects both devices [69], as shown in Fig. 2. A DC to AC inverter, with an efficiency \( \eta_{\text{inv}} \), is also considered [70,71]. The lead-acid battery integrated in this study has a monthly self-discharge rate (BSD) of 5%. This value is converted to an equivalent half-hourly self-discharge rate, BSDhalf, to be integrated in the S-CHP model.

The S-CHP system’s electrical output is consumed directly by the household when there is a demand, by converting it to AC using an inverter. Any electricity excess is stored in the battery as defined by the actual charge current, \( I_c \), and any electricity shortfall is supplied by the battery as defined by the actual discharge current, \( I_d \). Here, \( I_c \) and \( I_d \) depend on the battery’s specifications, specifically, the former on the maximum state of charge, \( SOC_{\text{max}} \), and its maximum allowed charge current, \( I_{\text{max},c} \), and the latter on the minimum state of charge, \( SOC_{\text{min}} \), and its maximum allowed discharge current, \( I_{\text{max},d} \).

When the battery is full or unable to store additional electricity due to technical limitations, that is, when the available charge current \( I_{\text{Q2}} \) is larger than \( I_{\text{max},c} \), the surplus energy is provided to the grid (\( E_{\text{Q2}} \)). On the other hand, when the battery is empty or unable to meet the household electricity demand, the grid is assumed to be available to cover this demand (\( E_{\text{Q1}} \)). Therefore, two possible situations arise: (i) an energy surplus, in which the S-CHP system generates more energy than the household demand (\( E_{\text{Q1}} > 0 \)), and (ii) a shortfall, in which the system generates less energy than the demand (\( E_{\text{Q1}} < 0 \)).

\[ E_{\text{Q1}}(i) = E_{\text{Q1}}(i) \cdot \eta_{\text{inv}} \cdot \eta_{\text{cc}} - E_{\text{Q2}}(i), \]

where \( E_{\text{Q1}}(i) = P_{\text{bat}}(i) \cdot \Delta t, \Delta t = 0.5 \) h is the time step, \( E_{\text{Q1}}(i) \) is the electricity generated by the collectors, \( E_{\text{Q2}}(i) = \eta_{\text{inv}} \cdot \eta_{\text{cc}} \cdot E_{\text{grid}}(i) \) is the electricity consumed by the pump, and \( E_{\text{grid}}(i) \) is the household electricity demand at time-step \( i \).

A number of 12 V lead-acid batteries units are considered, with a maximum allowable charge and discharge current of \( I_{\text{max},c} = I_{\text{max},d} = C/10 \), where \( C \) is the battery capacity (100 Ah per single unit). The total number of batteries required varies with the number of PVT collectors (\( N_i \)), according to the expression: \( C_{\text{bat}} = 600 \times N_i \). This correlation was selected following a preliminary analysis to ensure that the battery SOC is maintained within a reasonable range, and was a compromise between the energy storage capacity and the installed cost of the system, with the objective of minimising the number of batteries while also minimising the interaction of the investigated household(s).
The equations governing the interactions between the various electrical components are summarised in Table 1 and those modelling the battery performance features are summarised in Table 2.

### 2.2. Weather data and single-family reference house

The performance of the S-CHP systems in the domestic applications of interest were simulated by modelling a reference house in EnergyPlus [37], which provides estimates of the household’s energy demands over a year, including the electricity needed for lighting, cooling and other household appliances, and the thermal energy required for space heating (SH) and domestic hot water (DHW). The reference house considered here is a double-glazed, 2-floor semi-detached household with a total floor area of ~115 m², and U-values of 0.26 W/(m²·K) and 0.18 W/(m²·K) for the façade and roof respectively. Typical occupancy profiles of 4 inhabitants (2 adults and 2 children) are considered, following the guidelines provided in the Spanish Building Code (Código Técnico de la Edificación) [56], which differentiates between working and non-working days, and provides loads and schedules for lighting and home appliances, as well as for occupancy and the air change rate. Based on the aforementioned building code [56], the following temperature set-points are set in the EnergyPlus household model to estimate the heating and cooling demands: (i) 20 °C primary and 17 °C secondary for SH (January to May and October to December), and (ii) 25 °C primary and 27 °C secondary for air conditioning (June to September).

The weather data (solar irradiance and ambient temperature) provided by EnergyPlus [72] are also used as inputs to the S-CHP model through the use of lookup tables. The direct normal and diffuse horizontal solar irradiance components are converted to a total incident solar irradiance, \( I_r \), received on the tilted plane of the collector [73]. The collector tilt angle, \( \beta \), is optimised for maximum annual solar irradiation at each location with the Photovoltaic Geographical Information System (PVGIS) online tool [74], resulting in the following values: \( \beta = 32° \) in Athens, \( \beta = 38° \) in London, and \( \beta = 37° \) in Zaragoza.

Energy demand profiles are also generated in EnergyPlus at half-hourly time-steps for the reference houses at the selected locations. The total electrical and thermal demands integrated over the annual period are: 18.3 kWh/m² and 30.7 kWh/m² in Athens, 24.3 kWh/m² and 54.7 kWh/m² in London, and 27.7 kWh/m² and 29.7 kWh/m² in Zaragoza, based on the monthly demand profiles shown in Fig. 5.

The cooling demand is found to vary strongly with location, and more than the other household energy demands, with the highest associated consumption experienced by the household located in Athens, where a greater amount of electricity is required to attain the desired comfort temperatures in the summer period (see dotted lines in Fig. 5) due to the higher irradiance level and higher ambient temperature at this location. A constant Seasonal Energy Efficiency Ratio (SEER) of 3 for the air-conditioning system is assumed at all locations for the calculation of the electricity consumption needed to satisfy the cooling demand. Furthermore, although the same lighting schedules and usage profiles for home appliances are considered in all three locations, the electrical consumption due to lighting varies slightly between the locations depending on the different available natural light levels.

Finally, the same DHW demand is experienced at all locations (see long dashed lines in Fig. 5), as expected given that: (i) the same DHW schedules and usage profiles are assumed, and (ii) variations in the DHW due to geographical variations in the mains water supply temperature are not considered, and thus the same mains water supply temperature is assumed for all locations. Finally, the highest SH demand occurs in London (see continuous lines in Fig. 5), which is attributed to the low irradiance levels (particularly in winter) together with the lower ambient temperature at this location. Conversely, the household located in Athens has the lowest SH demand.

