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Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications

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ABSTRACT

A modelling methodology is developed and used to investigate the technoeconomic performance of solar combined cooling, heating and power (S-CCHP) systems based on hybrid PVT collectors. The building energy demands are inputs to a transient system model, which couples PVT solar collectors via thermal store to commercial absorption chillers. The real energy demands of the University Campus of Bari, investment costs, relevant electricity and gas prices are used to estimate payback times. The results are compared to: evacuated tube collectors (ETCs) for heating and cooling provision; and a PV-system for electricity provision. A 1.68-MWp S-CCHP system can cover 20.9%, 55.1% and 16.3% of the space-heating, cooling and electrical demands of the Campus, respectively, with roof-space availability being a major limiting factor. The payback time is 16.7 years, 2.7 times higher than that of a PV system. The lack of electricity generation by the ETC-based system limits its profitability, and leads to 2.3 times longer payback time. The environmental benefits arising from the system's operation are evaluated. The S-CCHP system can displace 911 tons CO_2/year (16% and 1.4 × times more than the PV-system and the ETC-based system, respectively). The influence of utility prices on the systems' economics is analysed. It is found that the sensitivity to these prices is significant.

1. Introduction

Fossil fuels are considered important primary energy resources that have acted to satisfy the growing energy demand worldwide, which is attributed to population growth and industrialization [1,61]. It is estimated that in 2035 more than 80% of the energy consumption in developed countries will be satisfied by fossil fuels [2]. An increased penetration of renewable energy into the energy infrastructure can play a central role in shifting this trend towards a more sustainable and cleaner energy future [3]. The building sector is associated with a significant share of the total energy consumption, e.g., it accounts for over 40% of the total energy consumption while generating 36% of the greenhouse emissions in Europe [4]. However, the energy demand in buildings still relies heavily on fossil fuels. For example, only 16% of the energy for heating and cooling is covered by renewable energy, the majority of which arises from biomass combustion with a smaller contribution from modern renewables, including solar thermal and geothermal energy [5].

Solar heating and cooling (SHC) technologies, as part of wider efforts for decarbonisation, can provide heating, including space heating (SH) and domestic hot water (DHW), as well as cooling, thus increasing the renewable energy share and reducing the dependence on fossil fuels and the associated emissions [62]. Recently, they have been gaining increasing attention and research efforts [6]. Different types of solar thermal (ST) collectors, namely flat plate (FPC), evacuated tube (ETC), parabolic trough (PTC), etc., can be used to harvest solar energy in SHC and/or solar power systems [7,8].

An alternative to SHC systems based on ST collectors relies on PV systems coupled to electrically-driven reversible heat-pump/chiller (HP/CH) units [9,10], which can provide both space heating/cooling depending on the operation mode. Furthermore, the synergistic combination of PV and ST collectors has given rise to hybrid photovoltaic-thermal (PVT) systems, which appear as highly suitable solutions, as they combine the advantages of PV and ST systems, generating both electricity and a useful thermal output

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Nomenclature

Abbreviations

AbCH	Absorption chiller
AdCH	Adsorption chiller
COP	Coefficient of performance
CPVT	Concentrated PVT
CS	Cost savings
DC/AC	Direct current/alternating current
DHW	Domestic hot water
ESCO	Energy services company
ETC	Evacuated tube collector
FIT	Feed-in-tariff
FPC	Flat plate collector
HP/CH	Heat-pump/chiller
HVAC	Heating ventilation and air conditioning
IEA	International Energy Agency
pc-Si	Poly-crystalline silicon PV module
O&M	Operation and maintenance costs
PC	Polycarbonate
PBT	Payback time
PTC	Parabolic trough collector
PV	Photovoltaic
PVT	Photovoltaic-thermal system
S-CCHP	Solar combined cooling, heating and power
S-CHP	Solar combined heating and power
SH	Space heating
SHC	Solar heating and cooling
ST	Solar thermal
LCC	Life cycle cost

Symbols

A_c	PVT collector aperture area (m^2)
A_{cT}	Total PVT collector area in each parallel system (m^2)
c_e	Electricity price (€/kWh)
c_{ng}	Natural gas price (€/kWh)
C_0	Investment costs (€)
$C_{O\&M}$	Operation and maintenance (O&M) costs (€/yr)
d	Discount rate (%)
E_{Cov}	Electricity demand covered (kWh)
E_{grid}	Electricity exported to the grid (kWh)
I_{tot}	Total global solar irradiance (W/m^2)
i_F	Fuel inflation rate (%)
I_{SC}	Open circuit current (A)
n	Node (−)
q_u	Useful heat flow per meter square (W/m^2)
Q_{Cov}	SH demand covered (kWh)
T_a	Ambient temperature (K)
T_{fm}	Fluid mean temperature (K)
T_r	Reduced temperature (K)
V_t	Storage tank volume (L)
V_{oc}	Open circuit voltage (V)

Greek

η_{boil}	Boiler efficiency (%)
η_{el}	Electrical efficiency (%)
η_{th}	Thermal efficiency (%)

simultaneously from the same aperture area [11], with a higher overall efficiency than separate stand-alone systems [12,13]. The integration of PVT systems with heating and cooling technologies allows the simultaneous generation of DHW, SH, cooling and electricity, and thus has the potential to cover a significant amount of the energy demands of buildings [14].

Most of the studies in literature have focused on integrating ETC [15,16], FPC [17,18] or PTC [19,20] with absorption (AbCH) or adsorption chillers (AdCH). ETC-based SHC systems have attracted more attention as they have a better temperature match with AbCH (ETCs reach higher fluid temperatures) [21] with relatively lower costs [22]. Previous studies were mainly focused on component design [23], system integration [24], technology comparison [25], parametric analyses [26] and optimisation [27], performance assessment and applications [7]. There are also some studies that have considered compound parabolic concentrators coupled to single/double effect LiBr-H_2O AbCH [28,29] or coupled to AdCH [30]; while other authors have analysed solar desiccant and evaporative cooling (DEC) systems [31]. Most of the studies concerned with PVT systems have focused on combining concentrated PVT (CPVT) collectors with LiBr-H_2O AbCH [32,33], while studies on flat-plate PVT collectors are scarcer [34,35]. However, previous research concluded that the integration of PVT-water collectors with AbCH or AdCH is very promising [6].