### 2.3. Economic assessment

Three economic parameters are used in the optimisation of the S-CHP systems of interest:

- Levelised Production Cost (LPC) of total (electrical and thermal) energy generated (\( LPC_{gen} \));
- Levelised Production Cost (LPC) of total household energy demand covered (\( LPC_{cov} \));
- Payback Time (PBT).

To this end, the capital/investment cost including all system components except the auxiliary heater and the O&M costs of the system (\( C_{CCHP} \)) are considered, as well as the utility (electricity and natural gas) savings (referred to as fuel savings, \( FS_{S-CHP} \)) and the costs incurred to satisfy the electrical and thermal demand of the household that cannot be covered (referred to as annual running costs, \( C_{CCHP} \)). To estimate the annual fuel savings, \( FS_{S-CHP} \), the total utility (electricity and natural gas) costs saved in the household due to the electricity and thermal (SH and DHW) energy demand covered by the S-CHP system are estimated (Eq. (24)). Then, these values, are converted into present worth values and added to obtain the Life Cycle Savings (\( FS_{LC} \)), considering the market discount rate (\( d \)) and the fuel inflation rate (\( \eta_{fuel} \)), as follows:

\[
FS_{S-CHP} = E_{cov} \cdot \eta_{fuel} + \frac{Q_{cov}}{\eta_{fuel}} \cdot \eta_{fuel}
\]

(Eq. (24))

| Table 1 | S-CHP system battery storage and grid interaction model equations. |
| Description | Energy surplus (\( E_{net} > 0 \)) | Energy shortfall (\( E_{net} < 0 \)) | Eq. |
| Available charge/discharge current | \( I_{CH}(i) = \frac{P_{bat}(i)}{\eta_{bat} \cdot V_{Bat}} \) | \( I_{DIS}(i) = \frac{P_{bat}(i)}{\eta_{bat} \cdot V_{Bat}} \) | (12) |
| Actual charge/discharge current | \( I_C(i) = 0 \) | \( I_D(i) = 0 \) | (13) |
| Battery charge/discharge power | \( P_{BAT}(i) = I_{BAT}(i) \cdot V_{Bat} \) | \( P_{BAT}(i) = I_{BAT}(i) \cdot V_{Bat} \) | (14) |
| Power exported/imported to/from grid | \( P_{G}(i) = P_{bat}(i) - P_{bat}(i) \) | \( P_{G}(i) = P_{bat}(i) - P_{bat}(i) \) | (15) |

### Table 2 | Battery performance features. |
| Description | Equation | Eq. |
| Battery capacity | \( C = \frac{C_{bat}}{V_{Bat}} \) | (18) |
| Battery discharge capacity | \( C_{D}(i) = (I_{D}(i) \cdot \eta_{bat}) \) | (19) |
| Battery charge capacity | \( C_{CH}(i) = (I_{CH}(i) \cdot \eta_{bat}) \) | (20) |
| Change in battery capacity | \( \Delta C(i) = C_{CH}(i) - C_{D}(i) \) | (21) |
| Battery capacity at next time-step | \( C(i + 1) = (C(i) + \Delta C(i)) \cdot (1 - \varepsilon_{dis}) \) | (22) |
| Battery state of charge | \( SOC(i) = \frac{C(i)}{C_{bat}} \) | (23) |
The S-CHP system’s investment cost is estimated from price lists available from solar retailers in the EU (VAT included). The main costs of system are associated with the storage tank, the PVT collectors, the pump station, the electronic controller and the piping and fixings. The cost of the storage tank is estimated using a correlation based on market prices of existing tanks across a range of storage volumes. The total installation costs are also considered [77]. The auxiliary heater price is not considered as it is assumed that the households already have one installed. Table 3 details the price breakdown.

Actual electricity and natural gas prices for domestic consumers in the three locations: Athens (Greece), London (UK) and Zaragoza (Spain) are used to calculate the running costs, the values considered are excluding taxes and levies. Band DC1 (2500 kW h < consumption < 5000 kW h) is selected for the electricity prices, as the total household electricity consumption is between ~2800 kW h and ~3500 kW h [86]. For the natural gas prices, Band D1 (consumption < 20 GJ, 55555 kWh) is selected for Athens and Zaragoza where the total natural gas consumption to satisfy the combined household demands for SH and DHW, assuming a boiler efficiency of 90.1% [87], amount to ~3800 kW h and ~2400 kW h respectively at the two locations, whereas Band D2 (20 GJ, 55555 kW h < consumption < 200 GJ, 55555 kW h) is selected for London where the total natural gas consumption is ~7000 kW h [86]. Table 4 details the specific values selected. It should be noted that the natural gas price for London is significantly lower than in the other cases due to the higher band required to satisfy the demand. If the demand was lower than 55555 kW h, the natural gas price would increase to 0.0768 €/kWh [88].

The current feed-in-tariffs (FITs) available in the UK (0.048 €/kWh) and Athens (0.105 €/kWh) [89,90] are not included in the techno-economic optimisation as in Spain there is currently no such incentive and also because the aim here is to compare the economics of these systems without financial incentives in place. However, FITs are considered at the end of the analysis in order to examine the role of this incentive in improving their economic proposition. Conversion factors to CO2 emissions specific to each location are used to obtain the annual displaced emissions [91–93] (see Table 4). A market discount rate of 3.5% is considered, applicable to projects with up to 30-year lifetimes [94], and the fuel inflation rate is set to 2.7% based on the inflation rates in the different countries under study [95,96], which is in line with the fuel inflation rate considered in previous studies [97].

Considering the electricity and natural gas prices and the conversion factors to primary energy detailed above, together with the household energy demand in each country, Table 5 summarises the annual energy consumption within different bands: D1, D2 and D3 for natural gas consumption, and DA, DB, DC, DD and DE for electricity consumption.
electricity and thermal energy (both SH and DHW) household demand converted to equivalent electricity as detailed above (\(E_{\text{TD}}\)), the annual household running costs (\(C_{\text{conv}}\)) (equivalent to buying natural gas and electricity from the grid to satisfy all household demand by conventional means), and the equivalent levelised production cost (\(LPC_{\text{conv}}\)) of the household (estimated as \(C_{\text{conv}}/E_{\text{TD}}\)).

In Table 5, we can observe the importance of the utility prices that significantly affect the economics of the S-CHP system. In particular, despite the significantly lower annual energy demands compared to London, the higher electricity and natural gas prices in Zaragoza (20% and 47% higher, respectively) mean that the \(LPC\) of the system in London is lower because the household inhabitants spend less money to satisfy their energy demands by conventional means. Due to the lower electricity price in Athens with respect to Zaragoza (~34% lower), the \(LPC\) in this case is even lower. Consequently, and as will be demonstrated in the next section, it is more challenging to achieve a cost-effective renewable system capable of competing with conventional non-renewables in London and Athens than in Zaragoza.

### 2.4. System sizing and technoeconomic performance assessment

The objective of this work is to compare, from a technoeconomic perspective, optimised S-CHP systems based on two PVT collector designs: (i) a novel polycarbonate flat-box design, which was selected as the most promising such design in previous research [26], and (ii) a benchmark reference (sheet-and-tube) design. Three different climates are selected for this study, representing: (i) Mediterranean (Athens, Greece), (ii) temperate oceanic (London, UK), and (iii) semi-arid (Zaragoza, Spain). A methodology is developed to obtain an estimate of the annual energy, cost and emission savings. Based on these results, the \(PBT\) and \(LPC\) of the optimal system configuration are estimated for S-CHP systems featuring both polymeric flat-box and benchmark sheet-and-tube PVT collector designs, and the results are compared at the three locations. Finally, performance profiles on selected days for both collector designs are presented and discussed.

#### 3. Results and discussion

##### 3.1. Selection of key performance indicators for system sizing

The aim of this first exercise is to identify the decision factors based upon which the S-CHP system can be optimised, given irradiance, ambient temperature, and household energy-demand data. The system performance indicators are evaluated for the case of Zaragoza, which was selected amongst the locations of interest here as it is an intermediate case between those of Athens and London. As mentioned above, the analysis is undertaken in half-hourly steps over an average week in each month. The monthly outputs are then weighted to obtain annually averaged results.

Two parameters are varied in sizing the S-CHP system: the number of PVT collectors (\(N\)) and the ratio \(V_f/N\). The PVT collector flow-rate (\(V_f\)) is kept constant at 50 L/h (per collector), which is within the flow-rate range recommended by the PVT manufacturer [53]. The performance indicators considered in this research are:

- Levelised production cost per unit equivalent electrical energy generated (\(LPC_{\text{conv}}\), €/kWh\(_{\text{eq,gen}}\)).
- Levelised production cost per unit equivalent electrical energy covered (\(LPC_{\text{cov}}\), €/kWh\(_{\text{eq,conv}}\)).
- System payback time (\(PBT\)).
- Grid interaction: difference between the electricity imported (\(E_{\text{grid}}\)) and exported (\(E_{\text{exp}}\)) from/to the grid to satisfy the household electricity demand.
- Thermal energy balance: difference between the auxiliary heating required to cover the household thermal energy demand (\(Q_{\text{aux}}\)) and the rejected excess heat (\(Q_{\text{dump}}\)) to avoid tank overheating.
- Percentage of thermal (SH and DHW) and electrical demand covered (\(\%\text{cov}\)).

Initially, a preliminary analysis was undertaken to select a reasonable value for the ratio \(V_f/N\). A flow rate value of 90 L/collector was found to provide a high level of thermal energy demand, so this is the value considered as a starting point of the sizing exercise. Then, for the system sizing in each location, first of all, the number of PVT collectors (\(N\)) is varied up to 33, which corresponds to a total PVT array area of around 50 m\(^2\) and the maximum usable roof area on the single family
and covered (Zaragoza (Spain), with di
number of collectors increases, the excess heat rejected to the ambient
decreases at a far lower rate, plateauing at a minimum value that cor-
to minimise the
demand covered slightly increasing with
30
N
465 L/collector, which implies a storage tank volume between 250
45 L/collector), the water at the top of the tank quickly reaches the
utilisation of energy stored in the tank is a
ected signi
Q_dump decreases again.
Similarly, turning now to selected economic indicators, the levelised
cost of energy covered (LPC_{cov}, yellow dots in Fig. 7 left), levelised cost
of energy generated (LPC_{gen}, blue diamonds in Fig. 7 left) and the system
system payback time (red crosses in Fig. 7 left) reach a minimum
around the same V_{c/N}. Furthermore, it is observed that the thermal
energy balance, ∑Q_{aux} = ∑Q_{dump}, occurs at V_{c/N} = 120 L/collector, which is similar to that corresponding to the optimal values of the
aforementioned key performance indicators.
Based on these results, a set of decision factors were selected for use
in the subsequent analyses. These factors are: (i) the minimisation of the PBT, which also leads to the minimum grid interaction on an an-
nually averaged basis, and (ii) the minimisation of the LPC_{cov}, which also leads to the maximum thermal energy demand covered and hence the
minimum auxiliary heat required.

### 3.2. Technoeconomic optimisation for system sizing

Following the procedure described in Section 3.1, the S-CHP system

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2 For interpretation of colour in Figs. 6-9, the reader is referred to the web version of this article.
sizing (number of collectors, \(N\), and water storage tank volume, \(V_t\)) is optimised for reference households located in the three locations of interest to this work (Athens, London and Zaragoza). As in the previous section, only the case of Zaragoza is considered here in detail, since it presents an intermediate case as explained before, and equivalent results are obtained in the other cases. Key results relating to the performance of optimised systems installed at the other two locations over the course of the year are also shown in order to compare the systems’ performance at the different locations.