Despite its potential, there are still very few companies worldwide commercialising PVT collectors [36], which in most cases do not have optimised designs. In an attempt to overcome this, previous work by the authors [23] focused on the design and characterisation of novel designs based on a flat-box structure and polymeric materials for flat-plate PVT collectors. Promising results were obtained, with a polycarbonate flat-box design achieving ~4% higher optical efficiency and ~16% lower heat-loss coefficient than those of an equivalent commercial sheet-and-tube PVT collector, also with 10% lower weight and about 20% lower capital cost.

Previous research on a wider solar combined heating and power (S-CHP) system based on these polycarbonate flat-box PVT collectors also showed promising results for the simultaneous provision of SH, DHW and power to single-family homes [37]. Reasonable-to-attractive payback times (*PBT*) were obtained for these S-CHP systems installed in Mediterranean cities such as Athens (15.6 years) or Zaragoza (11.6 years) [37]. Sensitivity analyses on the economics of these systems concluded that in reasonable future scenarios (e.g. 10% reduction in the PVT collector price and storage tank price, 20% reduction in the installation costs, fuel inflation rates of 3.5%) the *PBT* can decrease to ~10 years [38].

This research aims to go beyond the aforementioned studies, by investigating the integration of such polycarbonate flat-box PVT collectors with AbCH units (single-effect LiBr-H_2O) via thermal stores in wider solar systems for the combined provision of SH, cooling and electricity to buildings. As a case study, the real monthly natural gas consumption and quarter-hourly electricity load profiles of the University Campus of Bari (Italy) are selected, in order to estimate hourly SH, cooling and electricity demands. These demands are then used as inputs to a transient model, along with real hourly weather data, to conduct year-round simulations. The performance data of a commercially available AbCH unit manufactured by MAYA [39] is also integrated into the transient model. The costs of the system's components, the system installation costs, as well as key economic parameters (e.g. discount rate, fuel inflation rate, utility prices) are considered in order to assess the technoeconomic feasibility of the proposed solar combined cooling, heating and power (S-CCHP) system. The results are then compared to two alternative solar systems: i) ETC-based SHC system for the provision of heating and cooling, but without power generation;

and ii) a PV system that matches the electricity demand of the Campus (including the electricity required to run the current HVAC system for air-conditioning), but without thermal energy generation.

2. Methodology

The proposed PVT-based S-CCHP system, as well as the alternative ETC-based SHC system, have been modelled in TRNSYS [40], in transient simulations considering real weather data [41], conducted in hourly time-steps over a year. For the purpose of this analysis, faster transients are neglected [63]. The main outputs are the energy generated by the solar collectors (electricity and thermal energy in the case of PVT collectors, and thermal energy in the case of the ETCs), the SH, cooling and electricity demands that can be covered by the systems, and the auxiliary heating (natural gas) needs. Current electricity and natural gas prices are considered in order to estimate the annual cost savings which, together with the investment cost and the operation and maintenance costs (O&M), allow an estimation of the system's payback time (*PBT*). The existing scenario of gas-fired boilers operated within an Energy Service Contract by an ESCO for the provision of SH is considered to estimate the avoided costs of thermal energy with the S-CCHP/SHC systems. The electricity generation surplus of the S-CCHP system at any time step is fed to the grid at a feed-in tariff (FIT) guaranteed by the distribution system operator according to current Italian regulations [42]. The annual CO_2 emission reductions and primary energy savings that arise from the proposed system's operation are evaluated based on the corresponding CO_2 emission and primary energy factors for electricity and natural gas in Italy.

A limiting factor for the size of the systems is the available roof-space in the Campus' buildings (23,600 m^2). For comparison purposes, the proposed PVT-based S-CCHP system and the PV system have the same installed electrical capacity. The maximum number of PVT collectors that can be installed is 7,020, which corresponds to a total area of 10,850 m^2 and an installed electrical capacity of 1.68 MW_p. Based on previous studies [43] and preliminary analysis, the selected V_t/A_{cT} ratio for the storage tank volume is 50 L/m^2. The PV system of the same installed power (1.68 MW_p), comprises 8,830 m^2 of PV modules. For the ETC-based SHC system, the same installed area as the PVT-based S-CCHP system is considered for comparison purposes, which corresponds to 3920 ETCs (ETC unitary size of 2.77 m^2 [44]).

2.1. Energy demand of the University Campus of Bari

The Campus consists of 12 university buildings with a heated area of 127,300 m^2 and a heated volume of 495,300 m^3 (Fig. 3 left). The SH demand is 28.8 kWh/m^2-year, currently covered by gas-fired boilers of 82% efficiency and a hot water delivery temperature of 80 °C, with an annual consumption of 393,000 Nm^3 of natural gas. The DHW demand is negligible. The cooling demand is estimated to be 11.9 kWh/m^2-year, currently covered by HVAC systems. The total electricity demand of the Campus is about 11 GWh/year. Subtracting the electricity consumed by the HVAC systems for air-conditioning, the rest of the electricity consumption is 85.2 kWh/m^2-year. Fig. 1 shows the monthly energy demand breakdown of the Campus. It should be noted that space heating (SH) and cooling demands shown in Fig. 1 refer to thermal-energy demands (e.g. without considering the HVAC and gas boiler systems' efficiency).

Only monthly natural gas bills are available, so based on the information provided by the Campus heating system operator (Enel Distribuzione), a flat profile from 8 a.m. to 6 p.m. (10 h/day) from Monday to Friday is assumed to estimate the hourly SH demand, from November to March. Quarterly-hour data is available for the total electricity consumption from the local distribution system operator (Enel Distribuzione), which is aggregated to estimate the hourly electricity consumption. To estimate the cooling demand, based on previous studies [45,46], it is assumed that during summer (June to September), around 35% of the total electricity consumption is consumed by the HVAC systems for air-conditioning from 8 a.m. to 8 p.m. (12 h/day). A COP of 3 is assumed when converting the electricity consumed by HVAC systems to cooling demand. Instead of using a flat profile, the hourly cooling demand is estimated following a distribution profile correlated to the ambient temperature (e.g. higher cooling needs around midday, 11 a.m.–3 p.m., when ambient temperatures are higher). These hourly SH, cooling and electricity demands are inputs to the transient model.