Firstly, the number of PVT collectors \((N)\) is varied up to 33, with \(V_t/N\) fixed at 90 L/collector, such that the tank volume \((V_t)\) varies according to \(N\). These results, shown already in Fig. 6, indicate that to minimise the LPC\(_{cov}\), the number of PVT collectors required is significantly higher (some months more than double) than to minimise the PBT; specifically, between 9 and 23 PVT collectors in the former case and 4–16 in the latter for the household located in Zaragoza. This leads to a greater interaction with the electricity grid, exporting a significant amount of electricity generated from the PVT system (and an averaged grid interaction, \(\Sigma E_{grid} - \Sigma E_{exp}\) of 70.1 kWh/week in the former case vs. 0.6 kWh/week in the latter). Due to the larger S-CHP dimensions (\(N\) and \(V_t\)) in the former case, the PBT is also considerably higher (20 vs. 8 years based on the annually-averaged results), as the increase in fuel savings do not outweigh the higher investment cost. As stated above, the number of collectors \((N)\) is selected to minimise the PBT, hence 8 PVT collectors are selected, with which grid interaction \((\Sigma E_{grid} - \Sigma E_{exp})\) is also minimised. In Fig. 6 it is also observed that from 8 PVT collectors the slope of the LPC\(_{cov}\) significantly decreases, decreasing at much lower extent from there onwards until it reaches a minimum. Furthermore, between 7 and 8 PVT collectors, the excess of heat rejected to the ambient \((Q_{dump})\) is very close to the auxiliary heat \((Q_{aux})\), so the excess of thermal energy and auxiliary heat needed is balanced.

With the number of PVT collectors selected \((N) = 8\), for a fixed \(V_t/N = 90\) L/collector, the S-CHP system performance is assessed in each month in order to obtain the weekly equivalent electricity covered (\(E_{eqw}\)), the associated fuel savings (\(FS_{S-CHP}\)) and the weekly running costs (\(A_{S-CHP}\)). Following this assessment, the monthly results are added to obtain the annual fuel savings (537 €/year), which in this case lead to a PBT of 14.7 years (\(C_{0} = 7252\) €), and the equivalent electricity covered (3016 kWheq/year), and annual running costs (374 €/year), which lead to an LPC\(_{cov}\) of 0.257 €/kWh\(_{eq}\).

To verify whether the value of \(V_t/N\) used initially was optimal, and following the procedure detailed in Section 3.1, this parameter is varied in the range 30–465 L/collector. The results show that, averaged over an annual period, \(V_t/N = 90–105\) L/collector leads to the lowest LPC\(_{cov}\) (see yellow dots in Fig. 7 left) which coincides approximately with the \(V_t/N\) that maximises the covered thermal-energy demand (grey squares in Fig. 7 right). The minimum PBT is achieved at a lower \(V_t/N\), however the variation in PBT is relatively small (15.1–15.5 years, dark red crosses in Fig. 7 left) over the corresponding range of \(V_t/N\) values between 60 and 105 L/collector. Conversely, the excess heat rejected to the ambient \((Q_{dump},\) dark blue diamonds in Fig. 7 right) decreases notably (by around 21%) as \(V_t/N\) is increased from 60 to 105 L/collector. Based on these results, a \(V_t/N\) of 90–100 L/collector is considered a good compromise and, as results for \(V_t/N = 90\) L/collector are already estimated from previous analysis, \(V_t/N = 100\) L/collector is selected in this case for further analysis. The results show that the slight increase in the annual fuel savings in this case, does not outweigh the higher investment cost \((C_{0})\) due to the larger tank \((V_t = 0.80\) m\(^3\) vs. 0.72 m\(^3\) in the former case).

Based on the aforementioned analyses, the system size selected for the household in Zaragoza comprises 8 PVT collectors and a storage tank with \(V_t = 0.72\) m\(^3\). This leads to \(V_t/A_T = 58.4\) L/m\(^2\) (PVT collector area, \(A_T = 1.54\) m\(^2\)), which is inside the range established by the Spanish Building Technical Code (50 < \(V_t/A_T\) < 180, in L/m\(^2\)) [56].

Finally, the effect of Feed-In-Tariffs (FITs) on the economics of the systems was also considered. At present, there is no FIT available to PV installations in Spain. Therefore, in order to understand the role of this incentive in Spain and specifically for the system in Zaragoza, we considered the FIT presently available to small PV installations in the UK (0.0476 €/kWh) [89]. The results show that in this case the PBT is reduced by 1.5 years due to the FIT, achieving a PBT\(_{FIT}\) of 13.5 years.

A similar procedure to that described for the location of Zaragoza is conducted for Athens and London leading to the sizing of these systems. The weekly (electrical and thermal) energy results during the different months of the year for the systems sized for the households located in Athens and London are shown in Fig. 8. The results for the location of Zaragoza are not shown as they are between the former locations, so the equivalent conclusions can be drawn. As expected, the larger auxiliary heat needs \((Q_{aux})\) occur in the winter months (see green squares in Fig. 8), particularly from December to February, which is attributed to the higher SH demand and also lower irradiance during those months (see Fig. 8). Comparing the results of the different locations, it is observed that, as expected, the auxiliary heating needs \((Q_{aux})\) in London in winter are higher than in Athens (and Zaragoza although not shown here), due to the higher SH demand in the former (see Fig. 5).

In Athens, the more electricity is imported from the grid \((E_{grid})\) in the summer months, from June to September (see orange diamonds in Fig. 8 left), due to the higher cooling demand (see Fig. 5), which also leads to less electricity exported to the grid \((E_{exp})\) over this period. The solar irradiance is also higher in summer months, and is available
during the hours in which cooling demand is highest, leading to a higher total electricity demand covered ($E_{cov}$) in summer months. Due to the higher cooling demand, the grid balance ($\Sigma E_{grid} - \Sigma E_{exp}$) is positive in some summer months in Athens (Fig. 8 left), while in the case of London it is negative in summer months, which implies that electricity is exported to the grid ($E_{exp}$) in the latter case (Fig. 8 right).

### 3.3. PVT collector operation optimisation

With the optimal S-CHP system size determined at each location, the flow-rate per collector ($V_p$) is optimised in each month, within the range of 5–300 L/h. Lower collector flow-rates are typically preferred to maintain the PV module at low temperature to achieve the maximum electrical efficiency. However, high flow-rates lead to higher pumping work and thus less net electricity available. The results show that the same PVT collector flow-rate in each case study leads to the minimum LPC$_{gen}$, LPC$_{cov}$ and PBT, as well as to the maximum thermal energy demand covered ($Q_{cov}$) and hence minimum auxiliary heat ($Q_{aux}$) needed and maximum percentage of thermal energy demand covered.