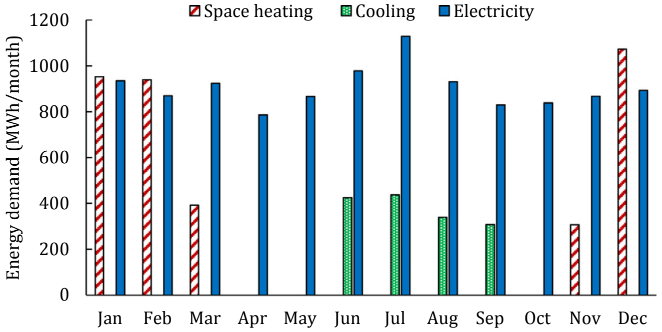

Fig. 1. Monthly space heating, cooling and electricity demands of the University Campus of Bari.

2.2. PVT-based combined cooling, heating and power system

Due to the considerable size and energy demand of the University Campus of Bari (12 buildings throughout the city of Bari, as shown in Fig. 3), the total number of PVT collectors is divided in 45 parallel solar combined cooling, heating and power (S-CCHP) sections of the same size, each of them with its DC/AC inverter and connected to the internal MV grid of the Campus. This facilitates operation and maintenance, and allows the systems to run according to the Campus needs while limiting the sizes of the different components (e.g. storage tanks and absorption chillers). Considering the latitude of Bari, the PVT collectors are titled at 35°, facing south, and are connected in parallel so that all of them have the same inlet water temperature and water flow-rate. Based on previous studies [14,37], a constant PVT collector flow-rate of 50 L/h is assumed.

In the proposed S-CCHP system, the thermal output of the PVT collectors is connected, through a water storage tank, to the current gas-fired boilers and is used to preheat the water to satisfy the SH demand, reducing the gas consumption. In normal operation, the collector outlet flow enters the heat exchanger coil located inside the storage tank, heats the water in the tank, exits from the lower part of the tank and returns to the PVT collector inlet to be heated again. As shown in Fig. 2, a bypass valve is required to control the outlet temperature of the cooling fluid to ensure that this stream only heats (and does not cool) the water in the tank [11,37]. A differential temperature controller (Type 2b) controls the valve position by comparing the temperature at the entrance of the heat exchanger coil at the top of the water storage tank with the temperature of the cooling fluid at the PVT collector outlet. The electricity required to run the circulator pump of this active closed loop system is extracted from the electricity generated by the PVT

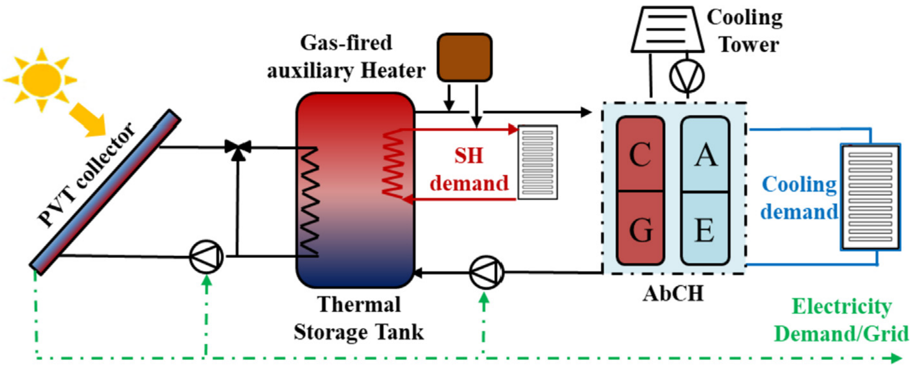

Fig. 2. Schematic diagram of an S-CCHP system based on PVT collectors integrated with a single-effect LiBr-H_2O AbCH through a thermal store.

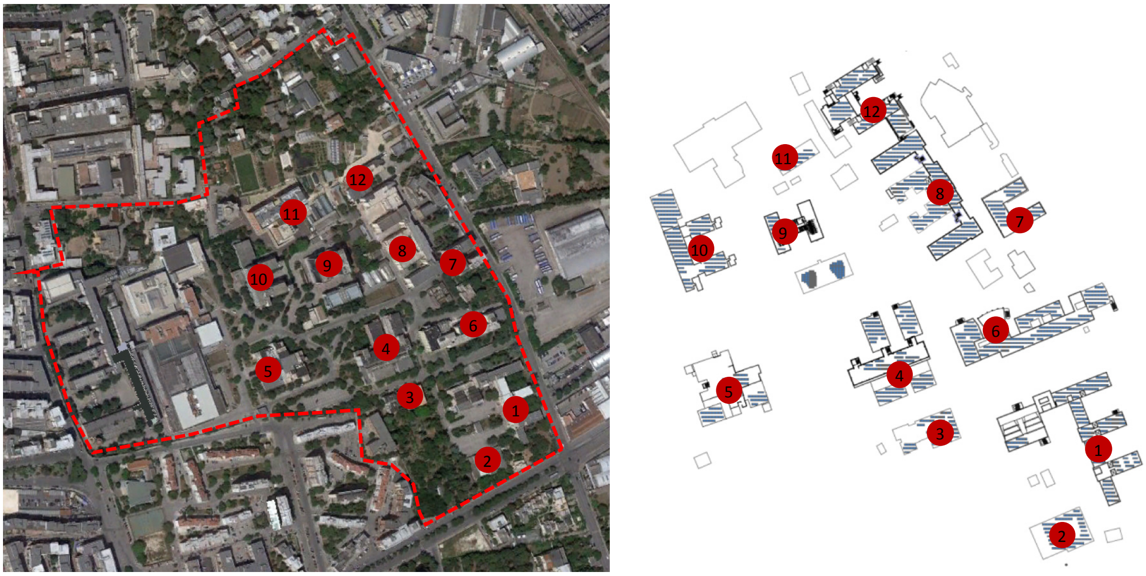

Fig. 3. (Left) University Campus planimetry, where red dots indicate the Campus' buildings with roof-space available for this analysis; and (right) layout of the proposed standard PV system, where striped-blue areas indicate roof areas covered by the proposed PV system.

collectors.

In cooling mode, a single-effect LiBr-H_2O AbCH unit is fed by the thermal output of the PVT collectors (through the backup gas-fired boilers when required) in order to provide cooling (see Fig. 2). The electrical output of the PVT collectors is used to match the Campus's annual electricity demand.