As with the previous section, only the case of Zaragoza is shown in detail here as similar results are obtained in the other cases. In all the cases, the results show that low PVT collector flow-rates are recommended to maximise the thermal energy demand covered for all the months and hence minimise the PBT (see annually averaged results for Zaragoza location in Fig. 9). However, low PVT collector flow-rates lead to higher excess of heat rejected to the ambient ($Q_{dump}$) (see dark blue diamonds in Fig. 9 right). As shown in Fig. 9 (right), a zero net thermal energy balance ($\Sigma Q_{aux} = \Sigma Q_{dump}$) is obtained in Zaragoza for $V_p \sim 65$ L/h. It is observed that the electrical demand covered only varies slightly over the range of PVT collector flow-rates, between 66.8% at low flow-rate to 65.6% at high flow-rate (see orange triangles in Fig. 9 right), which is attributed to the higher electricity consumption of the circulator pump reducing the electricity available to satisfy the household demand.

The results show that if the PVT collector flow-rate is fixed to 30 L/h throughout the year (optimal annually averaged as shown Fig. 9 left), slightly higher annual fuel savings are achieved, which leads to a 0.4% lower PBT and a 0.6% lower LPC$_{cov}$ than with the previous constant flow-rate of 50 L/h. The effect of incorporating a variable-speed pump, which is adjusted on a monthly basis to provide the optimal flow-rate to the PVT collectors in each month, was also investigated. The PBT was found to be 0.3% lower and the LPC$_{cov}$ was 0.1% lower than with the constant flow-rate of 30 L/h. Thus, in this case, it can be concluded that the higher cost of the variable speed pump (which has not been considered in this calculation) might not outweigh the slight improvement in the system performance.

Furthermore, if the goal is to minimise the thermal energy balance ($\Sigma Q_{aux} - \Sigma Q_{dump} \sim 0$), a constant PVT collector flow-rate of 65 L/h should be selected (see Fig. 9 right), with which a $PBT$ of 14.9 years and
an LPC of 0.261 €/kWh is achieved. In this case, when the total electricity PVT generation is considered, an LPC of 0.178 €/kWh is estimated. If all of the household energy demand was instead satisfied by conventional means (buying natural gas and electricity from the grid), as detailed in Table 5, an equivalent LPC of 0.184 €/kWh is obtained. Therefore, it can be concluded that the proposed S-CHP system based on the polymeric flat-box PVT collector is a promising alternative to a business-as-usual scenario when installed in Zaragoza, even without the need of government incentives. If a FIT equivalent to alternative to a business-as-usual scenario when installed in Zaragoza, even without the need of government incentives. If a FIT equivalent to this can be attributed mainly to the higher investment cost of the PVT collector (sheet-and-tube design) is integrated into the S-CHP system, and the results are compared to those from the polymeric collector (benchmark PVT collector). The same analysis as above is undertaken when the benchmark PVT collector (sheet-and-tube design) is integrated into the S-CHP system, and the results are compared to those from the polymeric flat-box PVT collector system. As before, the results of the optimal S-CHP system show that low PVT collector efficiency curve in Section 2.1. With a constant PVT collector flow-rate of 50 L/h, a slightly higher collector flow-rate is also recommended (Vf = 50 L/h in this case). Slightly lower electrical demand covered is achieved with the benchmark PVT collector (65.5% compared to 66.7% for the PC flat-box collector) across the range of PVT collector flow-rates, due to the less effective heat extraction as shown in the PVT thermal efficiency curve in Section 2.1. A constant PVT collector flow-rate of 50 L/h, a PBT of 16.3 years, an LPC of 0.273 €/kWh and an LPC of 0.190 €/kWh are achieved. The PBT of the benchmark PVT S-CHP system is higher than that of the equivalent polymeric flat-box PVT-based system by an additional 1.4 years, and this can be attributed mainly to the higher investment cost of the benchmark PVT collector (380 €/collector vs. 301 €/collector).

### 3.4. Comparison of optimised S-CHP systems at different locations

Table 6 summarises the features of the optimised S-CHP system configurations for both the polymeric flat-box PVT and the benchmark PVT systems in the three locations studied in the present work. It is observed that the optimal sizing and operating parameters of the system are within a relatively small range for the three locations (between 8 and 11 PVT collectors, a hot water storage tank volume of 0.68–0.83 m³ and a PVT collector flow-rate between 30 and 65 L/h), despite the differences in terms of irradiance levels, ambient temperature, and household energy demand (see Section 2.2). As expected, a higher number of PVT collectors and a larger storage tank together with lower PVT collector flow-rates are required in London due to the lower irradiance levels together with the significantly higher SH demand (around twice the equivalent to Zaragoza and four times higher than the SH demand in Athens).

Table 6 also shows the annual energy generation results of the optimised S-CHP system configurations. The results show that at all locations, the polymeric flat-box PVT-based S-CHP system outperforms the benchmark sheet-and-tube equivalent system due to the more efficient heat extraction of the former, which increases both the electricity and thermal energy generated by the system.

Of the three locations, Athens has the highest electricity generation (EPVT), as well as the highest household electricity demand covered (Ecov), despite the slightly larger optimal collector array size than for Zaragoza and significantly higher irradiance levels than London. Nevertheless, it is found that more electricity should be imported from the grid (Epgrid) for the Athens case which is attributed to the higher electricity demand, specifically in summer months, due to the higher cooling demand. The results of the thermal energy demand covered show that Athens achieves the highest percentage (61.3%), despite the lowest total amount of thermal energy covered by the S-CHP system (Qcov). This is attributed to the low thermal energy demand (see Fig. 5), which also leads to the lowest auxiliary heat requirement (Qaux). Conversely, in London it is only possible to cover ~29% of the total thermal energy demand, due to the high household thermal energy demand together with the low irradiance levels.