2.2.1. PVT collector

Polycarbonate flat-box PVT collectors proposed by the authors are used in this work, in which the heat transfer from the absorber to the fluid is improved by means of 3 × 2 mm channels [23]. The PVT collectors are implemented in a transient model developed in TRNSYS with the modified Type 560 [14] to match the thermal performance (η_{th}) curve shown in Eqs. (1) and (2). The PVT collector has a nominal electrical power of 240 W_p and an aperture area (A_c) of 1.55 m^2. The nominal electrical efficiency (η_{el}) of the PVT collector is 14.7%, and the temperature coefficient of the PV cells is 0.45%/K [23],

$$\eta_{\text{th}} = \frac{q_u}{I_{tot}} = 0.726 - 3.325 \cdot T_r - 0.0176 \cdot I_{tot} \cdot T_r^2, \quad (1)$$

$$T_r = \frac{T_{\text{fm}} - T_a}{I_{tot}}, \quad (2)$$

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

2.2.2. Stratified water storage tank

The tank is modelled using 6 fully mixed equal-volume segments that divide the cylinder along its vertical axis (Type 534). 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 preheated water for SH demand is supplied via a port at the top of the tank (at node $n = 1$), and returns at a lower temperature at the middle ($n = 4$). The currently available gas-fired auxiliary heaters (nominal efficiency of 82%) are used to heat the water up to the delivery temperature for SH (80 °C). An immersed heat exchanger connected to the PVT collector runs from the top ($n = 1$) to the bottom ($n = 6$) of the tank to heat the water inside the tank (see Fig. 2). To satisfy the cooling demand, the AbCH generator is connected to a second port leaving the tank at the top ($n = 1$) and entering at the bottom node ($n = 6$).

The storage tank volume is varied by changing the value 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 in each parallel system in square meters. The size of the solar immersed heat exchanger coil also varies with the tank size, through the variation of the tank height, such that the ratio between the coil heat transfer area, and the total PVT collector area, is not lower than 0.15 [47] to ensure adequate heat transfer. More details of the stratified water storage tank model can be found in previous work [37].

2.2.3. Absorption chiller

Considering that the cooling demand of the Campus is met by 45 absorption chillers running in parallel, the commercial WFC-SC-20 AbCH unit by MAYA [39] is selected with a cooling capacity of 70 kW and a nominal COP of 0.70. The performance data of this commercial AbCH (i.e. the variation of the cooling capacity factor and heat input factor with hot water temperature and cooling water temperature) is considered in Type 107 AbCH model, of which the data file is modified accordingly.

The AbCH generator is connected with the top of the storage tank through the currently available gas-fired auxiliary heaters to ensure that the water enters the AbCH at 72.5 °C at least (70 °C is the minimum temperature to start the cycle). Chilled water is provided at 7 °C and returns at 12.5 °C. The nominal cooling water flow-rate of the AbCH is used, along with an inlet cooling water temperature of 27 °C. At each time step, the heat rejection is estimated by considering the above parameters along with the outlet cooling water temperature. The cooling tower capacity is calculated from the maximum heat rejection at any time step (140 kW). The electricity consumption of the AbCH specified in the manufacturer's technical data [39] is extracted from the electricity generated by the PVT collectors.

2.3. Alternative ETC-based solar heating and cooling system

An SHC system based on direct-flow ETCs is proposed as an alternative to the PVT-based S-CCHP system for the provision of heating and cooling. An equivalent system to Fig. 2 is proposed but, in this case, the PVT collectors are replaced by ETCs, and there is no electricity generation. The same AbCH and stratified water storage tank as for the S-CCHP system are used. For the ETCs, the commercially available Thermomax DF400 is selected [44], as it has higher optical efficiency and lower heat loss coefficients than the proposed PVT collectors (see Eq. (3)). The selected ETC has an absorber area of 2 m^2, an aperture area of 2.16 m^2 and the nominal flow-rate is used (120 L/h). The performance data of the ETC provided by the manufacturer is implemented in Type 71 in TRNSYS.

$$\eta_{th} = \frac{q_u}{I_{tot}} = 0.768 - 1.36 \cdot T_r - 0.0053 \cdot I_{tot} \cdot T_r^2, \tag{3}$$

2.4. Alternative PV system

The PV system consists of a set of modules tilted at 30° and 10°, according to the available possibilities for building integration, with an aperture area of 1.44 m^2 and PV modules whose technical specifications are reported in Table 1. Assuming adequate distances between PV modules to maximise yield, it is estimated that a unitary area of 14 m^2/kW would be required, thus the maximum installed power of the PV system is 1.68 MW_p (total available roof-space of 23,600 m^2).

The planimetry of the University Campus and the layout of the PV system are reported in Fig. 3. The figure on the right shows the roof areas covered by the proposed PV system (striped-blue areas). According to the Italian legislation, the integration of the PV modules on the building's roof is required to facilitate the permitting procedures and, on the other side, it is the only option due to the scarcity of ground area for PV modules. The location of the PV modules on top of each building also requires a distributed type of installation with 11 DC/AC inverters which connect the PV generators to the internal electricity network. This slightly increases the investment and maintenance costs and it has been included in the cost figures considered in the economic analysis.

Table 1
Technical specifications of the PV system.

Parameter	Value
Max. voltage	1000 V_{DC}
Max. power	275 W_p
Voltage at nominal power	31.7 V
Current at nominal power	8.69 A
Open circuit Voltage (V_{OC})	38.7 V
Open circuit current (I_{SC})	9.17 A
Nominal electrical efficiency (η_{el})	16.9%
Temperature coefficients	V_{OC}: 0.31%/°C; I_{SC}: 0.06%/°C
Efficiency losses	<0.7%/year

2.5. Economic analysis

The investment costs (C_0) of all proposed solar systems have been estimated from price lists available from solar retailers in the EU [48–50]. As shown in Fig. 4, the main costs of the system are associated with the PVT collectors (43%) [23] or ETC collectors (38%) [44,51], storage tank (9–10%) [52] and absorption chiller (18–21%) [6]. The cost of the storage tank is estimated using a correlation based on market prices of existing tanks across a range of storage volumes [37,38]. The total installation costs are also considered [11]. The auxiliary heater price is not considered as the University Campus, which forms the present case study, already has gas-fired boilers available.

The system's payback time (*PBT*) is defined as the period of time required to recover the investment of the S-CCHP system, and it can be calculated as follows [37,53],

$$PBT = \frac{\ln\left[\frac{C_0 \cdot (i_F - d)}{CS_{S-CCHP}} + 1\right]}{\ln\left[\frac{1+i_F}{1+d}\right]} \tag{4}$$

where d is the discount rate (5%) [54,55] and i_F refers to the fuel inflation rate (3.5%) considered for the annual cost savings, $CS_{S\text{-}CCHP}$ [56]. In turn, the annual cost savings ($CS_{S\text{-}CCHP}$) are estimated by accounting for the total electricity and natural gas fuel savings due to the electricity and thermal (SH and cooling) energy demand covered by the S-CCHP system, along with the O&M costs of the system ($C_{O\&M}$), and the income for the electricity exported to the grid, as follows [37],

$$CS_{S-CCHP} = E_{Cov} \cdot c_e + \frac{Q_{Cov}}{\eta_{boil}} \cdot c_{ng} + E_{grid} \cdot FIT - C_{O\&M} \tag{5}$$

where E_{Cov} and Q_{Cov} are the electricity and SH demand covered, E_{grid} is the electricity exported to the grid, c_e is the component of the electricity price that is avoided/saved by the onsite generation and consumption (0.145 €/kWh), c_{ng} is the natural gas price (0.098 €/kWh) and FIT is the current feed-in tariff applicable to the excess electricity fed into the grid with the net metering option [42] (0.073 €/kWh). These values correspond to the current tariffs for the University Campus of Bari. It should be noted that the University Campus has a 15-years heating service contract with the local

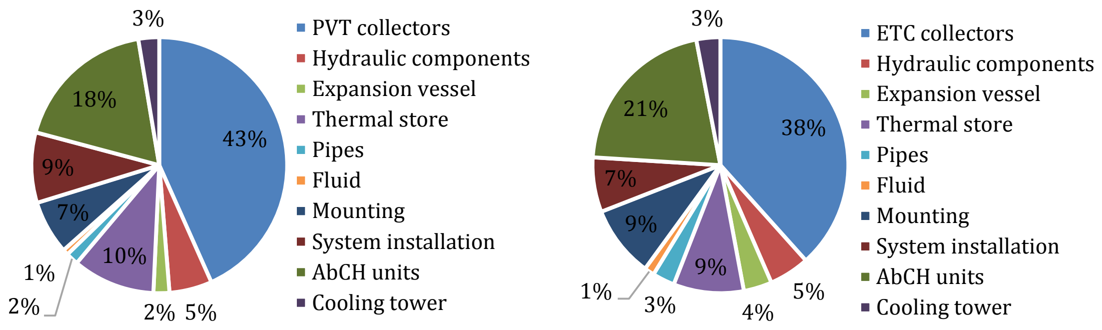

Fig. 4. Breakdown of the investment costs (including installation) of (left) the proposed PVT-based S-CCHP system and (right) the ETC-based SHC system for the University Campus of Bari. Details of these configurations (e.g. total solar field area and total investment cost) are shown in Table 2.

energy provider for the natural gas supply, maintenance of boilers and related distribution system, and for the repowering of inefficient and old boilers. This results in a unitary heating service cost which also includes the depreciation of investment costs incurred by the ESCO and system's maintenance. In particular, the global service contract does not allow a reduction of the demand (or likewise a reduction of the gas consumption with the proposed solar systems) of more than 20% relative to reference values without incurring penalties. The cooling demand is currently satisfied by electricity-driven HVAC units in the University Campus, so the associated energy savings by the S-CCHP system are included in the electricity term in the economic analyses.

The O&M costs amount to 1% of the total equipment costs for the PVT-based S-CCHP system, 0.6% for the ETC-based SHC system, and 150 €/MW_p for the PV system [57]. The PV and ETC-based SHC system *PBTs* are estimated using the same equations, considering their investments and cost savings.

3. Results and discussion

3.1. Transient PVT-based combined cooling, heating and power system results

This section presents detailed results obtained in TRNSYS on an hourly basis with the aim of understanding the operation and performance of the proposed PVT-based S-CCHP system. Nine representative days from Saturday to the following Sunday are selected in this analysis to assess the influence of the weekend (when there is no SH or cooling demands) on the system's performance. Figs. 5 and 6 show the results from the 4th to the 12th of February.

It is observed that the SH and electricity demands (purple lines with diamonds) are much higher than the thermal and electrical energy generated by the S-CCHP system, so only a limited amount of the Campus energy demands is expected to be covered, due to the limitation of the available roof-space discussed before. The results show that in days with high irradiance levels (dashed-dotted yellow line with triangles in Fig. 5), more electricity and SH demand are covered (dashed blue lines with squares). Fig. 5 shows that in the particular week considered here, all the electricity generated by the system (red lines with circles) is directly consumed onsite ($E_{\text{S-CCHP}} = E_{\text{Cov}}$).

Fig. 6 shows that the temperature at the top of the hot-water storage tank (dotted lines with triangles) increases considerably during the weekends (first two and last two days shown in this plot) as there is no SH demand, so no water is extracted from the storage tank. This allows covering a higher amount of SH demand on the following Monday.

Figs. 7 and 8 show results from the 15th to the 23rd of July. Similar electricity results than for the winter week (Fig. 5) are obtained, with all the electricity generated directly consumed onsite. From these figures, it is observed that, similar to the winter operation, the temperature at the top of the tank (dotted lines with triangles) increases considerably during the weekends (first two and last two days) reaching almost 90 °C (see Fig. 8), as there is no cooling demand, so no water is extracted from the storage tank. This enables a situation, on the following Monday, wherein the temperature reached at the top of the tank is high enough to run the AbCH, so all the cooling demand can be satisfied until the end of the day (blue lines with squares), when some auxiliary heat is

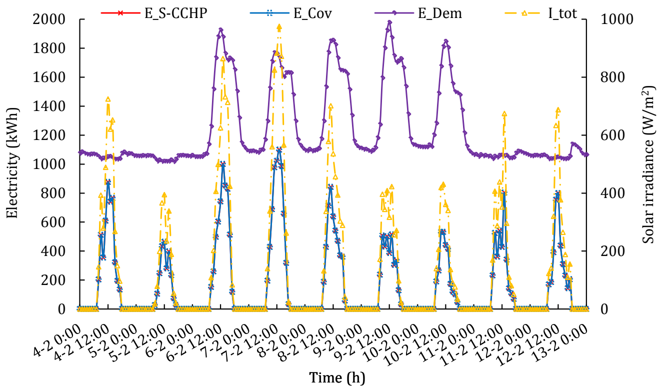

Fig. 5. Electricity generated ($E_{\text{S-CCHP}}$), electrical demand covered (E_{Cov}), electrical demand (E_{Dem}) and total solar irradiance at a tilted angle (I_{tot}) for the S-CCHP system during 4–12 February.