When the system economics are considered, in particular the utility costs, different conclusions can be drawn. As shown in Table 7, the lowest PBT is achieved when the S-CHP system is located in Zaragoza, around 7 years and almost 13 years lower than in Athens and London, respectively. The main reason is attributed to the significantly higher utility prices in Spain compared to the other locations (see Table 4), specifically, ~21% and ~9% higher electricity and natural gas prices respectively than in the UK and ~52% and ~4% higher electricity and natural gas prices respectively than in Greece. As a consequence, the fuel savings (FS) thanks to the integration of the proposed S-CHP systems is very sensitive to the utility prices. The same analysis as above is undertaken when the benchmark PVT collector (sheet-and-tube design) is integrated into the S-CHP system, and the results are compared to those from the polymeric flat-box PVT collector system. As before, the results of the optimal S-CHP system show that low PVT collector efficiency curve in Section 2.1. With a constant PVT collector flow-rate of 50 L/h, a PBT of 16.3 years, an LPC of 0.273 €/kWh and an LPC of 0.190 €/kWh are achieved. The PBT of the benchmark PVT S-CHP system is higher than that of the equivalent polymeric flat-box PVT-based system by an additional 1.4 years, and this can be attributed mainly to the higher investment cost of the benchmark PVT collector (380 €/collector vs. 301 €/collector).

### Table 6

Annual energy results (kWh/year) and annual household electrical and thermal energy demand covered (%) of the optimised S-CHP system configurations in households located in each of the assessed locations.

| Location          | Athens, Greece | London, UK | Zaragoza, Spain |
|-------------------|----------------|------------|-----------------|
| **Polymer flat-box PVT** | **Benchmark PVT** | **Polymer flat-box PVT** | **Benchmark PVT** | **Polymer flat-box PVT** | **Benchmark PVT** |
| N                 | 9              | 11         | 8               |
| Act               | 14.0 m²        | 17.0 m²    | 12.4 m²         |
| Vt                | 0.68 m³        | 0.83 m³    | 0.72 m³         |
| Vf                | 50 L/h         | 50 L/h     | 30 L/h          |
| Bvert             | 3674           | 3025       | 2977            |
| Brot              | 2263           | 1823       | 1822            |
| Bpott             | 1249           | 957        | 958             |
| Qaux              | 1057           | 909        | 866             |
| Qcov              | 1283           | 1634       | 1589            |
| Qtot              | 811            | 3939       | 3984            |
| Qtot-cov           | 61.3           | 29.3       | 28.5            |
| Qf-cov             | 64.4           | 65.6       | 65.5            |
increase considerably (see first two columns on Table 8), which leads to a more favourable PBT for the proposed solar solution. As shown in Table 8, in this case, all the PBT are below the system’s lifetime (~25 years), even when FIT are not considered. Conversely, the LPC_
to
\text{var} and LPC_
to
\text{gen} increase, as higher prices increase the total annual running costs of the household. It should be noted that, in this case (which is more realistic as it considers the taxes and levies that the end-user will have to pay), a reasonable PBT (15.6 years) is also obtained in Athens without the need of FIT. Thus, it can be concluded that the PBT values obtained in Zaragoza and Athens are on the order of magnitude expected for this type of solar system installed in the South of Europe. The results show that, in Northern climates, such as the UK, characterised by lower irradiance levels and high household space heating demand, it might be more beneficial to size these S-CHP systems for the provision of DHW-only, instead of DHW and SH, as this will lead to a smaller system size required to satisfy a more constant hot water demand throughout the year. However, this alternative has not been assessed here as it is beyond the main scope of this work. Nevertheless, in the aforementioned climates, to promote the installation of these S-CHP systems the implementation of some financial incentive might still be necessary to lower the PBT further.

Finally, the potential emission reductions that can be achieved by the integration of the optimised S-CHP systems into households are found to be sensitive to the country where these systems are installed. The high CO2 emission factor of the electricity grid in Greece (see Table 4) makes these systems particularly promising in this location, where they have the potential to displace around 3.87 tons CO2 over a year, compared to the 1.54 and 1.65 tons CO2/year for London and Zaragoza, respectively. By comparison, PV-only solutions displace 3.56, 4.10, 3.41, 3.98 tCO2/year for the same total cost which, however, would correspond to installed PV-covered surface areas of 43, 49 and 41 m², respectively. The benefits, therefore, appear noteworthy in the case of space restrictions.

### 3.5. Daily performance analysis of optimised configurations

#### 3.5.1. Optimised S-CHP system in Zaragoza

Figs. 9 and 10 show the selected performance profiles of the optimised S-CHP system (N = 8 and V \text{t} = 0.72 m³) in Zaragoza, over three days in winter (February) and three days in summer (July), respectively. Results are compared in the plots for the PC 3×2 flat-box PVT system (for which V \text{t} is set to the optimal 65 L/h) and the benchmark S&T PVT system (for which V \text{t} is set to the optimal 50 L/h). In the first two figures, the differences in the performance and operation of both systems between cloudy and sunny days are presented. It should be noted that the elevated total irradiance (I\text{f}) peaks (Fig. 10 left) in winter are due to the correction factors considered to calculate the solar irradiance at tilted angle.

The detailed results concerning the thermal performance indicate that on the selected winter days, for both the optimised polymeric flat-box PVT-based and benchmark S-CHP systems, around 52% of the entire thermal (DHW plus SH) demand is covered in Zaragoza. Both S-CHP systems perform very similarly because the improvement in the thermal performance of the polymeric flat-box PVT collector compared to the benchmark PVT collector (see Section 2.1) is too low to result in a noticeable difference on an annual basis (Fig. 10 left). However, as shown in previous sections, considerably better economics are achieved with the polymeric flat-box PVT-based S-CHP system, thanks to the lower PVT collector price. It is observed that the early thermal energy demand peak due to SH requirement (orange squares in Fig. 10 left) on the first of the three winter days cannot be covered by the S-CHP systems, because the temperature of the water in the storage tank at the beginning of the day is too low (a result of very low solar irradiance received on the previous day). However, on the second day, thanks to the larger amount of thermal energy stored in the tank, part of the early morning SH demand peak can be covered with the S-CHP system, as well as most of the thermal energy demand later in the day.