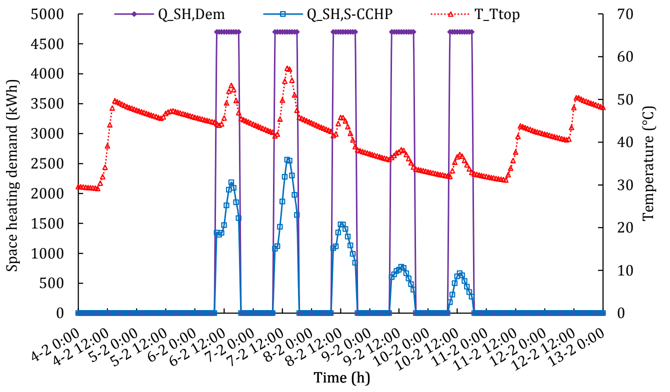

Fig. 6. Total SH demand ($Q_{\text{SH,Dem}}$), SH demand covered ($Q_{\text{SH,S-CCHP}}$), and water temperature at the top of the storage tank (T_{Ttop}) for the S-CCHP system during 4–12 February.

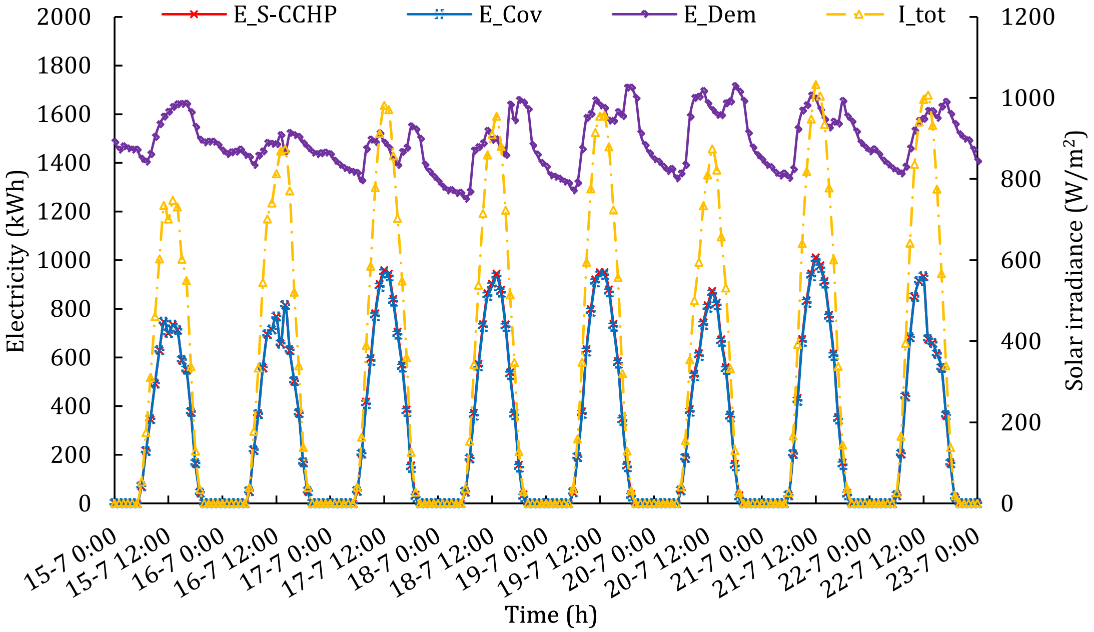

Fig. 7. Electricity generated ($E_{S\text{-}CCHP}$), electrical demand covered (E_{Cov}), electrical demand (E_{Dem}) and total solar irradiance at a tilted angle (I_{tot}) for the S-CCHP system during 15–23 July.

needed (yellow line with crosses) to increase the temperature of the water entering the AbCH to 72.5 °C (dashed-dotted green line with pluses), required to run the unit.

Conversely, in the rest of the days, more auxiliary heat is needed, specially at the beginning and end of the day. Here, it should be highlighted that the improved thermal performance of the PVT collectors in summer, especially during the main hours of the day (12–5 p.m.), due to higher solar irradiance levels, matches the higher hot water requirements of the AbCH owing to higher cooling demand at those periods. Therefore, there is a double benefit: on the one hand, hot water from the top of the tank is extracted to run the AbCH, avoiding overheating problems, and on the other, the water returning to the tank is at a lower temperature which maintains the bottom of the tank at a lower temperature, thus lowering also the temperature of the water entering the PVT collectors.

3.2. Technoeconomic assessment

In this section, the annual technoeconomic results of the proposed PVT-based S-CCHP system are compared with two solar alternatives: i) ETC-based SHC system for the provision of heating

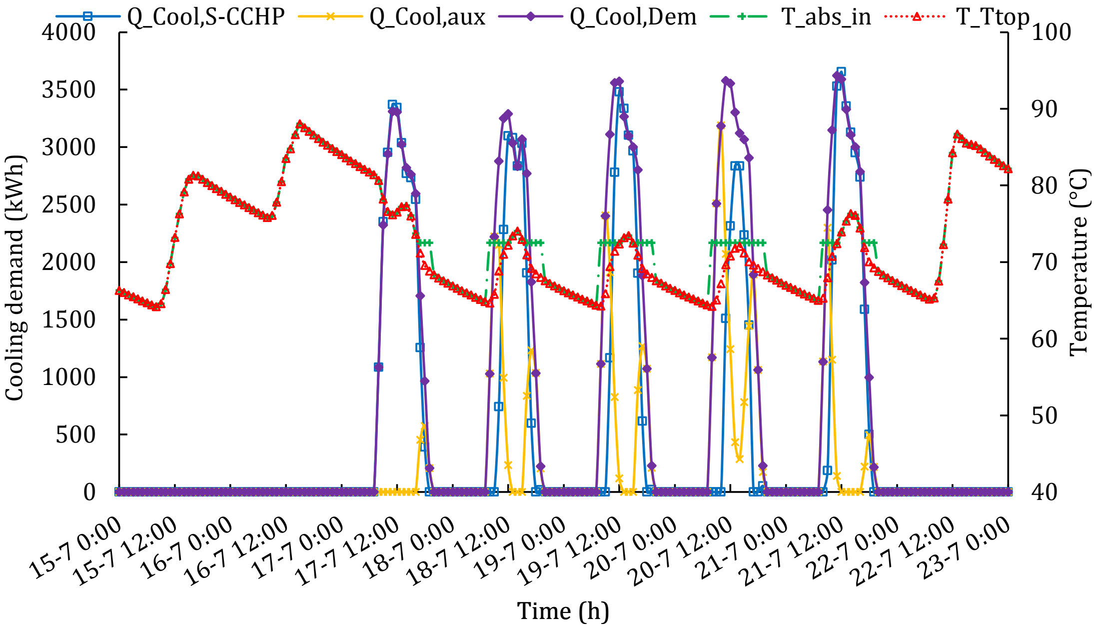

Fig. 8. Thermal energy required by the AbCH ($Q_{Cool,Dem}$), thermal energy provided by the proposed S-CCHP system ($Q_{Cool,S\text{-}CCHP}$) and auxiliary energy required ($Q_{Cool,aux}$) to satisfy the cooling demand for the S-CCHP system during 15–23 July.

and cooling (Section 3.2.1); and ii) a standard PV system to provide the electricity demand of the Campus (including the electricity required to run the current HVAC system for air-conditioning) (Section 3.2.2).

3.2.1. Comparison of the PVT-based S-CCHP with an ETC-based SHC system

Table 2 shows annual performance and economic results for the proposed PVT-based S-CCHP system and for the equivalent ETC-based SHC system. It is observed that the ETC-based SHC system covers a higher percentage of the SH (27.7% *vs*. 20.9%) and cooling (74.2% *vs*. 55.1%) demands. However, the annual CO_2 emission reduction and primary energy savings achieved by the PVT-based S-CCHP system are considerable higher (911 *vs*. 386 tons CO_2/year, and 5,460 *vs*. 1,320 MWh_{pe}/year, respectively), which is attributed to the electricity generation by the S-CCHP system since the electrical output accounts for 68% of the total CO_2 emission reduction, and 71% of the primary energy savings. Here it should be noted that only the CO_2 emissions associated with the system's operation are considered in the present work. Given the indicated promise of this technology in terms of its potential environmental benefits, a complete environmental impact assessment in the form of life cycle analyses appears useful, which is proposed as an avenue for further work.

Despite the lower investment cost of the ETC-based SHC system (13% lower), its *PBT* is considerably (2.3 times) higher than the S-CCHP system, which is again due to the electricity demand covered by the S-CCHP system (and, at lesser extent, excess electricity sold to the grid), which accounts for 66% of the total cost savings. The reason is the higher (1.5 times) price of electricity than natural gas (see Table 2). As a consequence, it can be concluded that in this particular case where there are simultaneous SH/cooling and electricity demands, a system capable of simultaneously generating electrical and thermal energy such as the proposed S-CCHP system appears as a more suitable alternative than an SHC system.

In order to understand the influence of utility (electricity, natural gas) prices on the systems' economics, two additional scenarios are assessed: i) the current national utility prices in Italy where the University Campus is located; and ii) the current national utility prices in Denmark, which has the highest combined rates ($c_{ng} + c_e$) in the EU [58]. The results show that the cost-competitiveness of the analysed solar systems is very sensitive to the utility prices. In the case of the SHC system, Table 2 shows that the natural gas price should be considerably higher for this system to become an interesting alternative. In turn, it is observed that the proposed S-CCHP system has a *PBT* below the system's lifetime (~25 years) [59,60] when considering the current utility prices applicable to the University Campus (16.7 years), so the system is expected to generate profits during the last ~8 years of its life. It is also observed that the S-CCHP system emerges as a promising decarbonisation solution if utility prices increase, which is likely to occur given recent trends [38]. Specifically, if utility prices in Italy approach those currently in Denmark, the *PBT* more than halves to 10.2 years.

3.2.2. Comparison of the PVT-based S-CCHP system with a PV system

Table 3 shows the annual performance and economic results for the proposed PVT-based S-CCHP system with three different sizes, as well as for the equivalent PV system. With the S-CCHP system presented in Section 3.1 (same installed power as the PV system, 1.68 MW_p) it is possible to cover 20.9% of SH, 55.1% of cooling and 16.3% of electricity demands of the University Campus of Bari. It should be noted that the percentage of onsite electricity consumption is very high (>99% of the electricity generated by the PVT collectors is directly consumed), and the surplus electricity at any time step is exported to the grid with the feed in tariff FIT reported in Eq. (5).

In the PV system, 7.7% of the electricity generated is fed into the grid and the electricity demand covered increases up to 20.7%. However, this influences the profitability of the investment, because the current avoided cost from onsite generation (0.145 €/kWh) is applied to the electricity generated and consumed onsite, while a lower tariff (a FIT of 0.073 €/kWh) is applied to the excess electricity exported to the grid with the net metering option. As discussed before, the limited amount of energy demand coverage is due to the restraint roof-space availability in the buildings.

The PVT-based system *PBT* is 16.7 years, which is considerable longer (2.7 times) than the *PBT* of the equivalent PV system (6.1 years). This is attributed to the much higher investment cost of the S-CCHP system. Another handicap that hinders the potential of the proposed S-CCHP system is the lower price of natural gas than the electricity price. If the natural gas price was the same ($c_{ng} = c_e = 0.145$ €/kWh), the S-CCHP system's *PBT* would decrease to 14.6 years. An incentive of the proposed S-CCHP system is high potential CO_2 emission reduction and primary energy savings (911 tons CO_2/year and 5460 MWh_{pe}/year), which are 16% and 12% higher than for the PV system. As noted above, a complete lifecycle analysis is proposed as further work to evaluate the full environmental impact of these solar alternatives from cradle-to-grave.

For comparison purposes, two additional S-CCHP system sizes were analysed: i) a system with the same installed area as the PV system (8,830 m^2, 1.37 MW_p); and ii) assuming that half of the available roof-space is covered by PVT collectors (11,800 m^2, 1.84 MW_p). Table 3 shows that in the former case, the lower amount of energy demand covered due to the lower PVT collectors installed area leads to a higher *PBT* and a lower CO_2 emission reduction.

Table 2
Energetic and economic results of a PVT-based S-CCHP system and an ETC-based SHC system for different utility-price scenarios.