In Fig. 10 (right) it is also interesting to observe that there is a mismatch between the peak electricity demand (orange squares) and the peak electricity generation (dark blue diamonds and light blue crosses). In this case, the batteries installed as part of the system allow the storage of surplus electricity for later use, such that less electricity is exported to the grid during the morning and afternoon (yellow crosses and green circles). However, some flexibility is still required to import/export electricity from/to the grid, even though FIT are not provided, otherwise a very large battery storage capacity would be required to store the surplus electricity on summer days, which would lead to a significantly increased investment cost and system payback time. On the selected winter days, detailed results show that 9% more electricity is exported

![Table 7](image)

**Table 7**

| System economics of the optimised novel polymeric flat-box PVT-based and benchmark PVT-based S-CHP systems in the three locations, with and without financial incentives (utility prices excluding taxes and levies). |
|----------------|----------------|----------------|
| Athens (Greece) | Polymeric | FIT* 0.105 | 0.105 |
| (UK) | flat-box PVT | FIT* 0.105 | 0.105 |
| Benchmark | No FIT | 22.0 | 15.2 |
| London (UK) | Polymeric | 16.8 | 10.3 |
| (Spain) | flat-box PVT | FIT* 0.048 | 0.048 |
| Benchmark | No FIT | 27.7 | 22.2 |
| Zaragoza | Polymeric | 14.9 | 17.9 |
| (Spain) | flat-box PVT | FIT* 0.105 | 0.105 |
| Benchmark | No FIT | 14.9 | 17.9 |

* FIT = 0.048 €/kWh.
* FIT = 0.048 €/kWh.
* FIT = 0.105 €/kWh.

![Table 8](image)

**Table 8**

| Utility prices and system economics when all taxes and levies are included of the optimised polymeric flat-box PVT based S-CHP systems in the three locations, with and without financial incentives. |
|----------------|----------------|----------------|
| Athens (Greece) | Polymeric | FIT* 0.105 | 0.105 |
| (UK) | flat-box PVT | FIT* 0.105 | 0.105 |
| Benchmark | No FIT | 22.0 | 15.2 |
| London (UK) | Polymeric | 16.8 | 10.3 |
| (Spain) | flat-box PVT | FIT* 0.048 | 0.048 |
| Benchmark | No FIT | 27.7 | 22.2 |
| Zaragoza | Polymeric | 14.9 | 17.9 |
| (Spain) | flat-box PVT | FIT* 0.105 | 0.105 |
| Benchmark | No FIT | 14.9 | 17.9 |

* FIT = 0.048 €/kWh.
* FIT = 0.048 €/kWh.
* FIT = 0.105 €/kWh.
to the grid for the system with the PC 3 × 2 flat-box PVT collectors, compared to the benchmark system with S&T PVT collectors. This is despite the similar amount of the electricity demand covered (around 69%) for both system variants, and is due to the 4% higher amount of electricity generated by the optimised polymeric flat-box PVT collector as a result of its enhanced electrical performance.

Fig. 11 (left) shows time-resolved results over the three consecutive days considered in July. This figure suggests that it is possible to cover almost all (> 99%) of the DHW demand (as there is no SH demand) with both the novel and benchmark PVT systems, despite the lower irradiance on some of the days due to cloud cover. Furthermore, Fig. 11 (right) shows that thanks to the batteries, it is possible to store most of the electricity generated early in the morning when there is low electricity demand, which can be used later in the day to cover an important part of the peak electricity demand occurring in the early evening, due to the cooling electricity consumption required to maintain the internal space comfort temperature at 25 °C [56]. Despite that, some electricity should also be exported to the grid, particularly on days with higher irradiance levels, due to the capacity limitations of the batteries. For the winter case, detailed results show that both systems cover a similar fraction of the household electricity demand (around 68%), however, the system with the optimised polymeric flat-box PVT collectors exports 12% more electricity to the grid.

3.5.2. Optimised S-CHP system in London

For the optimised S-CHP system (N = 11 and Vt = 0.83 m³) installed in London, only the results related to the thermal energy performance in winter (Fig. 12 left), and those corresponding to the electrical performance in summer (Fig. 12 right) are shown in this section, as these are the most relevant results. Equivalent observations to those presented in the previous section can be made for the electrical and thermal performance in winter and summer, respectively.

In Fig. 12 (left), it is possible to observe the differences in the system thermal performance between cloudy and sunny days. The results indicate that on the selected winter days it is only possible to cover around 20% of the entire thermal (DHW plus SH) demand for both the optimised polymeric flat-box PVT-based and benchmark-PVT based S-CHP systems, due to the very low irradiance levels on two of the three days. It is observed that from 12 pm on the first day until 6 am on the second day shown in Fig. 12 (left), all of the thermal demand can be covered thanks to the high irradiance (clear sky day) of the first day which results in a large amount of thermal energy stored in the tank. However, due to the very low irradiance levels of the second day (< 400 W/m² peak), a very limited amount of heat can be extracted...
from the PVT collectors, which in turn limits the amount of household thermal energy demand that can be covered. Finally, even though the third day has higher irradiance levels than the second, the amount of thermal demand covered is small as the tank temperature has significantly decreased (to around 27–38 °C from bottom to top of the tank) due to the previous day’s heat extraction and thermal losses.

The electrical performance results over the three consecutive days in July that were selected for this investigation (see Fig. 12 right) are similar to those generated in Zaragoza. On the first day, the higher electricity generation compared to demand allows the batteries to be charged, so less electricity is exported to the grid. It is observed that only at the end of each day, due to the peak electricity demand for cooling purposes, some electricity should be bought from the grid. Both systems are able to cover 87% of the total electricity demand.

3.5.3. Optimised S-CHP system in Athens

Similarly as before, only the results concerning the thermal energy performance in winter (Fig. 13 left), and those corresponding to the electrical performance in summer (Fig. 13 right) for the S-CHP system ($N = 9$ and $V_t = 0.68 m^3$) located in Athens are shown.

In Fig. 13 (left), it is possible to observe the differences in the thermal energy performance and operation of both systems between cloudy and sunny days. The results indicate that on the selected winter days it is possible to cover around 70% and 68% of the entire thermal energy (DHW plus SH) demand for both the optimised polymeric flat-box PVT and benchmark-PVT systems respectively. In Fig. 13 (left), it is observed that the thermal demand peak on the first day cannot be covered by the amount of thermal energy stored in the tank (due to lower irradiance levels on the previous day not shown here), but thanks to the high irradiance levels in the middle of the day (the first day is a clear sky day) and the thermal storage capacity of tank, the thermal energy demand is met not only for that afternoon, but also the entire following day and early morning of the third day. However, due to the very low irradiance levels on the third day (peaking at about 400 W/m$^2$), only a limited amount of the thermal energy demand can be covered after the tank is discharged during the early morning peak.