Utility prices	PVT-based S-CCHP system			ETC-based SHC system		
	Current prices	National prices	Danish prices	Current prices	National prices	Danish prices
Installed area (m^2)	10,850	10,850	10,850	10,850	10,850	10,850
Total investment (C_0, M€)	4.88	4.88	4.88	4.24	4.24	4.24
SH demand covered (%)	20.9	20.9	20.9	27.7	27.7	27.7
Cooling demand covered (%)	55.1	55.1	55.1	74.2	74.2	74.2
Electricity demand covered (%)	16.3	16.3	16.3	–	–	–
Annual CO_2 emission reduction (tons CO_2/year)	911	911	911	386	386	386
Primary energy savings (MWh_{pe}/year)	5,460	5,460	5,460	1,320	1,320	1,320
Natural gas price (c_{ng}, €/kWh)	0.098	0.032	0.071	0.098	0.032	0.071
Electricity price (c_e, €/kWh)	0.145	0.133	0.252	0.145	0.133	0.252
Payback time (*PBT*, years)	16.7	23.2	10.2	37.8	>100	35.8

Table 3
Energetic and economic results of different-sized PVT-based S-CCHP and PV-only systems.

	S-CCHP system			PV system
Installed power (MW_p)	1.68	1.37	1.84	1.68
Installed area (m^2)	10,850	8,830	11,800	8,830
Total investment (C_0, M€)	4.88	4.17	5.22	1.60
SH demand covered (%)	20.9	17.8	22.4	–
Cooling demand covered (%)	55.1	45.9	58.8	–
Electricity demand covered (%)	16.3	13.3	17.7	19.1
Payback time (*PBT*, years)	16.7	17.5	16.5	6.1
Annual CO_2 emission reduction (tons CO_2/year)	911	752	986	784
Primary energy savings (MWh_{pe}/year)	5,460	4,500	5,910	4,880

Conversely, the results show that if more PVT collectors are installed, the higher energy demand covered compensates the higher investment cost, obtaining a lower *PBT* (16.5 years). Therefore, these results confirm that in this case, the limiting factor for the optimum system's sizing is the roof-space availability.

Finally, it is noted that this technoeconomic assessment does not include the subsidies available in the Italian framework for energy saving measures ('*White certificates*' or '*conto energia termico*' in particular). These subsidies would provide a further income for the solar based generation of heating, power and cooling, based on the avoided fossil fuels' consumption, that would increase the investment profitability. However, these were not considered due to the uncertainty on their continuing availability and also in order to make the results more transferable to other countries.

4. Further discussion and conclusions

A modelling methodology has been developed and used to examine the technoeconomic performance of solar combined cooling, heating and power (S-CCHP) systems based on PVT collectors. The University Campus of Bari is selected as a case study to demonstrate how the methodology can be used to analyse the suitability and value of the proposed systems when providing space heating (SH), cooling and electricity to the Campus buildings. The hourly energy demand profiles of the Campus have been estimated based on real consumption data provided by Campus managers, and have been used as inputs to the transient S-CCHP model developed in TRNSYS, which features an array of novel hybrid flat-box PVT collectors coupled via a thermal store to a commercial single-effect LiBr-H_2O AbCH unit. The current gas-fired boilers are used as a backup heating system. Three alternative solar systems are analysed and compared based on the following technologies: PV panels with an electrical output only, PVT collectors, and evacuated tube collectors (ETCs) with no electricity generation.

Transient simulations are run over a full year on an hourly basis, for which real performance data for the different system components are implemented (e.g. commercial AbCH and ETC). The investment costs of the solar systems in each case, and current electricity and gas prices are considered for the economic analyses. The hourly results are summed to obtain the annual energy yields and energy demands covered by each system, which are then used to estimate the systems' *PBT*, CO_2 emission reduction potential, and primary energy savings potential.

The results show that, due to the high hot water delivery temperature (80 °C) and the limited roof-space availability, the proposed S-CCHP system only covers 20.9% of the SH demand of the Campus, when it is used to preheat the water to satisfy the SH demand. However, the hot water generated by the PVT collectors can be used in summer to run the commercial AbCH units, with which 55.1% of cooling demand is covered. Thus, the proposed S-CCHP system has the potential to considerably reduce the electricity needs in summer used by the current HVAC systems for air-conditioning. Furthermore, the proposed system covers an additional 16.3% of the electricity demand. Still, due to the considerably higher investment cost of the S-CCHP system compared to a PV system of the same installed power, the *PBT* of the former is significantly higher (16.7 years *vs*. 6.1 years).

Furthermore, an alternative SHC system has also been assessed, in which the PVT collectors have been replaced by evacuated tube collectors (ETCs), for the provision of heating and cooling to the University Campus, but without electricity generation. The results show that, in this case, the no generation of electricity limits the profitability of the ETC-based SHC system, which has 2.3 times longer *PBT* than the S-CCHP system. Therefore, it can be concluded that the lower price of natural gas compared to the electricity price hinders the potential of the solar thermal solutions when these systems are proposed to substitute current gas-fired boilers.

In order to understand the influence of utility prices on the economics of S-CCHP/SHC systems, two scenarios with current national utility prices of two countries are assessed: Italy, where the study is based, and Denmark, which was selected as it is the EU country with the highest combined utility prices. The results show that the cost-competitiveness of the solar systems considered here is very sensitive to these prices and that the proposed S-CCHP systems could become a promising decarbonisation solution, achieving a *PBT* of 10.2 years, if utility prices increase, which is likely to occur given recent trends.

In terms of the systems' potential for CO_2 emission reductions and primary energy savings, the results show that the PVT-based S-CCHP system has the potential to displace around 911 tons of CO_2 and to save around 5,460 MWh_{pe} of primary energy per year. By comparison, these values are 16% and 12% greater than those associated with the equivalent PV system, and 1.4 times and 3 times greater than those associated with the ETC-based SHC system. This promising environmental performance suggests that a useful avenue for further work involves complete environmental impact assessments through lifecycle analyses, which can provide a more holistic picture of the benefits of the proposed PVT-based S-CCHP system and any alternatives.

This work suggests that PVT-based S-CCHP systems have an important potential to decarbonise urban areas, in particular where space is at a premium since both electrical and thermal outputs are generated from the same area. Additional research on solar heating and cooling technologies is required to enhance efficiency and reduce investment costs, in order to make these solutions cost-competitive with other mature renewable energy alternatives such as commercial PV panels.

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