The electrical performance results on the selected summer days (Fig. 13 right) show that significantly higher electricity generation takes place early in the day (due to the high irradiance levels), in contrast to the lower electricity demand at those times, which allows the batteries to be charged. Later in the day, part of the electricity demand (mainly due to cooling) is then covered by the batteries. In Athens, a key system limitation concerns the storage capacity of the batteries, because even though batteries help to reduce the effect of the...
mismatch between electricity generation and consumption, not all electricity generated during the day can be stored and later delivered to cover the peak electricity demand in the afternoon and evening. Nevertheless, both system variants are able to cover around 63% of the total electricity demand.

4. Further discussion and conclusions

This paper has been concerned with the technoeconomic performance of solar combined heat and power (S-CHP) systems based on a novel polymeric flat-box PVT collector design proposed and modelled by the authors in previous research [26]. A quasi-steady model of a complete S-CHP system was developed in software EES, comprising a PVT collector array, a water storage tank and a lead-acid electrical battery subsystem. The electrical and thermal energy demands of single-family homes in three different locations (selected to represent a range of regions and climates), namely: Athens (Greece), London (UK) and Zaragoza (Spain) were modelled in EnergyPlus. These energy demand breakdowns along with local weather data, also from EnergyPlus, were used as inputs to the S-CHP system model. The model was run on a half-hourly basis over a carefully selected average week in each month, and key system sizing and operational parameters were assessed and optimised for each month. The monthly results were then used to predict annual performance based on which optimal system size (specifically, the number of PVT collectors and hot-water storage tank size) and operating conditions (specifically, the PVT collector flow-rate) were selected for each location.

An objective of the study was to identify optimal S-CHP systems that minimise payback-time and the associated levelised production cost per kWh of covered household energy. Another objective was to minimise the interaction of these systems with the grid (imported vs. exported electricity) and to limit the amount of excess heat rejected to the atmosphere, which is required in order to avoid tank overheating. To meet these objectives, a methodology was developed with which to identify optimal component sizes and also system operating conditions in a systematic way for two S-CHP systems; one based on the novel PVT collectors of interest and one on conventional sheet-and-tube PVT collectors as benchmark case for comparison.

The results show that 9 PVT collectors and a 0.68 m³ storage tank are recommended for optimal performance in Athens, together with a constant flow-rate through the PVT collector array of 50 L/h. With this configuration, the proposed S-CHP system is capable of covering 64% of the electrical and 61% of the thermal energy demands of the reference house at this location. In London, 11 PVT collectors and a 0.83 m³ storage tank are recommended, which together with a constant flow-rate of 30 L/h can cover 66% of the electrical and 29% of the thermal energy demands of the reference house. Finally, in Zaragoza, 8 PVT collectors, a 0.72 m³ storage tank and a constant flow-rate of 65 L/h make it possible to cover 67% of the electrical and 45% of the thermal energy demands of the reference house. It is highlighted that the S-CHP systems based on flat-box collectors outperform their sheet-and-tube equivalents at all studied locations, generating up to 3% more electricity and covering up to 3% more thermal energy demand on an annual basis, at a significantly (21%) lower PVT collector cost.

When considering the economic aspects of the implementation of these S-CHP systems, it is found that in Athens and Zaragoza the proposed systems appear as promising decarbonisation solutions and offer a reasonable-to-attractive payback time (15.6 and 11.6 years respectively), when all taxes and levies are included in the utility prices, even without incentives. Thus, considering a 25-year lifetime, the S-CHP system installations are expected to generate profits for the household for ~10 years in Athens and ~13 years in Zaragoza, thanks to both electricity and fuel-cost savings. In London, due to the low solar irradiance levels and lower ambient temperatures, the estimated system payback time (22.7 years) is closer to the system’s lifetime, although this decreases to ~20 years when the FIT currently available in the UK is considered. Therefore, it can be concluded that in order to accelerate the uptake of this technology, which offers a higher (by up to 32%) emission reduction potential compared to PV-only solutions, financial incentives may be required in some regions (e.g. Northern climates), or alternatively the system investment cost should decrease by almost half to make this a cost-effective proposition.

The flat-box PVT-based S-CHP system also outperforms the benchmark equivalent in terms of payback time (9–11% lower) and levelised production cost (4–8% lower) at all studied locations, which can be mainly attributed to the lower cost of the PV collectors; specifically, 301 € vs. 380 €. Furthermore, the optimised S-CHP system also leads to a significant reduction in CO₂ emissions compared to satisfying the household energy demands by conventional means. The high carbon emission factor of the electricity grid in Greece makes these systems particularly promising at this location. Specifically, potential savings of 3.87 tons CO₂ over a year in Athens, 1.54 tons CO₂/year in London and 1.65 tons CO₂/year in Zaragoza were identified. By comparison, PV-only solutions displace 3.56, 1.21, 1.22 tCO₂/year for the same area and 10.85, 3.41, 3.98 tCO₂/year for the same cost, but with installed PV-covered surface areas of 43, 49 and 41 m², respectively.

This technoeconomic analysis shows that the geographical location and climate have a significant effect on the performance and cost-effectiveness of the proposed S-CHP system, with low irradiance conditions resulting in a higher demand for auxiliary heat and higher fuel costs, and high irradiance conditions resulting in a lower demand for auxiliary heat but also a higher electricity demand, particularly in the summer for cooling purposes. Beyond the potential energy generated (and demand covered) by the S-CHP system, the results show that these type of systems, whose payback time depends on the achievable fuel savings, are particularly sensitive to utility prices, specific to each location. A clear example of this observation arises in the case of Athens, where, despite the potential of the proposed S-CHP system to cover ~65% of the electrical and ~62% of the thermal energy demands, the system payback time is higher than that of Zaragoza, where a lower fraction of thermal demand is covered but utility prices are higher.

Finally, it is noted that the costs of the various S-CHP system components considered in the present work were obtained from current European retailers, except for the novel PVT collector, which was estimated from raw material prices and production costs. Thus, a further reduction of these costs, especially the collector manufacturing costs, can be expected with the widespread uptake of the technology. Further, an increase in the price of fossil fuels, amongst other factors, is expected to lead to higher utility prices, which can act to decrease further the payback times of the proposed S-CHP systems from those reported here.

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